



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO DI RICERCA IN

FISICA

Ciclo 38

Settore Concorsuale: 02/A1 - FISICA SPERIMENTALE DELLE INTERAZIONI
FONDAMENTALI

Settore Scientifico Disciplinare: FIS/01 - FISICA SPERIMENTALE

DESIGN, CONSTRUCTION AND OPERATION OF A DRIFT CHAMBER
PROTOTYPE FOR THE SAND INNER TRACKER OF THE DUNE EXPERIMENT

Presentata da: Francesco Chiapponi

Coordinatore Dottorato

Alessandro Gabrielli

Supervisore

Alessandro Gabrielli

Co-supervisore

Michele Pozzato

Esame finale anno 2026

Abstract

The Deep Underground Neutrino Experiment is a long-baseline neutrino experiment under construction in the United States. It will be composed of a Near Detector system and a Far Detector composed of four multi-kt LArTPCs. The experiment will primarily measure the leptonic CP violation phase and discriminate the ordering of neutrino masses. One component of the Near detector complex is the System for on-Axis Neutrino Detection apparatus, which will host a calorimeter, a system of trackers, and an active LAr target inside a superconducting magnet.

A drift chamber-based tracking system is being developed, featuring passive target planes of polypropylene and carbon, to provide multiple nuclear targets for the measurement of neutrino cross-sections. A small-scale and a medium-scale drift chamber prototype have been built and tested at the CERN SPS H4 beam line.

My work focused on the design of the prototypes, their construction and commissioning. This thesis describes the R&D studies that I personally conducted to validate the proposal of a drift chamber-based tracker for SAND and presents the preliminary results obtained from the analysis of the beam test data.

As a corollary to these activities, the thesis also presents the results of the experimental tests and simulations of the noise affecting the front-end of the TIGER ASIC, executed in the context of the R&D project on μ RWELL detectors, which will compose the muon system of the IDEA detector for the Future Circular Collider. TIGER is used for the readout of μ RWELLS and was also employed during the drift chamber prototype beam test; hence, the studies on the TIGER front-end were synergistic with the work carried out for both DUNE and the FCC project. The results of the tests of the TIGER readout applied to μ RWELLS are presented, together with the beam test of several prototypes featuring different layouts.

Contents

Introduction	4
1 Neutrino Physics	6
1.1 Neutrinos in the Standard Model	6
1.2 Origin of neutrino masses	7
1.2.1 Dirac neutrinos	7
1.2.2 Majorana Neutrinos	9
1.2.3 Experimental searches	10
1.3 Theory of neutrino oscillations	11
1.3.1 Three flavors oscillations in vacuum	11
1.3.2 CP symmetry violation	13
1.3.3 Propagation in matter	13
1.4 Neutrino oscillation experiments	15
1.4.1 Solar neutrino experiments	15
1.4.2 Atmospheric neutrino experiments	16
1.4.3 Reactor neutrino experiments	18
1.4.4 Accelerator neutrino experiments	19
1.5 3ν global fits and open problems	21
1.5.1 Mass ordering	24
2 The DUNE experiment	25
2.1 The Long Baseline Neutrino Facility	26
2.2 Far Detector reference design	26
2.2.1 Horizontal Drift SP detector module	27
2.2.2 Vertical Drift SP detector module	27
2.3 Near Detector reference design	30
2.3.1 ND-LAr	32
2.3.2 ND-GAr	32
2.4 Scientific programme	34
2.4.1 Sensitivities and systematics	34
2.4.2 Sensitivity for neutrino mass ordering and CP-violation	36
2.4.3 Measurements of oscillation parameters	37
2.4.4 Supernova neutrino measurements	38
2.4.5 Oscillation physics with atmospheric and solar neutrinos	40
2.4.6 Proton decay measurements	40

3	System for on-Axis Neutrino Detection	42
3.1	Physics programme	42
3.1.1	Beam Monitoring	43
3.1.2	Reducing the systematic uncertainties	43
3.1.3	Precision measurements and searches for new physics	44
3.1.4	Requirements	45
3.2	Detector components	47
3.2.1	The superconducting magnet	47
3.2.2	The electromagnetic calorimeter	47
3.3	The inner tracker	48
3.3.1	The "solid hydrogen" concept	50
3.3.2	Straw Tube Tracker	51
3.3.3	Drift tracker	51
3.3.4	The GRAIN detector	51
4	The Drift Chamber proposal	54
4.1	Motivations and design	54
4.1.1	Drift chamber layout	55
4.1.2	Drift cell design	55
4.2	The $30 \times 30 \text{ cm}^2$ prototype	56
4.3	The $120 \times 80 \text{ cm}^2$ prototype design	57
4.3.1	Cathode planes	58
4.3.2	Wire planes	58
4.4	On detector electronics: design and production	62
4.4.1	Wire boards	63
4.4.2	Interface cards	63
4.4.3	Grounding scheme	64
4.5	Detector assembly	65
4.5.1	Cathode planes	65
4.5.2	Wire planes	68
4.5.3	External box	69
4.6	Quality controls	72
5	Readout Electronics and Preliminary Tests	78
5.1	Choice for the Readout Electronics	78
5.2	TIGER-GEMROC readout chain	79
5.2.1	Data Acquisition Software	79
5.3	Alternative readout with VTX amplifiers	81
5.4	Preliminary tests in Ferrara	83
5.4.1	Noise measurements	83
5.4.2	Functionality tests	84
6	Beam Test of the Drift Chamber prototype	87
6.1	The setup	87
6.2	Data taking	88
6.2.1	Acquisitions with VME electronics	90

7	Data analysis and preliminary results	92
7.1	The offline software	92
7.1.1	Hit digitisation with TIGER	92
7.1.2	Hit digitisation with VTX	93
7.1.3	GEM hit clusterisation	96
7.1.4	Detectors alignment	96
7.2	Preliminary analysis results	97
7.2.1	Drift cell efficiency	97
7.2.2	Distance-Time relation	98
7.2.3	Spatial resolution	100
	Conclusions	103
A	Introduction to Drift Chambers	105
A.1	Charge production	105
A.2	Drift and Diffusion	108
A.3	Charge multiplication	112
A.3.1	General considerations on the choice of the gas	113
A.4	Signal generation	113
A.5	Coordinate measurement	114
A.5.1	Coordinate measurement in the wire direction	117
A.6	Stability of operation	117
B	Review of Existing Drift Chambers	119
B.1	The KLOE Drift Chamber	119
B.2	The NOMAD Drift Chamber	121
B.3	The MEG II Drift Chamber	122
C	The μRWELL technology for the IDEA Muon System at FCC-ee and the TIGER/GEM-ROC readout system	127
C.1	The Future Circular Collider	127
C.2	The IDEA detector concept	129
C.2.1	Physics requirements	129
C.2.2	Detector components	130
C.2.3	The Muon System of the IDEA detector	132
C.3	The μ RWELL Technology	135
C.4	R&D Programme on μ RWELL Detectors	136
C.4.1	Resistivity Scan	137
C.4.2	Pitch Scan	137
C.4.3	Bidimensional Readout	139
C.4.4	TIGER-GEMROC Beam Test	143
C.5	Noise Studies	143
C.5.1	TIGER Front-End Simulations	146
C.6	Future prospects in μ RWELL R&D	149

Introduction

Since their discovery neutrino oscillations have become one of the most direct evidence of the fact that the Standard Model of particle physics is not a complete theory. The complementary use of multiple experimental channels and sources, exploiting either the solar and atmospheric neutrino fluxes or artificial ones produced by nuclear reactors or particle accelerators, has made possible to determine many of the parameters related to neutrino masses. However, some of them have yet to be determined, such as the ordering of neutrino masses and the potential CP-violating phase of the neutrino mixing matrix, the latter of which would have a profound impact on the whole lepton sector of particle physics.

The Deep Underground Neutrino Experiment (DUNE) will be a next-generation neutrino oscillation Long Baseline accelerator experiment, leveraging innovative detector technologies and the most powerful neutrino beam available at the time of completion.

To achieve its goals, the international DUNE experiment, hosted by the U.S. Department of Energy's Fermi National Accelerator Laboratory (Fermilab) in Illinois, comprises three central components: a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab, a massive far detector (FD) situated 1.5km underground at the Sanford Underground Research Facility (SURF) in South Dakota, 1300 km away, and a composite near detector (ND) installed just downstream of the neutrino source.

The Near Detector (ND) complex will be composed of three detectors able to provide complementary information on the neutrino beam and to refine the interaction models that will be necessary to analyse the FD data. The ND will also be capable of conducting searches on neutrino interactions, including a wide range of measurements of neutrino cross sections, studies of nuclear effects, and searches for dark matter, providing high-granularity and resolution.

The System for on-Axis Neutrino Detection (SAND) will be the only one in the ND complex to be fixed in an on-axis position, from which it will monitor the neutrino beam flux. The detector will reuse the magnet and calorimeter from the KLOE experiment. For the inner volume, a system of trackers and an active LAr target is planned. The tracking system will be based on a low-density tracker and thin ($1-2\%X_0$) passive target planes of CH_2 and carbon, which will provide multiple nuclear targets for the measurement of ν -p and ν -C cross-sections.

Two alternative options for the tracker are currently under study: a straw tube- and a drift chamber-based trackers. Small and medium scale prototypes of both options are being built. In this thesis I will illustrate their design and the procedures followed during the construction of the detectors, together with the quality controls that have been adopted to monitor the process and ensure a precise knowledge of the key parameters of the chamber, such as the effective tension applied to each wire, which is directly related to their sagitta. The beam test at the CERN SPS H4 beam line provided important data to characterise the performance of the drift chamber prototype in terms of drift cell efficiency, drift velocity, and spatial resolution of the single wire planes. Two different readout electronics were also tested, based on the TIGER ASIC and on the VTX preamplifier coupled to a VME digitiser, respectively.

This thesis is organised as follows:

- Chapter 1 presents an overview of the current status of neutrino physics from the theoretical and

experimental points of view;

- Chapter 2 describes the physics programme and design of the DUNE experiment;
- Chapter 3 describes the physics objectives and structure of the SAND detector;
- Chapter 4 is dedicated to a detailed description of the design and construction phases of the two drift chamber prototypes;
- Chapter 5 provides information about the beam test setup and the readout chain employed;
- Chapter 6 describes the offline software used for the analysis, together with the first results.
- Appendix A contains an overview of the drift chamber technology.
- Appendix B provides an overview of existing drift chambers from which the SAND drift chamber project took inspiration.
- Appendix C describes the beam tests conducted to characterise μ RWELL prototypes and the readout electronics, in the context of the R&D programme for the muon system of the IDEA detector.

Chapter 1

Neutrino Physics

1.1 Neutrinos in the Standard Model

The Standard Model of particles physics is a gauge theory defined by the $SU(3) \times SU(2)_L \times U(1)_Y$ symmetry, with the subscripts L and Y indicating the left chirality of the particles and their hypercharge, respectively.

Whereas the strong sector symmetry $SU(3)$ remains unbroken and therefore it is an exact symmetry at any energy level, the electroweak forces undergo spontaneous symmetry breaking via the Higgs mechanism, reducing the symmetry of the model at low energies to $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$, with Q being the electric charge.

Neutrinos in the Standard Model are massless neutral leptons that can interact only weakly, either via Neutral Current (NC) or Charged Current (CC) interactions, the first being mediated by Z^0 bosons, and the latter by $W^\pm$ bosons.

Three types, or flavor states, of neutrinos and antineutrinos are currently known: electron-type, muon-type and tau-type (ν_e , ν_μ and ν_τ respectively). They are defined by the charged lepton to which they couple in weak charged current interactions.

Flavor neutrino states take part in weak CC and NC processes described, to an impressive accuracy, by the Standard Model weak interaction Lagrangian terms [1]:

$$\mathcal{L}_I^{CC} = -\frac{g}{2\sqrt{2}} j_\alpha^{CC} W^\alpha + h.c., \quad j_\alpha^{CC} = 2 \sum_{l=e,\mu,\tau} \bar{\nu}_{lL} \gamma_\alpha l_L \quad (1.1)$$

$$\mathcal{L}_I^{NC} = -\frac{g}{2\cos\theta_W} j_\alpha^{NC} Z^\alpha, \quad j_\alpha^{NC} = 2 \sum_{l=e,\mu,\tau} \bar{\nu}_{lL} \gamma_\alpha l_L \quad (1.2)$$

where θ_W is the Weinberg angle .

Due to parity violation in weak interactions, only left-handed particles l_L , ν_{lL} or right-handed anti-particles $\bar{l}_R$, $\bar{\nu}_{lR}$ participate to the interaction. For this reason, only LH neutrinos and RH antineutrinos have been introduced in the SM.

The number of flavor states has been proven to be exactly three thanks to the precise measurement of the decay width of the Z boson, $Z \rightarrow \nu_\alpha \bar{\nu}_\alpha$ produced at LEP in e^+e^- collisions [2].

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu\nu}} = 2.984 \pm 0.008$$

This is clearly shown in Figure 1.1.

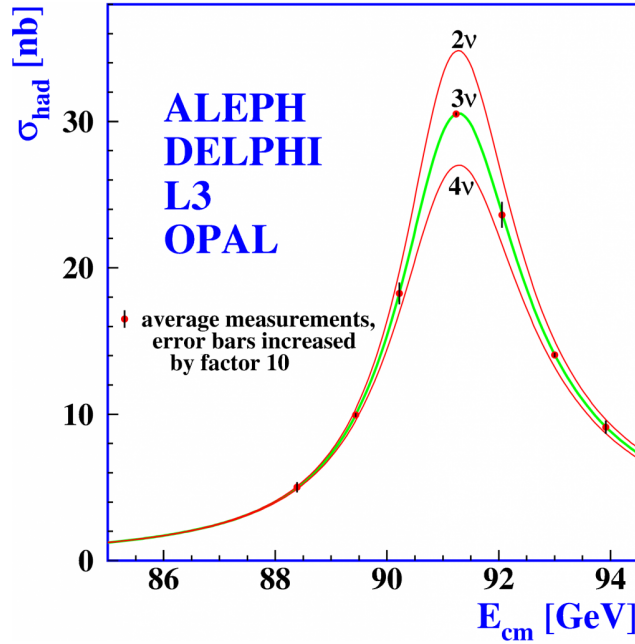


Figure 1.1: Comparison between experimental data from LEP and theoretical predictions of the total cross section for the production of hadrons as a function of the center-of-mass energy for the 2, 3 and 4 neutrino families. [2]

According to the SM, since neutrinos are massless their flavor is conserved during propagation. However, experimental evidences have proven neutrino mixing, indicating the existence of physics beyond the Standard Model (BSM).

1.2 Origin of neutrino masses

The discovery of neutrino oscillations has established one of the core aspects of neutrino physics: neutrinos have a non-zero mass. The origin of neutrino masses however is still uncertain, since there is a variety of possible ways to generate them. Considering the minimal version of the Standard Model, in which no RH neutrino is introduced, there is no way to generate a mass term for neutrinos via Yukawa couplings.

1.2.1 Dirac neutrinos

The simplest extension to the Standard Model which can give mass to neutrinos introduces the right-handed components of the flavor neutrino fields, $\nu_{\alpha R}$. They are called sterile neutrinos, since they are singlets under the whole gauge group and do not interact with any particle. In this so-called minimally extended Standard Model the asymmetry between the lepton and quark sector due to the absence of RH neutrino fields is removed, and Dirac mass terms for neutrinos are generated through the Brout-Englert-Higgs mechanism as with the other fundamental fermions.

$$\mathcal{L}_{mass}^{Dirac} = m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \quad (1.3)$$

where $\psi_{L(R)}$ is the left(right)-handed chiral component of the Dirac spinor ψ . The SM Higgs-lepton Yukawa Lagrangian takes the form:

$$\mathcal{L}_H = - \sum_{\alpha, \beta=e, \mu, \tau} Y'_{\alpha\beta} l_{\alpha L} \bar{\psi}_{\alpha L} \Phi l'_{\beta R} - \sum_{\alpha, \beta=e, \mu, \tau} Y'^{\nu}_{\alpha\beta} \bar{\psi}_{\alpha L} \tilde{\Phi} \nu'_{\beta R} + h.c., \quad (1.4)$$

where $\psi_{\alpha L}$ are the left-handed lepton isospin doublets while

$$\tilde{\Phi} = i\sigma_2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v+h \\ 0 \end{pmatrix}. \quad (1.5)$$

Performing the same operations as before the matrices of Yukawa couplings Y^l and Y^ν can be diagonalized:

$$V_L^{l\dagger} Y^l V_R^l = Y^l, \quad \text{with} \quad Y_{\alpha\beta}^l = y_{\alpha\beta}^l \delta_{\alpha\beta} \quad (\alpha, \beta = e, \mu, \tau)$$

and

$$V_L^{\nu\dagger} Y^\nu V_R^\nu = Y^\nu, \quad \text{with} \quad Y_{\alpha\beta}^\nu = y_{\alpha\beta}^\nu \delta_{\alpha\beta} \quad (k, j = 1, 2, 3).$$

Transforming the leptonic fields as follows,

$$\begin{aligned} l_L &= V_L^{l\dagger} l'_L = \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}, & l_R &= V_R^{l\dagger} l'_R = \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} \\ n_L &= V_L^{\nu\dagger} \nu'_L = \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}, & n_R &= V_R^{\nu\dagger} \nu'_R = \begin{pmatrix} \nu_{1R} \\ \nu_{2R} \\ \nu_{3R} \end{pmatrix} \end{aligned}$$

leads to the diagonalized Higgs-lepton Yukawa Lagrangian:

$$\begin{aligned} \mathcal{L}_H &= - \left(\frac{v+h}{\sqrt{2}} \right) [\bar{l}_L Y^l l_R + \bar{n}_L Y^\nu n_R] + h.c. \\ &= - \left(\frac{v+h}{\sqrt{2}} \right) \left[\sum_{\alpha, \beta=e, \mu, \tau} y_{\alpha\beta}^l \bar{l}_{\alpha L} l_{\beta R} + \sum_{k=1}^3 y_K^\nu \bar{\nu}_{kL} \nu_{kR} \right] + h.c.. \end{aligned} \quad (1.6)$$

The neutrino masses for the fields $\nu_k = \nu_{kL} + \nu_{kR}$ are given by:

$$m_k = \frac{y_k^l v}{\sqrt{2}} \quad (k = 1, 2, 3). \quad (1.7)$$

Although this mechanism of generation of neutrino masses is legitimate, if we look at the value of the Yukawa coupling g_{ν_e} , it is many orders of magnitude smaller than the couplings for the other fermions [3]:

$$2 \cdot 10^{-13} \leq g_{\nu_e} \leq 10^{-12} \quad \text{while} \quad g_t \simeq 7 \cdot 10^{-1}, \quad g_b \simeq 2 \cdot 10^{-2}, \quad g_\tau \simeq 7 \cdot 10^{-3}$$

It looks extremely implausible that they have a common origin. This is also true if we think about the smallness of neutrino masses: even if their absolute values are still unknown, neutrino oscillation and cosmological data have estimated the mass of the heaviest neutrino to be

$$5 \cdot 10^{-2} \text{eV} \simeq \left(\sqrt{\Delta m_A^2} \right) \leq m_3 \leq \left(\frac{1}{3} \sum_i m_i \right) \simeq 3 \cdot 10^{-1} \text{eV}$$

where Δm_A^2 is the atmospheric neutrino mass-squared difference [3].

For these reasons, other explanations for neutrino masses have also been considered. A new beyond-the-Standard Model theory has been developed trying to account for neutrino masses generation in a more natural way. To be precise there is not a single theory but many [4, 3, 5]. One of the most popular is the Weinberg effective Lagrangian, which allows the introduction of neutrino masses using only left-handed Majorana neutrino fields.

1.2.2 Majorana Neutrinos

A new Lorentz invariant mass term can be generated exploiting the fact that the charge conjugated field

$$\nu_{eL}^c = C\bar{\nu}_{eL}^T \quad (1.8)$$

is right-handed. A generic Majorana mass term may be written as

$$-\frac{1}{2}m_M\bar{\nu}_{eL}\nu_{eL}^c + h.c. \quad (1.9)$$

It is straightforward to see that the above mass term is not invariant under a global $U(1)$ transformation

$$\nu_{eL} \rightarrow e^{-i\theta}\nu_{eL} \quad (1.10)$$

corresponding to the non conservation of lepton number L . Considering all neutrino flavors, the Majorana mass term has the form

$$\mathcal{L}^M = -\frac{1}{2}\bar{\nu}_L M^M \nu_L^c + h.c. \quad (1.11)$$

where M^M is a complex 3×3 matrix. It can be diagonalised by the transformation $M^M = U m U^T$, with $U U^\dagger = 1$ and $m_{ik} = m_i \delta_{ik}$, $m_i > 0$. Lagrangian 1.11 thus becomes

$$\mathcal{L}^M = -\frac{1}{2} \sum_{i=1}^3 m_i \bar{\nu}_i \nu_i \quad (1.12)$$

where ν_i are mass eigenstates with eigenvalues m_i .

$$\nu_i = \sum_l U_{il}^\dagger \nu_{lL} + \sum_l (U_{il}^\dagger \nu_{lL})^c \quad (1.13)$$

It's straightforward to verify that the field ν_i satisfies the Majorana condition $\nu_i = \nu_i^c$, and that the flavor neutrino fields ν_{lL} are given by a superposition of mass eigenstates ν_i , whose contributions are weighted by coefficients U_{il} .

$$\nu_{lL} = \sum_{i=1}^3 U_{li} \nu_i \quad (1.14)$$

The matrix U is called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

Type-I seesaw mechanism

The Standard Model for three generations of neutrinos can be extended to contain m right-handed neutrinos ν_R building a gauge invariant renormalizable Lagrangian $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\nu_R}$

$$\mathcal{L} = i\bar{\nu}_L \gamma^\mu \partial_\mu \nu_L + i\bar{\nu}_R \gamma^\mu \partial_\mu \nu_R - \bar{\nu}_L M_D \nu_R - \frac{1}{2}\bar{\nu}_L^c M_L \nu_L - \frac{1}{2}\bar{\nu}_R^c M_R \nu_R + h.c. \quad (1.15)$$

It contains a $m \times 3$ complex Dirac mass matrix M_D together with Majorana mass matrices M_L and M_R for left-handed and right-handed neutrinos, which are respectively $m \times m$ and 3×3 symmetric matrices [6]. Notice that Majorana mass terms are not produced through SM Higgs mechanism and Spontaneous Symmetry Breaking. Writing the complete mass term for $3 + m$ neutrino generations results in

$$\mathcal{L}_{mass} = -\frac{1}{2} (\bar{\nu}_L \bar{\nu}_R^c) \begin{pmatrix} M_L & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c. \quad (1.16)$$

where $\nu = (\nu_L, \nu_R^c)^T$ is a $(3 + m)$ -dimensional vector. Since the Majorana mass term for LH neutrinos is forbidden from SM gauge invariance, it is physically reasonable to choose $M_L = 0$.

The mass matrix can be diagonalised by unitary matrix U to give $3 + m$ mass eigenstates. If the mass eigenvalues of M_R are much higher than the scale of electroweak symmetry breaking v , we obtain three light neutrinos ν_l and m heavy neutrinos, N .

$$U^T \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} U = \begin{pmatrix} M_l & 0 \\ 0 & M_h \end{pmatrix} \quad (1.17)$$

$$\mathcal{L}_{mass} = -\frac{1}{2} \bar{\nu}_l M^l \nu_l - \frac{1}{2} \bar{N} M^h N \quad (1.18)$$

where M_l and M_h are 3×3 and $m \times m$ real diagonal matrices.

This way values for LH neutrino masses compatible with experimental bounds are obtained.

1.2.3 Experimental searches

Different methods are used to estimate the absolute neutrino mass: cosmological studies, search for neutrinoless-double β decay and direct measurements based on the kinematics of single β decay.

Neutrinoless double-beta decay

The most promising experimental technique to confirm whether neutrinos are Majorana particles or more canonical Dirac fermions is the search for the neutrinoless double-beta decay [7], a process which is possible only if neutrinos and antineutrinos are the same particle. While in the normal double-beta decay a nucleus undergoes two simultaneous beta decays emitting two antineutrinos, via $(A, Z) \rightarrow (A, Z + 2) + 2e + 2\bar{\nu}$, if neutrinos are Majorana particles the antineutrino emitted by a nucleon is absorbed by the second nucleon, resulting in a final state which contains only two electrons, $(A, Z) \rightarrow (A, Z + 2) + 2e$. This implies that lepton number L gets violated in the decay. Figure 1.2 shows the characteristic discrete spectrum which would be the signature of this process, since the sum of the energies of the two electrons would correspond to the total available energy.

Some of the experiments which are investigating this field include CUPID, Gerda and CUORE. [8, 9, 10]. The strongest constraints up to date are set by KamLAND-Zen collaboration, using Xenon: half-life time of the decay $T_{1/2} > 1.1 \times 10^{26}$ years and effective Majorana mass $m_{\beta\beta} < (0.06 - 0.16)\text{eV}$ [11].

Single β decay

The single β decay of tritium, $\text{H}^3 \rightarrow \text{He}^3 + e^- + \bar{\nu}_e$, can provide an efficient way to assess the neutrino mass. In the decay kinematics the neutrino mass modifies the phase space for the emission of electrons with kinetic energy E . The shape distortion of the differential β decay spectrum

$$R_\beta(E; E_0, m_\nu^2) \propto (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2} \quad (1.19)$$

is maximal near the kinematic endpoint E_0 , which is defined as the maximal energy of the β decay electrons assuming a zero neutrino mass. The squared effective electron antineutrino mass, $m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$, is probed with a precise measurement of the β decay spectrum shape near the endpoint.

The most stringent results on the effective electron antineutrino mass were obtained by the KATRIN experiment [13], which obtained a best-fit value of $m_\nu^2 = -0.14_{-0.15}^{+0.13}\text{eV}^2$, setting an upper limit of 0.45 eV (90% CL). Other results were obtained by the Troitsk [14] and Mainz [15] experiments, which found respectively $m_\nu < 2.05\text{eV}$ (95% CL) and $m_\nu < 2.3\text{eV}$ (95% CL).

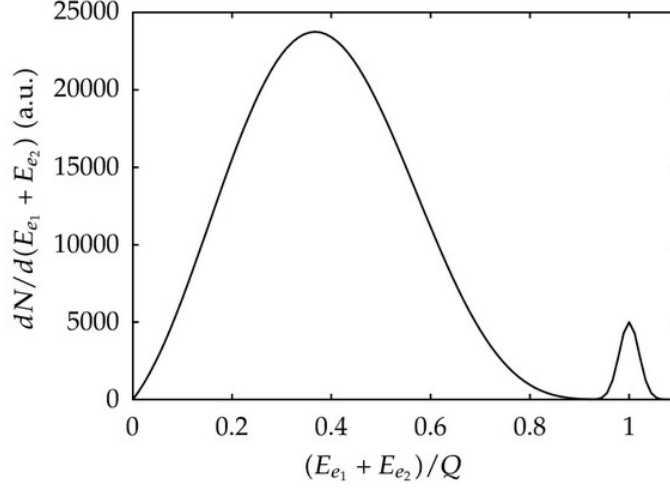


Figure 1.2: Distribution of the sum of the two electron energies for $0\nu\beta\beta$ and $2\nu\beta\beta$, obtained assuming that the $2\nu\beta\beta$ rate is 100 times faster than the $0\nu\beta\beta$, and the FWHM detector energy resolution is 5%. [12]

Cosmological observations

Cosmological data are able to provide the most stringent limits on the neutrino masses. Experiments such as WMAP and Planck provide an upper limit of the sum of the three flavors masses. Such results are model dependent and, considering the Λ CDM Standard Cosmological Model, it is possible to obtain $\sum m_\nu < (0.11 - 0.54)\text{eV}$ [16].

1.3 Theory of neutrino oscillations

Neutrino oscillations are a quantum mechanical phenomenon due to neutrinos being produced via charged current interactions as flavor states, which are a linear superposition of mass eigenstates. Since different mass eigenstates evolve differently as the neutrino propagate, the flavor composition of a neutrino state can change with time. This theory arises naturally if the neutrino mass is non-zero: in this case there is no reason to expect the mass eigenstates ν_k to coincide with the flavor eigenstates ν_α . Neutrino oscillations were first proposed by Bruno Pontecorvo in 1957 and confirmed in 1998 by the Super-Kamiokande experiment, providing a clear evidence that the Standard Model is not a complete theory [17].

1.3.1 Three flavors oscillations in vacuum

The 3 orthonormal flavor eigenstates ν_α (where $\alpha = e, \mu, \tau$) are connected to 3 orthonormal mass eigenstates ν_i via the PMNS mixing matrix U [17]:

$$\nu_\alpha = \sum_{i=1}^3 U_{\alpha i} \nu_i \quad \nu_i = \sum_{\alpha} U_{\alpha i}^* \nu_\alpha \quad (1.20)$$

If we are dealing with Dirac neutrinos, it is characterised by three mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and the Dirac charge-parity (CP) symmetry-violating phase δ . It can be seen as the product of three rotations

(one depending on the δ phase):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{23} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ 0 & -s_{13}e^{-i\delta} & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.21)$$

where $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$. In the standard parametrization it has the form

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \quad (1.22)$$

If instead neutrinos are Majorana particles, two additional phases α_1 and α_2 enter in the mixing matrix through the diagonal matrix S^M

$$U^M = US^M(\alpha) \quad (1.23)$$

where

$$S^M(\alpha) = \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.24)$$

The mass eigenstates ν_i show a time dependence:

$$\nu_i(t) = e^{-iE_it} \nu_i \quad (1.25)$$

with $E_i = \sqrt{p^2 + m_i^2}$ in natural units (i.e. $c=1$). If we consider a flavor state $\nu_\alpha(t)$ which represents a neutrino of definite flavor created at $t=0$ ($\nu_\alpha(0) = \nu_\alpha$), from Eq. 1.20 and 1.25 the time evolution of this state is given by:

$$\begin{aligned} \nu_\alpha(t) &= \sum_i U_{\alpha i} e^{-iE_it} \nu_i \\ &= \sum_\beta \left(\sum_i U_{\alpha i}^* e^{-iE_it} U_{\beta i} \right) \nu_\beta \end{aligned} \quad (1.26)$$

The amplitude of the transition $\nu_\alpha \rightarrow \nu_\beta$ is then:

$$\mathcal{A}_{\nu_\alpha \rightarrow \nu_\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_i U_{\alpha i}^* U_{\beta i} e^{-iE_it} \quad (1.27)$$

The transition probability is given by the square of the modulus of the amplitude:

$$P_{\nu_\alpha \rightarrow \nu_\beta}(t) = |\mathcal{A}_{\nu_\alpha \rightarrow \nu_\beta}(t)|^2 = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* e^{-i(E_i - E_j)t} \quad (1.28)$$

Due to their tiny masses, neutrinos are always ultra-relativistic ($p \gg m$) and we can approximate in natural units:

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}; \quad t \simeq L \quad (1.29)$$

with L being the distance travelled by the neutrinos. Equation 1.28 can be written as:

$$\begin{aligned} P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) &= \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{ij}^2 L}{2E}\right) \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \\ &\quad + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right) \end{aligned} \quad (1.30)$$

where $\Delta m_{ij}^2 = m_i^2 - m_j^2$.

As can be seen from Eq. 1.30 the oscillation depends on Δm_{ij}^2 , three mixing angles θ_{ij} and the Dirac CP-violating phase δ . It also depends on the ratio L/E , which is one of the main features that define the different types of neutrino oscillation experiments. Historically Δm_{21}^2 is called "solar mass splitting", while Δm_{31}^2 is the "atmospheric mass splitting".

Furthermore, looking at the expression for the mixing matrix U , one can notice that the two complex Majorana phases $\alpha_{1,2}$ do not enter in the oscillation probability. This means that oscillation experiments cannot tell whether neutrinos are Dirac or Majorana particles.

From Eq. 1.30 it is possible to derive the survival probability for the flavor ν_α :

$$P_{\nu_\alpha \rightarrow \nu_\alpha}(L, E) = 1 - 4 \sum_{k>j} |U_{\alpha k}|^2 |U_{\alpha j}|^2 \sin^2 \left(\frac{\Delta m_{kj}^2 L}{2E} \right) \quad (1.31)$$

1.3.2 CP symmetry violation

Experimentally has been demonstrated that all mixing angles are not null. As a consequence, if the Dirac phase δ were equal to 0 or π , no CP violation would be present in neutrino oscillations. This would introduce an asymmetry in the behaviour of neutrinos and antineutrinos leading to a difference in the probability of $\nu_\alpha \rightarrow \nu_\beta$ with respect to its CP conjugate $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$.

An observable for such effect would be the CP asymmetry

$$A_{\alpha\beta}^{CP} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \quad (1.32)$$

for $\alpha \neq \beta$ and $\alpha, \beta = e, \mu, \tau$.

From the definition of transition probability the previous expression becomes

$$\begin{aligned} A_{\alpha\beta}^{CP} &= 4 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right) \\ &= 4 s_{\alpha\beta} J_{CP} \left(\sin \frac{\Delta m_{32}^2 L}{2E} + \sin \frac{\Delta m_{21}^2 L}{2E} + \sin \frac{\Delta m_{31}^2 L}{2E} \right) \end{aligned} \quad (1.33)$$

where $s_{\mu e} = 1 = s_{\tau\mu}$ and $s_{\tau e} = -1$. J_{CP} is called Jarlskog invariant

$$J_{CP} = \text{Im}(U_{\mu 3} U_{e 3}^* U_{e 2} U_{\mu 2}^*) = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin \delta \quad (1.34)$$

In order to have $J_{CP} \neq 0$, and hence a non vanishing asymmetry $A_{\alpha\beta}^{CP}$, the three mixing angles and the phase δ must be all non-zero, the neutrino masses must be all different, and $\alpha \neq \beta$.

From the last requirement it is clear that the neutrino survival probabilities $P_{\alpha\alpha}$ are independent from the CP violating phase δ . The search for CP violation should be performed looking for a difference between the neutrino and antineutrino oscillation probabilities between different flavors. This difference arises from the phase δ in the leptonic mixing matrix, but it is also influenced by the effects of the neutrino propagation through the Earth crust, as we will discuss in the next paragraph.

1.3.3 Propagation in matter

While neutrinos travel through matter, they can coherently interact with electrons and nuclei in the medium and their oscillation probability is modified. This effect is called the MSW effect, from the names of the physicists Mikhaev, Smirnov and Wolfenstein, who first pointed it out [18, 19].

The MSW effect originates from the fact that electron neutrinos and antineutrinos have different interactions with matter compared to other flavor states, in particular ν_e is the only flavor which can take part both in CC interactions, and NC elastic interactions with electrons, while ν_μ and ν_τ can only have NC interactions with electrons. This means that electron neutrinos will feel an extra potential:

$$V_e = \pm \sqrt{2} G_F N_e \quad (1.35)$$

where N_e is the electron number density in the medium, G_F is the Fermi constant and the sign is positive for neutrinos and negative for antineutrinos. It is often a good approximation to consider that the oscillations take place just between two generations. U can be considered in this case as the 2×2 rotation matrix with mixing angle θ .

$$R_\theta = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad (1.36)$$

If we consider electron neutrinos propagating in a dense medium (e.g. the Sun or the Earth) it is convenient to define the *matter* mixing angle θ_m , such that the neutrino matter eigenstates can be written as

$$\begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix} = R_{\theta_m}^T \begin{pmatrix} \nu_e \\ \nu_\alpha \end{pmatrix} \quad (1.37)$$

The survival probability for electron neutrinos would be

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_m \sin^2 \left(\frac{\Delta\mu^2 L}{4E} \right) \quad (1.38)$$

where θ_m and $\Delta\mu^2$ are the mixing angle and the squared mass difference due to matter effects:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta} \quad (1.39)$$

$$\Delta\mu^2 = \Delta m^2 \sqrt{(\cos 2\theta - a)^2 + \sin^2 2\theta} \quad (1.40)$$

Here a is related to the electron density in matter

$$a = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} \quad (1.41)$$

but it could also be rewritten as the ratio between the oscillation length and the matter induced refraction length

$$a = \frac{L_{osc}}{L_m} \quad \text{where} \quad L_m = \frac{2\pi}{\sqrt{2} G_F N_e} \simeq 7600 \text{ km} \left(\frac{0.5}{Y_e} \right) \left(\frac{5 \text{ g} \cdot \text{cm}^{-3}}{\rho} \right) \quad (1.42)$$

where we used also $N_e = Y_e \rho / m_p$, being $Y_e = N_e / (N_n + N_p)$ the number of electrons per nucleon.

We should point out that the survival probability in Eq. 1.38 is computed considering a constant density for the propagation medium, which is sometimes a good approximation for the Earth. In this case the matter effects just change the mixing angle and the frequency of the oscillations among neutrinos. If we consider instead the case of the Sun, whose density cannot be assumed to be uniform, the mixing angle would change continuously.

In order to observe significant matter effects long baselines or high matter densities are required. Furthermore, neutrino oscillations can be highly enhanced if the resonant condition for a is met. When $\cos 2\theta = a$ the matter mixing angle becomes maximal, i.e. $\theta_m = \pi/4$, while the effective mass splitting becomes minimum, taking the value $\Delta\mu^2 \simeq \Delta m^2 \sin 2\theta$. This happens regardless of the value of θ . At the resonance we have then $L_{osc} = L_m \cos 2\theta$.

Since the parameter a depends on the sign of Δm^2 , oscillation probabilities for neutrinos and antineutrinos can be different even without CP violation. Moreover, since the resonant condition happens only for $a > 0$, this could provide important information on the neutrino mass hierarchy.

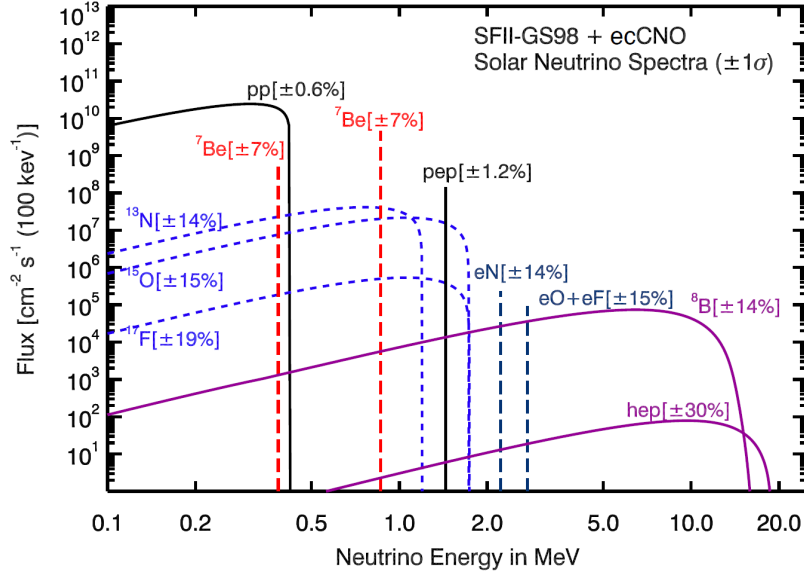


Figure 1.3: Spectrum of the different solar neutrino contributions. [26].

1.4 Neutrino oscillation experiments

Neutrino oscillation experiments are built in order to retrieve the PMNS parameters and the mass-squared difference. It is possible to make a first subdivision between different neutrino oscillation experiments, depending on which probability the experiment is trying to measure: *appearance* experiments measure the presence of neutrino flavors that are not present in the initial composition of the flux, while *disappearance* experiments measure the survival probability of neutrino flavors generated at the production point, comparing the initial and final flux.

A further distinction can be made based on the parameters different experiments are sensitive to, since experiments using different neutrino sources are sensitive to different sets of parameters. The most relevant ones are:

1. Solar neutrino experiments, sensitive to $\sin^2 \theta_{12}$ and Δm_{21}^2
2. Reactor neutrino experiments, sensitive to θ_{13} and Δm_{21}^2
3. Atmospheric neutrino experiments, sensitive to $\sin^2 \theta_{23}$ and Δm_{31}^2
4. Accelerator experiments, sensitive to δ_{CP} , $\sin^2 \theta_{23}$, Δm_{31}^2 , Δm_{32}^2 and θ_{13}

1.4.1 Solar neutrino experiments

This class of experiments comprehend radiochemical experiments, such as Homestake, Gallex/GNO [20, 21] and Sage, and Cherenkov experiments such as Kamiokande and Super-Kamiokande [22, 23], together with SNO [24, 25]. Figure 1.3 shows the flux of solar neutrinos which is composed, according to the Standard Solar Model (SSM), by electron neutrinos originated from various reactions, in an energy range between 0.1 to 20 MeV [27].

Radiochemical experiments exploit the inverse beta decay reaction of solar neutrinos with ^{37}Cl , ^{71}Ga or ^{71}Ge . The Homestake experiment, running from 1970 to 1994, was able to detect ν_e with an energy threshold above 800 keV, through the reaction $\nu_e + ^{37}\text{Cl} \longrightarrow ^{37}\text{Ar} + e^-$. It observed only one third of

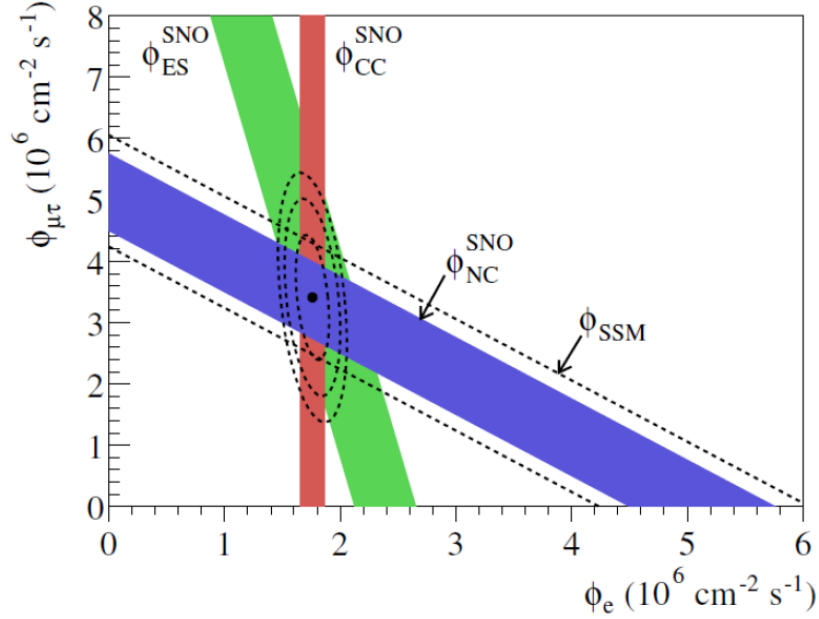


Figure 1.4: Flux of muon and tau neutrinos $\Phi_{\nu\tau}$ over electron neutrino Φ_e as measured by SNO. The three coloured bands correspond to the three possible interactions: electron scattering ES (green); charged current CC (red); neutral current NC (blue). The dashed band gives the prediction from the SSM which is in agreement with the NC measurements [28].

the expected flux of solar neutrinos predicted by the SSM model. This was the origin of the so-called *solar neutrino problem*. Subsequent experiments, namely Gallex (Gallium Experiment), its successor GNO (Gallium Neutrino Observatory) and Sage (Soviet-American Gallium Experiment) confirmed a deficit of 1/2 w.r.t. the predicted SSM flux. Thanks to an energy threshold lowered down to 233 keV, these experiments managed to be sensitive to the dominant pp reaction.

The Kamiokande and Super-Kamiokande (SK) water Cherenkov experiments confirmed in turn the 1/2 deficit. Cherenkov detectors are able to measure elastic scattering processes. Their main advantages therefore are the sensitivity to the three neutrino flavors, and the possibility to reconstruct direction and energy, since neutrino elastic scattering processes $\nu_x e \rightarrow \nu_x e$ preserve directionality.

The Sudbury Neutrino Observatory (SNO) provided a crucial independent measurement of CC and NC interactions of solar neutrinos using heavy water as scintillator. The experiment was sensitive to three main reactions: the CC interactions $\nu_e + d \rightarrow p + p + e^-$, the NC interaction $\nu_x + d \rightarrow p + n + \nu_x$, and the elastic scattering $\nu_x + e^- \rightarrow \nu_x + e^-$. The important result of SNO was the solution to the solar neutrino problem, since the combined ν_τ and ν_μ fluxes were found to be two times more intense than the ν_e one, while the total flux was in agreement with the predictions from the SSM. This is shown in Figure 1.4.

1.4.2 Atmospheric neutrino experiments

Atmospheric neutrinos are produced by the decay of mesons resulting from cosmic ray interactions with the atmosphere. K and π decays give mainly ν_μ 's while μ decay gives both ν_μ 's and ν_e 's. It is possible to distinguish different types of experiments built to detect atmospheric neutrinos. Experiments such as

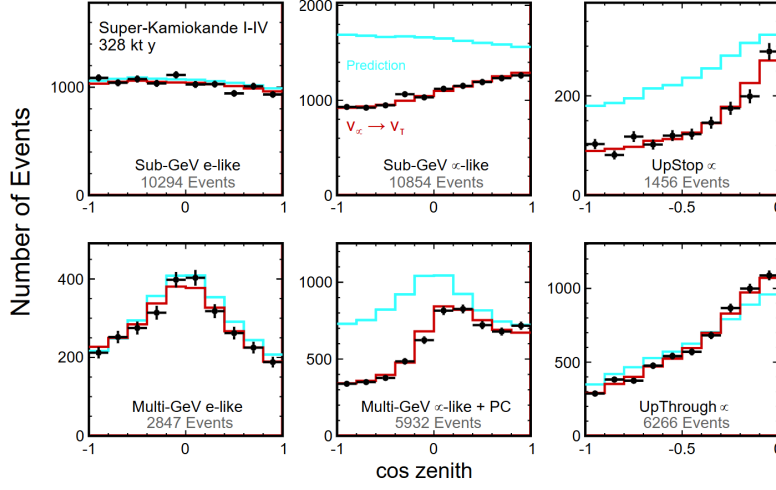


Figure 1.5: Super-Kamiokande results: experimental data are compared to MC predictions with (red histograms) and without (blue histograms) the contribution of neutrino oscillations [26].

Soudan-2 [29] and MACRO [30] use iron calorimeters, constituted of layers of iron, acting as a passive material, and active plastic scintillators layers, which are able to track electromagnetic showers produced by $e^\pm$ or long muon tracks. The Super-Kamiokande and IMB [31] experiment instead exploit Cherenkov emission.

The measurements performed in the 80's and 90's observed a noticeable ν_μ deficit, later confirmed in 1998 by Super-Kamiokande. SK showed that while the electron events had no reduction, the muon events had a deficit of almost 50% for up-going neutrinos (see Figure 1.5). This is a clear effect of atmospheric neutrino oscillations from ν_μ to ν_τ . These results were later confirmed by Soudan-2 and MACRO.

In more recent years another class of atmospheric experiments have contributed to the study of atmospheric neutrino oscillations detecting Cherenkov light emitted by muons produced in ν_μ CC interactions in ice or sea water. ANTARES, IceCube and KM3NeT are neutrino telescopes built for high-energy neutrino astronomy.

ANTARES consists of an array of PMTs deployed under the Mediterranean Sea, at a depth of about 2.5 km, instrumenting a 10^5 m^3 volume [32]. The KM3NeT project [33] is based on the same technology of ANTARES, with a different design and improved detectors. It is composed by two blocks of three-dimensional array of PMTs: the first is ARCA (Astroparticle Research with Cosmics in the Abyss), located near Capo Passero (Sicily, Italy), while the second is called ORCA (Oscillation Research with Cosmics in the Abyss), off-shore Toulon (France). IceCube is a detector deployed in ice in Antarctica at the South Pole, at a depth between 1.45 and 2.45 km. From 2010 a new component has been added to the existing array of ice-buried PMTs: a region of $\sim 10^7 \text{ m}^3$ volume with denser PMT spacing called DeepCore to extend the observable energies down to 10 GeV.

The aforementioned experiments have been able to measure ν_μ disappearance by observing the interactions of up-going ν_μ . ANTARES reported a measurement of ν_μ disappearance with 20 GeV threshold [34]. The ν_μ disappearance measurements from IceCube DeepCore [35] provided a precision comparable to the measurements by Super-Kamiokande and long-baseline accelerator neutrino experiments.

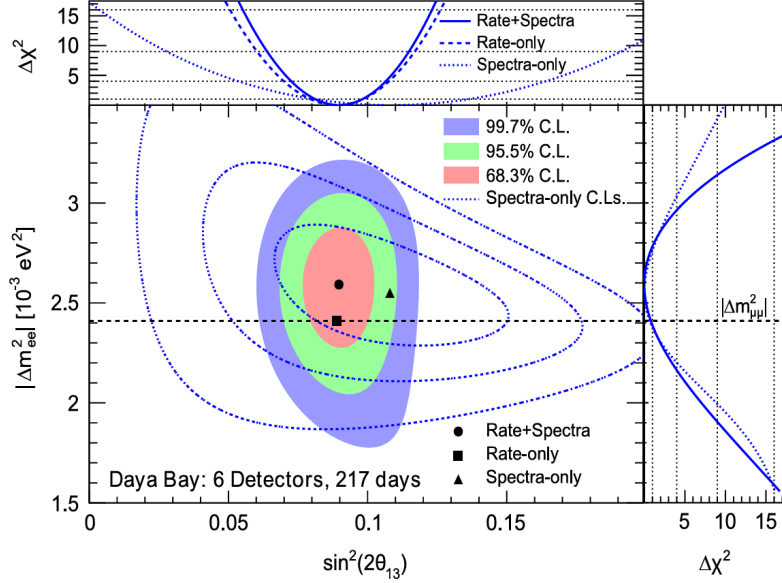


Figure 1.6: Allowed regions for $\sin^2 2\theta_{13}$ and $\Delta m_{ee}^2 = \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$, obtained from a Daya Bay [41].

1.4.3 Reactor neutrino experiments

Beta decays of fission fragments produce electron antineutrinos, which are emitted isotropically from the reactor core. Reactor experiments can measure the disappearance probability of the $\bar{\nu}_e$ exploiting the inverse beta decay process $\bar{\nu}_e + p \rightarrow e^+ + n$. This process can be detected by looking for the coincidence of the positron and the neutron signals. The positron can be detected through the two photons emitted by the annihilation with a surrounding electron, while the neutron, once thermalised, undergoes neutron capture on nucleus, producing a delayed energy release with respect to the photon signal.

Among reactor experiments, we can count Long Baseline experiments, like KamLAND [36], and Short Baseline experiments such as Daya Bay [37], Double Chooz [38], and RENO [39]. KamLAND consisted in 1 kt of high-purity liquid scintillator optimised to study the Δm_{12}^2 oscillation parameter. Combining its results with those from solar neutrino experiments it was able to constrain a small allowed region for the values of Δm_{12}^2 and θ_{12} [40]:

$$\Delta m_{12}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{eV}^2 \quad (1.43)$$

$$\tan^2 \theta_{12} = 0.44 \pm 0.03 \quad (1.44)$$

The Daya Bay detector design was very similar to that of Double Chooz and RENO, consisting of a cylindrical stainless steel vessel that houses two nested acrylic cylindrical vessels. The innermost vessel is filled with gadolinium-doped liquid scintillator as the primary antineutrino target. It is surrounded by a liquid scintillator layer to contain γ rays from the target volume.

The light from liquid scintillator is detected by an array of PMTs mounted on the stainless steel vessel. Optically separated by the vessel, the outside region is instrumented as a veto detector with either liquid scintillator (Double Chooz) or water Cherenkov (Daya Bay and RENO) detector. The first definite and most precise measurement of θ_{13} has been achieved by the Daya Bay collaboration, see Figure 1.6.

1.4.4 Accelerator neutrino experiments

A conventional neutrino beam is generated by colliding high-energy protons onto a target, producing pions and kaons, which then decay into neutrinos or antineutrinos. Before decaying, the beam of charged π and K is focused using magnetic horns, while other undesired particles are stopped in the beam dump. By selecting the direction of the current inside the horns, it is possible to choose the dominant component of the beam to be either neutrinos or antineutrinos.

Since pions are the most abundant product of high energy collisions, an accelerator neutrino beam usually contains a dominant amount of muon-type neutrinos, coming from the decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ or $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$. However, there will always be contamination from wrong sign neutrinos, and even from ν_e or $\bar{\nu}_e$ coming from kaon and muon decays. For this reason many accelerator experiments employ a second detector in addition to the main one, in order to monitor the beam providing information about the flux, the energy spectrum, and the interaction cross sections. It is usually located close to the beam source, and for this reason it's called *near detector*.

The energy of the neutrino beam E_ν depends on that of the parent pion beam E_π , according to the relation

$$E_\nu = \frac{[1 - (m_\mu/m_\pi)^2]E_\pi}{1 + \gamma^2\theta^2} \quad (1.45)$$

where $\gamma = E_\pi/m_\pi$ and θ is the angle between the pion and the neutrino direction. One can notice that if $\theta = 0$, E_ν is linearly proportional to the pion energy, while for $\theta \neq 0$ the energy of neutrinos depends on the off-axis angle θ , being not so strongly dependent on E_π for a wide range of pion energies. This method allows to obtain a neutrino beam with a narrow energy spectrum, peaked at the energy determined by θ . Indeed, it has been adopted in T2K and NOvA experiments, and it has been chosen for the DUNE experiment too.

Accelerator experiments must tune the ratio of baseline and neutrino energy (L/E) in order to maximise the sensitivity to the oscillation effects to be studied. It is possible to distinguish between Short Baseline (SBL) and Long Baseline (LBL) experiments. SBL experiments have a baseline of 1 km and are able to study neutrino oscillations at the 1 eV scale. On the other hand, LBL experiments use 1 GeV neutrino beams and a baseline ranging from a few hundred to a thousand km in order to study the parameter region around the first oscillation maximum at $L/E \sim 500 \text{ GeV/km}$, originated by the atmospheric mass splitting $\Delta m_{31}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2$.

Short Baseline experiments

The Liquid Scintillator Neutrino Detector (LSND) experiment searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations exploiting the inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$. The detector was a tank filled with 167 t of diluted liquid scintillator, located 30 m from the neutrino source. It found an excess of $87.9 \pm 22.4 \pm 6.0$ events over the expected background [42].

The MiniBoone experiment at Fermilab investigated the same parameter space as LSND, additionally searching for ν_e appearance. It profited from the Booster Neutrino Beamline (BNB) which produces a neutrino (antineutrino) beam with an energy spectrum peaked at 600 (400) MeV. The detector consisted of a 12.2 m diameter sphere filled with 818 t of mineral oil, 541 m far from the beam origin. The experiment reported an excess in both neutrino and antineutrino modes with a 4.8σ significance [43].

The short-baseline neutrino (SBN) programme [44] consists of three liquid Argon time-projection chamber detectors located along the BNB at Fermilab. Starting from the closest one from the beam source, there is the Short-Baseline Near Detector, located 110 m from the production target, followed by MicroBooNE (470 m) and ICARUS (600 m). SBN main goals include searches for New Physics, such as eV-scale sterile neutrinos, detailed studies of neutrino–nucleus interactions at the GeV energy scale, and the advancement of the liquid Argon detector technology that will also be used in the DUNE/LBNF Long Baseline neutrino experiment in the next decade.

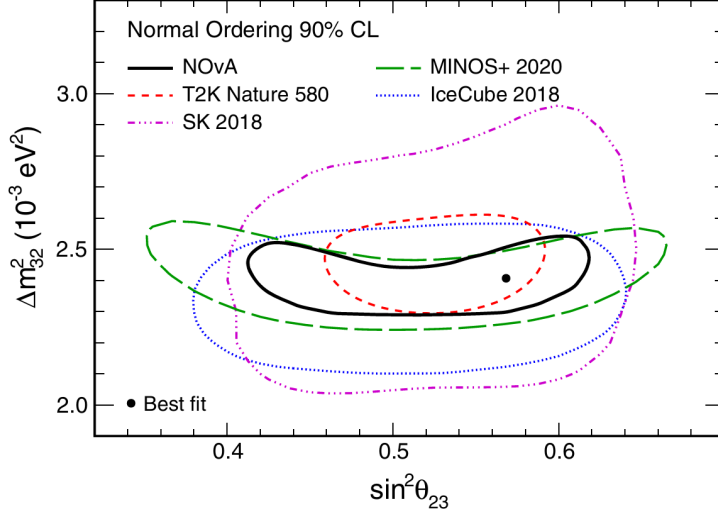


Figure 1.7: The 90% confidence level region for Δm_{32}^2 and $\sin 2\theta_{23}$ [51].

Long Baseline experiments

Among LBL accelerator experiments, K2K (KEK-to-Kamioka) [45] in Japan and MINOS (Main Injector Neutrino Oscillation Search) [46] at Fermilab were the first to confirm the atmospheric oscillation results. K2K used the KEK proton synchrotron to produce a ~ 1.3 GeV ν_μ beam directed towards the Super-Kamiokande detector. The near detector, located 300 m from the neutrino source, was a 1 kt water Cherenkov detector combined with a set of fine-grained detectors. K2K measured the ν_μ disappearance with a confidence level of 4.3σ , obtaining also a value for $\Delta m_{31}^2 = 2.8 \times 10^{-3} \text{eV}^2$. This results were in good agreement with the one obtained by MINOS, which measured $\nu_\mu \rightarrow \nu_\mu$ oscillations. The MINOS detectors (the near and far detectors) were both iron-scintillator tracking calorimeters with toroidal magnetic fields. The far detector, located in the Soudan mine, 735 km from Fermilab, had a mass of 5.4 kt, while the near detector had a total mass of 0.98 kt and was located 1 km downstream of the production target.

In Europe, the OPERA experiment [47] was located at the Gran Sasso National Laboratory. Using the CNGS (CERN to Gran Sasso) neutrino beam it was able to confirm the $\nu_\mu \rightarrow \nu_\tau$ oscillations [48].

The successor of K2K, T2K (Tokai-to-Kamioka) uses a muon neutrino beam with a baseline of 295 km. It exploits a near detector 280 m downstream the neutrino source and a far detector composed by the on-axis iron-scintillator tracking detector INGRID, and the Super-Kamiokande detector, located 2.5° off-axis to set the peak of ν energy spectrum at ~ 0.6 GeV. T2K has been the first to observe $\nu_\mu \rightarrow \nu_e$ oscillation [49] reporting also the hint of CP violation, excluding δ_{CP} values of 0 and π at the 95% confidence level.

The NOvA experiment uses the upgraded Fermilab NuMI beamline with an off-axis configuration. Its 14 kt far detector is located near Ash River, Minnesota, 810 km away from the source, while the near detector has a mass of 290 t and is 1 km far from the source. The energy spectrum of the beam is peaked around 2 GeV at 14.6 mrad off-axis. Both detectors are tracking calorimeters consisting of planes of polyvinyl chloride cells alternating in vertical and horizontal orientation filled with liquid scintillator. NoVA confirmed ν_e appearance from ν_μ beam and, using an antineutrino beam, was able to observe $\bar{\nu}_e$ appearance from $\bar{\nu}_\mu$ [50].

T2K and NOvA has been able to perform precision measurements on the parameters $\sin 2\theta_{23}$ and

Δm_{32}^2 , in both appearance and disappearance channels, as can be seen in Figure 1.7. Furthermore, Figure 1.8 shows the allowed regions in $\sin 2\theta_{23}$ and δ_{CP} obtained from a joint analysis of T2K and NOvA data.

In the near future, a next generation of long baseline experiments will start to operate. Two concurrent and complementary experiments will be DUNE and Hyper Kamiokande [52].

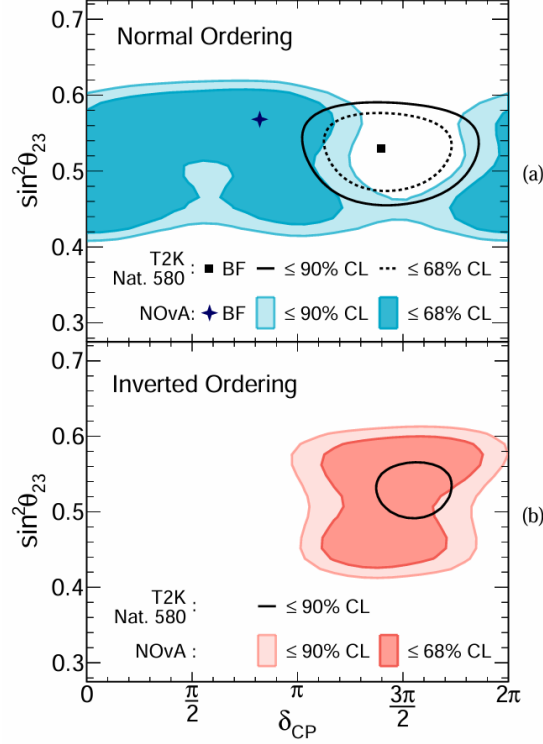


Figure 1.8: 2D credible intervals for δ_{CP} and $\sin 2\theta_{23}$ for both inverted and normal ordering from 2020 T2K and NOvA results [51].

1.5 3ν global fits and open problems

In the previous section, we reviewed the different experimental neutrino data samples, discussing their dominant sensitivity to one or two oscillation parameters. However, every data sample also offers subleading sensitivities to other parameters as well. Although the information they can provide about such parameters may be limited, in combination with the rest of the data samples, relevant information can emerge. This constitutes the main philosophy behind global analyses of neutrino oscillation data: joint analyses that try to exploit the complementarity of the different experiments to improve our knowledge of the neutrino oscillation parameters. In Table 1.1 are shown the results of a combined analysis of neutrino oscillation data in the framework of the three-flavor neutrino oscillation, a similar overview is also offered by Figure 1.9.

¹IceCube/DeepCore 3-year data (2012-2015) [54].

²IceCube/DeepCore 9.3-year data (2012-2021) [55].

Table 1.1: Three-flavor oscillation parameters from NuFIT [53] obtained considering Normal or Inverted Ordering and with (without) the inclusion of the atmospheric neutrinos results provided by the Super-Kamiokande collaboration.

		w SK-ATM		w/o SK-ATM	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
Normal Ordering	$\sin^2 \theta_{12}/10^{-1}$	$3.08^{+0.12}_{-0.11}$	$2.75 \rightarrow 3.45$	$3.07^{+0.12}_{-0.11}$	$2.75 \rightarrow 3.45$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$
	$\sin^2 \theta_{23}/10^{-1}$	$4.70^{+0.17}_{-0.13}$	$4.35 \rightarrow 5.85$	$5.61^{+0.12}_{-0.15}$	$4.30 \rightarrow 5.96$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \rightarrow 49.9$	$48.5^{+0.7}_{-0.9}$	$41 \rightarrow 50.5$
	$\sin^2 \theta_{13}/10^{-2}$	$2.215^{+0.056}_{-0.058}$	$2.030 \rightarrow 2.388$	$2.195^{+0.054}_{-0.058}$	$2.023 \rightarrow 2.376$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \rightarrow 8.89$	$8.52^{+0.11}_{-0.11}$	$8.18 \rightarrow 8.87$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \rightarrow 364$	177^{+19}_{-20}	$96 \rightarrow 422$
	$\Delta m_{21}^2/10^{-5}eV^2$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$
$\Delta m_{31}^2/10^{-3}eV^2$	$2.513^{+0.021}_{-0.019}$	$2.451 \rightarrow 2.578$	$2.534^{+0.025}_{-0.023}$	$2.463 \rightarrow 2.606$	
Inverted Ordering	$\sin^2 \theta_{12}/10^{-1}$	$3.08^{+0.12}_{-0.11}$	$2.75 \rightarrow 3.45$	$3.08^{+0.12}_{-0.11}$	$2.75 \rightarrow 3.45$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$
	$\sin^2 \theta_{23}/10^{-1}$	$5.50^{+0.12}_{-0.15}$	$4.40 \rightarrow 5.84$	$5.62^{+0.12}_{-0.15}$	$4.37 \rightarrow 5.97$
	$\theta_{23}/^\circ$	$47.9^{+0.7}_{-0.9}$	$41.5 \rightarrow 49.8$	$48.6^{+0.7}_{-0.9}$	$41.4 \rightarrow 50.6$
	$\sin^2 \theta_{13}/10^{-2}$	$2.231^{+0.056}_{-0.056}$	$2.060 \rightarrow 2.409$	$2.224^{+0.056}_{-0.057}$	$2.053 \rightarrow 2.397$
	$\theta_{13}/^\circ$	$8.59^{+0.11}_{-0.11}$	$8.25 \rightarrow 8.93$	$8.58^{+0.11}_{-0.11}$	$8.24 \rightarrow 8.91$
	$\delta_{CP}/^\circ$	274^{+22}_{-25}	$201 \rightarrow 335$	285^{+25}_{-28}	$201 \rightarrow 348$
	$\Delta m_{21}^2/10^{-5}eV^2$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$
	$\Delta m_{32}^2/10^{-3}eV^2$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \rightarrow -2.438$

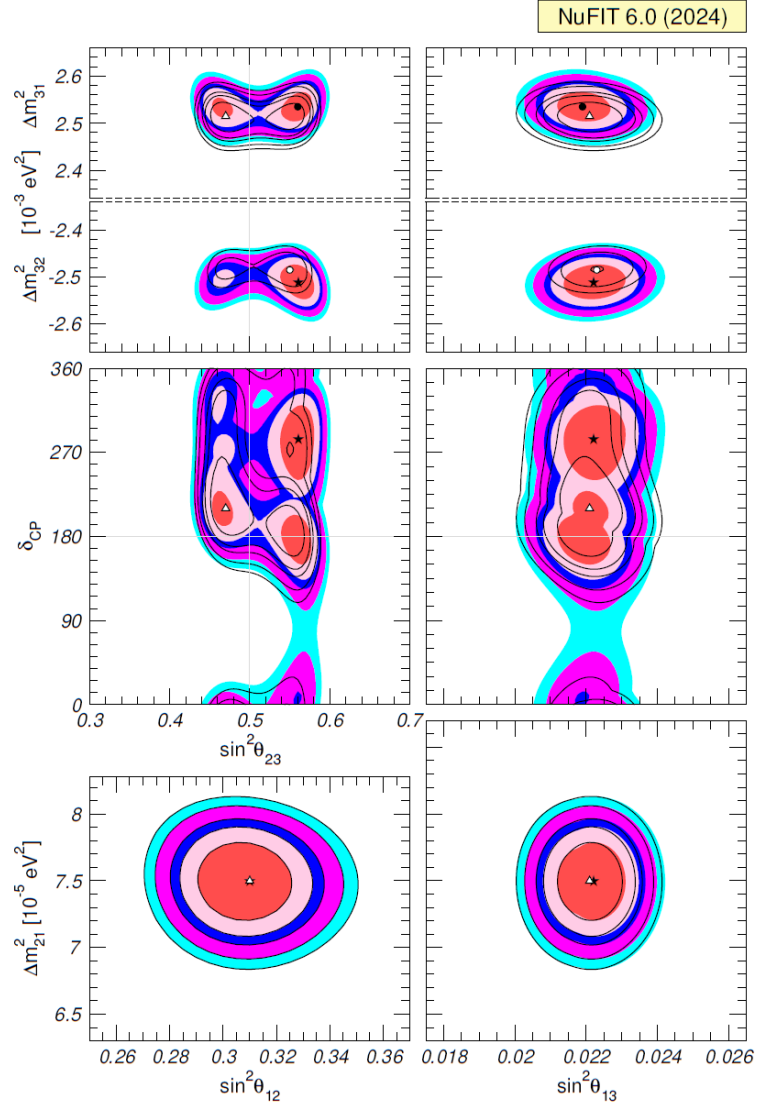


Figure 1.9: Global analysis on 3ν oscillations. Colored regions (black contours) correspond to the variant with IC19¹ and without SK-atm (with IC24² and with SK-atm) [53].

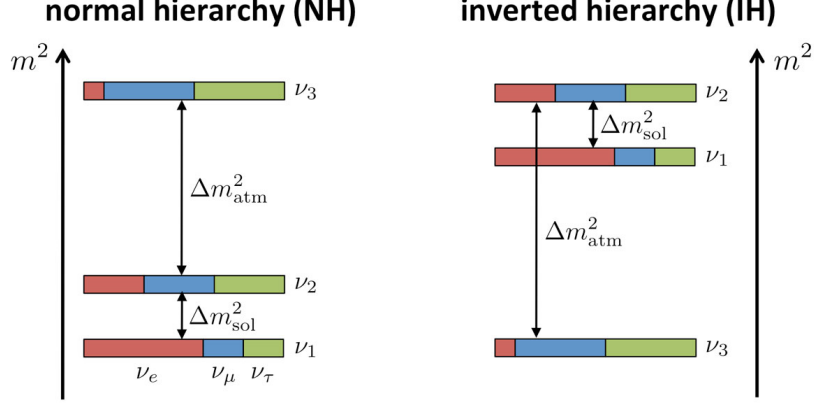


Figure 1.10: Neutrino mass eigenstates possible orderings in normal (left) and inverted (right) hierarchy. The flavor composition of the three states is shown by dividing the bars into colours: red for ν_e , blue for ν_μ and green for ν_τ [56].

According to the current knowledge of oscillation parameters, it is possible to quantify the presence of leptonic CP violation in terms of the Jarlskog invariant. Its maximum value at 1σ (3σ) for both orderings is

$$J_{CP}^{max} = 0.0333 \pm 0.0007 (\pm 0.0017) \quad (1.46)$$

The results reported are not conclusive yet, and we will have to wait for the next generation of experiments to fully answer fundamental questions:

1. The determination of the absolute mass of neutrinos;
2. The determination of the mass ordering (normal or inverted);
3. The measurement of CP asymmetries in the leptonic field;
4. The determination of the θ_{23} octant

1.5.1 Mass ordering

Concerning neutrino mass eigenvalues, from experimental results two scenarios are possible: the so-called *Normal* and *Inverted* Ordering. In Normal Ordering, neutrino mass eigenvalues are ordered $m_1 < m_2 < m_3$, while in Inverted Ordering $m_3 < m_1 < m_2$ (Figure 1.10).

Since Δm_{21}^2 is measured by solar neutrino experiments, its sign could be determined thanks to the matter effect of neutrino travelling through the Sun. The same is not possible for Δm_{31}^2 , measured by atmospheric neutrino experiments, because in this case matter effects are negligible. Until now the sign of Δm_{31}^2 is unknown, giving origin to the uncertainty on the mass ordering.

Chapter 2

The DUNE experiment

DUNE (Deep Underground Neutrino Experiment) is an international experiment, hosted by the Fermi National Accelerator Laboratory (Fermilab) of the US Department of Energy. It is a long baseline neutrino oscillation experiment which aims to answer fundamental questions about the universe, through a broad study of the three flavor neutrino physics scenario with unprecedented detail. DUNE primary goals will be the search for leptonic charge parity (CP) violation, the determination of neutrino mass ordering and the precise measurement of neutrino mixing parameters.

The experiment is divided into three central components (Figure 2.1): a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab; a massive Far Detector (FD) situated 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota and 1300 km from Fermilab; a composite Near Detector (ND) installed just downstream of the neutrino source.

The Long Baseline Neutrino Facility (LBNF) project, also hosted by Fermilab, provides the beamline and civil construction for the DUNE experiment. The organization and management of LBNF is separate from that of the experiment; its design and construction are organized as a U.S. DOE/Fermilab project incorporating international partners.

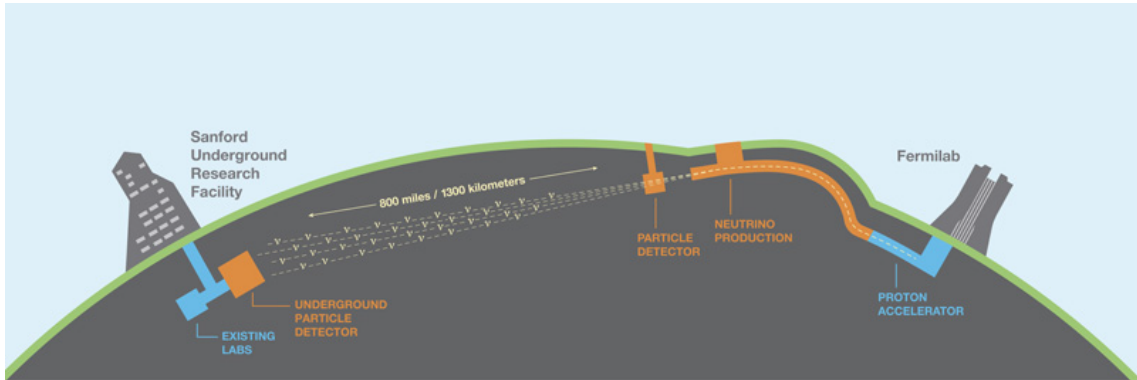


Figure 2.1: Configuration of the LBNF beamline at Fermilab, in Illinois, and the DUNE detectors in Illinois and South Dakota, separated by 1300 km [57].

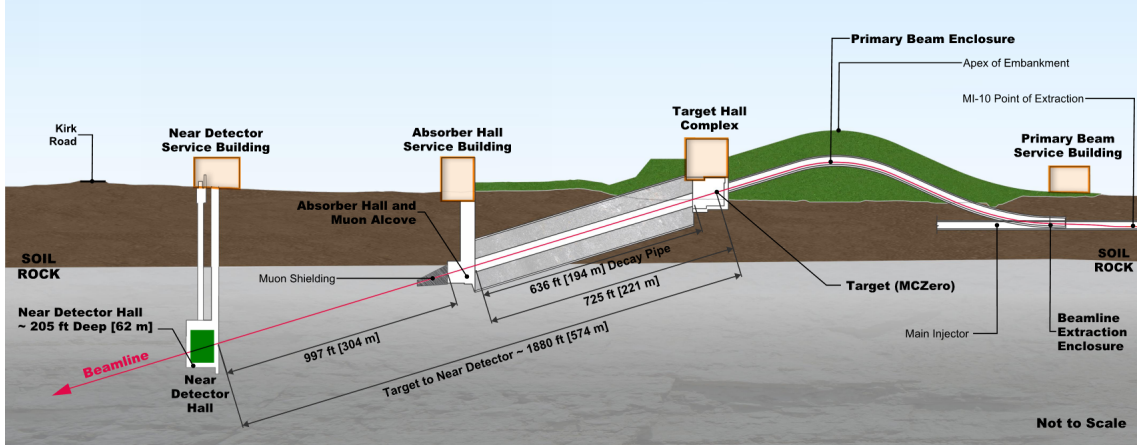


Figure 2.2: Neutrino beamline and DUNE near detector hall at Fermilab in Illinois [57].

2.1 The Long Baseline Neutrino Facility

The LBNF beamline at Fermilab will deliver the world’s most intense wide-band neutrino beam to the Far Detector. The upgrade to the Proton Improvement Plan II (PIP-II) will provide between 1.0 and 1.2 MW of proton beam power, later upgradeable to 2.4 MW.

The proton beam will be focused in a wide energy band ranging from 60 GeV to 120 GeV. The secondary particles are produced when the beam strikes the graphite target. After being focused by a set of magnetic horns, the secondaries are sent toward the Far Detector passing through a 194 m long decay pipe, where they decay generating the neutrino beam. At the end of the decay pipe, an absorber pile removes the residual hadrons. The focusing structure is optimised to provide a neutrino beam with an energy peaked around 2-3 GeV and up to 10 GeV. This allows to cover the first and second neutrino oscillation maxima, which for a 1300 km baseline are approximately 2.4 and 0.8 GeV. A schematic layout of the beamline is shown in Figure 2.2.

Selecting the horns current polarity both ν_μ or $\bar{\nu}_\mu$ beams with small contamination of ν_e , $\bar{\nu}_e$ and ”wrong sign” muon neutrinos can be produced. The two operation modes of the horns are called Forward Horn Current (FHC) and Reverse Horn Current (RHC), yielding a neutrino or an antineutrino beam, respectively. The expected neutrino unoscillated fluxes at FD site with the 120 GeV proton beam are shown in Figure 2.3, for both FHC and RHC operating modes.

The general specifications of the primary beam and the characteristics of the ν beam are listed in Table 2.1, corresponding to the parameters expected following the PIP-II [58] upgrade.

2.2 Far Detector reference design

The DUNE FD will consist of four independent modules based on the Liquid Argon Time Projection Chamber (LArTPC) technology. Each module will have a fiducial mass of at least 10 kt and a total mass of 17.5 kt, while the cryostat will have dimensions 18.9 m(w) $\times$ 17.8 m(h) $\times$ 65.8 m(l).

LArTPC technology combines tracking and calorimetry capabilities, which allow for the identification of ν_μ interactions, as well as for good resolution to both lepton and hadronic energies and scalability to the required detector mass. The 1300 km baseline is one of the main strengths of DUNE as it provides high sensitivity to matter effects, helping to resolve the mass ordering.

During Phase I, only two modules, FD1 and FD2, will be operating, while the remaining two, FD3 and FD4, will be present in Phase II. FD1 will consist in a single-phase (SP) horizontal drift (HD)

Parameter	Values
Energy	120 GeV
POT	7.5×10^{13}
Spill duration	9.6 μ s
POT per year	1.1×10^{21}
Cycle time	1.2 sec
Beam Power	1.2 MW
Beam size at target	1.5 to 1.7 mm
$\Delta p/p$	11×10^{-4} 99%
Beam divergence (x,y)	(15,17) μ rad

Table 2.1: Summary of the primary proton beam parameters [59].

LArTPC. The technology chosen for FD2 will be again a single-phase LArTPC but with vertical drift (VD). The design of the third and fourth modules is yet to be defined.

In the LArTPC technology, ionization charges drift towards an anode under the influence of a strong electric field. The charges collected at the anode allow to reconstruct two of the three spatial coordinates (y and z), while the third one is obtained exploiting the time difference between the arrival time of the electrons and the reference time t_0 of the event. The t_0 is deduced using the scintillation light produced by LAr, which is collected by the Photon Detection System (PDS). Knowing the electron drift velocity, it is possible to calculate the position. Figure 2.4 shows the operating principle of a SP LArTPC. This design requires very low-noise electronics to achieve readout with a good signal-to-noise (S/N) ratio because no signal amplification occurs inside the cryostat. This technology was pioneered by the ICARUS project and is the one used for Fermilab’s currently operating MicroBooNE detector.

2.2.1 Horizontal Drift SP detector module

The design of FD1 is shown in Figure 2.5. The inner volume is divided in four drift regions by alternating vertical Anode Plane Assemblies (APAs) and Cathode Plane Assemblies (CPAs). The drift distance is of 3.5 m, with a constant electric field of 511 V/cm produced by biasing the cathode planes at -180 kV. Ionization electrons drift horizontally toward the anode planes.

The three anode walls are made of 50 APAs each, arranged in a 2×25 grid. Each APA consists of a $6.2 \text{ m} \times 2.32 \text{ m}$ aluminum frame with three layers of active wires, strung at angles chosen to reduce ambiguities in event reconstruction.

A Photon Detection System is embedded inside the inactive space of the Anode Plane Assemblies structure, covering 12.5% of the APA surface. Photon detectors, so-called X-ARAPUCAs [60], are used to collect the scintillation light exploiting a dichroic short-pass filter to shift the wavelength of the UV photons to the visible spectrum at 430 nm, and trap them in a closed box. A SiPM placed inside the box collects the shifted light (Figure 2.6). The current signal from the APA wires and the timing information from the X-ARAPUCAs are used to reconstruct the events.

2.2.2 Vertical Drift SP detector module

The second module of the Far Detector (FD2) will implement the vertical drift SP technology, maximizing This way the detector active volume. In this design, the cathode is suspended at mid-height of the module, with electrons drifting vertically toward anodes placed at the bottom and top of the detector (Figure 2.7). The cathode is biased at -325 kV and the anode planes are grounded. The field cage ensures the uniformity of the electric field at 500 V/cm.

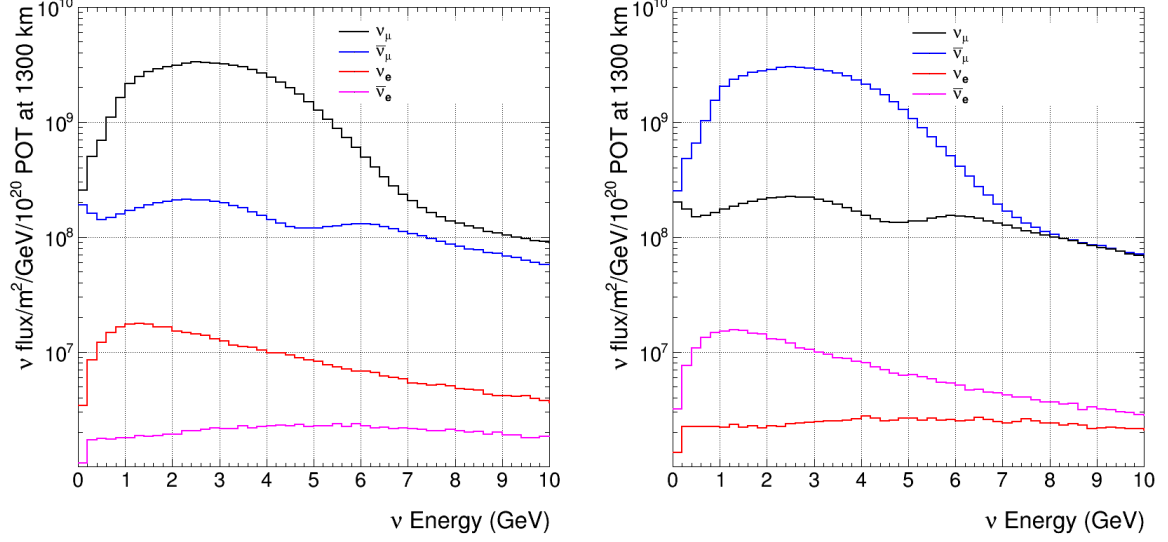


Figure 2.3: Neutrino (left) and antineutrino (right) Fluxes at the Far Detector as a function of energy in the absence of oscillations with the horns working in FHC (left) and RHC (right) modes. In addition to the dominant ν_μ ($\bar{\nu}_\mu$) flux, the minor components are also shown [59].

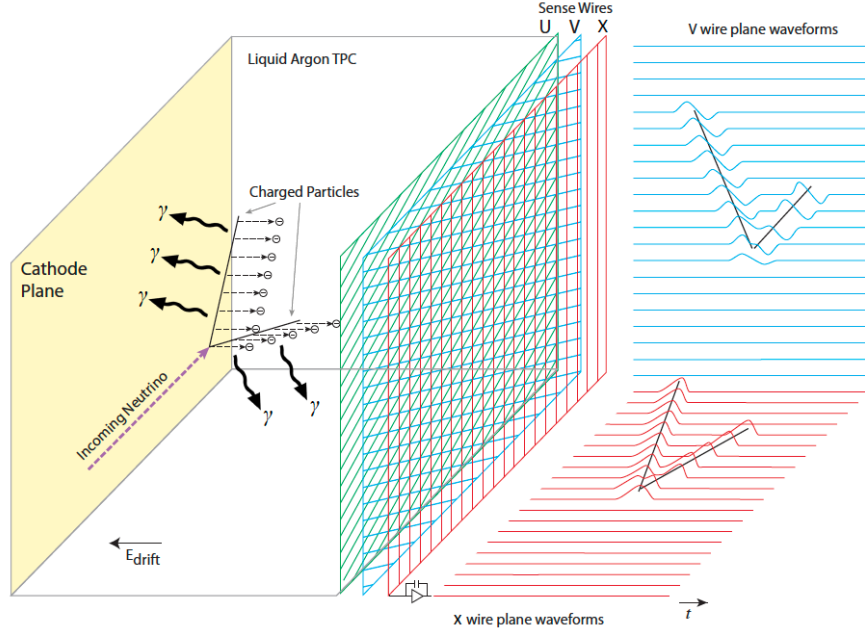


Figure 2.4: The general operating principle of the SP LArTPC. Negatively charged ionization electrons from the neutrino interaction drift horizontally opposite to the E field in the LAr and are collected on the anode, which is made up of the U, V and X sense wires. The right-hand side represents the time projections in two dimensions as the event occurs [57].

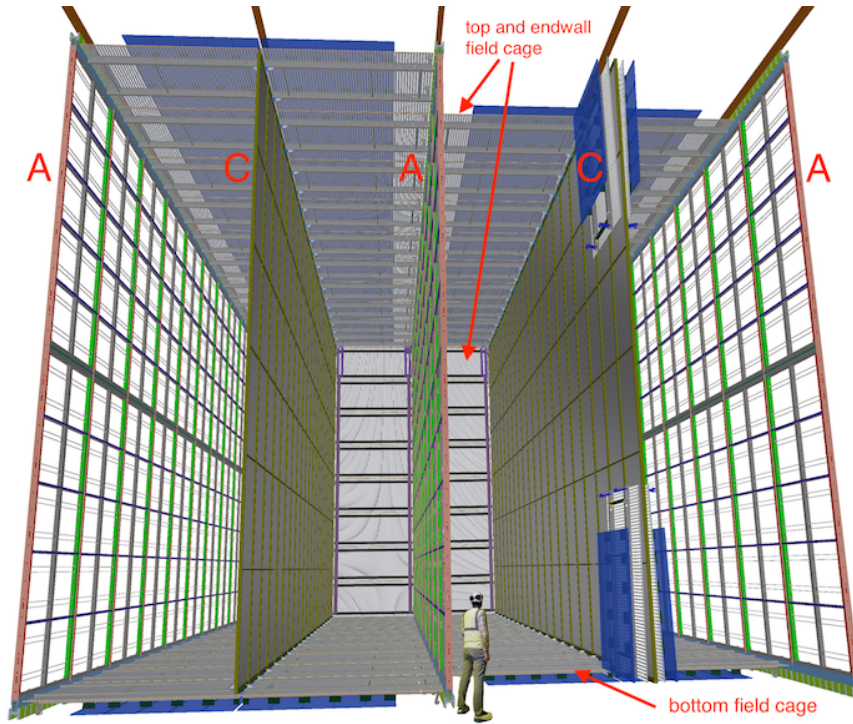


Figure 2.5: A 10 kt DUNE FD SP module, showing the alternating 58.2 m long (into the page), 12.0 m high anode (A) and cathode (C) planes, as well as the field cage that surrounds the drift regions between the anode and cathode planes [57].

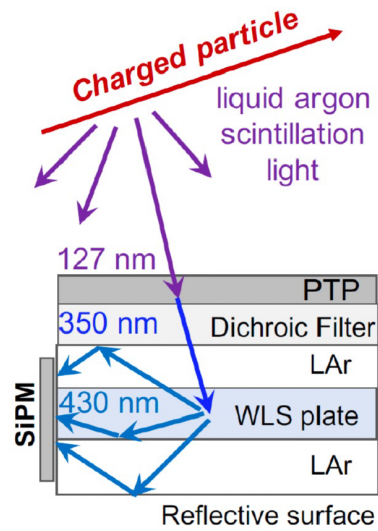


Figure 2.6: Working principle of an X-Arapuca cell.

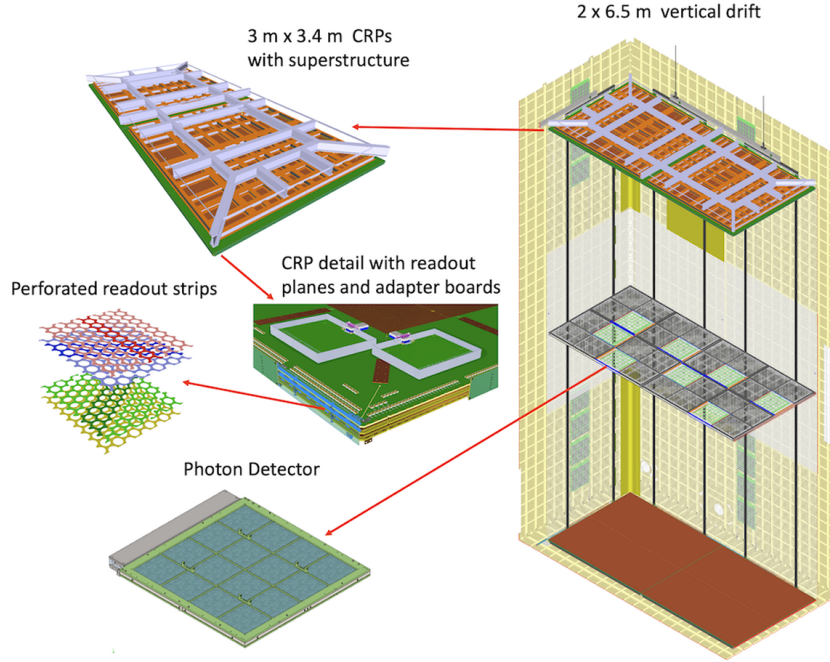


Figure 2.7: Detailed view of the Vertical Drift LArTPC detector [61].

The anode planes are mounted on frames, to form Charge Read-out Planes (CRPs). The CRPs composing the top anode plane are suspended from the cryostat roof with cables, while the bottom CRP is held by some bearing supports directly posed on the cryostat floor. The anodes are made of perforated printed circuit boards (PCBs), which help in minimising deformations when hung horizontally. Each section of an anode plane will consist in stacking two double-sided anode PCBs, plus a shield layer facing the cathode, as shown in Figure 2.8. The first layer of PCB faces the cathode and its back side is the first induction plane. The second layer has the second induction plane and its back face is the collection plane. The cathode will be a thin structure to reduce the loss of active volume and roughly 60% transparent to allow the free flow of the Argon.

The PDS is based again on X-ARAPUCAs, placed on the cathode surface, and on the walls of the cryostat behind the field cage, designed to be semi-transparent.

2.3 Near Detector reference design

The Near Detector complex will be located at Fermilab 574m downstream of the neutrino beam source and will consist of three elements: during Phase I there will be ND-LAr, the Temporary Muon Spectrometer (TMS) and SAND, while in Phase II TMS should be replaced by the Gaseous Ar TPC (ND-GAr). ND-LAr and TMS/ND-GAr are mounted on rails to allow them to move off-axis relative to the beam direction, while SAND (System for On-Axis Neutrino Detection) will remain fixed in the on-axis position (see Figure 2.10). The capability to move off-axis will allow to study neutrino interactions with different energy spectra at different off-axis locations, minimizing the errors arising from the near-to-far flux difference due to the different angular acceptance.

The Near Detector complex will serve as the experiment's control, measuring and monitoring the beam near the production point, before oscillations take place. It will also constrain the flux, providing

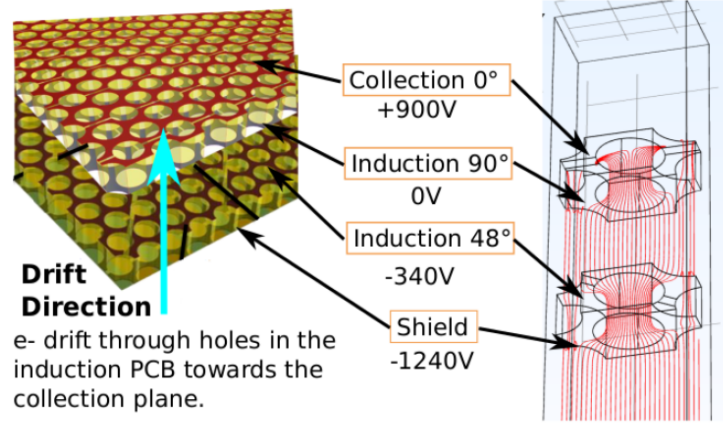


Figure 2.8: Structure of the PCB (left) and electric field simulation between two holes of the anode planes.

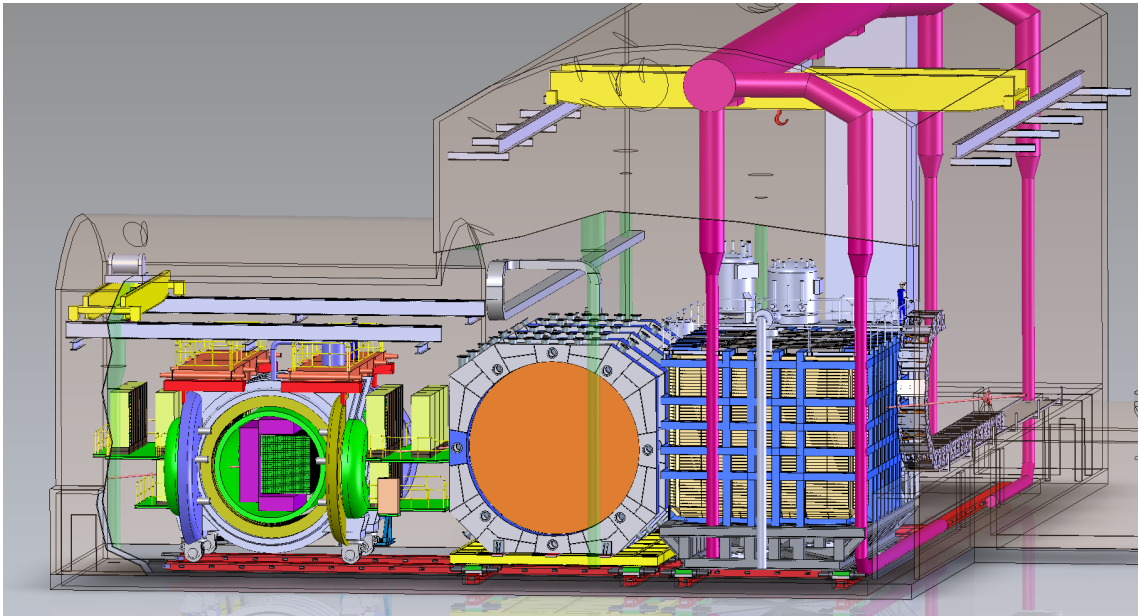


Figure 2.9: DUNE ND. The neutrino beam enters from the right. Neutrinos first encounter ND-LAr (right), ND-GAr (centre), and SAND (left).

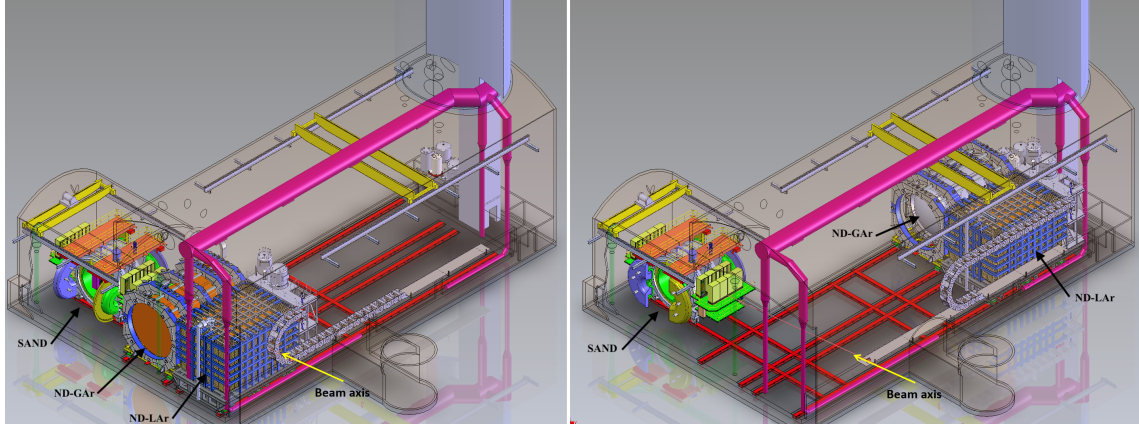


Figure 2.10: Representation of the Near Detector hall, with all the detectors in the on-axis configuration (left) and with ND-LAr and ND-GAr in an off-axis configuration (right) [62].

essential input for the neutrino interaction model.

2.3.1 ND-LAr

ND-LAr will consist of a large TPC composed of several identical and optically insulated modules, hosted in a common tank of liquid Argon; each module consists of a high-voltage cathode, a field cage that minimizes the amount of inactive material between modules, a pixel-based charge readout and a light collection system. See Figure 2.11 for more clarification. The segmentation of the TPC allows to overcome the problem of event pile-up due to the intense neutrino flux near the source. ND-LAr will be composed of 5×7 individual modules, for a total active volume of $5 \times 7 \times 3 \text{ m}^3$ and a fiducial mass of 67 t.

This detector will have the same target nucleus and will use the same fundamental detection principles of the FD, reducing the sensitivity to nuclear effects and the systematic uncertainties driven by the detector. The LArTPC is large enough to provide high statistics ($1 \times 10^8 \nu_\mu\text{-CC}$ events/year on axis) and a sufficient volume to provide containment of the hadronic system.

2.3.2 ND-GAr

ND-GAr consists of a high pressure gaseous time projection chamber (HPgTPC) surrounded by an electromagnetic calorimeter in a 0.5 T magnetic field, provided by a superconductive magnet.

The ND-GAr will be placed downstream of ND-LAr, operating at 10 bar in an Ar-CH₄ mixture, 90–10%; It will measure momentum and sign of the charged particles exiting ND-LAr, extending this measurements to lower energies.

In addition, neutrinos interacting with the gaseous Argon constitute a large, independent sample of $\nu\text{-Ar}$ interactions that can be studied with a very low momentum threshold for charged particle tracking, and with systematic uncertainties that differ from those of the LArTPC.

ND-LAr and ND-GAr can move to take data at positions off the beam axis. This capability is referred to as the DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM). As the detectors move off-axis, generally together, the incident neutrino flux spectrum changes, with the mean energy dropping and the spectrum becoming narrower. The data taken at different off-axis angles will allow for the deconvolution of the neutrino flux and interaction cross section, as well as the mapping of the reconstructed versus true-energy response of the detector.

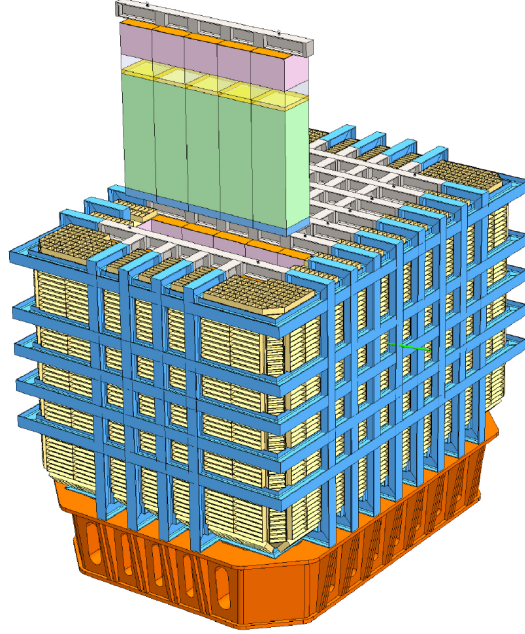


Figure 2.11: Representation of ND-LAr, with details of one of the seven rows of five modules.

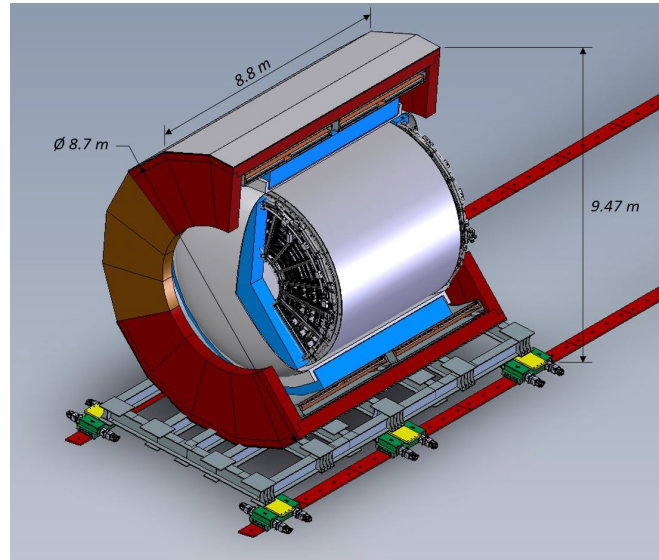


Figure 2.12: Schematic of ND-GAr which shows the HPgTPC, its pressure vessel, the ECAL, the magnet and return iron yoke. [63]

2.4 Scientific programme

The scientific goals behind the DUNE experiment are grouped into a *primary* scientific programme and an *ancillary* scientific programme [57].

The primary programme aims to answer some fundamental open questions in neutrino and astroparticle physics:

- Confirmation of the CP-violation in the leptonic sector, which could provide a possible explanation of the matter-antimatter asymmetry in the Universe;
- Determination of the neutrino mass ordering;
- Achievement of precision measurements of three-flavor neutrino oscillations;
- Search for proton decay, which would represent a confirmation of the GUT theories;
- Detection and measurement of the ν_e flux of a core-collapse supernova, which should shed light on the nature of this astrophysical event.

The ancillary science programme instead consists of a series of objectives that the experiment has not specifically planned to achieve, but that could nevertheless be enabled by the facility's design:

- BSM physics research through neutrino flavor transition measurements;
- Neutrino oscillation measurements using atmospheric neutrinos;
- Research on neutrino interaction physics through measurements of neutrino cross sections, studies of nuclear effects, and nucleon structure measurements.

2.4.1 Sensitivities and systematics

The ν_μ energy spectrum measured at the Near Detector is used to predict the expected spectra of ν_μ and ν_e at the Far Detector site [64]. The observed energy spectrum of neutrino events at the ND is a combination of the beam flux Φ , the detector efficiency ϵ , and the neutrino interaction cross section σ .

$$N_{ND}^{data}(\nu_\mu) = \Phi_{ND}(\nu_\mu) \otimes \epsilon_{ND}(\nu_\mu) \otimes \sigma_{ND}(\nu_\mu) \quad (2.1)$$

In order to extrapolate the spectra observed at the FD this formula has to be corrected taking into account differences in the beam flux between the Near and Far Detector, together with different detection efficiencies and interaction cross sections.

The expected signals in the FD are given by:

$$N_{FD}^{data}(\nu_\mu) = N_{ND}^{data}(\nu_\mu) \otimes \frac{\Phi_{FD}(\nu_\mu)}{\Phi_{ND}(\nu_\mu)} \otimes P(\nu_\mu \rightarrow \nu_\mu) \otimes \frac{\epsilon_{FD}(\nu_\mu)}{\epsilon_{ND}(\nu_\mu)} \otimes \frac{\sigma_{FD}(\nu_\mu)}{\sigma_{ND}(\nu_\mu)} \quad (2.2)$$

$$\begin{aligned} N_{FD}^{data}(\nu_e) = & \underbrace{N_{ND}^{data}(\nu_\mu) \otimes \frac{\Phi_{FD}(\nu_\mu)}{\Phi_{ND}(\nu_\mu)} \otimes P(\nu_\mu \rightarrow \nu_e) \otimes \frac{\epsilon_{FD}(\nu_e)}{\epsilon_{ND}(\nu_\mu)} \otimes \frac{\sigma_{FD}(\nu_e)}{\sigma_{ND}(\nu_\mu)}}_{\text{expected signal events}} \\ & + \underbrace{N_{ND}^{data}(\nu_e) \otimes \frac{\Phi_{FD}(\nu_e)}{\Phi_{ND}(\nu_e)} \otimes P(\nu_e \rightarrow \nu_e) \otimes \frac{\epsilon_{FD}(\nu_e)}{\epsilon_{ND}(\nu_e)} \otimes \frac{\sigma_{FD}(\nu_e)}{\sigma_{ND}(\nu_e)}}_{\text{beam } \nu_e \text{ events}} \\ & + \text{NC background extrapolated from } N_{ND}^{data}(\nu_e) \\ & + \nu_\tau \text{ background extrapolated from } N_{ND}^{data}(\nu_\mu) \end{aligned} \quad (2.3)$$

Source of Uncertainty	MINOS Absolute/ ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e .
Detector effects				
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
Neutrino interaction modeling				
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	5.7%	8.8%	3.6 %	Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.

Figure 2.13: Dominant systematics on the ν_e appearance channel for T2K and MINOS and the ones expected in the LBNE experiment, the preliminary name used for DUNE [65].

The main sources of uncertainties are described in Figure 2.13. They are estimated looking at similar experiments, such as MINOS and T2K, and are thought to be:

- **Beam flux uncertainties:** they are related to the precision with which the absolute normalisation and shape of the different components of the neutrino beam will be measured by the ND. The ND has been designed to significantly improve performance relative to the current generation of high-intensity flux neutrino detectors.
- **ν_μ energy-scale uncertainty:** since the spectrum of ν_μ events in the ND is used to predict the ν_e appearance signal at the FD, the uncertainty on ν_μ energy-scale is propagated as an uncertainty on the ν_e appearance signal.
- **Absolute ν_e energy-scale uncertainty:** in order to obtain the desired mass-ordering and CP-violation sensitivity an accurate measurement of the ν_e appearance signal shape is necessary. The measurement of the absolute energy scale of ν_e depends on the detector response and it is expected to be an important systematic uncertainty in the DUNE oscillation analysis.
- **Simulation uncertainties:** they refer primarily to uncertainties in the neutrino-target nucleus interaction in the Near and Far Detectors.

Since the FD is a LArTPC, the only way to be sensitive to all of these classes of uncertainty simultaneously is with a LArTPC at the near site, with kinematic acceptance at least as good as the FD. ND-LAr is optimized to meet this requirement and is critical for all stages of the experiment. A downstream

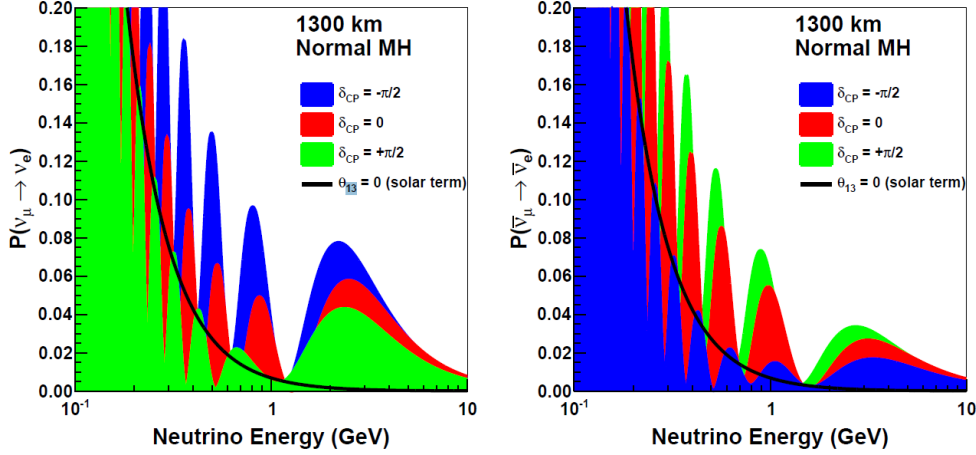


Figure 2.14: The appearance probability at a baseline of 1300 km, as a function of neutrino energy for different values of δ_{CP} , assuming Normal Ordering. The black line indicates the oscillation probability if θ_{13} were equal to zero. This situation is the one faced by the DUNE FD, since it will be at about ~ 1300 km from the neutrino source.

muon spectrometer (TMS/ND-GAr) measures the momentum and charge sign of exiting muons. The SAND detector remains on the axis and has a broad and complementary cross section and an exotic physics programme in addition to monitoring the neutrino beam.

2.4.2 Sensitivity for neutrino mass ordering and CP-violation

The DUNE experiment will determine the neutrino mass ordering and the value of δ_{CP} measuring the probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \nu_e$ oscillations. In particular, the oscillation probability of neutrinos through matter in a constant density approximation is, at first order [66]:

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} + \delta_{CP}) \\
 & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2
 \end{aligned} \quad (2.4)$$

where $\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$, $a = G_F N_e / \sqrt{2}$, G_F is the Fermi constant, N_e is the number density of electrons in Earth, L is the beamline in km, and E_ν is the neutrino energy in GeV (see Figure 2.14). When the $\bar{\nu}_\mu \rightarrow \nu_e$ channel is considered, both δ_{CP} and a switch signs: This way a neutrino-antineutrino asymmetry $\mathcal{A}$ is introduced through δ_{CP} and the matter effect (a).

$$\mathcal{A} = \mathcal{A}_{CP} + \mathcal{A}_{matter} = \frac{P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)}{P(\nu_\alpha \rightarrow \nu_\beta) + P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)} \quad (2.5)$$

In the few-GeV energy range, the asymmetry due to the matter effect increases with the baseline, as the neutrinos pass through more matter; therefore, an experiment with a longer baseline will be more sensitive to the mass ordering. For baselines longer than 1200 km, the degeneracy between the asymmetries introduced by the matter effect and the CP violation can be resolved. This can be understood

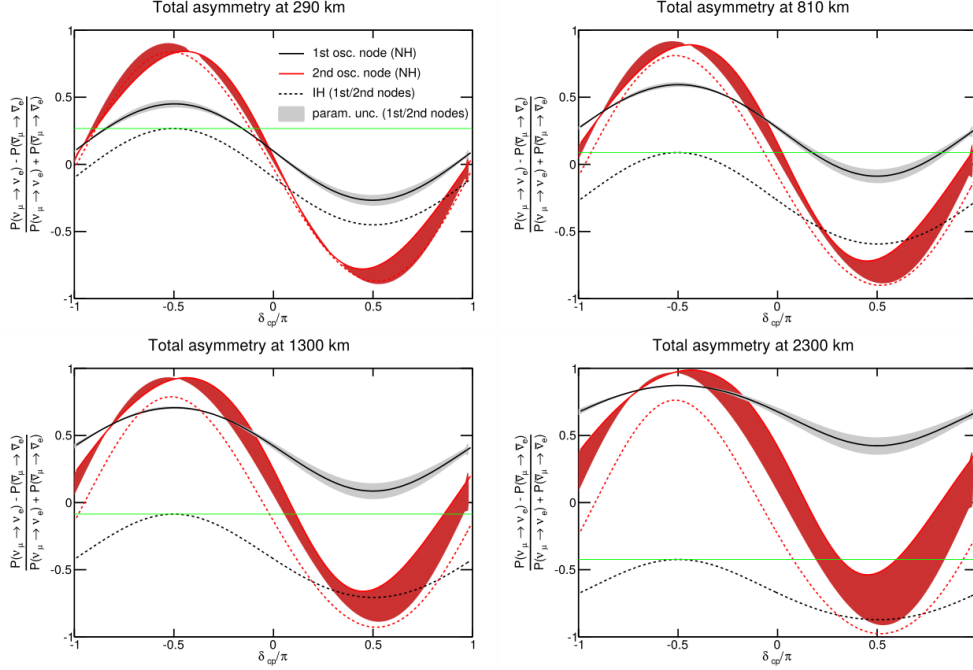


Figure 2.15: Total $\nu/\bar{\nu}$ asymmetries as a function of δ_{CP}/π for four different baselines. The black (red) lines indicate the asymmetries at the first (second) node, the full ones being for Normal Ordering (NO) and the dashed ones for Inverted Ordering (IO). The green lines indicate the asymmetry at the first node for maximal CP violation ($\delta_{CP} = \pi/2$) with Inverted Ordering. In the first row it is shown how the value of δ_{CP} is ambiguous if the mass ordering is not known. In the second row it is clear how the ambiguity is resolved [67].

describing the two terms with a dependence on the baseline length and neutrinos energy near the peaks of oscillation probability:

$$\mathcal{A}_{CP} \propto L/E \quad (2.6)$$

$$\mathcal{A}_{matter} \propto L \times E \quad (2.7)$$

Figure 2.15 shows the total neutrino-antineutrino asymmetry $\mathcal{A}$ at the first (black) and second (red) oscillation peak, as a function of δ_{CP} for four different values of L .

The expected sensitivity to leptonic CP violation is shown in Figure 2.16 as a function of the value of δ_{CP} (left) and for different exposures (right). DUNE will be able to determine the mass ordering with a 5σ confidence level independently from the value of δ_{CP} and with an exposure of 100 kt-MW-years, corresponding to about 3 years of data. From the right panel of Figure 2.16 one can notice that the sensitivity is greatly affected by the value of δ_{CP} and by external constrain in θ_{13} Figure 2.17 instead shows that a 5σ sensitivity over the mass ordering will require an exposure of 200-400 kt-MW-yr, corresponding to 7 years of data collection.

2.4.3 Measurements of oscillation parameters

The DUNE experiment will improve sensitivity on the key parameters exploiting $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ transitions. The sensitivity to $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$ and the octant of θ_{23} as a function of exposure is plotted

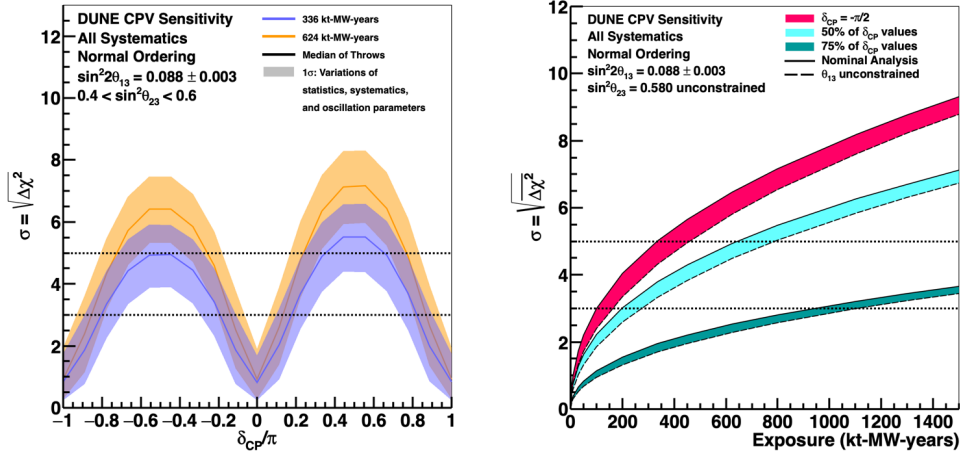


Figure 2.16: Left: Significance of the DUNE determination of CP violation as a function of the true δ_{CP} value for 336 kt-MW-years (blue) and 624 kt-MW-years (orange) of exposure. The width of the bands covers 68% of fits in which random throws are used to simulate statistical variations and select the true values of oscillation and systematics parameters. The median sensitivities are represented by the solid lines. Normal Ordering is assumed. Right: Significance of DUNE's determination of CP violation for $\delta_{CP} = -\pi/2$ and for 50% and 75% of possible δ_{CP} values, as a function of exposure. Normal Ordering is assumed. The widths of the bands are due to the application of an external constraint on $\sin^2 \theta_{23}$. [68]

in Figure 2.18.

The determination of the octant of θ_{23} is still an open question. The problem is whether or not its value is exactly 45° , producing maximal mixing between mass eigenstates 2 and 3. The latest results of T2K, in fact, leave both lower ($< 45^\circ$) and upper ($> 45^\circ$) octant scenarios open, depending on the mass hierarchy being considered. A value of θ_{23} being exactly 45° would hint at new not yet considered symmetries, while, for example, an excess in the upper octant of the order of the Cabibbo angle would point in the direction of quark-lepton universality models. The octant of θ_{23} will be determined combining the oscillation measurements of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$, which depend both on $\sin^2 \theta_{23}$. The sensitivity to the octant as a function of θ_{23} is plotted in Figure 2.19.

2.4.4 Supernova neutrino measurements

During its experimental life, estimated in ~ 20 yr, DUNE should have a 40% chance of observing neutrinos from a core-collapse supernova in the Milky Way. This would be of great importance for our understanding of this astrophysical phenomenon, which has only been confirmed in its basic characteristics by the observation of neutrino events from SN1987, a supernova in the Large Magellanic Cloud, 50 kpc away.

Supernovae promise an extremely varied environment to study neutrino oscillation, with their initial flavor composition being strictly linked to the expanding shock and turbulence. In this case the oscillation patterns would be very different for Normal Ordering and Inverted Ordering and furthermore, the oscillations of neutrinos and antineutrinos would manifest rather differently, making their observation with high statistics of particular interest.

Currently, experiments searching for neutrinos from a core-collapse supernova are sensitive primarily to $\bar{\nu}$'s, while DUNE will be very sensitive to the $\nu_e/\bar{\nu}_e$ component of the flux, via the absorption

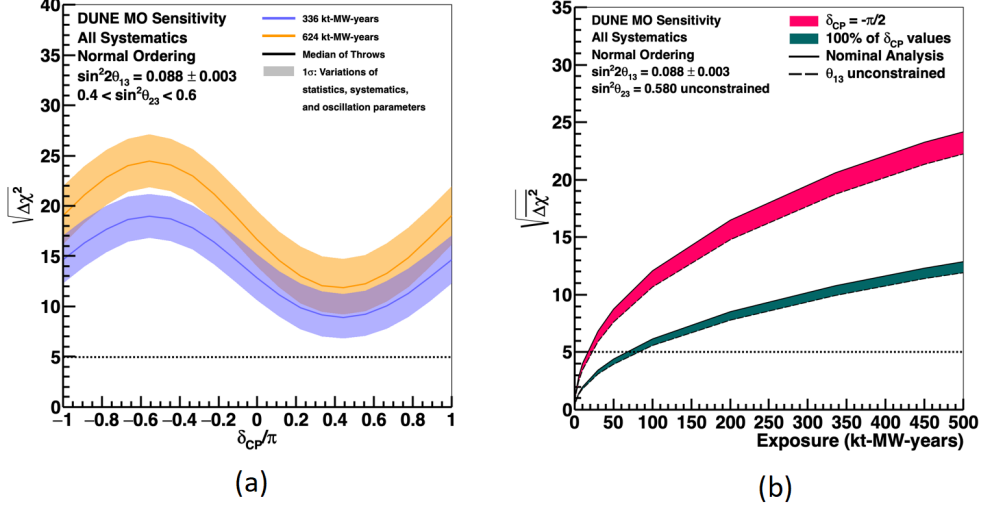


Figure 2.17: (a) Significance of the DUNE determination of the neutrino mass ordering as a function of the true δ_{CP} value for 336 kt-MW-years (blue) and 624 kt-MW-years (orange) of exposure. The width of the bands covers 68% of fits in which random throws are used to simulate statistical variations and select the true values of oscillation and systematics parameters. The median sensitivities are represented by the solid lines. Normal Ordering is assumed. (b) Significance of DUNE's determination of the neutrino mass ordering for $\delta_{CP} = -\pi/2$ and for 100% of possible δ_{CP} values, as a function of exposure. Normal Ordering is assumed. The widths of the bands are due to the application of an external constraint on $\sin^2 \theta_{23}$. [68]

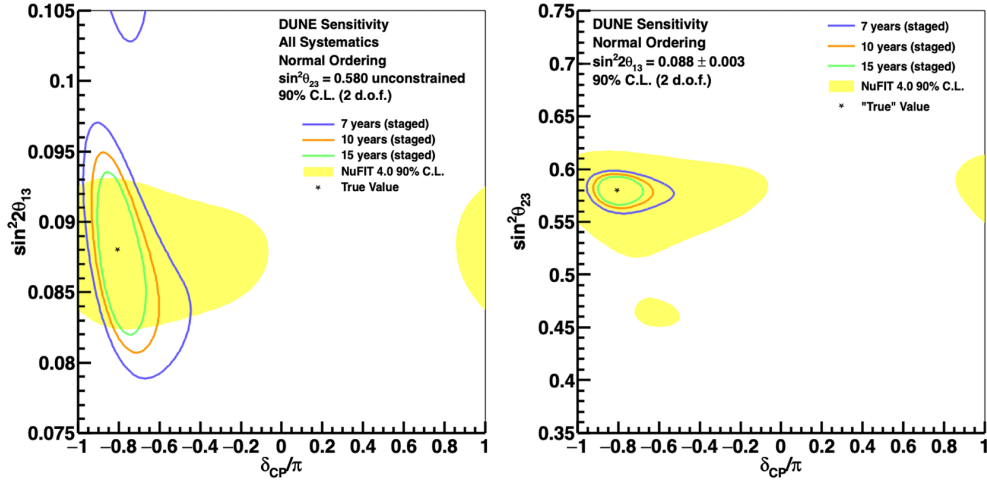


Figure 2.18: Left: two-dimensional 90% CL region in $\sin^2 \theta_{13}$ and δ_{CP} , for 7, 10, and 15 years of exposure, with equal running in neutrino and antineutrino mode. Right: corresponding region in $\sin^2 \theta_{23}$ and δ_{CP} . [69]

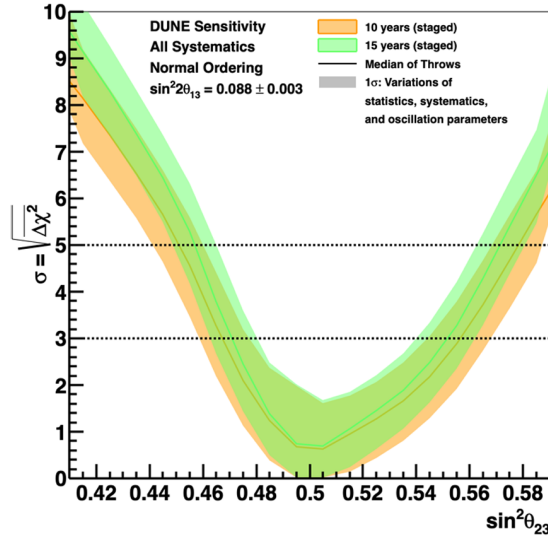


Figure 2.19: Sensitivity to determination of the θ_{23} octant as a function of the true value of $\sin^2 \theta_{23}$, for ten (orange) and fifteen (green) years of exposure. True Normal Ordering is assumed. The solid lines show the median sensitivity. [69]

interaction

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* \quad (2.8)$$

This interaction can be identified via the coincidence of the electrons with the gamma produced by the de-excitation of the ${}^{40}\text{K}^*$. Independently from the model of supernova burst, DUNE is expected to observe about 3000 neutrino events from a collapse at 10 kpc, and will be able to determine the parameters describing the electron neutrinos spectrum.

2.4.5 Oscillation physics with atmospheric and solar neutrinos

Thanks to its large target mass and to its underground location, DUNE will be able to study atmospheric neutrino oscillations. Since the atmospheric sample contains ν 's of all flavors over a vast range of energy and path lengths, including some for which matter effects are relevant, all oscillation parameters could be measured, ordering a very useful complementary programme to the main accelerator one. Solar neutrinos are also potentially detectable. However, because of the presence of low-energy backgrounds, such as radioactive decays, the detection of these neutrino sources is very challenging. The solar neutrino event rate for a final Far Detector fiducial mass of 40 kt is of ~ 100 per day. Initial studies suggest that with a sophisticated event selection and possibly additional shielding a high-statistics solar neutrino sample could be selected, which will help to improve the measurement of Δm_{21}^2 [67].

2.4.6 Proton decay measurements

Proton decay is predicted by almost all Grand Unified Theories (GUTs), together with baryon number violation. Since the unification scale is in excess of about 10^{15}GeV with respects to energies accessible to accelerator experiments, the detection of this process would be one of the only viable experimental strategies to probe these theories. The non-detection of proton decay instead would set constraints on proton lifetime and progressively rule out theories based on its predictions.

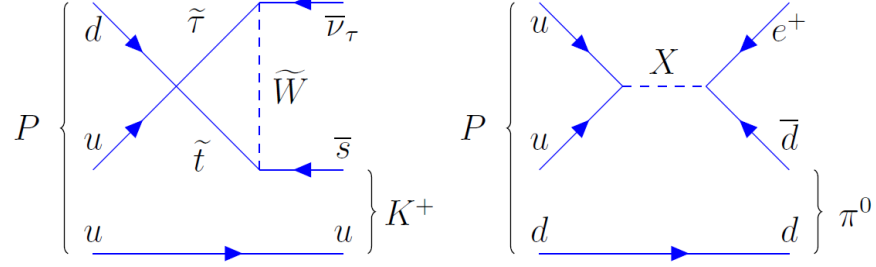


Figure 2.20: Feynman diagrams for two major proton decay modes: the main decay for SUSY GUTs $p^+ \rightarrow K^+ \bar{\nu}$ (left) and the main decay for gauge-mediation GUTs $p^+ \rightarrow e^+ \pi^0$ (right) [65].

Given the scale of energy deposition in the few hundred MeV to few GeV range, a detector optimised for neutrino oscillation physics at long baselines is naturally well suited for sensitive searches for nucleon decay. Furthermore, DUNE will have the capability to detect two dominant proton decay modes (see Figure 2.20):

$$p^+ \rightarrow K^+ \bar{\nu} \quad (2.9)$$

$$p^+ \rightarrow e^+ \pi^0 \quad (2.10)$$

Since kaons have an high ionization rate the first decay mode is particularly interesting for large LArT-PCs, where kaons would be detected with great efficiency. The second mode instead is better detectable by water Cherenkov experiments since the mass of the proton is converted into the electromagnetic shower energy.

Chapter 3

System for on-Axis Neutrino Detection

SAND is one of the three detector components of the DUNE Near Detector. It will permanently operate in an on-axis position, monitoring the beam to produce a statistically significant neutrino beam spectrum measurement and detect spectral variations on a weekly basis. Besides the primary goal of monitoring, SAND has a rich stand-alone physics programme, shown in the following. Figure 3.1 shows the exploded view of SAND, with its sub-detectors clearly visible. It will be composed of:

- a superconducting solenoid magnet, reused from the KLOE experiment [70];
- an electromagnetic calorimeter (ECAL), also recovered from the KLOE experiment;
- a low-density tracker;
- a liquid Argon detector (GRAIN).

3.1 Physics programme

The general expression for the number of measured events for a process X, both at the Near and Far detectors, is:

$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{osc}(E_\nu) \sigma_X(E_\nu) R_{phys}(E_\nu, E_{vis}) R_{det}(E_{vis}, E_{rec}) \quad (3.1)$$

where Φ is the incoming neutrino flux, P_{osc} is the oscillation probability, σ_X is the cross section of the process on a given nucleus, R_{phys} is the physics response introduced by nuclear smearing and R_{det} is the detector acceptance for the final state particles. E_ν , E_{vis} and E_{res} are the true neutrino energy, the total energies of the visible final-state particles, and the final reconstructed energy, respectively. In order to unfold the main terms of the expression, different detectors and nuclear targets must be used. For this reason, a capable Near Detector complex is mandatory. In particular, a precise beam-monitor detector is needed, capable of operating in a high rate environment. With the help of SAND, the ND will provide constraints on all systematic uncertainties relevant to the oscillation analysis.

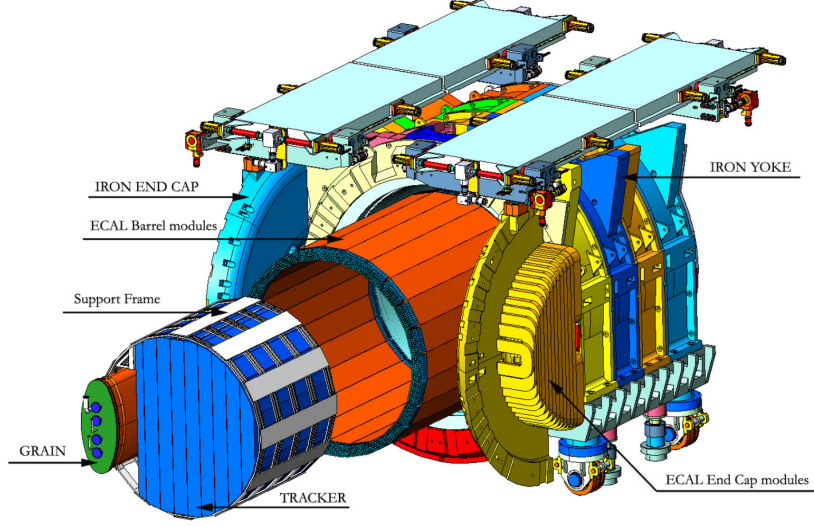


Figure 3.1: Exploded view of the SAND detector. Starting from the left, one can see GRAIN, the tracker, the calorimeter (barrel and end-cap) and the magnet system.

3.1.1 Beam Monitoring

The on-axis beam monitoring offered by SAND will be possible exploiting different and complementary neutrino processes, including:

- Absolute ν_μ flux from $\nu + e \rightarrow \nu + e$ elastic scattering;
- Relative ν_μ flux vs E_ν from $\nu + p \rightarrow \mu^- + p + \pi^+$ with $E_\nu < 0.5$ GeV
- Absolute $\bar{\nu}_\mu$ flux from $\bar{\nu} + p \rightarrow \mu^+ + n$ QE. At $Q^2 = 0$ the QE cross section is constant and dominated by β decay;
- Relative $\bar{\nu}$ flux vs E_ν from $\bar{\nu} + p \rightarrow \mu^+ + n$ QE with $E_\nu < 0.25$ GeV;
- Ratio of $\bar{\nu}_\mu/\nu_\mu$ fluxes vs E_ν from coherent π^-/π^+ on C, inside the CH_2 and graphite targets.
- Ratio of ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ from $\nu(\bar{\nu})$ CC interactions on H
- Determination of parent $\mu/\pi/K$ distribution from $\nu(\bar{\nu})$ CC interactions on H and CH_2 at low E_ν

3.1.2 Reducing the systematic uncertainties

In order to constrain the systematic uncertainties relevant for the neutrino oscillation analysis, all the variables entering in Eq. 3.1 need to be decoupled and measured independently:

- $\Phi(E_\nu)$: flux measurements benefit from detectors with low-density tracker materials, in order to achieve high resolution and precise neutrino energy scale measurements. SAND will be able to measure the fluxes for all (anti)neutrino flavors with high accuracy.
- $R_{phys}(E_{vis}, E_{rec})$: having in the same detector both Ar and lighter targets helps to disentangle the physics response function from R_{det} . SAND is able to constrain the physics response function thanks to the presence of LAr and Hydrogen targets in the inner tracker, for which $R_{phys} = 1$.

- $\sigma_X(E_\nu)$: the cross section measurements require to have in the Near Detector the same target of the Far Detector, in this case the LAr. Once the flux is precisely measured, the cross section on Argon can be evaluated by using the large sample of interactions provided by GRAIN. The cross section measurements need the knowledge of R_{phys} and R_{det} .
- $R_{det}(E_{vis}, E_{rec})$: the only way to evaluate the FD response factor is through measurements performed in a ND based on the same technology (LAr). Determining the $\sigma_X R_{phys}$ product is possible in SAND due to the presence of a variety of different nuclear targets.

The determination of R_{phys} separately from σ_X in the tracker is possible by defining a set of kinematic variables sensitive to nuclear smearing effects: the use of CC interaction samples allows us to compare the distributions of these kinematic variables from events in Ar and H targets. Comparing the measurement of $\sigma_X R_{phys}$ and the constraints on R_{phys} offered by SAND with the measurements made in the LAr ND ArgonCube makes it possible to unfold R_{det} in liquid Argon and validate the predictions for the FD.

3.1.3 Precision measurements and searches for new physics

Electroweak sector

Due to SAND capabilities, it will be possible to precisely determine the weak mixing angle $\sin^2 \theta_W$ in (anti)neutrino deep inelastic scattering (DIS). The strategy for measuring $\sin^2 \theta_W$ will take advantage of the ratio of neutrino NC and CC DIS interactions:

$$R_\nu = \frac{\sigma_{NC}^\nu}{\sigma_{CC}^\nu}. \quad (3.2)$$

Thanks to the tracker capabilities, it will be possible to efficiently identify the ν_e CC interactions and separate the NC interactions from the CC ones, which will allow for a significant reduction in systematic uncertainties.

Another independent way to measure $\sin^2 \theta_W$ exploits the NC ν_e -e elastic scattering. This channel is not affected by hadronic uncertainties, but it is limited by the low statistics due to its small cross section. Through the use of this channel, the $\sin^2 \theta_W$ value can be found from the ratio:

$$R_{\nu e} = \frac{\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)}{\sigma(\nu_\mu e \rightarrow \nu_\mu e)} \quad (3.3)$$

in which the systematic uncertainties that arise from the electron selection and identification cancel out [71]. The $\nu(\bar{\nu})$ -H interactions are used to measure the ν_μ and $\bar{\nu}_\mu$ fluxes needed to determine $R_{\nu e}$. SAND can measure ν -e elastic events with small background (which can be calibrated in situ with data).

One possible way to increase the statistics consists in a combined analysis of the events collected in SAND and in the ND LArTPC detector. In fact, the inner tracker reduces the systematic uncertainties, while the LArTPC increases the statistics.

Furthermore, since DIS and the $\nu - e$ channels are characterised by different scales of momentum transferred, they represent an excellent tool to test the running of the value of $\sin^2 \theta_W$ in a single experiment.

Neutrino-nucleus interaction

Thanks to its modular structure, the inner tracker is able to integrate many different nuclear targets. The comparison between different neutrino-nucleus interaction topologies allows to constrain nuclear effects in Ar. Furthermore, it is possible to study neutrino interactions on H by subtracting measurements on dedicated graphite (pure C) targets from those on the CH₂ plastic targets. One of the advantages of this technique is that the neutrino CC events are perfectly balanced in a plane transverse to the beam

direction (up to the tiny beam divergence) , since the H target is at rest. This way, the muon and hadron vectors are back-to-back in the same plane. On the contrary, events from heavy nuclear targets are affected by both initial- and final-state nuclear effects, resulting in a significant missing transverse momentum and a smearing of the transverse plane kinematics. The results of the dedicated analysis show that purities of 80 - 95% of the selected H samples are achievable, with efficiencies of kinematic selection in 75 - 95% depending on the process considered [72, 73].

Isospin Physics, Nucleon Structure and QCD tests

The availability of large statistics of neutrino-hydrogen interactions in SAND allows for the testing of isospin sum rules, including the Adler sum rule [74], which gives the isospin of the target, and the Gross-Llewellyn-Smith (GLS) sum rule [75].

SAND will also offer a precise calibration of the energy scale uncertainties together with an excellent precision in the determination of both neutrino and antineutrino fluxes. These peculiar features will allow for a measurement of the structure functions and cross sections with an accuracy comparable to the one achievable in electron-scattering experiments.

Due to the statistics and the energy reachable in DUNE, the ν - $\bar{\nu}$ data collected by SAND could be used to perform global QCD analysis, in order to study the parton distribution functions, perturbative and non-perturbative corrections in a wide range of the transferred momenta Q^2 and Bjorken x variable. The presence of H and other various nuclear targets (Ar, C) allows to separate valence and sea quark distributions, d and u quark distributions, the strange quark s and $\bar{s}$ distributions.

Searches for New Physics

All the precision measurements described in the previous paragraphs are potentially sensitive to many Beyond the Standard Model (BSM) effects, which would produce deviations from the SM predictions. For example, the excellent electron identification capability and resolution of the tracker make SAND very suitable for testing the low energy anomaly found by the MiniBooNE experiment. Among the various possible explanations that could be tested in order to understand the origin of this anomaly, which includes both SM and BSM physics, there is the oscillation into sterile neutrinos. This could be studied measuring the CC ratios for both neutrinos and antineutrinos $R_{e\mu} = (\nu_e N \rightarrow e^- X) / (\nu_\mu N \rightarrow \mu^- X)$ and $\bar{R}_{e\mu} = (\bar{\nu}_e N \rightarrow e^+ X) / (\bar{\nu}_\mu N \rightarrow \mu^+ X)$ together with the NC/CC ratio $R_{\nu(\bar{\nu})p}$ as a function of L/E. These measurements would be sensitive to both appearance and disappearance anomalies in all four neutrino spectra.

In addition SAND has an excellent sensitivity to the appearance of ν_τ , which could result from both sterile neutrino oscillations or BSM interactions. The detector can further improve the sensitivity of the ND complex to searches for Dark Sector physics including for example heavy sterile neutrinos, axions, dark photons, WIMPs and many others.

3.1.4 Requirements

Each neutrino spill will have a duration of 9.6 μs , a repetition cycle of 1.2 s. The spill will be subdivided into 6 batches, each of them composed of 84 proton bunches at a base frequency of 53.1 MHz. Individual bunches will be separated by about 19 ns and are distributed over time with an RMS of about 1 ns. The last 2-3 bunches of each batch will be empty to separate consecutive batches.

The expected neutrino interaction rates are 0.135/ton/spill in the Forward-Horn-Current (FHC) beam and 0.072/ton/spill in the Reverse-Horn-Current (RHC) beam, resulting in a total number of events in the entire SAND detector of about 83.5 events/spill (FHC) and 44.4 events/spill (RHC), respectively. Most of the interactions occurs in the magnet yoke or in the ECAL due to their large mass.

Name	Requirement	Rationale
Continuous on-axis monitor	Continuously stay on-axis to monitor the ν beam	The other ND detectors are not required to stay periodically on-axis to monitor the ν beam
Beam monitoring statistics	Inner tracker with a fiducial mass higher than 5 t	This mass is large enough to provide a precise measure of ν_μ CC energy spectrum in one week
μ momentum resolution	The inner tracker shall reconstruct muon momentum with a resolution better than 5% at 1 GeV/c and better than 10% at 5 GeV/c	The muon momentum resolution shall be sufficient for a precise measurement of its spectrum
Vertex position	The position of ν interaction vertex shall be measured to < 5 cm	The localization of the ν interaction is required in order to measure the beam spectrum as a function of the position, which elucidates beamline variations
Timing resolution	Inner tracker with a timing resolution < 10 ns	The timing resolution shall be sufficient to resolve activity from different beam buckets (18.83 ns)

Table 3.1: SAND capability requirements for the neutrino beam monitoring system.

The beam monitoring role of SAND requires the detection of 1% change in muon rate nearly in real time, and the monitoring of the rate of on-axis neutrino interactions with a sensitivity better than 1% in a week. SAND can also enhance the robustness of the neutrino oscillation programme by measuring the muon and neutrino energy and vertex distributions.

To provide statistically significant feedback on changes in the beam over a short time period (one week) SAND must monitor the beam on-axis with a target mass that is large enough to provide a high rate of neutrino interactions. Regarding the collection and identification of ν_μ CC, this mass is estimated to be more than 20 t for reconstructing the muon momentum and more than 5 t for reconstructing the neutrino energy. SAND must measure the muon and neutrino energy and vertex distributions to detect changes in the beamline. Furthermore, the vertices in ν_μ CC interactions must be measured well enough to identify the sample events with respect to the beam center. A reconstruction with a resolution < 5 cm is enough to distinguish interactions that occur over distances where the spectrum may vary.

The ND operates in a high-rate environment due to the intensity of the neutrino beam, the presence of cosmic rays and beam-induced background activity. SAND must therefore be able to separate cosmic rays, rock muons, and other beam-induced activity from the neutrino interactions in the fiducial volume, and distinguish neutrino interactions also in the presence of event pile-up.

The SAND timing system must be capable of identifying and selecting activity occurring within the neutrino beam delivery window: $\sigma_t < 10$ ns on the tracker and $\sigma_t < 400$ ps on ECAL hits. Better resolution (1 ns) on the tracker would further enable directionality capabilities. These timing requirements are also useful to fulfil the previous requirement about the vertex measurement.

All the requirements needed to SAND to act as a neutrino monitor system are summarised in Table 3.1.

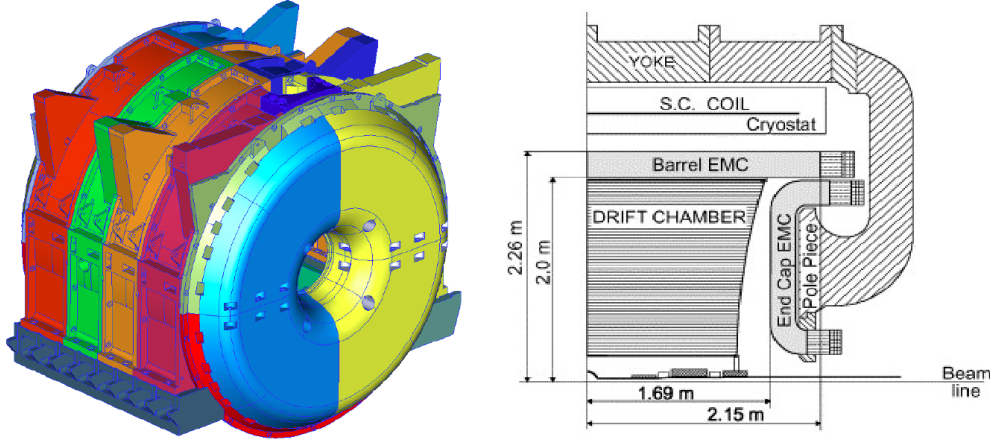


Figure 3.2: The KLOE detector: (left) 3D engineering CAD model of the magnet and (right) vertical cross section [76].

3.2 Detector components

3.2.1 The superconducting magnet

The SAND detector will employ the existing superconducting magnet operated in the KLOE (K_L^0 Long Experiment) experiment. The magnet was designed in conjunction with its iron yoke to produce a 0.6 T magnetic field over a 4.3 m long, 4.8 m diameter inner volume. The coil consists of a single conductor layer made from a Rutherford (Nb-Ti) cable co-extruded with high-purity Aluminium. It was located inside a cryostat surrounded by the return yoke (see Figure 3.2).

The cooling of the coil was performed by thermo-siphoning cycles: gaseous He at 5.2 K was injected at 3 bar (absolute pressure) from the cryogenic plant and liquefied through Joule-Thomson valves into a liquid He reservoir in thermal contact with the coil. Current leads were directly cooled by liquid He, while the radiation shields were cooled by gaseous He at 70 K from the cryogenic plant.

3.2.2 The electromagnetic calorimeter

The ECAL is a lead scintillating fibre sampling calorimeter, which offers a time resolution below the ns range, excellent energy resolution and 4π hermeticity. As can be seen in Figure 3.3, the calorimeter is cylindrical and is located inside the KLOE magnet, close to the coil cryostat. Two additional end-cap calorimeters ensure hermeticity. The barrel consists of 24 modules, 4.3 m long, 23 cm thick and trapezoidal in cross section, with bases of 52 and 59 cm. Each end-cap consists of 32 vertical modules, from 0.7 to 3.9 m long and 23 cm thick, with rectangular cross section. Both ends are bent in a C-like shape to allow their insertion in the calorimeter barrel. The calorimeter weight is about 100 t and the readout system includes 4880 phototubes. Due to the large overlap of the barrel and end-caps, the KLOE calorimeter does not have an inactive gap at the interface between those components.

All ECAL modules are stacks of approximately 200 grooved, 0.5 mm thick, lead foils alternated with 200 layers of cladded scintillating fibres of 1 mm diameter, glued together with a special epoxy. The average density is 5 g/cm^3 , the radiation length is $\sim 1.5 \text{ cm}$, and the total thickness of the calorimeter is ~ 15 radiation lengths. Each module is read at both ends by phototubes coupled through light guides to match the circular photocathodes. The readout divides the calorimeter module in five layers: the first four are 4.4 cm thick, while the last one is 5.2 cm thick. The readout segmentation gives an r - Φ (in

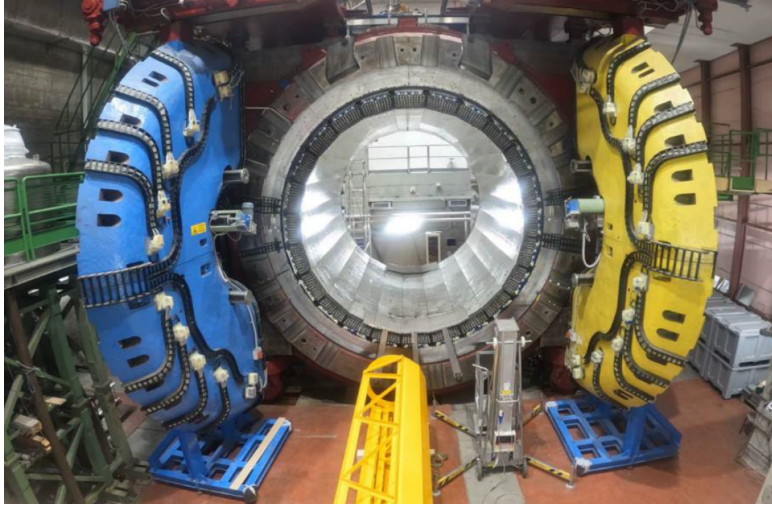


Figure 3.3: A view of the KLOE calorimeter inside the magnet, whose end-caps are open. The barrel ECAL modules are slabs with a trapezoidal cross section extending for the whole length of the barrel. [76].

the case of the barrel) or x - z (in the case of the end-caps) readout resolution of 1.3 cm ($4.4/\sqrt{12}$ cm).

The energy and time resolutions of the calorimeter were evaluated in the commissioning and running phases of KLOE and were found to be [76].

- $\sigma_E/E = 5\%/\sqrt{E(\text{GeV})}$
- $\sigma_t = 54/\sqrt{E(\text{GeV})}$ ps

3.3 The inner tracker

The inner volume of SAND will be instrumented with a low-mass gas-based tracker and a small Liquid Argon detector (GRAIN). The reference design for the tracker employs a Straw Tube Tracker (STT); however, an alternative solution is currently under investigation, based on the Drift Chamber technology. All the capability requirements and opportunities for the inner tracker are summarised in Table 3.2.

The inner volume structure of SAND is schematised in Figure 3.4. The neutrino beam enters from the right side of the barrel, perpendicular to the magnetic field. The tracker will fill most of the magnetic volume, with the tracking planes interleaved with compact polypropylene (hereafter labelled by its brute formula CH_2) and graphite (C) modules, to add mass and act as an additional target for neutrino interactions. The rest of the volume is occupied by the GRAIN detector, located upstream.

The tracker has been designed to provide high resolution in momentum, angle, and space through high granularity of the detector while maintaining low density to minimise secondary interactions. In particular, the tracker must:

1. Include a large target for neutrino interactions, with a fiducial mass of at least 5 t;
2. Provide less than 1 X_0 from the centre to the ECAL;
3. Provide less than 1 λ_l from the centre to the ECAL;
4. Offer a range of different target materials;

Name	Requirement	Rationale
Density	Average density $\rho < 0.22 \text{ g/cm}^3$	Low density is essential to minimise multiple scattering and to allow precise magnetic spectrometry
Momentum resolution	Charged particle momentum resolution $\leq 5\%$ up to $p \sim 5 \text{ GeV}/c$	Precise momentum measurements via curvature are needed to perform kinematic reconstruction
Radiation length	Less than 1 radiation length from its center to ECAL	Minimise radiation lengths allow precise curvature measurement, particularly for $e^\pm$
Interaction length	Less than 1 interaction length from its center to ECAL	Minimise interaction lengths minimises secondary hadronic interactions
Carbon & Hydrocarbon targets	Have both hydrogen-rich and pure carbon targets	A mixture of pure carbon and hydrocarbon target allows to isolate interactions on free protons via subtraction
Nuclear target	Inner tracker with configurable with other nuclear targets	Deploying other nuclear targets allows to investigate A-dependence of cross section
Argon target (GRAIN)	The inner SAND volume shall have an Ar target	Argon target allows a direct comparison of ν -Ar interactions with ν -H ones

Table 3.2: Capability requirements for the inner tracker of SAND.

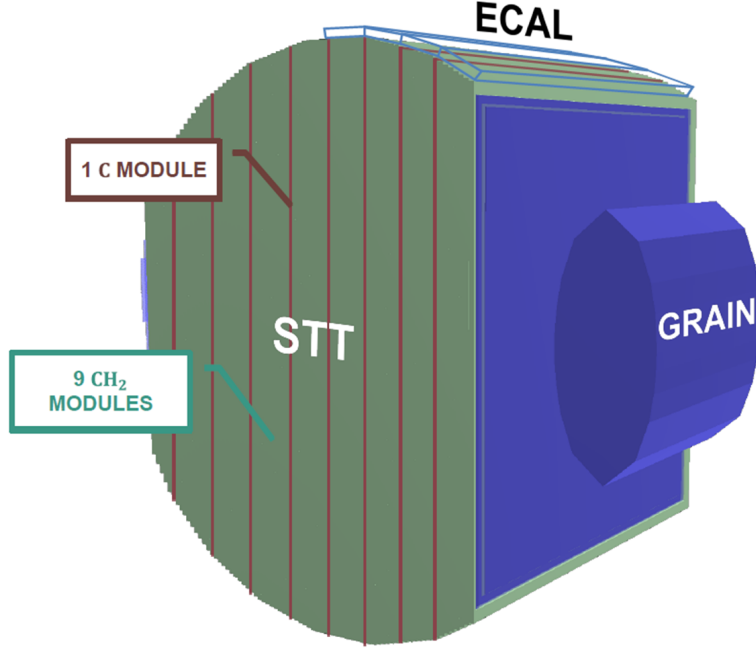


Figure 3.4: The Straw Tube Tracker geometry showing the alternating sequence of C and CH₂ modules, in red and green respectively. The first and last five modules are tracking modules (blue).

5. Achieve a charged particle momentum resolution $< 5\%$ at $1 \text{ GeV}/c$ and $< 10\%$ up to $5 \text{ GeV}/c$;
6. Offer particle identification capability for e, π, K, p, μ with the help of the ECAL;

In order to fulfil the first three requirements, apparently in contrast with each other, the neutrino targets have been separated from the tracking system. Both STT and drift chamber options will have about the same target mass, which is foreseen to be $\sim 3.3 \text{ t}$ for CH₂ and 0.7 t for graphite. In order to achieve the goal of keeping the detector transparent to secondary particles, the target has been spread over the volume in smaller modules, resulting in an average density of $\sim 0.16 \text{ g/cm}^3$. The total radiation length is slightly smaller for the STT ($2.7 X_0$) due to the presence of a transition radiator (TR), which instead will not be present in the drift modules ($3 X_0$). The TR is composed of 105 polypropylene foils $18 \mu\text{m}$ thick acting as transition radiator to improve e/π separation.

One of the most important features of the tracking modules is the possibility of removing the TR and substituting the CH₂ slab with a different nuclear target; a broad range of target materials, such as C, Ca, Fe, Pb, etc., can be installed in place of the target radiator, provided that they can be manufactured in the form of thin planes.

3.3.1 The "solid hydrogen" concept

The configuration of the neutrino targets in the inner tracker allows the implementation of a "solid" hydrogen target by subtracting measurements on dedicated graphite targets from those on polyethylene or polypropylene targets [77]. LBNF (anti)neutrino beam with its unprecedented high intensity flux will offer the possibility to study $\nu(\bar{\nu})\text{-H}$ interactions as never done before. The channel used for this

purpose is $\nu_\mu + \text{H} \rightarrow \mu^+ + n$ (CCQE on H), where the antimuon is reconstructed in the tracker using a track fitting algorithm, while the neutron is reconstructed from the excellent ECAL timing resolution.

For CC interactions, the signal/background ratio in the selection of H interactions can be improved by exploiting the event kinematics. Since the H target is at rest, CC events are expected to be perfectly balanced in a plane transverse to the beam direction (up to the tiny beam divergence), and the muon and hadron vectors are back-to-back in the same plane. Instead, events from nuclear targets are affected by the smearing of several nuclear effects, resulting in a significant missing transverse momentum and a smearing of the transverse plane kinematics. A detailed study of neutrino interactions on hydrogen can be found in [78].

The choice of polypropylene targets is motivated by the need to have plastic materials with the highest possible hydrogen content (14.4% by mass) and that can be easily manufactured in thin foils of arbitrary size. Both C and CH₂ targets must have comparable thicknesses in terms of radiation and nuclear interaction lengths and are alternated throughout the entire tracking volume to ensure that they result in a difference between their detector acceptances for final state particles within 10^{-3} .

In summary, the inner tracker design is overall very well equipped to meet the physics goals set for SAND. It is foreseen to provide very good spatial ($< 200 \mu\text{m}$), angular ($\sim 2 \text{ mrad}$), momentum ($\sim 3\%$) and timing resolutions, while also offering good particle identification by exploiting both the ionisation dE/dx and transition radiation for the e/π separation.

3.3.2 Straw Tube Tracker

The Straw Tube Tracker design consists in 86 modules with a total 344 straw planes. Figure 3.5 shows a representation of a standard module. Looking at a single CH₂ module, it is composed of:

- a solid polypropylene (CH₂) target slab, 5 mm thick;
- a radiator of 150 CH₂ polypropylene foils, $18 \mu\text{m}$ thick, interposed with $117 \mu\text{m}$ air gaps. The radiator is configured in such a way as to guarantee a correct electron identification;
- 4 straw tube layers, XXYY, glued together. Each straw has a diameter of 5 mm and Mylar walls $12 \mu\text{m}$ thick, coated with Aluminium. The anode is a Gold-plated Tungsten wire with $20 \mu\text{m}$ diameter.

The tubes will be filled with a gas mixture of Xe/CO₂ (70/30) at an internal absolute pressure of 1.9 atm ($\sim 1 \text{ atm}$ overpressure).

3.3.3 Drift tracker

A drift chamber module consists of a 5 mm target and a tracking station composed by three wire planes alternated with Mylar foils (see Figure 3.6). At the moment, each wire plane is foreseen to have a different orientation: $+5^\circ$, 0° , -5° . The current design includes one module with a C target, followed by 9 modules with polypropylene targets packed in a unique Carbon frame, which defines what we call *super-module*. Chapter 4 will provide a more exhaustive and complete description of the drift chamber-based tracker.

3.3.4 The GRAIN detector

The GRAIN (GRanular Argon for Interaction of Neutrinos) detector consists of a LAr volume instrumented with optical systems in order to readout the scintillation light resulting from charged particles generated by neutrino interactions in Ar. GRAIN measurements will help to constrain systematic uncertainties from nuclear effects. Moreover it will be permanently located on-axis for cross-calibration with the other detectors. The novelty of this detector consists in its capability to reconstruct the charged

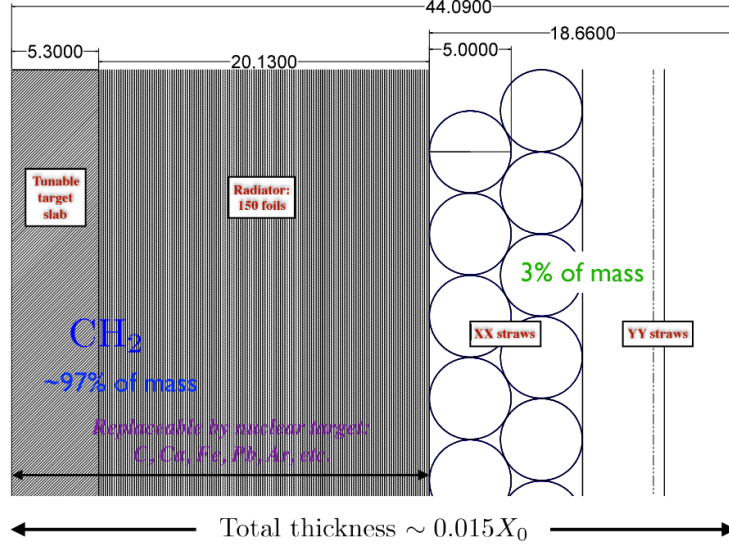


Figure 3.5: Scheme of a compact STT module including three main elements (left to right): (a) a polypropylene CH_2 target; (b) a radiator with 150 polypropylene foils for $e^\pm$ ID through Transition Radiation process; (b) four straw layers XXYY (beam along z axis and B field along x axis).

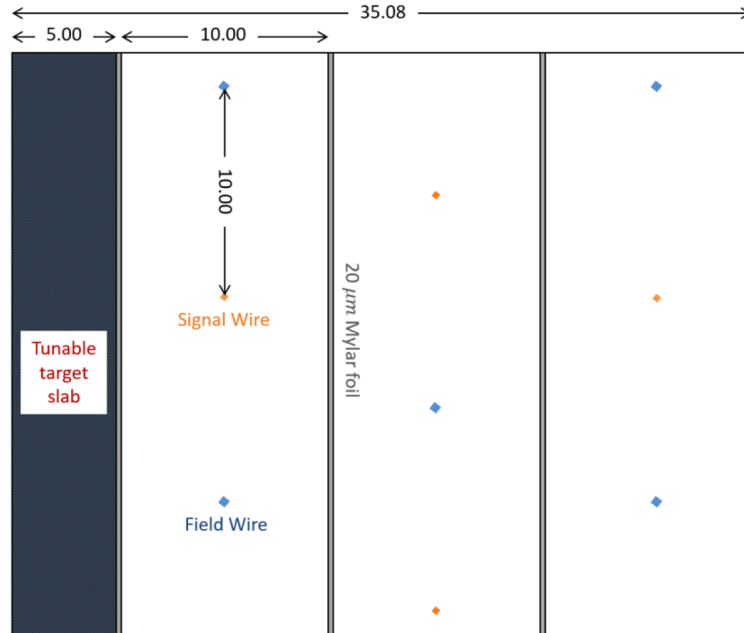


Figure 3.6: Drawing of a drift chamber module, composed by three wire planes interleaved with Mylar foils. The eight of each module depends on its position inside the SAND volume and can range from about 3 to 4 meters.

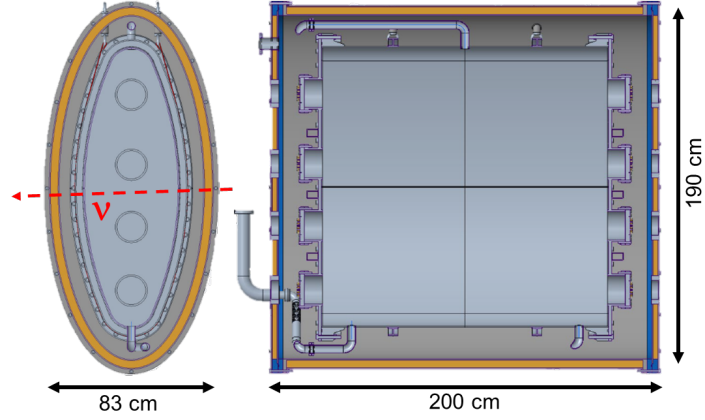


Figure 3.7: 2D rendering of GRAIN, showing the inner and outer vessels.

particle trajectories propagating in the LAr volume using only the scintillation light. The high event rate and pile-up in fact would prevent the use of a classical LArTPC.

Two optical systems are currently being developed: one based on lenses and one based on Coded Aperture Masks, both coupled to SiPM matrices. Both optical systems offer advantages and present disadvantages; lens-based cameras are better known, and the detected image is a direct reconstruction of the source image. However, they are difficult to build due to the cryogenic environment. Because of the high refractive index of LAr, they have also a limited Field of View and occupy a large volume. On the other hand, mask-based cameras are easy to build, have a larger depth of field, and feature a much more compact design. The drawback of this technology is that complex reconstruction algorithms are required in order to reconstruct the image of the source. Since the scintillation light is emitted in the Vacuum UltraViolet (VUV) range [79], a wavelength-shifter is required in order to convert VUV light into visible light, where SiPMs have their optimal photon detection efficiency (PDE). One possible choice is Tetraphenylbutadiene, an organic compound emitting fluorescent radiation when excited by UV light [80]. Its spectrum is peaked at 430 nm which matches the PDE spectrum of the SiPMs and does not vary with the wavelength of incident light in the UV range.

The cryostat is composed by an inner and an outer vessel. It is shown in Figure 3.7. The outer vessel is made of multiple layers of Aluminium alloy, honeycomb, and Carbon fibre. The inner vessel is made of Aluminium, with a height of 147 cm, a width of 150 cm and a maximum depth of 47 cm. The overall thickness of vessels was kept as thin as possible (6 mm) in order to minimise the material budget, resulting in a thickness that is only a small fraction of a radiation length. The ~ 1 t LAr volume's depth is kept to just one interaction length. This allows to minimise the energy loss, showering, and multiple scattering in the passive material.

Chapter 4

The Drift Chamber proposal

Drift chambers (DCs) have been used in particle physics experiments since long time. They guarantee precision in tracking, fast time response and robustness in high-rate environments. As already mentioned, such a detector has been proposed as a backup solution for the inner tracker of SAND. It is expected to provide a reliable alternative to straw tubes, achieving the same performance and physics goals, while simultaneously reducing the number of channels and, possibly, the overall complexity.

Up to now, two drift chamber prototypes have been built in order to test their performance and validate the mechanical solutions for the final detector. In this chapter, I will illustrate the design and construction of the detector, as well as the quality checks that have been adopted to monitor the process and ensure precise knowledge of the key parameters of the chamber, such as the effective tension applied to each wire, which is directly related to the sagitta.

4.1 Motivations and design

The requirements for the inner tracker of SAND have been listed in Section 3.3. The primary objective of the drift chamber tracker is to pursue them while preserving the concept of a light tracker with a diffuse target composed of different materials.

A DC-based tracker offers some advantages with respect to the STT: first, the gas pressure inside the drift chamber is nearly equal to atmospheric pressure, requiring only a few millibars of overpressure to circulate the gas within the volume; second, by incorporating larger, interconnected drift volumes, the number of channels can be significantly reduced, depending on the size of the cell. This results in reduced complexity of the tracking system, which can be built in a single production site, thereby reducing the risks associated with transportation and, consequently, also the costs.

The design of the SAND drift chamber, the drift cell geometry, and the mechanical solutions adopted have been partially inspired by existing drift chambers; in particular:

- the use of crimping pins and of the preamplifier are taken from the KLOE drift chamber;
- the stereo angle design and chamber modularity, as well as the choice of the material for sense and field wires, are inspired by the NOMAD drift chamber;
- the design for the wire boards emulates the one of the MEG II drift chamber.

Appendix B provides an more detailed overview of the aforementioned drift chambers.

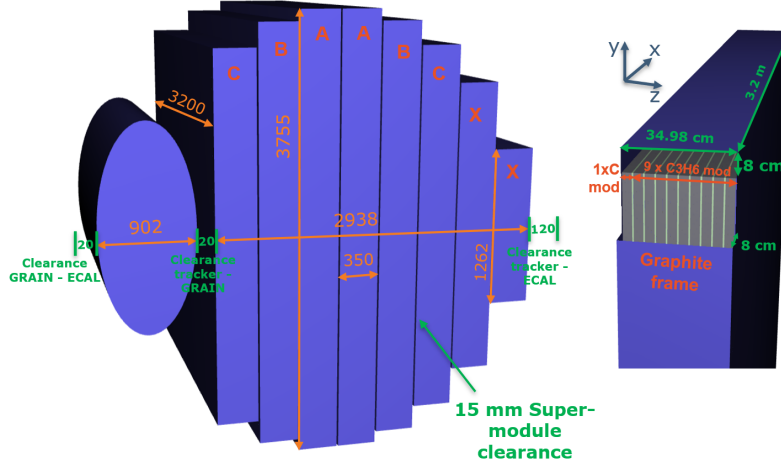


Figure 4.1: *Left*: potential layout for the inner volume of SAND, occupied by the GRAIN detector and by 8 super-modules. *Right*: view of the 10 modules composing a super-module.

4.1.1 Drift chamber layout

As a first choice, it has been decided to adopt the same configuration of the STT, characterised by multiple tracking modules with targets made of graphite and plastic. The Transition Radiation detector, instead, is not included in the base design. The active part of a module consists of a drift chamber with three wire planes.

In order to fill the inner volume of SAND, modules must have a width of 3.2 m and an height that can vary between 1.2 and 3.8 m, depending on the position with respect to the central axis. This is shown in Figure 4.1, which depicts the layout of the inner tracker based on drift chamber technology. Ten modules, nine equipped with CH_2 targets and one with graphite, form a super-module that is ~ 35 cm thick. Overall, the tracker will have ~ 240 DC planes.

4.1.2 Drift cell design

The drift cell is composed of a central anode wire enclosed between two cathode planes made of Mylar sheets. Two additional field-shaping wires complete the cell, delimiting the drift volume. Three wire planes form a tracking module, as shown in Figure 3.6.

The anode (sense) wire has been chosen to be a Gold-plated Tungsten (Au-W) wire, with a diameter of $20\ \mu\text{m}$, while field wires are made of a Copper-Beryllium (CuBe) alloy, with a $100\ \mu\text{m}$ diameter. The latter are positioned to reduce low-field regions inside the drift cell as much as possible, keeping the ratio between field and sense wires close to one. The Mylar sheets constituting the cathode planes have a thickness of $20\ \mu\text{m}$ with a 70 nm layer of Aluminium on both sides. The use of cathode planes instead of wires allows to avoid inhomogeneities in the electric field originating from the different angles of adjacent wire planes, which would result in a more complex time-to-distance relation, as it would depend on the hit position along the wire.

The final dimensions of the drift cell have yet to be decided. Currently, two options are being evaluated: the first consists of a $2 \times 1\text{ cm}^2$ cell, where 2 cm is the distance between two neighbouring field wires; the second option, instead, foresees a smaller cell with dimensions $1.4 \times 1.2\text{ cm}^2$. Depending on the cell geometry, the total number of wires ranges between $\sim 7.2 \times 10^4$ and $\sim 10.4 \times 10^4$ for the two options, respectively. The number of readout channels is roughly half of the total, with the other half

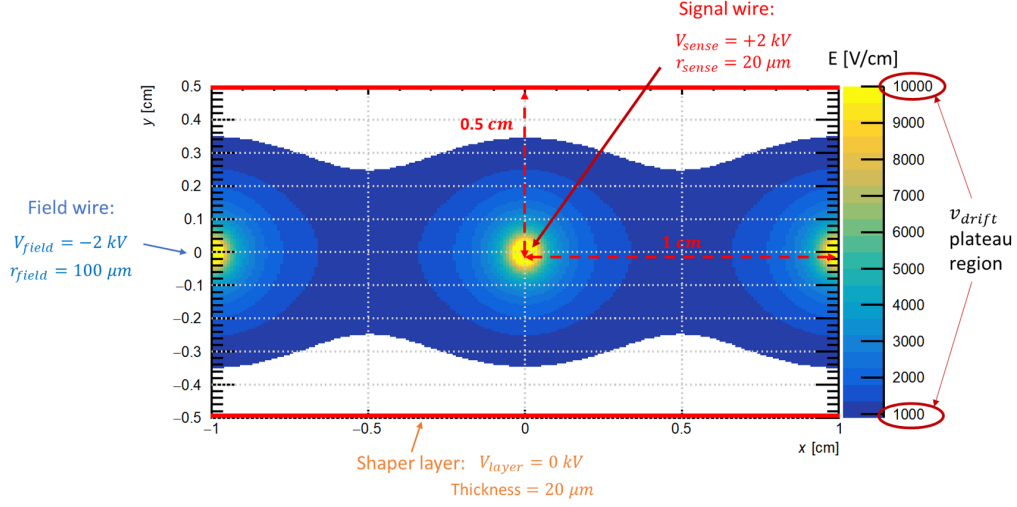


Figure 4.2: Layout of a drift cell with dimensions $2 \times 1 \text{ cm}^2$. The electric field map is shown. This configuration has been adopted for the small-scale prototype.

being field wires.

Detailed simulations of the electric field have been performed with Garfield++ [81] to study the layout of the drift cell. The example shown in Figure 4.2 displays the electric field map for a $2 \times 1 \text{ cm}^2$ cell: a 4 kV voltage difference applied between field and sense wires results in a saturated drift velocity of about $50 \mu\text{m/ns}$ in $\sim 60\%$ of the cell. In general, a drift velocity saturated throughout the entire cell volume would lead to a constant time-distance relation, not dependent on any eventual inhomogeneities of the electric field induced by the displacement of wires or Mylar planes.

Each wire plane composing a tracking module has a different orientation with respect to the magnetic field axis to allow 3D track reconstruction. In principle, increasing the angular separation between wire planes enhances the reconstruction capability. Ideally, the three wire planes would be rotated by 45° relative to one another to maximise this effect. However, this would require placing the readout electronics on every side of the modules, which may complicate any interventions on the front end boards located near the barrel calorimeter. For this reason, it has been decided to have wires inclined by just 5° , so that the majority of the channels can be read out on just one side of the modules, facing the end-caps.

Experimental tests are necessary to determine the optimal configuration and evaluate the performance of the detector. To this purpose, I personally oversaw the design and construction of two prototypes that have been operated in the laboratories of the INFN Section of Bologna and at CERN.

The first prototype has an active area of $30 \times 30 \text{ cm}^2$ and features a drift cell with a $2 \times 1 \text{ cm}^2$ cross section, while the second has an active area of $120 \times 80 \text{ cm}^2$ and adopts a $1.4 \times 1.2 \text{ cm}^2$ area cell. I will discuss them in more detail in Sections 4.2 and 4.3.

4.2 The $30 \times 30 \text{ cm}^2$ prototype

An illustration of the layout of the first small-scale prototype can be found in Figure 4.3. The three wire planes are visible, while the Mylar sheets are omitted. The figure also shows a picture of the detector still open on the assembly table, waiting for the last cathode plane. We used $20 \mu\text{m}$ diameter Gold-plated Tungsten sense wires and field wires made of Copper-Beryllium alloy with a diameter of $100 \mu\text{m}$. They were mechanically tensioned at 50 g and 150 g, respectively, and crimped to metal pins.

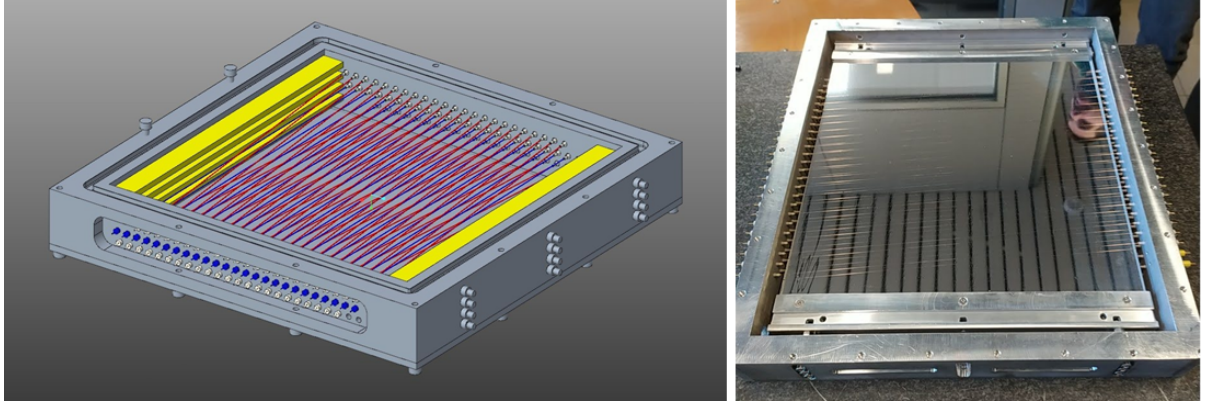


Figure 4.3: *Left*: layout of the first drift chamber prototype, with $30 \times 30 \text{ cm}^2$ active area. In yellow are shown the metallic clamps holding the Mylar planes. The planes are omitted, to make the three wire layers visible. *Right*: photo of the prototype almost finished. The third wire plane is barely visible, with the Mylar foil just below it.

The Mylar sheets were stretched orthogonally with respect to the wire direction, using metallic clamps connected to the external metallic box with three screws, which allow the cathode planes to be properly tensioned, ensuring good planarity.

The electric field configuration is shown in Figure 4.2: Mylar planes are grounded, field wires are kept at a negative voltage, while sense wires are at a positive voltage. The scheme of the electrical connections for sense wires is analogous to the one adopted in the KLOE drift chamber shown in Figure B.2: the high voltage is provided at one end of the wire, while the opposite end is connected to the readout preamplifier.

Although the primary goal of this first prototype was to gain experience in the construction and operation of drift chambers, as well as in the design of the readout system, some preliminary performance indicators were obtained. The prototype encountered noise issues, mainly induced by external sources, which significantly affected data quality and necessitated extensive use of software-based filtering. From a physics standpoint, the detector did not yield high-precision measurements, primarily due to limitations in the tracking system: a setup consisting of five modules, each composed of two orthogonal planes of 16 scintillator bars, 30 cm in length [82]. With a spatial resolution of approximately 2 mm, this system was insufficient for a detailed performance characterisation of the chamber. Nonetheless, the prototype demonstrated an overall detection efficiency greater than 95%, with reduced efficiency observed near the cell edges — an effect attributed mainly to electronic noise. Furthermore, r - t (distance - drift time) relations were successfully extracted, yielding an average drift velocity of approximately $60 \mu\text{m}/\text{ns}$. Overall, the experience proved highly valuable, providing essential insights into mechanical construction, noise mitigation, and readout design, and laying the groundwork for the successful development of the next prototype.

4.3 The $120 \times 80 \text{ cm}^2$ prototype design

The structure of this mid-scale prototype follows the layout described in the previous section, with three wire planes separated by Mylar sheets which act as cathode planes. The distance between two Mylar sheets is 1.2 cm, while the half-width of the drift cell, which is the distance between a sense and a field wire, is 7 mm. Figure 4.4 shows a section of the drift chamber. The wires in the first and third layers are inclined at an angle of 4.95° in opposite directions, while the middle plane has straight wires.

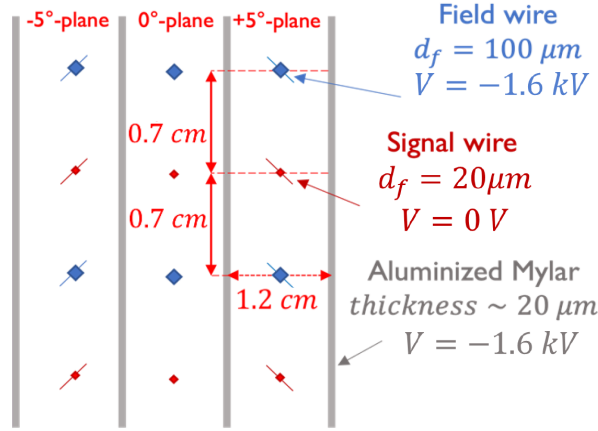


Figure 4.4: Section of the drift chamber prototype. Wire orientations and the voltage applied to each electrode are shown.

Contrary to the small-scale prototype, the electrode configuration has changed: sense wires are grounded, while field wires and Mylar sheets are held at a negative voltage. This arrangement should reduce electrical noise, as the readout is connected to the grounded sense wires, providing a stable reference potential. Additionally, the reduced distance between sense and field wires allows to obtain a more uniform electric field, as shown in Figure 4.5.

Figure 4.6 displays the arrangement of wire and Mylar planes to form the active part of the detector, which is housed inside a gas-tight box, as shown in Figure 4.7. The lateral walls are made of Aluminium plates screwed together, while the top and bottom covers are composed of a metallic frame that holds a 300 μm -thick polyester film. This way, the detector is kept as transparent as possible to the passage of particles in the transverse direction.

4.3.1 Cathode planes

As already mentioned, the cathode planes are made of bi-aluminised Mylar, segmented into three sheets, 400 mm wide. The Al coating has a thickness of about 70 nm. The Mylar planes are stretched orthogonally with respect to the wire direction to deal with the few space available for positioning the six screws (three per side), which allow for the mechanical tensioning of each sheet. In fact, along the wire direction, the volume is completely occupied by the wire frames and the readout electronics.

Ideally, the Mylar should be as flat as possible to create a homogeneous electric field. However, for manufacturing reasons, the Mylar already had some creases that could not be removed, even after its tensioning. We decided to use this prototype to test whether these defects in the sheets somehow limit the performance of the detector.

4.3.2 Wire planes

Wires are soldered onto PCB boards, which allow us to bias field wires and read signals from sense wires. The boards are mounted on frames made of Stesalite, which is a glass fibre-based composite known for its high strength-to-weight ratio and dimensional stability. Although this material is no longer in production, a sufficient quantity was available in stock at INFN Bologna, making it a practical choice for the current prototype. In the future, the usage of carbon-fibre frames will be considered.

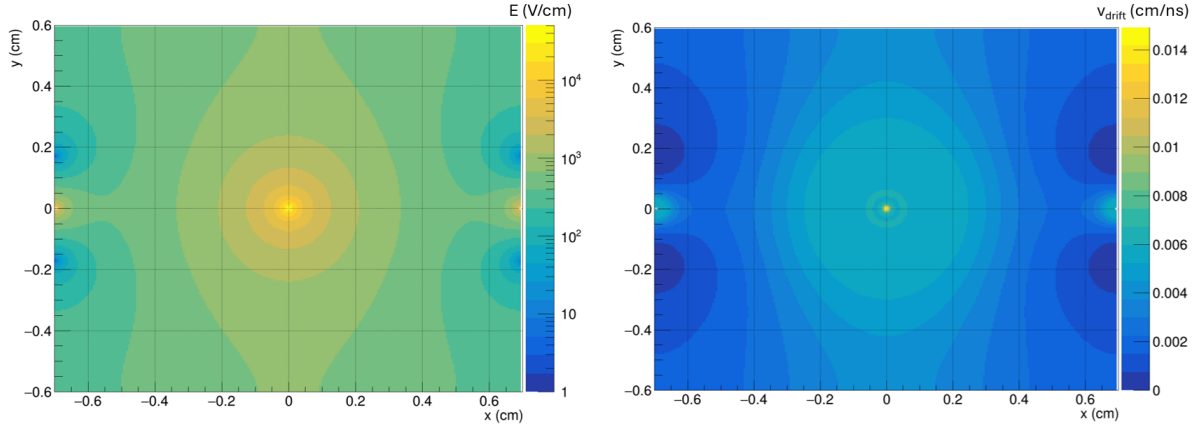


Figure 4.5: Electric field (left) and drift velocity maps (right) in a $1.4 \times 1.2 \text{ cm}^2$ drift cell. A tension of 1700 V is applied on both Mylar planes, located at $y = \pm 0.6 \text{ cm}$, and field wires, positioned at $x = \pm 0.7 \text{ cm}$ and $y = 0 \text{ cm}$.

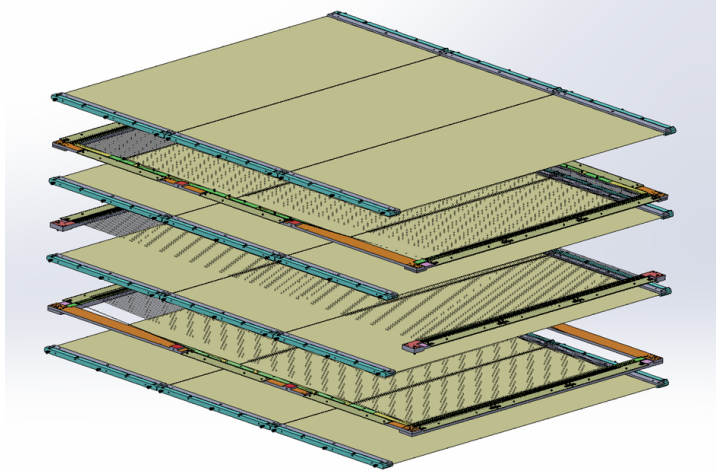


Figure 4.6: Exploded view of the drift chamber layers. The cathode planes are segmented in three sections.

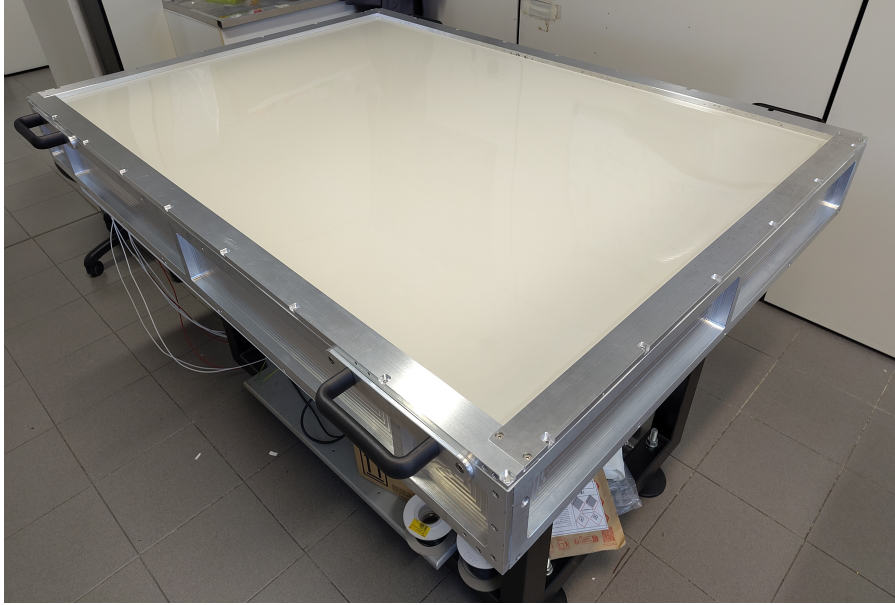


Figure 4.7: Mid-scale drift chamber prototype. The detector has been completed and the external box is sealed.

The middle plane, having straight wires, does not require the lateral bars of the frame, which are instead necessary in the other planes to fix those wires that end on the long sides. The short sides accommodate a total of 56 sense and 57 field wires while on the long sides, 5 wires of each type are present. The three frames are connected through cylindrical pins made of peek, which ensure their precise positioning, and are screwed to a base frame made of Aluminium.

The detector is expected to operate in a vertical position, with wire planes perpendicular to the neutrino beam. However, during the R&D phase, it will also be operated with cosmic rays: this implies that the chamber must be operable in the horizontal configuration as well. Therefore, we simulate the frame deformations in both configurations.

The long bars of the frames are supported only at their ends, which causes them to flex vertically when the chamber is orientated horizontally. These bars are 45 mm wide but only 4.5 mm thick, making them prone to bending and thus requiring additional mechanical support in their central part. As shown in the simulations of Figure 4.8, the vertical deformation can be reduced from 1.4 mm to 0.2 mm by adding four long screws (two per side), which are inserted into two Aluminium plates on both sides of the frame.

The same simulations are performed for the frames when they are hung vertically. The deformations of the long bars in this configuration are less important and are greatly reduced by the presence of the lateral screws, as shown in Figure 4.9.

Regarding the short bars, they experience a longitudinal deformation caused by the force exerted by the wires. The central region experiences the highest stress and undergoes the largest deformations. In order to minimise it, an additional peek pin of 4 mm diameter is inserted in the middle of the bars. This way, the structure deforms approximately $150\text{ }\mu\text{m}$ in the direction orthogonal to the short sides, instead of the initial $200\text{ }\mu\text{m}$.

The precision of the wire position is provided by Plexiglas pins inserted in the Stesalite bars. The wires are stretched across the frame, touching the pins as shown in Figure 4.10. In the first and third layers, which have inclined wires, the contact between the pins and the wires is always guaranteed. In

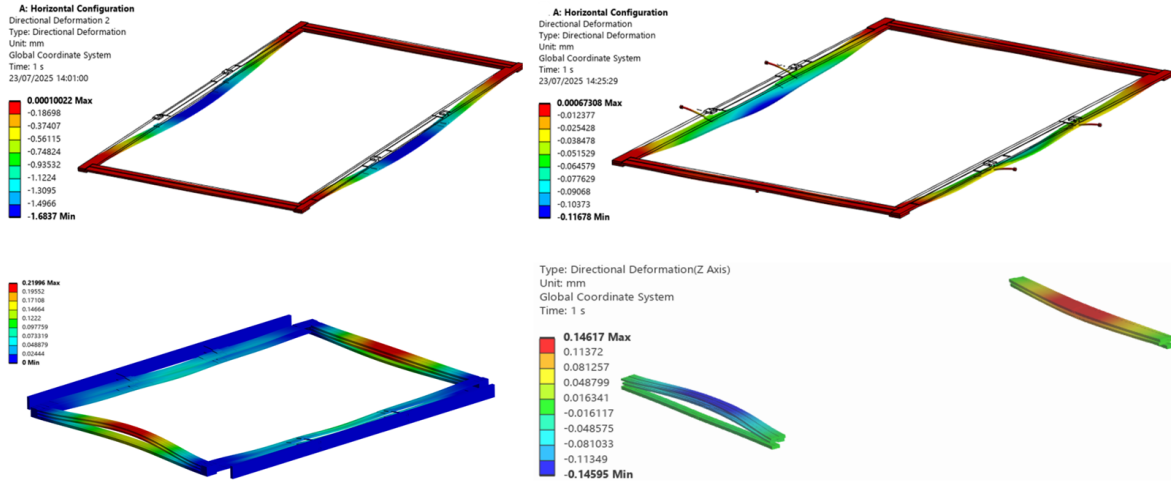


Figure 4.8: *Top*: simulations of frame deformations due to g force, for an horizontal setup. Deformations are shown for with (right) and without (left) lateral support for the Stesalite frame. *Bottom*: simulations of frame deformations due to wire tension. On the right, the longitudinal deformation of the primary structure with a 3-piece central pin of 4 mm diameter is shown. On the left, the same deformation is shown without any central support for the bar.

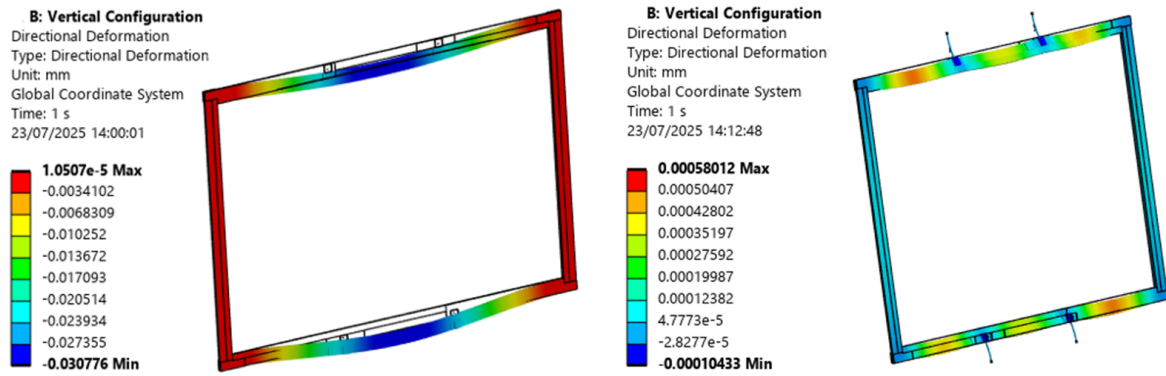


Figure 4.9: Simulations of frame deformations due to g force, when it is hung vertically. Deformations are shown for with (right) and without (left) lateral support for the Stesalite frame.

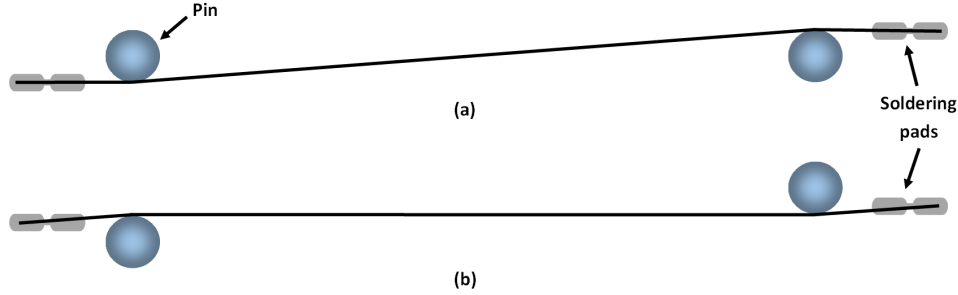


Figure 4.10: Scheme of two wires stretched across the camera and welded onto pads. The first wire (a) is inclined by 5° , easily touching the pins. The second (b) is a straight wire and its extremities must be inclined w.r.t. the pads to ensure the proper contact.

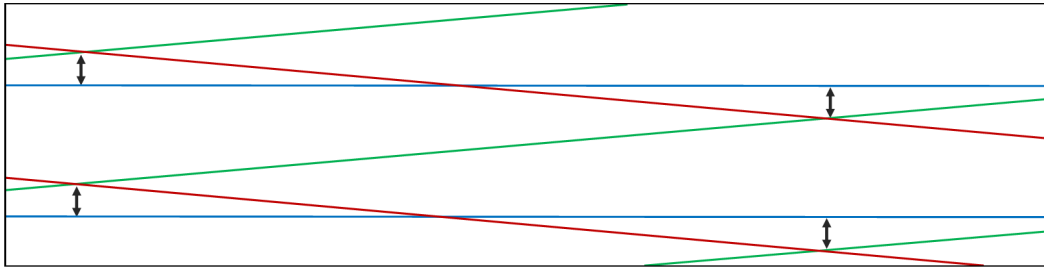


Figure 4.11: Detail of the wire scheme. The arrows indicate the displacement of the wires of the second layer (blue) to avoid the overlap with both first (red) and third (green) layer wires. Only sense wires are displayed.

the second layer, instead, the wires are straight, making it necessary to slightly offset the soldering pads from the direction tangent to the pin surface. In this regard, the soldering pads on the PCBs are wide enough to allow a slight inclination of the wires, which enables them to effectively wrap around the cylindrical pins, thereby ensuring proper contact.

Another key design objective was to minimise redundant vertical intersection points between wires of different layers. To achieve this, the positioning of the second layer, which contains the straight wires, was carefully coordinated with the inclined first and third layers. Figure 4.11 shows how the straight wires have been deliberately offset by one-quarter of the spacing interval to ensure that no point within the structure experiences a direct vertical overlap of all three wire layers. This is crucial to reduce ghost multiplicity.

4.4 On detector electronics: design and production

The detector prototype requires two types of boards to collect the signals from the wires and route them to a readout board hosting the Front End electronics. These boards have been designed by the Electronics Service of the INFN Section of Bologna.

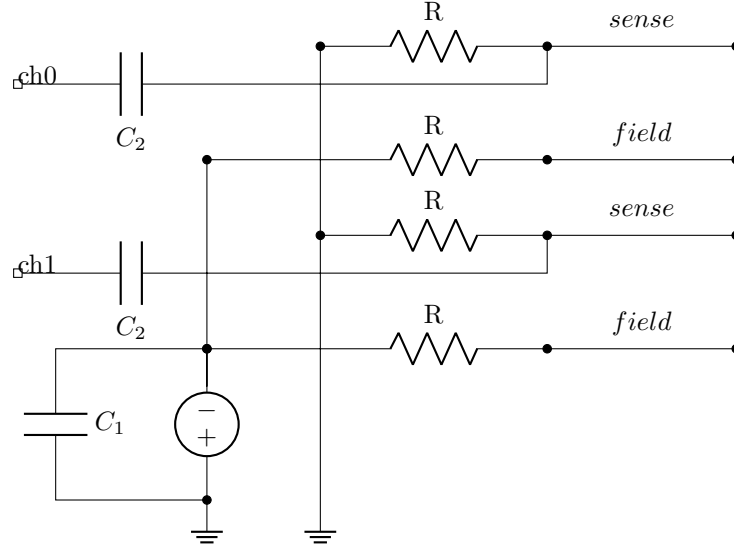


Figure 4.12: Schematic of the wire board circuit. Two field and two sense wires with their corresponding readout channels are shown for reference. $C_1 = 2 \text{ nF}$, $C_2 = 1 \text{ nF}$ and $R = 10 \text{ M}\Omega$.

4.4.1 Wire boards

Figure 4.13 displays two examples of PCB boards. The upper board, which we refer to as of "Type II", is used for wires ending on the long side of a frame and hosts just 5 wires. Instead, Type I boards are installed on the short side and contain a total of 38 wires. Half of these are sense wires, while the other half are field-shaping wires. The boards enable the biasing of the field wires and the readout of signals from the sense wires, which are routed to a connector located at the bottom of the board.

The pads on which the wires are soldered are divided into two parts connected by a thin track. This allows for the application of two welding points at each end of the wires, preventing the first from melting during the second welding.

The electrical scheme of the boards is depicted in Figure 4.12; only four wires (and two readout channels) are shown. Every field wire has a $10 \text{ M}\Omega$ resistor in series to dump the current in case of discharges, while sense wires have a 1 nF decoupling capacitor in series to the readout and a $10 \text{ M}\Omega$ resistor in parallel to ground. Moreover, the PCB components act as a low-pass filter with a cut-off frequency around 10 Hz .

The high voltage distribution network is hosted on the PCB plane opposite to that of the signals for safety reasons. The resistors in parallel with the sense wires are not strictly necessary, but they were included at a stage when it was still undecided whether the sense wires would be biased or not. Indeed, the board offers the possibility to bias both sense and field wires, although the final decision has been to keep the anode grounded.

Sense wires are not terminated, and the effective capacitance towards ground has been measured to be of around 40 pF . The characteristic impedance of a cell is in the range of $200\text{-}300 \text{ }\Omega$.

4.4.2 Interface cards

Three PCB boards of Type I are necessary to accommodate all the wires of a plane, plus two additional boards of Type II per side in the case of inclined wires. It was therefore natural to divide each wire

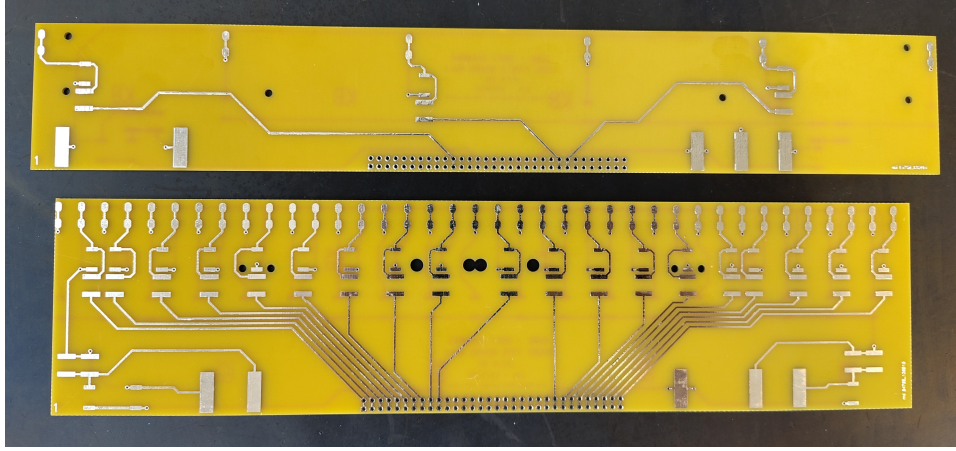


Figure 4.13: Top view of two PCB boards, to be installed on the long side of a wire frame (top) and on the short side (bottom). The first is called of Type II, while the latter is of Type I. The wire soldering pads are clearly visible in the upper part of each board, while the components are not yet mounted. The high voltage distribution network for field wires is host on the back of the PCB. The holes are used to fix the boards on the Stesalite bars with 2 mm diameter screws.

plane into three sectors, parallel to the wire direction. In this prototype, each sector has its own power supply in order to be able to remove the high voltage from a single sector in the event that a wire breaks.

Signals from three overlapping sectors are collected on the wire boards and sent through flat cables to an *interface card*.

Figure 4.14 shows the two sides of the interface card. In the back there are three connectors for the flat cables coming from the wire boards, while on the external face there is a multi-pin connector to which a readout board can be plugged in. In addition, three MMCX connectors allow the injection of an external signal in the readout board. This has been proven to be useful for reading out the signals of a photomultiplier tube (PMT) with the same Front End electronics of the drift chamber. More details about this can be found in the next chapter.

In total, there are three interface cards on the detector, located on the wall of the external box in correspondence with as many openings.

4.4.3 Grounding scheme

Particularly important is the grounding scheme of the detector. There are three distinct ground references in the setup: the ground of the readout electronics, that of the high voltage source, and the chassis ground, represented by the external metallic box. In principle, they could have been completely independent, since all the components of the active part of the detector are isolated from the external box, and the HV and analogue grounds are physically separated on the PCB boards. However, all the ground references were ultimately connected together: a choice that proved to be highly effective.

Looking at the layout of the interface card in Figure 4.14, one can notice several pads on the external face. The four on the right can be used to connect the ground plane of the card with the metal casing of the external box through the metallized screw holes.

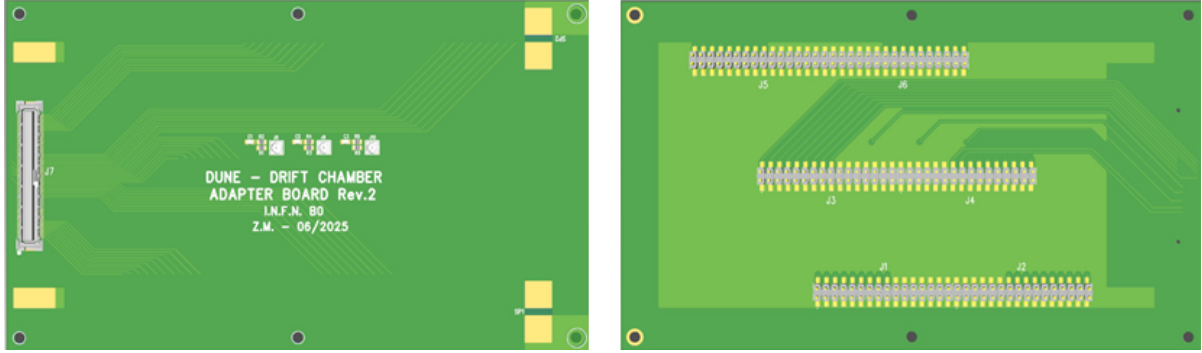


Figure 4.14: Front (left) and rear (right) view of the interface card.

4.5 Detector assembly

The assembly of the drift chamber prototype was carefully planned and completed within few weeks. Since a clean room was not available, the entire process was carried out in a laboratory, adopting appropriate procedures to reduce as much as possible the accumulation of dust and grease from human contact.

The workspace was organised as shown in Figure 4.15, with three tables. The first was dedicated to the assembly of the Mylar sheets; a second table was used to tension and weld the wires to the frames, which were then transferred, together with the Mylar sheets, to the final assembly station located on the third table. The procedures followed during the construction of the various detector components, along with the quality controls performed after each assembly stage, are described in the following sections.

4.5.1 Cathode planes

The Mylar sheets are assembled individually and then transferred to the detector structure, forming a cathode plane.

A single sheet is unrolled on a large Aluminium plate secured to the table (see Figure 4.16). Two L-shaped Stesalite bars are placed at both ends of the plate and kept in position with metallic pins. The Mylar is carefully attached to the bars using double-sided tape, trying to avoid creases in the sheet. At this stage, the element is not tensioned, and it won't be until it is in its final position on the detector. Figure 4.17 shows all the components of a Mylar sheet we have just described. To reinforce the bonding, a metal rod is screwed against the Stesalite bar, pressing the sheet firmly onto the adhesive tape.

Once assembled, each sheet is transferred to the detector structure using a special tool composed by two long metal bars equipped with handles. The bars are screwed to the metal sticks, so that the sheet can be moved keeping the Mylar flat. This way, we prevent the sheet from touching any part of the chamber during the installation, such as the table for the first cathode plane, or one of the wire layers for the following.

When a Mylar sheet is in the correct position, it is connected to the detector structure with three pairs of screws. The Stesalite bars of the first Mylar plane rest directly on the metal base of the chamber, with the upper planes laying directly on it. The presence of three screws on each side offers good flexibility in tensioning a sheet while maintaining it as flat as possible. This operation is critical since excessive or non-uniform tension results in the formation of longitudinal creases, as shown in Figure 4.18.

Preliminary tension tests allowed us to select the bi-adhesive with the best performance for our use-case. Indeed, we noticed that some tape samples did not offer good resistance to the strain of the Mylar, causing the tape to slide on the Stesalite bars a few days after glueing, thereby decreasing the

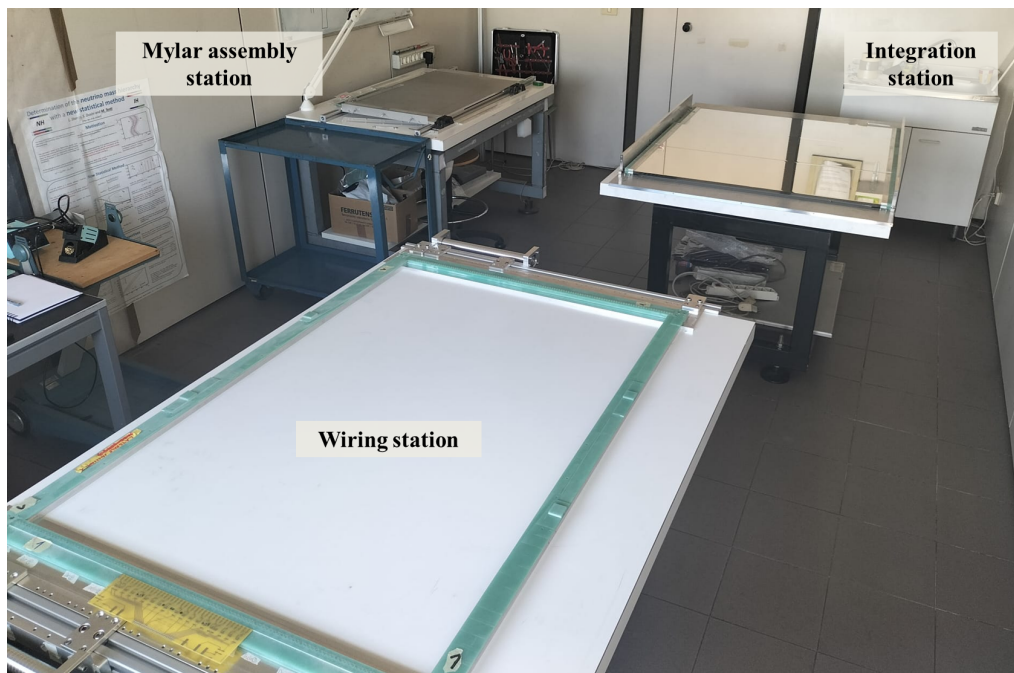


Figure 4.15: Overview of the laboratory used to assemble the prototype. The first Mylar plane has already been installed and the spinning of the first wire plane is ready to start.

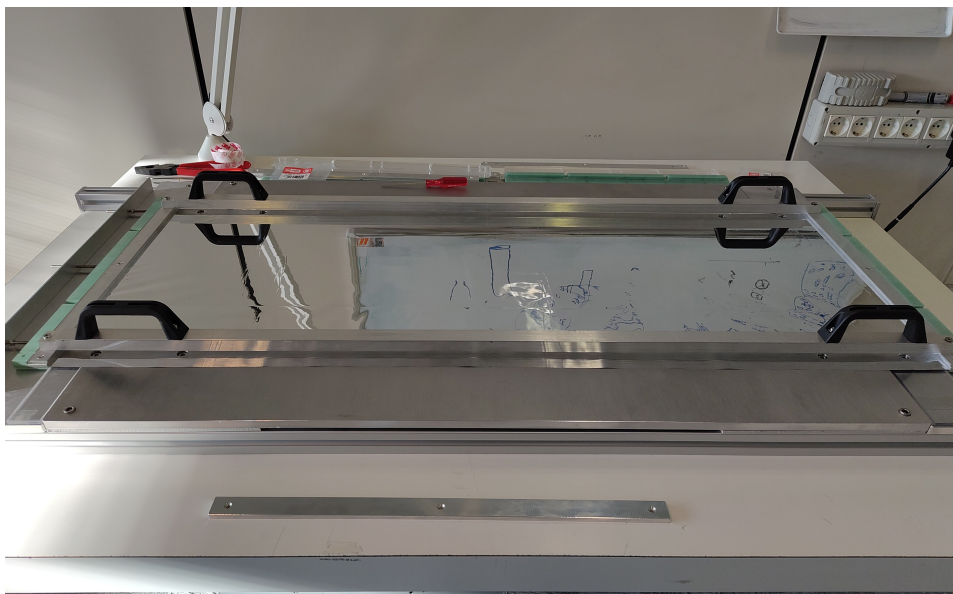


Figure 4.16: Mylar sheet assembly station. The tool for the transportation of the sheet are already in place.

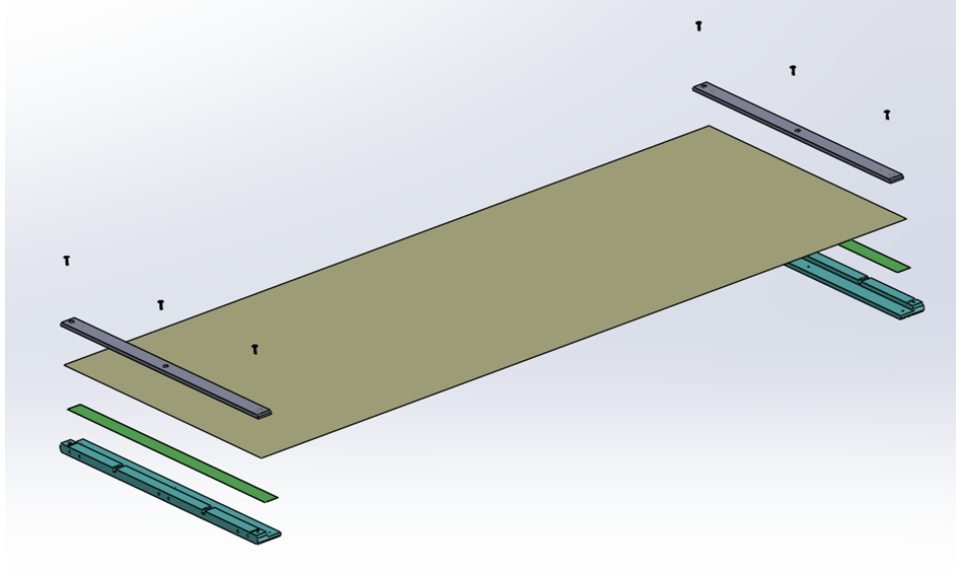


Figure 4.17: Single Mylar sheet. The components of the end clamps are clearly visible.

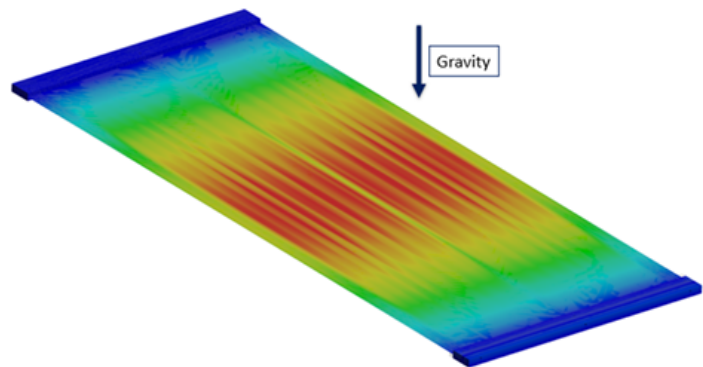
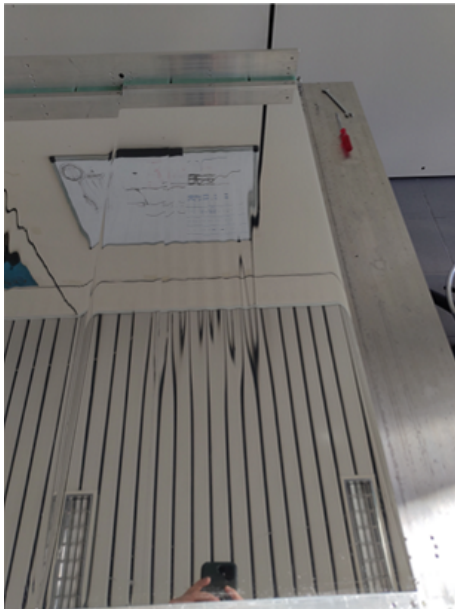


Figure 4.18: *Left*: photo of a Mylar foil which has been over-tensioned causing the formation of creases. *Right*: FEM simulation of an horizontal Mylar foil subject to excessive tension.

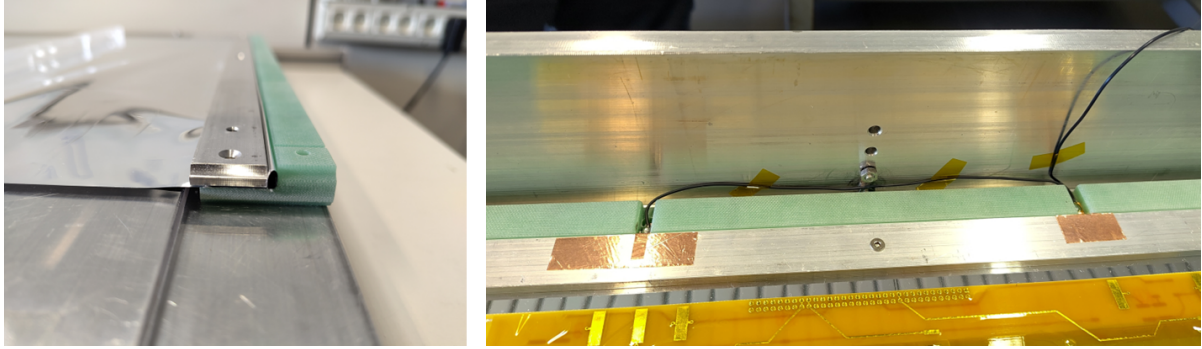


Figure 4.19: *Left:* detail of a clamp. The Mylar sheet folded against the metal plate ensures the distribution of the HV to both sides of the sheet. *Right:* electrical connection of one of the Mylar sheets. Each foil has two connections for redundancy.

tension of the sheet and producing creases.

The High Voltage (HV) is applied to a Mylar sheet through a non-screened cable soldered on an adhesive copper tape, which is glued on the Aluminium stick. In order to bias both sides of a sheet, its ends are folded as shown in Figure 4.19, so that the lower surface of the sheet also comes into contact with the metal stick.

We decided to group together four overlapping Mylar sheets (one from each cathode plane) and power them with the same power supply, so that in total three are needed. A CRC filter was also inserted in front of each HV line.

4.5.2 Wire planes

The assembly of the wire planes was carried on in parallel with that of Mylar planes. As a first step, the PCB boards on which the wires have to be soldered are installed on the Stesalite bars using epoxy glue. In particular, we employed Araldite®2011: a bi-component adhesive that has a cure time of ~ 10 hours at room temperature. The precise positioning of the boards is provided by small Teflon screws of 2 mm diameter, which connect the PCBs to the Stesalite bars. These screws do not serve a structural function (which is instead provided by the epoxy) but are useful during the curing phase, as they keep the boards pressed firmly against the bars.

The Stesalite bars are then assembled on a dedicated Aluminium frame, which keeps them in the correct position and aligned with respect to one another. Before the spinning process takes place, plastic pins are inserted into their housing in the bars. They have a diameter of 4 mm and must not protrude more than 2 mm to avoid touching the upper Stesalite frame once all wire planes are assembled.

The setup for the wire tensioning is shown in Figure 4.20. The process begins by stretching a wire over the frame using plastic gloves to keep the wire as clean as possible. One end is fixed on a PCB board with adhesive tape, while a weight is attached to the other end. The weight consists in a brass cylinder which has been carefully worked to obtain the desired weight. It is made of two parts which can be screwed together on one end of the wire, which is then leaned on a grooved cylinder. The diameter of the cylinder is big enough to bend the wire without being damaged, while the grooves help to align the wire with the soldering pads. It is able to slide along the metallic basement of the spinning structure to follow the evolution of the operations. Once the wire has been aligned, as shown in Figure 4.21, its ends are welded to the pads, starting from the one fixed with the adhesive tape. The wire in excess is then cut using a scalpel. Planes with inclined wires require also to operate along the long side of the frame.

Field wires are tensioned to 250 g, while for anode wires we choose a 50 g weight. First, all field wires

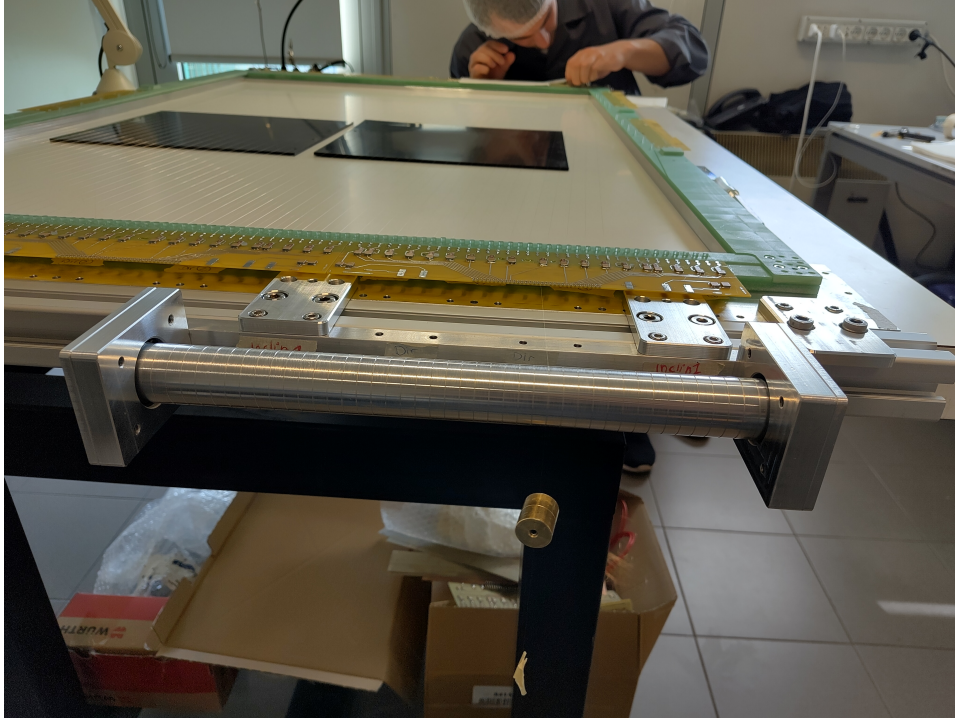


Figure 4.20: Overview of the spinning structure. In the foreground one can see the 250 g weight hanging from the grooved cylinder, attached to a $100\ \mu\text{m}$ field wire. In the back, an operator is cutting the wire in excess after it has been welded.

were installed, followed by the anode wires. This has been done for two reasons: firstly, because field wires are those to which we apply the larger tension, which can induce the larger deformations in the Stesalite frame; secondly, to avoid damaging anode wires during the spinning operations by field wires, the opposite being very improbable.

Once an entire frame has been completed, it is moved to its final position using a custom-made tool which guarantees the minimum deformation of the frame during the transfer and provides a solid support for the installation. The frame must be fixed with six pins made of Peek, one at each corner and two in the middle of the short sides. The transport structure helps to contrast the deformation of the frame due to the wire tension, which could prevent an easy insertion in the pins which are already fixed in the previous frame. Figure 4.22 shows one of the long screws employed to support the long sides of the frames with inclined wires. They are inserted before the removal of the transfer tool and are wrapped with Kapton tape to avoid direct contact with the metal plate of the clamps of the Mylar sheets.

After the installation of a wire frame, the same epoxy glue employed for the PCB boards is used on the wires with the dual purpose of providing an additional fixing point to the wires and keep the plastic pins in their slots. This is shown in Figure 4.23. After all these steps are completed, the wire plane appears as in Figure 4.24, where the last layer of wires has been laid on a cathode plane.

4.5.3 External box

As mentioned previously, the drift chamber layers are assembled on an Aluminium frame, which acts as the basement of the detector. The gas volume is enclosed within the walls of a box which is built upon



Figure 4.21: Detail of the pads of a PCB board: four of them have the wire already welded, while the fourth from the left has the anode wire stretched across it. All the wires are touching the plastic pins.

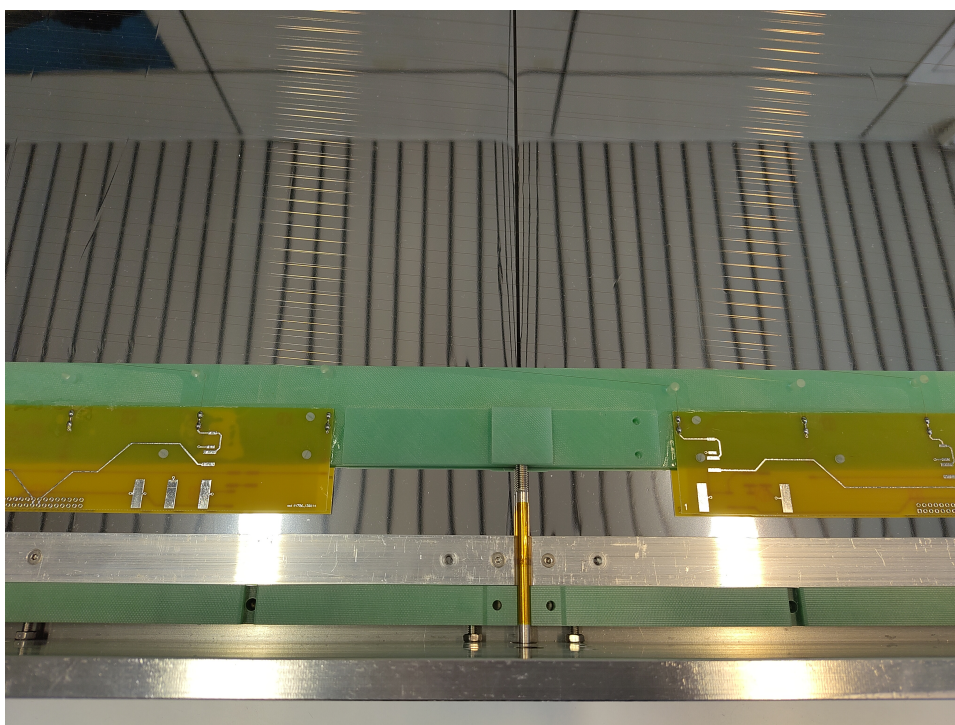


Figure 4.22: View of one of the screws for the lateral support of a frame. It fits perfectly in between two clamps holding the Mylar foils.

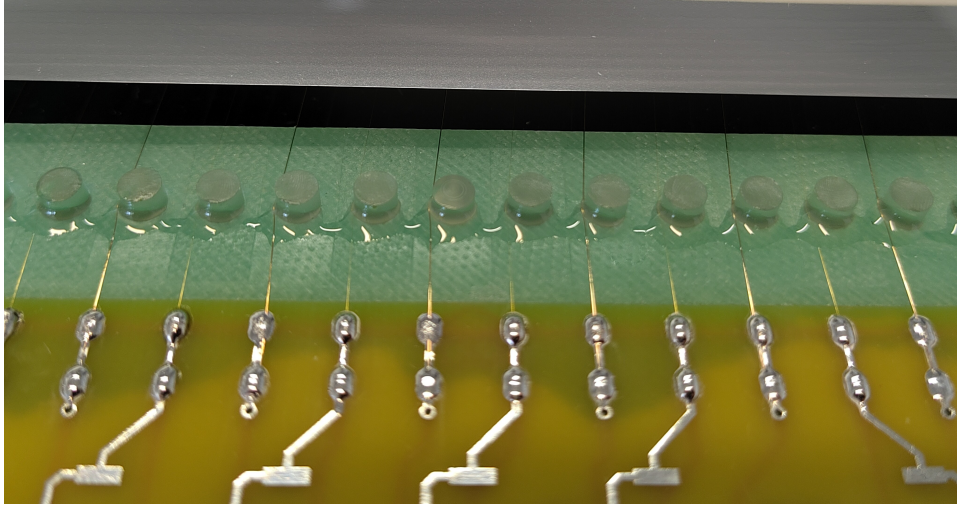


Figure 4.23: Detail of the wires and plastic pins glued with Araldite 2011.

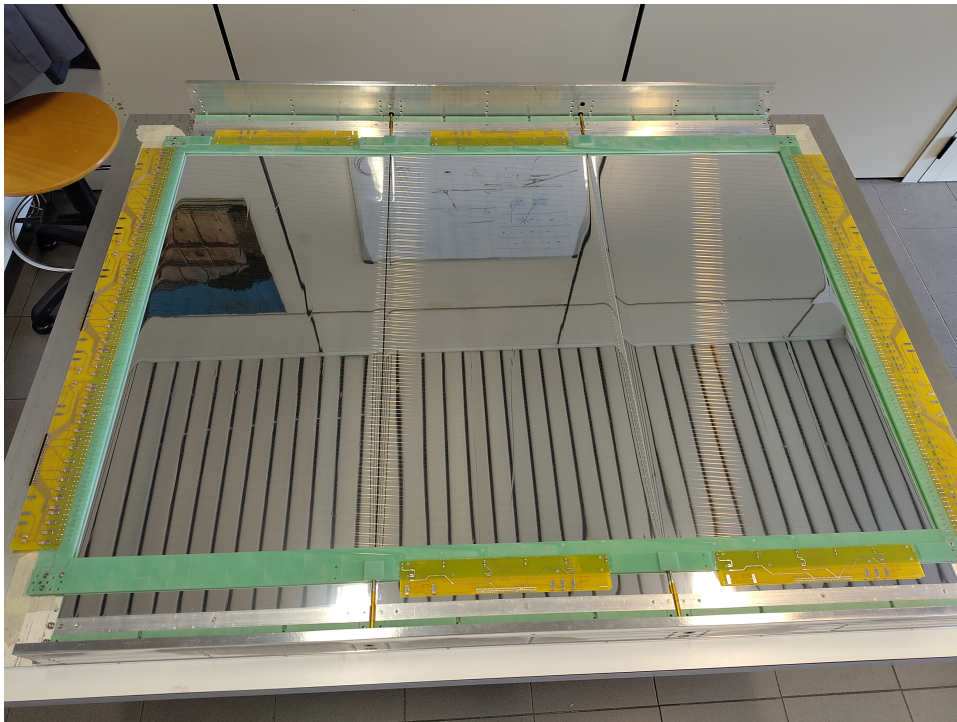


Figure 4.24: Top view of the drift chamber prototype. The last wire layer is visible, with the PCB boards glued on the Stesalite frame. the cathode plane is composed by three Mylar foils, stretched perpendicular to the wire direction.



Figure 4.25: View of the lateral walls of the gas box.

the basement. The side walls are made of 1 cm thick Aluminium plates with recesses designed to lighten their weight. Three rectangular holes are drilled on the readout side to allow the passage of the flat cables (see Figures 4.25, 4.26 and 4.27). The holes are closed by the interface cards, which are screwed to the wall. An additional opening serves to install a metal plate with 12 HV connectors to power the field and cathode planes. This way, the reference ground of the power supply is directly connected to that of the metal casing.

The top and bottom faces of the box are closed by two polyester sheets 300 μm thick, installed on a metallic frame. The junctions between the walls of the box are sealed with silicon, as are the interface cards. A plastic o-ring is positioned between the top and bottom covers and the body of the box, in a specially dug guide.

4.6 Quality controls

During the assembly process, several tests were performed to verify the quality of the work. After the completion of a wire plane, every weld is checked with the help of a microscope to ensure the wire has not been damaged. Figure 4.28 offers a good example of the imperfections that may be found: the image on the left shows an anode wire that has broken between the two welds; instead, on the right, a white lint fragment is stuck near the weld. Moreover, in both cases one can see the remnants of the solder past which, although it does not present any issues for the chamber operation, can be easily removed using ethyl alcohol.

Concerning the plane hosting straight wires, it is important to check whether every wire is touching its corresponding plastic pin, as only in this manner we can ensure the precise positioning of the wires. Figure 4.29 shows two pictures of the same wire. Although they may seem identical, they are not. Indeed, in the left picture, the wire is in contact with the pin, while in the picture on the right, it is slightly displaced.

This issue does not affect the other wire planes, as the inclination of the wires themselves ensures that they lean on the pins.

Another fundamental verification concerns the tension of the wires. Several factors can influence it: small differences in the spinning process can result in different values for the wire tension. Furthermore,

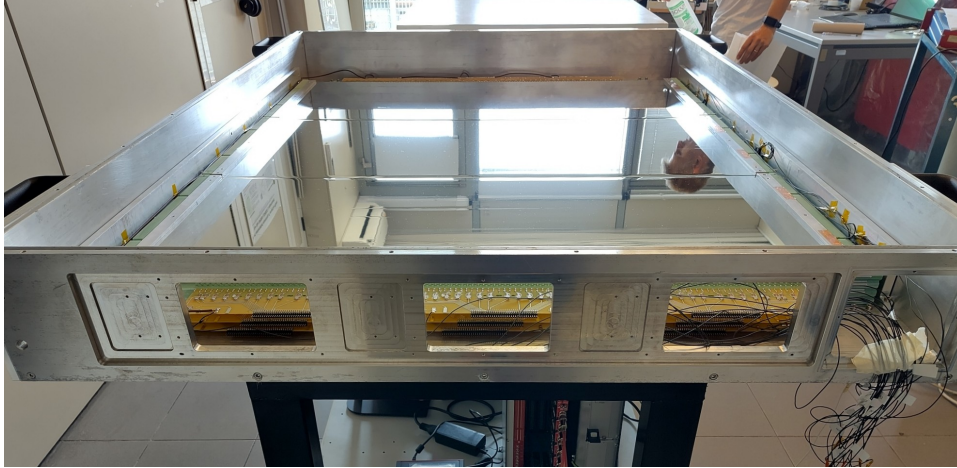


Figure 4.26: View of the gas box from the readout side. Four rectangular openings are drilled in the metal plate. The rightmost one is reserved to the high voltage connections, while the remaining three will be closed by the interface cards.

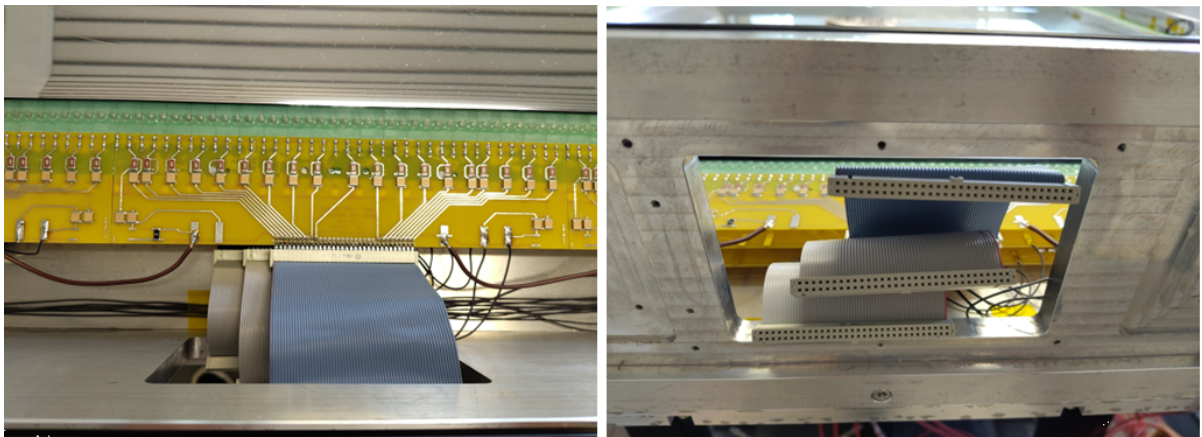


Figure 4.27: Detail of three flat cables coming from different wire planes. They are gonna be connected to an interface card. PCB boards from different planes are displaced about 10 mm from each other, to match the wire inclination.

the more wires get welded to the boards, the greater the deformation the Stesalite bar will undergo, thus modifying the tension of the wires that are already soldered.

The tension of a wire is strictly related to its sagitta f through the relation

$$f = \frac{\lambda L^2}{8T} \quad (4.1)$$

where T is the tension applied to a wire of length L and linear density λ . More information can be found in Appendix A.

A uniform distribution of the wire tensions across a plane and between different planes allows for the minimisation of the contribution of the wire displacement to the spatial resolution of the detector.

The tension of the wires is measured by applying the method of the resonance frequency: if an alternating current flows in the wire and an external magnetic field is introduced, the wire starts to oscillate. By varying the frequency of the current, it is possible to find the fundamental frequency of the wire, which maximises the amplitude of the oscillation. The mechanical stretch F of the wire can be found using the relation

$$F = \frac{L^2 d \rho \pi}{g T_{osc}^2} \quad (4.2)$$

where L is the wire length, d its diameter, ρ is the specific weight of the wire and T_{osc} is the oscillating period.

For our measurements, we employed the wire stretch meter housed in the CAEN Model SY502. A probe was connected at each end of a wire, while a small magnet was hung just above it, roughly at its centre, as shown in Figure 4.30. The instrument causes the oscillation of the wire and immediately provides the value of its tension. The measurement was performed before and after each wire plane was transferred from the assembly table to the detector to ensure that no damage was done to the wires during this operation.

The results are shown in Figures 4.31 and 4.32 for sense and field wires, respectively. The first thing one can notice is that, in both cases, the effective wire tension does not correspond to the nominal value. After checking that the instrument was calibrated correctly, it was determined that the origin of the discrepancy was due to the friction between the metal wires and the grooved cylinder used during the spinning.

The anode wires of the middle plane (with straight wires) show an average tension greater than that of the other planes. Our hypothesis is that it is due, once more, to the effect of friction, this time between the wire and the plastic pins. Indeed, in the middle plane wires only slightly touch the plastic pins, while in the other planes they have a wider surface of contact, which further reduces the effective tension applied to the wires during their tensioning. This effect is not visible for field wires, probably because the larger tension to which they are subjected makes it negligible.

As the wires were being stretched, a few of them were hindered by the presence of one of the small Teflon screws used for the PCB board. This may result in a tension that differs significantly from that of the neighbouring wires. In principle, the screws should have been removed after the boards were glued; however, this was not possible due to the glue itself. Given the results of the measurements, we nonetheless decided to leave everything as it was, without taking any action.

After the installation of each cathode or wire plane on the detector, we performed an electrical test of the components, biasing them with high voltage. The aim was to verify that no short-circuits were established between any of the components. Since these tests were performed in air to preserve the wires from discharges, the maximum voltage we could apply was 1000 V. The tests always yielded positive results during the assembly.

A few days after the completion of the prototype and before sealing the gas box, the electrical test was performed once more. However, this time, a non-zero current was observed on the field wires. The power supply measured a current of $\sim 4 \mu\text{A}$ at 100 V, which increased to $\sim 12 \mu\text{A}$ at 1000 V. The



Figure 4.28: *Left*: a sense wire broken between the two welds. *Right*: the sense wire is properly soldered, a small white lint is visible below the rightmost weld.

current was not constant but decreased over time. Approximately ten days later, however, we observed a current of $\sim 10 \mu\text{A}$ already at 10 V.

It was found that the epoxy glue applied to the wires became conductive, with a surface resistivity ranging from 10 to 25 $\text{M}\Omega/\text{cm}$. This was caused by the absorption of air humidity; indeed, after the adoption of an air conditioner to reduce the humidity in the room, the absorbed current was significantly lowered. After the sealing of the detector, the flow of dry gas inside the chamber extracted the remaining water residues from the Araldite.

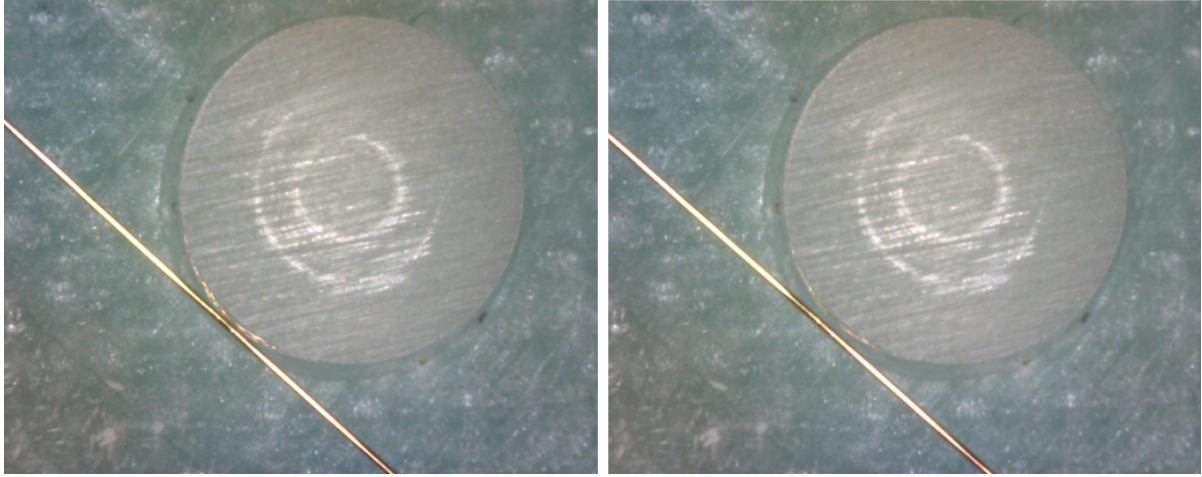


Figure 4.29: Picture of a field wire with its plastic pin acquired with a microscope. In the left image the wire is touching the pin correctly, while in the right image it is slightly distant from it.

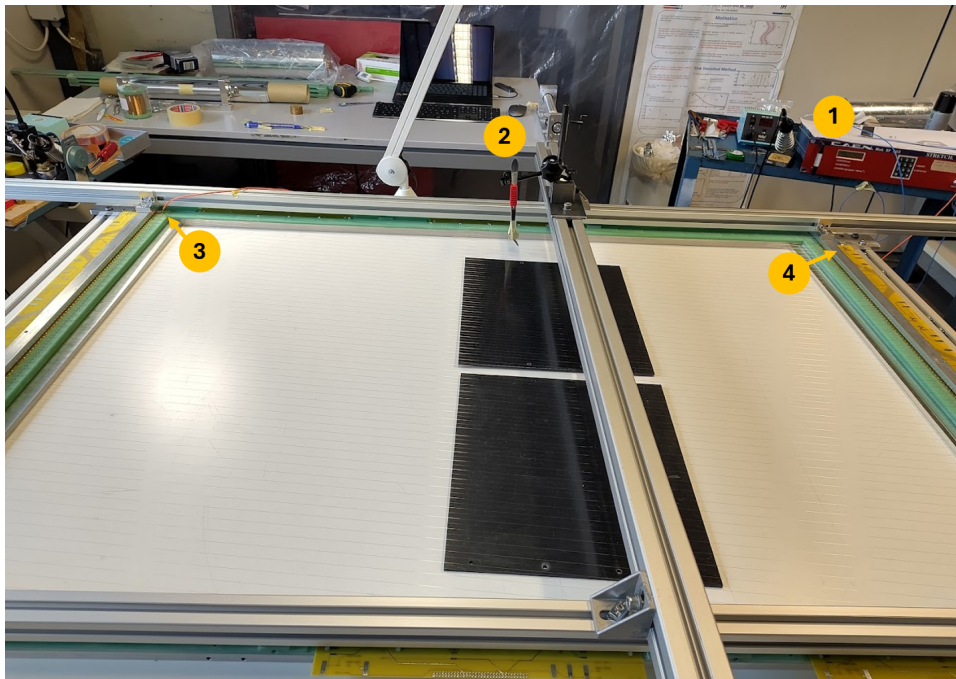


Figure 4.30: Setup for the measurement of the wire tension using the CAEN SY502 Module (1). A Bosch profile allows the movement of the magnet (2) which must be positioned above the wire to be measured. The probes connected at both ends of a wire are barely visible (3 and 4).

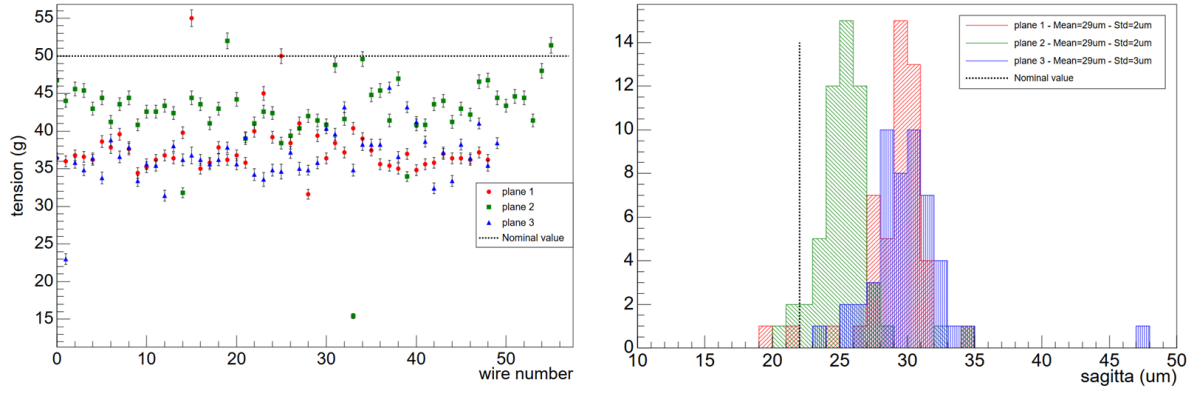


Figure 4.31: Sense wires: graph displaying the measured wire tensions (left) with the corresponding distribution for the sagitta (right) for the wire planes with inclined (plane 1 and 3) and straight wires (plane 2). The dashed lines in both graphs indicate the expected nominal values for the tension and the sagitta, respectively.

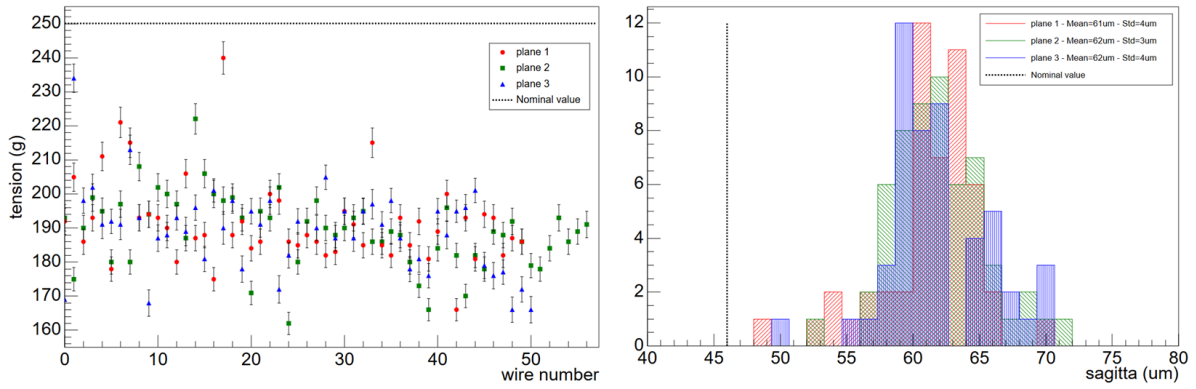


Figure 4.32: Field wires: graph displaying the measured wire tensions (left) with the corresponding distribution for the sagitta (right) for the wire planes with inclined (plane 1 and 3) and straight wires (plane 2). The dashed lines in both graphs indicate the expected nominal values for the tension and the sagitta, respectively.

Chapter 5

Readout Electronics and Preliminary Tests

After its completion, the detector was first operated in the laboratories of the INFN Section of Bologna and then transferred to INFN Ferrara, where it was tested together with the tracking system in preparation for the beam test.

Initially, the chamber was fluxed while the high voltage was gradually applied to clean the gas volume from dust residues. This phase lasted one week, during which twelve channels were read with a board mounting two VTX preamplifiers and connected to a VME digitiser.

In Ferrara, the chamber was tested with the TIGER-GEMROC readout chain, which was later employed during the two-week beam test period at CERN.

5.1 Choice for the Readout Electronics

Currently, there is no definitive electronics for the drift chamber readout. Experiments such as NOMAD and MEG II adopted a custom-made Front-End electronics optimised to match the wire parameters.

During this preliminary R&D phase, it was decided to rely on an already existing electronics with a robust readout chain. The two main available options are the VMM3a and TIGER ASICs; the latter will be described in detail in the next section.

VMM3, and its upgraded version, VMM3a [83], were developed by Brookhaven National Laboratory (BNL) and are capable of simultaneous precise charge and time measurements. This ASIC is capable of measuring both the signal peaking time or the time of a threshold crossing (ToT). The readout chain, based on SRS system, was developed by the RD51 collaboration at CERN [84].

The ASIC main benefit is a flexible settings for analogue input circuitry: a 10 bit ADC for charge measurement, a 8 bit ADC for time measurement, variable gain from 0.5 to 16 mV/fC, and variable peaking time (25–200 ns). This makes it attractive as a front-end electronics solution for a wide range of gaseous detectors, from MPGDs (Micro-Pattern Gas Detectors) to wire-based detectors.

Indeed, the VMM3a has been used for the readout of a straw tube prototype for the DUNE STT tracker, which was tested with the CERN SPS muon beam [85]. Unfortunately, persistent latching of the VMM3a has been observed in the ToT mode, making it inappropriate for the straw tube readout. Current information suggest an algorithmic issue in cases where the time between the threshold crossing and signal peak is shorter than one bunch clock. No such effect was found for VMM3 since the logic of the time-at-threshold mode is implemented differently in the previous chip revision.

Despite its potential, VMM3a was discarded in favour of the TIGER ASIC for two main reasons: the better time resolution of the latter, and the availability of support for the operation of the readout

chain.

Finally, a completely different chip has been used: the VTX preamplifier, the same employed for the readout of the KLOE drift chamber [86]. More details are provided at the end of this chapter.

5.2 TIGER-GEMROC readout chain

For the beam test we employed a unique readout chain for both the drift chamber and the GEMs. The TIGER-GEMROC readout chain, sketched in Figure 5.1, was developed for the Cylindrical Gas Electron Multiplier Inner Tracker (CGEM-IT), an innovative solution for the upgrade of the inner tracker of the BESIII experiment [87]. The system is based on an ASIC chip called Torino Integrated GEM Electronics for Readout (TIGER) and an FPGA module, the GEM Read Out Cards (GEMROC), developed in Ferrara [88]. The TIGER chip is a 64-channel mixed signal ASIC that enables simultaneous charge and time measurements, thanks to two dedicated branches: the T- and E-branch, which are optimised for measuring time and charge, respectively. It has a rate capability up to 60 kHz per channel, an input dynamic range from 2 to 50 fC, and low noise levels (~ 1 fC) [89]. Each GEMROC module can handle up to eight TIGER chips. It provides both analogue and digital supply voltages to the ASICs, monitors currents and operating temperature, and manages data coming from the TIGER front-end.

We employed Front-End Boards (FEBs) mounting two TIGER ASICs, for a total of 128 channels per board. Each FEB is provided with a heat exchanger made of copper, positioned directly on the back of the two ASICs and cooled with water. One board is able to read all the strips of one coordinate of a GEM, while the drift chamber requires three FEBs. To be precise, the drift chamber has 168 channels in total; therefore, two Front-End Boards would be sufficient. However, we decided to route the channels to three interface cards in order to shorten the track lengths and, hopefully, reduce noise. In this configuration, each card carries 56 signals, and only half of the FEB channels are used; however, this was a compromise to preserve the quality of the signals.

For the beam test, only two GEMROCs were available, for a total of 8 FEBs. Because of the limited area illuminated by the beam, only a small portion of the drift chamber could be studied at a time. Moreover, given the aforementioned limitation in the vertical excursion of the table, only two out of the three sectors were instrumented. This way, we preserved the possibility of illuminating different portions of the sectors with the beam by changing the chamber position. The remaining six FEBs were distributed to the trackers, privileging the readout of the x coordinate.

Figure 5.2 shows a TIGER FEB mounted on one of the interface cards during preliminary tests in Ferrara. The connector between a FEB and the detector does not have ground pins; hence, the board requires an external connection to the reference ground of the detector which, in this case, is provided by the two copper strips visible in the figure. They are soldered on the interface card, which, in turn, is connected to the metal case of the chamber.

The TIGER electronics, designed for triple-GEM detectors, also fit well with other MPGD technologies, such as the μ -RWELLS [90]. It has also been used with Straw Tube detectors, despite its limitation in reading out large amplitude signals. For this reason, we decided to adopt this chip for the drift chamber readout during the beam test. We expect the majority of the signals to be saturated at the working voltage of 1600 V, with the estimated signal amplitude being around 200 fC. Nevertheless, the time information remains usable, enabling a study of the detector performance in terms of efficiency and spatial resolution.

5.2.1 Data Acquisition Software

GUFI (Graphical User Frontend Interface) is the control software written in Python, developed to handle electronics operations and acquisitions [91]. The main Graphical User Interface can handle communication with up to 20 GEMROCs and is designed to handle quickly and easily the configuration

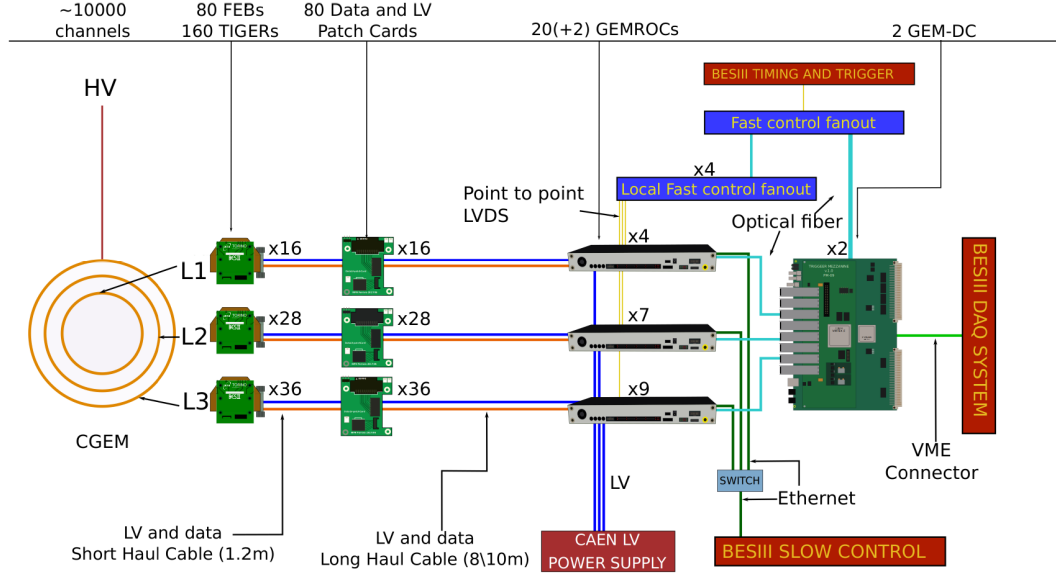


Figure 5.1: The TIGER-GEMROC readout system developed for the BESIII CGEM Inner Tracker [91].

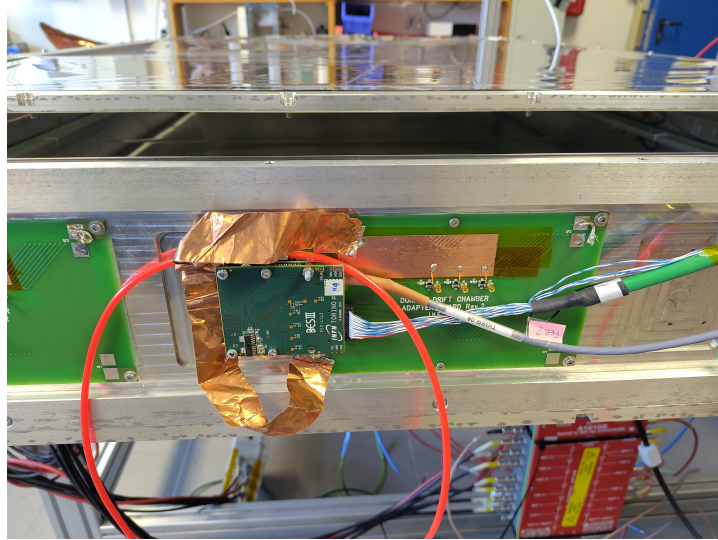


Figure 5.2: A TIGER FEB plugged on the interface card during the preliminary tests in Ferrara. The grey cable provides analogue and digital supply voltages to the ASICs, while the green cable is for data I/O. The red tube carries the cooling water.

of a large number of TIGER (up to 160) and channels (up to 10240). Configuration can also be scripted to make it easy for a user to load them and operate the system. Another interface manages the acquisition and the subrun division, and can also monitor TIGER and GEMROC parameters, reconfigure the system, and handle acquisitions independently. GUFU can provide a stream of data on voltage, current and temperature of TIGERs and GEMROCs, both during the acquisition or in idle state.

Among the various tools provided by the software, two are of particular interest for us: the so called *noise scan* and *threshold scan*.

Noise scan

During a noise scan, one test pulse at a time is sent to each TIGER channel. While the test pulse is sent at a fixed rate of ~ 50 kHz, the threshold is swept across all possible DAC values. Assuming that the noise amplitude is Gaussian, the standard deviation for the noise distribution can be estimated by fitting the detection efficiency η of the test pulse with the error function

$$\eta(T) = \text{erf}\left(\frac{T - \mu}{\sqrt{2}\sigma}\right) + \frac{1}{2} \quad (5.1)$$

where the efficiency is defined as $\eta = \frac{\text{Rate detected}}{\text{Rate injected}}$, T is the threshold in digits, μ is the test pulse amplitude and σ is the Gaussian noise standard deviation [91]. The resulting rate vs threshold plot is shown in Figure 5.3. From left to right, the first rising and the subsequent plateau derive from the detection of the test pulse: as indicated in Eq. 5.1, the steeper the rise of the test pulse rate, the lower the channel noise; the Gaussian peak corresponds to the baseline. This operation allows for the quantification of the amplitude of the noise for every channel of a chip.

Threshold scan

The threshold scan, instead, has the goal of determining the optimal thresholds for the T- and E-branches of TIGER. Since the noise on the branches is not fully correlated, exploiting the possibility of using two branches allows to lower the effective threshold while maintaining the same noise rate.

Figure 5.4 offers an example of the output of a threshold scan: for every channel of a TIGER chip, the total counts are plotted as a function of the threshold, expressed in digits. With this information, GUFU is able to set the threshold at which the noise rate is closest to the desired rate. For the users, the 2D histograms of channel counts versus threshold provide a quick overview of the noise on the entire FEB, which is very useful for understanding the general situation of the system.

5.3 Alternative readout with VTX amplifiers

During the beam test a different readout electronics for the drift chamber, based on VME modules, was also tested. In the new readout chain, signals are processed by VTX preamplifiers [92] and digitised using a VME modules. The VTX is a 6-channel ASIC with a gain of 1.0 mV/fC. More information can be found in Appendix B.

A 12-channel board was used to read four contiguous wires from each plane. Figure 5.5 shows the board mounted on an interface card. The signals were acquired using two Caen V1751 VME digitisers, which offer a sampling frequency of 1 GS/s. The trigger signal was sent to the first board and propagated to the second. The modules were controlled via USB through the V1718 VME bridge.

This readout has been chosen for its reliability and for the possibility it provides to observe signals through an oscilloscope or a digitiser. This was particularly important during the first stages of the drift chamber operations, and helped to minimise the noise on the front-end by optimising the grounding configuration of the detector, as will be better explained in the next section.

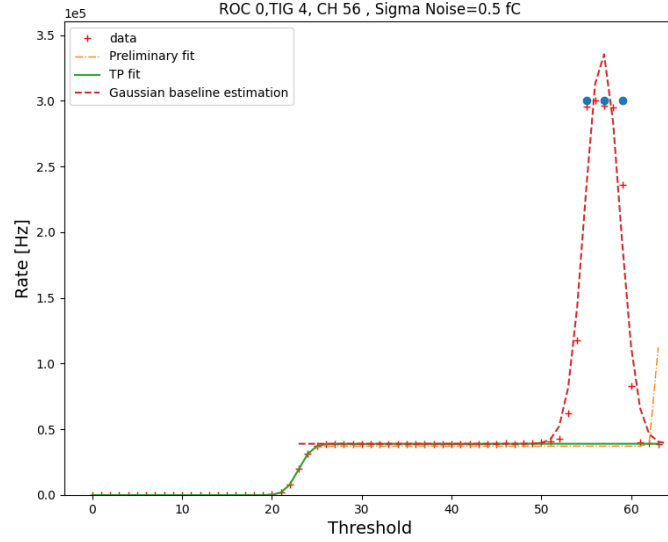


Figure 5.3: Example of output from the noise scan on a TIGER channel. The threshold is expressed in digits. The TIGER threshold DAC operates in inverse logic, so higher values correspond to lower thresholds, while 60 is the lowest. The plot shows the acquired data, a preliminary fit to estimate the test pulse and the baseline zone, the test pulse fit to estimate the noise, and the Gaussian fit to estimate the baseline.

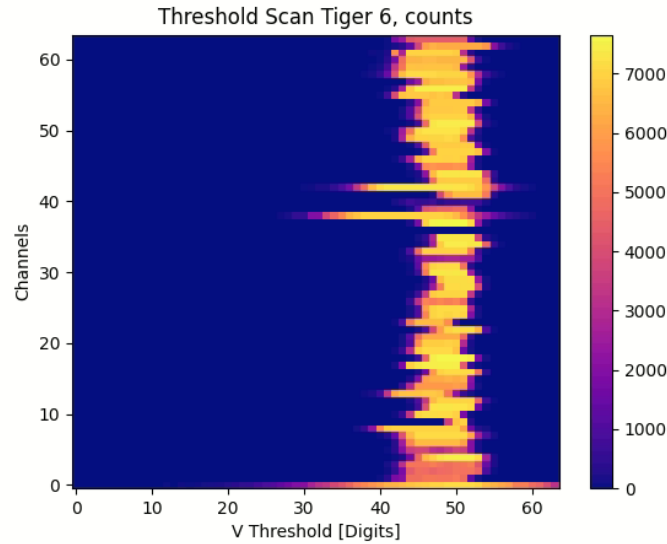


Figure 5.4: Example of threshold scan for one TIGER chip. For every channel, the total counts are plotted as a function of the threshold, expressed in digits.



Figure 5.5: The 12-channel board mounting two VTX preamplifiers during the tests in Ferrara.

The ground connections of the VTX board itself had to be tested, and modified with respect to the original design in order to obtain a good signal-to-noise ratio. In this regard, the metal case of the chamber offered a good reference for the electronics, thanks to its large mass, so that the best way to reduce the noise on the signal baseline proved to be the establishment of a connection to the gas box as short as possible.

The digitisation of the signals allowed us to study the full waveform of the signals for increasing values of the gain, avoiding the issue of saturation in the TIGER ASIC. The results of the acquisitions are presented in the next chapter.

5.4 Preliminary tests in Ferrara

As already mentioned, the chamber was operated in Ferrara before being transferred to CERN. The BESIII Ferrara group provided the tracking system, including both the trackers and the readout electronics, along with their valuable expertise on how to operate it. The readout system was first tested on the drift chamber alone and later on the entire setup to be used in the beam test.

5.4.1 Noise measurements

Using the noise and threshold scans, it was possible to study the noise amplitude for all the channels of the drift chamber. The measurements were repeated with several different configurations: with the detector alone, with HV cables connected, with HV applied, and with different grounding schemes. The first results revealed a worrying situation, as shown in Figure 5.6. The noise amplitude almost completely saturates the front-end, making it impossible to find a working configuration for the readout.

The issue was eventually traced to the internal electrical connections of the chamber. What cannot be seen in the scheme of Figure 4.12 is that sense wires were terminated to ground through a $200\ \Omega$ resistance, positioned on the opposite end of the wire with respect to the readout. The value of the resistance corresponds to the computed characteristic impedance of the wires and was intended to prevent signal reflection in the wires.

However, we found that this configuration resulted in an output capacitance of about $1\ \text{nF}$, which is exactly the value of the decoupling capacitor C_2 , and is far above the $100\ \text{pF}$ limit for which the TIGER front-end is optimised.

The problem was therefore solved by removing the connection to ground of the terminated end of each sense wire. The new output capacitance has been measured to be about 40 pF. The proof of the success of our actions can be found in Figures 5.7 and 5.8. The threshold scan now indicates a noise baseline whose amplitude is under control. Only three channels in the second TIGER chip of the FEB still appear to be noisy: channels 48, 50 and 52 which correspond to the three input lines used to inject the PMT signals. This last issue was solved by improving the reference ground of the MMCX connectors.

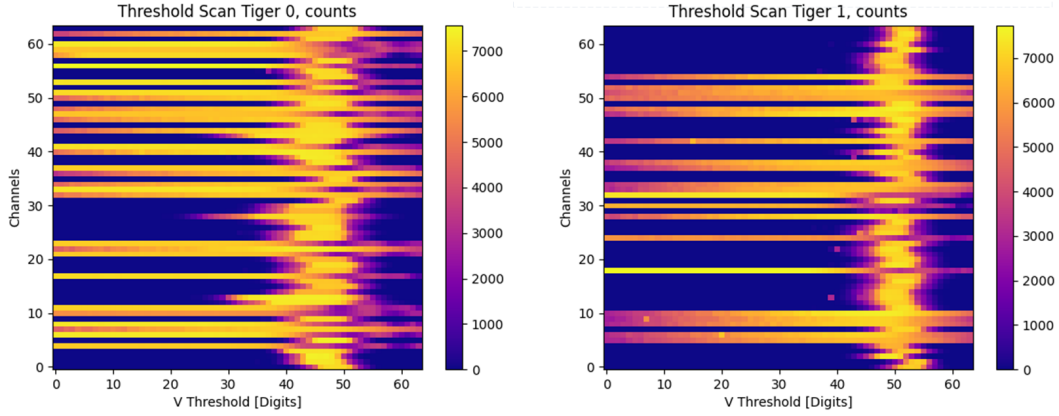


Figure 5.6: Threshold scan with wires terminated at 200Ω . The HV is on. Only 60 channels are connected to a wire and are affected by the large amplitude noise.

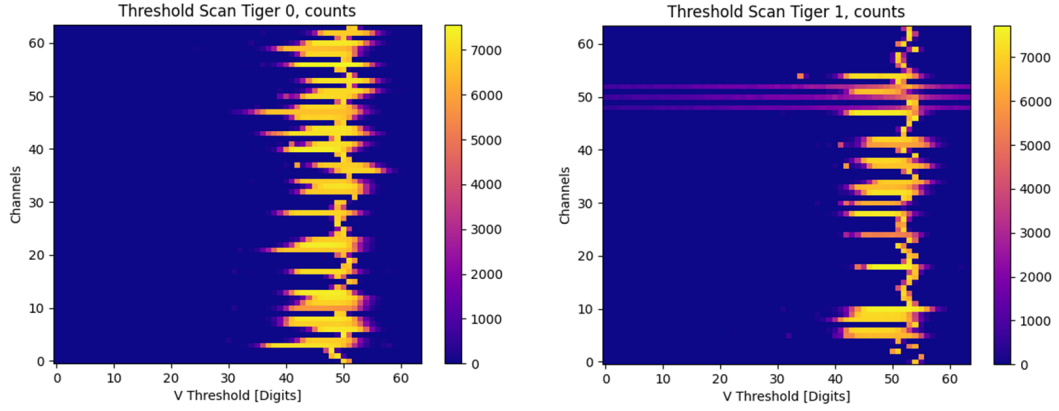


Figure 5.7: Threshold scan after the removal of wire terminations. The HV is on. The amplitude of the baseline is strongly reduced, for both connected and open channels.

5.4.2 Functionality tests

A Sr-90 radioactive source was used to test the readout system and obtain preliminary information about the operation of the detector. The source was positioned on top of the detector, which lay horizontally on a table, and moved from one sector to the others while monitoring the current absorbed by the HV channels. As expected, we observed the current increase in the channels connected to the sectors irradiated by the radioactive source. In this way, it was possible to verify qualitatively that the detector

was working.

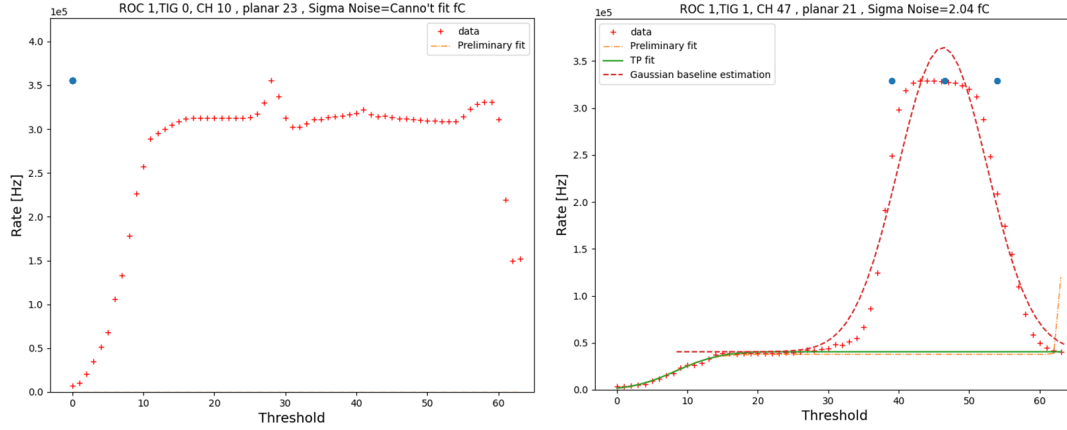


Figure 5.8: Examples of noise scan for two channels before (left) and after (right) the removal of the termination.

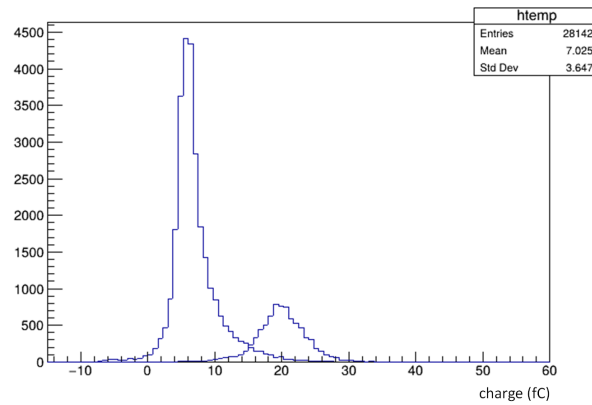


Figure 5.9: Charge distribution obtained with the chamber powered at 1200 V. The peak centered at 20 fC is due to the external input channels 48, 50 and 52, that at this stage were still noisy.

For a more quantitative characterisation of the chamber, we acquired cosmic rays in long runs lasting several hours. The trigger was generated by the coincidence of the signals from two PMTs, one located on top of the chamber and the other below the table.

The acquired data showed that for a tension of 1200 V¹ the electric field is not able to induce charge multiplication, as can be seen from Figure 5.9. The situation changes completely at 1500 V, when the signal charge is clearly visible in the plots of Figure 5.10. The one on the right, in particular, provides a qualitative indication that the drift chamber is working properly. In general, such plots contain several useful pieces of information: the low-charge horizontal band, without temporal correlation, provides insight into the noise of the system, while the area between 800 and 1400 ns is the region where the detector signal is located. The width of this zone depends on the volume traversed by the particle and the drift velocity.

During these preliminary operations, there was not enough time to perform a complete HV scan to determine the best working voltage for the chamber; therefore, this study was postponed to the beam

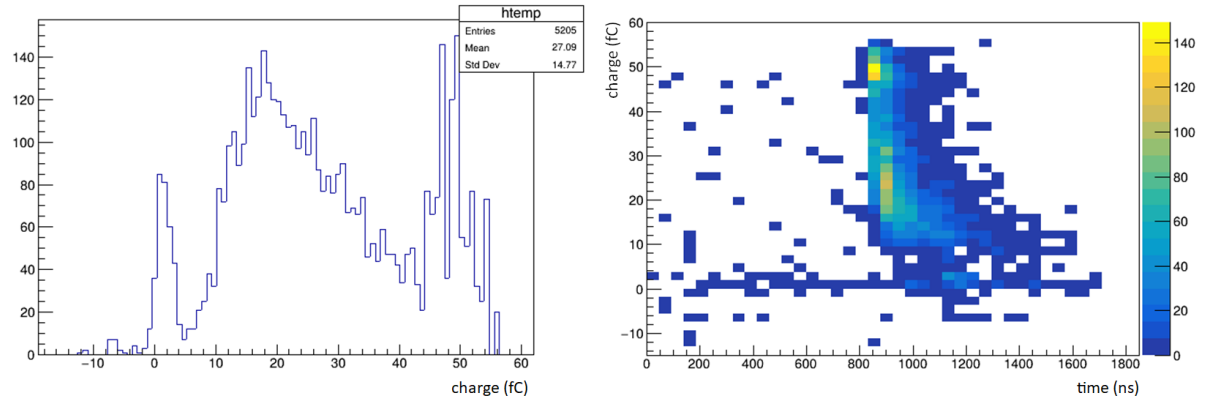


Figure 5.10: *Left*: charge distribution obtained with the chamber powered at 1200 V. All the channels of the FEB are considered. The saturation peaks are visible around 50 fC. *Right*: 2D histogram of the signal charge versus time.

test period.

¹From now on, when providing a value for the chamber high voltage, we assume that the same tension is applied both to field wires and to Mylar planes.

Chapter 6

Beam Test of the Drift Chamber prototype

In this chapter, the beam test of the drift chamber prototype is described. The detector was tested exploiting a muon beam of about 120 GeV, as we profited of the DRD1 Collaboration [93] beam test campaign at the SPS H4 beam line. The beam test has provided important data to characterise the performance of the drift chamber prototype, which will be discussed in the next chapter.

6.1 The setup

For the beam test, we used a telescope composed of four triple-GEM detectors and two plastic scintillators. The drift chamber was positioned in the middle of the setup, as shown in the scheme of Figure 6.1. The reference system adopted for the setup is also shown in the scheme. According to it, the drift chamber was installed vertically on a metallic frame and positioned on a movable table, which allowed for movement in the x and y directions, with the beam parallel to the z direction. This way, the wires were orientated horizontally, parallel to the y direction, while the Mylar planes hung vertically, as is foreseen to occur in the final configuration. The uppermost sector was named $S1$, followed by $S2$ and $S3$ at the bottom. During the beam test, the $S3$ sector was not illuminated due to the limited vertical range of the table. Instead of modifying the detector mount, we chose to focus the studies on the first two sectors. Figure 6.2 provides an overview of the experimental setup installed in the H4 beam line.

The chamber was filled with a mixture of Ar-CO₂ (85%-15%) and kept at an overpressure around 4 mBar. The maximum achievable gas flow was 9 l/h, limited by the available gas system.

The tracking system was composed of four triple-GEM detectors, such as the one in Figure 6.3, with an active area of $10 \times 10 \text{ cm}^2$. All trackers feature a 2D readout having two layers of orthogonal strips with a $650 \mu\text{m}$ pitch. However, to deal with the limited number of available readout boards, it was decided not to read both views from each detector. Overall, we had 4 x coordinates and 2 y coordinates for each track, preserving the higher resolution along the direction perpendicular to the drift chamber wires.

The GEMs worked with a gas mixture of Ar-CO₂ (70%-30%) and were fluxed at 5 l/h at atmospheric pressure.

The trigger signal was provided by the coincidence of the signals from two plastic scintillators that were both installed downstream of the last GEM of the telescope. They feature an active area of $15 \times 15 \text{ cm}^2$ and a PMT for the readout.

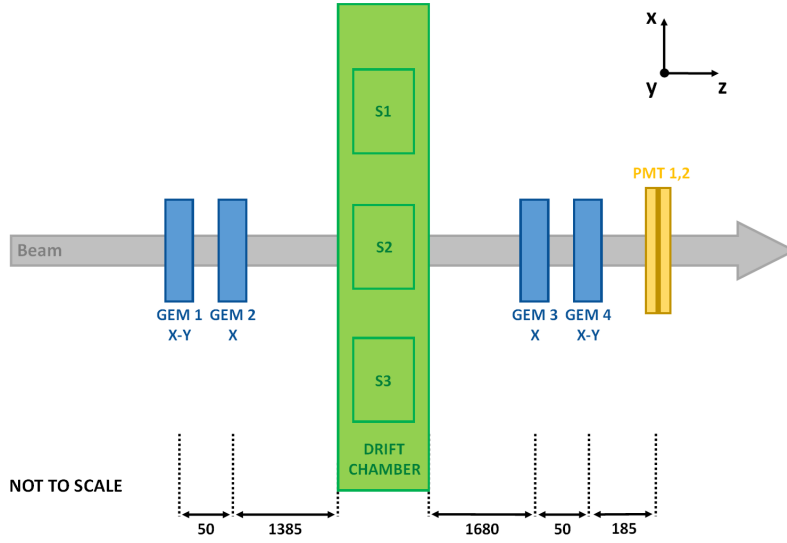


Figure 6.1: Scheme of the setup used at the beam test. The drift chamber is between two pairs of triple-GEM detectors. Two of them have both x and y views, while the others have just the x view. The two plastic scintillators are positioned downstream the last GEM. The distance between the detectors is given in *mm*.

6.2 Data taking

During the beam test period, about 230 million events were recorded in 720 runs, covering different chamber positions and various electric field configurations. The last 20 runs were finally dedicated to the usage of the VTX preamplifiers. The chamber was tested with a muon beam of about 120 GeV and rate up to 2^5 /spill with a spill duration of 4.8 s. We also profited from few runs with pions, as they were requested by other users.

HV scans were performed by varying the potential applied to the cathode planes and field wires from 1100 V up to 1700 V, in order to determine the optimal working point for the chamber. In this range we expect from simulations of the drift cell the gain to vary from $2.4e^4$ at 1500 V to $1.8e^5$ at 1700 V.

Starting from 1600 V occasional discharges were observed, indicated by over-currents greater than $10 \mu\text{A}$ in the HV channels powering the cathode planes, while the normal current absorption was below the sensibility of the instrument (10 nA). The origin of the discharges is not yet understood: they may be caused by the presence of impurities in the gas volume or by a construction defect leading to components being placed too close to one another.

This issue limited our ability to increase the voltage on the Mylar planes, as it generates transmission errors in the communication of the chips connected to the drift chamber. The origin of these errors was most likely related to the large baseline shift induced by discharges. To avoid this problem, some runs were acquired increasing the high voltage only on the field wires, reaching up to 2150 V.

Measurements were also taken moving the chamber with respect to the particle beam. In total, six different regions of the detector were studied.

The coincidence of two PMTs signals triggers the acquisition: the coincidence must be delayed by $8.62 \mu\text{s}$ and its width changed to 200 ns to match the requirements of the readout system, which is tuned for the BESIII setup. A copy of the trigger signal is sent to each drift chamber interface card through the MMCX connectors. The scheme of the trigger generation is shown in Figure 6.4.

Once generated, the trigger signal is sent to the Fanout module, which propagates it to the two

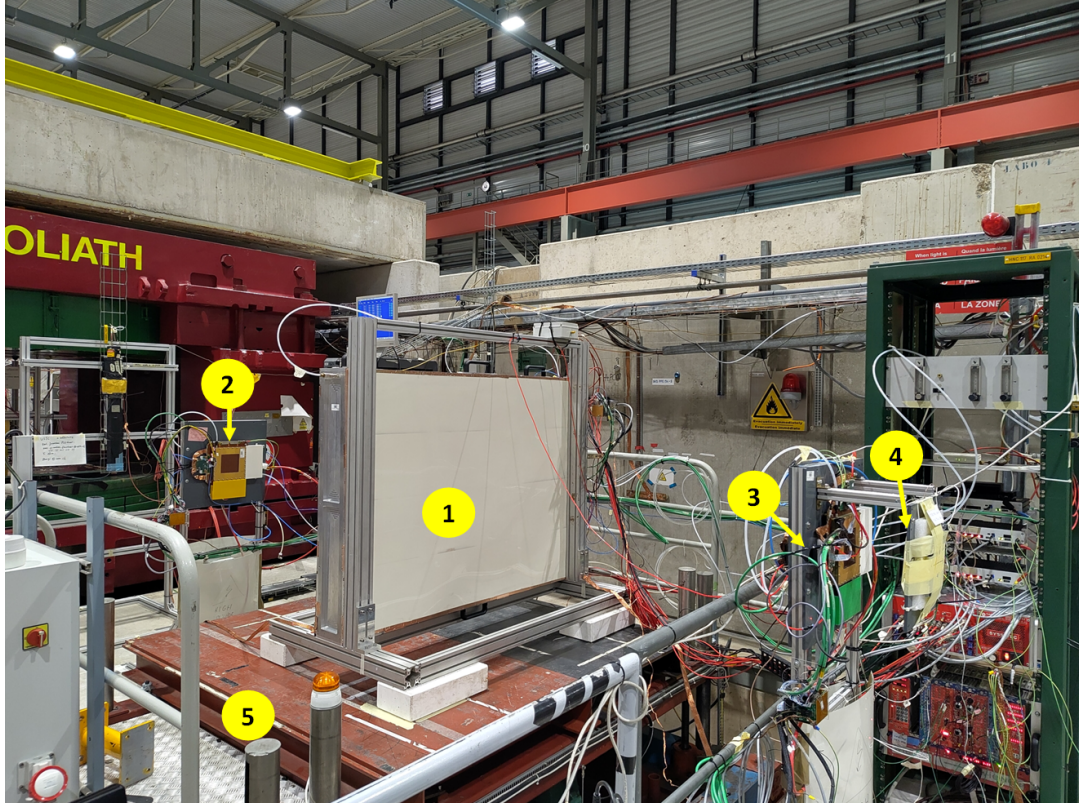


Figure 6.2: View of the beam area, with the drift chamber (1) positioned on a movable table (5) and the GEM telescope composed by two detectors located upstream (2) and two detectors downstream (3), together with the PMTs (4).

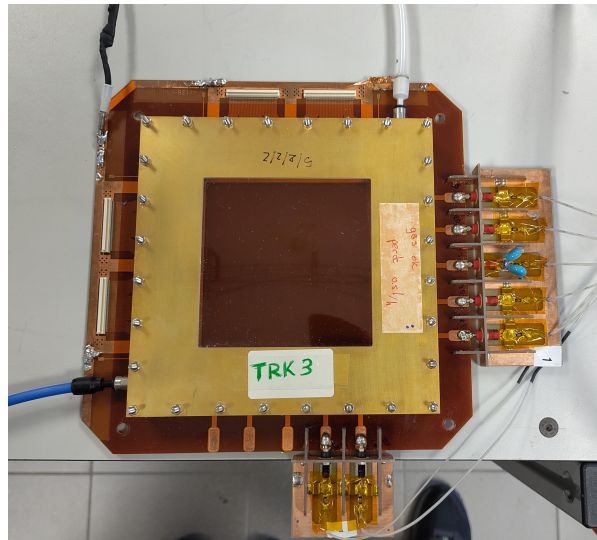


Figure 6.3: View of one of the triple-GEM trackers used during the beam test.

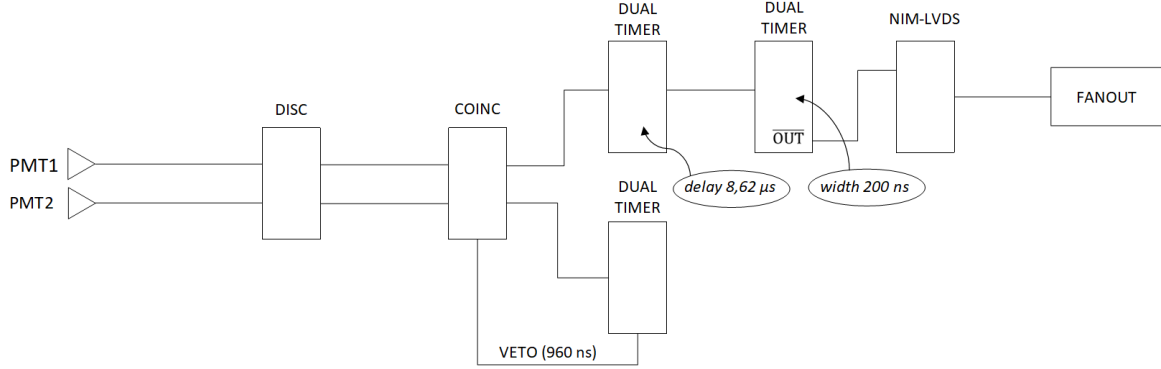


Figure 6.4: Scheme of the trigger generation.

GEMROCs. TIGER operates in a trigger-less mode, since it does not require an external trigger for operation, having one discriminator on both branches. The data to be acquired are selected by the GEMROC in correspondence of an external trigger and sent through an Ethernet port to the computer controlling the acquisition. The GEMROC modules are also responsible for the low voltage (LV) distribution to the FEBs, that requires 1.08 A at 1.4 V for the ASIC analogue part and 0.32 A at 2.5 V for the digital circuitry. Figure 6.5 shows the scheme of the acquisition system used for the beam test.

The SY5527LC CAEN mainframe hosts two A2519 boards (32 channels, max 5 A/channel and 50 W/channel) to power the GEMROC modules, one A1515 board that provides the HV to the GEMs, and one A1541DN board for the drift chamber high voltage.

Data and low voltage are fed to the FEBs through the intermediate Data Low Voltage Patch Cards (DLVPC). The connection from GEMROC to DLVPC is made via long haul cables (8 m and 10 m long for data and LV, respectively), while flexible short haul cables (1.2 m long) are used between DLVPCs and FEBs. This structure is inherited from the BESIII experiment.

6.2.1 Acquisitions with VME electronics

The setup, consisting of the board with two VTX preamplifiers and the VME modules, worked in parallel with the TIGER-GEMROC readout chain. The FEBs on the drift chamber were removed and replaced by the VTX board. The first six channels of each digitiser module were devoted to the acquisition of the signals from the 12 preamplified wires. The seventh channel of each digitiser received a copy of the trigger signal produced by the coincidence unit.

The most delicate part was the synchronisation of the acquisition systems, which is fundamental for reconstructing the events by subsequently combining the data from the drift chamber with those from the trackers. This was achieved by feeding the trigger signal generated by the last digitiser module to the Fanout (after it has been delayed and reshaped, as previously described). Since the VME system has a much slower acquisition rate than TIGER, it must control the entire readout process.

Using this setup, we performed an high voltage scan from 1100 up to 1700 V.

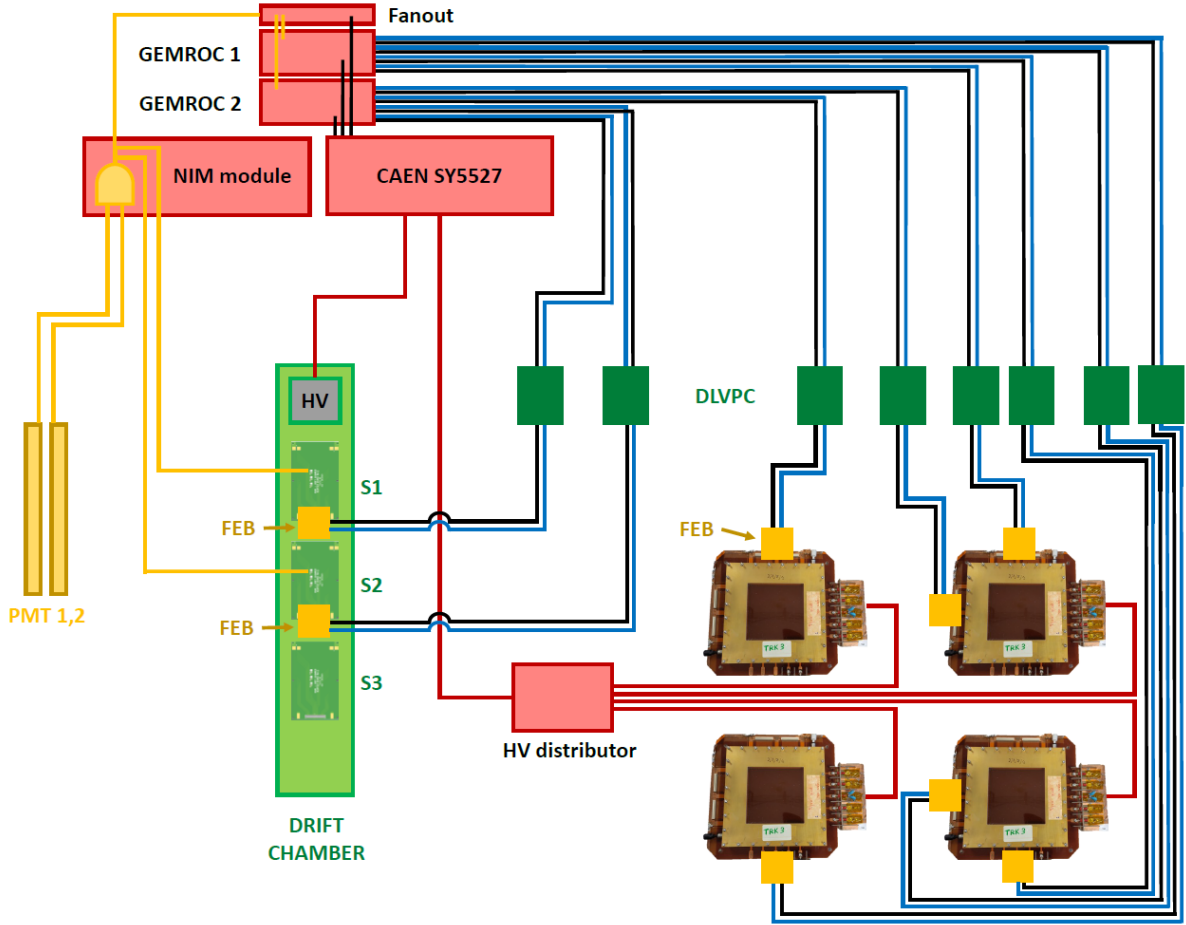


Figure 6.5: Scheme of the readout chain used at the beam test. In yellow is indicated the route of the trigger signal, from the two PMTs to the Fanout and GEMROC modules. The red lines represents the HV distribution to the drift chamber and the GEM trackers. The path of the data to and from the Front End Boards, passing through the DLVPC cards, is indicated in blue. It is parallel to that of the Low Voltage distribution, in black. Only the first two sectors of the drift chamber were instrumented.

Chapter 7

Data analysis and preliminary results

In this chapter, the first results obtained with the drift chamber prototype are presented. The raw data acquired with TIGER are stored in ROOT files that are first processed using the CIVETTA software. The analysis is then performed using a dedicated software specifically developed for this purpose.

7.1 The offline software

A preliminary analysis of the data was performed using the CIVETTA (Complete Interactive VErSatile Test Tool Analysis) [91]. This software is responsible for decoding the binary files produced by the GEMROCs and for providing all the information about the acquired signals through quick-look plots, such as charge vs time and charge vs strip, which are fundamental during a beam test to monitor the quality of the acquisitions. The decoded raw data are stored in a root file. A scheme of the offline software is shown in Figure 7.1.

Each trigger signal defines an *event*; for each event, the signal on a channel is recorded. This signal is called *hit*. Hit information is reconstructed to obtain the time and charge information. The hit digitisation depends on the front-end electronics.

In a GEM detector, the charges generated by the passage of a particle in the gas gap induce a signal on multiple strips. Contiguous hits in the same detector and same view have been used to define a *cluster* of strips. If dead strips are present, the clustering algorithm takes them into account and processes the hits, even if there is an empty strip between strips with a signal. The charge of the cluster Q_{cl} is defined by the sum of the charges of the single hits, while particle tracks are precisely located by performing the weighted mean of charge signals on anode strips.

In the case of the drift chamber, after the passage of a charged particle, we expect a signal in only one cell of each plane since the beam is almost perpendicular to the wire planes. Therefore, a clustering algorithm is not needed.

7.1.1 Hit digitisation with TIGER

Every time a signal oversteps the threshold, TIGER measures the charge and time information of the hit. An external trigger is used as a starting signal for the GEMROC to collect the information from each front-end board channel in a packet and send it to the acquisition computer.

The signal amplitude, and thus the input charge, is measured using the Sample&Hold method: the front-end output is sampled, its peak voltage is captured, and then digitised with a 10-bit Wilkinson

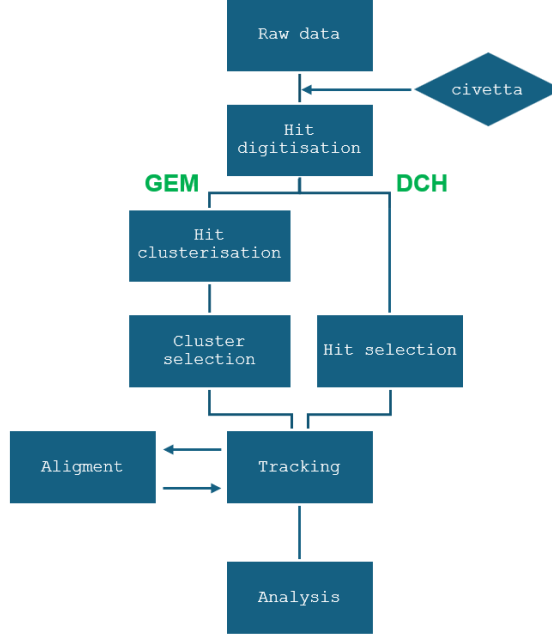


Figure 7.1: Offline software block diagram.

ADC. The time measurement, instead, is evaluated with two levels of accuracy: the coarse time, with a 5 ns time binning, and the fine time, which is measured by a low-power TDC based on analogue interpolation, offering a time binning of 50 ps. More details about the functioning of TIGER can be found in Appendix C.

Figure 7.2 shows the charge and time distributions obtained from a FEB connected to the drift chamber. As can be noticed, at 1500 V the majority of the signals are saturated around 50 fC. The saturation peak is not unique, as every channel has a slightly different dynamic range.

The time distribution is obtained by plotting the difference between the signal arrival time and the trigger. The shape of the distribution depends on the behaviour of the drift velocity inside a cell and can be fitted using the function [94]

$$f(t) = p_1 + \frac{p_2 \left(1 + p_3 e^{-\frac{t-p_5}{p_4}} \right)}{\left(1 + e^{-\frac{t-p_5}{p_7}} \right) \left(1 + e^{\frac{t-p_6}{p_8}} \right)} \quad (7.1)$$

Here, two distinct Fermi-Dirac functions describe the leading and trailing edges of the time distribution, while an exponential function is used for the central part. Among others, the parameter p_5 provides the t_0 of that given wire, p_6 is the maximum drift time, and p_7 describes the leading edge of the distribution. The determination of the t_0 is important, as it allows for the equalisation of the starting points of the time distribution for all sense wires.

7.1.2 Hit digitisation with VTX

The VTX provides an amplification of 1.0 mV/fC for the signals, which are then digitised with a frequency of 1 Gs/s. When a trigger signal arrives, the waveform is acquired over a time window of 2 μ s. As already mentioned, this electronics was used only for the drift chamber signals.

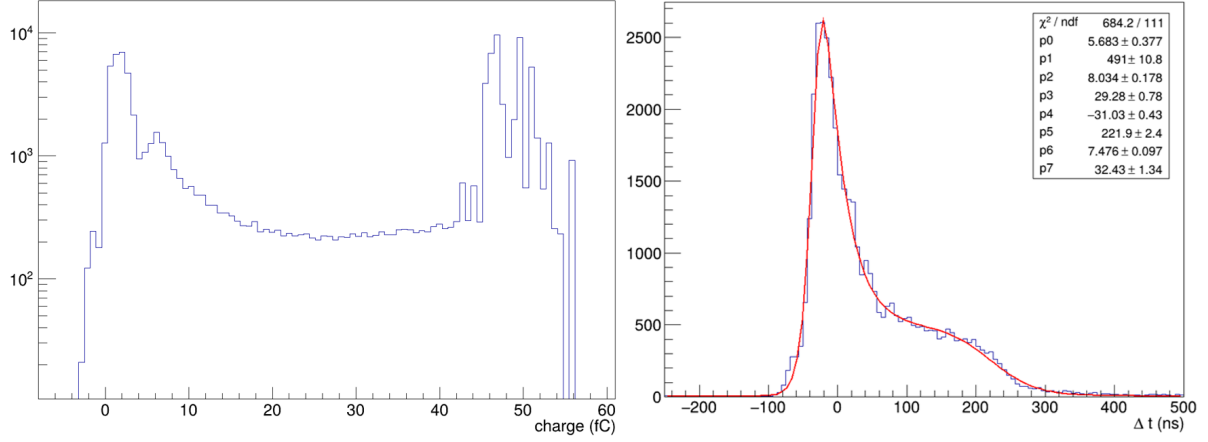


Figure 7.2: Charge (left) and time (right) distributions for a FEB connected to the drift chamber operating at 1500 V. The time distribution is fitted using Eq. 7.1.

The waveforms are analysed offline, applying a baseline shift to remove the offsets of the channels and filtering out the noise frequencies using a wavelet filter. The result for a sample signal is shown in Figure 7.3.

The wavelet transform is a powerful tool for signal analysis and processing, and it proves highly effective in several application domains such as compression, denoising, and, more generally, in situations involving non-stationary signals. It offers several noteworthy properties: it can analyse signals whose characteristics vary over time, thanks to its strong time–frequency localisation capabilities; it provides a multi-scale representation and can be efficiently implemented through a filter bank. Wavelet filtering allows to filter out short-duration patterns by decomposing a signal into wavelet coefficients, where each coefficient represents the strength of the wavelet pattern at a particular time. With a certain threshold, the unwanted coefficients are removed by zeroing them out and reconstructing the signal.

The signal charge is extracted from the maximum amplitude of the waveform, while the arrival time is recorded at 10% of the waveform amplitude. The two distributions for one of the channels of the VTX board are plotted in Figure 7.4.

Looking at the charge distribution, a few things can be noticed: firstly, the pedestal distribution has a Gaussian shape, with a mean value of 23 fC and a sigma of 6 fC; secondly, the signals have an amplitude that exceeds 400 fC, which corresponds to the 400 mV saturation of the VTX preamplifier. This shows how the TIGER dynamic range limits the acquisition of the drift chamber signals, even though the time measurement seems to remain accurate. Concerning the time distribution, a double peak can be noticed at small Δt , which is not present in the same distribution obtained with TIGER. This could be due to the baseline noise, which is not completely under control, and that affect the computation of the 10% waveform amplitude.

Unfortunately, a malfunctioning of the DAQ synchronisation prevented the alignment of the events acquired by the digitisers and the TIGER/GEMROC system. The reason is not yet understood and is currently under study. For this reason, it was not possible to match the time of the signals with the hit position, so the acquired data have been used to investigate only the charge and time distributions of the signals.

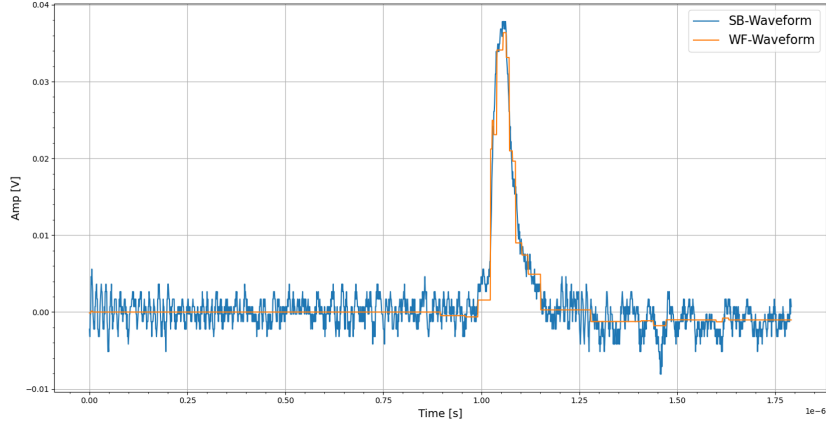


Figure 7.3: Example of digitised waveform. In blue is show the original waveform with the baseline shifted to 0 V, while in orange is plotted the waveform processed with the wavelet filter.

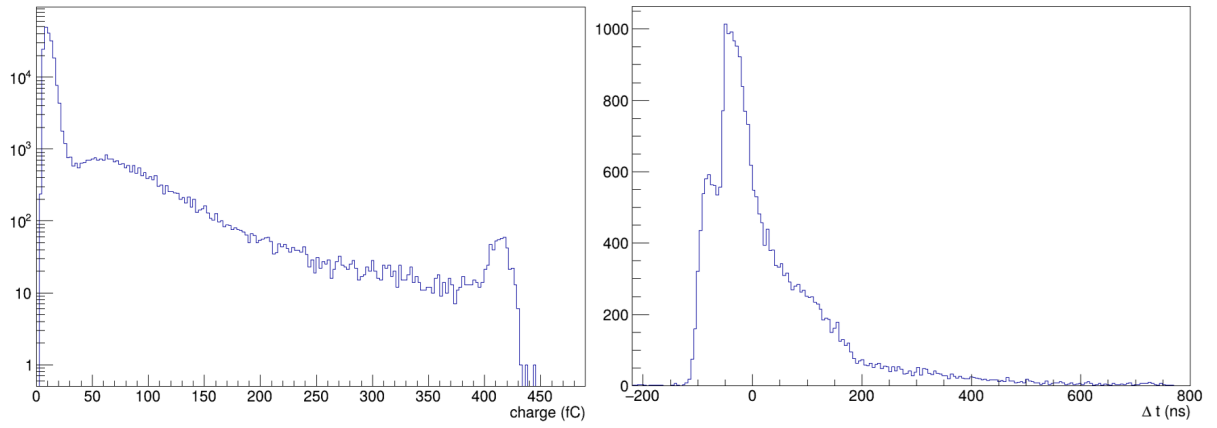


Figure 7.4: Charge (left) and time (right) distributions for a channel of the VTX board connected to the drift chamber, operating at 1500 V.

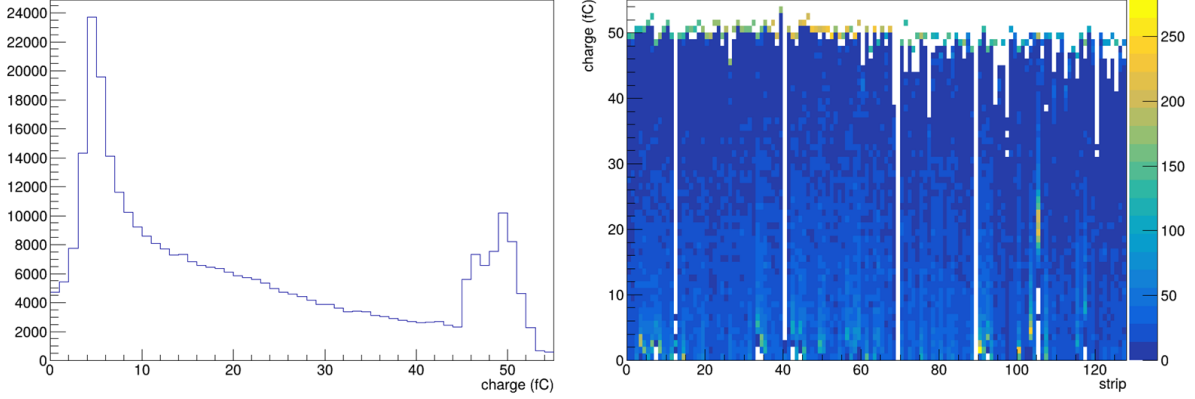


Figure 7.5: *Left*: hit charge distribution for the x-view of the first GEM tracker. *Right*: the corresponding histogram of charge versus strip.

7.1.3 GEM hit clusterisation

The strip position is defined as the coordinate in the middle of the strip, orthogonal to the direction of the length of the strip. To measure the incident particle position, two different algorithms can be deployed: the charge centroid (CC), also known as the centre of gravity, which uses the strip charge and position information, and the micro-Time Projection Chamber (μ TPC), which also uses the time information. The latter is not used in this analysis since only particle tracks orthogonal to the GEM surface have been detected.

The CC method measures the position of the particles using the weighted average

$$x_{CC} = \frac{\sum_i^N Q_{hit,i} x_{hit,i}}{\sum_i^N Q_{hit,i}} \quad (7.2)$$

where N is the number of hits in the cluster, called cluster size, $x_{hit,i}$ is the hit position, and $Q_{hit,i}$ is the hit charge.

One useful plot for checking the system status is the charge versus strip plot, in which only the hits in the time signal region have been selected. The example plotted in Figure 7.5 for one of the GEM trackers shows the hit charge distribution for each TIGER channel. The saturation peak is visible around 50 fC while some channels appear to be disconnected: strips 13, 41, 70, and 90.

To verify the spatial uniformity of the trackers and their alignment with respect to the beam, the profiles for muon and pion beams are shown in Figure 7.6. The muon beam has an oval shape and covers the entire detector in the x direction and almost the entire detector in the y direction. The pion beam is more collimated and circular.

7.1.4 Detectors alignment

Alignment procedures are necessary to remove the translations and rotations of the real detector position with respect to the one reconstructed by the software, as they can affect the resolution measurements. The detectors are installed perpendicular to the beam line with a precision within the millimetre.

The alignment of the tracker planes is performed using the reconstructed tracks. For each event, a track is fitted using all tracker planes. The fitted track is then extrapolated to each plane, and the residual is calculated as the difference between the expected position from the fit and the measured hit position on that plane. The distributions of these residuals are analysed to extract possible misalign-

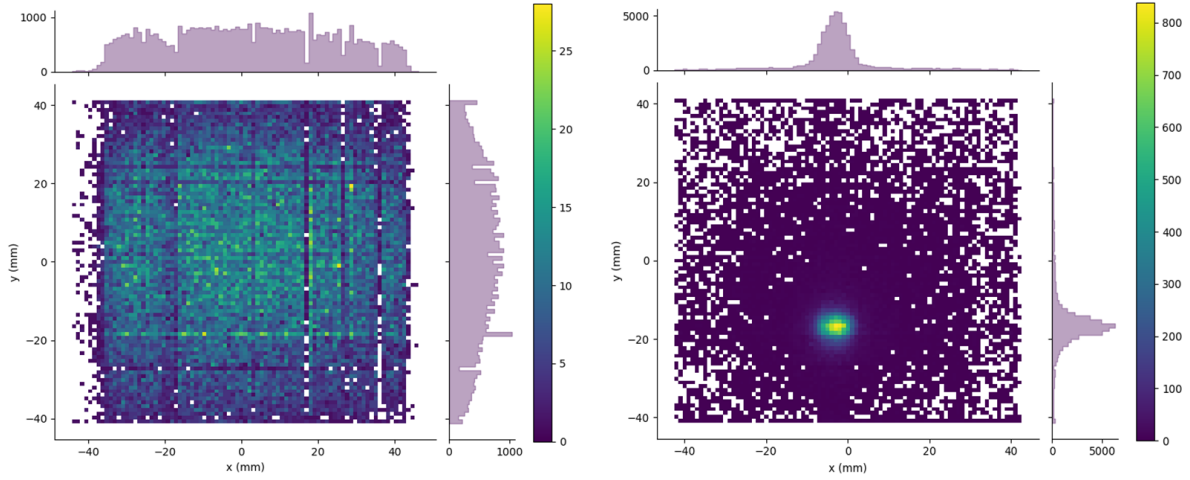


Figure 7.6: Beam profiles of muons (left) and pions (right). Projections of the profile are shown on the axes.

ments, such as shifts or rotations of the detector plane. Iterative corrections are applied until the mean of the residual distribution is consistent with zero, indicating proper alignment.

The shift alignments are the easiest to perform: once the residual distribution Δx_{trk} is evaluated and the Gaussian fit is performed, the central value of the Gaussian is used to shift the detector reference frame and remove the difference between the real position of the detector and the reconstructed one. The tilt in the xy plane is evaluated using the bi-dimensional plot Δx_{trk} vs y_{trk} , where y_{trk} is the position measurement. The angular coefficient obtained from the linear fit of the bi-dimensional distribution is used to rotate the detector in the xy plane. Figure 7.7 offers an example of the effects of the alignment procedures for the trackers.

7.2 Preliminary analysis results

In the following, the results obtained from the analysis of the beam test data are presented. The drift chamber has been characterised in terms of drift cell efficiency, drift velocity, and spatial resolution of the single wire planes.

7.2.1 Drift cell efficiency

The efficiency of a drift cell is defined by the ratio

$$\eta = \frac{N_d}{N_t} \quad (7.3)$$

where N_t is the total number of tracks traversing a cell, and N_d is the number of signals detected in that same cell. The tracks are selected by requiring at least one cluster in each tracker view. If multiple clusters are present, only those that minimise the χ^2 of the fitted track are kept. Signals in the drift chamber are required to have a charge greater than three times the standard deviation of the pedestal distribution, which follows a Gaussian shape.

In Figure 7.8, the efficiency of the cells for two wire planes is shown as an example, as seen in the reference frame of the trackers. The plot on the left, in particular, represents the first wire plane, which has inclined wires. In this case, only part of the wires is read, resulting in a sharp decrease in efficiency.

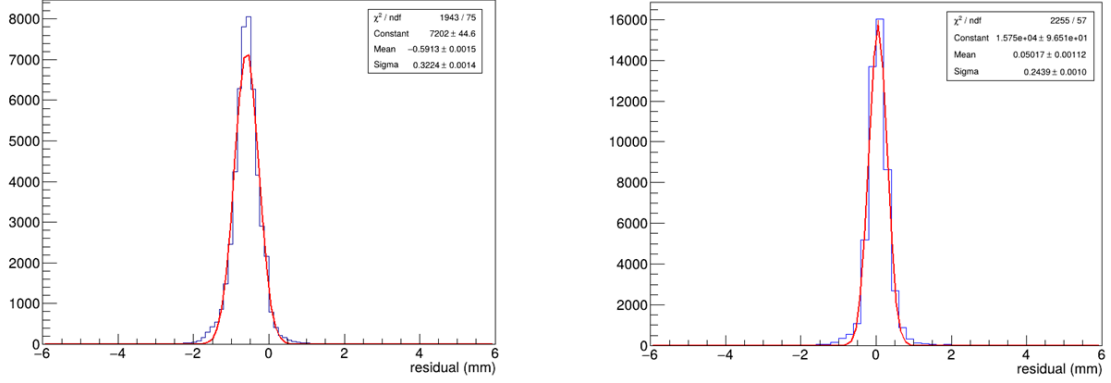


Figure 7.7: Example plots before (left) and after (right) the alignment procedure. The histograms show the Δx_{trk} to remove the shift between the real and reconstructed position.

Overall, the efficiency of the drift cells exceeds 95%, except in correspondence with the cell edges. This is due to the fact that the primary charges produced by a particle passing close to the boundary between two cells can be shared between them. Therefore, a lower signal is induced on the wires, as can be seen in Figure 7.9. Depending on the amplitude of the signals, they could be absorbed within the pedestals and, therefore, excluded by the threshold cut, resulting in the observed efficiency loss.

Another effect that has been observed during the HV scans was a drop in efficiency above 1500 V, as shown in Figure 7.10, where the efficiencies of the three wire planes are plotted versus the high voltage.

This effect turned out to be caused by a feature of TIGER when operated with wire-based detectors. The large signals produced in these kinds of detectors most of the time saturate the ASIC front-end; if this happens in combination with a high particle rate, such as the one at the H4 beam line, which is of about 20 kHz/cm², it can lead to high occupancy of the ADCs that prevents the chip from processing all the incoming signals.

This hypothesis was verified by performing an HV scan with a muon rate reduced below 1 kHz/cm². Figure 7.11 shows the results of this study, comparing the efficiencies for the second wire plane acquired at 1500 V and 1700 V for both normal and low muon rates. The outcome is clear: with a low particle rate, the efficiency behaves as expected, increasing with the HV, even at the cell boundaries, since the gain of the cells increases in turn.

This fact strengthened our belief in performing acquisitions with the VTX preamplifier, as this would have allowed to investigate the voltage region above 1500 V without having to deal with the front-end saturation and its related issues.

7.2.2 Distance-Time relation

The distance-time (r - t) relation is fundamental to characterise the behaviour of the drift velocity across the drift cell, which later allows for the reconstruction of the track distance from the wire.

The r - t distributions for the cells of the prototype were derived from the drift times and the distance of closest approach to the wire of the track reconstructed in the reference trackers. In this preliminary analysis, the distance was computed in the xy plane only, which, in a first approximation, is correct as long as we are dealing with tracks orthogonal to the wire planes.

In general, the r - t relation does not follow a universal function, as it depends on the shape of the electric field, which varies from detector to detector. The distribution appears roughly parabolic on either side of the wire, with some deviations close to the wire and at the cell border. In order to

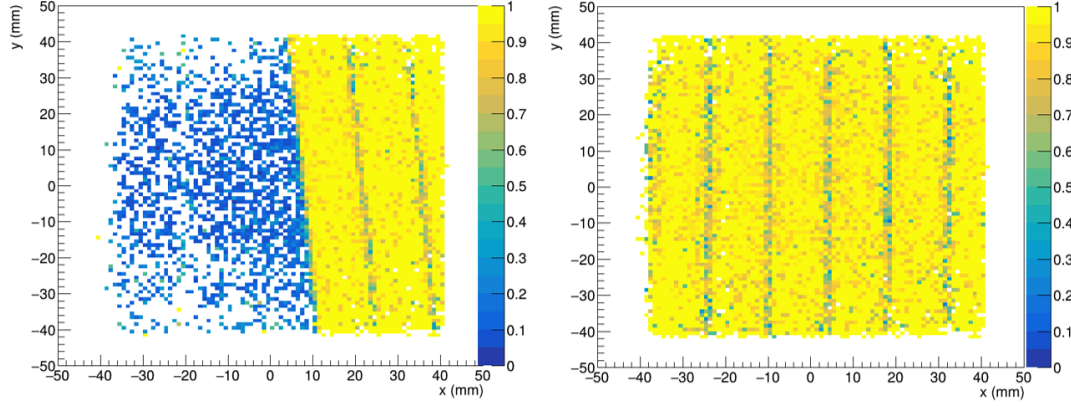


Figure 7.8: Efficiency of the cells for the first wire plane (left), with inclined wires, and the second wire plane (right), as seen in the reference frame of the trackers. The tension was of 1500 V.

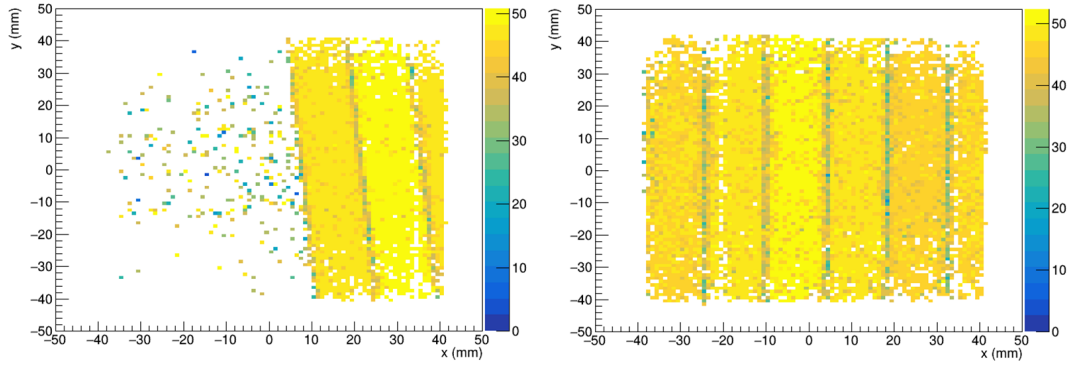


Figure 7.9: Distribution of the signal amplitude across the cells for the first (left) and the second wire plane (right), as seen in the reference frame of the trackers. The tension was of 1500 V.

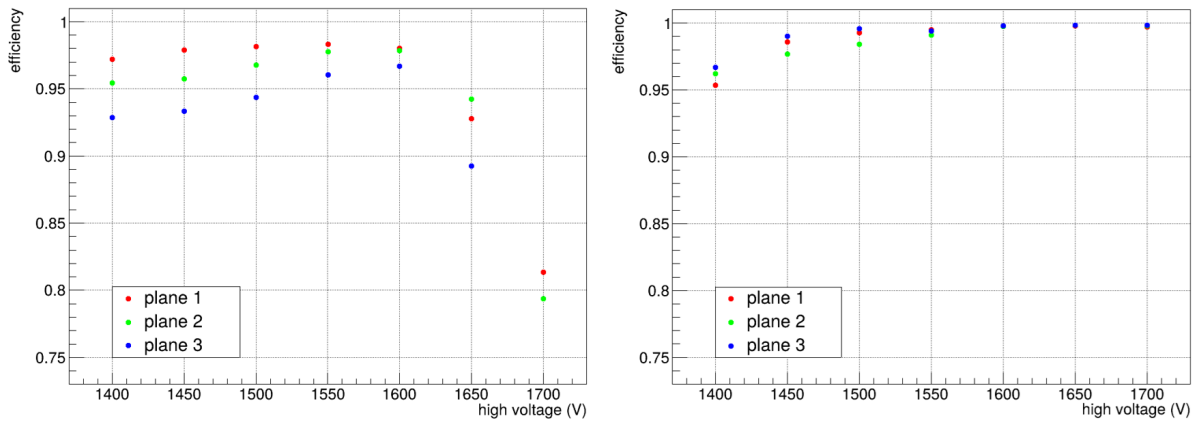


Figure 7.10: Variation of the wire plane efficiency with respect to the applied high voltage for normal (*left*) and lowered (*right*) muon rate.

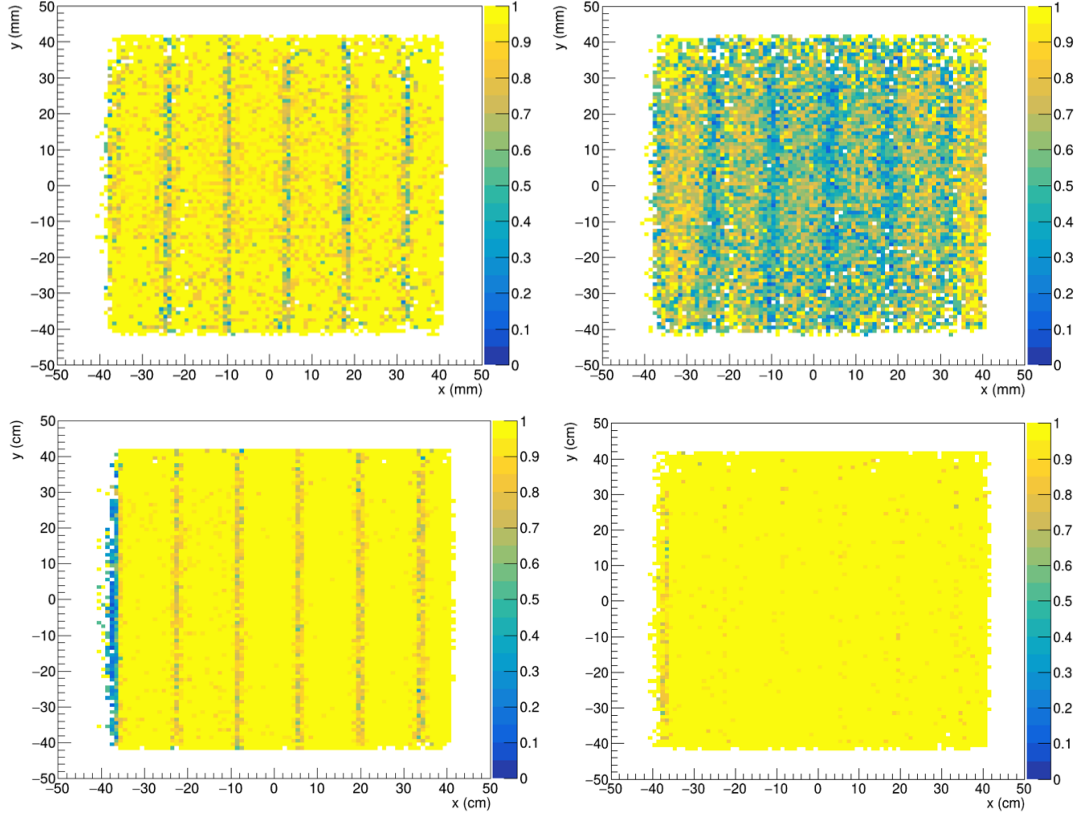


Figure 7.11: Comparison between the efficiency of the second wire plane for a tension of 1500 V (left) and 1700 V (right), computed at normal (top row) and low (bottom row) muon rate.

parametrize it, we adopted the function [95]

$$t = N \arctan(ar^2 + br) + c \quad (7.4)$$

Figure 7.12 reports the time-distance distribution for the cells of the second wire plane operated at 1500 V. For better results, the fit function was applied in two different distance ranges: between -3 mm and 3 mm, and from 3 mm to the end of the cell. The fit in the first region was extended to negative values to achieve a more precise reproduction of the vertex behaviour. The reconstructed distance from the wire was then computed by considering only the positive branch of the function.

The drift velocity does not appear to be constant everywhere inside the cell. In the first 3 millimetres from the wire, the average drift velocity is measured to be $\sim 50 \mu\text{m/ns}$, while it decreases down to $\sim 13 \mu\text{m/ns}$ in the outer region.

7.2.3 Spatial resolution

The first spatial resolution to be computed was that of the second wire plane, with the chamber operating at 1500 V. Tracks have been filtered according to their slope and the fit χ^2 , which is required to be below 10. The result is reported in Figure 7.13 where, on the left, the behaviour of the spatial resolution is shown as a function of the distance from the sense wire; it appears to decrease gradually with the distance down to $160 \mu\text{m}$, but rises again in the final 2 mm as a result of edge effects within the cell. Globally, the residual distribution is not Gaussian, and its FWHM is found to be $480 \mu\text{m}$.

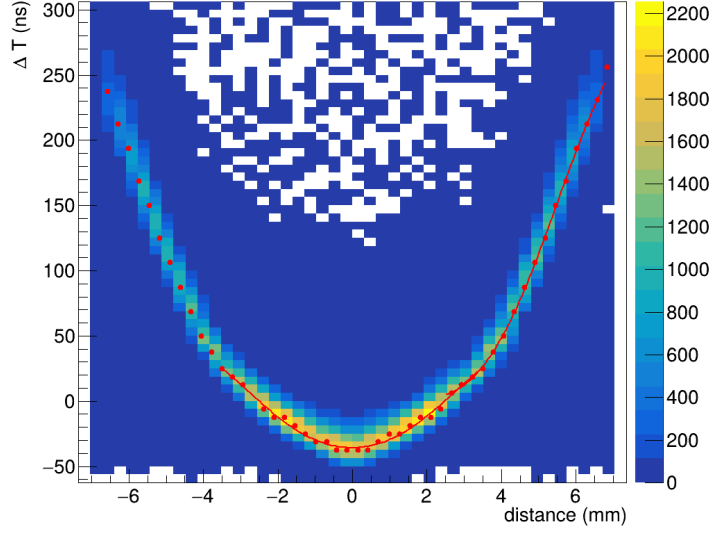


Figure 7.12: Distance-time distribution obtained from the wires of the second plane falling inside the tracker surface. The red dots represents the median of the histogram slices, and are fitted using Eq. 7.4 in the ranges -3 mm to 3 mm and 3 mm to 6 mm (solid red line). The chamber is operating at 1500 V .

The choice of analysing the drift chamber performance using the runs at 1500 V was guided by the fact that for this value of high voltage we have the highest statistics, even if a more intense electric field would have produced better results. The analysis are still in a preliminary phase, and the results are very likely to be improved.

Moreover, the impossibility of reaching voltages above 1700 V , due to the generation of discharges in the detector, limits the performance of the tracker; future interventions on the prototype will address this issue, as it is probably due not to the drift cell configuration, but to the presence of metallic support elements placed too close to the Mylar layers; their replacement with insulating elements will solve the problem, allowing for the complete characterisation of the prototype.

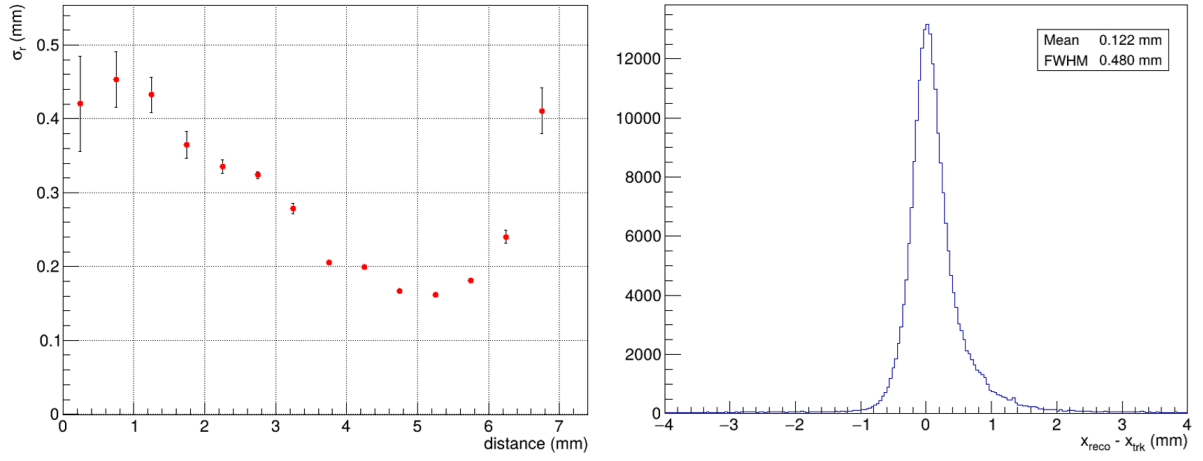


Figure 7.13: *Left*: spatial resolution as a function of the distance from the wire, for the second wire plane. *Right*: global residual distribution. Both results are preliminary.

Conclusions and future prospects

Since their discovery in 1998, neutrino oscillations have been extensively investigated through experiments using solar, atmospheric, accelerator, and reactor neutrinos. These studies have provided measurements of several key parameters; however, important questions remain, including the determination of the neutrino mass ordering and the presence of CP violation in the leptonic sector. The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino experiment designed to address these open issues.

DUNE will include a Far Detector consisting of four liquid argon time projection chambers (LAr TPCs) and a Near Detector complex composed of three distinct systems: ND-LAr and ND-GAr, which can be moved off-axis, and SAND, which remains fixed along the beam axis. These detectors are designed to provide measurements that constrain systematic uncertainties in the neutrino oscillation analyses at the Far Detector.

SAND is a multipurpose detector that integrates light tracking modules with passive targets made of various materials, a compact liquid argon volume (GRAIN), and an electromagnetic calorimeter housed within a magnetised region. This configuration enables precise measurements across multiple nuclear targets. These capabilities allow SAND to improve neutrino–nucleus interaction models, reduce uncertainties related to nuclear-effect, and support a broad independent physics programme.

In this context, my thesis focuses on the design and construction of the first drift chamber prototypes, which could potentially serve as the inner tracker of the SAND detector, as an alternative to the baseline design exploiting straw tubes. They represent the starting point of an R&D process that will demonstrate whether this technology can be applied to our study case from a physical and engineering point of view.

The use of a drift chamber-based technology is expected to provide a reliable alternative to straw tubes, achieving the same performance and physics goals while simultaneously reducing the number of channels and, possibly, the overall complexity of the project.

The quality controls that have been adopted to monitor the process and ensure precise knowledge of the key parameters of the chamber are presented. The spinning process and the tensioning procedure successfully achieved uniformity in the sagitta distribution within $5\,\mu\text{m}$ for both field and sense wires.

The beam test at the CERN SPS H4 beam line provided important data to characterise the performance of the drift chamber prototype in terms of drift cell efficiency, drift velocity, and spatial resolution of the single wire planes. Two different readout electronics were also tested, based on the TIGER ASIC and the VTX preamplifier coupled to a VME digitiser, respectively.

Although the TIGER ASIC is not the ideal solution, since it was not designed to work with drift-chamber detectors, it was chosen because it was the only available option to read out the entire detector at the time of this work.

In fact, TIGER showed some limitations in reading the drift chamber channels, which were partly expected because of its small dynamic range compared to the amplitude of the signals in our detector. However, it was able to provide very good time information that allowed us to compute the spatial resolution for the single wire plane, which was found to be below $500\,\mu\text{m}$.

The efficiency of the drift cells was apparently found to drop at higher voltages; however, this turned out to be caused by a combination of the high particle rate at the SPS and the large amplitude of

the acquired signals, which saturate the chip occupancy. Operating at a particle rate below 1 kHz, the efficiency of the wire planes exceeded 95% everywhere inside the drift cells.

In the near future, more detailed analysis will be performed on the beam test data, applying a reconstruction algorithm to evaluate the chamber efficiency and spatial resolution in reconstructing the particle trajectories. The data acquired during the beam test exploiting the movable table will allow to monitor the drift chamber performance across its area. Further tests will be conducted with cosmic rays using interface cards with a new design, incorporating VTX chips directly on them. This will allow to read an entire sector of the detector with VME digitiser modules, with the possibility of studying the energy reconstruction capability of the drift chamber.

The promising results obtained in this thesis work have been crucial in validating the design from both mechanical and physical performance perspectives and provide an important starting point for the design and construction of a full-scale prototype, which will be of crucial importance, as one of the major difficulties in realising this project lies precisely in its engineering.

Appendix A

Introduction to Drift Chambers

A drift chamber is an apparatus able to measure the space coordinates of the trajectory of a charged particle, detecting the electron-ion pairs produced in the gas of the chamber and measuring their drift times. Georges Charpak introduced in 1968 the multiwire proportional chamber (MWPC), showing that an array of many closely spaced anode wires could each act as independent proportional counters [96]. Drift chambers are an evolution of MWPCs, since Charpak itself noted that the time of a signal could be useful for coordinate determination.

A.1 Charge production

Charged particles can interact with the gas of the chamber, ionising the gas along their flight paths. It is possible to distinguish between primary and secondary ionisation. The sum of the two contributions is called total ionisation. In primary ionisation, few electrons (one, ore sometimes two or three) are ejected from the atom encountered by the charged particle. However, the biggest contribution to the charge created along the track comes from secondary ionisations, where electrons are ejected from atoms not encountered by the fast particle. Primary electrons in fact can have enough energy to further ionise atoms or create intermediate excited states, which later decay emitting secondary electrons. The total number of ion pairs can be expressed as

$$n_T = \frac{\Delta E}{W_i} \quad (\text{A.1})$$

where ΔE is the total energy loss in the gas volume considered, and W_i is the effective average energy to produce one pair. W_i depends on gas used and, above few keV for electrons and few MeV for α particles, is independent of the initial energy.

The Bethe-Block formula gives the average energy loss per unit length due to Coulomb interactions:

$$\frac{dE}{dx} = -2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 v^2 W_{max}}{I^2 (1 - \beta^2)} \right) - 2\beta^2 - \delta \right] \quad (\text{A.2})$$

where N_a is the Avogadro number, m_e the classical electron radius, Z , A and ρ are the atomic number and mass, and the density of the medium, respectively, I is its effective ionisation potential, and δ the density correction. z is the charge of the incident particle (in units of e), and $\beta = v/c$ its velocity. W_{max} represents the maximum energy transfer in a single collision

Looking at the interaction mechanism, two different events can take place: close collisions, with large energy transfer, produce ionisations, while distant collisions involve smaller energy transfers, resulting in both excitations and ionisations. In Figure A.1 the probability for the two processes is shown as a function of the energy transfer in a single collision, for 100 keV incident electrons.

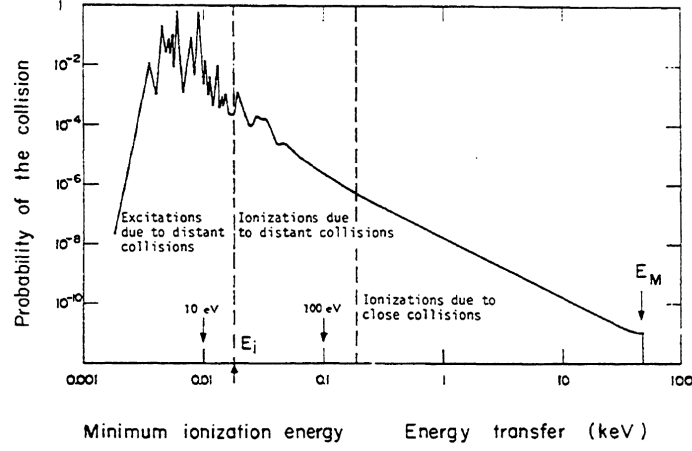


Figure A.1: Probability for excitation and ionisation processes induced by 100 keV electrons in water, as a function of the energy transfer in a collision [97].

In ionisation events, electrons are ejected with an energy E which can assume any value, up to W_{max} . Those having an energy above a few keV are normally called δ -rays. These electrons are responsible for secondary ionisations, since they have enough energy to escape a significant distance away from the primary radiation beam and produce further ionization. The angle of emission of a δ electron of energy E is given by [98]

$$\cos^2 \theta = \frac{E}{W_{max}} \quad (\text{A.3})$$

For minimum ionising particles ($W_{max} > 1 \text{ MeV}$), they are emitted perpendicularly to the incident track. Depending on their energy, δ electrons will cover a certain distance in the gas, suffering elastic and inelastic scattering from molecules. For practical purposes an effective range R_e can be defined, which is two or three times smaller than the total range travelled by electrons:

$$R_e = 0.71 E^{1.72} \quad (\text{E in MeV}) \quad (\text{A.4})$$

The above formula is valid up to energies of few hundred keV. Figure A.2 shows the range of electrons in Argon as a function of energy. Since the average energy loss in Argon is 2.5 keV/cm the centre of mass of the detected charge, and hence the position information it carries, will be systematically displaced with respect to the original track. This sets the limit to the best accuracy of position between 20 and 30 μm for a single gas counter operating at atmospheric pressure.

In thin materials the total energy loss is given by a small amount of interactions. Each one has a wide range of possible energy transfers, which are described by the classical formulation due to Landau. The energy-loss distribution in thin media is therefore [100]:

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})} \quad (\text{A.5})$$

where λ is the reduced energy, *i.e.* the normalised deviation from the most probable energy loss ΔE_{mp} :

$$\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi} \quad \text{where} \quad \xi = K \frac{Z}{A} \frac{\rho}{\beta^2} X \quad (\text{A.6})$$

being ΔE the actual energy loss given by the first term of the Bethe-Block formula. The landau distribution is shown in Figure A.3. The long tail at very large energy losses is due to the production

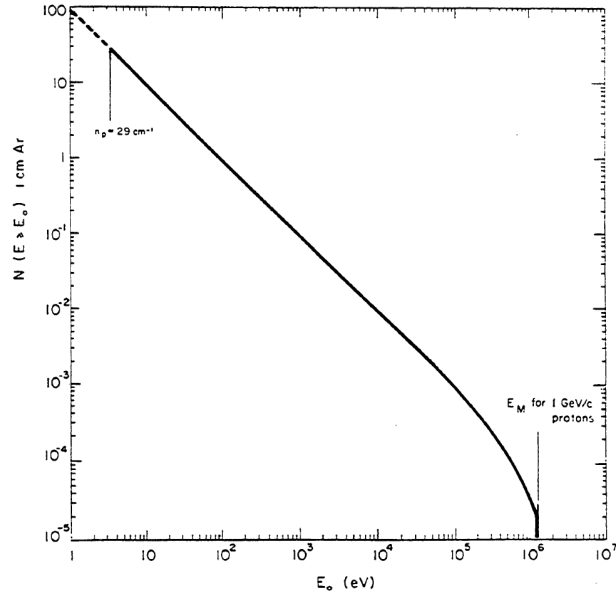


Figure A.2: Range of electrons in Ar under normal conditions as a function of energy [98].

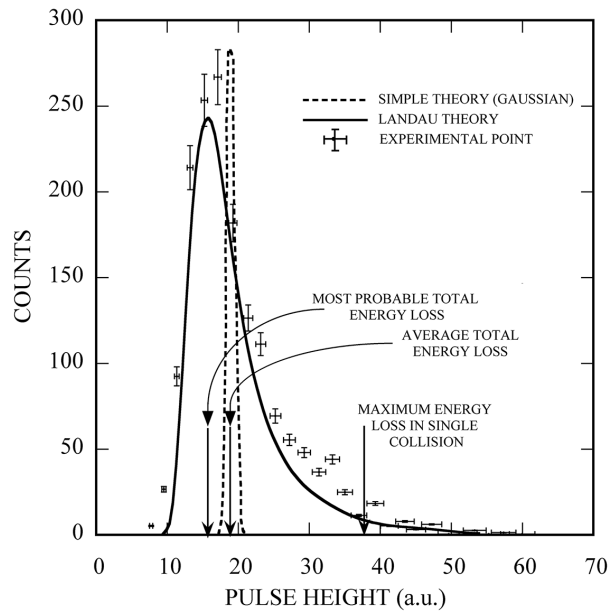


Figure A.3: Energy loss distribution: comparison of experimental data obtained in an Ar-CO₂ counter, with the distribution computed using a single Gaussian theory and the Landau expression [99].

Gas	$\lambda(\text{cm})$	$u(\text{cm/s})$	$D^+(\text{cm}^2/\text{s})$	$u^+(\text{cm}^2\text{s}^{-1}\text{V}^{-1})$
H ₂	1.8×10^{-5}	2×10^5	0.34	13.0
He	2.8×10^{-5}	1.4×10^5	0.26	10.2
Ar	1.0×10^{-5}	4.4×10^5	0.04	1.7
O ₂	1.0×10^{-5}	5.0×10^5	0.06	2.2
H ₂ O	1.0×10^{-5}	7.1×10^5	0.02	0.7

Table A.1: Classical mean free path, thermal velocity, diffusion coefficient and mobility for different molecules, under normal conditions.

of one or more δ electrons. As a consequence, the energy resolution of thin counters for fast particles is very poor, and each track should be sampled several hundreds times in order to identify a particle in the relativistic rise region exploiting the small increase in dE/dx . Moreover, the large fluctuation in energy loss must be taken into account when designing the amplification electronics for a gaseous detector, because of the large dynamic range of signals.

The ionisation created by a particle along its track can be effectively described by the cluster-size distribution which is, the number of electrons liberated directly or indirectly with each primary encounter. Figure A.4 summarises the experimental determination of cluster-size distributions [101]. Knowing this distribution, it is possible to calculate the ionisation distribution along the track length summing the cluster size as many times as there are primary encounters in the track.

A.2 Drift and Diffusion

The charges produced during the particle flight, quickly lose their energy in multiple collisions with the gas molecules. In the absence of other effects, charges diffuse following a Gaussian law:

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(\epsilon/kT)} dx \quad (\text{A.7})$$

where dN/N is the fraction of charges found in the element dx at a distance x from the origin, after a time t , and D is the diffusion coefficient. The r.m.s. value of the charge distribution, for linear and volume diffusion, is given by

$$\sigma_x = \sqrt{2Dt} \quad \text{and} \quad \sigma_V = \sqrt{6Dt} \quad (\text{A.8})$$

During diffusion, ions have an average thermal velocity of about 10^5cm/s , which is roughly two order of magnitude smaller than that of electrons, because of their small mass.

Positive ions can be neutralised recombining with a negative charge carrier, which could be either an electron or a negative ion. Another possibility is the process of charge transfer with a molecule of its own gas or with different molecules having a lower ionisation potential.

For what concern electrons instead, they can be neutralised by an ion, or can be attached by an electro-negative molecule, or can be absorbed by the detector walls. The attachment probability is practically zero for noble gases and hydrogen.

When an electric field is applied, ions acquire a net movement along the direction of the field. The average velocity of this movement is called *drift* velocity w^+ , not be confused with the instant velocity of ions. Since w^+ is found to be proportional to the reduced electric field E/P , where P is the gas pressure, it is convenient to define the quantity

$$u^+ = \frac{w^+}{E} \quad (\text{A.9})$$

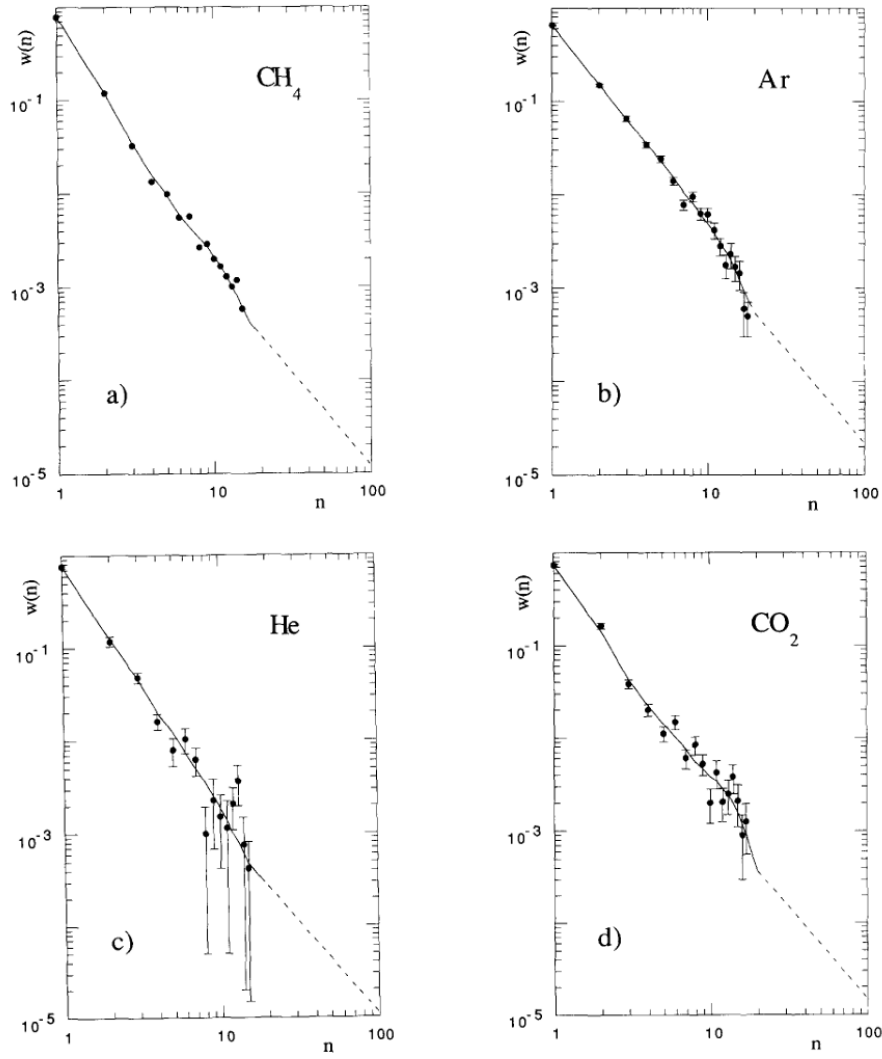


Figure A.4: Experimental cluster-size distributions [101]. The continuous lines are interpolations while dashed lines are extrapolations corresponding to the $1/n^2$ law expected for large n .

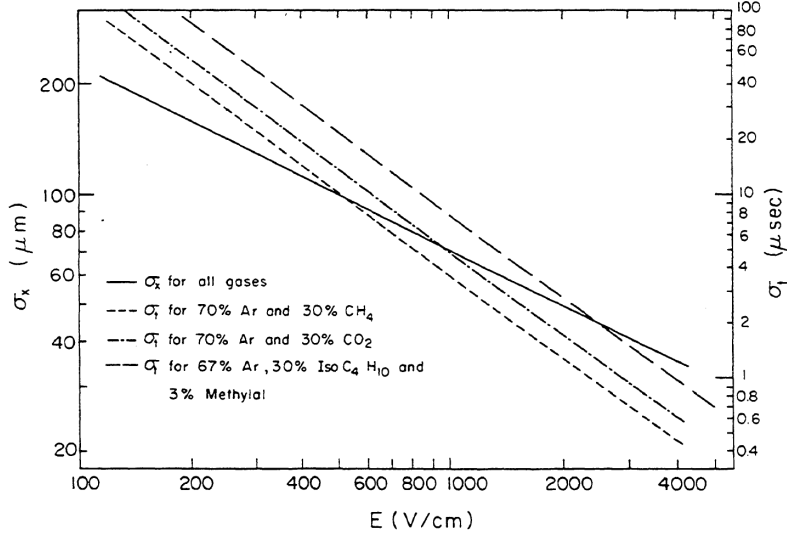


Figure A.5: Diffusion in space σ_x and in time σ_t of positive ions, for a drift length of 1 cm at normal conditions, as a function of the electric field [102].

called mobility. It is specific to each ion moving in a given gas, and remains constant up to very high fields, since the average energy of ions is almost unmodified. Table A.1 collects properties of different ions, such as mean free path, thermal velocity, diffusion coefficient and mobility. The r.m.s. linear diffusion for ions migrating in a time t over a length x is given by

$$\sigma_x = \sqrt{2Dt} = \sqrt{\frac{2kTw+t}{eE}} = \sqrt{\frac{2kTx}{eE}} \quad (\text{A.10})$$

Indeed, from classical arguments it is possible to obtain the following relation between mobility and diffusion coefficient

$$\frac{D^+}{u^+} = \frac{kT}{e} \quad (\text{A.11})$$

Figure A.5 shows the variation of σ_x w.r.t. the electric field, at 1 atm, and the equivalent time dispersion σ_t for several gas mixtures. It can be noticed that σ_x is the same for all gases.

Moving to electrons, it has been found that, except for very low fields, their mobility is not constant (contrarily to what happens for ions). Indeed, due to the small mass, electrons can substantially increase their energy between collisions with the gas molecules. Electron drift velocity can be written as [103]

$$w = \frac{e}{2m} E\tau \quad (\text{A.12})$$

where τ is the mean time between collisions. The collision cross section, and therefore τ , for some gases varies very strongly with the electric field as electron wavelength approaches those of the electron shells of the gas molecules.

It has been found that the addition of even small fractions of another gas can dramatically change the drift properties, as shown in Figure A.6 and A.7. This second plot displays the expected drift velocity compared to the experimental one, for Ar-CO₂ mixture which are of interest for the operation of our drift chamber prototype.

During the drift in electric fields electrons diffuse, as a result of multiple collisions with the gas molecules. The extent of the diffusion depends on the gas, but also on E , due to the increase of the electron energy. The distribution is Gaussian and its r.m.s. is given by Eq. A.8.

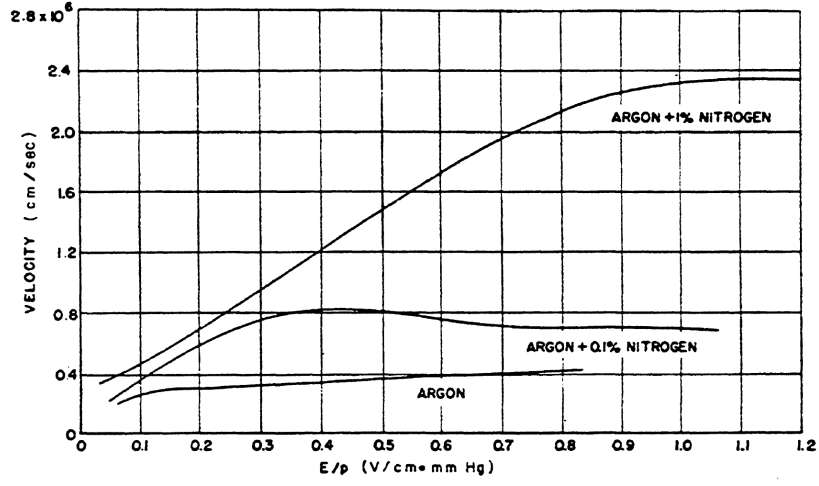


Figure A.6: Drift velocity of electrons pure argon and in different Argon-Nitrogen mixtures [104].

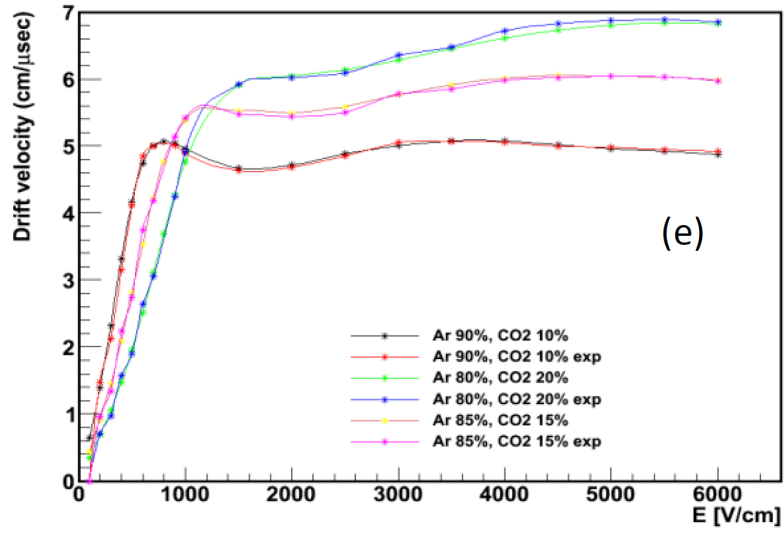


Figure A.7: Simulation results and experimental measurements for the drift velocity of electrons in Argon-based mixtures for different mixing ratios [105].

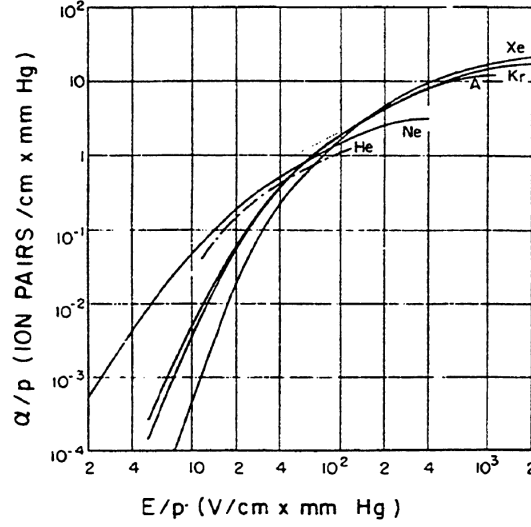


Figure A.8: First Townsend coefficient as a function of the reduced electric field [103].

A.3 Charge multiplication

When the electric field is increased above few kV per cm, inelastic electron-molecule collisions may result in the creation of an electron-ion pair. When the energy of an electron increases over the first ionisation potential of the gas the result of the impact can be an ion pair, while the primary electron continues its trip. The ionisation probability increases rapidly above threshold and has a maximum which for most gases is around 100 eV. The main free path for ionisation is defined as the average distance an electron has to travel before gaining enough energy to become involved in an ionising collision. The inverse of the mean free path is called the first Townsend coefficient α , and represents the number of ion pairs produced per unit length. Classic values of the Townsend coefficient as a function of field for pure noble gases are provided in Figure A.8.

Considering n electrons at a given position, after a path dx the increase in the number will be $dn = n\alpha dx$. Integrating over the drift length, it is possible to obtain the total number of electrons $n = n_0 e^{\alpha x}$, so that the multiplication factor M is given by

$$M = \frac{n}{n_0} = e^{\alpha x} \quad (\text{A.13})$$

In case of a non uniform field, the Townsend coefficient will depend on the position, $\alpha = \alpha(x)$.

The multiplication factor has a phenomenological limit of $M \sim 10^8$, which corresponds to the Raether condition

$$\alpha x \sim 20 \quad (\text{A.14})$$

Indeed, secondary processes, like photon emission, induce the generation of avalanches spread over the gas volume and space charge deformation of the electric field, which result in a spark breakdown. In order to operate in a safety limit, avoiding breakdowns, the gain should not exceed values of $\sim 10^6$.

One of the first gaseous detectors is the *proportional counter*, composed by a cylindrical cathode and a thin metal wire stretched on the axis. In this configuration the electric field in the vicinity of the central wire is proportional to the inverse of radius, so that electrons, in absence of a magnetic field, will move radially towards the anode in an increasing electric field. In most of the region when charges are produced by primary ionisations, the electric field only makes ions drift while, very close to the

anode, normally at few wire radii, the field gets strong enough to start the multiplication, generating an avalanche.

The proportional counter owes its name to the fact that the signal generated in the wire is proportional to the number of electrons collected. Increasing the E field, trying to achieve the highest possible gain, would lead in a region of limited proportionality which, for even higher fields, ends in the so called Geiger-Müller region. In this last operating mode, processes of photon emission during the avalanche can give origin to secondary multiplicative processes in different regions of the detector, so that the full length of the wire is surrounded by electrons and ions.

A.3.1 General considerations on the choice of the gas

The optimal operation of a wire-based detectors impose several requirements, such as low working voltage, high gain, good proportionality, high rate capabilities, long lifetime and fast recovery. They have to be carefully considered when choosing the gas mixture.

It has been found that avalanche multiplication occurs in noble gases at much lower fields than in complex molecules, making them the preferred choice as main component of the mixture. Among noble gases, for economic reason Xenon and Krypton are disfavoured w.r.t. Argon. With such a gas, however, it is not possible to obtain gains higher than 10^3 - 10^4 without entering in the discharge region. The excited atoms in fact can return to the ground state only through radiative processes, emitting photons which have enough energy to extract electrons from the cathode, initiating a new avalanche. Argon ions, on the other hand, migrate to the cathode extracting electrons as soon as they are neutralised.

The addition of polyatomic molecules changes completely the operation of a counter. Indeed, the large amount of non-radiative excited states allows the absorption of photons in a wide energy range. This is a common property of organic and inorganic compounds, such as hydrocarbon and alcohol families, and CO_2 , CF_4 and others. These molecules act as quenchers, dissipating the excess energy either by elastic collisions or by dissociation into simpler radicals. Obviously, the quenching efficiency increases with the number of atoms in the molecule, so that isobutane (C_4H_{10}) is very often used for high-gain stable operation.

The addition of small quantities of electronegative gases, like freons, allow to achieve the highest possible gains before Geiger-Müller discharge, thanks to the capture of free electrons forming negative ions that cannot induce avalanches.

Unfortunately, the use of polyatomic gases can seriously affect the lifetime of counters. The products of the dissociation process, which is at the basis of the quenching actions, can form liquid or solid polymers after molecular recombination. These products will deposit on cathodes and anodes, forming a thin layer of insulator which substantially modifies the operation of the counter. This effect is more important in case of high fluxes of radiation, and can quickly consume the available molecules if the counter is sealed. In order to limit the ageing of the detector a single inorganic quenching gas, like CO_2 , can be used, with the drawback of a limiting the chamber stability for high fields.

A.4 Signal generation

The movement of charges, the ions toward the cathode and electrons toward the anode, produces a change in energy of the system, which results in an induced current flowing between the anode and the cathode. This is the origin of the signals detected in a gaseous detector, which can then be read out by amplifiers.

As already mentioned, the multiplication process takes place within few wire radii, *i.e.* typically within less than $50\text{ }\mu\text{m}$ from the wire surface. Since electrons created in the avalanche move to the wire with a velocity which is usually around $50\text{ }\mu\text{m}/\text{ns}$, the whole process develops in less than 1 ns. Electrons will therefore generate a short signal pulse, while ions, whose velocity is about a factor 1000 smaller,

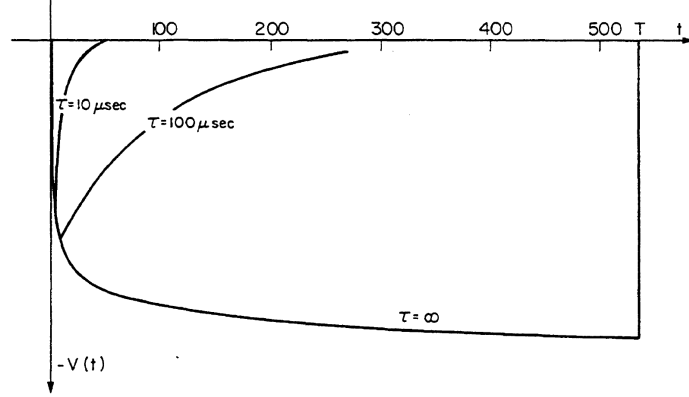


Figure A.9: Time development of the pulse in a proportional counter. T is the total drift time of positive ions. Pulse shape obtained with several differentiation time constants is shown [106].

will produce a signal with a long tail. The expressions for the two contributions are respectively

$$v^- = -\frac{Q}{2\pi\epsilon_0 l} \ln \frac{a + \lambda}{a} \quad (\text{A.15})$$

and

$$v^+ = -\frac{Q}{2\pi\epsilon_0 l} \ln \frac{b}{a + \lambda} \quad (\text{A.16})$$

where it is assumed that all charges are produced at a distance λ from the wire, a is the wire radius and b is the cathode radius. Typical values for a proportional counter are $a = 10 \mu\text{m}$, $\lambda = 1 \mu\text{m}$ and $b = 10 \text{ mm}$.

Neglecting the electron contribution, being just about 1% of the total, and assuming a constant mobility of the ions, it is possible to obtain the signal induced on the anode [106]:

$$v(t) = -\frac{Q}{4\pi\epsilon_0 l} \ln \left(1 + \frac{t}{t_0} \right) \quad (\text{A.17})$$

Figure A.9 shows the time development of the signal for an Ar-filled counter under normal conditions. The total drift time of ions, T , is obtained requiring $r(T) = b$, and is found to have a value of $550 \mu\text{s}$ for a typical operational voltage of $V_0 = 3 \text{ kV}$. It is therefore normal practice to terminate the counter with a resistor R , in order to differentiate the signal with a time constant $\tau = RC$, increasing the rate capability of the detector. Very short pulses can be obtained using low impedance terminations.

What we have discussed so far considering a proportional counter is valid also for drift chambers, given the proper modification of geometric parameters, since their unit-element can be considered equivalent to an isolated proportional counter.

A.5 Coordinate measurement

The novelty of drift chambers w.r.t. MWPCs is the possibility to obtain the distance between the wire and the track from the measurement of the drift time:

$$x = \int_{t_0}^{t_1} w dt \quad (\text{A.18})$$

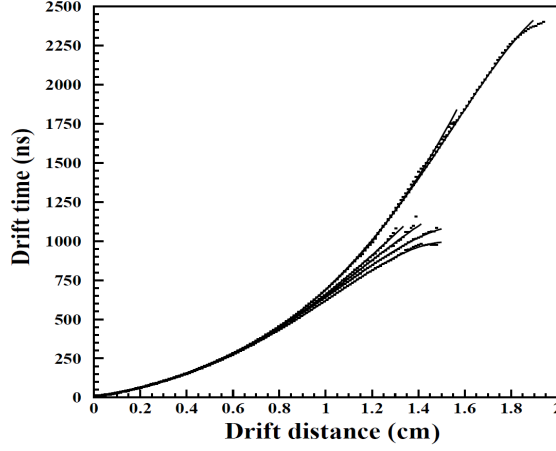


Figure A.10: KLOE drift chamber: space-time relation for different incidence angles [107].

where the drift velocity w in general is not constant across the cell. In order to have a precise coordinate measurement is therefore fundamental to know accurately the space-time relationship for the drift chamber cells. This may not be always possible because of the various mechanical tolerances which could locally modify the electric field shape and intensity. It is therefore very important to carefully choose the gas mixture and the cell design in order to obtain a saturated drift velocity, so that the sensitivity to local field variations is strongly reduced. In case this is not possible, the non-saturated drift velocity would require tight control of the gas mixture, as well as of the whole calibration procedure. Figure A.10 shows an example of space-time relation obtained for the KLOE drift chamber. The drift velocity was not saturated in this case.

The relation between space and drift time has to be determined following a calibration procedure. The drift time t_{drift} is extracted from the time measured when the signal crosses a certain threshold, while the spatial information is provided by an external tracker.

For an ideal drift cell, the time distribution would coincide with the distribution of the drift time, resulting in a flat distribution starting from a null drift time for tracks passing near the anode, up to an arbitrary value, corresponding to tracks passing near the cathode. Experimentally, however, some non-linear effects related to the electric field distribution inside the cell have to be considered, together with different time delays due to trigger latency, and different cable lengths of the read-out electronics. To summarise, the measured time can be seen as the sum of several components:

$$t_{meas} = t_0 + t_{tof} + t_{prop} + t_{walk} + t_{drift} \quad (\text{A.19})$$

where t_0 is a fixed offset which depends on cable/fibre lengths, t_{tof} is the particle time of flight, t_{prop} is the propagation time of the signal along the anode wire, and t_{walk} is the time walk of the signal.

The main goal of the calibration is the calculation of the time pedestal $t_{tof} + t_{prop} + t_{walk}$, which is found fitting the rising edge of the time distribution with a Fermi-Dirac function. An example of such distribution is shown in Figure A.11. The peak at the beginning of the time distribution is due to non-linear effects in the avalanche region very near (a few wire diameters wide) the anode wire, and to the occurrence of δ -ray electrons which pass closer the anode wire than the muon track.

The intrinsic accuracy of a drift chamber can be estimated measuring the same track in a set of trackers and computing the standard deviation of the difference between the fitted coordinate and the one measured with the drift chamber. Its typical values ranges between 50 and 200 μm . Figure A.12 displays the spatial resolution achieved by the KLOE drift chamber. As can be seen, its main contributions come from:

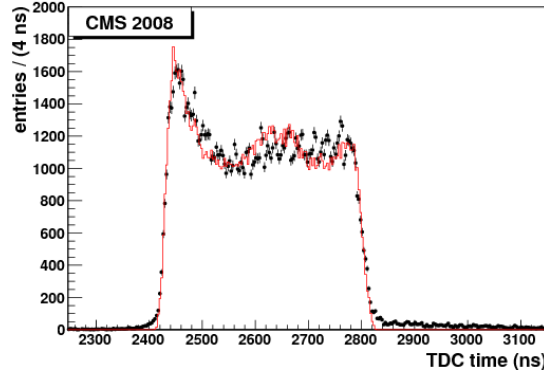


Figure A.11: Time distribution for CMS Drift Tube Chambers, compared to simulated data (red line) [108].

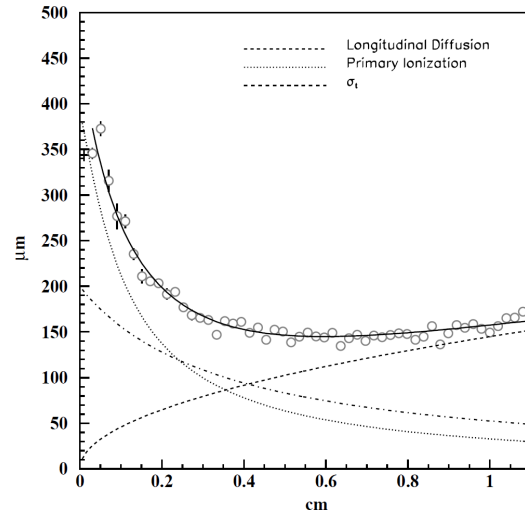


Figure A.12: Different contributions to the spatial resolution of the KLOE drift chamber. The contribution due to the time resolution is multiplied by the drift velocity [107].

- electron diffusion, proportional to the square root of the drift distance;
- a constant electronics noise, which affects the time resolution σ_t ;
- primary ionisation statistics, which is particularly important close to the anode wire.

A.5.1 Coordinate measurement in the wire direction

The other two missing coordinates can be determined with several different methods. The first possibility consists in the measurement of the pulse-height ratios on the cathode electrodes, like strips, pads or wires: knowing the electrode response, the coordinate of the avalanche between the pick-up electrodes is computed. The second method is called "charge division", since the position of the avalanche along the wire is determined measuring the pulse height at both ends. The last method instead relies on the measurement of the difference of arrival times at the two ends of the wire, applying the known propagation time of the signal along the wire.

Another possibility, which is not a "true" coordinate measurement, is based on the stereo measurement of track. Lets consider multiple parallel drift chambers, each measuring only one drift coordinate. If sense wires are arranged in different directions, the track of a particle which crosses all the wire planes is measured in different stereo directions, allowing the 3D reconstruction of the full track.

A.6 Stability of operation

The reliability of a gas detector during normal operation is based on the precise knowledge of the space-time relation or, equivalently, of the drift velocity. The major factors which could affect $w(t)$ are the electric field strength and direction, the atmospheric pressure, the gas composition and temperature, the presence of external electric or magnetic fields, and the mechanical imperfections. The choice of the gas is of fundamental importance for a stable operation. As already discussed, selecting a gas which saturates the drift velocity obviously strongly reduces the dependence on the reduced electric field E/P .

Small displacements of the wires from their ideal position can modify the shape of the E field and lead to electrostatic instabilities. Designing a drift chamber it must be taken into account that the gravitational force will produce a sag f in the wires, whose entity depends on the tension T which has been applied to the wire, on its length L and its orientation with respect to the direction of $\vec{g}$, as given by

$$f = \frac{\lambda L^2}{8T} \quad (\text{A.20})$$

where λ is the linear density of the wire.

The sagitta can be reduced increasing the mechanical tension. However, there is a maximum force T_c that can be applied to the wire, above which inelastic deformations take place. It is proportional to the wire cross section. The minimum achievable sagitta of a wire is instead independent of its cross section.

The length of the wires in turn, puts certain constraints on the high voltage that can be applied before electrostatic instabilities take place. The critical voltage above which the cell becomes unstable is given by

$$V_c = k \frac{D\sqrt{T}}{L} \quad (\text{A.21})$$

where D is the distance between sense and field-shaping wires, and k is a constant which depends on the cell geometry.

Among the various materials, Tungsten is the one that allows the smallest sagittas, sustaining quite large tensions, as shown in Table A.2. However, large tensions require stiff supports for the chamber

Material	Tensile strength (kg/mm ²)	Sagitta (μm) for a 100 cm long wire
Al	4 – 16	21 – 84
Cu	21 – 37	30 – 53
Fe	18 – 25	39 – 54
W	180 – 410	6 – 13

Table A.2: Maximum stresses before deformation and corresponding sagittas for several wire material [109]. A 1 m long wire has been considered.

endplates. The design of a chamber must take into account that a deformation of the endplates will impact on the sagitta of the wires.

Appendix B

Review of Existing Drift Chambers

The design of the SAND drift chamber, the drift cell geometry, and the mechanical solutions adopted have been partially inspired by existing drift chambers, which I will briefly describe in the following sections.

B.1 The KLOE Drift Chamber

The KLOE experiment [70] at the Frascati ϕ -factory DAFNE has been designed with the main goal of precisely measuring the CP-symmetry violation parameters in the decay of neutral kaons coherently produced through the decay $\phi \rightarrow K^0 \bar{K}^0$. The kaon pairs are in an antisymmetric state, giving rise to the weak eigenstates $K_L K_S$. The design of the KLOE drift chamber [107] was driven by the event topology of the K_L decays, which have a mean free path of 343 cm, and vertices that are mostly distributed at large polar angles. To maximise the acceptance for the decays into charged and neutral channels, a large tracking volume is therefore required, together with high and uniform reconstruction efficiency, good momentum resolution ($\sigma_{p_T}/p_T \simeq 0.4\%$), and high transparency to reduce regeneration, multiple scattering, and the conversion of low-energy photons.

Tracker Design

The requirements for three-dimensional track reconstruction and uniform efficiency throughout the chamber volume led to the choice of drift cells with an almost square shape, arranged in coaxial layers with alternating stereo angles. Detailed studies of the field configuration, performed with accurate simulation codes and on prototypes [95], have shown that a ratio of field to sense wires of 3:1 is a satisfactory solution that ensures good electrostatic properties of the drift cell while still maintaining an acceptable track sampling frequency. The drift cell configuration is shown in Figure B.1 on the left.

A light gas mixture of 90% He - 10% iC_4H_{10} was chosen to minimise multiple scattering and density, ensuring good efficiency and spatial resolution, as well as safe operating conditions in terms of ageing in the DAFNE radiation environment.

Gold-plated $25\ \mu\text{m}$ diameter Tungsten wires are used as anodes, while for field wires $80\ \mu\text{m}$ diameter Silver-plated 5056-Al tempered alloy wires are chosen to limit field emission and gas amplification near the field wire surface, while simultaneously having low Z and low density. At a voltage difference of 1800–2000 V, the gas gain is $\sim 10^5$.

Wire-crimping is the standard choice for wire clamping. With Aluminium, the proper choice of feedthrough material is important. The metal pins, made of copper, are fabricated by precision machining of short sections from drawn tubes. The outer diameter of the pin is 1 mm and the internal hole is $150\ \mu\text{m}$. The insulating bushing, made of delrin, is injection-moulded over the metallic pin to ensure

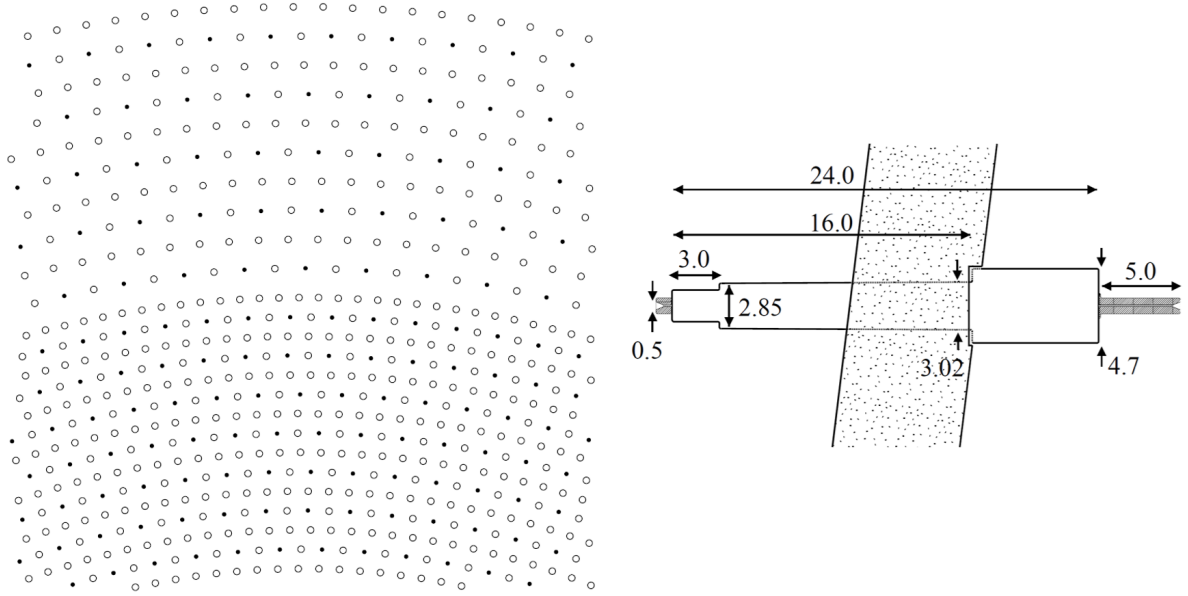


Figure B.1: *Left*: drift cells configuration at $z = 0$: a portion of chamber at the boundary between small cells (inner layers) and big cells (outer layers) is shown. Full dots indicate sense wires, open circles the field wires. *Right*: details of the feedthrough shown inserted in the chamber end plate (dimensions in mm).

good gas tightness. The feedthrough, shown in Figure B.1, is used to hold both W and Al wires and provides a wire location accuracy of $\leq 30 \mu\text{m}$. A reliable crimp is obtained with a pneumatic tool with cylindrical jaws and a carefully adjusted residual gap. The same feedthrough is used in the construction of the first SAND drift chamber prototype, adopting a manual crimp.

High Voltage Supply and Readout

Since the number of cells is a multiple of six for all layers, connections to the wires are made in groups of six, as shown in the scheme of Figure B.2. In order to evenly distribute the material of circuits and cables over the end plates, the high voltage and signal lines of different layers are connected alternately at either end. Figure B.2 on the right shows a photograph of the six channel HV cards and preamps, which are mounted on the chamber end plates. All wires are connected through $10 \text{ M}\Omega$ limiting resistors, and decoupling between 6-channel cards is done by means of a $1 \text{ M}\Omega$ – 470 pF filter. The readout chain consists of an on-detector preamplifier, which is the VTX, and a shaper-discriminator circuit that feeds a custom-built integrated TDC. The measured preamplifier response is of the order of 1.0 mV/fC . The sense wires have a capacitance of $\sim 30 \text{ pF}$, a resistance of $\sim 360 \Omega$ and are not terminated on the HV side. The input network transfers about $1/3$ of the charge to the preamplifier. With a gas gain of 10^5 , the average output pulse height for a single electron cluster is $\sim 8 \text{ mV}$. The preamplifier output pulses are sent to an amplifier–discriminator–shaping circuit via 50Ω miniature coaxial cables, 15 m long.

The VTX preamplifier was the first electronics adopted for the readout of the small scale drift chamber prototype due to the availability of spare 6-channels cards and the possibility of acquiring the full signal waveform with a digitiser module.

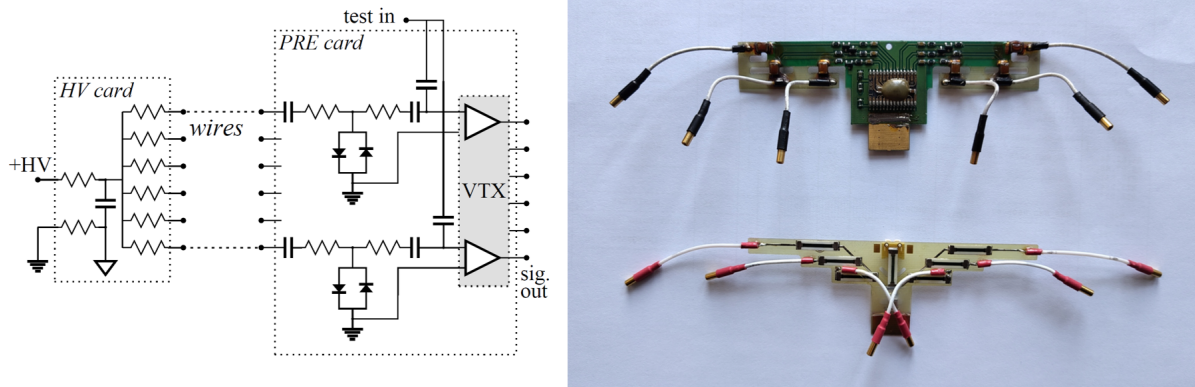


Figure B.2: *Left*: wire connections to high-voltage supply and preamplifiers. *Right*: photograph of the preamplifier (top) and high-voltage boards (bottom).

B.2 The NOMAD Drift Chamber

The NOMAD experiment [110] was built to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the CERN SPS neutrino beam predominantly composed of ν_μ 's with a mean energy of 24 GeV. The search was based on the identification of τ 's produced by ν_τ 's charged current interactions through the kinematics of their decay products.

This method of oscillation search necessitated excellent measurement quality of all the secondary particles produced in the neutrino interactions and the identification of electrons and muons. This was made possible thanks to an active target, constituted by a set of large drift chambers located inside a dipole magnet. A schematic view of the components of the NOMAD experiment is given in Figure B.3.

Tracker Design

The drift chambers act simultaneously as neutrino target material and tracker for charged particles. Given this dual role, the chambers walls had to be as massive as possible in order to maximise the number of neutrino interactions and as light as possible to limit multiple scattering, secondary particle interactions, and photon conversions. These conditions imposed the use of a low Z material with good mechanical properties, mainly composite plastic materials.

The fiducial volume of the NOMAD detector consists of 44 drift chambers, each comprising three measurement planes, which allow for the reconstruction of one spatial point. Each drift chamber has an active area of about $3 \times 3 \text{ m}^2$ and consists of four panels enclosing 3 drift gaps of 8 mm (see Figure B.4) filled with an Ar (40%) - C₂H₆ (60%) gas mixture at atmospheric pressure. The central gap (Y plane) is equipped with 44 sense wires parallel to the X axis, while the outer gaps have 41 wires at -5° (U plane) and $+5^\circ$ (V plane) with respect to the X axis. The magnetic field is parallel to the X axis. For a high momentum track crossing the chambers along the Z axis, the Y coordinate is obtained from the Y plane, whereas the X coordinate is calculated by combining the U and V plane measurements. Because of the small stereo angle, the resolution in X is about 10 times worse than that in Y.

As the reader might notice, the configuration of the three wire planes of each chamber is identical to the one adopted for the SAND drift chamber preliminary design. Indeed, the direction of the magnetic field in SAND

Drift Cell Design

The chamber drift cell is composed of a polyester skin with Aluminium strips glued on each side of the drift gap, a $20\text{ }\mu\text{m}$ diameter gold-plated Tungsten sense wire placed in the centre, and two Cu-Be potential wires, $100\text{ }\mu\text{m}$ in diameter, placed at a distance of $\pm 32\text{ mm}$ with respect to the sense wire.

The strips are 2.8 mm wide, $12\text{ }\mu\text{m}$ thick, and separated by a 1.2 mm gap large enough to avoid any sparking due to potential differences between adjacent strips (400 V). The strip bands are tilted as the wires, with respect to the X axis by -5° , 0° and $+5^\circ$ depending on the drift gap. For the U and V planes a triangular zone of 25 cm by 3 m is left unequipped.

The sense wires are held at a typical voltage of 1750 V through a $4.7\text{ M}\Omega$ resistor, while the potential wires are kept at -3200 V through a $10\text{ M}\Omega$ resistor that is shared by all potential wires of a drift plane. Figure B.5 shows the electrical scheme of a drift cell, with high voltage and signal readout connections. The strips in-between have a potential equally distributed so that the drift field perpendicular to the sense wire is of the order of 1 kV/cm in most of the cell. The corresponding gain is of the order of 10^5 .

The 3 m long potential and sense wires are soldered and glued at both ends with a precision of about $100\text{ }\mu\text{m}$. Since the time-distance relation is extremely sensitive to the relative position of the wires with respect to the strips, the dominant error comes from the strip positioning. The final determination of the wire position in the experiment will be the result of a software alignment procedure

Signal Readout

The sense wire signal is read out by a transimpedance preamplifier located on a board connected directly to the chamber printed board, and AC coupled through a 1 nF capacitor. The preamplifier signal goes through a discriminator and is sent via a 30 m long cable to the TDC units. The gold-plated Tungsten wire has a resistance of $165\text{ }\Omega/\text{m}$, while the characteristic impedance is not real and, for high frequencies, larger than 100 MHz , has a value of $360\text{ }\Omega$. The end of the wire opposite to the readout is left unconnected. To reduce the noise and radio emitters that are easily collected by the long sense wires, a $12\text{ }\mu\text{m}$ thick aluminium foil is used as reinforcement for the shielding provided by the drift cell field shaping strips.

B.3 The MEG II Drift Chamber

The MEG experiment at the Paul Scherrer Institut searches for the charged-Lepton-Flavor-Violating decay $\mu^+ \rightarrow e^+\gamma$. MEG [112] has reached a sensitivity level of 5.3×10^{-13} for the branching ratio. The goal of the MEG II experiment [113] is to improve the MEG sensitivity by one order of magnitude through a total upgrade involving substantial changes to the experiment.

Tracker Design

The new positron tracker is a unique volume, ultra-light He-based cylindrical drift chamber (CDCH), designed to minimise the material budget crossed by positrons with momentum $> 45\text{ MeV}/c$. The CDCH is the first cylindrical drift chamber ever designed and built in a modular way, featuring 9 layers, each divided in 12 identical 30° sectors, with 192 square drift cells, for a total 12000 wires in a full stereo configuration. The chamber radially extends from $R_{in} = 196\text{ mm}$ to $R_{out} = 284\text{ mm}$, with an active area 193 cm long.

Each layer has 192 square cells with a 5:1 ratio of field to sense wires to ensure the proper electrostatic configuration. As can be seen from Figure B.6, each layer is composed by one anode sublayer and two cathode sublayers. The cell size varies linearly between 6.7 mm at the inner radius and 8.7 mm at the outer radius, while the alternating stereo angles vary from 5.8° to 8.5° . The anodes are $20\text{ }\mu\text{m}$ diameter Tungsten wires, while the cathodes are 40 and $50\text{ }\mu\text{m}$ Aluminium wires. The latter are placed in the

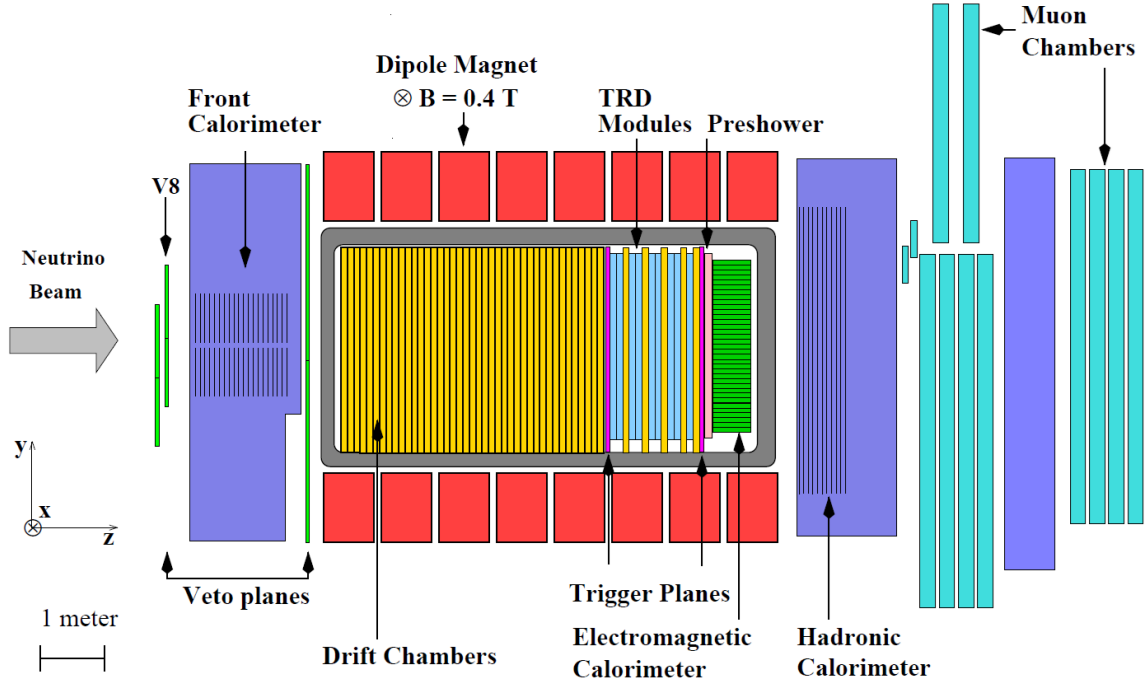


Figure B.3: Side-view of the NOMAD detector. Z axis is horizontal and nearly coincides with the neutrino beam direction. Y axis is vertical and points to the top of the figure. X axis is along the magnetic field direction.

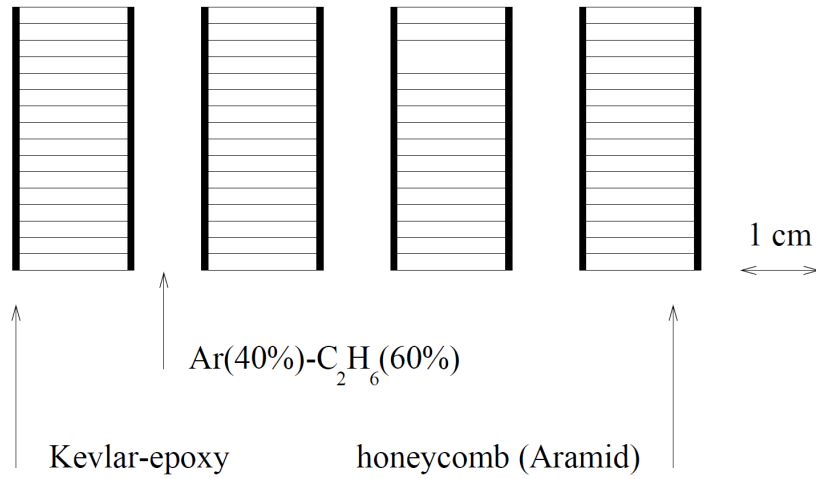


Figure B.4: A side-view of one NOMAD drift chamber cut by a plane orthogonal to the x axis.

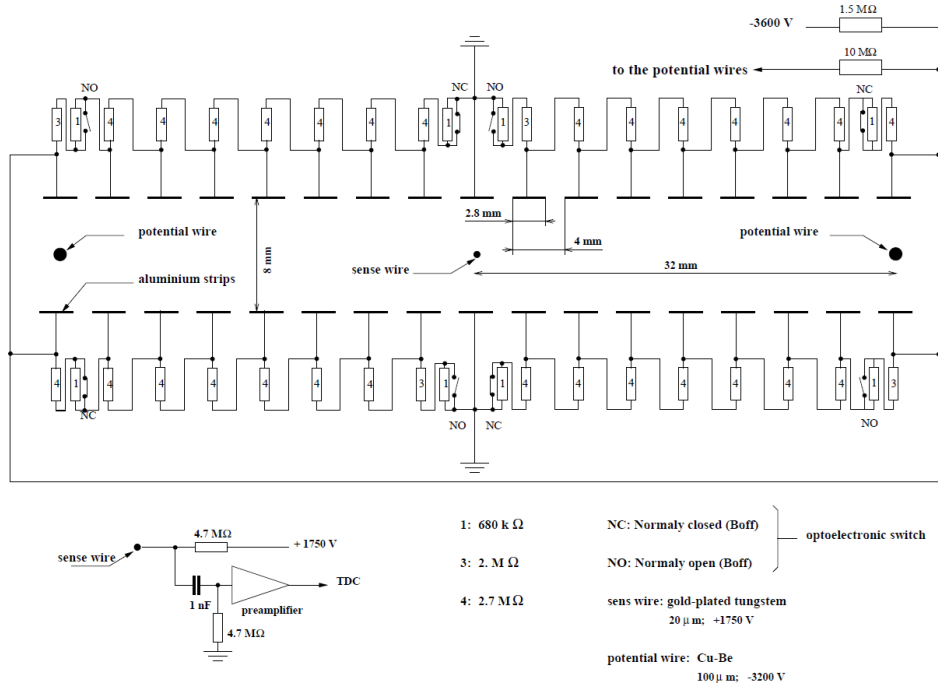


Figure B.5: A close-up of a drift cell and its HV connections [111].

sense wire layers, between two adjacent ones. The 40 μ m wires are instead located in the top and bottom sublayers, with the stereo view orientations. Two layers of guard wires, made with 50 μ m Aluminium wires, surround the active volume of the chamber to equalise the gain of the innermost and outermost layers.

The CDCH drift gas is a 90% He - 10% iC₄H₁₀ mixture, chosen for its low radiation length (~ 1400 m), fast drift velocity (~ 2 cm/s), which allow to achieve a spatial resolution of 120 μ m [114].

The CDCH is read out from both ends of each sense wire, for a total of 3456 channels. The readout is based on a low-noise, low-distortion, and wide-bandwidth differential pre-amplification stage, followed by the waveform digitiser. The readout allows for the possibility of using the Cluster Counting technique [115, 116] to improve spatial resolution and the CDCH performance.

Wiring Procedure

For the construction of the drift chamber, MEG II followed the approach of separating the wire anchoring function from the mechanical and gas containing ones. A 32-wire frame is created by soldering the wires on two 400 μ m thick PCBs. The chamber is assembled by alternately stacking a multiwire frame and a spacer made of peek on the wire support end-plate, as shown in Figure B.7. Despite the conceptual simplicity of the building strategies, great precision is needed to ensure the electrostatic stability of the drift cells, in particular in the positioning of both wires and PCBs. The firsts must be placed with an accuracy of 20 μ m and stretched with an accuracy of 0.5 g.

This is ensured by a wiring robot, shown in Figure B.9, which has been designed for monitoring the wire positions and their alignments within a few tens of μ m, applying mechanical tension and maintaining it constant and uniform throughout the whole chamber, and soldering the wires on the PCBs using a contactless procedure. In order to fulfil all these requirements, the wiring robot is composed of three systems:



Figure B.6: *Left*: the entire drift chamber with all layers mounted. The hyperbolic profile of the chamber is visible. *Right*: drift cells configuration.

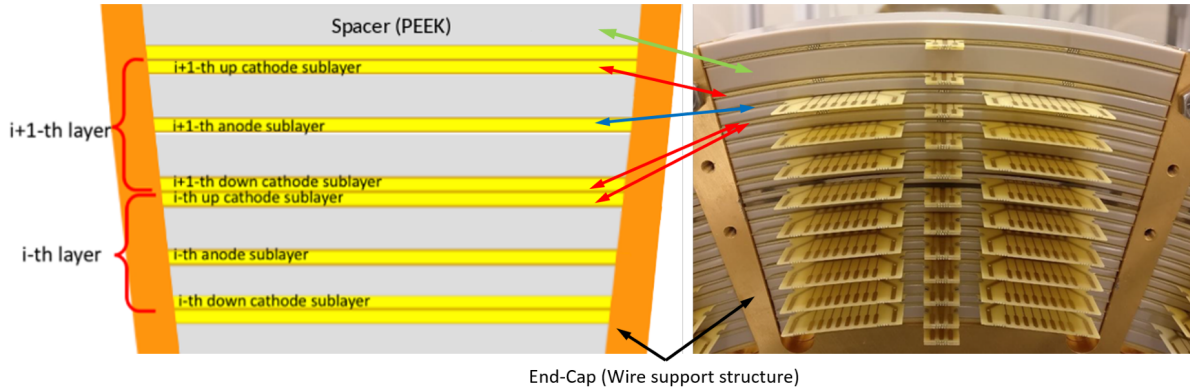


Figure B.7: Schematic view (*left*) and real picture (*right*) of the stack of wire PCBs and spacers on the end-cap wiring support structure defining the drift chamber geometry.

- A wiring system that uses a semi-automatic machine to simultaneously stretch the multiwire layer with a control on the wire mechanical tension better than 0.2 g, and on the wire position of the order of $20\ \mu\text{m}$.
- A soldering system composed of an infrared laser soldering system and a tin feeder.
- An automatic handling system that extracts the multiwire layers from the wiring system and places them in a storage/transport frame.

Such robotic system, and in particular the wire stretching and soldering stages, are being considered for the future development of an automated wiring machine for the SAND full-scale detector modules.

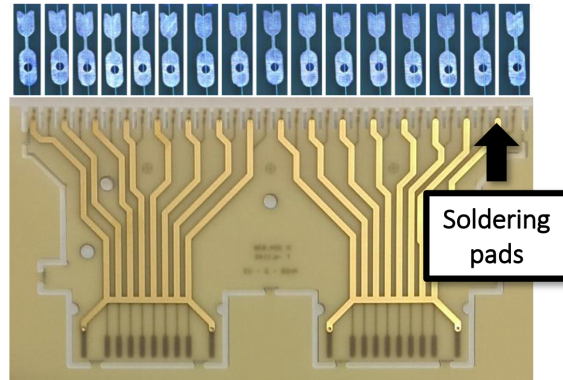


Figure B.8: Picture of a wire PCB with a close-up view of the soldering pads for sense and field wires.

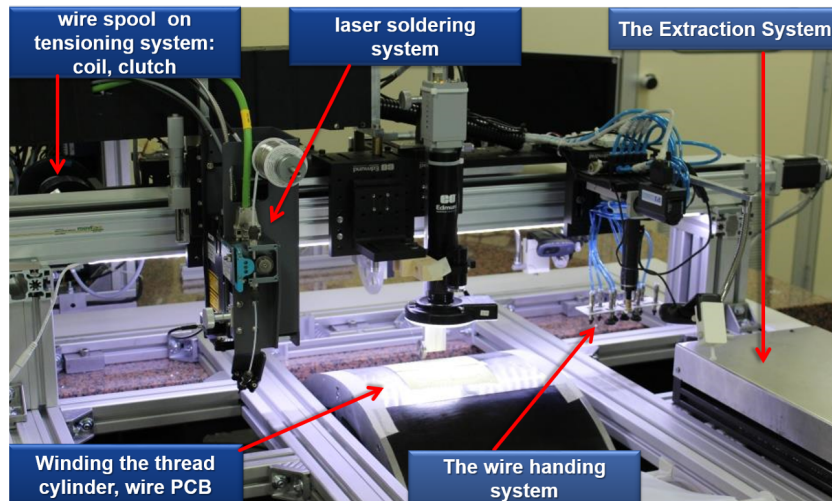


Figure B.9: View of the wiring station with the robotic system.

Appendix C

The μ RWELL technology for the IDEA Muon System at FCC-ee and the TIGER/GEMROC readout system

During the PhD, I also participated in the R&D activities for the development of the Muon System for the IDEA detector, which is being proposed as one of the experiments for the Future Circular Collider (FCC). This work has been synergistic with the activities carried out for DUNE, as it involved the development and commissioning of gaseous detectors, namely μ RWELLS and drift chambers, which, despite the differences, share common physics processes and, in this case, even the same readout system.

In the following, a brief introduction to FCC and its physics case is provided, together with a description of the status of the IDEA detector design, focusing on the muon system, which will be based on the μ RWELL detector technology.

The μ RWELL is a novel gaseous detector technology [90]; I was personally involved in the R&D programme and in several beam tests with the aim of testing prototypes featuring different layouts of the readout plane, and comparing the performance of two electronics: the APV25 and the TIGER ASIC. The different prototypes tested and the results of the analysis are presented at the end of the appendix.

C.1 The Future Circular Collider

With the remarkable discovery of the Higgs boson, the Standard Model appears to be a well-established theory, with its predictions constrained primarily by uncertainties in theoretical calculations and input parameters. However, numerous experimental observations undeniably point to the existence of new phenomena in the universe. These include non-baryonic dark matter, the observed cosmological baryon-antibaryon asymmetry, and the presence of finite yet exceedingly small neutrino masses. These phenomena collectively indicate the presence of physics beyond the Standard Model.

The remarkable agreement between the predicted and observed masses of particles such as the W boson, top quark, and Higgs boson, coupled with the absence of significant deviations in collider experiments thus far, suggests that the energy scale of new physics or the associated coupling strengths may be exceptionally high or weak, respectively. Any new hint or discovery, whether it manifests as the observation of a new particle, an entirely unobserved phenomenon, or even a subtle deviation from Standard Model predictions, would represent a monumental breakthrough in our understanding of

fundamental physics. The next-generation accelerator project must possess the capacity for the most comprehensive and far-reaching research endeavours: the Future Circular Collider is positioned to fulfil this role.

In particular, FCC-ee will probe the properties of the Z and W bosons, the Higgs boson, and the top quark with unprecedented precision through e^+e^- collisions. This precision will enable investigations into physics at much higher energy scales or with much smaller coupling strengths.

The accelerator design of the FCC-ee achieves high luminosity at multiple collision energies, ranging from 88 to 365 GeV. To enable $t\bar{t}$ operation at such collision energies, the cost-effective circumference of the accelerator is approximately 91 km. The FCC-ee employs a double-ring collider configuration with two beam lines, one for electrons and the other for positrons, which intersect at four interaction points (IPs), characterised by a horizontal crossing angle of 30 mrad. Beam current varies significantly across the energy spectrum, and adjustments are primarily made by modifying the number of bunches.

In contrast to conventional electron storage rings, where equilibrium beam parameters are predominantly influenced by synchrotron radiation, the FCC-ee experiences additional effects due to *beamstrahlung*, a particular form of synchrotron radiation that arises as a result of the opposing bunch's electromagnetic field.

A top-up injection scheme is implemented to maintain the stored beam current and luminosity at their peak levels throughout the physics run. Without the top-up injection, the integrated luminosity would be significantly lower, by over an order of magnitude. The installation of a booster synchrotron within the collider tunnel is therefore essential.

For the FCC-ee, the pre-injector complex comprises two separate linacs for electrons and positrons, up to a beam energy of 2.86 GeV. The particles are then injected into the damping ring for emittance reduction. A high-energy linac boosts the beam energy from 2.86 GeV up to 20 GeV in order to inject the beams directly into the booster ring. The baseline for the positron source is based on a conventional scheme using electrons from the linac impinging on a tungsten target. This approach allows all linacs to operate at 100 Hz with 4 bunches per pulse.

The FCC-ee achieves maximum peak and integrated luminosities at four main working points, corresponding to the Z pole (91 GeV), the WW threshold (161 GeV), the Higgs production peak (240 GeV) and the $t\bar{t}$ threshold (340-365 GeV). Achieving full bunch filling for Z boson running poses the most demanding requirements in terms of the number of bunches, bunch intensity, and injector flux. This entails a linac bunch intensity of 2×10^{10} particles for both electron and positron species. Alternative injector scenarios may involve a longer 20 GeV linac without a pre-booster or a recirculating superconducting linac.

Integrated luminosity targets amount to the production of 6×10^{12} Z bosons (as required by the search for sterile right-handed neutrinos), more than 2×10^8 WW pairs, in excess of 2×10^6 Higgs bosons, and 2×10^6 $t\bar{t}$ pairs. All these objectives can be achieved during a 15-year period, which includes a one-year shutdown necessary to reconfigure the machine and instal additional RF systems for the highest-energy $t\bar{t}$ running.

Circular colliders offer the advantage of providing collisions at multiple interaction points. Consequently, various experimental collaborations are tasked with the study of an optimisation of diverse detector designs. These detectors must, on one hand, align their expected performance with the requirements of the physics programme and statistical precision offered by the FCC-ee. This encompasses aspects such as heavy-flavor tagging, particle identification, tracking, particle-flow reconstruction, as well as lepton, jet, missing energy, and momentum and angular resolution. On the other hand, these detectors must adhere to constraints dictated by machine performance and interaction region layout. These constraints include minimising the impact of beam-induced background, accommodating interaction rates, ensuring event size and readout speed are suitable, and limiting the detector solenoid magnetic field to 2 T to prevent substantial effects on luminosity. Precise measurements of the significant centre-of-mass energy spread (90 MeV at the Z pole, 500 MeV at the highest FCC-ee energies) necessitate an angular resolution better than $100 \mu\text{rad}$ for muons, and the luminometer must be situated

just 1 m from the interaction point while maintaining a luminosity precision better than 10^{-4} , among other requirements.

Two general-purpose detector concepts have been studied and optimised for the FCC-ee: CLD and IDEA. The CLIC-like Detector (CLD) [117] is a well-established option based on the detector design developed for CLIC, featuring a silicon tracker and a 3D-imaging, highly-granular calorimeter, enveloped by a conventional superconducting solenoid coil. IDEA [118] in turn is an innovative and potentially more cost-effective design, incorporating a short-drift wire chamber and a dual-readout calorimeter, interspersed with a thin, lightweight superconducting solenoid coil. This choice allows for an exploration of various technology and cost considerations. In the following section, a more detailed description of the IDEA detector can be found.

C.2 The IDEA detector concept

In the following, the concept of an Innovative Detector for E^+e^- Accelerator (IDEA) is described. It attempts to provide optimal performance in most of the accessible physics while dealing with the constraints required by the accelerator. The physics drivers influencing the detector design are presented, along with an overview of the detector and its components

C.2.1 Physics requirements

The physics accessible at FCC-ee comprises a detailed measurement of the Higgs boson properties, high precision electroweak and heavy-flavor studies at the Z boson centre of mass energy, precision measurements of the W boson and top quark parameters, and searches for new physics. The main objective of the tracking systems is to provide good momentum, angle, and impact parameter resolution for tracks with p_t below 100 GeV/c. At higher momenta, the requirement on the momentum resolution is driven mostly by the measurement of the Higgs recoil mass in HZ events with $Z \rightarrow \mu^+\mu^-$. The precision of this measurement depends on the centre of mass energy spread due to beamstrahlung, which is $\sim 0.1\%$ at FCC-ee, and the experimental error on the momentum measurement of the two muons from the decay of the Z boson.

A track momentum resolution, $\sigma_{p_t}/p_t \sim 10^{-5}$ is required to preserve the precision driven by the beam energy spread. Given the constraints on the magnetic field of the detector solenoid, this leads to a rather large tracking volume.

Heavy-flavor physics and flavor tagging profit from high accuracy in secondary vertex measurements, implying the need for powerful vertex detectors with hit resolutions at the few micron level. Typical momenta are generally lower for these types of physics, necessitating low mass tracking detectors.

Particle identification, in particular separation of pions from kaons up to a few tens of GeV, is also important to enhance the signal over background for many specific rare processes and to allow some level of strange flavor tagging. Jet energy and angular resolution are of key importance to exploit final states involving decays to high energy quarks. Typical examples are Z, W or Higgs boson decays to two jets or hadronic decays of top quarks. A useful figure of merit is the separation of Z from W decays using the di-jet invariant mass, leading to a required jet energy resolution $\sim 40\%/\sqrt{E}$. A new generation of calorimeters, based on particle flow and/or dual readout, is needed to achieve such precisions. Extreme electromagnetic resolutions, attainable only with crystals, can provide high quality neutral pion identification that is important for the measurement of many heavy-flavor quark and tau final states. Resolved neutral pions also play a role in improving the jet resolution. A good photon energy resolution is relevant in improving the signal-to-noise ratio of the process $H \rightarrow \gamma\gamma$ and in correcting the electron track energy for bremsstrahlung radiation.

C.2.2 Detector components

The IDEA detector is based on a sophisticated tracker and a crystal Dual-Readout (DR) electromagnetic calorimeter within a superconducting solenoid magnet, followed by a DR fibre calorimeter, and completed by a muon detection system placed within the iron yoke that closes the magnetic field. Figure C.1 provides an overview of the layout of the IDEA detector. In the following, all the components of the detector are presented.

Silicon Tracker

The innermost detector, surrounding the beam pipe at radii between 13.7 and 35.6 mm, is a silicon pixel detector. Its active elements are based on $50\,\mu\text{m}$ thick monolithic active pixel sensors (MAPS). Two alternative layouts are being explored: the first uses a traditional approach, where modules are mounted on a carbon fibre support, with overlapping structures to allow full coverage and alignment; the second layout is based on curved detectors, using a concept similar to the ALICE ITS upgrade [119], which is able to achieve an excellent ($\sim 5\,\mu\text{m}$) resolution, high efficiency at low power, and a low dark-noise rate.

An outer vertex detector is also present just outside of the drift chamber tracker, between 130 and 315 mm. It is composed of a barrel section and forward discs, and provides precise and efficient tracking of charged particles before the Crystal ECAL.

Drift Chamber

The IDEA drift chamber is a single-volume, cylindrical wire chamber that is co-axial with the 2 T solenoidal field. It extends from an inner radius of 0.35 m to an outer radius of 2 m, with a length of 4 m and consists of 112 co-axial layers at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, as shown in Figure C.2. The drift chamber is designed to provide good tracking, high-precision momentum measurement, and excellent particle identification by adopting the “cluster counting” technique. The main peculiarity of this chamber is its high transparency in terms of radiation lengths, obtained as a result of the novel approach adopted for the wiring and assembly procedures [120]. The total amount of material in the radial direction towards the barrel calorimeter is of the order of $1.6\% X_0$, whereas, in the forward direction, it is about $5.0\% X_0$, 75% of which is in the end plates instrumented with the front-end electronics.

The chamber design inherits some aspects of drift chambers previously built and operated, such as those from the KLOE experiment and the MEG2 experiment. The detector features approximately-square cells, as shown in Figure C.3, with the size varying between 12.0 and 14.5 mm, for a total of 56,448 drift cells. The chamber is operated with a very light gas mixture, 90% He – 10% isobutane (C_4H_{10}), corresponding to a maximum drift of ~ 400 ns.

A drift distance resolution of $100\,\mu\text{m}$ has been obtained in a MEG2 drift chamber prototype [114] (7 mm cell size), with a very similar electrostatic configuration and gas mixture. A better resolution is expected for the IDEA drift chamber as a result of the longer drift distances and the employment of cluster timing techniques.

A layer of silicon micro-strip detectors surrounds the outside of the drift chamber, providing an additional accurate spatial point as well as precisely defining the tracker acceptance.

Crystal Calorimeter

The IDEA calorimetry system is composed by a homogeneous electromagnetic crystal calorimeter, followed by a fibre-sampling calorimeter. Both detectors feature a Dual-Readout technology enabling them to resolve, in the 2-jet final states, events generated by W bosons instead of Z bosons or Higgs bosons.

From the ratio between the scintillation and Cherenkov signals, it is possible to reconstruct the electromagnetic fraction of each shower, event by event, and cancel the effects of its fluctuation over the energy shower measurement error.

The crystal calorimeter is located between the tracking system and the solenoid, with a radial envelope of 2150-2500 mm, and is divided into a central barrel section and two end-caps. Figure C.4 shows a cutout view of the calorimeter.

Its section is designed to achieve an electromagnetic energy resolution better than $3\%/\sqrt{E} \oplus 1\%$ and includes the simultaneous readout of scintillation and Cherenkov photons which, when integrated with the DR fibre hadronic calorimeter section, can provide a hadronic energy resolution of about $30\%/\sqrt{E} \oplus 3\%$ [121, 122].

Each crystal tower has nominal front face dimensions of $10 \times 10 \text{ mm}^2$ and is composed of two longitudinal segments of $6 X_0$ (front, E1) and $16 X_0$ (rear, E2) for a total depth of $22 X_0$. The two-layer segmentation represents a tool for particle identification based on the longitudinal energy deposit pattern, with the front segment measuring the e.m. shower before it reaches its maximum lateral development, thus effectively reducing the Molière radius for the separation of neighbouring e.m. showers.

The light is read out from the crystals using SiPMs located on both faces of the front crystal segment, and of the rear segment, where the respective front-end boards and cooling system will also be located. One SiPM with an active area of about $6 \times 6 \text{ mm}^2$ is glued to the front crystal and two SiPMs of the same size are glued to the rear crystal. The protective window of one of the two rear SiPMs is replaced with a thin optical filter, with a thickness of 0.1 mm, designed to filter out photons with a wavelength around the scintillation maximum while letting pass those originating from Cherenkov radiation. In this way, a dual readout of the scintillation light and Cherenkov radiation is performed on the rear crystal, which is then used in energy corrections for early showering hadrons.

The baseline crystal choice consists of lead tungstate crystals, PbWO_4 , because of their excellent calorimetric properties (small Molière radius of 2.0 cm and short radiation length of 0.89 cm); however, other crystal candidates are under study, namely BGO and BSO crystals, which, given their higher light output, slower decay time, and different emission peak of scintillation light, can offer a complementary approach for the development of such a calorimeter.

Hadronic Calorimeter

For what concern the hadronic section for the IDEA calorimeter, the proposal is based on a fibre-sampling dual-readout calorimeter, consisting of alternating rows of scintillating and Cherenkov fibres inserted in a metal absorber. Both iron and brass tubes are considered for the absorber material, with iron having the advantage of providing most flux return of the magnetic field and therefore being the current baseline. The capillary-tube technology has been pioneered in recent years by a consortium of European Institutes led by INFN. The tubes are stacked together in a hexagonal pattern to form towers, which are trapezoids pointing toward the interaction point.

The fibres typically had a 1 mm diameter. For Cherenkov signal detection, the fibre cores were made of fused silica or PolyMethyl MethAcrylate (PMMA), with a fluorinated polymer single cladding. Scintillating fibres, on the other hand, featured a polystyrene core with PMMA single or double cladding, emitting in the blue region (wavelength 400–450 nm, depending on the manufacturer). The choice of the absorber material significantly influences the production rate of secondary particles in hadronic showers, impacting signal generation and defining transverse and longitudinal containment dimensions. Additionally, the absorber must provide adequate structural integrity. Currently, two techniques are under investigation, both of which are promising for full-scale experiment construction. The first, developed under the INFN HiDRa R&D project, employs capillary tubes. The second, advanced by a consortium of Korean institutes, utilises finned plates produced by skiving, where fibres and copper rods are embedded to form a granular structure. At present, the former looks able to provide better mechanical precision, while the latter provides a simpler and faster construction technique.

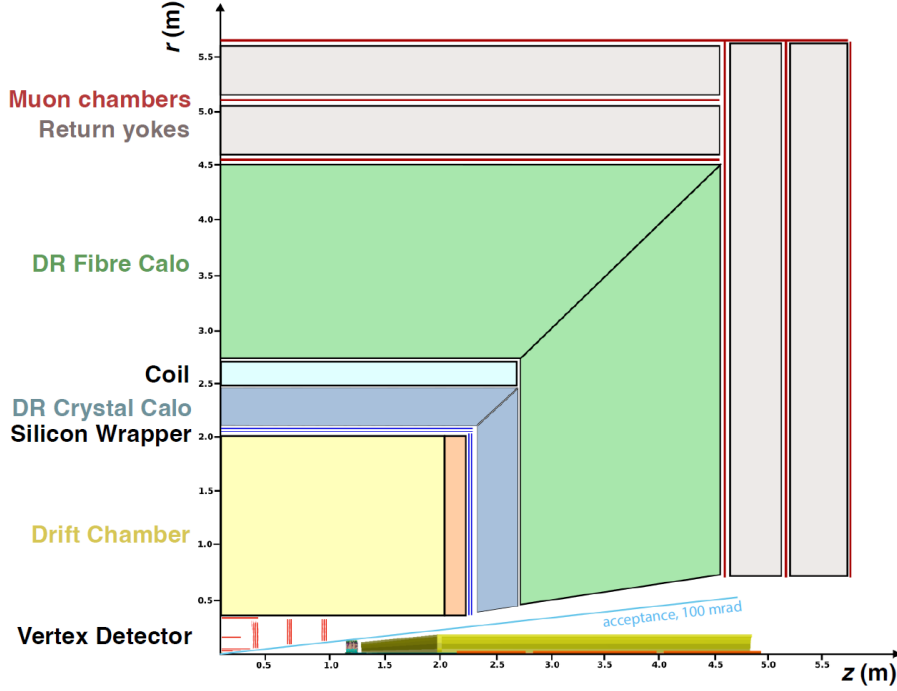


Figure C.1: Layout of the IDEA detector.

The light produced inside the calorimeter is transported via optical fibres to light sensors located on the back side of the absorber material, simplifying the services required for the operation of the whole detector. The use of SiPMs also offers the possibility of sampling the lateral shower profile with high granularity, improving particle ID performance and the identification of complex final states containing non-isolated objects (each SiPM is coupled to a single fibre). R&D is ongoing in order to exploit the time profile of developing showers as additional information, providing an effective 3D segmentation.

C.2.3 The Muon System of the IDEA detector

The IDEA muon detector acts as an high-efficiency muon tagger and a high-resolution tracker for charged particles, for the search for long-lived particles decaying outside the tracker volume. It is also responsible for catching the hadronic shower tails not contained in the hadronic calorimeter.

The muon system plays a fundamental role in the search rare flavor-changing processes, which are sensitive to potential new physics. The abundant production of beauty and charm hadrons at Z_0 pole offers outstanding opportunities in flavor physics that generally exceed those available at Belle II and are complementary or more sensitive to the heavy-flavor programme of the LHC. A good mass resolution and muon identification are crucial for separating close-in-mass states like those resulting from $B^0 \rightarrow \mu^+ \mu^-$ (5366 MeV/c) and $B_s^0 \rightarrow \mu^+ \mu^-$ (5279 MeV/c) decays (see Figure C.5), which are a powerful test of minimal flavor violation.

A precise reconstruction of displaced decays through high-resolution tracking can provide clear signatures of Long-Lived Particles, allowing for the search of Heavy Neutral Leptons [123].

The performance requirements for the muon system are still at a preliminary stage; however, they can be summarised as follows:

- efficiency $> 98\%$ for muon identification;

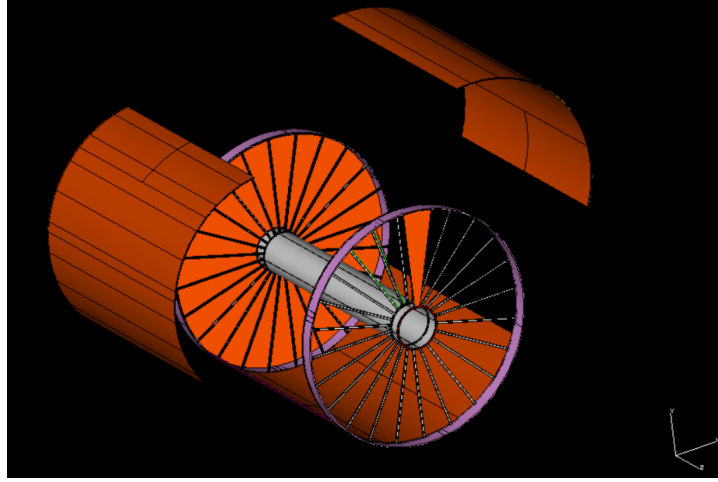


Figure C.2: Schematic drawing of the drift chamber, showing the mechanical structure. The endplates are made of 48 spokes (24 per end-cap) forming 24 azimuthal sectors.

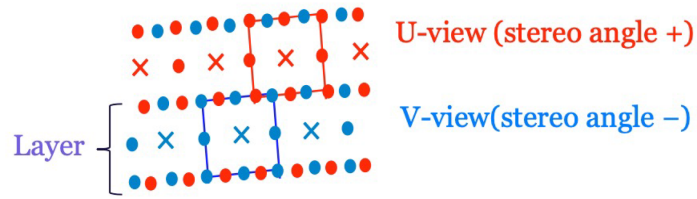


Figure C.3: Cell layout in the middle of the drift chamber ($z=0$). Field wires are indicated with full dots, blue or red depending on the sign of the stereo angle, while sense wires are indicated with the symbol “x”. The cells are approximately square, and the field to sense wires ratio is 5:1.

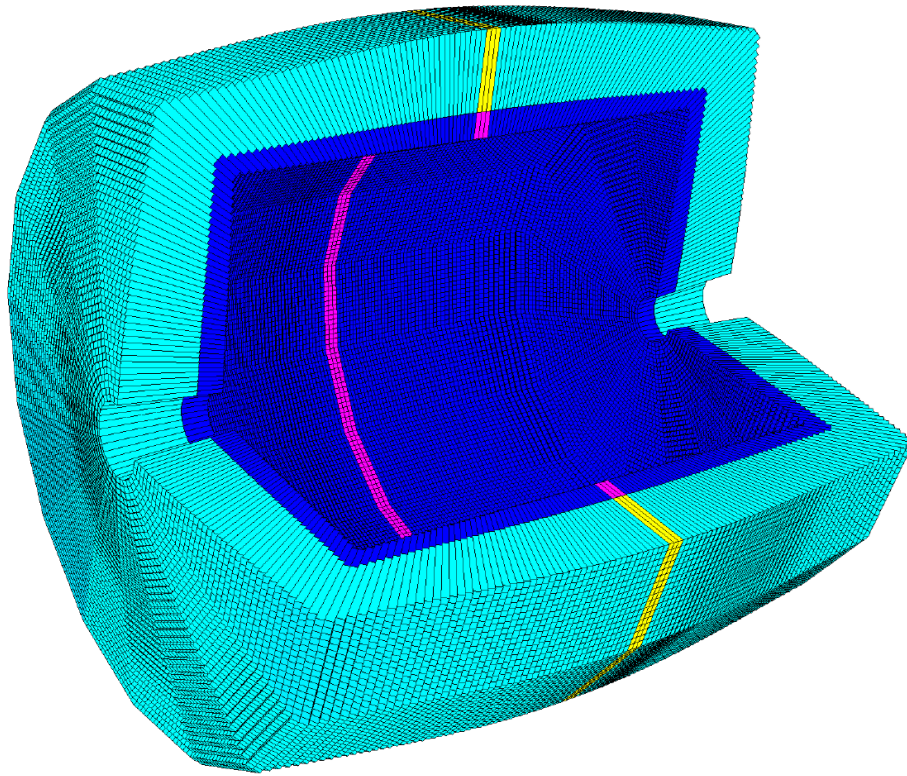


Figure C.4: 3D view of the DR crystal calorimeter showing the front (dark blue) and rear (light blue) crystal segments. Three non-projective spacer rings, used to mitigate projective tracks by displacing either half of the detector in z , are shown in purple (front segments) and yellow (rear segments).

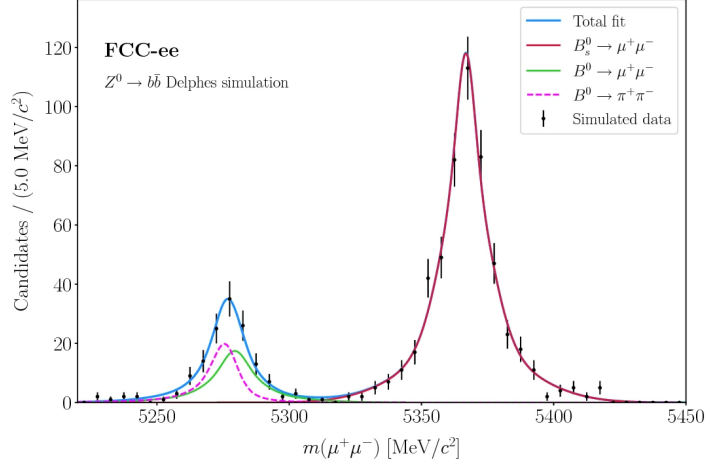


Figure C.5: Reconstructed invariant mass of $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^-$ signals for $5 \times 10^{12} Z_0$ decays. Also shown is the background contribution from misidentified $B^0 \rightarrow \pi^+ \pi^-$ events [125].

- spatial resolution of the order of $100 \mu\text{m}$ for a standalone momentum measurement of Long-Lived Particles;
- rate capability $< 1 \text{ kHz}/\text{cm}^2$.

The design of the muon system must also take into account the necessity of adopting mass production for the detector elements to preserve the cost-effectiveness of the project.

The detector system will feature a central cylindrical barrel region closed at both ends by two end-caps to ensure hermeticity. This apparatus will consist of at least three layers of detectors covering the barrel and end-cap regions, housed within the iron yoke that encloses the solenoidal magnetic field. Each layer will consist of a large mosaic of μRWELL detectors [124], covering around 1500 m^2 . This technology is described in detail in the following Section.

In order to profit from the industrial production capabilities of this technology, a modular design has been adopted. The basic μRWELL "tile" will have an active area of $50 \times 50 \text{ cm}^2$ with a two dimensional strip readout. The strip pitch of approximately $0.4\text{-}1.5 \text{ mm}$ provides a typical spatial resolution in the range of $100\text{-}500 \mu\text{m}$. The choice of the detector design (tile size, strip pitch, and strip width) represents a compromise among the largest μRWELL detector that can be industrially mass-produced, the maximum input detector capacitance tolerable by the Front-End Electronics, the spatial resolution required by the experiment, and the costs of electronics for the readout channels.

Since the μRWELL technology has not yet been used to realise a full detector system, a rigorous R&D programme will be undertaken in the coming years to address integration issues.

C.3 The μRWELL Technology

The μRWELL is a novel Micro-Pattern Gas Detector (MPGD) technology: a spark-protected single-stage amplification detector. It consists of two main elements, shown in Figure C.6: the cathode and the μRWELL Printed Circuit Board (PCB). The cathode is a simple PCB with a thin copper layer on one side. The μRWELL PCB consists of a multi-layer circuit realised using standard photo-lithography techniques. It is composed of a WELL-patterned single copper-clad polyimide foil acting as the detector amplification element; a resistive layer, realised with a Diamond-Like-Carbon (DLC) film sputtered onto

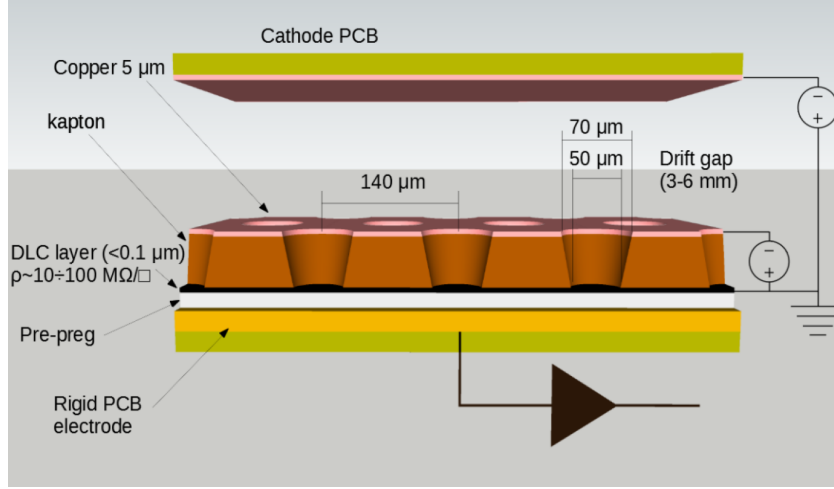


Figure C.6: Scheme of a μ RWELL, showing the layout of the PCB, the WELL pattern, and where the potential differences are applied. The drift gap is ~ 6 mm.

the bottom side of the polyimide foil, and a standard PCB for readout purposes, segmented into strip or pad electrodes.

When the voltage is applied between the copper layer and the DLC, the WELL acts as a multiplication channel for the ionisation produced in the drift gas gap, as shown in Figure C.7. The high resistivity of the DLC decreases the discharge probability, allowing to reach gains of the order of 10^4 , and improving detector performance thanks to the charge dispersion effect [126]. The spark suppression mechanism relies on a localised voltage drop caused by the streamer-induced current in the resistive layer, quenching the multiplication processes. This allows the detector to operate at high gains with a single amplification stage, without significantly affecting its capability to be efficiently operated in high particle fluxes [127]. With this technology, an efficiency of $\sim 98\%$ is achievable, with a rate capability up to 10 MHz/cm^2 and a spatial resolution of the order of $50 \mu\text{m}$ [128, 129].

C.4 R&D Programme on μ RWELL Detectors

Since the μ RWELL is proposed for the IDEA muon system, one of the main challenges is to provide a suitable space resolution below $400 \mu\text{m}$, while minimising the number of FEE channels to contain the total cost.

The R&D on μ RWELL aims to test different designs of the detector readout in order to optimise its performance, enhancing at the same time stability under high irradiation and simplifying the construction procedures for an easy technology transfer to industry. Another key aspect of the R&D programme will be the design and development of a dedicated FEE system based on a custom-made ASIC. R&D is performed in synergy with Working Package 1 (WP1) of the Detector R&D Collaboration for Gaseous Detectors (DRD1).

The R&D programme has initially focused on the optimisation of the DLC resistivity and strip pitch in μ RWELL with strip readout (1-D μ RWELL), while a second phase concerned the technology for bidimensional readout. The results of the tests performed on 1-D and 2-D detector prototypes are described as follows.

In the coming years, the μ RWELL R&D programme will focus on the study and design of the 2-D readout to achieve the desired stability and performance, along with the study of the integration of the

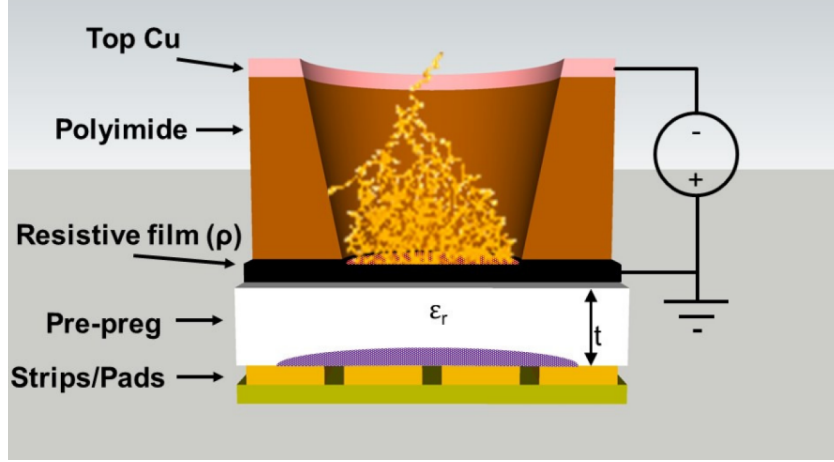


Figure C.7: Principle of operation of the μ RWELL.

readout electronics and the research for the industrialisation of the detector mass production.

C.4.1 Resistivity Scan

For the DLC optimisation, a set of 1-D detectors with different resistivity values, ranging from 10 to $80 \text{ M}\Omega/\square$, and a fixed strip pitch of $400 \mu\text{m}$ were tested in 2021.

The measurement aimed to optimise the number of channels by increasing signal induction through charge dispersion [130, 131], lowering the DLC resistivity. However, it is important not to reduce the resistivity too much, as otherwise the discharges will no longer be properly quenched, compromising the DLC protection. The $10\text{--}80 \text{ M}\Omega/\square$ range was chosen because operating the detector below 10 is not considered safe.

Figure C.8 represents a schematic view of the setup employed during the beam test at the CERN SPS H4 beamline. The DUTs were manufactured with an active area of $400 \times 50 \text{ mm}^2$ and tested with a gas mixture of $\text{Ar-CO}_2\text{-CF}_4$ 45-15-40. The trackers were GEM with X-Y readout and an active area of $10 \times 10 \text{ cm}^2$. The readout of all the detectors has been performed using the APV25-SRS readout system [132].

The results are summarised in Figures C.9 and C.10: the detector efficiency is plotted as a function of the high voltage for the different detectors under test (DUTs). All of them show a nice efficiency plateau region, around 98%, 100 V wide, and a spatial resolution below $50 \mu\text{m}$, except for the $10 \text{ M}\Omega/\square$ detector. Indeed, the efficiency plateau is reached at higher gain due to the larger charge spread, which, because of the front-end electronics threshold, reduces the signal collected per strip.

C.4.2 Pitch Scan

In 2022, a dedicated set of 1-D detectors was produced with strip pitches of 0.4, 0.8, 1.2, and 1.6 mm, and a fixed DLC resistivity of $40 \text{ M}\Omega/\square$. The goal was again to optimise the number of channels, assessing the performance obtained when the number of channels is reduced by increasing the pitch. The beam test results are described as follows.

Figure C.11 shows how the chambers reach the efficiency plateau at different HV values, as a larger strip pitch results in lower signals collected per strip, implying a higher gain to achieve full detection efficiency.

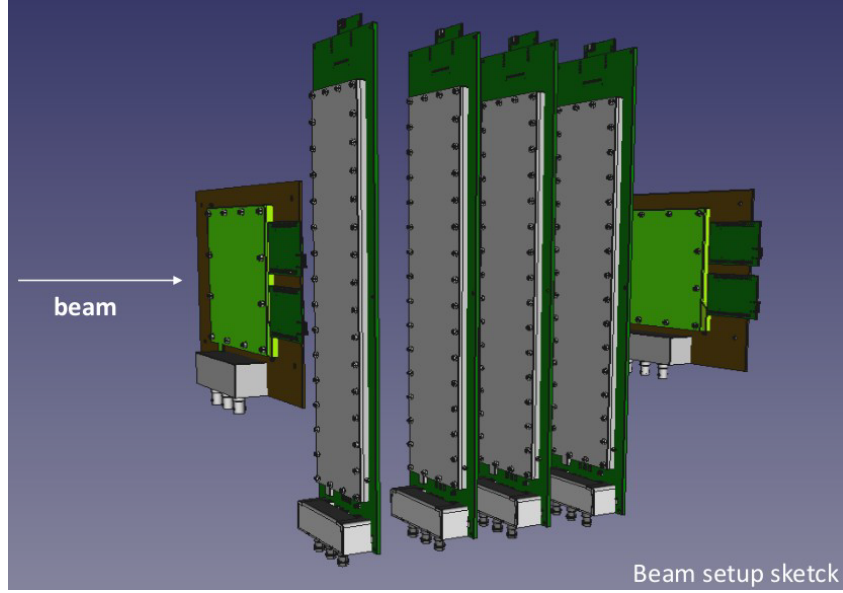


Figure C.8: Beam test setup: the 4 DUTs are positioned in between two trackers with X-Y readout and $10 \times 10 \text{ cm}^2$ active area.

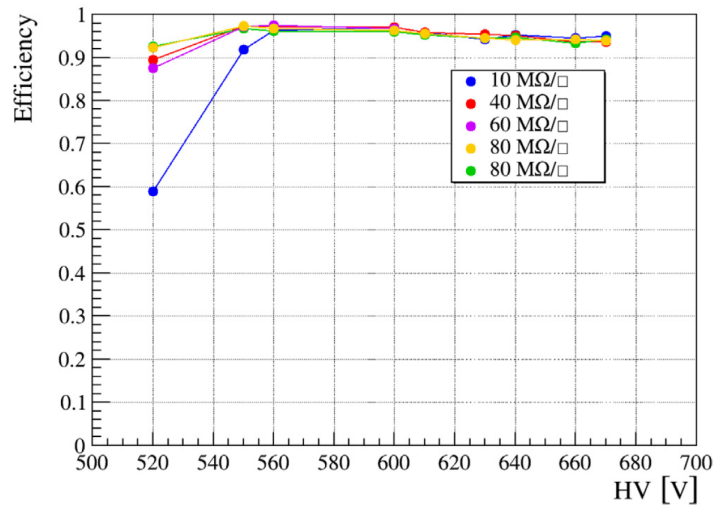


Figure C.9: Efficiency as a function of the HV for different DLC resistivity [133].

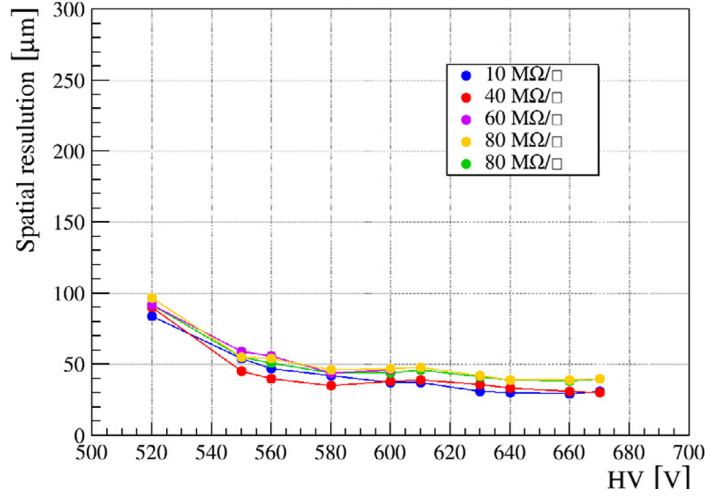


Figure C.10: Spatial resolution as a function of the HV for different DLC resistivity [133].

The cluster size *i.e.* the number of strips above threshold, behaviour with high voltage is shown in Figure C.12. If the multiplicity is one, the readout operates in digital mode, and the resolution is given by $\text{pitch}/\sqrt{12}$; whereas, if the multiplicity is two or higher, the centroid method becomes effective. It can be observed that the centroid becomes efficient immediately for the 0.4 mm pitch, achieving a resolution of about $100\ \mu\text{m}$, whereas the 0.8 mm pitch reaches comparable performance only at higher voltages, and the same applies to the 1.2 mm pitch. The 1.6 mm pitch shows an almost entirely digital behaviour, except at very high gain values, where the performance drops below $400\ \mu\text{m}$. The spatial resolution is shown in Figure C.13.

C.4.3 Bidimensional Readout

So far, the R&D has been carried out with 1-D μRWELL detectors; However, for IDEA a bidimensional readout is required. It must be assessed whether it is possible to optimise the number of channels by reading both coordinates on the same detector or if the two views should remain separated. The possibility of implementing a 2-D readout directly on the detector would certainly have a strong impact on the compactness of the muon system, but stability, performance, and robustness must be ensured.

Moving from 1-D to 2-D layouts may result in an halved collected charge on each view; therefore, it is important to perform this transition without excessively increasing the HV (and therefore the detector gain), because this could push the operation into less stable and less durable regimes.

Several layouts for a 2-D readout of μRWELL detectors have been proposed and are under study to achieve better particle tracking reconstruction. These approaches are sketched in Figure C.14:

- two 1-D (X and Y) detectors positioned back to back and coupled through a common cathode;
- one μRWELL with the top electrode segmented to obtain a second coordinate in addition to the one from the usual readout PCB;
- a 2-D μRWELL based on the Capacitive-Sharing (CS) readout.

The first approach is the safest, but it requires a number of detectors that is doubled, while the number of channels is the same as that used in the following approaches.

The TOP readout approach enables a 2-D readout avoiding the splitting of the charge between X and Y strip layers, as the detector is segmented in such a way that charge induction occurs on two planes

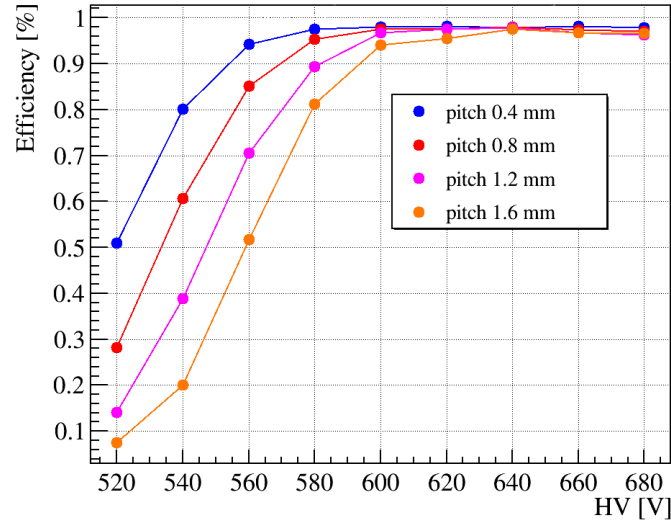


Figure C.11: Efficiency as a function of the HV for different values of the strip pitch.

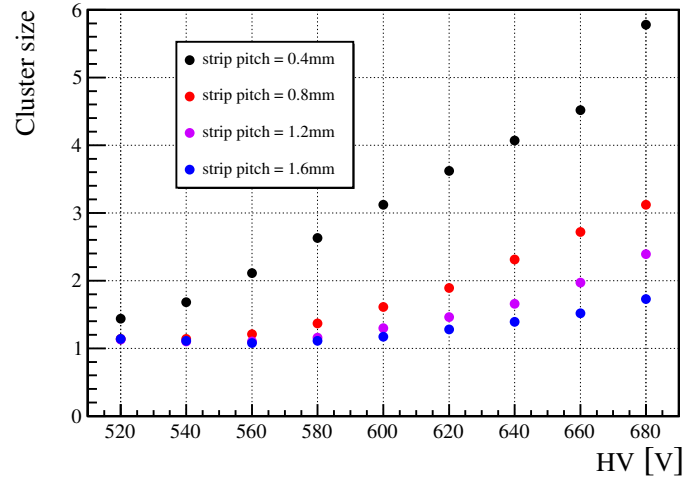


Figure C.12: Cluster size as a function of the HV for different values of the strip pitch.

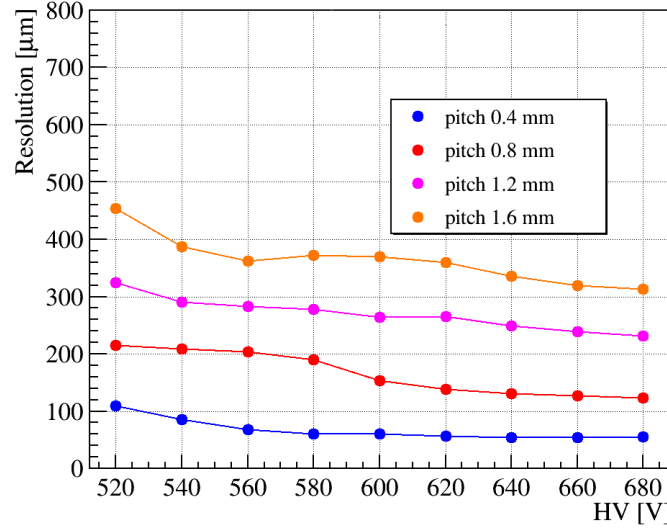


Figure C.13: Spatial resolution as a function of the HV for different values of the strip pitch.

with opposite orientation with respect to the drift direction. This configuration allows the detector to operate at lower high-voltage values compared to the COMPASS-like [134] solution, namely the X-Y strips placed in the PCB readout plane; however, it comes with the drawback that part of the top layer region is effectively lost, since neither amplification nor primary-electron collection takes place in the gaps separating the top strips.

The last method uses a COMPASS-like readout with staggered conductive pads placed between the X and Y strip layers. It exploits the capacitive coupling between different layers of pads or strips, sandwiched between polyimide foils, to simultaneously transfer and spread the signal produced in the amplification stage [135]. The pads increase the size of the induced signal, allowing for a more accurate reconstruction even with larger pitches. The trade-off is a higher input capacitance and a more complex PCB design.

A beam test was performed in 2023 in the H8 test line of the CERN North Area using a muon beam of 140 GeV/c momentum and a set of detectors based on both TOP and Capacitive-Sharing readout. The μ RWELL under test featured an active area of $10 \times 10 \text{ cm}^2$, DLC resistivity of $50 \text{ M}\Omega/\square$, and a strip pitch of 1.2 mm for CS and 0.8 mm for TOP readout. The common cathode layout, with a pair of 1-D μ RWELL stacked back to back, featured instead a strip pitch of 0.76 mm and a $50 \text{ M}\Omega/\square$ resistivity. In both beam tests the APV25 electronics have been adopted.

Figure C.15 presents the efficiency curves of the three proposed 2-D layouts, while Figure C.16 shows the spatial resolution for CS and TOP layouts. The Capacitive-Sharing configuration achieves an efficiency of about 98%. Compared to the other layouts, the CS configuration shows a plateau shifted by approximately 100 V, which is partially attributed to charge sharing between the two views in the PCB below the amplification stage. Additionally, it may also be influenced by the incomplete charge transfer to the readout, with some loss of charge within the various layers of the CS layout. The spatial resolution improves with HV, achieving values of $\sim 150 \mu\text{m}$ at 600 V.

The TOP readout detectors present an efficiency at the plateau of around 70%, caused by the dead zone induced on the active area by the readout strip pattern placed directly on the top electrode. The resolution in the X-coordinate is almost digital, compatible with that resulting from a null charge spread ($\text{pitch}/\sqrt{12}$). The Y-coordinate resolution changes as a function of the voltage applied due to the DLC spread, reaching values below $200 \mu\text{m}$ for voltages above 550 V.

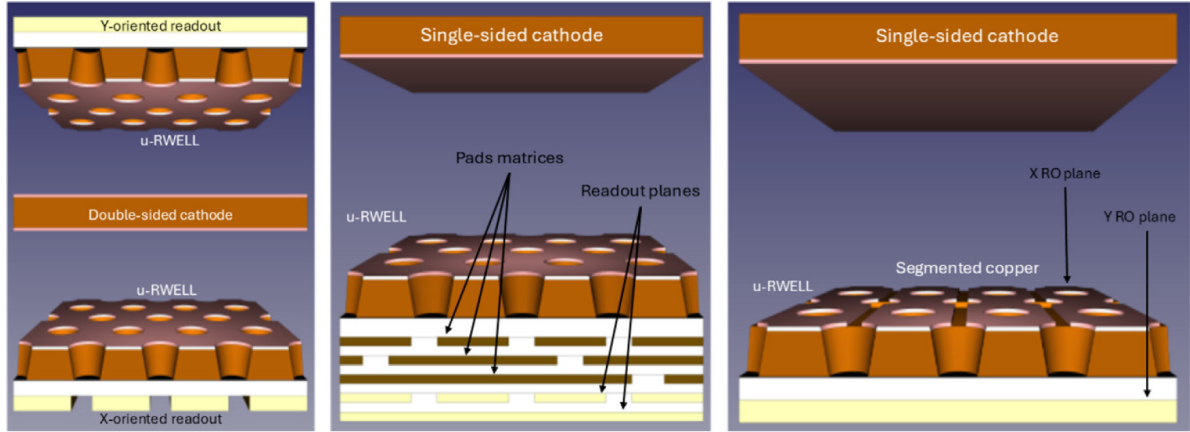


Figure C.14: Bidimensional μ RWELL: the common cathode layout (*left*), the capacitive-sharing layout (*centre*), and the top-segmented readout (*right*).

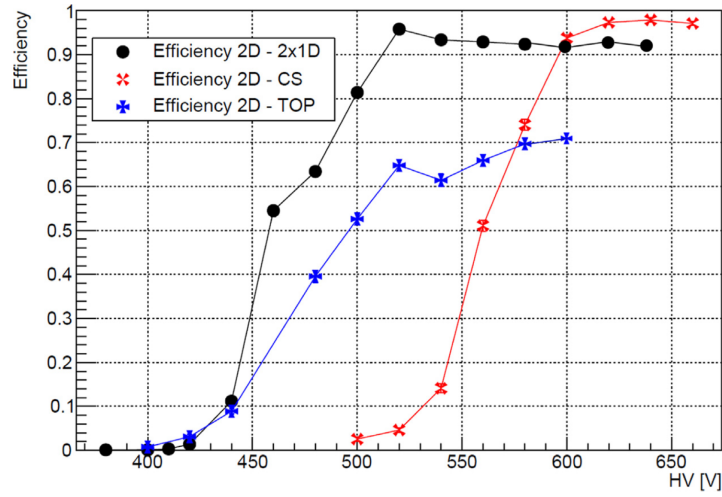


Figure C.15: Efficiency as a function of the HV for different 2-D μ RWELL layouts [136].

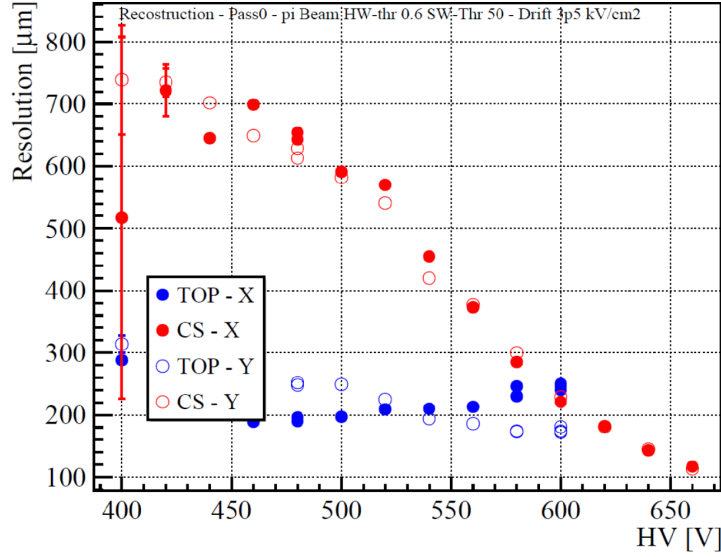


Figure C.16: Spatial resolution as a function of the HV for CS (*red*) and TOP (*blue*) layouts [137].

C.4.4 TIGER-GEMROC Beam Test

A third phase of the R&D programme focused on electronics integration. As already mentioned, all the studies presented so far have been performed using the APV25-SRS readout system. One of the goals of the R&D is to use a new readout chain, namely the TIGER-GEMROC system, which has been described in Section 5.2 of this thesis.

APV25 is the first electronics used for μRWELL readout, because of its well known and reliable behaviour: it is a 128 channel chip that provides an acquisition rate up to 5 kHz, a time resolution better than 10 ns, and a linear charge measurement up to ~ 40 fC thanks to 27 waveform samplings. The readout is based on the Scalable Readout System (SRS) developed at CERN by the RD51 collaboration. The choice of TIGER-GEMROC system as an alternative readout was guided by its superior performance, thanks to a dual-branch shaper optimised for time and charge measurements. It achieves a TDC resolution better than 50 ps RMS and linearity up to ~ 50 fC, and an acquisition rate of 60 kHz per channel.

In July 2024, a beam test was conducted to evaluate the performance of the μRWELL detectors with the TIGER-GEMROC readout chain. During the test performed at the SPS H4 beamline (muon beam of 140 GeV/c), the previously mentioned 1-D detectors with different strip pitch values (0.4, 1.2, 1.6 mm) were tested with the TIGER-GEMROC system. A gas mixture of Ar-CO₂-CF₄ 45-15-40 was used.

As shown in Figures C.17 and C.18, the μRWELL detectors exhibit good performance, achieving an efficiency of about 95% at the plateau and a spatial resolution better than 100 μm for the 0.4 mm strip pitch DUT. The results obtained with the TIGER-GEMROC readout chain are in good agreement with those from the APV25, with only a small shift in the operating HV, attributed to the different threshold settings of the two readout systems.

C.5 Noise Studies

The TIGER ASIC was developed for the cylindrical GEMs of the BESIII experiment. For this reason, its front-end is not optimised for μRWELL detectors. The main issue encountered in the integration of

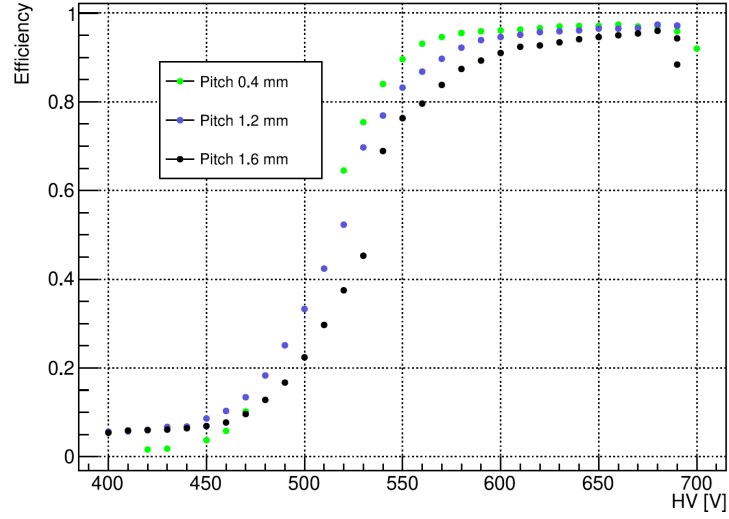


Figure C.17: Efficiency as a function of the HV for different 2-D μ RWELL layouts [136].

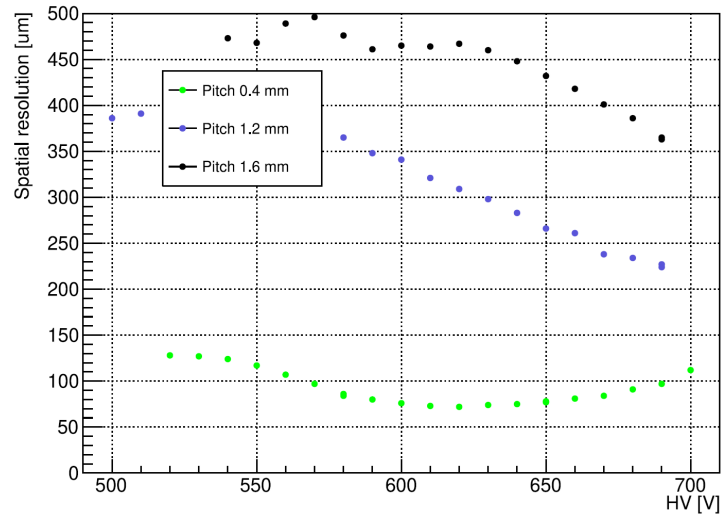


Figure C.18: Spatial resolution as a function of the HV for CS (*red*) and TOP (*blue*) layouts [136].

TIGER readout with these detectors is represented by the noise which, nominally, should be below 2 fC ($< 1500e^-$ ENC on the E-branch); however, as we will see, the amplitude observed when the ASIC is coupled to a μ RWELL exceeds 4 fC, motivating the need for a dedicated campaign for the optimisation of the front-end noise.

The 2024 beam test provided good physics results, even though in some of the Front-End Boards (FEBs) the noise level was high, around 8 fC, so that the higher noise and higher threshold have a significant impact on the efficiency and resolution of the detector.

In 2025, it was decided to conduct a systematic study of the ground configuration and the integration of the electronics with the detector to achieve a much deeper understanding of the setup. The tests were conducted in the laboratories of the INFN Section of Ferrara during March and April 2025. The noise level in the front-end was studied using:

- the noise scan tool provided by the GUFi software (see Section 5.2.1);
- the charge distribution of each channel obtained with random trigger acquisitions.

This last tool allows to compute the effective threshold for every FEB channel by fitting the charge distribution of each channel with the function

$$f(x) = p_0 + \frac{p_1}{1 + \exp\left(-\frac{x-p_2}{p_3}\right)} \quad (\text{C.1})$$

where the parameter p_2 represents the effective threshold, as shown in Figure C.19. The distribution of the values obtained in this manner can be fitted with a Gaussian function to provide an average value for the effective threshold of a FEB, which is related to the noise on the front-end (see Figure C.20).

The laboratory tests were conducted on a single TIGER FEB connected to a 1-D μ RWELL with a strip pitch of 0.4 mm, shown in Figure C.21. The connection between the detector and the Front-End Board is provided by a Panasonic connector that does not have any ground pin. To overcome this issue, a copper strip is soldered between the FEB and the detector ground plane, as shown in the picture on the right. Low Voltage (LV) and data are transmitted to and from the FEB through two separate shielded cables. A transition board, called DLVPC (Data and Low Voltage Patch Card), is inserted between the FEB and the GEMROC module. The transition board is a leftover from the BESIII readout system and, although it is not functionally required for the configuration under study, its removal is not feasible within the current setup constraints. The scheme of the connections is reported in Figure C.22. A Caen SY5527LC mainframe was used, hosting one A2519 board (32 channels, max 5 A/channel and 50 W/channel) to power the GEMROC modules and one A1515 board that provides the high voltage to the μ RWELL.

During the test campaign in Ferrara, the noise was characterised starting from a configuration with the FEB and the detector only, with no SHV cables connected; then in a configuration with the SHV cables connected to the μ RWELL, and finally with the high voltage switched on. For each configuration, several different grounding connections were studied. The ground of the mainframe was chosen as the system's main ground.

The noise measurements provided a much higher comprehension of the setup, achieving a noise reduction from 8 to 4 fC. The most important results are summarised in the following statements (in order of impact on noise reduction):

1. an optimal connection between the FEB and the detector ground plane is of capital importance. It is preferable to have a single, large copper strip soldered at both ends. Copper tape does not offer a stable connection over long periods;
2. the shields of the HV cables must be connected to the detector ground plane;
3. the shields of the data and LV cables must be connected to ground, possibly on the GEMROC module;

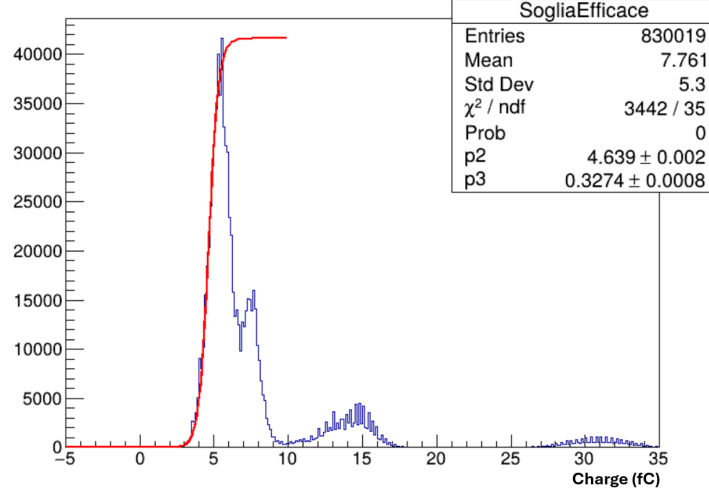


Figure C.19: Charge distribution for one FEB channel. In red is reported the fit used to extract the effective threshold.

4. a Faraday cage built around the FEB, and a second one around the DLVPC, both connected to the main ground, are useful for reducing the noise;
5. the analogue and digital ground of the system should be connected together on the GEMROC, and not on the DLVPC.

The outcome of the studies provides important suggestions for the improvement of the experimental setup. In particular, at the beginning of 2026, the production of an upgraded version of the Front-End Board mounting TIGER is foreseen, with the aim of reducing the noise. It will feature a new design with better grounding connections, a simpler design, and a more stable and robust data connector.

C.5.1 TIGER Front-End Simulations

In the context of the noise studies on the TIGER front-end, the simulations of signal processing with the ASIC have proven to be particularly useful. Their aim is to extend the optimisation of the μ RWELL detector and its integration with TIGER electronics.

A PARAmetrized SIMulation (PARSIFAL) library is developed to simulate the detector response and study the performance with different detector configurations and electronics [138, 139]. The library contains the parametrisation, extracted from GARFIELD++, of key physics processes such as primary and secondary ionisation, the drift and diffusion of electrons and ions, and the signal generation on the readout plane. The behaviour of the resistive layer is modelled according to charge dispersion studies from the literature [131].

PARSIFAL allows for the investigation of several features of μ RWELL detectors, such as the strip multiplicity with different DLC parameters, the charge collected, and the number of strips above threshold (cluster size) with different detector gain settings, as well as the spatial performance of the charge centroid algorithm. Furthermore, it is possible to simulate the response of different front-end electronics to signals generated in the detector. In particular, the APV25 and TIGER electronics have been simulated.

I have been directly involved in the TIGER front-end simulations, reproducing the response of the time and energy branches (T-branch and E-branch, respectively) to injected μ RWELL current signals

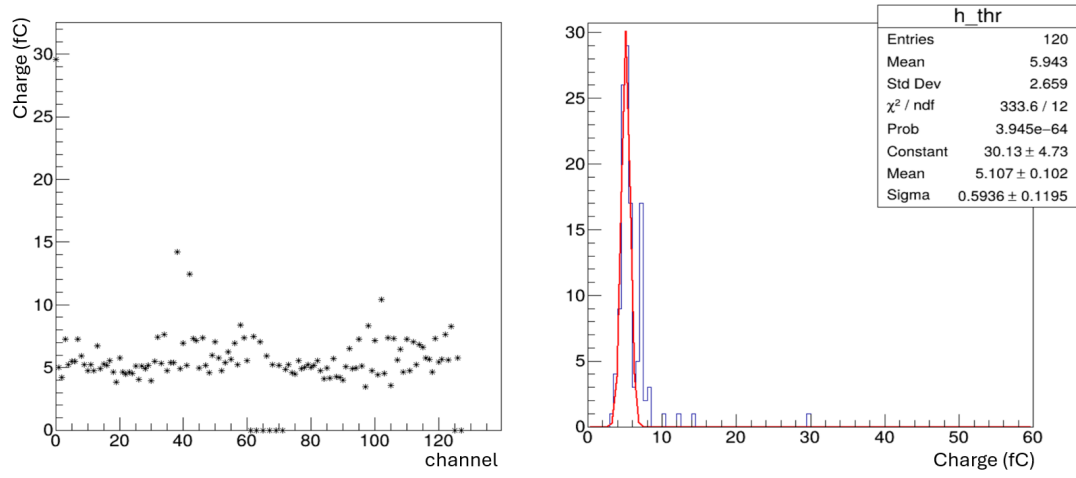


Figure C.20: Distribution of the effective threshold for all the channels of a Front-End Board. The Gaussian fit of the histogram provides the average value of the effective threshold.

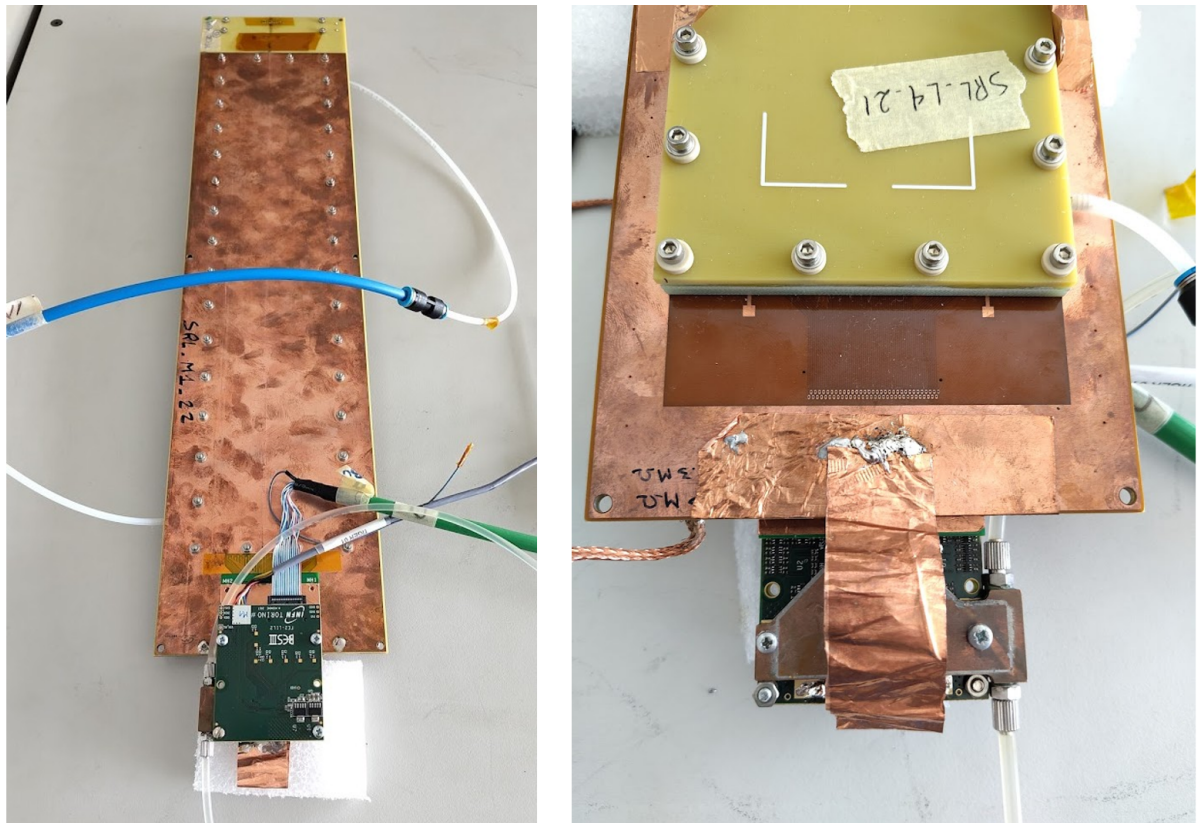


Figure C.21: *Left*: the 1-D μ RWELL used for the noise studies. Only the TIGER Front-End Board is connected. *Right*: detail of the FEB connection to the μ RWELL ground plane.



Figure C.22: Scheme of the connections of the TIGER-GEMROC system. The Low Voltage cable is indicated in red, the data cable in blue. Between the FEB and the FPGA there is the DLVPC card.

through the corresponding electronics transfer functions. The studies concerned the investigation of the following aspects:

- time-walk dependence on signal charge;
- dependence of the reconstructed charge on the signal duration for different values of the threshold;
- measured noise in APV25 and TIGER front-ends following the introduction of white noise in the signal waveform.

As a first step, the time-walk dependence on signal charge (Figure C.24) was studied; this was done by injecting current delta-pulses into the ASIC front-end at a fixed time and measuring the time-shift due to time-walk while increasing the detector gain. The results obtained for different values of the T-branch threshold proved to be compatible with experimental measurements.

Another interesting study is the dependence of the reconstructed charge on the signal duration for different values of the threshold, which can account for increasing noise levels. The two plots of Figure C.25 show the charge detected on the E-branch as a function of the signal duration for threshold values ranging from 10 to 150 mV. In the left plot, the signal had a constant charge of 40 fC and hence an amplitude inversely proportional to its duration. In order to understand the results in the plot, one must consider that in the E-branch, the charge is obtained by sampling the voltage signal after a fixed number of clock counts following the crossing of the threshold. The higher the threshold, the later the signal is sampled, with the risk of measuring the signal after the peak has been reached, leading to a loss of charge. For very long signals, exceeding the branch peaking time (170 ns), however, this can become an advantage since, for low threshold values, the sampling can happen too early. The right plot of Figure C.25 is obtained using a signal of constant amplitude (0.4 fC/ns) and total charge increasing with its duration. The reconstructed charge shows a linear behaviour up to a duration of ~ 150 ns, while for longer signals, it tends to stabilise between 50 and 60 fC, which is the limit of the dynamic range of TIGER.

The introduction of white noise in the signal waveform is a crucial step towards a realistic simulation of the experimental setup, opening up the possibility of studying how it affects detector performance and, in turn, how it can be reduced by modifying the front-end parameters. Figure C.23 shows the response of time and energy branch of TIGER to a current delta pulse, which can represent the signal produced in a μ RWELL, omitting the ionic tail.

The injection of only the noise waveform in the simulated front-end highlights the differences between APV25 and the two TIGER branches. Figure C.26 shows the variation of the detected charge (due to the injected noise) as a function of the amplitude of the injected waveform. N samples of noise waveform ($N \sim 1000$) are generated with a white spectrum ranging from 340 MHz to 2 GHz, with the amplitude of each frequency component randomly distributed around a mean value that is varied between 0.03 and 0.3 (a.u.). For each mean value of the amplitude, the distribution of the measured charge in the E-branch is fitted with a Gaussian to extract its mean value, which is then inserted on the y axis of the plots.

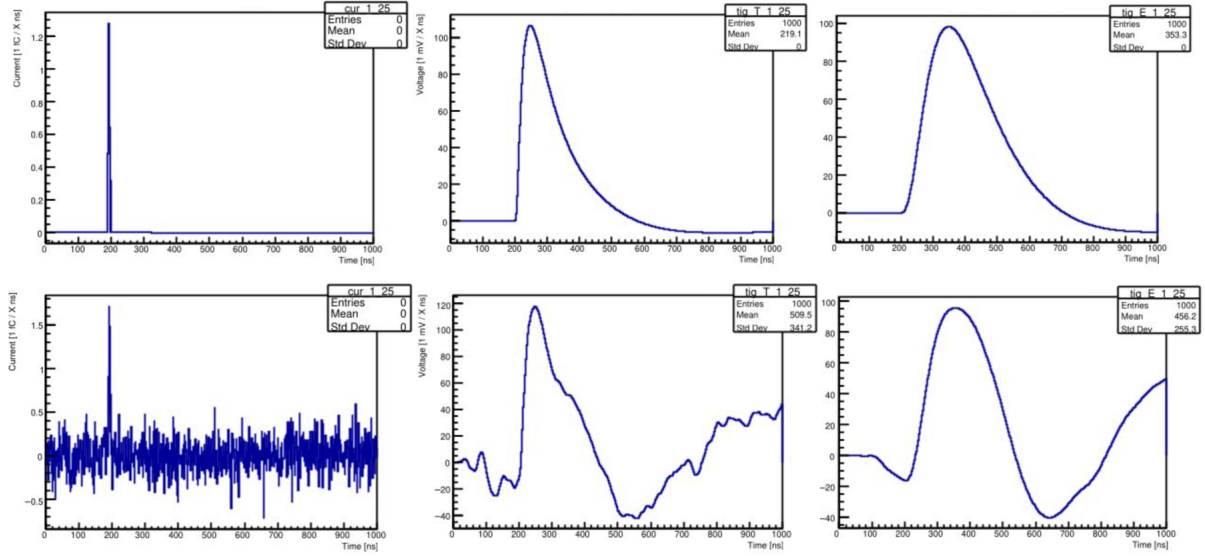


Figure C.23: Simulation of TIGER front-end response to a delta pulse in absence (*top row*) and with the introduction of white noise (*bottom row*). In the first column the current signal is represented, while the second and third columns contain the waveforms produced in the time and energy branches, respectively.

Given the same white noise amplitude, the noise collected on the E-branch of TIGER, with a peaking time of 170 ns, is larger than that on the T-branch and APV25, which have similar peaking times of 60 and 50 ns, respectively. In general, the longer the peaking time is, the larger the noise amplitude becomes.

A tuning procedure with experimental data is ongoing to foster the integration of the detector and the electronics; In this case, complete μ RWELL signals are used, like the one shown in Figure C.27, in which the electronic peak and the subsequent ionic tail are clearly visible. White noise is also included. The comparison between the simulated performance of μ RWELL with TIGER readout and the experimental data is shown in Figure C.28. The performance, expressed in terms of detected charge, cluster size, efficiency, and spatial resolution, is consistent between the experiment and simulation, with the exception of the spatial resolution. This may be due to different noise on the front-end with respect to the one superimposed on the simulated signals.

C.6 Future prospects in μ RWELL R&D

The R&D programme on μ RWELL will continue in the coming years, with the aim of selecting the technology for the 2-D readout so that its performance is compatible with the physics requirements of the IDEA muon system and the overall cost of the infrastructure is achievable. The readout electronics play a fundamental role in this context, and future developments will be crucial for the whole project.

A new ASIC is under development in Torino for the AMBER experiment [140], which could become the baseline choice for μ RWELL readout: ToRA (Torino Readout for AMBER). It will be 64 channel ASIC compatible with MPGD and wire-based detectors, featuring a moderate time resolution (1-2 ns or better), Time-over-Threshold charge measurement, and an analogue front-end inspired to VMM [141] and TIGER designs, with four gains: 2,6,8 and 12 mV/fC.

A beam test is scheduled in May 2026 to test the new TIGER Front-End boards, validating the design

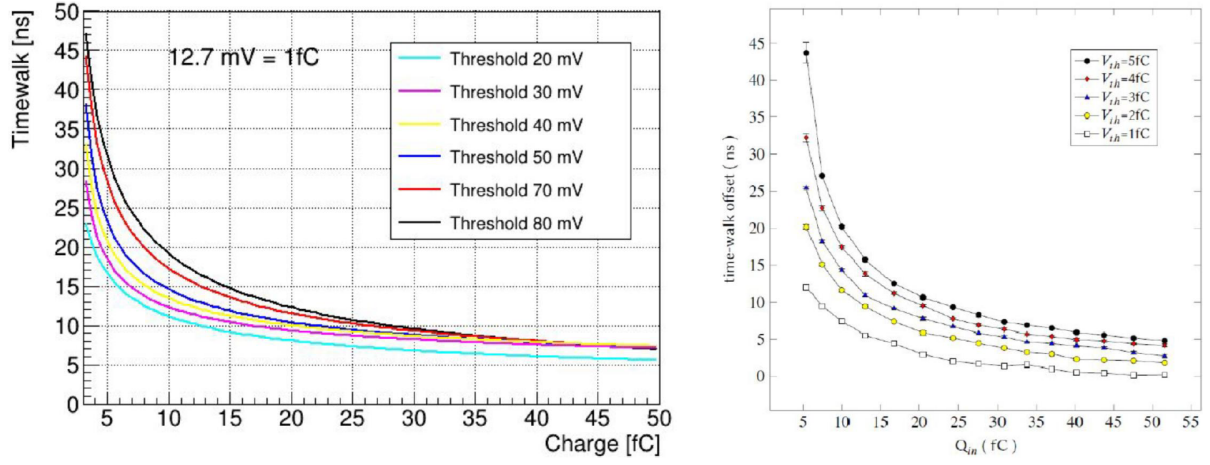


Figure C.24: Time-walk extracted from TIGER T-branch as a function of the signal charge. Different thresholds are used. Results obtained from simulations (*left*) are compared to experimental data (*right*).

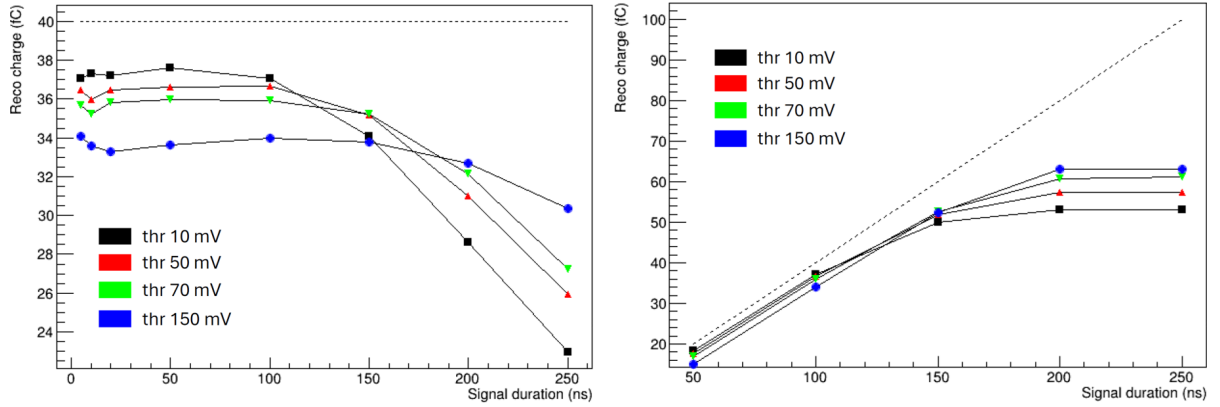


Figure C.25: Reconstructed charge as function of the signal duration for a fixed signal charge of 40 fC (*left*) and for constant signal amplitude of 0.4 fC/ns.

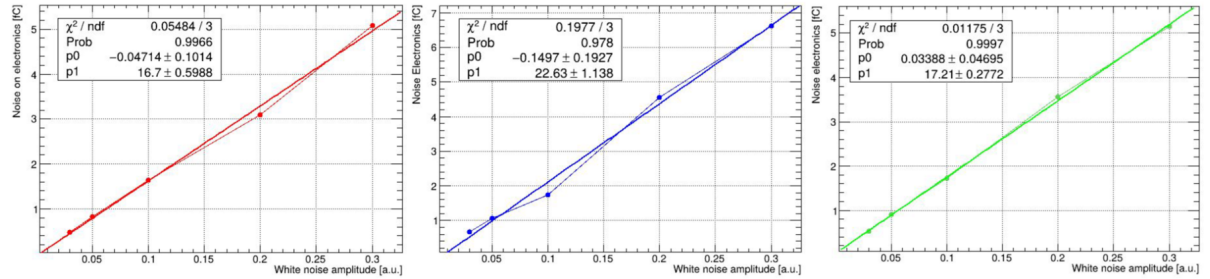


Figure C.26: Measured noise amplitude as a function of the injected amplitude for APV25 (*left*), TIGER energy branch (*centre*) and time branch (*right*).

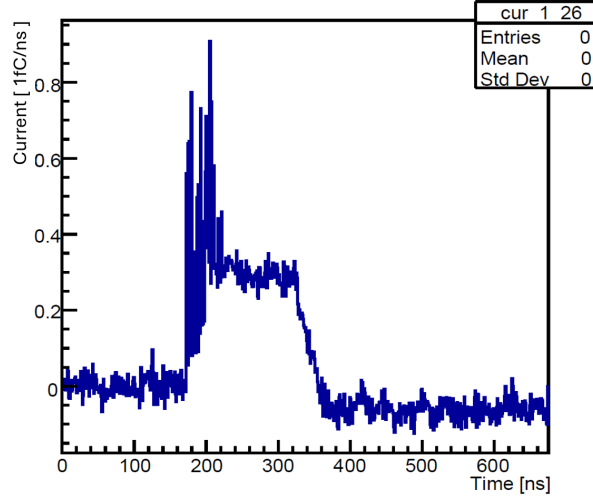


Figure C.27: Full μ RWELL signal simulated in PARSIFAL, with the electronic peak followed by the ionic tail.

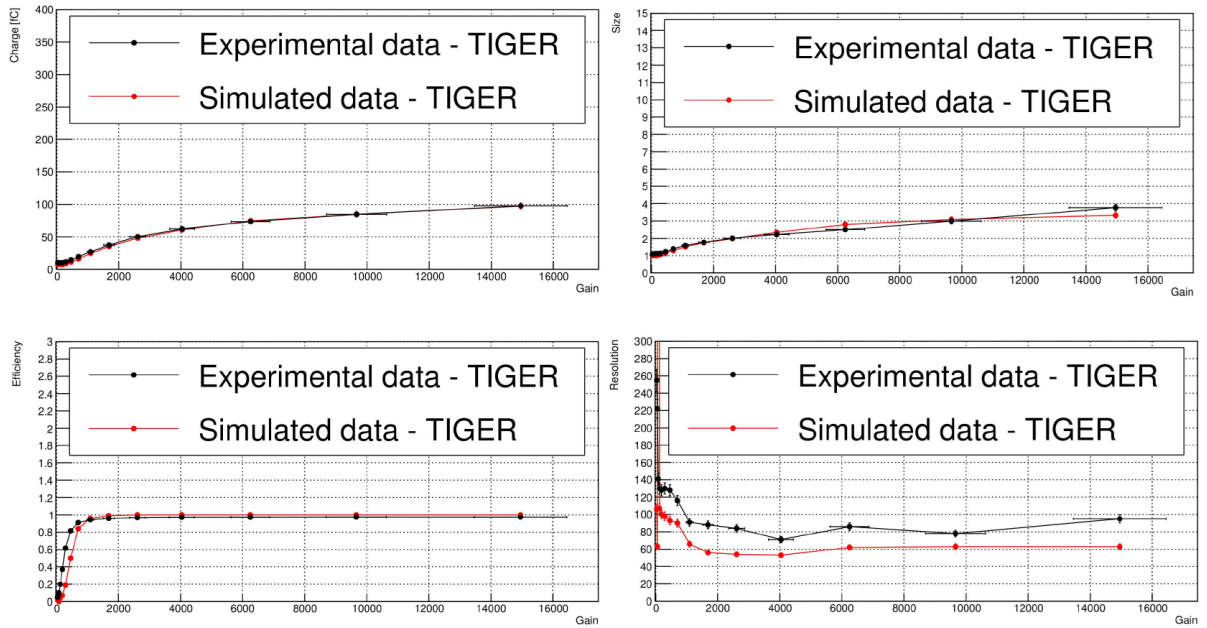


Figure C.28: Comparison of detector performance obtained from experimental data (*black*) and simulations (*red*). Clockwise from top left, the following quantities are plotted against the detector gain: reconstructed charge, cluster size, spatial resolution and efficiency.

choices for noise minimisation. However, activities involving the TIGER electronics will not continue after the completion of the noise studies due to the project's decommissioning and lack of support for further R&D. For this reason, a collaboration has started with the Torino group to establish a synergy for the development of the ToRA chip and its readout chain. The plan is to export all the knowledge developed on TIGER integration to ToRA, including the grounding scheme and noise optimisation, together with the μ RWELL and electronics simulation.

Bibliography

- [1] W. N. Cottingham and D. A. Greenwood. *An Introduction to the Standard Model of Particle Physics*. 2nd ed. Cambridge University Press, 2007.
- [2] D.Decamp et al. ALEPH Collaboration. 1990.
- [3] S. Bilenky. *Neutrinos: Majorana or Dirac?* 2020. arXiv: [2008.02110 \[hep-ph\]](https://arxiv.org/abs/2008.02110). URL: <https://arxiv.org/abs/2008.02110>.
- [4] A. Broncano, M. B. Gavela, and Elizabeth Ellen Jenkins. “The Effective Lagrangian for the seesaw model of neutrino mass and leptogenesis”. In: *Phys. Lett. B* 552 (2003). [Erratum: Phys.Lett.B 636, 332 (2006)], pp. 177–184. DOI: [10.1016/S0370-2693\(02\)03130-1](https://doi.org/10.1016/S0370-2693(02)03130-1). arXiv: [hep-ph/0210271](https://arxiv.org/abs/hep-ph/0210271).
- [5] Yi Cai et al. “Lepton number violation: seesaw models and their collider tests”. In: *Frontiers in Physics* 6 (2018), p. 40.
- [6] Fujikawa, Kazuo. “Operatorial characterization of Majorana neutrinos”. In: *Eur. Phys. J. C* 80.3 (2020), p. 285. DOI: [10.1140/epjc/s10052-020-7855-4](https://doi.org/10.1140/epjc/s10052-020-7855-4). URL: <https://doi.org/10.1140/epjc/s10052-020-7855-4>.
- [7] Furry W.H. 1939.
- [8] Azzolini O. et al. *Final result of CUPID-0 phase-I in the search for the ^{82}Se* . 2019. arXiv: [1906.05001v1](https://arxiv.org/abs/1906.05001v1).
- [9] Agostini M. et al. “Final Results of GERDA on the Search for Neutrinoless Double- β Decay”. In: *Phys. Rev. Lett.* 125 (25 2020), p. 252502. DOI: [10.1103/PhysRevLett.125.252502](https://doi.org/10.1103/PhysRevLett.125.252502). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.125.252502>.
- [10] Adams D.Q. et al. (CUORE Collaboration). *Improved Limit on Neutrinoless Double Beta Decay in ^{130}Te with CUORE*. 2019. arXiv: [1912.10966v1](https://arxiv.org/abs/1912.10966v1).
- [11] Gando A. et al. “Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen”. In: *Phys. Rev. Lett.* 117 (2016), p. 082503. DOI: [10.1103/PhysRevLett.117.082503](https://doi.org/10.1103/PhysRevLett.117.082503). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.117.082503>.
- [12] Andrea Giuliani and Alfredo Poves. “Neutrinoless Double-Beta Decay”. In: *Advances in High Energy Physics* 2012.1 (2012), p. 857016. DOI: <https://doi.org/10.1155/2012/857016>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1155/2012/857016>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1155/2012/857016>.
- [13] KATRIN Collaboration et al. “Direct neutrino-mass measurement based on 259 days of KATRIN data”. In: *Science* 388.6743 (2025), pp. 180–185. DOI: [10.1126/science.adq9592](https://doi.org/10.1126/science.adq9592). eprint: <https://www.science.org/doi/pdf/10.1126/science.adq9592>. URL: <https://www.science.org/doi/abs/10.1126/science.adq9592>.
- [14] Aseev V.N. et al. “An upper limit on electron antineutrino mass from Troitsk experiment”. In: *Phys. Rev. D* 84 (2011), p. 112003. DOI: [10.1103/PhysRevD.84.112003](https://doi.org/10.1103/PhysRevD.84.112003). arXiv: [hep-ex/0412056](https://arxiv.org/abs/hep-ex/0412056).

- [15] Kraus Ch. et al. “Final results from phase II of the Mainz neutrino mass search in Tritium beta decay”. In: *Eur. Phys. J. C* 40 (2005), 447–468. DOI: [10.1140/epjc/s2005-02139-7](https://doi.org/10.1140/epjc/s2005-02139-7). arXiv: [hep-ex/0412056](https://arxiv.org/abs/hep-ex/0412056).
- [16] Planck Collaboration. “Planck 2018 results - VI. Cosmological parameters”. In: *A&A* 641 (2020), A6. DOI: [10.1051/0004-6361/201833910](https://doi.org/10.1051/0004-6361/201833910). URL: <https://doi.org/10.1051/0004-6361/201833910>.
- [17] K. Zuber. *Neutrino Physics, Second Edition*. Series in High Energy Physics, Cosmology and Gravitation. Taylor & Francis, 2011. ISBN: 9781420064711. URL: <https://books.google.it/books?id=ODRaQiIINvkC>.
- [18] L. Wolfenstein. “Neutrino oscillations in matter”. In: *Phys. Rev. D* 17 (9 1978), pp. 2369–2374. DOI: [10.1103/PhysRevD.17.2369](https://doi.org/10.1103/PhysRevD.17.2369). URL: <https://link.aps.org/doi/10.1103/PhysRevD.17.2369>.
- [19] S.P. Mikheyev and A.Yu. Smirnov. “Resonant neutrino oscillations in matter”. In: *Progress in Particle and Nuclear Physics* 23 (1989), pp. 41–136. ISSN: 0146-6410. DOI: [https://doi.org/10.1016/0146-6410\(89\)90008-2](https://doi.org/10.1016/0146-6410(89)90008-2). URL: <https://www.sciencedirect.com/science/article/pii/0146641089900082>.
- [20] J.N. Abdurashitov et al. “Solar neutrino flux measurements by the Soviet-American Gallium Experiment (SAGE) for half the 22 year solar cycle”. In: *J. Exp. Theor. Phys.* 95 (2002), pp. 181–193. DOI: [10.1134/1.1506424](https://doi.org/10.1134/1.1506424).
- [21] M. Altmann et al. “Complete results for ve years of GNO solar neutrino observations”. In: *Phys. Lett. B* 616 (2005), pp. 174–190. DOI: [10.1016/j.physletb.2005.04.068](https://doi.org/10.1016/j.physletb.2005.04.068).
- [22] Y. Fukuda et al. “Solar neutrino data covering solar cycle 22”. In: *Phys. Rev. D* 77 (1996), pp. 1683–1686. DOI: [10.1103/PhysRevLett.77.1683](https://doi.org/10.1103/PhysRevLett.77.1683).
- [23] J. Hosaka et al. “Solar neutrino measurements in super-Kamiokande-I”. In: *Phys. Rev. D* 73 (2006), p. 112001. DOI: [10.1103/PhysRevD.73.112001](https://doi.org/10.1103/PhysRevD.73.112001).
- [24] B. Aharmim et al. “Electron energy spectra, fluxes, and day-night asymmetries of B-8 solar neutrinos from measurements with NaCl dissolved in the heavy-water detector at the Sudbury Neutrino Observatory”. In: *Phys. Rev. C* 72 (2005), p. 055502. DOI: [10.1103/PhysRevC.72.055502](https://doi.org/10.1103/PhysRevC.72.055502).
- [25] B. Aharmim et al. “Measurement of the ν_e and Total ^8B Solar Neutrino Fluxes with the Sudbury Neutrino Observatory Phase-III Data Set”. In: *Phys. Rev. C* 87.1 (2013), p. 015502. DOI: [10.1103/PhysRevC.87.015502](https://doi.org/10.1103/PhysRevC.87.015502).
- [26] S. Navas et al. “Review of particle physics”. In: *Phys. Rev. D* 110.3 (2024), p. 030001. DOI: [10.1103/PhysRevD.110.030001](https://doi.org/10.1103/PhysRevD.110.030001).
- [27] Bahcall et al. “Standard solar models and the uncertainties in predicted capture rates of solar neutrinos”. In: *Rev. Mod. Phys.* 54 (3 1982), pp. 767–799. DOI: [10.1103/RevModPhys.54.767](https://doi.org/10.1103/RevModPhys.54.767). URL: <https://link.aps.org/doi/10.1103/RevModPhys.54.767>.
- [28] Q.R. Ahmad et al. “Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory”. In: *Phys. Rev. Lett.* 89 (2002), p. 011301.
- [29] W.W.M. Allison et al. “Measurement of the atmospheric neutrino flavour composition in Soudan 2”. In: *Physics Letters B* 391.3 (1997), pp. 491–500. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/S0370-2693\(96\)01609-7](https://doi.org/10.1016/S0370-2693(96)01609-7). URL: <https://www.sciencedirect.com/science/article/pii/S0370269396016097>.

- [30] M. Ambrosio et al. “Measurement of the atmospheric neutrino-induced upgoing muon flux using MACRO”. In: *Physics Letters B* 434.3 (1998), pp. 451–457. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/S0370-2693\(98\)00885-5](https://doi.org/10.1016/S0370-2693(98)00885-5). URL: <https://www.sciencedirect.com/science/article/pii/S0370269398008855>.
- [31] Casper D. et al. “Measurement of atmospheric neutrino composition with the IMB-3 detector”. In: *Phys. Rev. Lett.* 66 (20 1991), pp. 2561–2564. DOI: [10.1103/PhysRevLett.66.2561](https://doi.org/10.1103/PhysRevLett.66.2561). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.66.2561>.
- [32] Oleg Kalekin (on behalf of the ANTARES collaboration). “The ANTARES underwater neutrino telescope”. In: *Journal of Physics: Conference Series* 160.1 (2009), p. 012036. DOI: [10.1088/1742-6596/160/1/012036](https://doi.org/10.1088/1742-6596/160/1/012036). URL: <https://dx.doi.org/10.1088/1742-6596/160/1/012036>.
- [33] Adrián-Martínez S. et al. “Letter of intent for KM3NeT 2.0”. In: *J. Phys. G: Nucl. Part. Phys.* 43 (2016), p. 084001. DOI: [10.1088/0954-3899/43/8/084001](https://doi.org/10.1088/0954-3899/43/8/084001). URL: <https://dx.doi.org/10.1088/0954-3899/43/8/084001>.
- [34] Albert A. et al. “Measuring the atmospheric neutrino oscillation parameters and constraining the 3+1 neutrino model with ten years of ANTARES data”. In: *J. High Energy. Phys.* 113 (2019). DOI: [10.1007/JHEP06\(2019\)113](https://doi.org/10.1007/JHEP06(2019)113). URL: [https://doi.org/10.1007/JHEP06\(2019\)113](https://doi.org/10.1007/JHEP06(2019)113).
- [35] Abbasi R. et al. “Measurement of atmospheric neutrino mixing with improved IceCube DeepCore calibration and data processing”. In: *Phys. Rev. D* 108 (1 2023), p. 012014. DOI: [10.1103/PhysRevD.108.012014](https://doi.org/10.1103/PhysRevD.108.012014). URL: <https://link.aps.org/doi/10.1103/PhysRevD.108.012014>.
- [36] Decowski M. P. “KamLAND’s precision neutrino oscillation measurements”. In: *Nuclear Physics B* 908 (2016). Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015, pp. 52–61. ISSN: 0550-3213. DOI: <https://doi.org/10.1016/j.nuclphysb.2016.04.014>. URL: <https://www.sciencedirect.com/science/article/pii/S0550321316300529>.
- [37] Daya Bay Collaboration. *A Precision Measurement of the Neutrino Mixing Angle θ_{13} using Reactor Antineutrinos at Daya Bay*. 2007. arXiv: [hep-ex/0701029](https://arxiv.org/abs/hep-ex/0701029) [hep-ex]. URL: <https://arxiv.org/abs/hep-ex/0701029>.
- [38] Maury Goodman Thierry Lasserre. *Double Chooz, A Search for the Neutrino Mixing Angle θ_{13}* . 2006. arXiv: [hep-ex/0606025](https://arxiv.org/abs/hep-ex/0606025) [hep-ex]. URL: <https://arxiv.org/abs/hep-ex/0606025>.
- [39] RENO Collaboration. *RENO: An Experiment for Neutrino Oscillation Parameter θ_{13} Using Reactor Neutrinos at Yonggwang*. 2010. arXiv: [1003.1391](https://arxiv.org/abs/1003.1391) [hep-ex]. URL: <https://arxiv.org/abs/1003.1391>.
- [40] Gando A. et al. “Reactor on-off antineutrino measurement with KamLAND”. In: *Phys. Rev. D* 88 (3 2013), p. 033001. DOI: [10.1103/PhysRevD.88.033001](https://doi.org/10.1103/PhysRevD.88.033001). URL: <https://link.aps.org/doi/10.1103/PhysRevD.88.033001>.
- [41] Lachenmaier T. “The measurement of the neutrino mixing angle θ_{13} with reactor neutrino experiments”. In: *Progress in Particle and Nuclear Physics* 83 (2015), pp. 31–58. ISSN: 0146-6410. DOI: <https://doi.org/10.1016/j.pnpnp.2015.05.001>. URL: <https://www.sciencedirect.com/science/article/pii/S0146641015000290>.
- [42] Aguilar A. et al. “Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam”. In: *Phys. Rev. D* 64 (11 2001), p. 112007. DOI: [10.1103/PhysRevD.64.112007](https://doi.org/10.1103/PhysRevD.64.112007). URL: <https://link.aps.org/doi/10.1103/PhysRevD.64.112007>.
- [43] Aguilar-Arevalo-A-A. et al. “Updated MiniBooNE neutrino oscillation results with increased data and new background studies”. In: *Phys. Rev. D* 103 (5 2021), p. 052002. DOI: [10.1103/PhysRevD.103.052002](https://doi.org/10.1103/PhysRevD.103.052002). URL: <https://link.aps.org/doi/10.1103/PhysRevD.103.052002>.

- [44] Pedro A.N. Machado, Ornella Palamara, and David W. Schmitz. “The Short-Baseline Neutrino Program at Fermilab”. In: *Annual Review of Nuclear and Particle Science* 69. Volume 69, 2019 (2019), pp. 363–387. ISSN: 1545-4134. DOI: <https://doi.org/10.1146/annurev-nucl-101917-020949>. URL: <https://www.annualreviews.org/content/journals/10.1146/annurev-nucl-101917-020949>.
- [45] Ahn M. H. et al. “Measurement of neutrino oscillation by the K2K experiment”. In: *Phys. Rev. D* 74 (7 2006), p. 072003. DOI: [10.1103/PhysRevD.74.072003](https://doi.org/10.1103/PhysRevD.74.072003). URL: <https://link.aps.org/doi/10.1103/PhysRevD.74.072003>.
- [46] Adamson P. et al. “Combined Analysis of ν_μ Disappearance and $\nu_\mu \rightarrow \nu_e$ Appearance in MINOS Using Accelerator and Atmospheric Neutrinos”. In: *Phys. Rev. Lett.* 112 (19 2014), p. 191801. DOI: [10.1103/PhysRevLett.112.191801](https://doi.org/10.1103/PhysRevLett.112.191801). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.112.191801>.
- [47] Agafonova N. et al. “Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment”. In: *Phys. Rev. Lett.* 115 (12 2015), p. 121802. DOI: [10.1103/PhysRevLett.115.121802](https://doi.org/10.1103/PhysRevLett.115.121802). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.115.121802>.
- [48] Agafonova N. et al. “Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam”. In: *Phys. Rev. Lett.* 120 (21 2018), p. 211801. DOI: [10.1103/PhysRevLett.120.211801](https://doi.org/10.1103/PhysRevLett.120.211801). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.120.211801>.
- [49] Abe K. et al. “Observation of Electron Neutrino Appearance in a Muon Neutrino Beam”. In: *Phys. Rev. Lett.* 112 (6 2014), p. 061802. DOI: [10.1103/PhysRevLett.112.061802](https://doi.org/10.1103/PhysRevLett.112.061802). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.112.061802>.
- [50] Acero M. A. et al. “First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA”. In: *Phys. Rev. Lett.* 123 (15 2019), p. 151803. DOI: [10.1103/PhysRevLett.123.151803](https://doi.org/10.1103/PhysRevLett.123.151803). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.123.151803>.
- [51] Acero M. A. et al. “Improved measurement of neutrino oscillation parameters by the NOvA experiment”. In: *Phys. Rev. D* 106 (3 2022), p. 032004. DOI: [10.1103/PhysRevD.106.032004](https://doi.org/10.1103/PhysRevD.106.032004). URL: <https://link.aps.org/doi/10.1103/PhysRevD.106.032004>.
- [52] Abe K. et al. “The Hyper-Kamiokande Experiment - Snowmass LOI”. In: (2020). arXiv: [2009.00794](https://arxiv.org/abs/2009.00794) [physics.ins-det].
- [53] Esteban-I. et al. “NuFit-6.0: updated global analysis of three-flavor neutrino oscillations”. In: *J. High Energ. Phys.* 216 (2024). DOI: [10.1007/JHEP12\(2024\)216](https://doi.org/10.1007/JHEP12(2024)216). URL: [https://doi.org/10.1007/JHEP12\(2024\)216](https://doi.org/10.1007/JHEP12(2024)216).
- [54] Aartsen M. G. et al. “Measurement of atmospheric tau neutrino appearance with IceCube DeepCore”. In: *Phys. Rev. D* 99 (3 2019), p. 032007. DOI: [10.1103/PhysRevD.99.032007](https://doi.org/10.1103/PhysRevD.99.032007). URL: <https://link.aps.org/doi/10.1103/PhysRevD.99.032007>.
- [55] IceCube Collaboration. *Measurement of atmospheric neutrino oscillation parameters using convolutional neural networks with 9.3 years of data in IceCube DeepCore*. 2024. arXiv: [2405.02163](https://arxiv.org/abs/2405.02163) [hep-ex]. URL: <https://arxiv.org/abs/2405.02163>.
- [56] C.W. Kim C. Giunti. *Fundamentals of Neutrino Physics and Astrophysics*. 2007.
- [57] DUNE Collaboration. *Deep Underground Neutrino Experiment (DUNE) Far Detector Technical Design Report Volume 1: Introduction to DUNE*. 2020. arXiv: [2002.02967v3](https://arxiv.org/abs/2002.02967v3) [physics.ins-det].
- [58] The PIP-II Collaboration. *The PIP-II Reference Design Report*. 2015. URL: <http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1370>.
- [59] DUNE Collaboration. *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 3: Long-Baseline Neutrino Facility for DUNE*. 2015. arXiv: [1601.05823](https://arxiv.org/abs/1601.05823) [physics.ins-det].

- [60] Oleg Kalekin (on behalf of the ANTARES collaboration). “The ANTARES underwater neutrino telescope”. In: *Journal of Physics: Conference Series* 160.1 (2009), p. 012036. DOI: [10.1088/1742-6596/160/1/012036](https://doi.org/10.1088/1742-6596/160/1/012036). URL: <https://dx.doi.org/10.1088/1742-6596/160/1/012036>.
- [61] Abed Abud A. et al. “The DUNE Far Detector Vertical Drift Technology. Technical Design Report”. In: *Journal of Instrumentation* 19.08 (2024), T08004. DOI: [10.1088/1748-0221/19/08/T08004](https://doi.org/10.1088/1748-0221/19/08/T08004). URL: <https://dx.doi.org/10.1088/1748-0221/19/08/T08004>.
- [62] DUNE Collaboration. *Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report*. 2021. arXiv: [2103.13910v1](https://arxiv.org/abs/2103.13910) [physics.ins-det].
- [63] Abed Abud A. et al. “Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report”. In: *Instruments* 5.4 (2021). ISSN: 2410-390X. DOI: [10.3390/instruments5040031](https://doi.org/10.3390/instruments5040031). URL: <https://www.mdpi.com/2410-390X/5/4/31>.
- [64] LBNE Collaboration. *The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe*. 2014. arXiv: [1307.7335](https://arxiv.org/abs/1307.7335) [hep-ex].
- [65] C. Adams et al. “The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe”. In: *Snowmass 2013. Workshop on Energy Frontier*. June 30-July 3, 2013.
- [66] S.J. Parke H. Nunokawa and J.W. Valle. “CP Violation and Neutrino Oscillations”. In: *Prog. Part. Nucl. Phys.* 60 (2008), pp. 338–402. arXiv: [0710.0554](https://arxiv.org/abs/hep-ph/0710.0554) [hep-ph].
- [67] B. Abi et al. *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics*. 2020. arXiv: [2002.03005](https://arxiv.org/abs/2002.03005) [hep-ex]. URL: <https://arxiv.org/abs/2002.03005>.
- [68] DUNE Collaboration. *Snowmass Neutrino Frontier: DUNE Physics Summary*. 2022. arXiv: [2203.06100](https://arxiv.org/abs/2203.06100) [hep-ex]. URL: <https://arxiv.org/abs/2203.06100>.
- [69] Abi B. et al. “Volume I. Introduction to DUNE”. In: *Journal of Instrumentation* 15.08 (2020), T08008. DOI: [10.1088/1748-0221/15/08/T08008](https://doi.org/10.1088/1748-0221/15/08/T08008). URL: <https://dx.doi.org/10.1088/1748-0221/15/08/T08008>.
- [70] “The KLOE Detector Technical Proposal”. In: *Proceedings of the 19th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, CA, USA* (1999). eprint: [hep-ex/0002030](https://arxiv.org/abs/hep-ex/0002030).
- [71] W.J. Marciano and Z. Parsa. “Neutrino electron scattering theory”. In: *J. Phys.* G29 (2003), pp. 2629–2645.
- [72] Adamov G. et al. *A Proposal to Enhance the DUNE Near Detector Complex*. 2019. URL: <https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=13262>.
- [73] Duyang H. et al. “A novel approach to neutrino–hydrogen measurements”. In: *Eur. Phys. J. Plus* 139 (2024), p. 1014. DOI: [10.1140/epjp/s13360-024-05783-y](https://doi.org/10.1140/epjp/s13360-024-05783-y). URL: <https://doi.org/10.1140/epjp/s13360-024-05783-y>.
- [74] S.L. Adler. “Tests of the Conserved Vector Current and Partially Conserved Axial-Vector Current Hypotheses in High-Energy Neutrino Reactions”. In: *Phys. Rev.* 136 (1964), B963–B966.
- [75] D.J. Gross and C.H. Llewellyn Smith. “High-energy neutrino - nucleon scattering, current algebra and partons”. In: *Nucl. Phys.* B14 (1969), pp. 337–347.
- [76] Adinolfi M. et al. “The KLOE electromagnetic calorimeter”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 482.1 (2002), pp. 364–386. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(01\)01502-9](https://doi.org/10.1016/S0168-9002(01)01502-9). URL: <https://www.sciencedirect.com/science/article/pii/S0168900201015029>.

- [77] H. Duyang et al. “A novel approach to neutrino–hydrogen measurements”. In: *The European Physical Journal Plus* 139.11 (2024). ISSN: 2190-5444. DOI: [10.1140/epjp/s13360-024-05783-y](https://doi.org/10.1140/epjp/s13360-024-05783-y). URL: <http://dx.doi.org/10.1140/epjp/s13360-024-05783-y>.
- [78] Gianfranco Ingrassia. “Study of Neutrino interactions on Hydrogen in the SAND detector of DUNE”. PhD thesis. alma, 2025. URL: <https://amsdottorato.unibo.it/id/eprint/11966/>.
- [79] Hofmann M. et al. “Ion-beam excitation of liquid argon”. In: *Eur. Phys. J. C* 73 (2013), p. 2618. DOI: [10.1140/epjc/s10052-013-2618-0](https://doi.org/10.1140/epjc/s10052-013-2618-0). URL: <https://doi.org/10.1140/epjc/s10052-013-2618-0>.
- [80] Burton W. M. et al. “Fluorescence of Tetraphenyl-Butadiene in the Vacuum Ultraviolet”. In: *Appl. Opt.* 12.1 (1973), pp. 87–89. DOI: [10.1364/AO.12.000087](https://doi.org/10.1364/AO.12.000087). URL: <https://opg.optica.org/ao/abstract.cfm?URI=ao-12-1-87>.
- [81] Veenhof R. et al. *Garfield++*. URL: <https://garfieldpp.docs.cern.ch/>.
- [82] Bernardini P. et al. “On the performances of a particle tracking detector based on triangular scintillator bars read out by silicon photomultipliers”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 967 (2020), p. 163882. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2020.163882>. URL: <https://www.sciencedirect.com/science/article/pii/S016890022030379X>.
- [83] George Iakovidis. “VMM3a, an ASIC for tracking detectors”. In: *Journal of Physics: Conference Series* 1498.1 (2020), p. 012051. DOI: [10.1088/1742-6596/1498/1/012051](https://doi.org/10.1088/1742-6596/1498/1/012051). URL: <https://doi.org/10.1088/1742-6596/1498/1/012051>.
- [84] M. Chefdeville and the RD51 collaboration. “RD51, a world-wide collaboration for the development of Micro Pattern Gaseous Detectors”. In: *Journal of Physics: Conference Series* 309.1 (2011), p. 012017. DOI: [10.1088/1742-6596/309/1/012017](https://doi.org/10.1088/1742-6596/309/1/012017). URL: <https://doi.org/10.1088/1742-6596/309/1/012017>.
- [85] Vitalii Bautin et al. “VMM3 ASIC as a potential front end electronics solution for future Straw Trackers”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1047 (2023), p. 167864. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2022.167864>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900222011561>.
- [86] S. Veneziano. “The KLOE drift chamber readout system”. In: *1999 IEEE Conference on Real-Time Computer Applications in Nuclear Particle and Plasma Physics. 11th IEEE NPSS Real Time Conference. Conference Record (Cat. No.99EX295)*. 1999, pp. 399–402. DOI: [10.1109/RTCON.1999.842652](https://doi.org/10.1109/RTCON.1999.842652).
- [87] M. Y. Dong. “The BESIII and its Upgrade”. In: *30 Years of BES Physics*. 2020, pp. 169–175. DOI: [10.1142/9789811217739_0023](https://doi.org/10.1142/9789811217739_0023).
- [88] A. Amoroso et al. “The CGEM-IT readout chain”. In: *Journal of Instrumentation* 16.08 (2021), P08065. DOI: [10.1088/1748-0221/16/08/P08065](https://doi.org/10.1088/1748-0221/16/08/P08065). URL: <https://doi.org/10.1088/1748-0221/16/08/P08065>.
- [89] Fabio Cossio. “A mixed-signal ASIC for time and charge measurements with GEM detectors”. PhD thesis. 2019. URL: <https://hdl.handle.net/11583/2743335>.
- [90] G. Bencivenni et al. “The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD”. In: *Journal of Instrumentation* 10.02 (2015), P02008. DOI: [10.1088/1748-0221/10/02/P02008](https://doi.org/10.1088/1748-0221/10/02/P02008). URL: <https://doi.org/10.1088/1748-0221/10/02/P02008>.
- [91] Alberto Bortone. *Deployment of the readout electronics for the BESIII Cylindrical GEM Inner Tracker*. 2021. arXiv: [2111.01597](https://arxiv.org/abs/2111.01597) [physics.ins-det]. URL: <https://arxiv.org/abs/2111.01597>.

- [92] R. Yarema et al. “A High Performance Multichannel Preamplifier ASIC”. In: *IEEE Trans. Nucl. Sci.* 39 (1992). Ed. by G. T. Baldwin, pp. 742–746. DOI: [10.1109/23.159698](https://doi.org/10.1109/23.159698).
- [93] DRD1 Collaboration. *DRD1 Extended R&D Proposal - Development of Gaseous Detectors Technologies*. URL: <https://cernbox.cern.ch/pdf-viewer/public/PP7BZroM3NYS2Vh/DRDC-P-DRD1.pdf?contextRouteName=files-public-link&contextRouteParams.driveAliasAndItem=public%2FPP7BZroM3NYS2Vh&contextRouteQuery.fileId=PP7BZroM3NYS2Vh>.
- [94] T. Baroncelli et al. “Study of MDT calibration constants using H8 testbeam data of year 2004”. In: (July 2006).
- [95] C Avanzini et al. “Test of a small prototype of the KLOE drift chamber in magnetic field”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 449.1 (2000), pp. 237–247. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(99\)01372-8](https://doi.org/10.1016/S0168-9002(99)01372-8). URL: <https://www.sciencedirect.com/science/article/pii/S0168900299013728>.
- [96] Charpak G. et al. “The use of multiwire proportional counters to select and localize charged particles”. In: *Nuclear Instruments and Methods* 62.3 (1968), pp. 262–268. ISSN: 0029-554X. DOI: [https://doi.org/10.1016/0029-554X\(68\)90371-6](https://doi.org/10.1016/0029-554X(68)90371-6). URL: <https://www.sciencedirect.com/science/article/pii/0029554X68903716>.
- [97] Amaldi U. *Fisica delle radiazioni*. Bollati Boringhieri, 1971.
- [98] E. J. Kobetich and Robert Katz. “Energy Deposition by Electron Beams and δ Rays”. In: *Phys. Rev.* 170 (2 1968), pp. 391–396. DOI: [10.1103/PhysRev.170.391](https://doi.org/10.1103/PhysRev.170.391). URL: <https://link.aps.org/doi/10.1103/PhysRev.170.391>.
- [99] Sauli F. “Electromagnetic interactions of charged particles with matter”. In: *Gaseous Radiation Detectors: Fundamentals and Applications*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 2014, 24–42.
- [100] J. E. Moyal. “Theory of ionization fluctuations”. In: *Phil. Mag. Ser. 7* 46.374 (1955), pp. 263–280. DOI: [10.1080/14786440308521076](https://doi.org/10.1080/14786440308521076).
- [101] Hansjörg Fischle, Joachim Heintze, and Bernhard Schmidt. “Experimental determination of ionization cluster size distributions in counting gases”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 301.2 (1991), pp. 202–214. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/0168-9002\(91\)90460-8](https://doi.org/10.1016/0168-9002(91)90460-8). URL: <https://www.sciencedirect.com/science/article/pii/0168900291904608>.
- [102] Schultz G., Charpak G., and Sauli F. “Mobilities of Positive Ions in Some Gas Mixtures Used in Proportional and Drift Chambers”. In: *Rev. Phys. Appl.* 12.1 (1977), pp. 67–70. DOI: [10.1051/rphysap:0197700120106700](https://doi.org/10.1051/rphysap:0197700120106700).
- [103] Townsend J. *Electrons in gases*. Hutchinson, 1947.
- [104] Brown S.C. *Basic data of plasma physics*. MIT Press, 1959.
- [105] Yasser Assran and Archana Sharma. “Transport Properties of operational gas mixtures used at LHC”. In: (2011). arXiv: [1110.6761](https://arxiv.org/abs/1110.6761) [[physics.ins-det](https://arxiv.org/abs/1110.6761)].
- [106] Sauli F. *Principles of operation of multiwire proportional and drift chambers*. Tech. rep. CERN, Geneva, 1975 - 1976. Geneva, 1977. DOI: [10.5170/CERN-1977-009](https://doi.org/10.5170/CERN-1977-009). URL: <https://cds.cern.ch/record/117989>.
- [107] A Ferrari. “The KLOE drift chamber”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 494.1 (2002). Proceedings of the 8th International Conference on Instrumentation for Colliding Beam Physics, pp. 163–172. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(02\)01461-4](https://doi.org/10.1016/S0168-9002(02)01461-4). URL: <https://www.sciencedirect.com/science/article/pii/S0168900202014614>.

- [108] Chatrchyan S. et al. “Performance of the CMS Drift Tube Chambers with Cosmic Rays”. In: *JINST* 5 (2010), T03015. DOI: [10.1088/1748-0221/5/03/T03015](https://doi.org/10.1088/1748-0221/5/03/T03015). arXiv: [0911.4855](https://arxiv.org/abs/0911.4855). URL: <https://cds.cern.ch/record/1223944>.
- [109] Walter Blum, Werner Riegler, and Luigi Rolandi. *Particle detection with drift chambers*. Berlin: Springer, 2008. DOI: [10.1007/978-3-540-76684-1](https://doi.org/10.1007/978-3-540-76684-1). URL: <https://cds.cern.ch/record/1105920>.
- [110] P. Astier et al. “Search for the Oscillation $\nu_\mu \leftrightarrow \nu_\tau$ ”. In: *CERN-SPSLC/91-21, CERN-SPSLC/91-48, CERN-SPSLC/91-53* ().
- [111] M Anfreville et al. “The drift chambers of the NOMAD experiment”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 481.1 (2002), pp. 339–364. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(01\)01371-7](https://doi.org/10.1016/S0168-9002(01)01371-7). URL: <https://www.sciencedirect.com/science/article/pii/S0168900201013717>.
- [112] J. Adam et al. “The MEG detector for $\mu^+ \rightarrow e^+ \gamma$ decay search”. In: *The European Physical Journal C* 2013 73:4 73 (4 2013), pp. 2365–. ISSN: 1434-6052. DOI: [10.1140/EPJC/S10052-013-2365-2](https://doi.org/10.1140/EPJC/S10052-013-2365-2). URL: <https://link.springer.com/article/10.1140/epjc/s10052-013-2365-2>.
- [113] A. M. Baldini et al. “The design of the MEG II experiment”. In: *The European Physical Journal C* 2018 78:5 78 (5 2018), pp. 380–. ISSN: 1434-6052. DOI: [10.1140/EPJC/S10052-018-5845-6](https://doi.org/10.1140/EPJC/S10052-018-5845-6). URL: <https://link.springer.com/article/10.1140/epjc/s10052-018-5845-6>.
- [114] A.M. Baldini et al. “Single-hit resolution measurement with MEG II drift chamber prototypes”. In: *Journal of Instrumentation* 11.07 (2016), P07011. DOI: [10.1088/1748-0221/11/07/P07011](https://doi.org/10.1088/1748-0221/11/07/P07011). URL: <https://doi.org/10.1088/1748-0221/11/07/P07011>.
- [115] Giovanni Francesco Tassielli, F. Grancagnolo, and S. Spagnolo. “Improving spatial resolution and particle identification”. In: *Nucl. Instrum. Meth. A* 572 (2007). Ed. by Franco Cervelli et al., pp. 198–200. DOI: [10.1016/j.nima.2006.10.300](https://doi.org/10.1016/j.nima.2006.10.300).
- [116] G. Chiarello et al. “Application of the Cluster Counting/Timing techniques to improve the performances of high transparency Drift Chamber for modern HEP experiments”. In: *Journal of Instrumentation* 12.07 (2017), p. C07021. DOI: [10.1088/1748-0221/12/07/C07021](https://doi.org/10.1088/1748-0221/12/07/C07021). URL: <https://doi.org/10.1088/1748-0221/12/07/C07021>.
- [117] N. Bacchetta et al. *CLD – A Detector Concept for the FCC-ee*. 2019. arXiv: [1911.12230](https://arxiv.org/abs/1911.12230) [physics.ins-det]. URL: <https://arxiv.org/abs/1911.12230>.
- [118] M. Abbrescia et al. “The IDEA detector concept for FCC-ee”. In: (2025). arXiv: [2502.21223](https://arxiv.org/abs/2502.21223) [physics.ins-det].
- [119] ALICE collaboration The. *Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector*. Tech. rep. Geneva: CERN, 2024. URL: <https://cds.cern.ch/record/2890181>.
- [120] G. Chiarello et al. “A new construction technique of high granularity and high transparency drift chambers for modern high energy physics experiments”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 824 (2016). Frontier Detectors for Frontier Physics: Proceedings of the 13th Pisa Meeting on Advanced Detectors, pp. 512–514. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2015.12.021>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900215015922>.
- [121] M.T. Lucchini et al. “New perspectives on segmented crystal calorimeters for future colliders”. In: *Journal of Instrumentation* 15.11 (2020), P11005. DOI: [10.1088/1748-0221/15/11/P11005](https://doi.org/10.1088/1748-0221/15/11/P11005). URL: <https://doi.org/10.1088/1748-0221/15/11/P11005>.

- [122] M.T. Lucchini et al. “Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter”. In: *Journal of Instrumentation* 17.06 (2022), P06008. DOI: [10.1088/1748-0221/17/06/P06008](https://doi.org/10.1088/1748-0221/17/06/P06008). URL: <https://doi.org/10.1088/1748-0221/17/06/P06008>.
- [123] L. Bellagamba, G. Polesello, and N. Valle. “Searches for heavy neutral leptons at FCC-ee in final states including a muon”. In: *The European Physical Journal C* 85.9 (2025). ISSN: 1434-6052. DOI: [10.1140/epjc/s10052-025-14749-y](https://doi.org/10.1140/epjc/s10052-025-14749-y). URL: <http://dx.doi.org/10.1140/epjc/s10052-025-14749-y>.
- [124] M. Giovannetti et al. “The micro-RWELL for future HEP challenges and beyond”. In: *Journal of Instrumentation* 20.05 (2025), p. C05002. DOI: [10.1088/1748-0221/20/05/C05002](https://doi.org/10.1088/1748-0221/20/05/C05002). URL: <https://doi.org/10.1088/1748-0221/20/05/C05002>.
- [125] Stéphane Monteil and Guy Wilkinson. “Heavy-quark opportunities and challenges at FCC-ee”. In: *The European Physical Journal Plus* 2021 136:8 136 (8 2021), pp. 837–. ISSN: 21905444. DOI: [10.1140/epjp/s13360-021-01814-0](https://doi.org/10.1140/epjp/s13360-021-01814-0). URL: <https://link.springer.com/article/10.1140/epjp/s13360-021-01814-0>.
- [126] K. Boudjemline et al. “Spatial resolution of a GEM readout TPC using the charge dispersion signal”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 574.1 (2007), pp. 22–27. ISSN: 0168-9002. DOI: [10.1016/j.nima.2007.01.017](https://doi.org/10.1016/j.nima.2007.01.017). URL: <https://www.sciencedirect.com/science/article/pii/S0168900207000241>.
- [127] G. Bencivenni et al. “Performance of μ -RWELL detector vs resistivity of the resistive stage”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 886 (2018), pp. 36–39. ISSN: 0168-9002. DOI: [10.1016/j.nima.2017.12.037](https://doi.org/10.1016/j.nima.2017.12.037). URL: <https://www.sciencedirect.com/science/article/pii/S0168900217314274>.
- [128] G. Bencivenni et al. “The μ -RWELL layouts for high particle rate”. In: *Journal of Instrumentation* 14.05 (2019), P05014. DOI: [10.1088/1748-0221/14/05/P05014](https://doi.org/10.1088/1748-0221/14/05/P05014). URL: <https://doi.org/10.1088/1748-0221/14/05/P05014>.
- [129] G. Bencivenni et al. “On the space resolution of the μ -RWELL”. In: *Journal of Instrumentation* 16.08 (2021), P08036. DOI: [10.1088/1748-0221/16/08/P08036](https://doi.org/10.1088/1748-0221/16/08/P08036). URL: <https://doi.org/10.1088/1748-0221/16/08/P08036>.
- [130] M.S. Dixit et al. “Position sensing from charge dispersion in micro-pattern gas detectors with a resistive anode”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 518.3 (2004), 721–727. ISSN: 0168-9002. DOI: [10.1016/j.nima.2003.09.051](https://doi.org/10.1016/j.nima.2003.09.051). URL: <http://dx.doi.org/10.1016/j.nima.2003.09.051>.
- [131] M.S. Dixit and A. Rankin. “Simulating the charge dispersion phenomena in Micro Pattern Gas Detectors with a resistive anode”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 566.2 (2006), 281–285. ISSN: 0168-9002. DOI: [10.1016/j.nima.2006.06.050](https://doi.org/10.1016/j.nima.2006.06.050). URL: <http://dx.doi.org/10.1016/j.nima.2006.06.050>.
- [132] M. J. French et al. “Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker”. In: *Nucl. Instrum. Meth. A* 466 (2001). Ed. by T. Ohsugi et al., pp. 359–365. DOI: [10.1016/S0168-9002\(01\)00589-7](https://doi.org/10.1016/S0168-9002(01)00589-7).
- [133] R. Farinelli et al. “ μ -RWELL muon system and pre-shower for FCC-ee”. In: *JINST* 20.06 (2025), p. C06064. DOI: [10.1088/1748-0221/20/06/c06064](https://doi.org/10.1088/1748-0221/20/06/c06064).
- [134] S Bachmann et al. “A GEM detector for the COMPASS experiment”. In: ().

- [135] Kondo Gnanvo et al. “Performance of a resistive micro-well detector with capacitive-sharing strip anode readout”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1047 (2023), p. 167782. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2022.167782>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900222010749>.
- [136] E. Di Fiore et al. “The μ -RWELL technology for the muon system at the IDEA experiment”. In: *Nucl. Instrum. Meth. A* 1082 (2026), p. 170960. DOI: [10.1016/j.nima.2025.170960](https://doi.org/10.1016/j.nima.2025.170960).
- [137] F. M. Melendi et al. “The μ -RWELL-based preshower and muon detectors of the IDEA detector concept”. In: *PoS ICHEP2024* (2025), p. 1103. DOI: [10.22323/1.476.1103](https://doi.org/10.22323/1.476.1103).
- [138] A. Amoroso et al. *PARSIFAL: a toolkit for triple-GEM parametrized simulation*. 2023. arXiv: [2005.04452](https://arxiv.org/abs/2005.04452) [[physics.ins-det](https://arxiv.org/abs/2005.04452)]. URL: <https://arxiv.org/abs/2005.04452>.
- [139] Farinelli, R. “PARSIFAL: Parametrized simulation of triple-GEM and micro-RWELL response to a charged particle”. In: *EPJ Web of Conf.* 295 (2024), p. 03028. DOI: [10.1051/epjconf/202429503028](https://doi.org/10.1051/epjconf/202429503028). URL: <https://doi.org/10.1051/epjconf/202429503028>.
- [140] Jan M Friedrich. “The AMBER Experiment at CERN”. In: *EPJ Web Conf.* 303 (2024), p. 06001. DOI: [10.1051/epjconf/202430306001](https://doi.org/10.1051/epjconf/202430306001). URL: <https://cds.cern.ch/record/2939702>.
- [141] Gianluigi de Geronimo et al. “The VMM3a ASIC”. In: *IEEE Transactions on Nuclear Science* 69.4 (2022), pp. 976–985. DOI: [10.1109/TNS.2022.3155818](https://doi.org/10.1109/TNS.2022.3155818).