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DETECTOR DEVELOPMENT AND DATA ANALYSIS OF THE HIGH ENERGY
PARTICLE DETECTORS ON-BOARD THE CSES SATELLITES

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Acronyms

ACRs	Anoumalous Cosmic Rays
ASI	Agenzia Spaziale Italiana
ASIC	Application-Specific Integrated Circuit
BOT	BOTtom containment panel
CD	Containment Detector
CME	Coronal Mass Ejection
CPT	Coherent Population Trap
CRs	Cosmic Rays
CSES	China Seismo-Electromagnetic Satellite
DIR	DIRection detector
DPCU	Data Processing and Control Unit
DSA	Diffusive Shock Acceleration
EFD	Electric Field Detector
EMC	ElectroMagnetic Compatibility
EN	ENergy detector
FM	Flight Model
FPGA	Field Programmable Gate Array
GEANT4	GEometry ANd Tracking
GNSS	Global Navigation Satellite System
GRBs	Gamma Ray Bursts
HCS	Heliospheric Current Sheet
HEPD	High Energy Particle Detector
HEPP	High-Energy Particle Package
HG	High Gain
HK	HouseKeeping
HMF	Heliospheric Magnetic Field
HPM	High-Precision Magnetometer
HV	High Voltage
IGRF	the International Geomagnetic Reference Field
IP	Ionospheric Photometer
ISM	Interstellar Medium
JSLC	Jiuquan Satellite Launch Center
LAIC	Lithosphere-Atmosphere-Ionosphere Coupling
LAT	LATeral containment panel
LED	Light Emitting Diode
LEO	Low Earth Orbit
LG	Low Gain

LP	Langmuir Probe
LV	low voltage
LVPS	low voltage power supply
LYSO	Cerium doped lutetium–yttrium oxyorthosilicate ($\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5\text{:Ce}$)
MAPS	Monolithic Active Pixel Sensors
MC	Monte-Carlo
MEED	Medium Energy Electron Detector
MILC	Magnetospheric–Ionospheric–Lithospheric Coupling
MIP	Minimum Ionizing Particles
MPV	Most Probable Value
NESSiE	Neutrino Experiment with SpectrometerS in Europe
PAP	Plasma Analyzer Package
p.e.	photo-electrons
PID	Particle IDentification
PMT	Photo-Multiplier Tubes
PMMA	PolyMethyl MethAcrylate
QM	Qualification Model
RAN	RANge detector
SAA	South Atlantic Anomaly
SCM	Search-Coil Magnetometer
SEPs	Solar Energetic Particles
SNRs	Supernova Remnants
SSN	Sun Spot Number
SW	Solar Wind
TR1	TRigger detector 1 st plane
TR2	TRigger detector 2 nd plane
ULFs	Ultra Low Frequencies
VLFs	Very Low Frequencies

Introduction

The near-Earth particle environment comprises several distinct components, including Galactic, Solar, and magnetospheric populations. Precision measurements of these particle populations provide valuable insights into the origin, acceleration, and propagation of Galactic Cosmic Rays and help identify acceleration mechanisms operating within the Solar System. Moreover, the temporal variability of these particles carries essential information for space weather monitoring, solar activity studies, and investigations of sudden variations in particle spectra that may be correlated with phenomena in the lithosphere such as earthquakes or volcanic activity.

This rich scientific program can be effectively pursued using satellites operating in near-Earth orbit, such as those in the China Seismo-Electromagnetic Satellite (CSES) mission. The CSES series is equipped with a suite of complementary instruments designed to monitor different aspects of the near-Earth environment, including electromagnetic fields, plasma parameters, and ionized particle fluxes. The redundancy of sensors enables comprehensive, simultaneous characterization of multiple physical quantities, while a satellite constellation provides enhanced spatial and temporal coverage. The CSES scientific mission is a collaboration between the China National Space Administration (CNSA) and the Italian Space Agency (ASI), with the participation of several Italian research institutions and universities, including the University of Bologna and the Istituto Nazionale di Fisica Nucleare (INFN).

Two satellites of the CSES constellation are currently in orbit. CSES-01 was launched on February 2, 2018, from the Jiuquan Satellite Launch Center (JSLC) aboard a Long March 2D rocket, and has been operating nominally since then. The second satellite, CSES-02, was launched on June 14, 2025, also from JSLC, to continue and enhance the mission's scientific objectives through improved instrumentation and expanded measurement capabilities.

Among the different instruments onboard the CSES satellite, the High Energy Particle Detectors (HEPD-01 on CSES-01, and HEPD-02 on CSES-02) are the two instruments with capabilities of measuring the particle environment in the magnetosphere, distinguishing electrons in the range 3–100 MeV, protons from 30–200 MeV, and light nuclei up to about 300 MeV/nucleon. These two instruments are the main subject of this thesis work, from their design and construction to the data analysis.

In Ch. 1, the Near-Earth particle environment will be discussed in detail. In Ch. 2, the CSES program, and the High-Energy Particle Detectors designed and constructed by the Italian Limadou collaboration will be presented. In Ch. 3, using data already collected by the HEPD-01 detector, a measurement of proton fluxes as a function of geomagnetic latitude is presented. Although still preliminary, this analysis reveals several distinct particle populations, Galactic, Solar, and magne-

tospheric, that extend results from previous measurements to lower energies. In Ch. 4, the design, construction, launch, and commissioning of the CSES-02 satellite, particularly for the HEPD-02 detector, will be reviewed. Most of the detector development has been done in Bologna, with many test phases done in INFN labs. The integration activities and space qualification campaigns are briefly discussed. Finally, in the last Ch. 5 the launch of CSES-02 and the detector's first commissioning phase are presented.

Chapter 1

The Near-Earth Particle Environment

Cosmic Rays (CRs) are charged energetic particles originating from outside the Earth. Since their discovery, through the pioneering work of V. Hess in the early 1900s, CRs have served as a powerful tool to study fundamental physics. In the first decades of the 1900s, subatomic particles (such as muons, pions, and kaons) were found in CRs, leading to the landmark detection of antimatter, first predicted by P. Dirac in 1928 and subsequently observed by C. Anderson in 1932 with the identification of a positron track in a cloud chamber [1]. Today, CRs continue to play a key role in fundamental physics, for example, in addressing questions about the nature of Dark Matter [2]. Together with photons, neutrinos, and gravitational waves, CRs represent all the information that we have to understand the Universe.

Since the advent of the space age, which began in 1957 with the launch of *Sputnik 1* into orbit, the particle environment in near-Earth orbit has been of central interest to the development of space programs. In fact, CRs pose a substantial hazard to manned and unmanned space travel once the atmosphere's protective layer is no longer present. The first satellite measuring particles in near orbit was launched in 1958, as the first American orbital mission, the *Explorer I*. The mission hosted an omnidirectional Geiger–Müller tube to detect CRs. The instrument showed the expected levels of CR flux. However, unexpected saturation occurred over South America. Later, this result was interpreted as proof of the existence of a belt of high radiation around the Earth, called after the Explorer I principal investigator, the *Van Allen Belts* [3].

Since the 1960s, many more particle detectors have been launched, with their complexity and capabilities growing over time. The near-Earth orbit progressively revealed a complex particle environment, its interactions with the Sun, which can modify the CR spectra and accelerate particles, and with the Earth's magnetosphere, which can either reject particles or trap them in magnetic bottles.

In the following sections, we will discuss the composition of the ionizing charged particle environment in near-Earth orbit: the particles with galactic origin will be described in Sec. 1.1, the particles accelerated in the Solar System in Sec. 1.2, while the effect of the Earth's magnetic field in modifying the particle fluxes and in creating radiation belts around the Earth will be described in Sec. 1.3. In particular, the possible relationship between sudden changes in particle rates in the radiation belts

and violent phenomena in the lithosphere, such as earthquakes, will be reviewed.

1.1 Galactic Cosmic Rays

Cosmic rays are charged messengers from the Universe. They are a non-thermal population of high-energy particles composed mainly of matter (electrons, protons, helium nuclei, and heavier nuclei) and a small component of antimatter (positrons and antiprotons). Along with neutral messengers, such as photons and neutrinos, they provide complementary information about the Universe. Unlike neutral messengers, such as photons and neutrinos, CRs are bent by astrophysical magnetic fields and do not point directly to sources. However, CRs' properties, such as their composition and spectral shapes, carry complementary information to the neutral messengers, and allow us to study CR origin, the mechanisms of acceleration, the propagation in the Galaxy, and to study fundamental topics such as the matter-antimatter asymmetry in the Universe, or Dark Matter annihilation [2].

1.1.1 Cosmic Ray Spectrum

The all-particle CR spectrum has been observed in an extensive range in energy, from tens of MeV to tens of EeV, with an intensity falling steeply with energy following a power-law dependence $\propto E^{-\gamma}$, see Fig. 1.1.1. The CR spectrum has several features that can be roughly described as a function of energy:

- **Below GeV** – In this energy region, the spectrum of cosmic rays is influenced by the heliosphere. Solar modulation and transient populations of accelerated particles within the Solar System, such as solar energetic particles (SEPs), can dominate the flux at times, see Sec. 1.2.
- **From GeV up to PeV** – This energy range is characterized by a spectral index $\gamma \simeq 2.7$. Cosmic rays in this region are believed to be predominantly of Galactic origin, as the Galactic magnetic field is sufficient to confine them within the Galaxy. Recent high-precision measurements have revealed subtle spectral variations indicating a more complex behavior than the simple power-law previously assumed.
- **At a few PeV** – A prominent feature known as the *knee* is observed around this energy, where the spectral index steepens from $\gamma \simeq 2.7$ to about $\gamma \simeq 3.0$. This transition is often interpreted as the point where Galactic accelerators, such as Supernova Remnants (SNRs), reach their maximum efficiency in accelerating protons and the emergence of an additional extragalactic component.
- **Hundreds of PeV** – A second feature, called the *second knee*, appears around $E \sim 100$ PeV, where the spectrum further steepens to $\gamma \simeq 3.3$. This is generally associated with the end of the Galactic component, corresponding to the maximum energy achievable for the heaviest nuclei in typical Galactic accelerators. Above this energy, the contribution from extragalactic sources is expected to become increasingly significant.

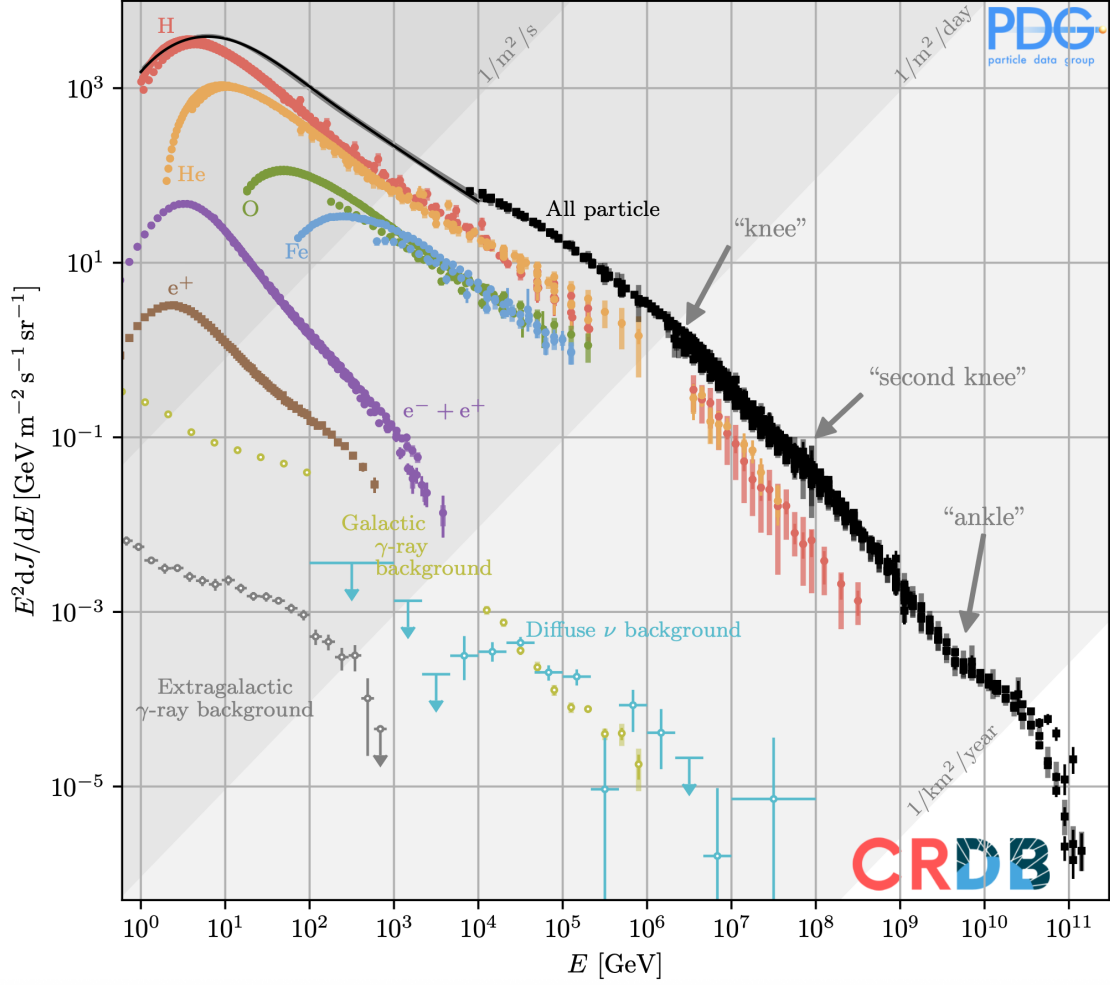


Figure 1.1.1: The spectrum of cosmic rays (CRs). Shown are measurements of the intensity of CRs, multiplied by kinetic energy squared. The various diagonal lines indicate energy-integrated intensities. Measurements employed in this figure are detailed in [2].

- **A few EeV** – A flattening of the spectrum, known as the *ankle*, is observed around $E \sim 3\text{--}5$ EeV, where the spectral index hardens to $\gamma \simeq 2.5$. The ankle is often interpreted as the transition region between the steeply falling Galactic component and a harder extragalactic component. However, other scenarios have been proposed.
- **A few tens of EeV** – The flux of cosmic rays exhibits a strong suppression consistent with the expected Greisen–Zatsepin–Kuzmin cutoff, a theoretical limit arising from energy losses of ultra-high-energy cosmic rays through interactions with the pervasive photon field of the cosmic microwave background.

1.1.2 Galactic Cosmic Rays Composition

Galactic CRs comprise a broad spectrum of charged particles and atomic nuclei. They are generally divided into two main categories: *primary CRs* directly accel-

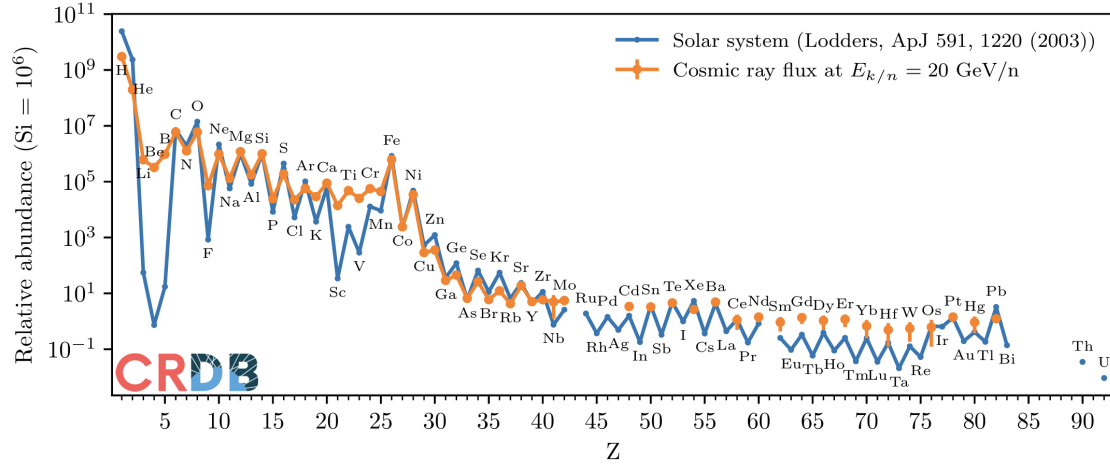


Figure 1.1.2: Cosmic ray abundances compared with Solar System ones [2].

erated at astrophysical sources, and *secondary CRs*, which are produced through spallation reactions when primaries interact with the interstellar medium (ISM), composed mainly of hydrogen and helium. As shown in Fig. 1.1.2, specific nuclei exhibit enhanced relative abundances in CRs compared to the Solar System, providing clear evidence of nuclear fragmentation occurring during their propagation through the Galaxy. Detailed studies of both primary and secondary components offer crucial insights into the origin, acceleration mechanisms, and transport properties of all CRs in the interstellar medium.

1.1.3 Origin and Acceleration of Galactic CRs

Galactic CRs are thought to originate from energetic astrophysical sources within the Milky Way capable of converting a significant fraction of energy into the acceleration of charged particles. The most widely accepted accelerators are SNRs, where strong shock waves produced by stellar explosions accelerate particles via Diffusive Shock Acceleration (DSA). In this process, charged particles gain energy by repeatedly crossing the SN shock front, naturally producing the observed power-law spectra of cosmic rays.

Observational evidence supporting this scenario includes γ -ray measurements from the Fermi experiment, which revealed spectral features consistent with the decay of neutral pions ($\pi_0 \rightarrow \gamma + \gamma$), being themselves the byproducts of hadronic interactions between high-energy protons and ambient gas in SNR environments. Such signatures provide evidence for hadronic acceleration within supernova remnants [4].

Additional evidence suggests that Galactic CRs may originate in OB associations, regions densely populated by massive, short-lived stars that end their lives as supernovae. These environments host an enhanced rate of supernova explosions. Measurements of the trans-iron elemental composition in CR show similarities with those expected from such regions, supporting the scenario of acceleration of CRs in SNRs [5].

Although a definitive identification of the sources of Galactic CRs remains elusive, SNRs are widely regarded as the dominant contributors. Other potential Galac-

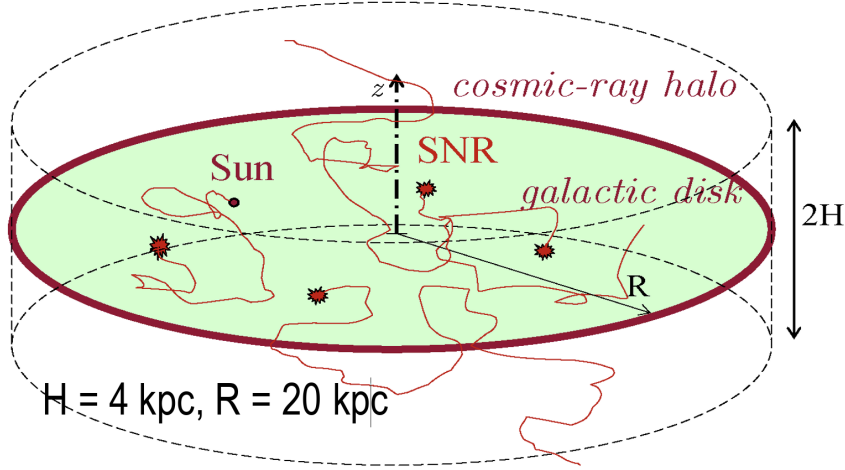


Figure 1.1.3: In this sketch are presented the conceptual elements of Galactic CR transport: production in the disk, diffusive propagation within the magnetized halo, and eventual leakage from the Galaxy’s boundaries.

tic accelerators, including pulsar wind nebulae, massive star clusters, and binary stellar systems, may also contribute to the observed flux [2].

1.1.4 Galactic CR Propagation in the Galaxy

Once accelerated, Galactic CRs propagate throughout the Galaxy, trapped by the Galactic magnetic field. In Fig. 1.1.3, a sketch of CRs as they propagate away from their sources located on the Galactic disk is presented. Their trajectories are diffusive, governed by scattering off turbulent Galactic magnetic fields, which randomize their directions and lead to an almost isotropic flux at Earth. During propagation in the ISM, CRs may undergo inelastic interactions, secondary production, decay, ionization losses, Coulomb interactions, and, for leptons, radiative losses such as synchrotron emission and inverse Compton scattering. The diffusion process confines CRs within the Galactic halo for millions of years before they eventually escape into intergalactic space.

The observed composition and secondary-to-primary ratios (see Fig. 1.1.2) provide strong evidence for this diffusive transport and allow estimates of the residence time and spatial distribution of GCRs within the Galactic halo.

1.1.5 Galactic CR Propagation in the Heliosphere

The Sun is a main-sequence star that produces energy through nuclear fusion in its core. The Sun radiates a continuous flow of charged particles, called the *solar wind* (SW), mainly consisting of protons and electrons, that propagates radially in the Solar System at speeds of 300–800 km/s.

The heliosphere is the region of space dominated by the Sun’s influence. The global shape of the heliosphere is determined by the interaction of the solar wind with the ISM, see Fig. 1.1.4. The *termination shock* marks the point where the solar wind slows to subsonic speeds due to interactions with the ISM, causing compres-

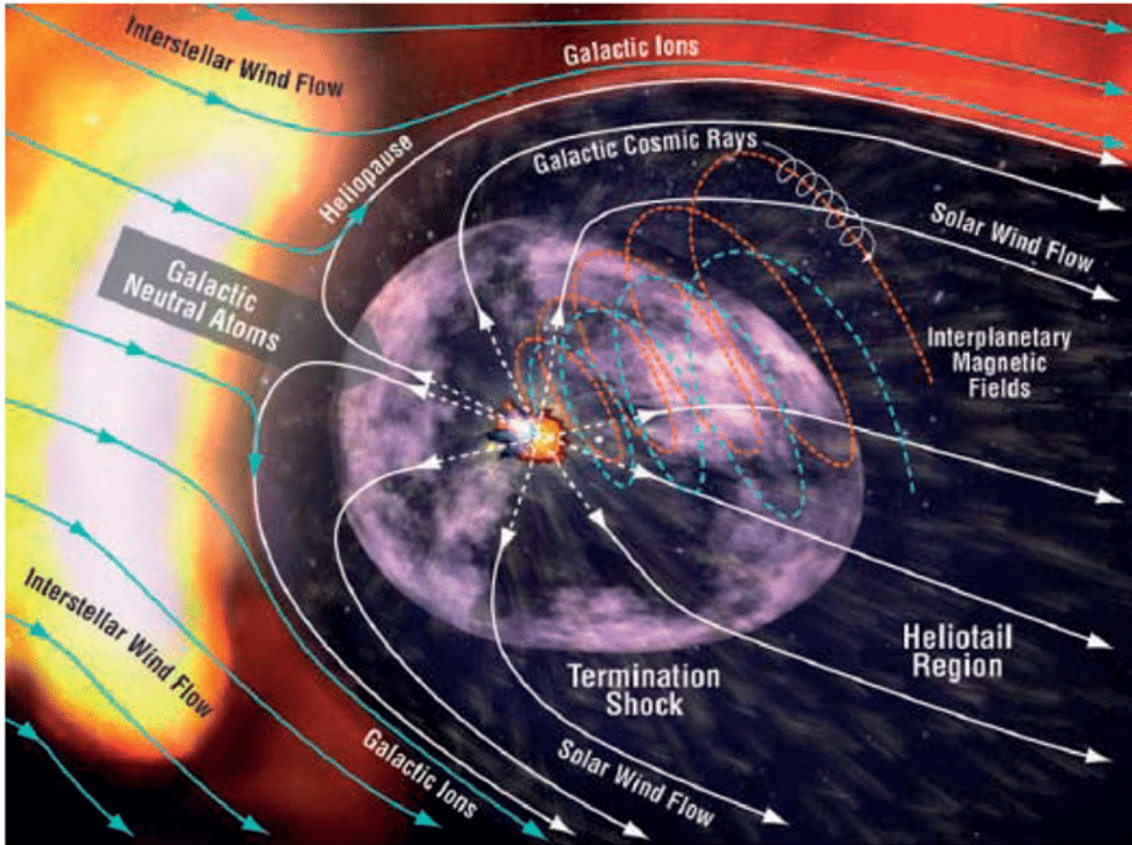


Figure 1.1.4: An artist's rendition of the structure of the heliosphere. The interaction between the ISM and the SW creates the heliopause that delimits the heliosphere.

sion, heating, and magnetic field changes. Beyond the termination shock lies the *heliosheath*, a turbulent region where the slowed solar wind continues to interact with the ISM. The outermost boundary, the *heliopause*, is where the solar wind pressure balances that of the ISM, marking the limit of the Sun's influence. The various structures of the heliosphere can be seen in Fig. 1.1.4.

The Sun generates a magnetic field that extends outward, embedded in the solar wind plasma, twisting it into a spiral shape known as the Parker spiral. This *Heliospheric Magnetic Field* (HMF) governs the motion of charged particles and plays a crucial role in solar modulation of Galactic CRs.

The Sun's magnetic field evolves over an 11-year solar cycle. At the start of the cycle, the Sun's magnetic field is relatively weak and simple, with a dipolar structure. As the cycle progresses, differential rotation and plasma convection twist and tangle the magnetic field lines, forming *sunspots* that correspond to particularly active regions. Magnetic activity reaches a maximum at the cycle's peak when the magnetic field reverses. Then the activity gradually declines. By the end of the cycle, the field returns to a simple dipolar configuration with the polarity reversed, completing the cycle.

When Galactic CRs enter the heliosphere, they are subject to diffusion, convection, drift, and adiabatic energy losses due to their interactions with the SW and the HMF, making the CR fluxes observed at Earth markedly different from those in

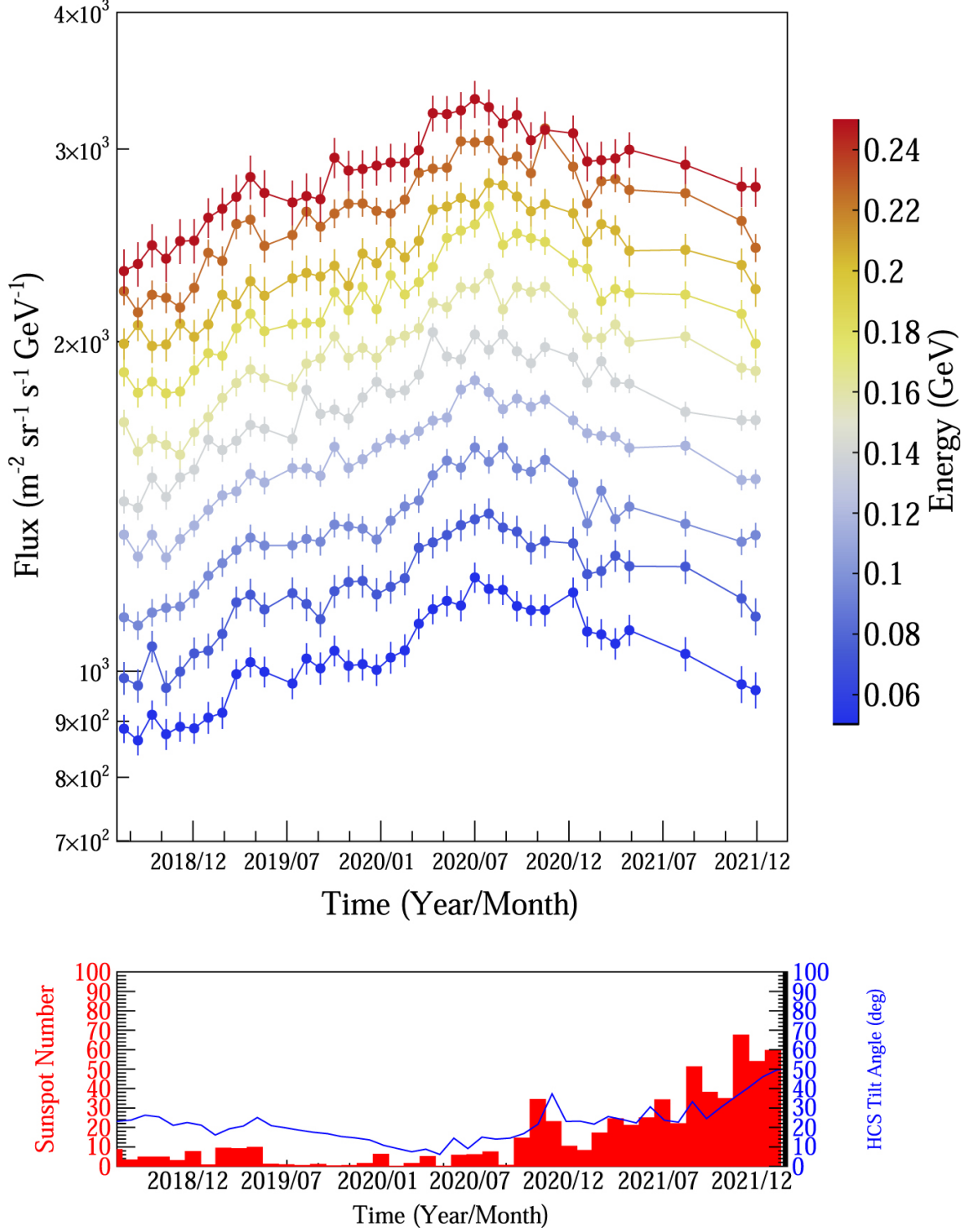


Figure 1.1.5: *Top* – Time profile of GCR protons measured by HEPD-01 in 10 energy intervals (upper panel) between 2018 and 2022. *Bottom* – Sunspot number (red) and HCS tilt angle values (blue) as a function of time, in the same period (bottom panel) [6].

interstellar space. These interactions also cause variations in Galactic CR intensity with energy, position, and time, depending on solar activity. The global effect of the heliosphere on CR is known as *solar modulation*. The solar-modulated energy

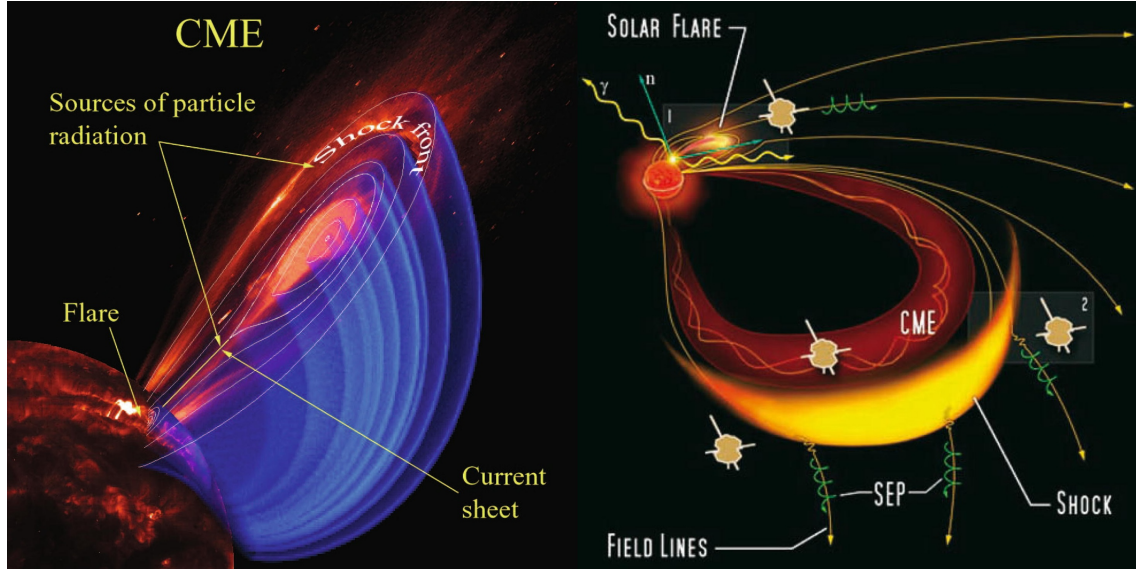


Figure 1.2.1: Left: a SEP generated in a flare. Right: SEPs associated with a CME interplanetary shock [7].

spectrum of GCRs is anti-correlated with solar activity; that is, the measured flux is higher during periods of low solar activity and lower during periods of high solar activity. This anti-correlation is clearly observed when comparing cosmic ray fluxes with the Solar Sunspot Number (SSN), a reliable indicator of solar activity. Figure 1.1.5 illustrates with HEPD-01 data the anti-correlation between SSN and GCR counts across portions of the 24th (2008-2019) and 25th (started $\sim$ 2019/2020) solar cycles [6].

1.2 Particles Accelerated in the Heliosphere

Many processes in the heliosphere can accelerate particles and produce significant ionizing radiation that can be observed in the vicinity of Earth. In some cases, it becomes the most important source of radiation in the Near-Earth environment. The following describes some of the most essential acceleration mechanisms available in the heliosphere.

1.2.1 Solar Energetic Particles

Solar Energetic Particles (SEPs) consist of protons, electrons, and heavier ions that have been accelerated to relativistic speeds during explosive solar events. These particles can be accelerated up to tens of GeV in energy, with flux intensities that can be several orders of magnitude higher than those observed for Galactic CRs. Due to their short-term nature, SEP events last up to a maximum of a few days.

As schematically presented in Fig. 1.2.1, two main mechanisms are responsible for SEP events:

- **Impulsive SEPs events** – the magnetic field lines of the Sun are twisted by the differential rotation of the star. When the magnetic stress becomes

too great, the field lines can suddenly reconnect, releasing vast amounts of magnetic energy in a *solar flare*. This process converts stored magnetic energy into kinetic energy, heat, and energetic particles. The reconnection region provides an environment that efficiently accelerates charged particles. Particles accelerated at flares are typically short-duration, ranging from several minutes to a few hours, and display a distinctive chemical composition.

- **Gradual SEPs events** – a *Coronal Mass Ejection* (CME) is a large-scale eruption of magnetized plasma that is expelled from the corona into interplanetary space. CMEs can travel at speeds exceeding 2000 km/s, and when they move faster than the local speed of magnetosonic waves, they create an interplanetary shockwave. This environment allows for the DSA in an analogous way to CR accelerating in an SNR, albeit on a different scale. Because this acceleration occurs over extended distances and timescales at the CME shock front, it produces prolonged energetic particle emission that can persist for several days as the shock travels through the heliosphere. These SEPs are distinguished by their long duration, high intensity, and broad spatial extent.

While flare-associated and CME-associated SEPs can be treated as distinct categories, in reality, solar eruptive events often involve both processes.

1.2.2 Space Weather

Solar phenomena, such as solar flares, coronal mass ejections, and variations in the solar wind, interact with Earth’s magnetosphere, ionosphere, and radiation belts, causing dynamic changes in their composition, structure, and intensity. These solar-driven processes influence geomagnetic storms, particle fluxes, and radiation levels in near-Earth space.

Solar activity, in particular SEPs, can pose significant risks to astronauts, satellites, and even ground-based systems due to the high levels of radiation they can emit. Understanding where and how these particles are accelerated is therefore essential for both space weather forecasting and the broader study of solar-terrestrial interactions.

1.2.3 Anomalous Cosmic Rays

Anomalous Cosmic Rays (ACRs) are a distinct component of the cosmic ray population that originates from neutral interstellar atoms that drift into the heliosphere, become ionized by solar ultraviolet radiation or charge exchange, and are then “picked up” by the solar wind magnetic field as pickup ions. These ions are carried outward with the solar wind until they encounter the heliospheric termination shock—the boundary where the supersonic solar wind slows abruptly due to interaction with the interstellar medium. Upon this shock, the ions undergo DSA, repeatedly scattering back and forth across the shock front. Through this mechanism, the particles are accelerated to energies of tens to hundreds of MeV. The resulting ACRs are enriched in elements such as helium, nitrogen, oxygen, and neon, reflecting their interplanetary origin, and they provide key insights into particle acceleration and transport processes occurring at the outer boundary of the heliosphere.

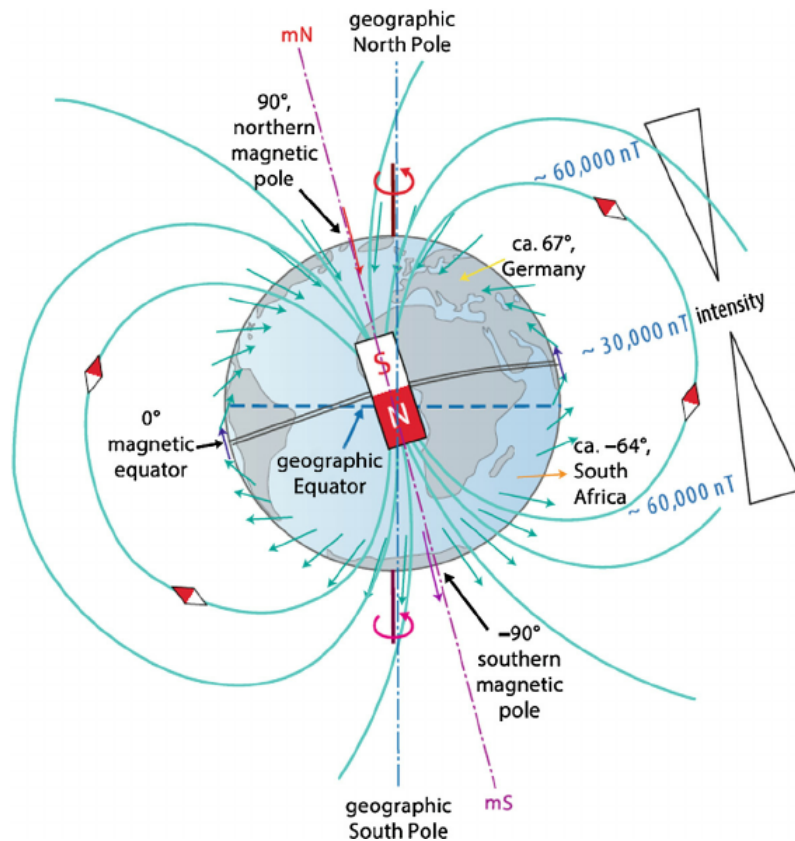


Figure 1.3.1: A schematic view of the Earth's magnetic field principal dipole.

1.3 Particles in the Magnetosphere

The Earth's magnetic field is generated by dynamo processes in the planet's liquid outer core. Charged particles impinging on the Earth from space are deflected by the Lorentz force, preventing low-energy particles from reaching the atmosphere. This shielding is strongest near the equator, while at high latitudes near the magnetic poles, particles can follow field lines into the upper atmosphere. A spectacular consequence of this precipitation of energetic particles is the aurora, observed as lights produced by atoms excited by the collision with incoming radiation.

Another critical effect of Earth's magnetic field on incoming charged particles is the creation of regions where radiation can be accumulated. The *Van Allen radiation belts* are toroidal regions of intense particle flux, mainly electrons and protons, originating from the solar wind and CRs, and constitute a significant source of radiation in near-Earth space.

In the following sections, the main properties of the Earth's magnetic field, the shielding effect, and the origin and main characteristics of the trapped populations will be discussed.

1.3.1 Earth's Magnetic Field

The Earth's magnetic field is a global field resulting from the summation of multiple sources. The principal field is the *inner magnetic field* and is caused by movements

in the planet's core and crust. It is the dominant field out to about 4 Earth radii. This field is essentially a dipole, with the central axis tilted by about 11° , as shown in Fig. 1.3.1. This field has a slow secular variation. At distances higher than 4 Earth's radii, an *external magnetic field* caused by current systems due to the interaction of the SW with the magnetosphere becomes the dominant source. At these distances, the magnetic field is compressed on the day side and has a long tail on the night side. The time variation of the external field is correlated with solar activity; therefore, it can be much more variable than the internal field.

Gauss showed in 1839 that the Earth's magnetic potential can be represented by a spherical harmonic series, with the dipole component dominating. A standard model currently employed to describe the inner Earth's magnetic field is the International Geomagnetic Reference Field (IGRF) model [8]. The IGRF model is described as the multipole expansion of the magnetic potential $V(r, \theta, \phi, t)$:

$$V(r, \theta, \phi, t) = a \sum_{n=1}^N \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} [g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi] P_n^m(\cos \theta). \quad (1.3.1)$$

Here, r, θ, ϕ refer to coordinates in a geocentric spherical coordinate system. The P_n^m are Schmidt semi-normalized associated Legendre functions of degree n and order m . The parameter N specifies the maximum spherical harmonic degree of expansion. The Gauss coefficients $g_n^m(t)$ and $h_n^m(t)$ determine the intensity of the multipoles. The model is based on magnetic field surveys at multiple stations worldwide, including repeated measurements, ship- and aircraft-based surveys, and spaceborne magnetometers.

The external component of Earth's magnetic field is generated by magnetospheric current systems, including the ring current, tail current, magnetopause currents, and field-aligned (Birkeland) currents.

The external magnetic field is usually described using the Tsyganenko models, which add a series of additional fields to the inner field generated by magnetospheric current systems [9]. The Tsyganenko model is a semi-empirical approach based on large sets of satellite magnetic field measurements and solar-geomagnetic activity indices.

1.3.2 Rigidity Cutoff

A charged particle in a magnetic field follows a trajectory given by the Lorentz force:

$$\frac{d\vec{p}}{dt} = q (\vec{v} \times \vec{B}), \quad (1.3.2)$$

where q , $\vec{v}$, $\vec{p}$ are respectively the particle charge, velocity, and momentum, while $\vec{B}$ is the magnetic field vector. When considering a simple dipolar magnetic field, a theory of possible particle trajectories can be analytically derived [10]. From this theory, it can be observed that for any location in the magnetosphere, only particles with a rigidity ($R = p/q$) exceeding a given *Störmer cut-off rigidity* can arrive from outside the magnetosphere. In contrast, trajectories with lower rigidity are forbidden. The Störmer cut-off rigidity is given by the formula:

$$R_c = \frac{M \cos^4 \lambda}{r^2 [1 + \sqrt{1 - \cos^3 \lambda \cos \epsilon \sin \xi}]^2}, \quad (1.3.3)$$

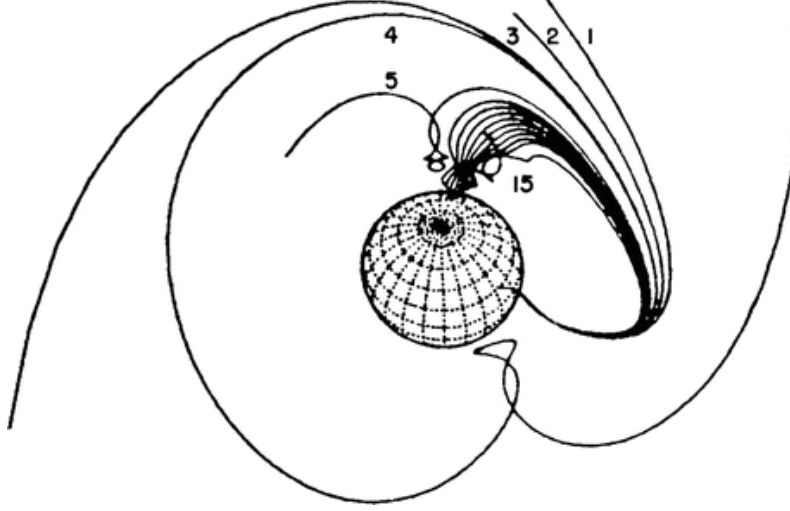


Figure 1.3.2: Illustration of the cosmic ray trajectory-tracing process in a realistic geomagnetic field. The highest rigidity is labeled 1 and the lowest rigidity is labeled 15 [11].

where M is the dipole moment, r is the distance from the dipole center, λ is the *geomagnetic latitude* from the magnetic equator, ϵ and ξ are angles indicating the particle arrival direction, ϵ is the azimuthal angle measured clockwise from the geomagnetic east direction (for positive particles), and ξ is the angle from the local magnetic zenith direction.

A few remarks about Eq. 1.3.3:

- **Vertical cutoff** – when considering incident vertical particles, the formula simplifies to the so called *vertical cutoff*, $R_{cv} = \tilde{R} \cos^4 \lambda / r^2$, where $\tilde{R} \sim 14.5$ GV when r is considered as the dipolar distance in units of Earth's radius. Essentially, in near orbit (~ 500 km altitude), at the equator the vertical cutoff is maximum and above 10 GV, while it can be well below 100 MV at high magnetic latitudes.
- **Forbidden Cone** – the dependence on the arrival direction in Eq. 1.3.3, shows that, for a given rigidity, there exists a cone of forbidden trajectories coming from magnetic east, contributing to the observed East-West CR asymmetry.

Because the Earth's magnetic field is quite close to a pure dipole, the Störmer rigidity cutoff remains, even today, an important reference quantity in many space applications.

To have a more realistic evaluation of the allowed and forbidden trajectories for an incoming charged particle in a specific location in the magnetosphere, a realistic Earth's magnetic field model, such as the ones introduced in Sec. 1.3.1 should be employed, and trajectories evaluated by solving Eq. 1.3.2. The inclusion of the Earth's shadow is also essential for getting a realistic result.

In Fig. 1.3.2, an example of tracing cosmic ray trajectories is shown. In the figure, high rigidity cosmic rays have simple trajectories. As the particle's rigidity decreases, bending increases and orbits become more complicated, forming intermediate loops. Trajectories that would usually be allowed in a pure magnetic field become forbidden

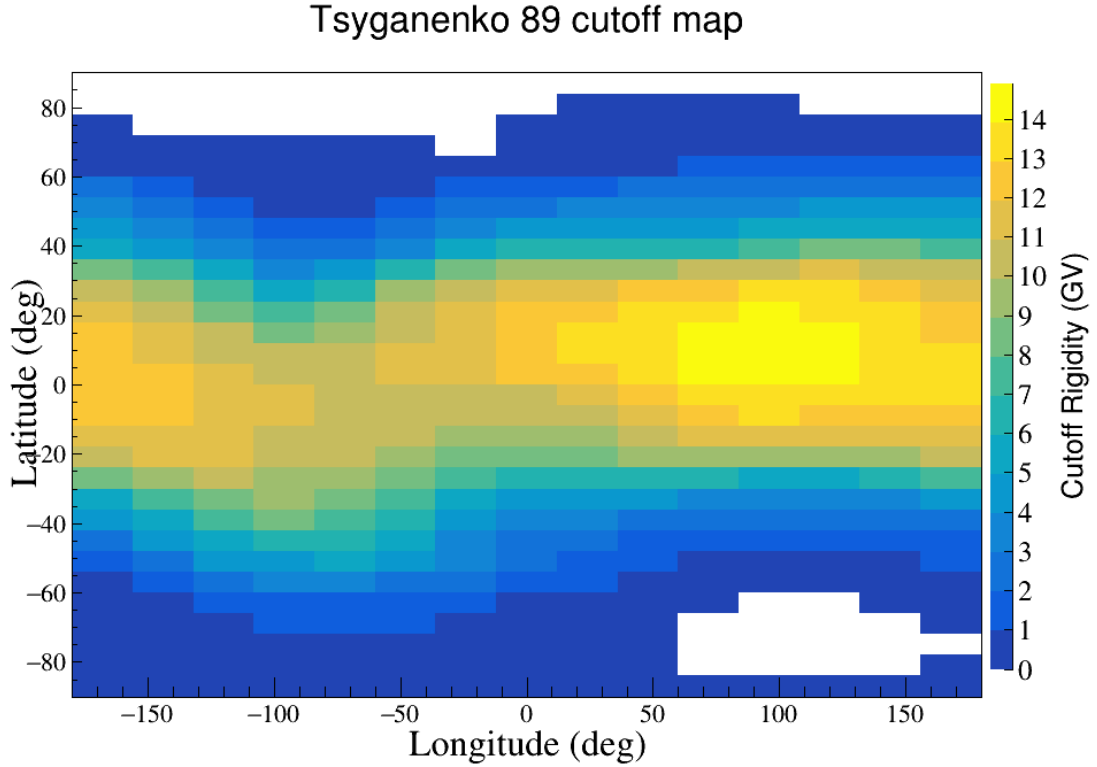


Figure 1.3.3: The vertical rigidity cutoff map computed for the HEPD-01 instrument. The magnetic field used is a combination of IGRF-13 [8] and T89 [9].

due to the presence of the Earth. At still lower rigidities, allowed trajectories may still exist. This complex structure of allowed and forbidden orbits forms the so-called *CR penumbra* [11]. The presence of a penumbra frustrates the CR physicists' efforts to define a unique cutoff for any given position and direction in the geomagnetic field.

In the case of this thesis, a computation of the *upper vertical rigidity cutoff* (rigidity above which all trajectories are allowed) was done employing particle tracing in the IGRF model and taking into account the magnetospheric modulation from Tsyganenko [9]. The cutoff map used is shown in Fig. 1.3.3.

1.3.3 Radiation Belts

Complementary to particles with trajectories rejected by the Earth's Magnetic field, trajectories completely bounded around the Earth are possible. The *Van Allen belts* are regions in the Earth's magnetic field where energetic charged particles are trapped. There are two belts, an inner and outer belt, that span from approximately 1000 km to 65000 km above the Earth's surface. These belts consist primarily of energetic electrons (with energies between 1 MeV and 50 MeV) and protons (with energies between 10 MeV and 1 GeV).

Particles bounded in the belts have a characteristic motion that can be separated into three periodic motions that have a different timescale, as depicted in Fig. 1.3.4: a fast *gyration* around the magnetic field lines, a slower *bouncing* along the field lines between mirror points in the northern and southern magnetic hemispheres,

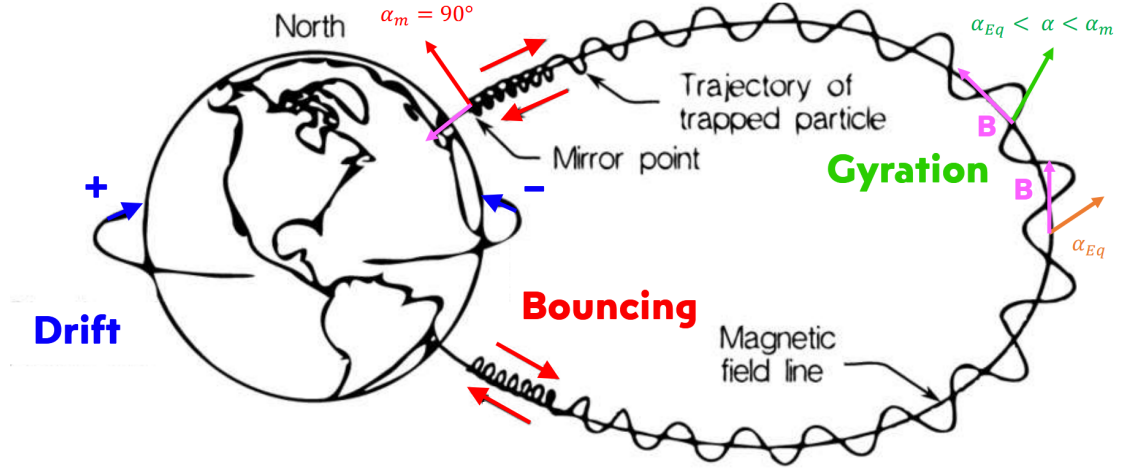


Figure 1.3.4: An artist's rendition of the three motion trajectories of trapped particles: gyration around the magnetic field line, north-south bouncing (magnetic mirroring), and a drift around Earth in opposite direction for opposite charge sign particles.

and a very slow longitudinal *drift* around the Earth. Mirror points are locations where the angle between the particle's velocity vector and the magnetic field line is 90° , causing the particle's velocity parallel to the magnetic field to drop to zero and reverse direction. If a mirror point is situated below the top of the atmosphere, the particle may interact with residual atoms of rarefied air, lose energy, and become lost.

While particles from outside the geomagnetic field cannot penetrate the belts, their interaction with the atmosphere can generate secondaries that can be trapped in the belts. An essential source of trapped particles is the production of secondary neutrons that can travel in Earth's magnetic field without disturbance and, after decay, become trapped protons.

1.3.4 Stability of the Radiation Belts

Van Allen belts are generally stable; however, changes in the magnetic field from impulsive solar phenomena can cause variations in their contents. Studies have also looked into the connection between seismic activity and local instabilities in the Van Allen belts. Some space experiments have detected abnormal particle fluxes a few hours before earthquakes [13]. These sudden bursts of particles are believed to result from precipitation of particles from the inner belt following interactions between seismo-electromagnetic emissions and Van Allen radiation-belt particles.

Possible Lithosphere-Atmosphere-Ionosphere coupling phenomena (LAIC) refer to the complex interactions and exchanges of energy and matter among the Earth's solid crust (lithosphere), the gaseous envelope surrounding the Earth (atmosphere), and the upper atmosphere ionized by solar radiation (ionosphere). Various theories and hypotheses have been proposed to explain the interconnectedness of the Earth's crust, atmosphere, and ionosphere. A possible proposed model is the MILC

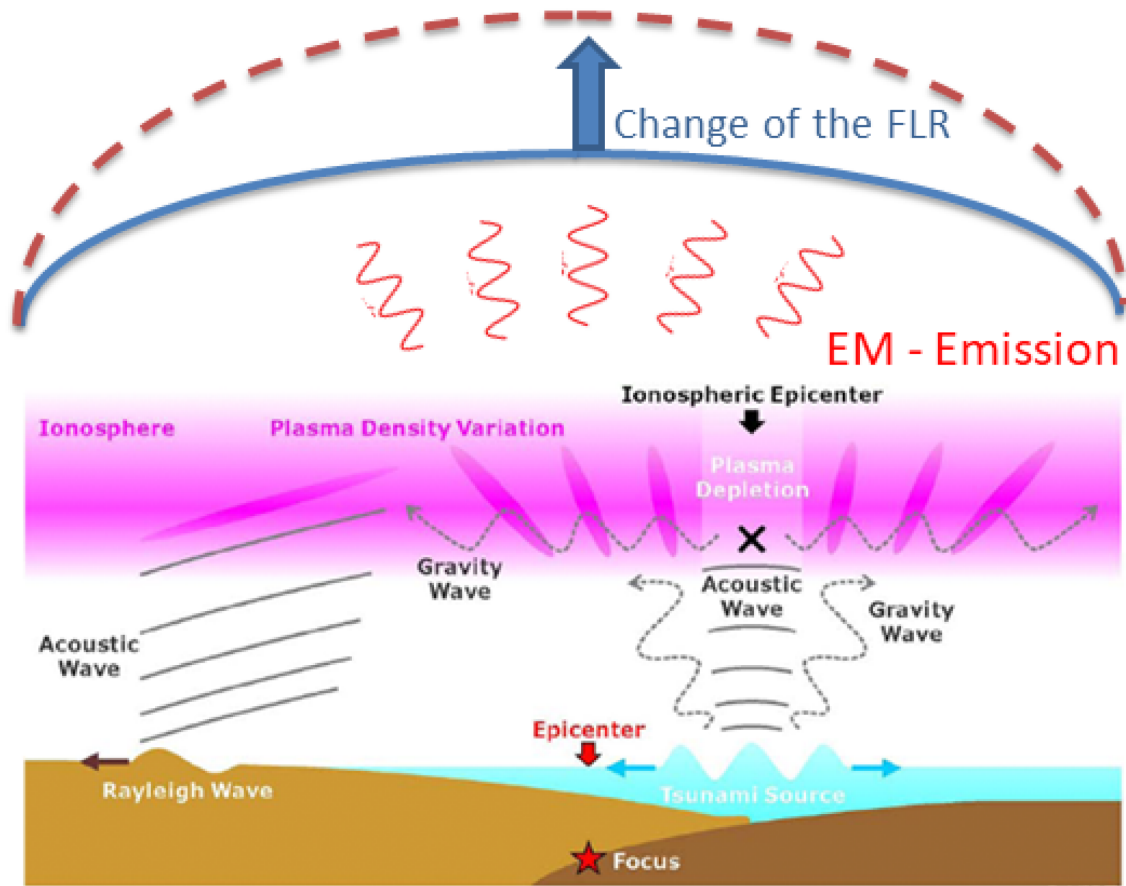


Figure 1.3.5: An artist rendition of a possible model describing Magneto-spheric-Ionospheric-Lithospheric Coupling (MILC model) [12].

model [12], sketched in Fig. 1.3.5.

Earthquakes are among the most hazardous natural disasters, with powerful earthquakes occurring approximately 20 times a year worldwide. An earthquake is a sudden release of a significant amount of elastic energy stored in the Earth's lithosphere, resulting in deformation, fractures, structural changes, and phase transformations, accompanied by the emission of seismic waves. During the preparatory phase of seismic events, various seismo-electromagnetic perturbations have been observed on the ground and in space. Proposed models explaining their generation mechanisms involve physical phenomena such as piezoelectricity, piezomagnetism, and electrokinetic processes. As these disturbances propagate through the Earth's crust, higher frequencies are attenuated, allowing only low-frequency components up to VLFs to reach the Earth's surface and extend into the near-Earth space [14, 15, 16, 17].

The interaction of these electromagnetic emissions with the ionospheric environment is believed to lead to direct and indirect perturbations in the plasma, electromagnetic fields, and particles trapped in the Van Allen radiation belts. Some observations from low Earth orbit (LEO) satellites support the scenario as mentioned above. Pre-seismic variations in electric and magnetic fields [18, 19, 20], ionospheric plasma temperature, and density [21, 22, 23] have been observed minutes to hours (2–6 hours) before moderate to strong earthquakes. Notably, analysis

of DEMETER data has provided valuable insights into ionospheric perturbations that may be associated with earthquakes; for example, the detection of an electromagnetic emission at a distinct frequency of 333 Hz two days before the 6.3 Mw earthquake in L'Aquila in 2009 [24].

Chapter 2

The China Seismo-Electromagnetic Satellite Missions

The China Seismo-Electromagnetic Satellite (CSES) program is a joint space initiative between China and Italy, conceived to study the near-Earth electromagnetic, plasma, and particle environment in low Earth orbit (LEO). A central scientific goal of the mission is to investigate the mechanisms coupling characteristics of the ionosphere and magnetosphere with the occurrence of natural phenomena such as earthquakes, volcanic activity, and lightning, as well as with artificial causes such as low-frequency electromagnetic emissions from ground-based transmitters. Other mission purposes include the measurement of cosmic ray particles, from the Galaxy and the Sun, and the constant monitoring of Space weather [25, 26].

To achieve these scientific purposes, CSES satellites are equipped with scientific payloads that measure various characteristics of the LEO environment, including electromagnetic field components, plasma parameters, energetic particles, and X-ray fluxes. This comprehensive instrumentation enables the satellites to act as full-fledged space observatories, continuously monitoring the entire globe and providing valuable data for both fundamental geophysical studies and space weather research.

The first satellite of the program, CSES-01, was launched on February 2, 2018, and has been operating continuously since then. More recently, a second satellite, CSES-02, was successfully launched on June 14, 2025, and is currently in commissioning. Together, these missions are intended to form the basis of a constellation of satellites, ensuring long-term monitoring capabilities and improved coverage.

Among the key scientific instruments aboard both satellites is the High-Energy Particle Detector (HEPD), designed, built, and operated by the Italian Limadou collaboration. On board CSES-01 is the original HEPD-01, while HEPD-02, a revised and upgraded version, is installed on CSES-02. Both detectors are specifically designed for high-precision measurements of the fluxes and energy spectra of electrons, protons, and light nuclei in the energy range from a few to several hundred MeV.

The present chapter is organized as follows: in Sec. 2.1, the CSES satellite missions are described; Sec. 2.2 discusses the scientific motivations underlying the program; finally, Sec. 2.3 and 2.4 provide a detailed overview of the High-Energy Particle Detectors and their in-flight performance.

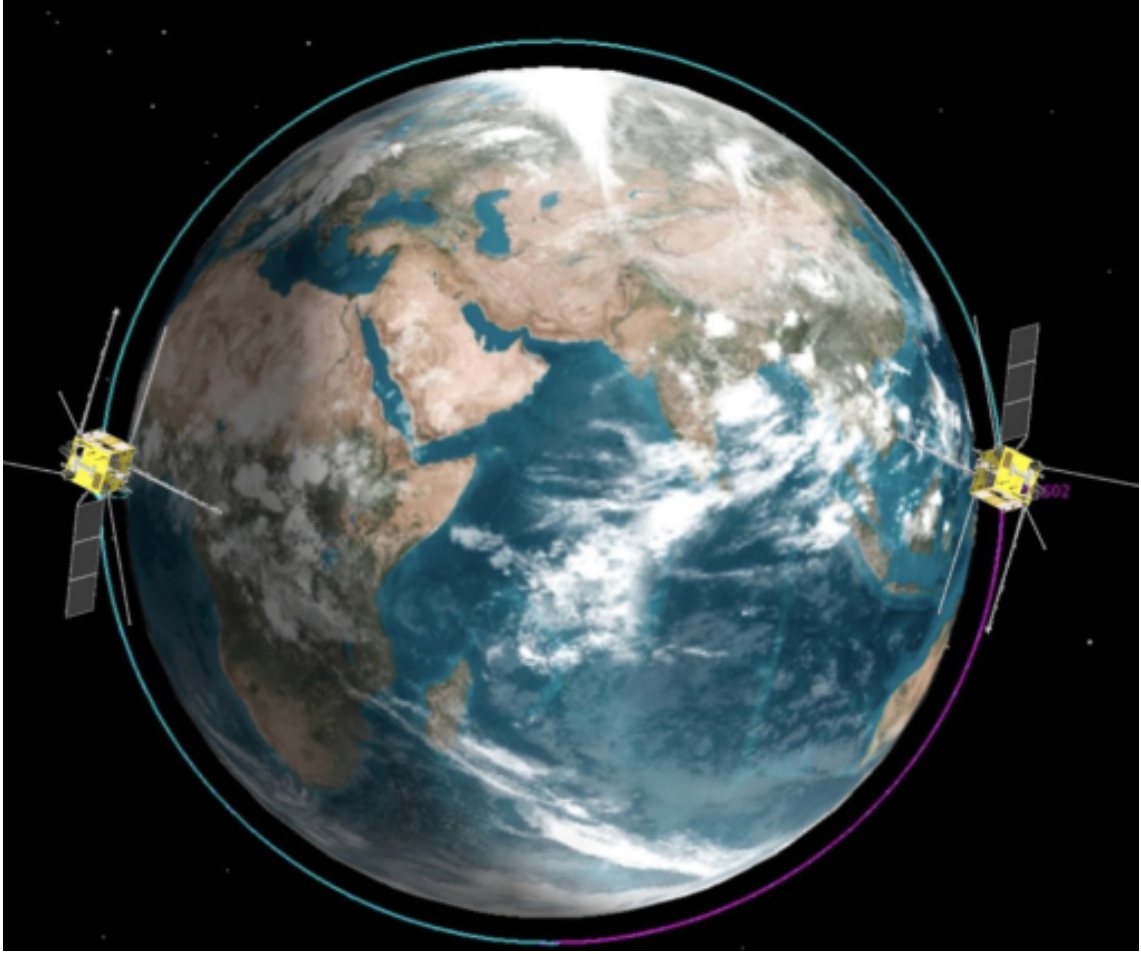


Figure 2.1.1: The two CSES satellites, CSES-01 and CSES-02, are on the same polar orbit, with a phase difference of 180° .

2.1 The CSES Satellite Constellation

The CSES constellation currently consists of two satellites: CSES-01 (Zhangzheng-1) and CSES-02 (Zhangzheng-1-02). Both are in orbit and have been operating continuously since their respective launches. The spacecraft are based on the CAST2000 platform, developed by DFH Satellite Co., Ltd., while the scientific payloads were designed and developed through collaboration between European and Chinese research institutes.

Both satellites were launched aboard unmanned Chinese Long March 2D rockets from the Jiuquan Satellite Launch Center located in Inner Mongolia. CSES-01 was launched on the 2nd of February, 2018, while CSES-02 was launched on the 14th of June, 2025. Both satellites are placed in a Sun-synchronous orbit with an inclination of 97.4° and an average altitude of 507 km. The CSES-02 was injected into the same orbital plane as CSES-01 with a 180° phase shift, enabling a complementary ground track, as seen in Fig. 2.1.1. This configuration effectively reduces the revisit time from 5 days to 2.5 days, significantly improving temporal resolution and correlation capabilities, and establishing a new dual-satellite system for ionospheric monitoring. Both satellites rely on an Earth-oriented 3-axis stabilization system with an attitude

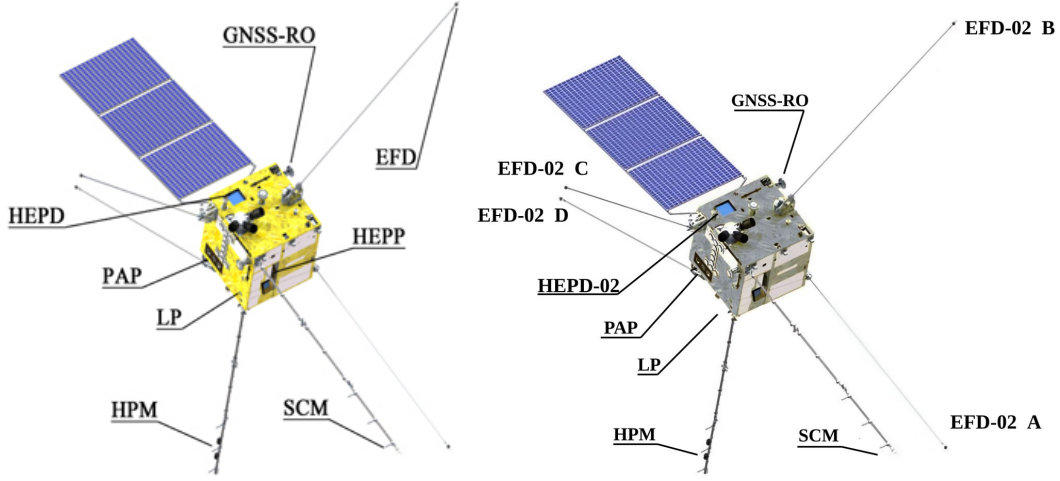


Figure 2.1.2: On the left (right), an artist rendition of the CSES-01 (CSES-02) satellite. The multiple scientific payload and subsystems are indicated.

pointing accuracy $\leq 0.1^\circ$.

Globally, CSES-01 has a mass of about 750 kg and a peak power consumption of about 900 W. The CSES-02 satellite has a similar total mass of about 900 kg and a peak power consumption of ~ 900 W. The available bandwidth for data transmission for the two satellites is 120 and 150 Mbps, respectively. Unlike CSES-01, whose payload operations were initially limited to latitudes between $\pm 65^\circ$ (later expanded to $\pm 70^\circ$), CSES-02 enables full-orbit payload operations even over the poles, significantly enhancing the capability to measure CRs.

Each CSES satellite hosts similar suites of scientific payloads able to measure different properties of the ionosphere, as described in detail in Ref. [26] and the CSES-02 webpage¹. A complete list of the instruments present aboard the two satellites follows. To see where these payloads are located on the satellites, see Fig. 2.1.2.

- **Magnetometers** – both satellites include a High-Precision Magnetometer (HPM), including a coupled dark-state scalar magnetometer and a fluxgate magnetometer, for measuring the low-frequency range, intensity, and three components of the magnetic field, and a Search-Coil Magnetometer (SCM) for measuring the three components of the magnetic field at higher frequency;
- **Electric Field Detector (EFD)** – measures the ionosphere electric field components in a wide frequency range, from DC up to 3.5 MHz. The detector is present in both satellites. The second version, EFD-02, developed by the Italian collaboration, features significant advancements allowing for measurements with enhanced sensitivity and spatial resolution;
- **Plasma analysis** – each satellite include two instruments for plasma investigation, i.e., a Plasma Analyzer Package (PAP) and a Langmuir Probe (LP), able to observe ion and electron density (in the range $5 \times 10^2 \div 10^7 \text{ cm}^{-3}$) and plasma temperature (in the range $500 \div 10000\text{K}$), ion drift velocity, and plasma composition (H^+ , He^+ , O^+);

¹<https://www.cseslimadou.it/cses02-china-seismo-electromagnetic-satellite/>

Table 2.1.1: Energy measurement ranges of particle detectors onboard CSES-01 and CSES-02 satellites.

Mission	Instrument	Electrons	Protons	Nuclei
CSES-01	HEPP-L	0.3–3 MeV	2.5–20 MeV	–
	HEPP-H	2–50 MeV	3–200 MeV	–
	HEPD-01	3–100 MeV	30–200 MeV	50–200 MeV/n
CSES-02	MEED	0.025–3.2 MeV	–	–
	HEPD-02	3–100 MeV	30–200 MeV	30–200 MeV/n

- **Plasma profile** – three-frequency (VHF/UHF) beacon transmitter for studying the ionospheric plasma profile;
- **A Global Navigation Satellite System (GNSS);**
- **Particle detectors** – CSES-01 contains the Chinese High-Energy Particle Package (HEPP) and the Italian High-Energy Particle Detector (HEPD-01), for measuring high-energy charged particles. Instead, in CSES-02, the Medium Energy Electron Detector (MEED) replaces the HEPP used in CSES-01, while HEPD-02 is a new and improved version of HEPD-01. In Tab. 2.1.1 are shown the energy ranges for different particle species that can be measured with these instruments.

Additionally, CSES-02 contains two additional instruments: a Coherent Population Trap (CPT) system and an Ionospheric Photometer (IP).

2.2 Scientific motivations

The primary objective of the CSES mission is to investigate how processes in the Earth’s lithosphere, such as earthquakes, seismic activity, and volcanic eruptions, can generate perturbations that propagate through the atmosphere, ionosphere, and magnetosphere, causing disturbances in electromagnetic fields, plasma, and energetic particles. In particular, analyze the spatial and temporal correlations between seismic events and electromagnetic emissions, ionospheric anomalies in electric and magnetic fields or plasma density, and particle precipitation from the radiation belts (see Sec. 1.3.4).

The second objective of the mission is to advance the study of solar-terrestrial interactions and cosmic-ray physics. Operating within Earth’s dynamic geomagnetic environment, CSES complements past missions on radiation belts (e.g., SAMPEX [27]) and cosmic rays (e.g., PAMELA [28], AMS-01 [29], AMS-02 [30]) by observing at similar or lower altitudes and covering an intermediate energy range. These objectives are among the main subjects of the HEPD detectors. In the following sections, we will expand more on the specific goals of the HEPD program on the CSES satellites.

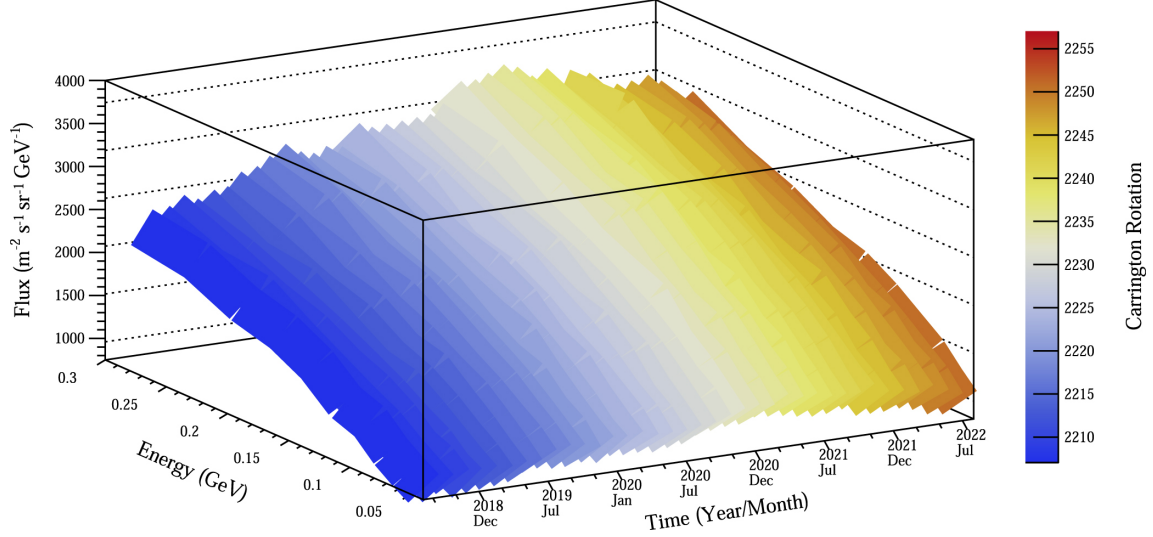


Figure 2.2.1: Evolution of HEPD-01 galactic CR protons as a function of energy and time between 2018 and 2022. The spectra slowly rise before 2020 July, reaching the solar minimum, and start decreasing from the second half of 2020 onward [6].

2.2.1 Cosmic-Ray and Solar Studies

HEPDs measure the fluxes of galactic CR electrons, protons, and light nuclei in the energy ranges of 3–100 MeV, 30–200 MeV, and 50–200 MeV/nucleon, respectively. These measurements are only possible at the highest geomagnetic latitudes ($\gtrsim 60^\circ$), where sub-GeV particles originating outside the magnetosphere—either accelerated by processes in the Galaxy or within the solar system—can penetrate down to the CSES orbital altitude.

The galactic CR fluxes in the MeV region are relatively poorly known, yet they are of fundamental importance for understanding the origin, acceleration, and propagation of cosmic rays. They provide a crucial link between the low-energy measurements made by Voyager beyond the heliosphere [31] and the high-energy observations from experiments such as PAMELA, AMS-01, and AMS-02 [28, 29, 30].

When observed from Earth, CR fluxes are strongly influenced by the SW and the HMF, see Sec. 1.1.5. These interactions produce variations in the CR energy spectra that depend on solar activity. Such variations can manifest as long-term periodic changes over the solar cycle, during which CR fluxes are at a minimum when the solar activity is at a maximum, and vice versa. An example of this effect is provided by the HEPD-01 measurements between solar cycles 24 and 25, where the CR flux reached its peak (see Fig. 2.2.1). Time-dependent CR spectra thus carry valuable information about the Sun’s activity and can be used to model CR propagation through the heliosphere—an essential step for understanding particles originating outside it and for searching for exotic components such as those potentially produced by dark matter annihilation.

Shorter scale periodicities also exist in CR fluxes. One evident case is the 27-day periodicity that is a consequence of the solar rotation and has been observed in the proton flux with the HEPD-01, as presented in Fig. 2.2.2.

Beyond solar modulation, each solar cycle also features numerous short-term

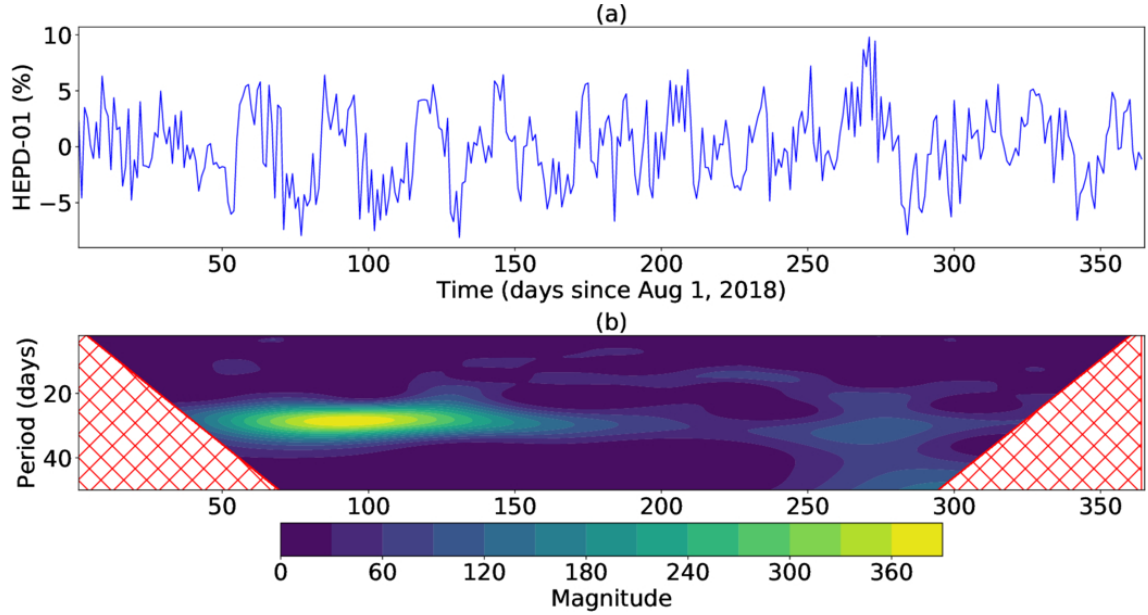


Figure 2.2.2: Top: Temporal evolution of the relative (detrended) proton flux measured by HEPD-01. Bottom: Wavelet analysis of the daily HEPD-01 proton flux during the August 2018–2019 period. Cross-hatched regions at both ends mark the cone of influence, where edge effects become significant. [32].

transient phenomena originating from the Sun, generating bursts of high-energy SEPs, see Sec. 1.2.1. Although they are relatively rare during periods of minimum solar activity, their acceleration and propagation can be investigated with reduced uncertainty compared to phases of maximum activity, when the heliosphere is more turbulent. During maximum activity, SEPs become more frequent, and a wide variety of data can be accumulated and compared, grouping different events according to some of their features (duration, spectral index, rollover energy, intensity, region of occurrence, etc.). The process-accelerating SEP is the closest laboratory for studying particle acceleration in astrophysical objects, and its study is of paramount interest for understanding CR acceleration.

HEPD-01 observed an enhancement in proton fluxes from space during the 28 October 2021 solar energetic particle event, associated with the significant, long-duration X1-class flare and the concomitant coronal mass ejection (CME) that erupted from the Active Region. The HEPD-01 data suggest that particles could have possibly been accelerated out from the ambient corona through the contribution of stochastic acceleration at the CME-driven shock [33].

2.2.2 Radiation Belts and Their Stability

The Earth’s radiation belts are zones of charged particles trapped by the Earth’s magnetic field. These belts are maintained by a balance of processes: particle injection (from solar and magnetospheric disturbances), radial transport, pitch-angle scattering (which leads to losses into the atmosphere), and energy changes due to wave-particle interactions.

Anomalous particle fluxes have been detected by several space experiments a few

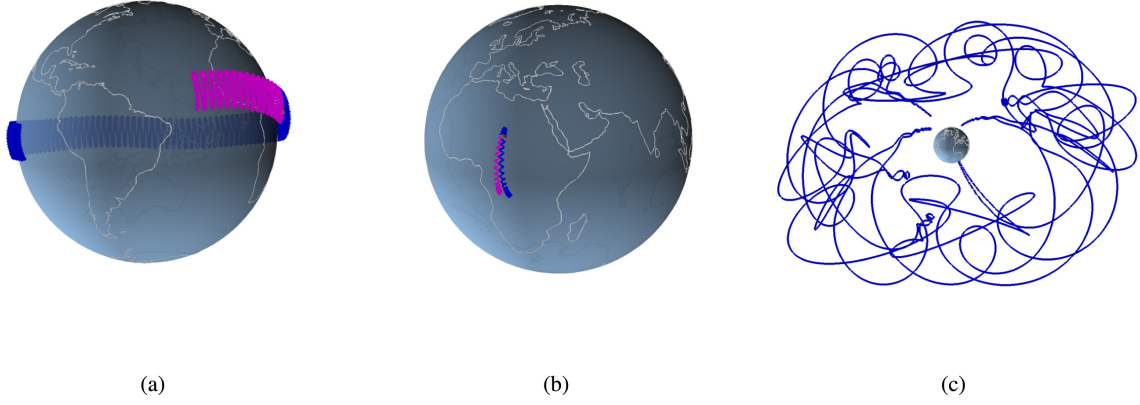


Figure 2.2.3: A 3D visualization of the reconstructed trajectories in HEPD-01. In all graphs, the blue (magenta) line is the trajectory traced backward (forward) in time. From left to right we have (a) a 186 MeV quasi-trapped proton with an equatorial trajectory with a generation point over the Pacific Ocean and absorption point over the Atlantic Ocean, (b) a 240 MeV untrapped proton with short lifetime bouncing in the northern hemisphere, and being absorbed in the southern hemisphere, and (c) a 31 MeV untrapped proton with long lifetime detected at high latitude [34].

hours before the occurrence of earthquakes. These short-term particle bursts have been interpreted as resulting from precipitation of inner-radiation-belt particles, driven by interactions between seismo-electromagnetic emissions and Van Allen belt particles. However, seismic activity is not the only possible explanation for such bursts.

Both HEPDs can measure particles in the magnetosphere at different locations, determining both their incoming direction and the angle relative to the local geomagnetic field. With the support of algorithms capable of tracing charged-particle trajectories within the magnetosphere, it becomes possible to identify the origin of these particles, whether they are trapped, precipitating, or of external origin, and categorize in more detail the origin of particle precipitation. In Fig. 2.2.3, a classification of trajectories from HEPD-01 measurements, that are not of cosmic origin, nor trapped permanently in the Earth's magnetic field, is presented.

2.2.3 Detection of Gamma-Ray Bursts

Gamma-Ray Bursts (GRBs) are highly energetic explosions observed in distant galaxies that produce intense flashes of γ -rays. When they occur, they often outshine entire galaxies for a few seconds or minutes.

HEPD-01 on CSES-01 has proven sensitive to prompt γ -ray signals in the 0.3–50 MeV band. It has detected several bright GRBs, showing time profiles consistent with high-energy photon light curves from Fermi-GBM, SWIFT-BAT, and INTEGRAL SPI-ACS [35]. Published HEPD-01 results and catalogs provide the observational foundation for these studies and illustrate the scientific potential of the HEPDs instruments for GRB physics [35].

HEPD-02 on CSES-02, with improvements in energy resolution and particle identification, will extend these capabilities, enabling more precise spectral mea-

surements and a larger sample of GRBs from low-Earth orbit.

2.3 The HEPD-01 aboard CSES-01

The HEPD-01 detector built by the Italian Limadou collaboration [26] is composed, from top to bottom, by:

- **Silicon Tracker** – consisting of two planes of double-sided silicon microstrip sensors ($213.2 \text{ mm} \times 214.8 \text{ mm} \times 0.3 \text{ mm}$) designed for reconstructing the trajectory of the incoming particle and measuring the energy loss per unit length, which is valuable for particle identification;
- **Trigger Plane** – consisting of a single layer of plastic scintillator segmented into six paddles of dimensions $20 \text{ cm} \times 3 \text{ cm} \times 0.5 \text{ cm}$ each, read out by photomultiplier tubes (PMTs). This system generates an effective trigger signal to synchronize data acquisition for the entire detector;
- **Range Calorimeter** – consisting of a first section with 16 planes of plastic scintillator ($15 \text{ cm} \times 15 \text{ cm} \times 1 \text{ cm}$) on top and a layer of nine cerium-doped lutetium yttrium orthosilicate ($\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5\text{:Ce}$, or LYSO) crystals ($4.8 \text{ cm} \times 4.8 \text{ cm} \times 4 \text{ cm}$) on the bottom designed for measuring the energy deposit and range of incoming particles;
- **Anticoincidence System** – consisting of five plastic scintillator planes (four lateral and one bottom) that are read out by PMTs. This system enables the detection of particles entering the apparatus from outside the acceptance region or those not completely contained within the calorimeter.

All the plastic scintillators are coupled to two Hamamatsu R9880U-210 photomultiplier tubes in opposite sides while the LYSO crystals are connected only to one PMT on the bottom side. The signal readout is performed by the Trigger Board, which is divided into two identical parts (HOT, COLD), each containing an FPGA, two ASIC integrated circuits consisting of EASIROC by Weeroc and four ADCs from Analogue Devices Inc. (AD7274). The collected PMT signals are inverted and attenuated by a specifically designed conditioning stage before sending them to the EASIROC. A global trigger is generated by the FPGA firmware each time the trigger pattern of an event complies with a predefined mask, and a signal is sent by the trigger board to the DAQ (data acquisition) board in order to start the acquisition of scientific data. Eight trigger masks are predefined, plus one configurable generic trigger mask which can be any combination of trigger counters and calorimeter planes:

- **T** – is the logical OR of the 12 PMTs of the segmented trigger plane;
- **$T \wedge P1$** – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the first calorimeter plane P1;
- **$T \wedge (P1 \vee P2)$** – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the first (P1) OR second (P2) calorimeter planes;

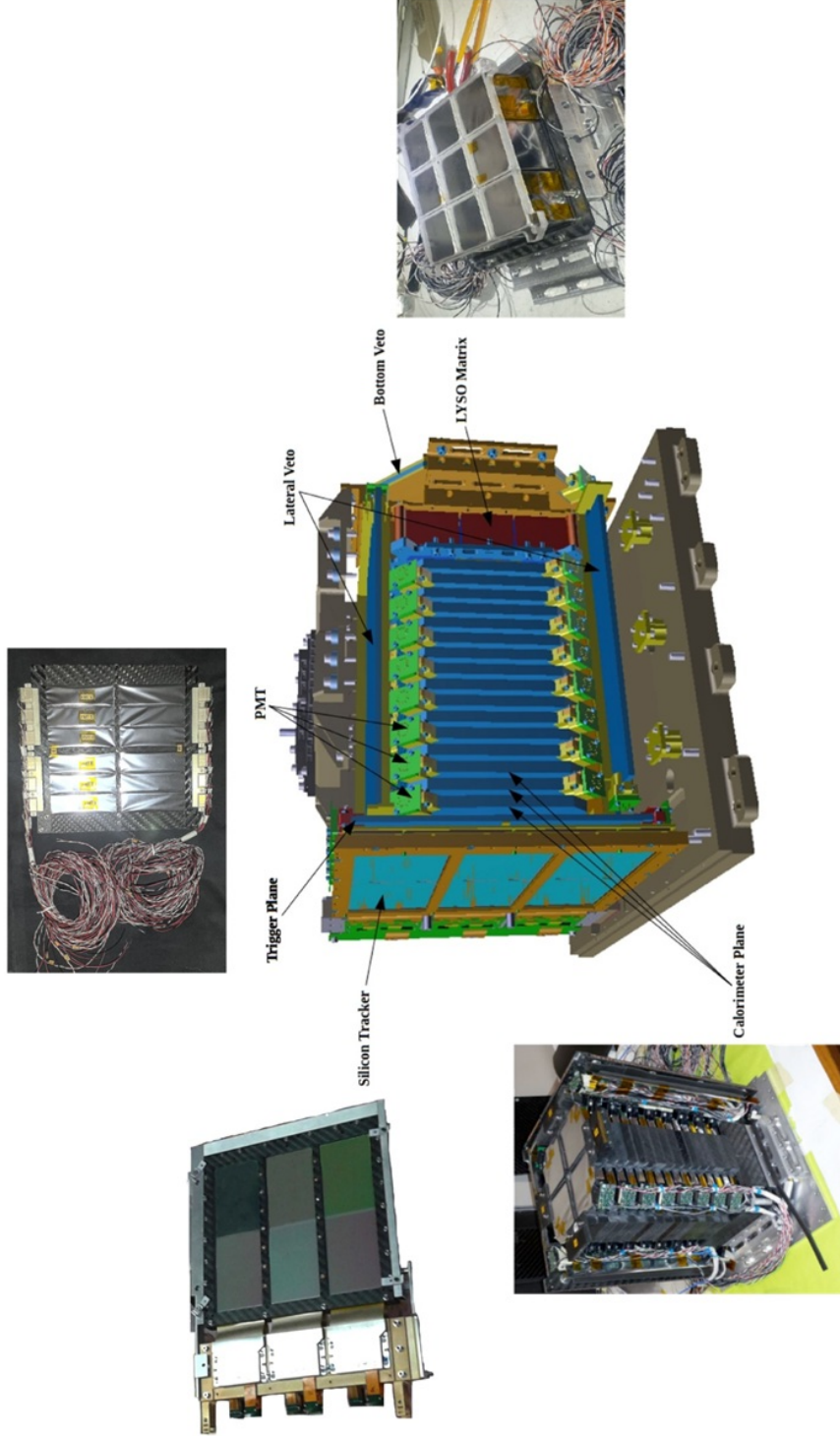


Figure 2.3.1: A CAD image of the HEPD-01 detector is shown. Photographs of various parts are displayed from bottom left to right: the calorimeter tower, the silicon tracker, the trigger plane, and the LYSO matrix.

- $(\mathbf{T3} \vee \mathbf{T4}) \wedge (\mathbf{P1} \vee \mathbf{P2})$ – is the AND logical coincidence of the OR signal from the 3rd (T3) and 4th (T) trigger planes and from the OR signal of the first (P1) and second (P2) calorimeter planes;
- $\mathbf{T} \wedge \mathbf{P1} \wedge \mathbf{P2}$ – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the first (P1) AND second (P2) calorimeter planes;
- $\mathbf{T} \wedge \mathbf{P1} \wedge \mathbf{P2} \wedge \mathbf{P3}$ – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the first three calorimeter planes (P1,P2, P3);
- $\mathbf{T} \wedge (\mathbf{P1} \vee \mathbf{P2}) \wedge (\mathbf{P15} \vee \mathbf{P16})$ – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the first (P1) OR second (P2) calorimeter planes;
- $\mathbf{T} \wedge (\mathbf{P1} \vee \mathbf{P2}) \wedge \mathbf{L}$ – is the AND logical coincidence of the global OR signal from all the trigger planes T and from the logical OR of first (P1) and second (P2) calorimeter planes, and the global OR of the Lyso crystals;

All the masks can be used with different VETO settings: no veto, only lateral veto, bottom veto alone, or whole veto (lateral and bottom). Although only one trigger mask can operate at a time, the rate meters of all the masks are acquired continuously. Different configurations of trigger mask and run duration can be applied depending on the zone along the orbit, for example, to avoid saturation. Five different orbital zones were defined as a function of latitude and longitude ranges:

- **Equatorial** – latitude range $[-30^\circ, +30^\circ]$, longitude range $[-180^\circ, +180^\circ]$; Trigger Mask $\mathbf{T} \wedge (\mathbf{P1} \vee \mathbf{P2})$ and No VETO;
- **South polar** – latitude range $[-65^\circ, -30^\circ]$, longitude range $[-180^\circ, +180^\circ]$; Trigger Mask $(\mathbf{T3} \vee \mathbf{T4}) \wedge (\mathbf{P1} \vee \mathbf{P2})$ and only lateral VETO;
- **North polar** – latitude range $[+30^\circ, +65^\circ]$, longitude range $[-180^\circ, +180^\circ]$; Trigger Mask $(\mathbf{T3} \vee \mathbf{T4}) \wedge (\mathbf{P1} \vee \mathbf{P2})$ and only lateral VETO;
- **South Atlantic Anomaly (SAA)** - latitude range $[-50^\circ, 0^\circ]$, longitude range $[-90^\circ, +20^\circ]$; Trigger Mask $(\mathbf{T3} \vee \mathbf{T4}) \wedge (\mathbf{P1} \vee \mathbf{P2})$ and lateral + bottom VETO;
- **Default** – when no orbit information is available, $\mathbf{T} \wedge (\mathbf{P1} \vee \mathbf{P2}) \wedge (\mathbf{P15} \vee \mathbf{P16})$ and No VETO.

The commissioning phase enabled the optimization of the orbital zones configuration.

In Figure 2.3.1, a CAD image of the detector is shown, along with photographs of some of the subsystems. On the lateral side of the sensitive detectors, two main subsystems complete the whole instrument: (i) an electronic subsystem made of four boards for trigger management, data acquisition, on-board data handling (OBDH), slow control, and low-voltage power distribution; and (ii) a power supply subsystem composed of a board (low-voltage power supply) that generates two low-voltage

Table 2.3.1: A summary of the technical and scientific requirements of HEPD-01.

Quantity	Range
Operating temperature	$-10^{\circ}\text{C} \div +35^{\circ}\text{C}$
Operating pressure	$\leq 6.65 \cdot 10^{-3} \text{ Pa}$
Power Budget	$\leq 38 \text{ W}$
Mass Budget	$\leq 45 \text{ kg}$
Data Budget	$\leq 50 \text{ Gbit/day}$
Life Cycle	$> 5 \text{ years}$
Kinetic Energy Range for e^{-}	$3 \text{ MeV} \div 100 \text{ MeV}$
Kinetic Energy Range for p	$30 \text{ MeV} \div 200 \text{ MeV}$
Energy Resolution	$\leq 10\%$ for e^{-} with $E > 5 \text{ MeV}$
Angular resolution	$\leq 8^{\circ}$ for e^{-} with $E > 5 \text{ MeV}$

power lines from the satellite power bus and a system (high-voltage power supply) that produces two high-voltage lines (up to 150 and 1200 V, respectively).

The HEPD-01 detector is housed in an aluminum box measuring $40.36 \times 53.00 \times 38.15 \text{ cm}^3$. The walls and base-plate are constructed from milled aluminum panels, with an exterior surface coated in black anodized material for effective thermal insulation. The detector, along with the power supply and electronics boxes, is fixed to the satellite cabin, providing the contact surface for heat dissipation. The instrument's total weight is approximately 45 kg, and its power consumption is below 30 W. The technical and scientific requirements of HEPD-01 are detailed in Tab. 2.3.1.

2.4 The HEPD-02 aboard CSES-02

The HEPD-02 design [36] is an enhancement of the HEPD-01 detector [26], incorporating two significant innovations never before utilized in a space-based experiment: Monolithic Active Pixel Sensors (MAPSs) for particle tracking [37] and the longest LYSO crystals ever employed in space (15 cm). The instrument consists of a trigger system, a direction detector, a range detector, and an energy detector. An exploded view of the system, with photographs of the modules, before the final assembly, is presented in Fig. 2.4.1, wherein, from the left to the right side of the figure, the following are shown:

- **Trigger Detector (TR1)** – the plane consists of five 2 mm thick plastic scintillator counters measuring $32 \times 154 \text{ mm}^2$ each. Both ends of the counters are connected to flat, 6 mm-thick light guides to direct light to the photocathode. The thickness of TR1 is minimized to enable triggering on MeV particles, which are of particular interest for HEPD-02 physics, in addition to minimizing multiple scattering.
- **Direction Detector (DIR)** – it is based on Monolithic Active Pixel Sensors (MAPS) technology, specifically the ALTAI detector, which integrates the sensor and readout circuitry on the same silicon wafer. This technology

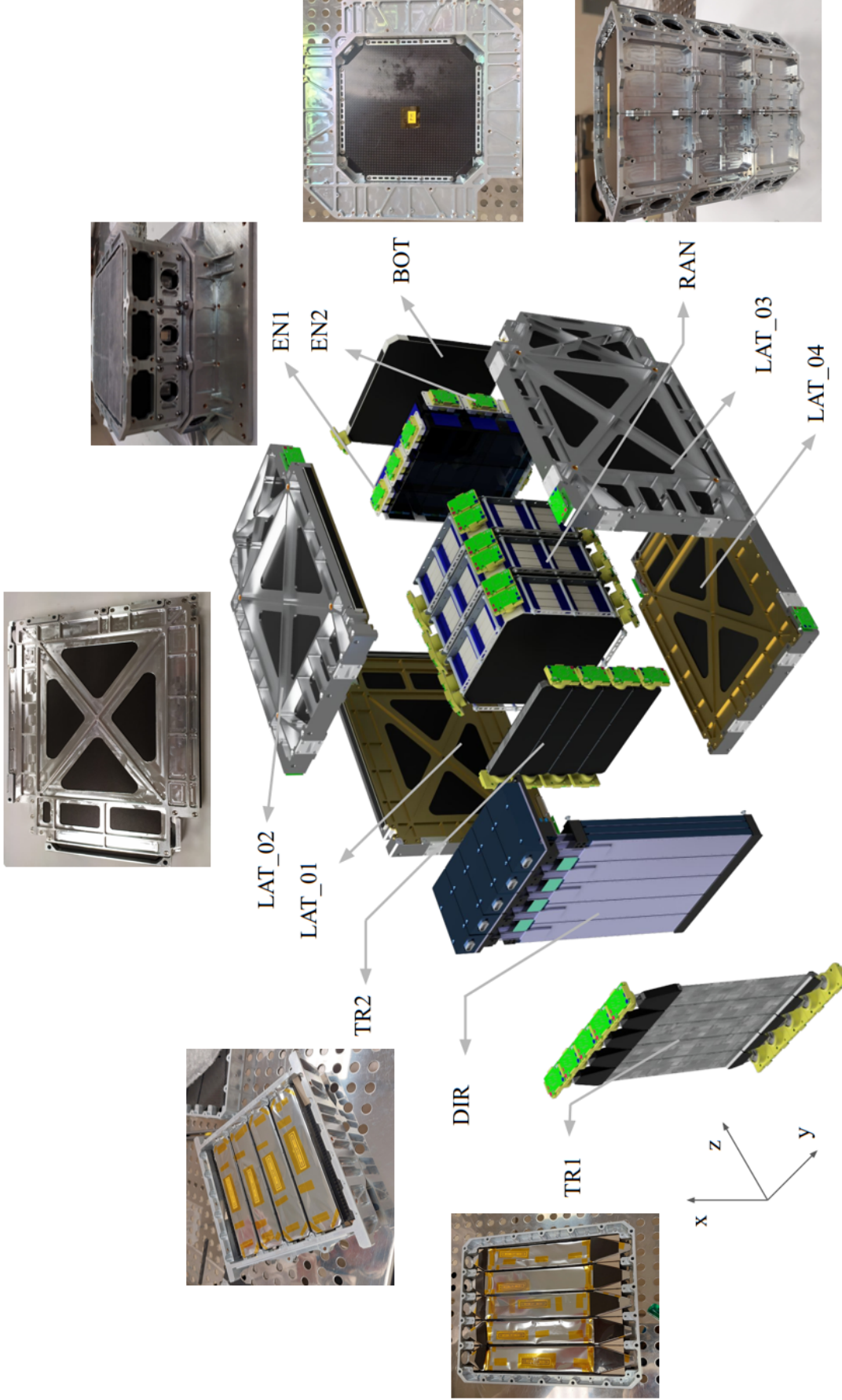


Figure 2.4.1.1: An exploded view of the HEPD-02 detector, from left to right: the two trigger planes (TR1 and TR2) with the direction detector (DIR) in between, one of the lateral containment panels (LAT), the two LYSO crystal planes (EN), the bottom containment panel (BOT), and the plastic scintillator tower (RAN) [36]

is a variation of the widely used ALPIDE detector [38], produced by Tower Semiconductors². The tracker [37, 39] has an active area of $150 \times 150 \text{ mm}^2$ and is made of five standalone tracking modules, called turrets. Each turret consists of three sensitive layers known as staves and a splitting board (TSP) for power supply and data line routing. Control and read-out are based on ultra-thin (180 nm) flexible printed circuits ensuring low material budget. Within each stave, there are 10 ALTAI detectors, arranged in two columns of five. Each ALTAI detector features a 1024×512 rectangular-pixel grid. The dimension of a pixel is $26.88 \times 29.24 \text{ }\mu\text{m}^2$, providing improved tracking resolution (systematic uncertainties on tracking: down to $4\div 5 \text{ }\mu\text{m}$ single-hit resolution)

- **Trigger Detector (TR2)** – the second trigger plane is composed of four 8 mm thick plastic scintillators, arranged perpendicular to the TR1 counters. Each scintillator has dimensions of $36 \times 150 \text{ mm}^2$. TR2 provides a good measurement of the energy loss of charged particles allowing for an enhanced particle identification (PID).
- **Range Detector (RAN)** – consisting of a tower of twelve 10 mm thick plastic scintillators measuring $150 \times 150 \text{ mm}^2$, numbered from RAN1 to RAN12. The scintillators are housed in three separate mechanical units.
- **Energy Detector (EN)** – the bottom part of the calorimeter is composed of segmented LYSO crystals. Each layer contains three bars measuring two orthogonal layers, EN1 and EN2, of three 25 mm thick LYSO crystal bars measuring $49 \times 150 \text{ mm}^2$. These crystals provide excellent energy measurements and enhance the detector’s capabilities in detecting GRBs [40, 41] increasing the detectable energy range .
- **Containment Detector (CD)** – made up of five 8 mm thick plastic scintillator panels: a bottom plane (BOT) measuring $166 \times 166 \text{ mm}^2$ positioned below the calorimeter, and four large lateral panels (LAT) surrounding it with an envelope size of $212 \times 286 \text{ mm}^2$. These panels enclose the entire detection volume and, when in anti-coincidence with the trigger, ensure the rejection of particles that are not fully absorbed by the calorimeter.

Each scintillator is read at diametrically opposite sides by two Hamamatsu R9880U-210 photomultiplier tubes (PMTs), for a total of 64 PMTs. In the case of the RAN, the PMTs are placed in alternating opposite corners in successive planes. The PMT readout and trigger system is built around CITIROC 1A ASICs by Weeroc and a MicroSemi A3PE3000L FPGA. Signals are collected from the last dynode of the PMTs to match CITIROC input polarity, avoiding inverters and reducing power consumption. Voltage dividers are used to attenuate signals and optimize the dynamic range of the CITIROCs. Each CITIROC features two preamplifiers, the High Gain (HG), with gain from 10 to 600, and Low Gain (LG) with gain between 1 and 60, allowing for a wide dynamic range suitable for detecting particles of different

²<https://towersemi.com/>

Table 2.4.1: A summary of the technical and scientific requirements of HEPD-02. They are quite similar to the HEPD-01 ones.

Quantity	Range
Operating temperature	$-10\text{ }^{\circ}\text{C} \div +35\text{ }^{\circ}\text{C}$
Operating pressure	$\leq 6.65 \cdot 10^{-3}\text{ Pa}$
Power Budget	$\leq 45\text{ W}$
Mass Budget	$\leq 50\text{ kg}$
Data Budget	$\leq 100\text{ Gbit/day}$
Life Cycle	$> 6\text{ years}$
Kinetic Energy Range for e^{-}	$3\text{ MeV} \div 100\text{ MeV}$
Kinetic Energy Range for p	$30\text{ MeV} \div 200\text{ MeV}$
Energy Resolution	$\leq 10\%$ for e^{-} with $E > 5\text{ MeV}$
Angular resolution	$\leq 10^{\circ}$ for e^{-} with $E > 3\text{ MeV}$

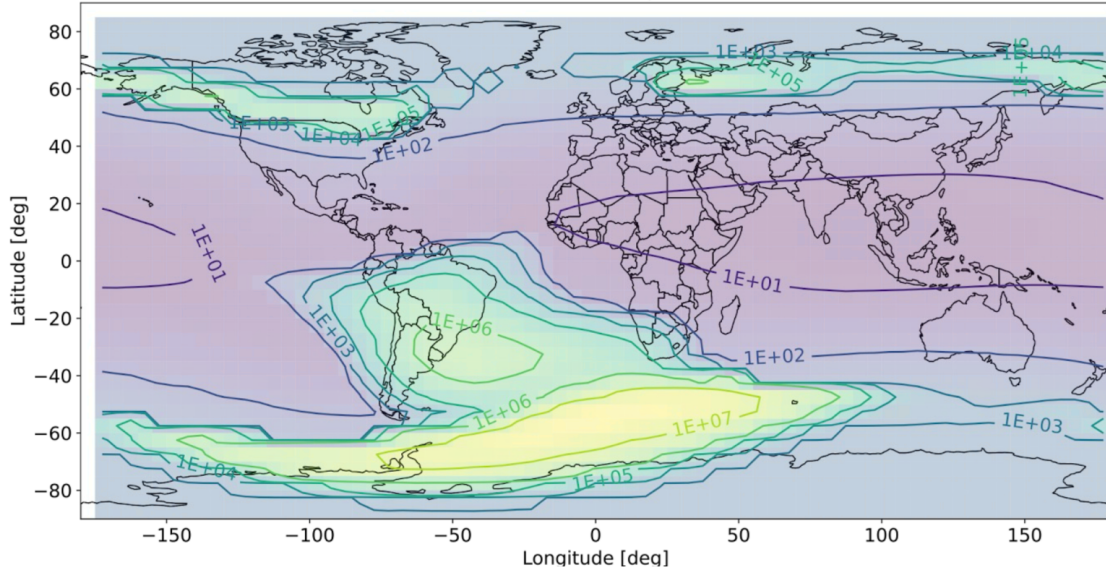


Figure 2.4.2: Expected particle rate seen by HEPD-02 along the orbital zones

charges³.

Timing signals are generated via fast shapers (15 ns peaking time) and discriminators with adjustable thresholds. The FPGA collects these signals and creates a global trigger when predefined logical conditions, called *trigger masks*, are met. The global trigger initiates ADC conversion on the CITIROC for all scintillators, and tracker acquisition is performed on a separate board. The data is then stored in a FIFO buffer and transferred via SpaceWire protocol. Two identical copies (Cold/Hot) of the circuits are made on the same board to increase overall reliability during flight. Three classes of trigger patterns of PMT signals, i.e., trigger masks are implemented from the PMT readout and trigger:

- **Event acquisition masks** – main triggers for event detection:

³To give an impression, since energy deposit is proportional to Z^2 , carbon nuclei deposit 36 times the energy deposited by a proton

- **TR1-AND** – is the logical OR of the AND coincidence of the two sides of the same TR1 counter ($\text{TR1-x-A} \wedge \text{TR1-x-B}$). It is the trigger with the lowest energy threshold;
- **TR1 $\wedge$ TR2** – is the AND logical coincidence of the global OR signal from all TR1 and from all TR2;
- **TR1 $\wedge$ TR2 $\wedge$ RAN2;**
- **Event monitor masks** – trigger masks designed for monitoring efficiencies of the counters, of the containment, and of the trigger conditions:
 - **RAN1 $\wedge$ RAN7 $\wedge$ RAN12** – for detector efficiency studies;
 - **TR2 $\wedge$ BOT** – this are the so called *passing through* events, they are used for monitoring and for calibration;
 - **(BOT $\wedge$ EN1 $\wedge$ EN2) $\wedge$ $\neg$ (TR1 $\wedge$ TR2 $\wedge$ LAT)** – upward going contained events;
 - **(RAN5 $\wedge$ RAN6 $\wedge$ RAN7 $\wedge$ RAN8) $\wedge$ $\neg$ (RAN4 $\wedge$ RAN9)** – lateral events used for calibration and monitoring of LAT counters.
- **GRB detection masks** – specifically designed for the detection of Gamma Ray Bursts:
 - **(EN1 $\wedge$ EN2) $\wedge$ $\neg$ (RAN12 $\wedge$ LAT $\wedge$ BOT)** – GRB detected in the LYSO crystals;
 - **(RAN5 $\wedge$ RAN6 $\wedge$ RAN7 $\wedge$ RAN8) $\wedge$ $\neg$ (RAN4 $\wedge$ RAN9 $\wedge$ LAT)** – GRB detected in the plastic scintillators.

The GRB masks are an innovation that enables HEPD-02 to detect Gamma Ray Bursts with energies ranging from 2 MeV up to 20 MeV, thanks to the high density of EN1/2 LYSO counters.

The data processing and control unit (DPCU board) of HEPD-02 manages the trigger configuration according to the orbit, allowing the simultaneous acquisition of different particle populations with variable rates, as shown in Fig. 2.4.2. Up to six trigger masks can operate in concurrent mode, of which four can be independently pre-scaled to prevent exceeding the data size and the satellite data budget during acquisition. The trigger configuration is set according to the orbital zone, i.e., the latitude and longitude provided by the satellite every 1 second, at which HEPD-02 is operating. 128 (8×16 : longitude $\times$ latitude) zones are configured with configurable stave acquisition masks, concurrent trigger masks and pre-scaling factors.

These are significant innovations with respect to HEPD-01 for which only one trigger mask operated per orbital zone, and only five orbital zones were set. Another remarkable innovation is the new Housekeeping (HK) system that allows for the active monitoring of the full detector status. It consists of packets sent periodically within Scientific data, and partially in the Telemetry data, containing the complete diagnostic of the detector. These are detector and board temperatures, high and low voltages, currents and anomaly counters. Diagnostic routines are implemented which recognizes any anomalous behavior and reports the subsystem involved, the type and severity of the error. An automatic action is undertaken to restore the

correct working depending on the specific case. In the event of an unrecoverable error preventing acquisition, all subsystems are powered down except for the low voltage power supply (LVPS) and the DPCU board, and an internal status error is reported towards the satellite awaiting external action.

The scintillator counter system of HEPD-02 (including TR1, TR2, RAN, EN, and CD) and all the electronic logic have been designed to satisfy the technical and scientific requirements detailed in Table 2.4.1. Details on the characterization of the scintillation detector system, the tuning of the overall detector system, and its performance will be given in Ch. 4.

Chapter 3

Data Analysis of HEPD-01: Dependence of Proton Flux from Geomagnetic Latitude

In this chapter, I use the data collected by HEPD-01 between 2018 and 2022 to calculate the proton spectrum as a function of geomagnetic latitude, θ_M , in the range from 0 to 1.2 radian, and in the energy interval between 30 MeV and 200 MeV.

The study of the cosmic-ray proton spectrum as a function of geomagnetic latitude is particularly relevant, as it probes different regions of the magnetosphere, where distinct particle populations dominate. In fact, at different latitudes, various components of cosmic rays become apparent in the measured flux. Near the equator, the spectrum is dominated by trapped particles, whereas at very high latitudes, the galactic component prevails. Previous measurements, such as those from AMS-01, have provided reference spectra for comparison. In this work, we investigate the proton component recorded by HEPD-01 as a function of magnetic latitude and compare the results with AMS-01 observations.

By analyzing the transition between regions, we can examine how the contributions from trapped, re-entrant, and galactic protons vary with θ_M . This analysis not only provides further confirmation of the results published by HEPD-01 but also explores the dependence of re-entrant particle flux on geomagnetic latitude.

Additionally, the HEPD-01 data analysis served as a valuable exercise to identify potential limitations and to inform improvements in the design of HEPD-02, ensuring enhanced performance for future measurements.

3.1 Flux Estimation

As described in Sec. 2.3, HEPD-01 is a particle detector optimized to detect electrons with energies ranging from 3 to 100 MeV, as well as protons and light nuclei with energies between 30 and 250 MeV/n. In summary, the apparatus consists of a dual-sided silicon microstrip tracking system, with a single-layer segmented trigger system positioned above a range calorimeter that comprises 16 plastic scintillator planes (P1, P2, ... P16), followed by a 3×3 array of LYSO crystals, the calorimeter is surrounded by an anticoincidence system composed of 5 plastic scintillators, as shown in Fig. 3.1.1. The main characteristics of the apparatus are a field of view

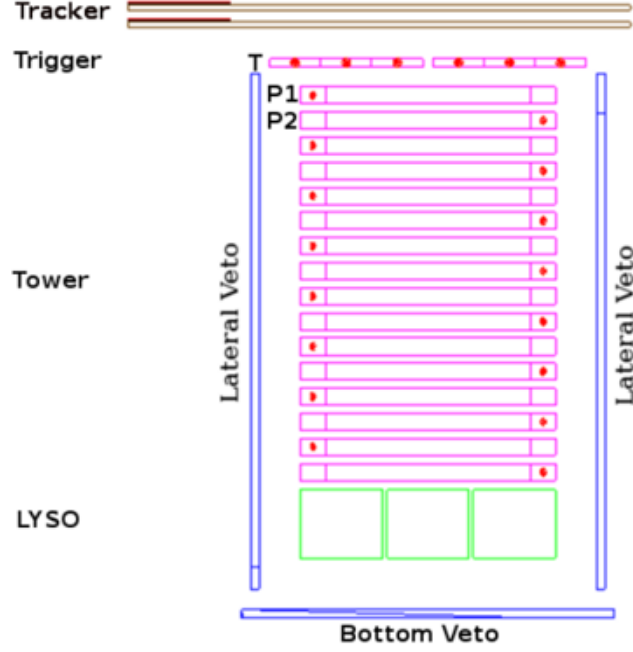


Figure 3.1.1: Schematic view of the HEPD-01 detector.

of $\pm 60^\circ$ and a geometrical acceptance of approximately $400 \text{ cm}^2\text{sr}$ at 90 MeV for protons.

The differential energy spectrum Φ is defined as the number of particles per unit area, per unit time, per unit solid angle per energy interval. For an isotropic distribution of CR, the average isotropic differential energy spectrum Φ in the bin $(E_i, E_i + \Delta E_i)$ is calculated as follows:

$$\Phi_i = \frac{N_i}{G_i \epsilon_i T_i \Delta E_i}, \quad (3.1.1)$$

where N_i is the number of particle candidates in the bin $(E_i, E_i + \Delta E_i)$ corrected for residual backgrounds and energy migrations, G_i is the geometrical factor in the bin measured in units of area and solid angle, ϵ_i is an additional efficiency correction, T_i is the instrumental livetime, and ΔE_i the width of the energy interval.

3.1.1 Event Selection

Data acquisition is initiated when a particle passes through one of the paddles of the trigger plane (T) and the first two planes of the upper calorimeter, P1 and P2. A further "offline" trigger is added by considering a trigger paddle and a calorimeter plane to be activated if both PMTs, operating in AND logic, register an ADC signal above a predefined threshold. This configuration was established in July 2018, at the end of the commissioning phase, during which various onboard trigger settings and thresholds were tested.

To suppress multiple particle events and reduce secondary particles generated in the upper payload, an offline selection is applied that requires only a single trigger paddle to be activated.

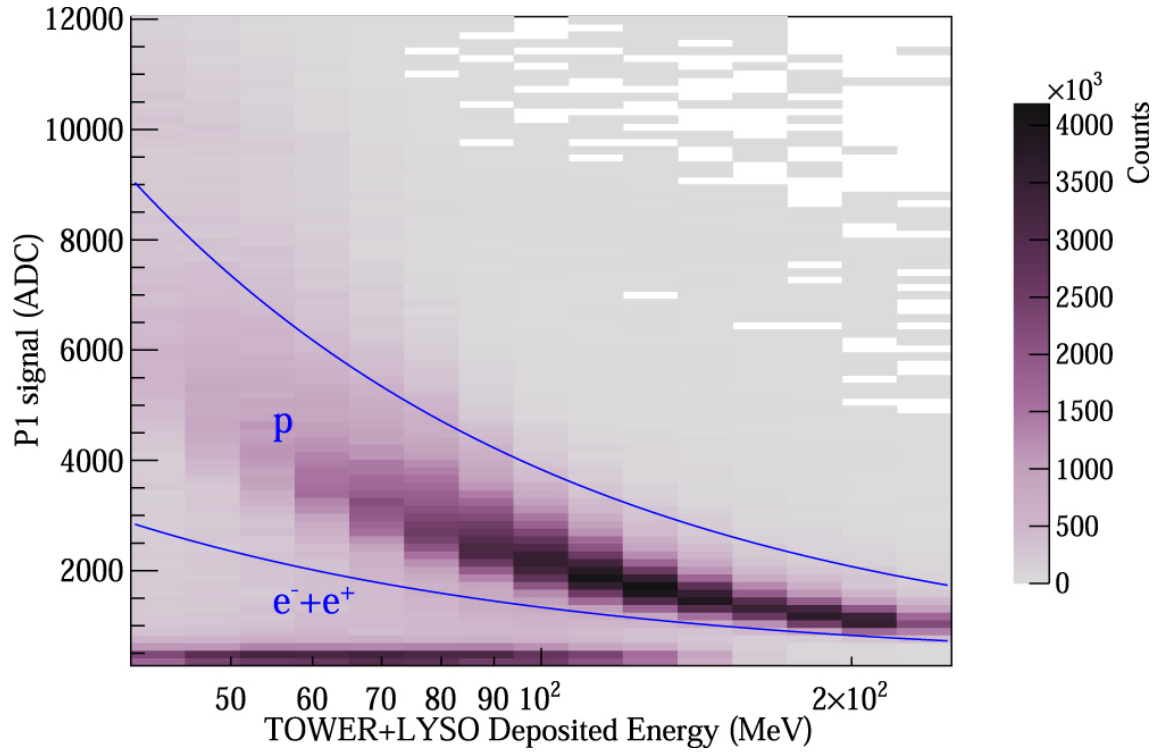


Figure 3.1.2: Proton and electrons+positrons signal on plane P1 as a function of the total energy deposited inside the calorimeter (TOWER+LYSO). To better visualize the separation in the plot, only vertical particles have been selected. The blue curves identify the selection employed to discriminate between protons and other populations [6].

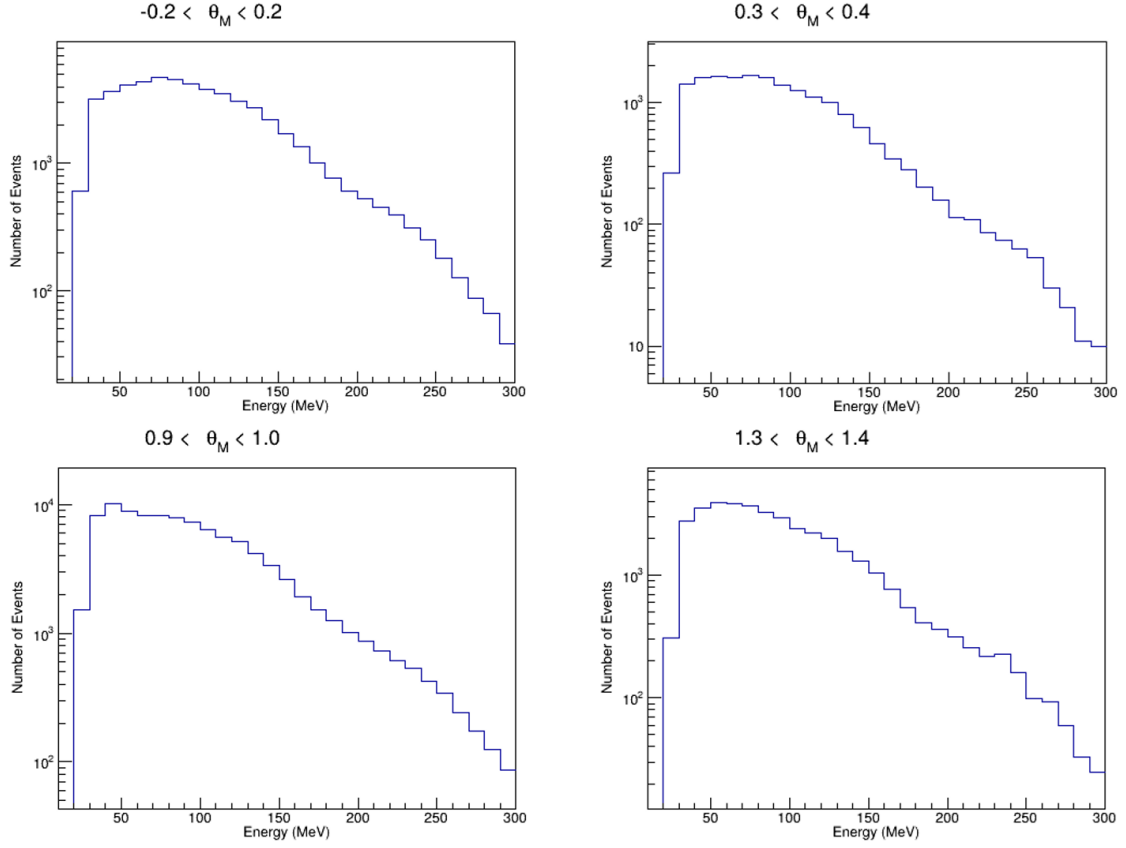


Figure 3.1.3: Example distributions of protons counts recorded by HEPD-01 in four magnetic latitude bands (in radian): $-0.2 < \theta_M < 0.2$ (upper left), $0.3 < \theta_M < 0.4$ (upper right), $0.9 < \theta_M < 1.0$ (bottom left), and $1.3 < \theta_M < 1.4$ (bottom right).

For precise energy reconstruction, candidates are further filtered by requiring full containment within the plastic scintillator tower or the LYSO matrix. Events that triggered signals above threshold in the bottom plane or lateral containment panels are rejected. This ensures complete energy absorption of the primary particle within the detector.

To discriminate protons from other particle populations, such as electrons (note that HEPD-01 cannot distinguish particles with the same mass but opposite charge Z), the signal deposited in the first scintillator plane (P1), $S(P1)$, is analyzed as a function of the total energy deposited in the full calorimeter (TOWER + LYSO), E_{dep} . As shown in Fig. 3.1.2, two distinct populations are clearly visible: electrons that are ultra-relativistic and tend to have the same energy loss in P1 for any measured total energy, and protons that exhibit larger energy losses in P1 at low energy. Therefore, protons are selected with a selection between two curves, each described by

$$S_i(P1) \propto \frac{A_i}{E_{\text{dep}}}, \quad i = 1, 2, \quad (3.1.2)$$

where A_i is a constant. These curves correspond to the 15% and 95% quantile thresholds used to define the proton band [6].

Eventually, the total number of proton events was recorded across geomagnetic latitude bands, excluding regions affected by the South Atlantic Anomaly. Examples

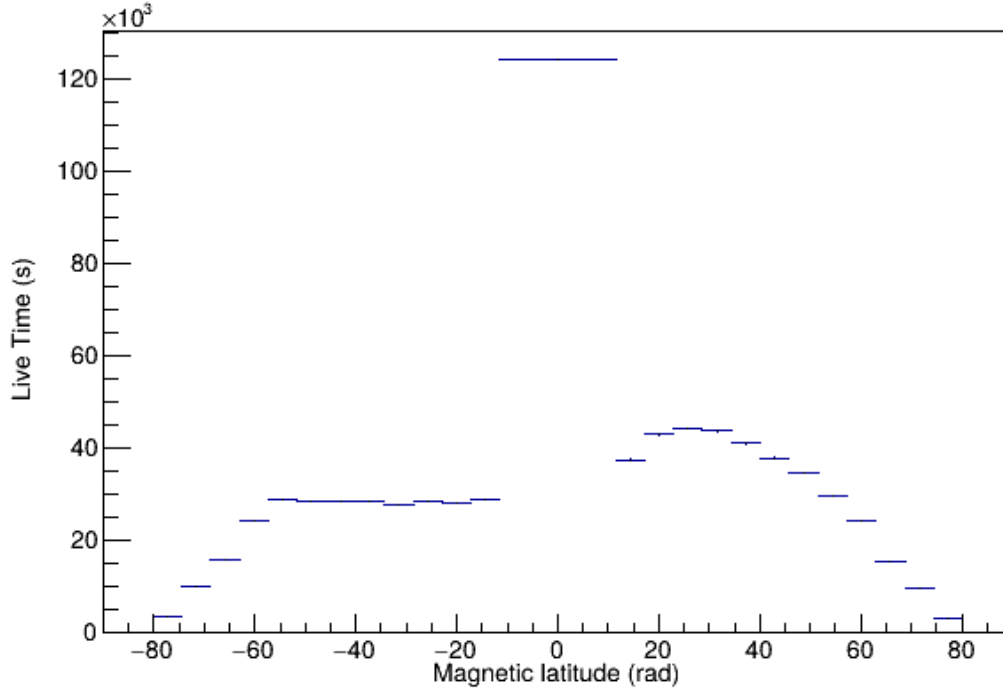


Figure 3.1.4: Example distribution of the live time of event recording spent at the different magnetic latitudes.

of proton counts versus energy in different latitude bands are presented in Fig. 3.1.3.

3.1.2 Livetime

The detector's livetime T is the period during which the detector is available for detecting events. It is the sum of all time intervals between the end of the processing of the previous event and the arrival of the next one. The trigger electronics board is responsible for calculating and managing the live and dead times that are appended to the scientific data on an event by event basis [42, 43]. In this analysis, the live time is integrated along different regions of magnetic latitude, as can be seen in the example given in Fig. 3.1.4. The apparent asymmetry is due to the exclusion of the SAA region.

3.1.3 Geometrical Factor

The geometrical factor accounts for how many particles are accepted by the detector from different directions over the surface area for an isotropic distribution of entering particles [44]. While the geometric factor can be calculated analytically for simple geometries, in general, it requires Monte Carlo methods for complex detectors.

A complete Monte Carlo (MC) simulation of the HEPD-01 detector has been developed by the Limadou Collaboration using the GEANT4 simulation toolkit [45]. In this simulation, particles are generated and propagated through a detailed description of active and passive elements of HEPD-01. The physical processes that

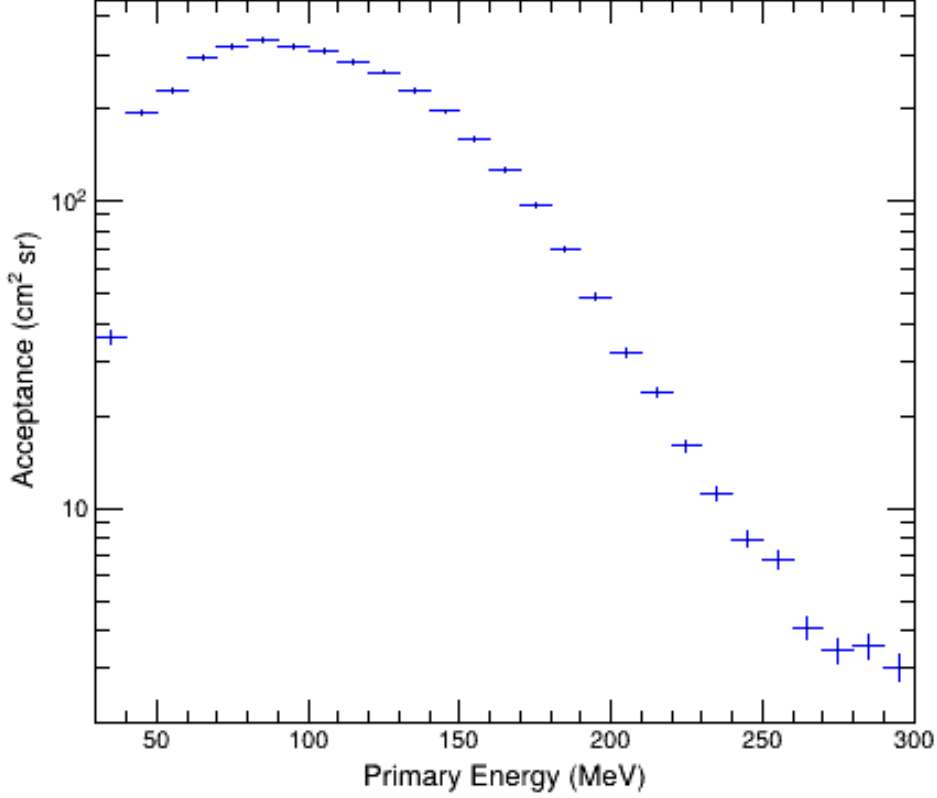


Figure 3.1.5: Total geometrical acceptance of the HEPD-01 detector for protons as a function of the energy as evaluated from the Monte Carlo distribution normalized to the total number of primary events generated in the simulation.

particles undergo in matter are fully simulated. Most importantly, when entering the calorimeter-sensitive volumes, the deposited energy is converted to scintillation photons, which are then propagated through the counters and collected at the photomultiplier tubes, and digitized. Properties of the MC were tuned and validated using both test-beam measurements and in-flight data.

To calculate the geometric factor, an isotropic distribution of particles has been generated over a surface of $40 \times 40 \text{ cm}^2$ on top of HEPD-01 over a whole hemisphere ($0^\circ < \theta < 90^\circ$ and $0^\circ < \phi < 180^\circ$). Particles were generated with a known energy distribution (flat or from a model) between 10 MeV and 10 GeV. The average geometric factor for a given bin in energy is the calculated by sampling:

$$G = G_{\text{gen}} \times \frac{N_{\text{acc}}}{N_{\text{gen}}}, \quad (3.1.3)$$

where $G_{\text{gen}} = \pi \times d^2$ ($d = 40 \text{ cm}$) is the generation geometric factor of the surface from which we generate events, N_{acc} is the number of events passing the in-flight trigger condition and the requirement of particle containment within the volume of the instrument (see Sec. 3.1.1), and N_{gen} is the number of event generated.

The distribution of the geometrical factor as a function of the proton primary energy is shown in Fig. 3.1.5. It shows a maximum around $350 \text{ cm}^2 \text{ sr}$ at 90 MeV.

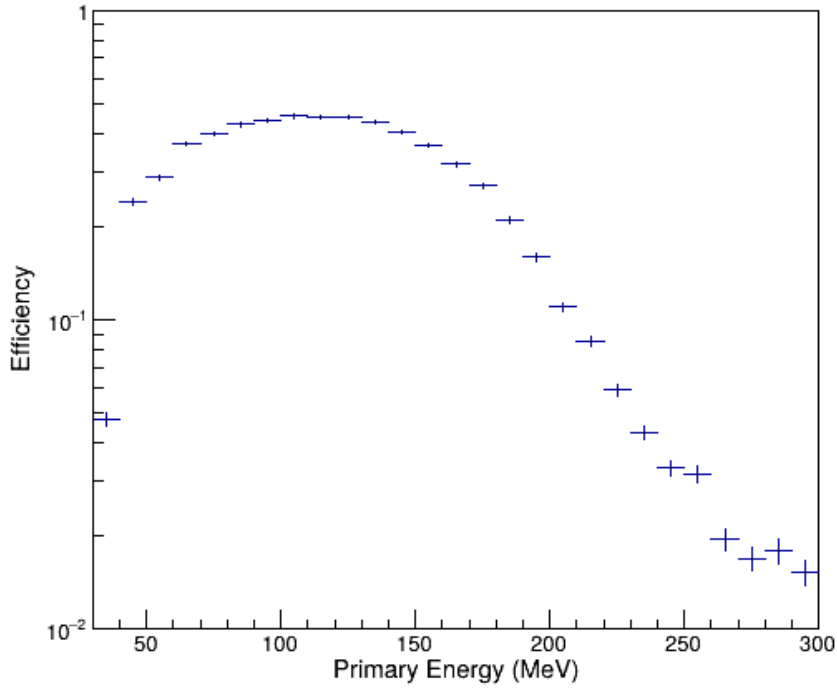


Figure 3.1.6: The efficiency of selecting contained protons versus primary energy as given from simulation.

The decrease at low energy is because low-energy particles are no longer sufficiently energetic to trigger the experiment. In contrast, the decrease at high energy is due to the containment condition, which reduces the number of events that produce energetic δ -rays that can trigger the veto detector.

3.1.4 Proton Identification Efficiency

In Sec. 3.1.1, the identification method for protons has been described, which eliminates the background of electrons. In this section, the efficiency of proton identification, ϵ , is evaluated as the fraction of protons selected by the proton identification condition relative to the total number of protons in HEPD-01.

The efficiency on the proton selection is obtained applying proton selection cuts to the simulation data after all other triggers and containment conditions. It is the fraction of the number of protons selected by the cut (the 2 curves $\propto E^{-1}$, defined above) over the total number of simulated protons contained in HEPD-01, see Fig. 3.1.6.

In Fig. 3.1.6, the proton identification efficiency as a function of the primary particle energy is presented.

Instrumental inefficiencies due to aging, for example, which cannot be estimated by simulation, are accounted for as systematic uncertainties.

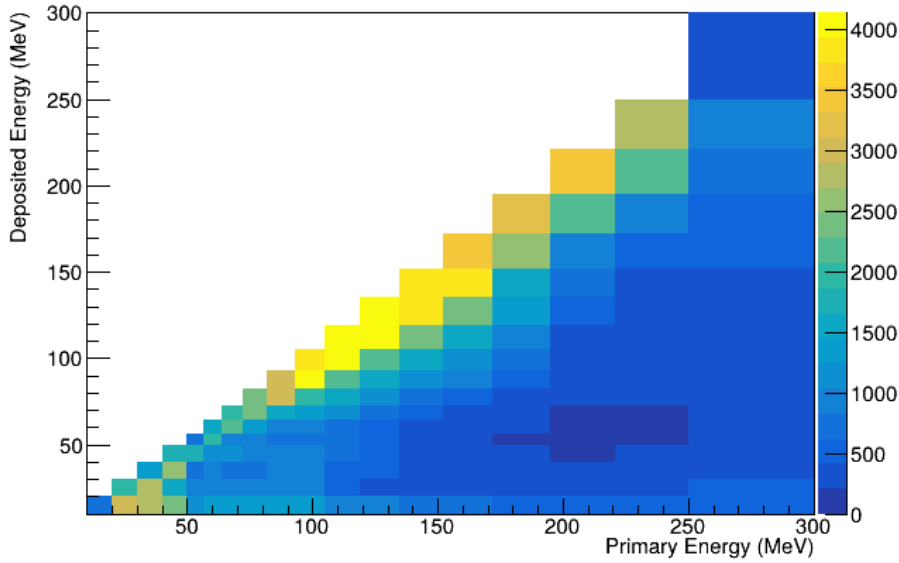


Figure 3.1.7: The HEPD-01 detector response matrix showing the deposited versus the primary energy, as obtained from a Monte Carlo simulation of an isotropic flux of protons in the range 10 MeV to 10 GeV.

3.1.5 Unfolding

The particle energy is estimated from the total energy deposited in the calorimeter. The conversion between the measured ADC signals and the energy deposited in the scintillators has been determined from test-beam data, as described in [46].

However, the measured energy deposited has finite resolution, and when measuring counts in a given energy bin, an unfolding procedure that accounts for energy bin-to-bin migrations is needed.

In Fig. 3.1.7, the calorimeter response matrix, i.e., the 2D distribution of the measured true generated energy of the particles versus the measured deposited energy in the calorimeter, is presented. To correctly account for the migration, the response matrix has been generated weighting the MC by a realistic incoming spectrum of particles derived with the `HelMod + GALPROP` simulation, able to describe the HEPD-01 Galactic proton flux [47]. As can be seen, the matrix is not diagonal and contains a large population of high energy events reconstructed at lower energy. Inelastic interactions in the detector, with the production of a leading neutron that leaves the detection volume unnoticed, are among the causes of such tails.

To correct for these deviations, an energy unfolding procedure has been applied to the counts derived in Sec. 3.1.1. To verify the unfolding procedure, the resulting counts were "folded" again using the response matrix, yielding a distribution that could be compared with the uncorrected data. The result of the verification is shown in Fig. 3.1.8, showing a good agreement, discrepancies are accounted as additional systematics.

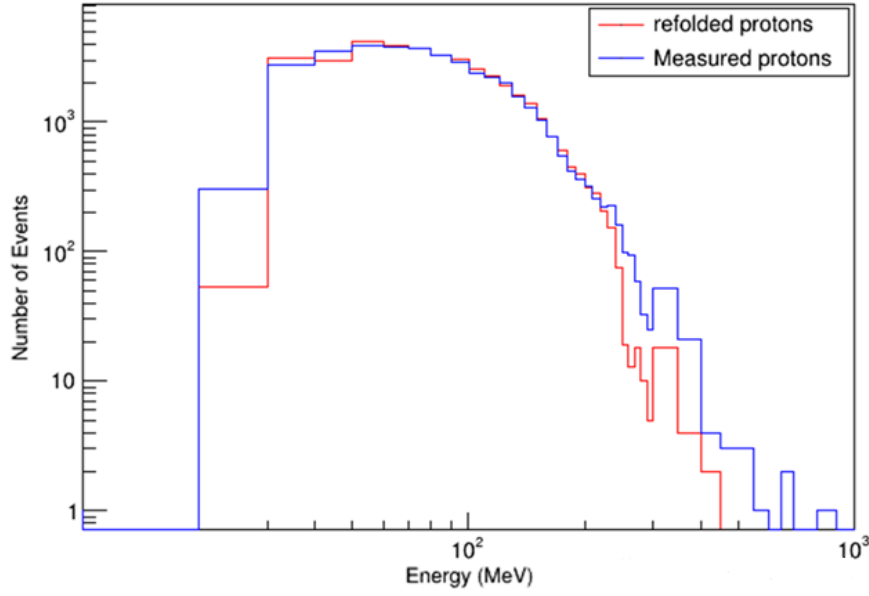


Figure 3.1.8: An example showing the comparison between the measured proton distribution versus deposited energy and the re-folded one obtained from the distribution de-convoluted with the Bayesian method.

3.1.6 Systematic Uncertainties

Systematic uncertainties have different sources.

The uncertainty due to the deconvolution procedure depends on the intrinsic accuracy of the unfolding technique used. As described in the previous section, it can be estimated by unfolding, comparing the measured counts to the "re-folded" distribution as in Fig. 3.1.8.

Another source of uncertainty lies in the comparison between simulation and flight data, as the digitization procedure and the limited statistics of the simulated proton sample introduce differences between flight data and Monte Carlo results. This uncertainty appears to be slightly time-dependent due to variations in the

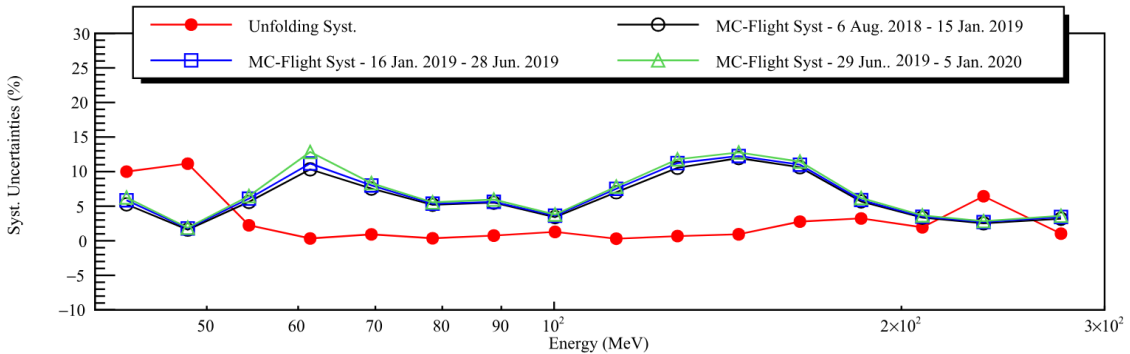


Figure 3.1.9: Systematic uncertainties as a function of energy: unfolding (red circles) and three time intervals Monte Carlo/flight systematics (black, blue, and green markers, respectively) [47].

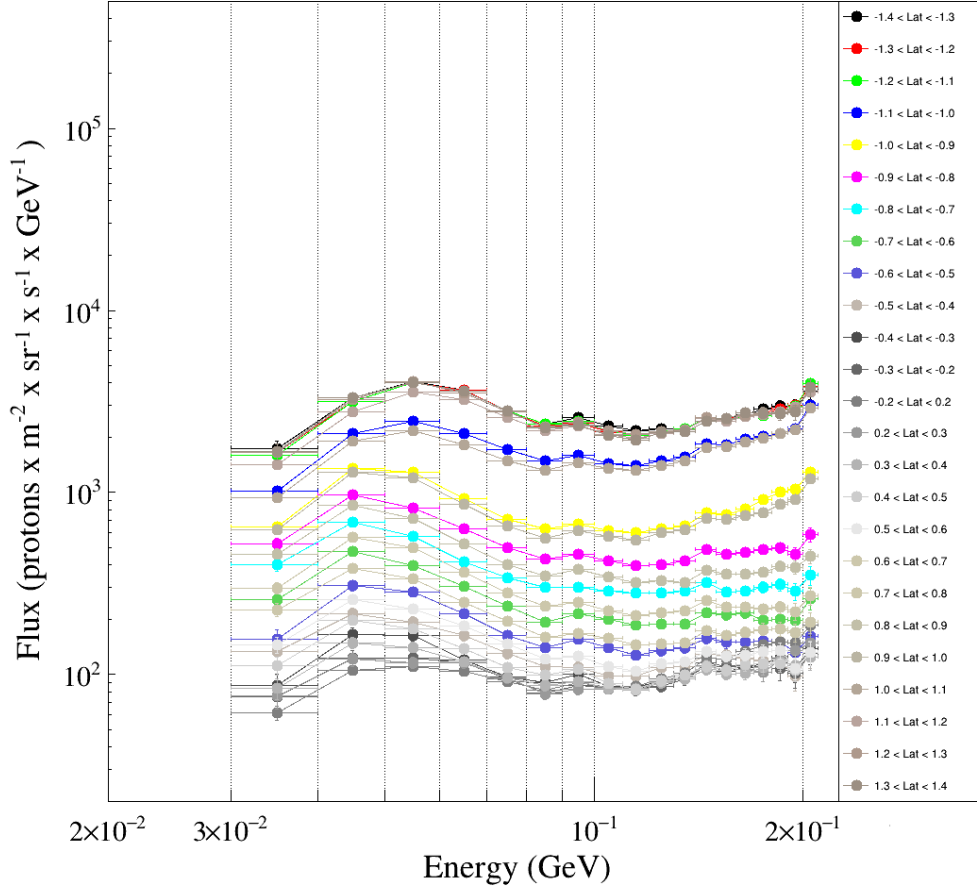


Figure 3.2.1: HEPD-01 measured proton spectra as a function of energy in several bands of magnetic latitudes in March 2022 (quiet period).

detector's response. By monitoring the signal distributions over time and comparing them to the reference period of August 2018 (first extended data taking a period after the commissioning phase of the satellite), a variation of $5\% \div 10\%$ was observed. It is taken into account as a systematic uncertainty.

In Fig.3.1.9, the unfolding systematic uncertainty is shown together with three systematics calculated on different time intervals (from August 2018 to January 2020), as given in [47].

3.2 Results and Discussion

The HEPD-01 flight data were analyzed using the selection criteria described above. Monthly distributions of protons passing the selection cuts were constructed in several bands of magnetic latitude θ_M , excluding the SAA region, and corrected for energy migrations.

In Fig. 3.2.1 and Fig. 3.2.2 are shown the proton flux versus primary energy in different bands of θ_M for two different periods: the month of March 2022, a month that has been chosen as representative of a quiet period with minimal solar activity,

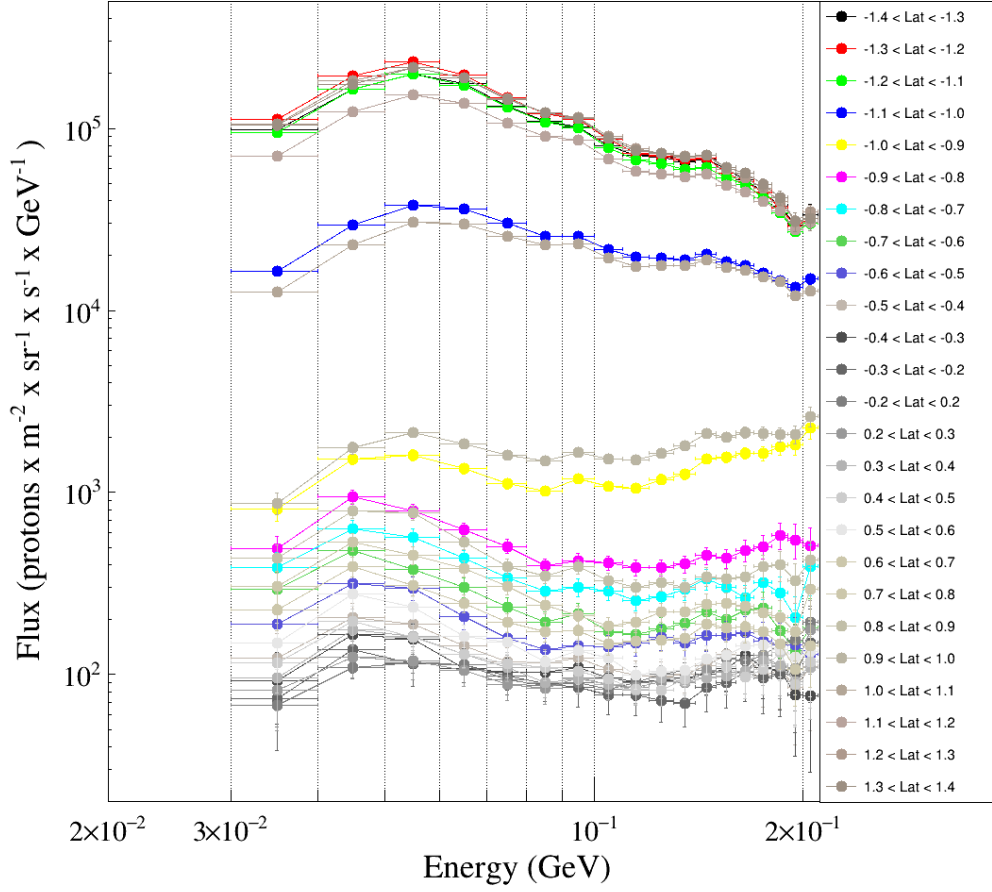


Figure 3.2.2: HEPD-01 measured proton spectra as a function of energy in several bands of magnetic latitudes during SEP event.

and the period from October 28 to 30, 2021 inclusive, correlated to the SEP event reaching the magnetosphere on October 28, 2021. Several conclusions can be drawn from the comparison of the two results:

- **Equatorial region** ($0 \leq \theta_M < 0.9$) – in this region, fluxes are similar to each other with some slight dependence on θ_M . These are fluxes of trapped populations, well below the rigidity cutoff, that are above the HEPD-01 range in these regions. The fact that these fluxes are due to trapped populations is confirmed by the fact that during SEP and in the quiet period, the fluxes in the same θ_M bins are very similar.
- **Transition region** ($0.9 \leq \theta_M < 1.1$) – in this region, there is a clear transition with fluxes changing rapidly as a function of θ_M . In these regions, the geomagnetic cutoff crosses the HEPD-01 measurement range, allowing the entry of cosmic particles originating outside the magnetosphere.
- **Polar region** ($1.1 \leq \theta_M < 1.5$) – in this region, the cutoff is below the HEPD-01 measurement range, and cosmic particles, which are more abundant than

the trapped ones, dominate. The fact that these are particles of cosmic origin is confirmed by the fact that their spectra do not depend on θ_M . Also, it is clear that, during the SEP event, the spectrum of solar particles becomes orders of magnitude more abundant than ordinary CRs.

In Fig. 3.2.3, a comparison between the data from HEPD-01 and AMS-01 flown in 1998 is presented [48]. AMS-01 measured upward and downward proton spectra at different geomagnetic latitudes. When the considered cutoff is sufficiently low, the measurements from HEPD-01 are compatible with those from AMS-01. The HEPD-01 measurement significantly extends the trapped-component measurement at lower energies, where data are missing.

The results presented in this section are preliminary; however, they confirm previous HEPD-01 publications [47], showing that the orbital selection done for galactic particles was adequate. This analysis has been carried out as a preparatory step for the computation of spectra with the HEPD-02 detector, which was put into orbit in July 2025.

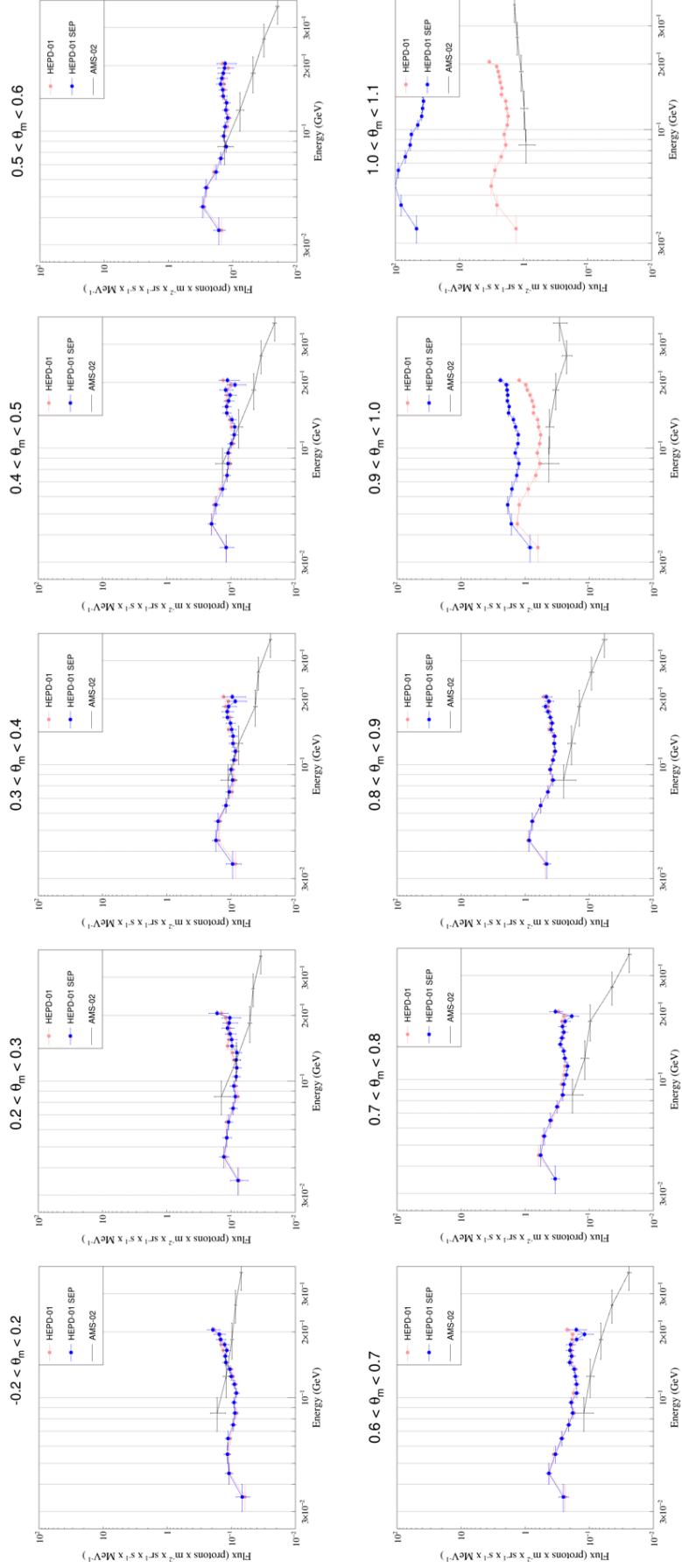


Figure 3.2.3: Comparison of HEPD-01 proton spectra measured in March 2022 quiet period (red), and during the SEP on 28th October 2021 (blue), with the results given by AMS (black) in several bands of magnetic latitudes.

Chapter 4

The HEPD-02 Scintillator System: Design, Construction, and Validation

The HEPD-02 detector was developed to achieve enhanced performance compared to the earlier HEPD-01 design [36]. As already discussed in Sec. 2.4, it introduces significant changes, including improved trigger logic and Housekeeping system, along with the first-ever use of MAPS for tracking particles in space, which enhances trajectory resolution. Two other critical improvements are the segmentation of the energy detector (EN) into two layers, each containing three LYSO bars, and the inclusion of a 2 mm triggering plane (TR1) at the top of the detector. Segmenting LYSO into bars read by photomultiplier tubes at each end enhances light collection efficiency and improves the mechanical design by reducing the amount of passive material compared to the previous HEPD-01 design. It also provides excellent energy measurements and can detect Gamma Ray Bursts (GRBs) [40, 41]. The presence of a thin first trigger plane on top of HEPD-02 allows for extending the instrument's energy range to lower energies and enhances particle separation. Two identical copies of HEPD-02 have been built: a qualification model (QM) and a flight model (FM). The performances of both models have been extensively studied.

In this Chapter, the several steps conducted from the design validation of the HEPD-02 detector through the space qualification tests are described. Since the Bologna group was responsible for the scintillation system, including the counters and the PMTs, I was involved in all stages, from prototyping to assembly and testing. Sections 4.1, 4.2 and 4.3 describe the scintillator system and the measurements performed to validate the design of all the counters. In Sec. 4.4, the photo-multiplier tube (PMT) characterization procedure and the sorting and coupling to the scintillators are discussed. Finally, in Sec. 4.5 and 4.6, the integration of HEPD-02 and the qualification tests are briefly described together with the performance results.

4.1 The HEPD-02 Scintillation Counters

The HEPD-02 scintillation counter system is designed to generate the trigger signal for the entire experiment, identify different types of particles and measure their energy. It is composed of two segmented trigger planes, TR1 and TR2, a tower of

twelve calorimeter tiles (RAN) followed by two orthogonal planes of LYSO crystals (EN). The whole system is surrounded by five panels of the containment detector (LAT and BOT). The plastic scintillators (TR1, TR2, RAN, LAT, and BOT) are made of EJ-200, a polyvinyl-toluene polymer manufactured by SCIONIX. It has a light yield of about 10^4 photons/MeV, a maximum emission wavelength of 420 nm and a decay time of about 2.1 ns¹. The crystal scintillators (EN1, EN2) are made of LYSO ($\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5\text{:Ce}$), manufactured by FILAR-OPTOMATERIALS. The bars, being 15 cm long, made their production complex. The expected light yield of LYSO is about 3×10^4 photons/MeV, with a maximum emission wavelength of 420 nm and a decay time of about 40 ns². In the following, the TR1 + TR2 + RAN + EN + CD counters are referred to by scintillating counters or scintillators.

All the scintillating counters were wrapped in aluminized Mylar and coupled to two Hamamatsu R9880U-210 PMTs, on the opposite sides. For LYSO crystals, an additional coating with black PVC tape was put on to prevent potential optical cross-talk due to their high light yield. The interface between scintillators and PMTs is provided by EJ-560 silicon rubber optical pads apart for the TR1 thin paddles for which Plexiglass light guides were glued to the scintillator ends to focus the light on the PMT aperture. To ensure a good optical contact between the PMT window, the optical pad, and the scintillator/light guide face, distances are controlled by adjustable spacers. Reading scintillators from both sides ensures uniform trigger-counter efficiency as a function of the longitudinal coordinate (defined as the coordinate along the axis passing through the centers of the two PMTs). Additionally, the sum of signals from the two opposite sides is roughly independent of the impact position. The PMT readout board has been designed to meet the satellite's power requirements and to read out the last dynode, matching the signal polarity required by the CITIROC ASIC [49].

4.2 Counter Prototype Validation

A prototype validation campaign [50], in which I actively participated, was conducted in the Bologna Laboratory (unless otherwise stated) to confirm that the scintillation photons produced by cosmic rays passing through the center of a counter were sufficient to provide a trigger and an energy-deposit measurement. This is particularly important for the TR1 trigger detectors, which are only 2 mm thick and are coupled to the PMTs through two asymmetric light guides. Indeed, these light guides have a trapezoidal shape ending in a 6×8 mm² window, with different lengths on the two sides; 25 mm at one side and 46 mm at the other. The asymmetry is imposed by the mechanical structure designed for HEPD-02 and the need to have an optimized angular aperture above the tracker system.

Prototypes of counters of TR1, TR2, RAN, EN, BOT, and LAT were realized using the scintillating materials, wrapping, and PMTs selected for production. The PMTs were read by electronic boards similar to the ones designed for flight. While the counters have been realized following procedures similar to those employed for the flight hardware, the supporting mechanics have been adapted from readily avail-

¹EJ200 Data Sheet, ELJEN TECHNOLOGY

²LYSO Data Sheet, Luxium Solutions

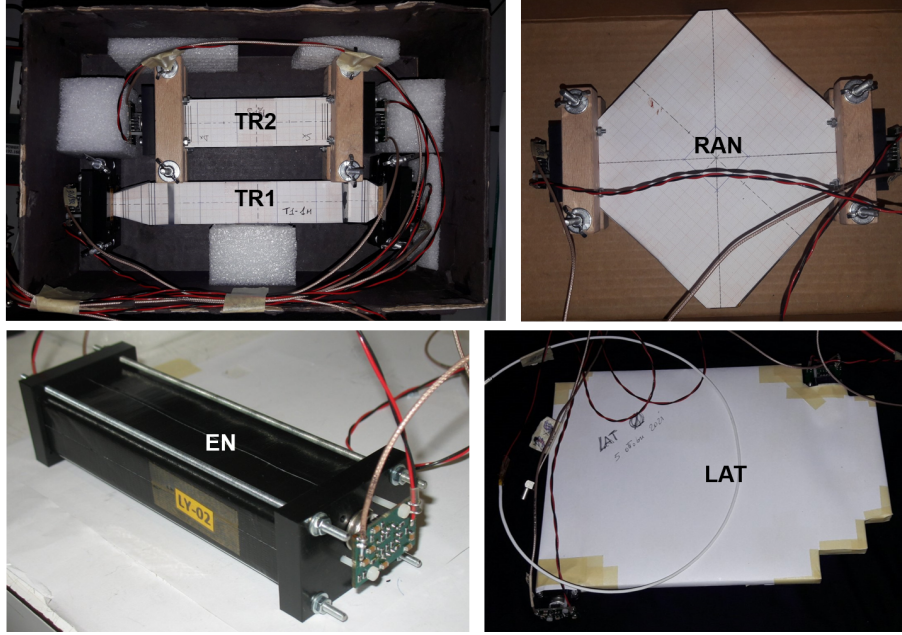


Figure 4.2.1: On the top left panel are shown the prototypes of the trigger plane counters (TR1 and TR2); on the top right, a calorimeter tile (RAN); on the bottom left, one of the LYSO crystals (EN); and on the right, a prototype of the lateral containment panel (LAT).

able laboratory components. The prototypes of the different counters are shown in Fig. 4.2.1. They were tested using a large scintillator tracking system available at the INFN Bologna laboratory, originally developed for tracking particles in a magnetic field as part of the NESSiE Collaboration’s R&D efforts [51]. It consists of 5 planes, each comprising 2 orthogonal layers of scintillators with triangular cross-sections, capable of reconstructing muons at inclinations up to 17 degrees with high efficiency and a spatial resolution of 2 mm [51].

4.2.1 Experimental Setup

The scintillator counter under test was placed inside a black box at the center of the NESSiE tracker. The PMT high voltages (HVs) were set to obtain a gain of $\sim 10^6$. NESSiE has been used to trigger the acquisition of the counter-under-test readout by a CAEN V1751 digitizer. Particle tracks were reconstructed from tracker data and then correlated with the pulse heights and integrated charges measured by the two PMTs. Off-time signals were used to evaluate the corresponding pedestals and noise levels. A schematic view of the NESSiE tracker with a TR1 counter placed on the central plane is shown in Fig. 4.2.2.

To accumulate sufficient statistics, the setup for each counter was left in acquisition for 1 to 2 weeks. The signals had a signal-to-noise ratio of $S/N > 10$ in all positions along all the counters. In the case of TR1, due to the asymmetry of the light guides, a difference of 10 to 15% between the signals on the two sides was observed. This asymmetry has no impact on the trigger efficiency and can be compensated for with the equalization of the PMTs.

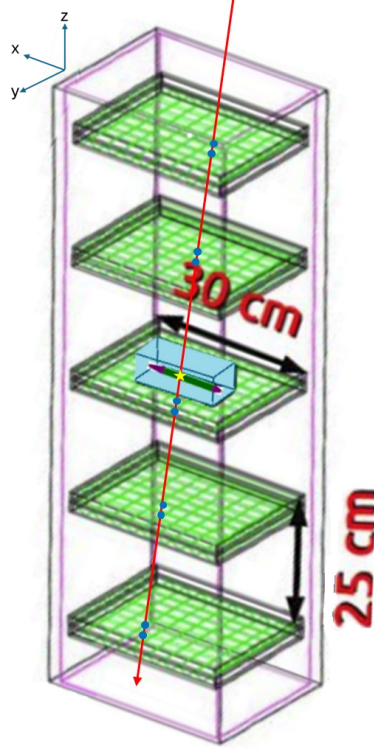


Figure 4.2.2: A schematic view of the validation setup showing NESSiE tracker with a box containing the counter under study (here, TR1) placed at the center.

4.2.2 Signal Level, Efficiency and Uniformity of Prototypes

All the scintillator prototypes were, in the first place, tested for efficiency and uniformity versus impact position using cosmic muons. The trigger efficiency is defined as the ratio of the number of events triggering the counter under study to the total number of events crossing this counter as given by the NESSiE tracker. It is derived from the logical OR of the PMTs imposing a threshold of 20 mV [52] to signals on both sides of each counter. The trigger efficiency was found to be better than 95% for all prototypes in all positions as shown in Fig. 4.2.3. The uniformity map is obtained calculating the Most Probable Value (MPV) of the sum of the PMT signals from the two sides as a function of the transversal and longitudinal coordinate given in cells of size $0.5 \times 0.5 \text{ cm}^2$. As can be seen in Fig. 4.2.4 a good spatial uniformity was also observed except very close to the PMT.

Afterwards, the integrated charge measured from both the PMTs of the counter under study $Q_{1,2}$ has been studied as a function of the impact position on the counter. For each position, the most probable value (MPV) of the signal distribution has been calculated with a Landau distribution convoluted with a Gaussian. The two PMT responses were equalized to the MPV average at the center of the counter. An example of the signal amplitudes recorded for the TR1, TR2, RAN and EN prototypes is shown in Fig. 4.2.5. In the case of TR1, a small shift between the PMTs can be observed and can be attributed to the different lengths of the light guides. In Fig. 4.2.6, the equalized MPV charge registered by each one of the two

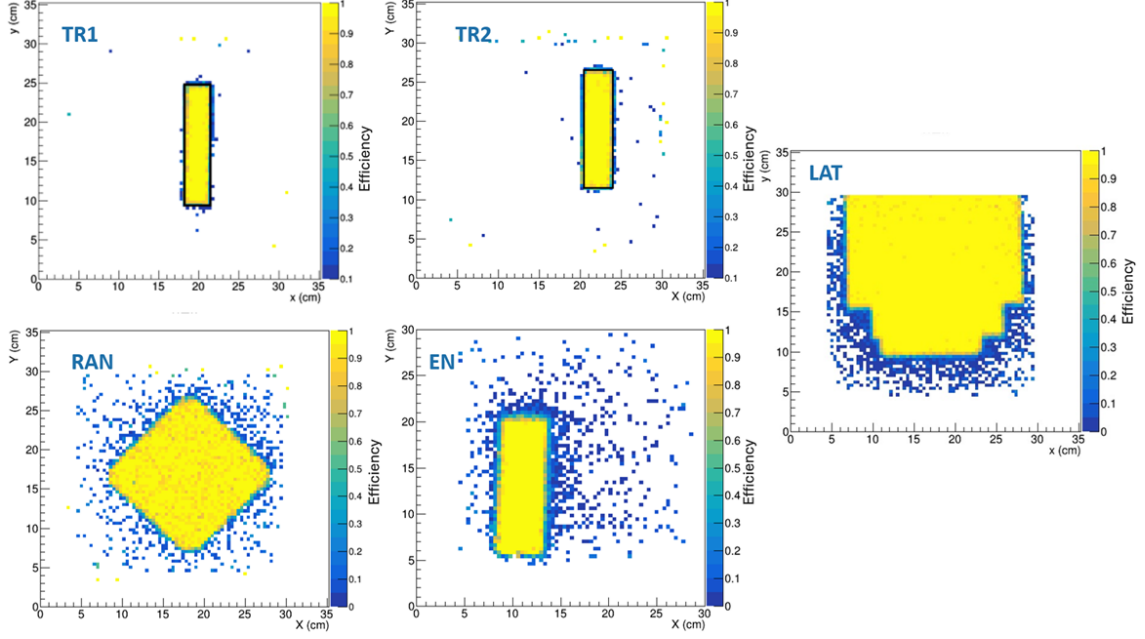


Figure 4.2.3: Efficiency map of: TR1 (top left), TR2 (center top), RAN (bottom left), EN (center bottom), and LAT (right) counters as a function of the transversal and longitudinal coordinate calculated in cells of size $0.5 \times 0.5 \text{ cm}^2$. The efficiency has been estimated using a threshold of 20 mV and applying the logical OR of the two PMTs. The efficiency is represented from 0 to 1 on the colored scale.

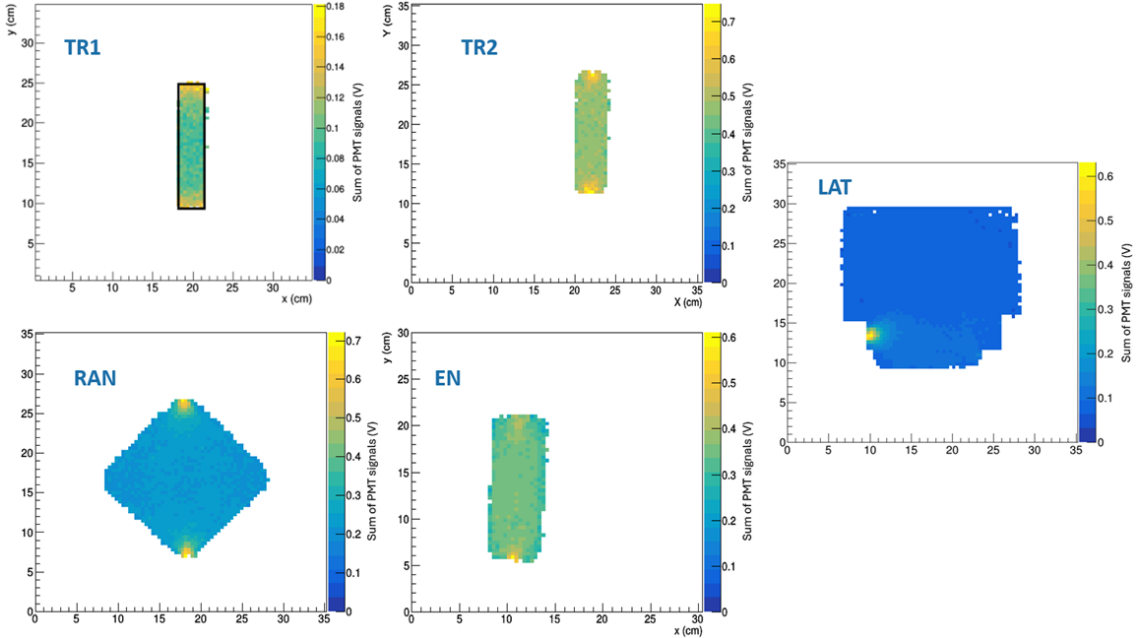


Figure 4.2.4: Uniformity map of: TR1 (top left), TR2 (center top), RAN (bottom left), EN (center bottom), and LAT (right) counters. The uniformity is calculated as the MPV of the sum of the signals from the two sides as a function of the transversal and longitudinal coordinate calculated in cells of size $0.5 \times 0.5 \text{ cm}^2$. The colored scale represents the MPV of the sum of signals in volts.

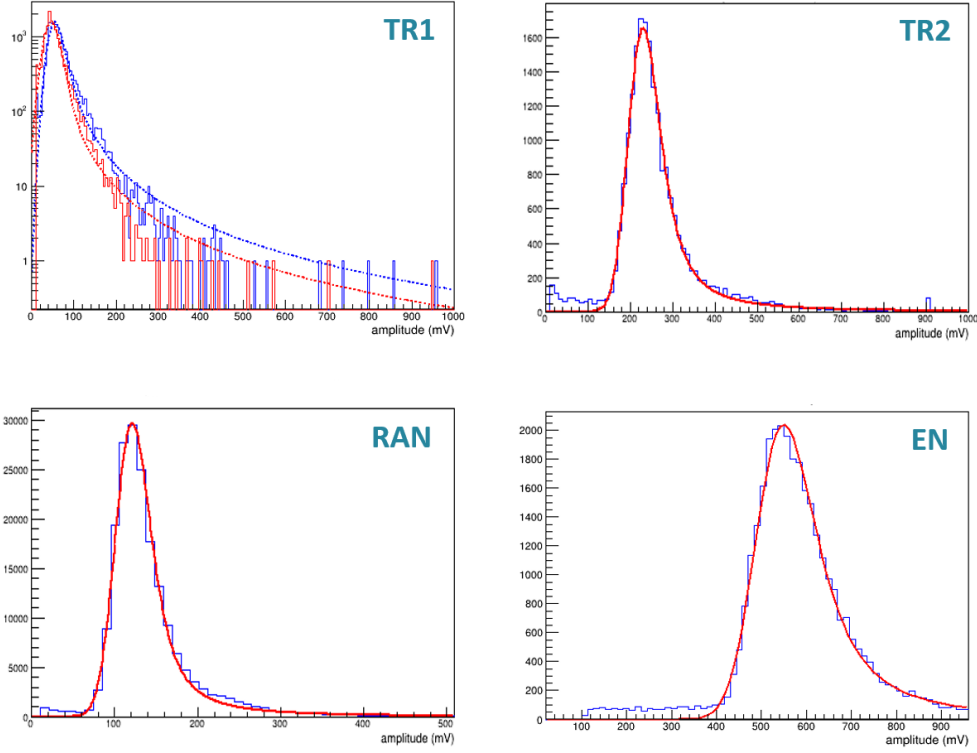


Figure 4.2.5: The signal amplitudes distributions recorded by the equalized PMTs for MIPs in: TR1 (top left), TR2 (top right), RAN (bottom left) and EN (bottom right). For TR1, the blue histogram is the signal recorded by the PMT connected to the short light-guide and the red one to the one connected to the long light-guide. The blue/red curves are the fits obtained using a Landau distribution convoluted with a Gaussian.

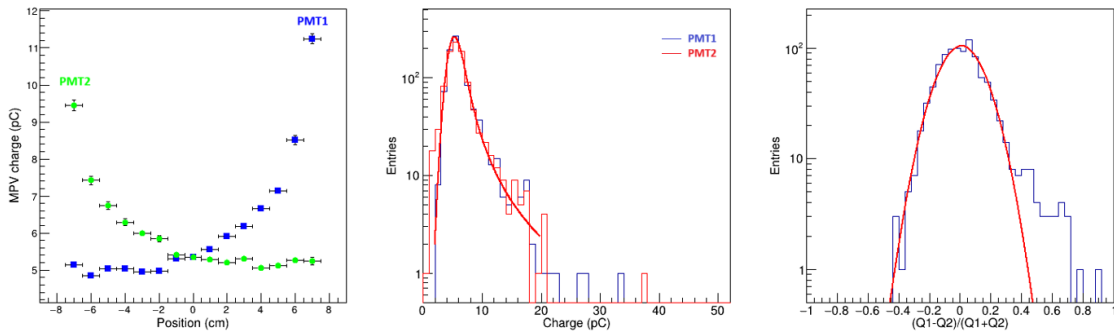


Figure 4.2.6: On the left is presented the most probable charge recorded by the two PMTs of the TR1 prototype versus the longitudinal coordinate. In the middle, the equalized PMT charge distributions for a sample of tracks passing through the center of the counter, and on the right, the charge asymmetry distribution for the same sample.

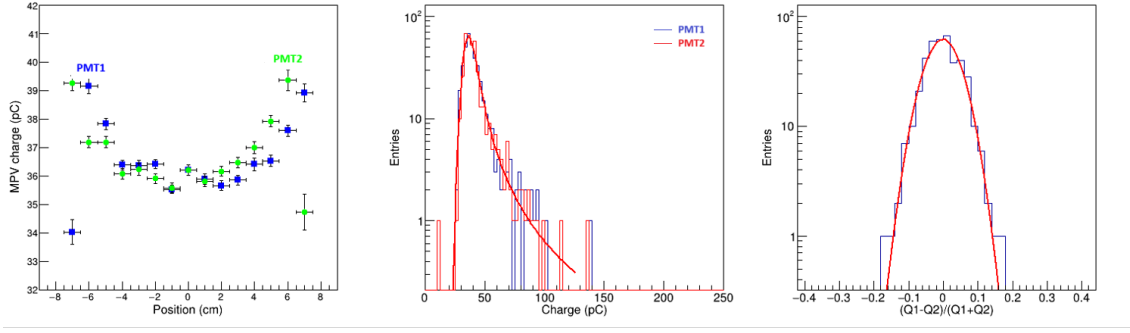


Figure 4.2.7: In the left panel: The most probable charge recorded by the PMTs versus impact position; in the middle panel: the equalized PMT charge distributions at the center of the scintillator bar, and in the right panel the $(Q1 - Q2)/(Q1 + Q2)$ distribution at the center of the TR2 counter prototype.

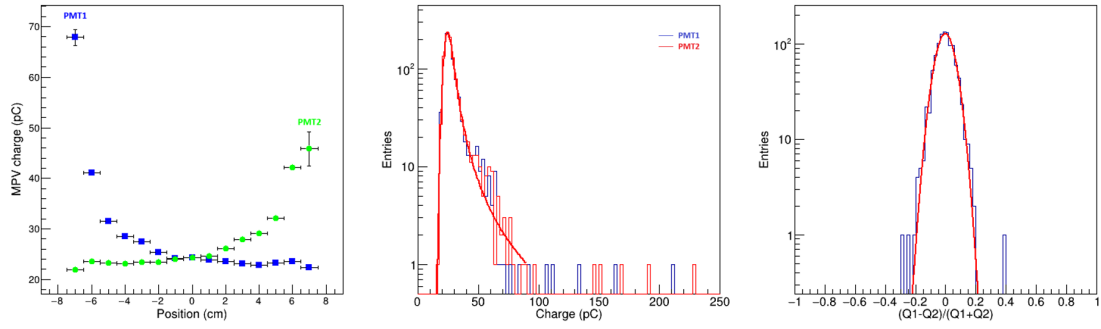


Figure 4.2.8: In the left panel: The most probable charge recorded by the PMTs versus impact position; in the middle panel: the equalized PMT charge distributions at the center of the scintillator bar, and in the right panel the $(Q1 - Q2)/(Q1 + Q2)$ distribution at the center of the RAN counter prototype.

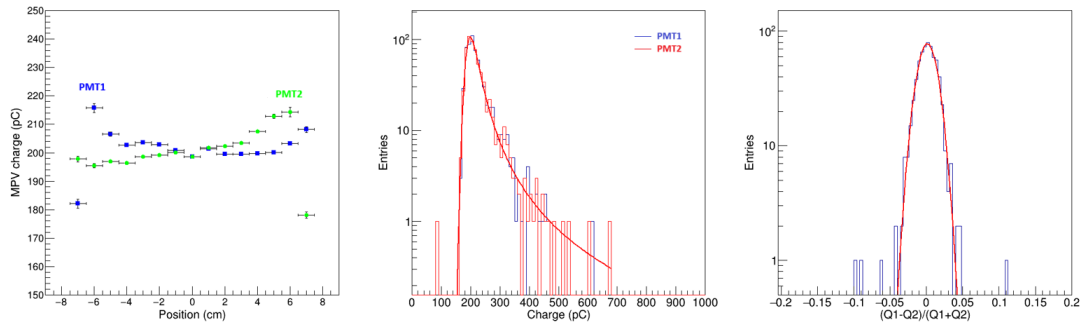


Figure 4.2.9: In the left panel: The most probable charge recorded by the PMTs versus impact position; in the middle panel: the equalized PMT charge distributions at the center of the scintillator bar, and in the right panel the $(Q1 - Q2)/(Q1 + Q2)$ distribution at the center of the EN counter prototype.

Table 4.2.1: For each counter sample, the following quantities were derived: (i) the MPV of the signal maximum amplitude, (ii) the MPV of the integrated charge, and (iii) the mean number of photo-electrons for a sample of minimum ionizing cosmic muons passing through an area of $\sim 1 \text{ cm}^2$ around the center of the counter. For TR1, a correction for the light-guide difference in photon transmission has been included.

Counter	Amplitude (mV)	Charge (pC)	N (p.e.)
TR1	43.7 ± 0.7	5.31 ± 0.06	27 ± 1
TR2	221.1 ± 1.5	35.1 ± 0.2	197 ± 4
RAN	114 ± 11	29.9 ± 0.1	130 ± 2
EN	513 ± 29	477 ± 27	2986 ± 194

PMTs of the TR1 counter under test as a function of the longitudinal coordinate, and the charge distribution observed at the center of the counter are shown.

The number of photo-electrons produced at the center of the counter can be derived directly from the measurement of the width of the distribution of the charge asymmetry $(Q_1 - Q_2)/(Q_1 + Q_2)$, with the assumption that the signal is attenuated similarly at the location of the two PMTs, a condition that approximately holds for TR1, TR2, RAN, EN and BOT. In first approximation, the following relation can be derived:

$$N = \frac{1}{2\sigma^2}. \quad (4.2.1)$$

where N is the number of photo-electrons detected at the PMT location, and σ is the width of the Gaussian fit of the charge asymmetry distribution. Figure 4.2.6 presents the charge asymmetry of TR1 obtained for a sample of events passing through an area of $\sim 1 \text{ cm}^2$ at the center of the counter. The asymmetry distribution has been fitted with a Gaussian, yielding an estimate of the number of photo-electrons of 27 ± 1 , in agreement with the expectations from the simulation.

The charge distributions and charge asymmetries were systematically studied for all counters; see Figs. 4.2.7, 4.2.8 and 4.2.9 for TR2, RAN and EN counters, respectively. In Tab. 4.2.1, the MPVs of the maximum signal amplitudes, integrated charges, and number of photo-electrons for impact positions in the middle of the counters are given. Counters TR2, RAN, EN, and BOT showed amplitude signals and charges well above the TR1 ones. Due to its geometry and PMT location, the LAT shows very different signal dependencies with respect to transversal and longitudinal coordinates on the two sides. However, these signals are well above the TR1 signal in magnitude at all locations.

4.2.3 TR1 Design Optimization

As noted in the preceding sections, the thickness of the TR1 counters was kept as small as possible to achieve the lowest detection threshold and to minimize scattering. A preliminary study was conducted before selecting a final thickness of 2 mm to ensure the signal was sufficiently strong to trigger the electronics. In ref. [53], two prototype counters of 2 mm and 3 mm thickness, respectively, were tested under cosmic muons. These prototypes were glued at both ends to 20 mm-long light guides.

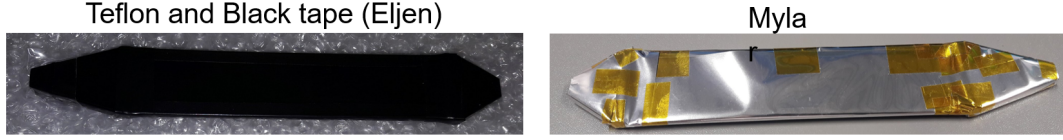


Figure 4.2.10: In the left panel: The TR1 prototype counter wrapped in PTFE white tape and black tape; and in the right panel the TR1 counter wrapped in Mylar

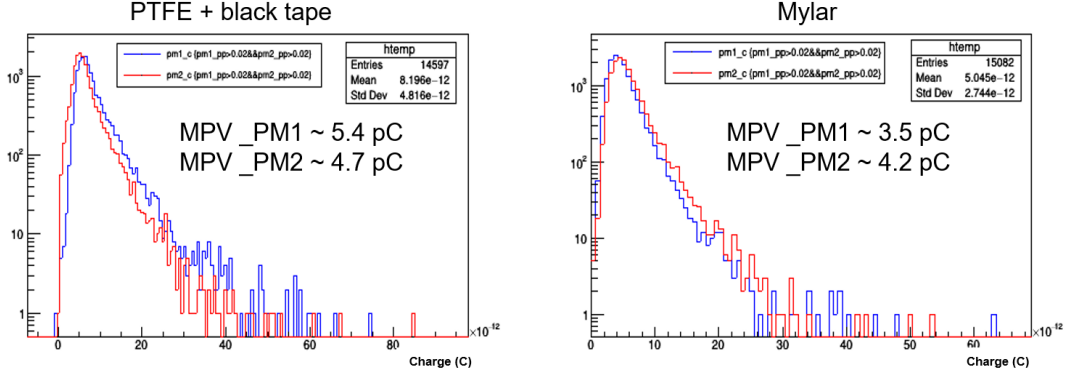


Figure 4.2.11: The charge distribution of cosmic muons recorded by the PMTs of the TR1 counter; wrapped in PTFE and black tape (left) and in Mylar (right). The blue histogram is for the PMT connected to the small light-guide, the red one is for the PMT connected to the long light-guide.

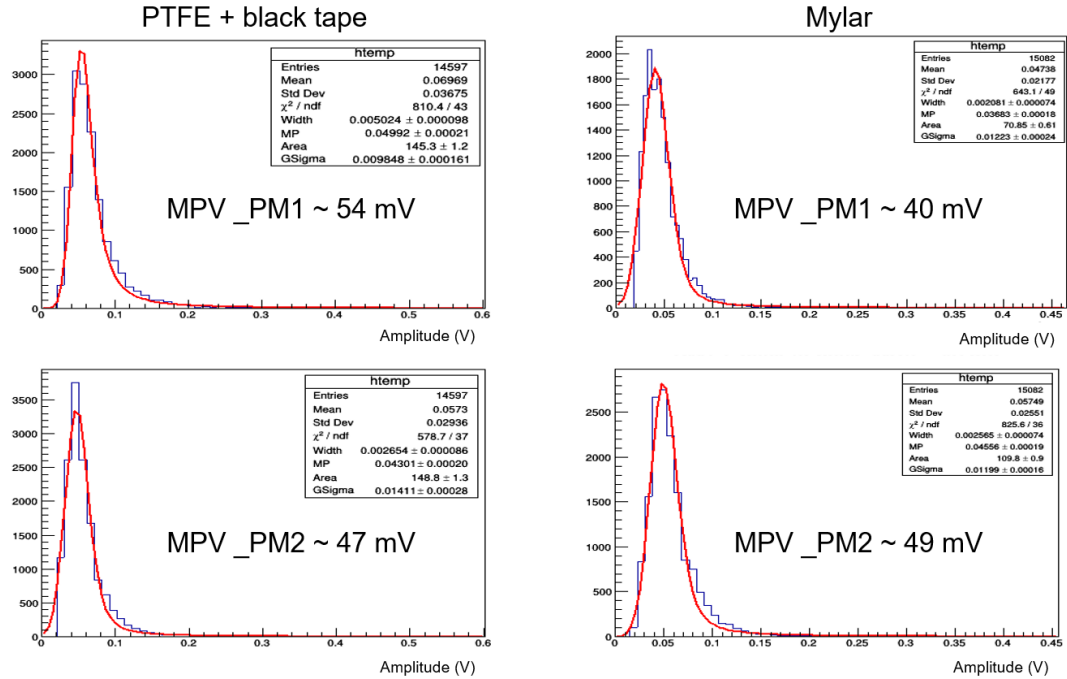


Figure 4.2.12: The peak-to-peak signal distributions of cosmic muons recorded by the PMTs of the TR1 counter; wrapped in PTFE and black tape (left) and in Mylar (right). The top panel presents the signal distribution for the PMT connected to the small light-guide, and the bottom panel presents the one for the PMT connected to the long light-guide.

It was found that the number of collected photoelectrons was sufficient to ensure good detection efficiency for low-energy particles in both models. A Monte Carlo simulation of the two counters, tuned on experimental data, showed that they had similar efficiency and spatial resolution. These results led the Limadou collaboration to select the thinner 2 mm counter.

Additionally, after selecting the final dimensions of the TR1 paddles, two wrapping materials were tested. The first one was reflective white tape (PTFE) covered with additional black tape. The second wrapper was Mylar. The TR1 counter wrapped in the two materials is shown in Fig. 4.2.10: on the left, in PTFE and black tape; on the right, in Mylar. We used the same counter provided by EL-JEN wrapped in PTFE, unwrapped it, and re-wrapped it in Mylar. The tests were performed under cosmic muons with the NESSiE tracker. In Fig. 4.2.11 are shown the charge distributions recorded by the 2 PMTs of the TR1 counter wrapped in PTFE and black tape (left) and in Mylar (right). The distributions were obtained for PMTs equalized at a gain $\sim 10^6$. As can be seen, the value of the mean MPV of charge collected by the TR1 counter wrapped in Mylar is $\sim 24\%$ lower than in the case of PTFE and black tape; however, the collected charge is still high enough. The same difference is observed from the mean MPV signal recorded (see Fig. 4.2.12). For TR1 wrapped in Mylar, the signal/charge recorded by the PMT coupled to the small light-guide is lower than expected and lower than that from the long light-guide. This effect was most likely due to a non-optimal optical connection of the PMT.

The PTFE wrapper appeared to be the most advantageous in terms of signal level; however, the wrapping procedure was complicated by the need to achieve the thinnest possible layer while avoiding large tape overlaps and maintaining optimal uniformity across all counters. On the other hand, although the signal recorded by the TR1 wrapped in Mylar appeared lower, it was still sufficiently high to trigger on MIPs. In addition, the wrapping procedure facilitates meeting the requirements for low thickness and uniformity. In light of all these considerations, the final choice was Mylar.

4.3 LYSO Crystal Characterization

To achieve a comprehensive characterization of the LYSO crystals, a series of dedicated measurements was conducted at the University of Trento [54]. These crystals, developed specifically for HEPD-02, feature non-standard dimensions that require careful crystal growth, cutting, and polishing, making it particularly crucial to understand their properties thoroughly. The characterization of the crystals involved calibrating the energy response and estimating the spectrum arising from the intrinsic activity of Lutetium. The light emission as a function of the particle impact point was also checked to select the best crystals for the FM.

The wrapped crystal and PMTs were provided by Bologna and were compliant with the flight model design. A voltage of 700 V was applied to the PMTs, yielding a gain of about 4×10^5 .

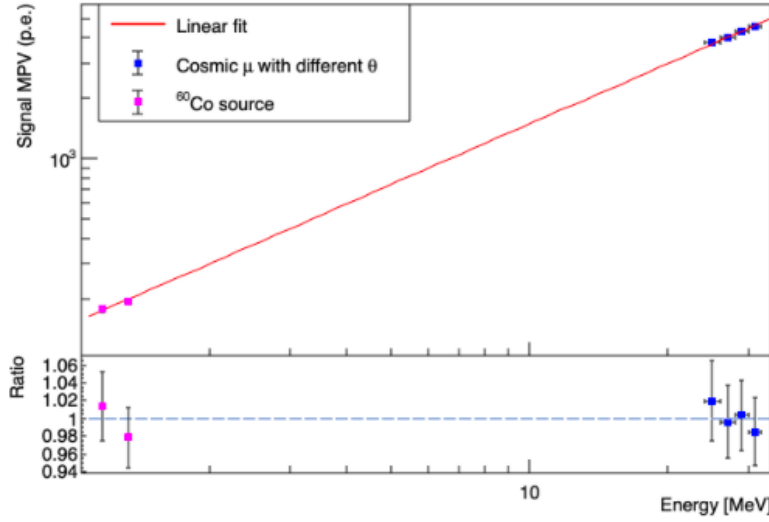


Figure 4.3.1: The energy calibration line for one PMT of a given sample derived from the measurement described in Section 4.3.1, accompanied by a ratio plot depicting the relationship between the fitted line and the measured points. The constant of the fitted line is considered to be zero.

4.3.1 Calibration of the Energy Response

The γ -ray emissions at 1.333 MeV and 1.173 MeV from a ^{60}Co sample were used to calibrate the crystals at low energies. The emitted radiation collected by LYSO crystals was measured using a trigger logic that required coincidence between the two PMTs of the LYSO crystal and a nearby NaI(Tl) detector. PMT signals were acquired using a Teledyne LeCroy HDO9104 oscilloscope (Teledyne LeCroy, 30020 Marcon, Italy). For calibration at higher energies, two EJ-200 plastic scintillators with dimensions of $50 \times 30 \times 10 \text{ mm}^3$ were placed above and below the crystal to trigger cosmic muons passing through the LYSO crystal. Minimum ionizing muons lose about 10 MeV/cm in LYSO, resulting in an energetic deposit of approximately 25 MeV for particles crossing the samples vertically. The the impact position and arrival direction of cosmic muons was evaluated with the use of HEPD-02 direction detector pototype [55, 56]. By selecting the arrival angle of the muons, measurements were performed between 25 and 30 MeV. Measurements of the amplitude distribution MPV for muons and ^{60}Co allowed the calibration illustrated in Fig. 4.3.1. All crystals showed similar calibration factors.

4.3.2 Estimation of Lutetium Intrinsic Activity

LYSO contains natural Lutetium, which comprises approximately 2.6% of the radioactive isotope ^{176}Lu . This material has an intrinsic radioactive background due to the decay of ^{176}Lu via β -emission, with a half-life of 3.76×10^{10} years. The mean and maximum emitted β energies are 182 keV and 593 keV, respectively, and the decay generates excited states of the daughter isotope ^{176}Hf , which produces a chain

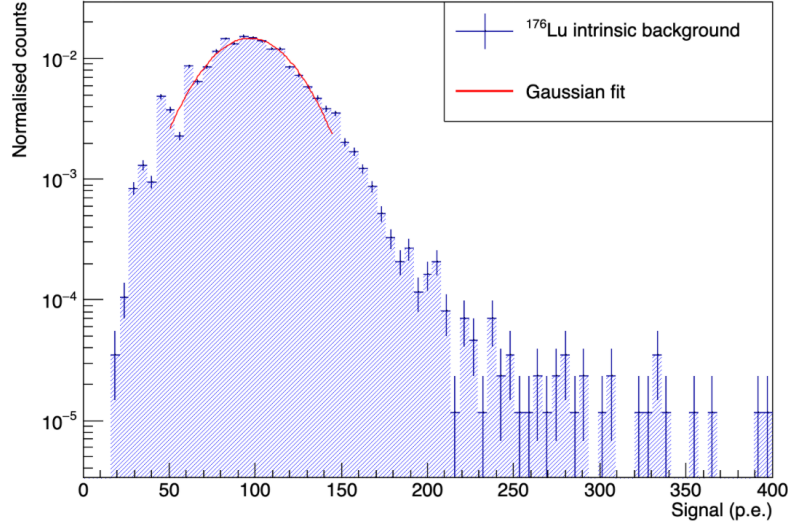


Figure 4.3.2: The intrinsic radioactivity spectrum generated by ^{176}Lu as measured by one PMT in a single LYSO sample.

of three γ -rays with energies of 88, 202, and 307 keV. This intrinsic radiation results in a spectrum consisting of four peaks at 88, 88 + 202, 88 + 307, and 88 + 202 + 307 keV, depending on the probability of one or more photons escaping the crystal³. The measurement was performed using trigger logic that required coincidence between the two PMTs coupled to the LYSO crystals, with signal thresholds in the mV range. The amplitude distribution obtained can be described by a Gaussian shape with an exponential tail, representing the convolution of the four γ lines and the β -decay radiation (see Fig. 4.3.2). The measured rate was consistent with the LYSO total activity of approximately 40Bq/g [57]. This measurement is essential for establishing the HEPD-02 experiment’s calorimeter thresholds, which should be kept as low as possible to detect the high-end of GRB spectra while maintaining a manageable rate coming from a ^{176}Lu intrinsic background [40].

4.4 Calibration of the Photo-Multiplier Tubes

The PMTs selected for HEPD-02 are the Hamamatsu R9880U-210. These PMTs are characterized by high gain, a fast time response, and a high quantum efficiency in the range of wavelengths of our scintillators (see Hamamatsu R9880U-series PMT datasheet⁴). In total, 128 PMTs were required for integrating the QM and FM of HEPD-02. In each one of the two detectors, the 64 PMTs were powered by 16 HV lines. In order to obtain the best possible match between the PMTs and the different scintillation counters that produce widely different numbers of photons when trig-

³https://www.luxiumsolutions.com/sites/default/files/2023-08/142266_Luxium_LYSO-Material-Data-Sheet_FIN.pdf

⁴https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R9880U_TPMH1321E.pdf

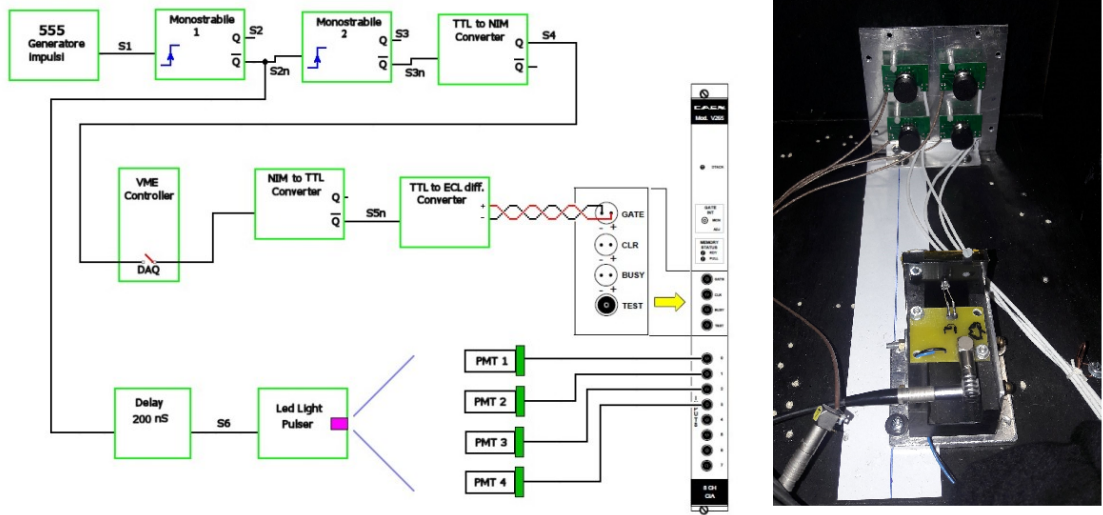


Figure 4.4.1: Diagram and picture of test bench for the characterization of the Photomultiplier tubes.

gered by Minimum Ionizing Particles (MIPs), and to determine which PMTs should be powered on the same HV line, a detailed characterization of the PMTs' gain versus the HV was realized. The procedure, entirely developed and carried out in Bologna also allowed for the discrimination of non-functional PMTs and verification of the nominal characteristics provided by Hamamatsu. Globally, 200 PMTs were tested.

4.4.1 PMT Gain Characterization

The method applied to calculate the gain of a PMT follows the method of photo-statistics [58]. In short, the PMT is placed inside a black box and illuminated with different light intensities from an LED voltage-controlled, see Fig. 4.4.1. For each LED intensity, the mean observed signal $\langle R \rangle$ is related to the number of photo-electrons emitted by the photo-cathode $\langle N \rangle$ by the gain factor G , or $\langle R \rangle = G\langle N \rangle$. The variance of the observed signal σ_R has essentially three contributions: (i) the Poisson statistics of the photo-emission process, (ii) the variance of the single photo-electron distribution δ_{spe} , and (iii) electronic noise. The LED intensities used in the tests are such that the electronic noise is always negligible with respect to σ_R . We can write

$$\sigma_R^2 = G(1 + \delta_{\text{spe}}^2)R. \quad (4.4.1)$$

By testing the PMT with different LED intensities, the σ_R^2 versus R curve allowed for the derivation of the term $G(1 + \delta_{\text{spe}}^2)$. To derive the gain G , the needed δ_{spe} was derived by fitting the single-photon distribution that was obtained using very low intensity on the LED with the PMT set at a reference voltage of 1000V. To study the dependence of the PMT gain on the HV, the procedure was repeated several times for different voltages from 600V to 1000V in steps of 50V. The procedure was repeated for all PMTs in bunches of four.

Example pedestal and single photo-electron distributions obtained during the calibration procedure are shown in Fig. 4.4.2 (left and right panels, respectively).

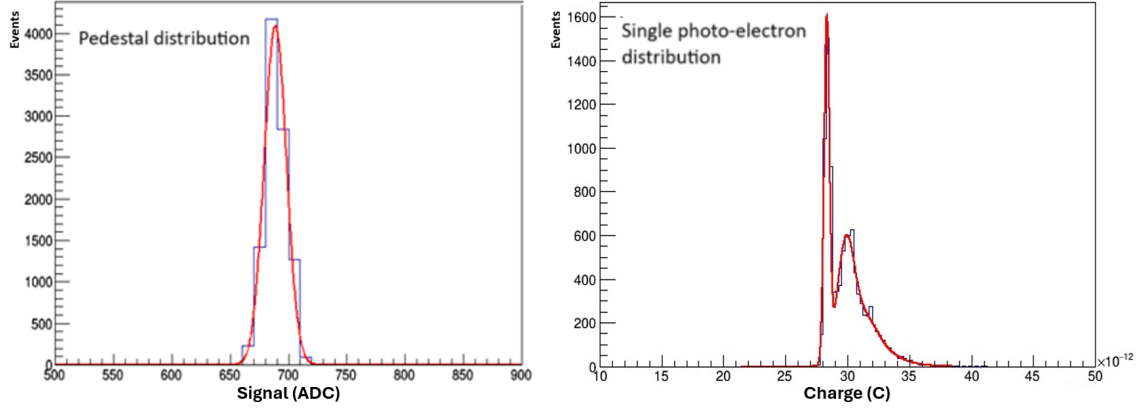


Figure 4.4.2: Some example distribution of the pedestal measured for one of the PMTs, on the left, and on the right, the single photo-electron distribution obtained

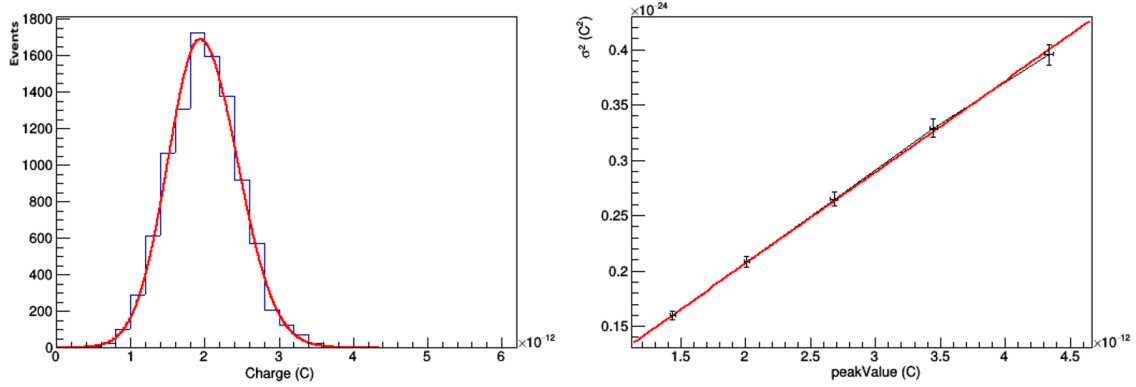


Figure 4.4.3: Some example charge distribution measured by one of the PMTs at a fixed HV and LED intensity on the left and, on the right, the σ_R^2 curve obtained at a fixed HV from the different charge distributions measured at different LED intensities.

While in Fig. 4.4.3, the charge distribution measured at a fixed HV and LED intensity (left panel), together with the resulting σ_R^2 curve versus LED intensity (right panel), is shown.

The characterization procedure ends with retrieving the gain versus high voltage, $G \propto HV^\gamma$, for every PMT and deriving the slope (γ), as can be seen in Fig. 4.4.4, for example.

A comparison of the gain measured to the nominal one given by Hamamatsu at 1000 V is given in Fig. 4.4.5. The PMTs tested were found to have gains ranging from 10^6 to 10^7 and are within 20% with respect to the nominal gains provided by Hamamatsu.

4.4.2 PMT Linearity Verification

For precise energy reconstruction, especially under the demanding conditions of space environment, it is critical that the PMTs exhibit a stable and well-characterized response over the full range of expected signals.

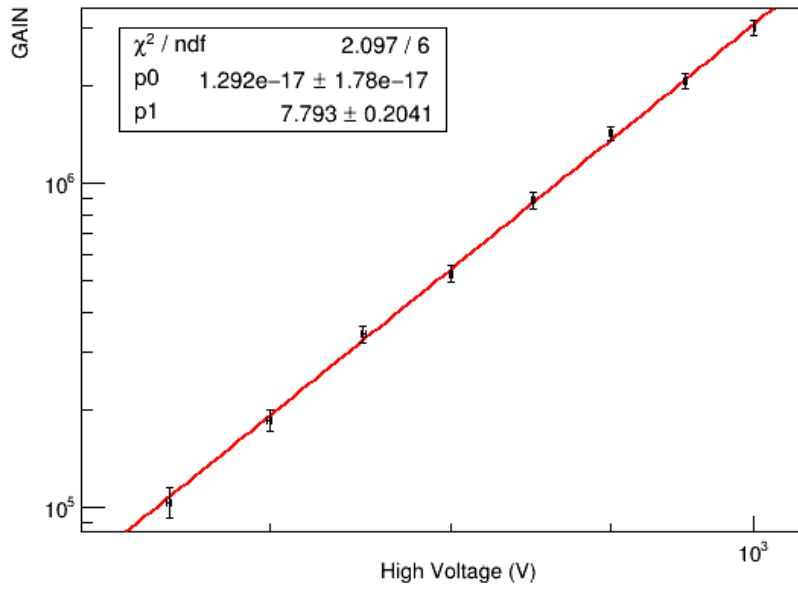


Figure 4.4.4: The measured gain versus high voltage applied for one of the characterized PMTs.

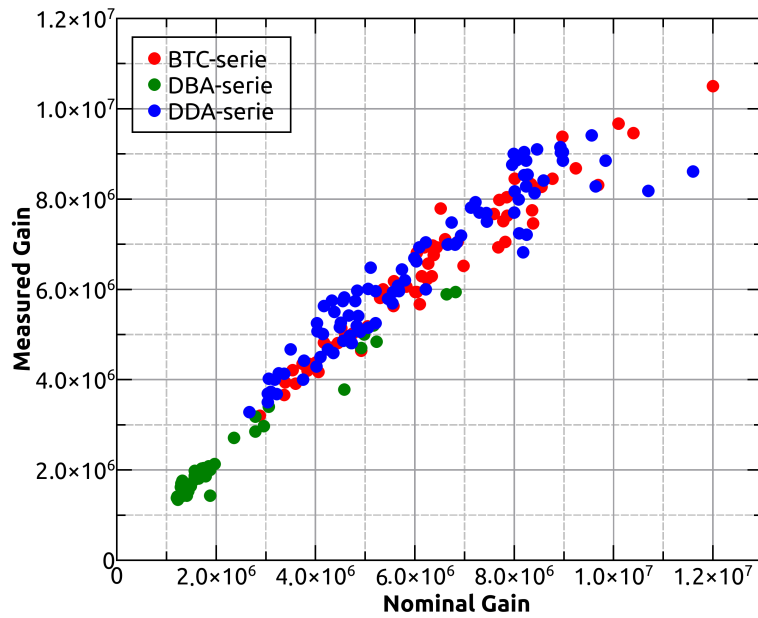


Figure 4.4.5: The measured gain versus nominal gain for the total bunch of PMTs tested at an HV of 1000 V. The different colors refer to different PMT productions.

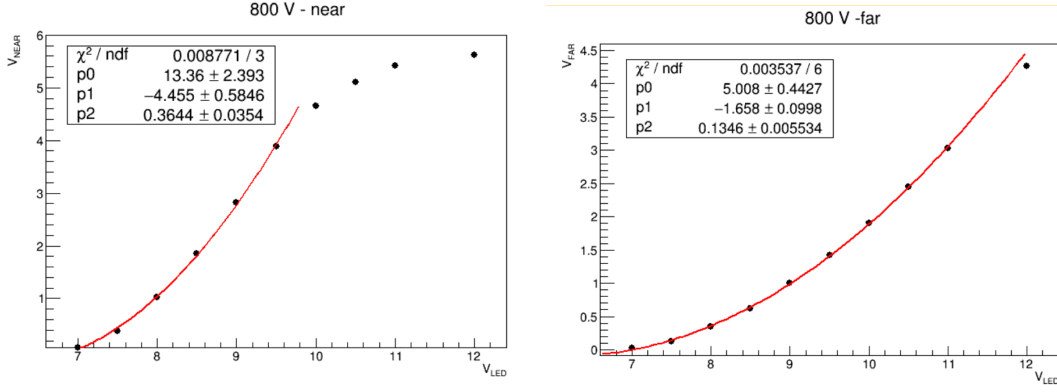


Figure 4.4.7: Peak-to-peak signal amplitude (in V) response versus LED intensity of a PMT placed at Near (left), and Far (right) position from the LED.

Table 4.4.1: The target PMT gain assigned to the different counter types.

Counter	Gain
TR1 - LAT	3×10^6
TR2 - RAN - BOT	10^6
EN	5×10^5

LED (55 mm, 110 mm) versus the LED intensity [60]. This method is used to remove effects caused by optical couplings when using optical filters. It relies only on geometrical factors. Provided the PMT window is fully illuminated, the intensity of light collected at the entrance window of the PMT, at a fixed LED power, is inversely proportional to the distance $I \propto 1/d^2$. As intensity increases, the PMT response is expected to deviate from linearity and begin to saturate.

Figure 4.4.6 shows the setup and the connection schema used for the study. An example PMT response versus LED intensity at the Near (55 mm) and Far (110 mm) positions from the LED is shown in Fig. 4.4.7, left and right, respectively. In this example, the PMT was powered at 800 V. The PMT response saturation is already apparent at the Near position. It is even more clearly seen in Fig. 4.4.8, left depicting the Near versus Far signal amplitude curve, where a non-linear behavior above $V_{\text{NEAR}} = 3.5$ V is observed. The red curve is a linear fit performed on V_{NEAR} versus V_{FAR} , in the range from 0 to 1.3 V. Figure 4.4.8, right shows the nonlinearity defined as the percent difference between measured signal amplitude and the linearity fit:

$$\text{non-linearity} = \frac{(V_{\text{NEAR}}/V_{\text{FAR}} - p_1)}{p_1}, \quad (4.4.2)$$

where p_1 the slope of the linear fit.

For a value of $V_{\text{NEAR}} \sim 3.5 \div 4$ V, there is about 10% divergence from linearity. The same results were obtained for PMTs set at 700 V, as can be seen in Fig. 4.4.9.

4.4.3 PMT Assignment

As observed in Sec. 4.2, different scintillators have a very different response in terms of produced scintillation light. Also, the results of the PMT gain characteriza-

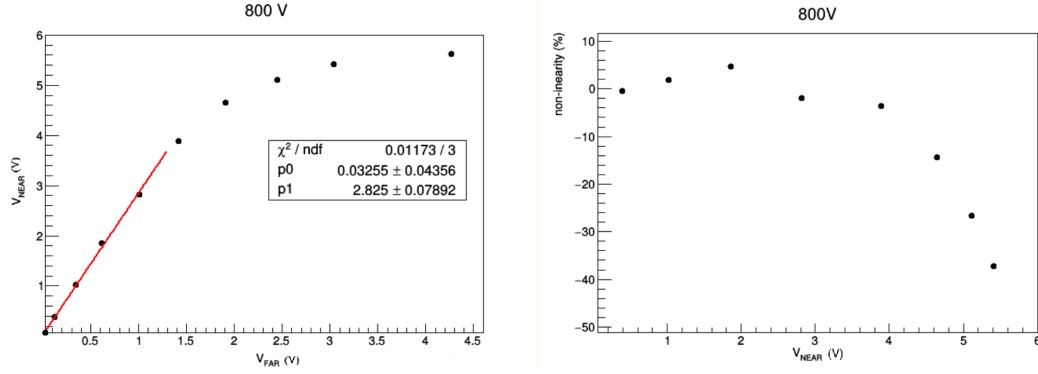


Figure 4.4.8: On the left, the PMT signal amplitude at near position (55 mm) versus the amplitude in far position (110 mm). The red line is a fit to data in the range from 0 to 1.3 V in V_{FAR} . On the right, the non-linearity factor versus the amplitude in near position V_{NEAR} . The PMT is powered at 800 V.

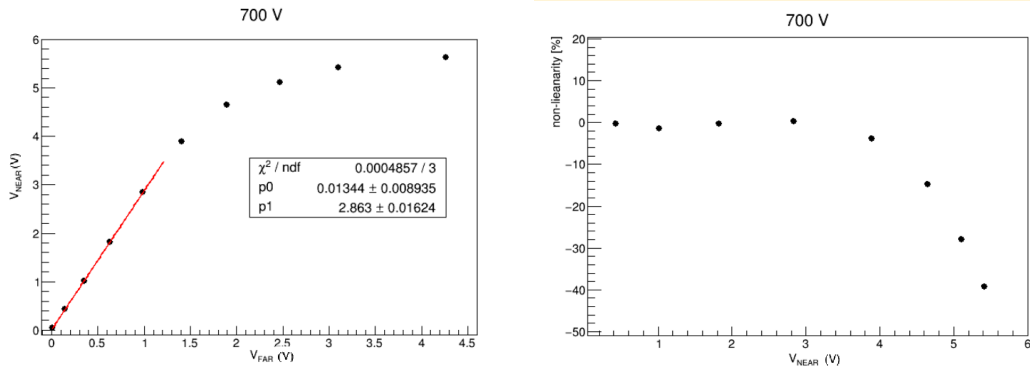


Figure 4.4.9: On the right, the PMT signal amplitude at near position (55 mm) versus the amplitude in far position (110 mm). The red line is a fit to data in the range from 0 to 1.3 V in V_{FAR} . On the left, the non-linearity factor versus the amplitude in Near position V_{NEAR} . PMT is powered at 700 V.

tion (see Sec. 4.4) show that the available PMTs cover a wide range of photo-multiplication gains, from 10^6 to 10^7 at an HV of 1000 V.

To ensure that the PMTs' responses matched well with the scintillator response, gains reported in Tab. 4.4.1 were considered as a baseline target for the PMT assignment to different kinds of counters. For each group of counters, from the lowest expected signal (TR1) to the highest (EN), we calculated the HV required for all the PMTs to achieve the target gain based on the calibration. Then, we assigned the PMTs with the lowest HV to the considered group, assigning them to the FM and the QM while trying to keep the HV variance within 20% for each model. The assigned PMTs were removed from the list, and the procedure was repeated group by group. For each group, a few PMTs were put aside as spares. Finally, the PMTs assigned to each line of the FM and QM had a gain within 12%, while the gain difference was $< 5\%$ for PMTs assigned to the same counter. This procedure ensures an HV range wide enough to allow further tuning while staying within the PMTs' optimal working range.

4.5 HEPD-02 Integration and Qualification

Before the integration of the detector, all the scintillation counters ($\sim 2 \times 32 + 12$) were wrapped and tested, then classified from the best (e.g., light yield, signal uniformity, etc.) to the least good. Particular attention was given to TR1 scintillators and LYSO crystals. The best counters were assigned to the flight model (FM), the second best to the qualification model (QM), and the remaining were kept as spares. The counters of the several subsystems were integrated into their individual mechanical structures and then into the HEPD box. In Fig. 4.5.1, some pictures of the integration stages are shown, from the mounting of the subsystems (bottom counter, top left) to the completion of cabling and the closing of the HEPD panels. The assembled HEPD-02 detector is shown in the bottom right panel.

After the final assembly of HEPD-02, a series of tuning and testing was performed to ensure that the detector was fully functional and that its response met the experiment's requirements. Tuning addressed the high-voltage lines and PMT thresholds, the high- and low-gain preamplification scales of the CITIROC, and their calibration. HEPD-02 also underwent an extensive calibration campaign, including beam tests and atmospheric muon measurements, to study the response of the detector subsystems and assess the detector's scientific performance. Finally, the detector underwent space-qualification testing. The following provides a brief overview of the tests conducted, highlighting the most important results. The Bologna group has implemented dedicated data-analysis programs to monitor and evaluate the response of the scintillating system and PMTs and to confirm their performance.

4.5.1 Space Qualification Tests

Before integration on board the CSES-02 satellite, the HEPD-02 needed to successfully pass qualification (QM) and functional, electrical, and environmental acceptance (FM) tests. Indeed, the detector must withstand mechanical stresses during launch and orbital maneuvers (up to 11 G sustained RMS acceleration and up to

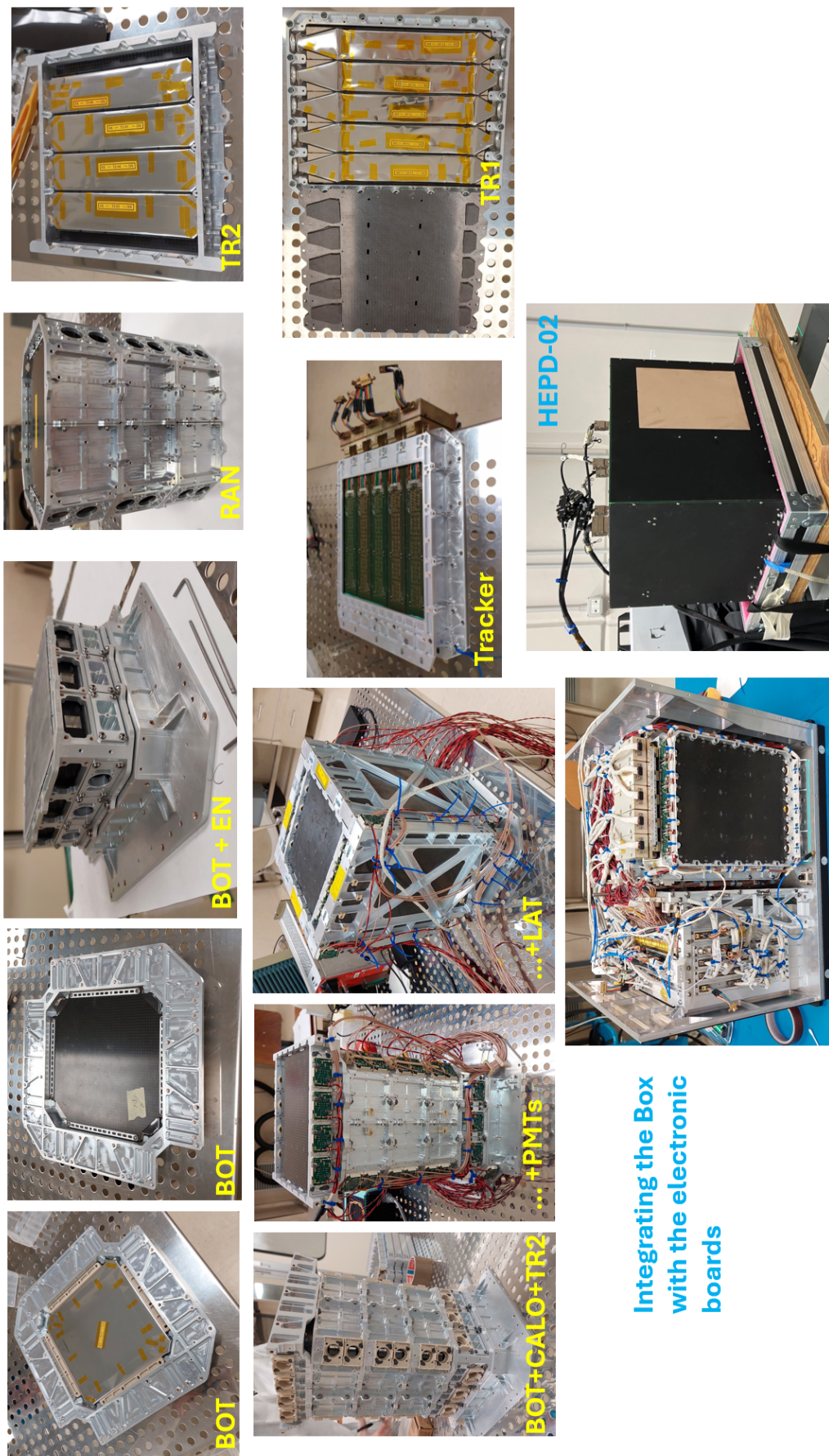


Figure 4.5.1: Pictures of HEPD-02 integration. On the top panel, from left to right, BOT counter assembly; mounting of EN1/2 structure on top of the BOT; RAN and TR2 counters in their mechanical structures, respectively. On the middle panel, from left to right, the RAN tower and the TR2 are assembled on top of the EN structure; integration of PMTs and boards; mounting of the LAT panels; and integration of the Direction detector and TR1 into their mechanical structures, respectively. Bottom panel, left: the final assembly of the detector and electronic box. Right, fully assembled HEPD-02 detector.

1000 G shock pulse). It also needs to operate at a pressure ≤ 6.7 mPa, in a wide range of temperatures (from -30 °C to $+50$ ° and endure thermal stresses (up to 4 °C/min change). Here is a summary of the space qualification tests applied to FM and QM:

- **Vibration tests** – Sinusoidal vibration tests were performed in the frequency range of $10\text{ Hz} \div 100\text{ Hz}$, with amplitudes up to 8 G at a sweep rate of 4 oct/min for the FM, and up to 12 G at 2 oct/min for the QM. Sustained random vibration tests were carried out in the frequency range of $10\text{ Hz} \div 2\text{ kHz}$, with overall levels of 7.6 G (for 1 min) on the FM and 11.3 G (for 2 min) on the QM. Eventually, only the QM underwent a pyroshock test, with a pulse spectrum in the range $100\text{ Hz} \div 4\text{ kHz}$ and peak accelerations up to 1000 G .
- **Thermal tests** – Thermal tests were conducted both in air and in vacuum conditions ($P < 6.7\text{ mPa}$). The temperature ranged from -20 °C to $+45$ °C for the FM, and from -30 °C to $+50$ °C for the QM. The temperature variation rate was 4 °C/min in air and 1 °C/min in vacuum. The dwell time at each hot and cold temperature point was greater than 4 h . The QM underwent $25.5 + 2$ burn-in-cycles in air and 6.5 cycles in vacuum, while the FM underwent $12.5 + 2$ burn-in-cycles in air and 3.5 cycles in vacuum.
- **Electromagnetic compatibility (EMC) tests** – EMC tests were carried out for both conducted and radiated emission and susceptibility at IFAC (Florence). The conducted emission tests covered the frequency range from 150 kHz to 10 MHz , while the conducted susceptibility was verified in the ranges $30\text{ Hz} \div 150\text{ kHz}$ and $10\text{ kHz} \div 200\text{ MHz}$ for the external harness. Radiated emission tests were performed in the frequency range from 200 MHz to 2 GHz , and radiated susceptibility tests were carried out from 10 kHz to 40 GHz .

Photographs of the HEPD-02 at the different qualification tests are shown in Fig. 4.5.2. The integrity and full functionality of HEPD-02 were monitored during and after every test. For example, the PMTs ADC signal of every counter was checked before and after each thermal-vacuum cycle. The MPV of the signal was also monitored after each along-axis vibration. An example of the stability of the signal during the thermal vacuum cycles is shown in Fig. 4.5.3 for both Cold and Hot cycles on the MAIN side. In Figures 4.5.4 are given a comparison of MPV of ADC signals at the center of all counters before, and after every vibration cycle. Results show the MPVs are stable and consistent with each other within $< 10\%$. The HEPD-02 detector successfully passed all qualification/acceptance tests.

4.5.2 Beam Tests

HEPD-02 was tested with different particles and energies at various facilities in Italy. The main objective of these tests was to validate the capabilities of HEPD-02 to identify particles and measure their kinetic energy and arrival direction. The beams at which the detector has been exposed are the following, some photographs of the tests are also shown in Fig. 4.5.5:

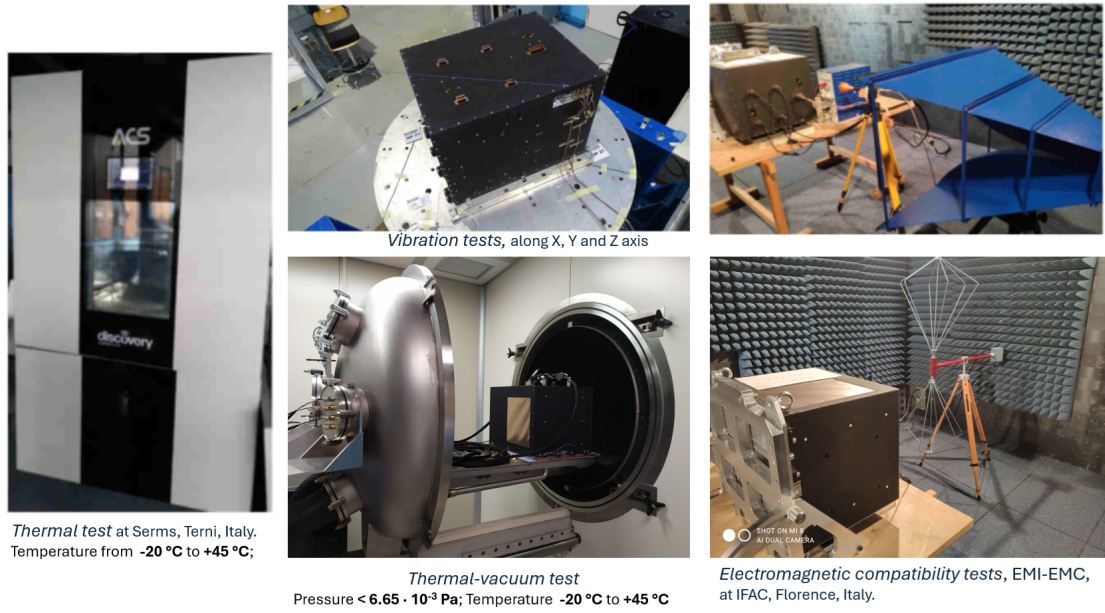


Figure 4.5.2: Photographs of HEPD-02 during space qualification tests, thermic (left), vibration (top center), thermal-vacuum (bottom center), and electromagnetic cleanliness (right).

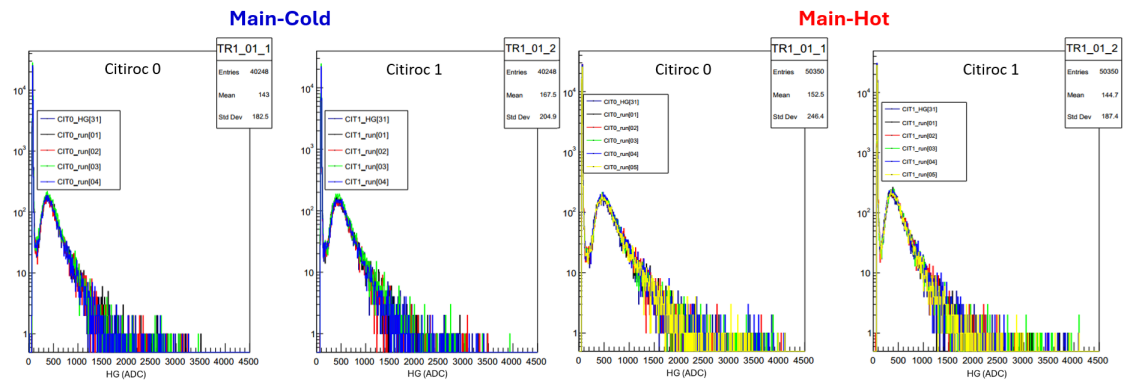


Figure 4.5.3: Example distributions of ADC signal during the Cold (left) and Hot (right) thermal-vacuum cycles.

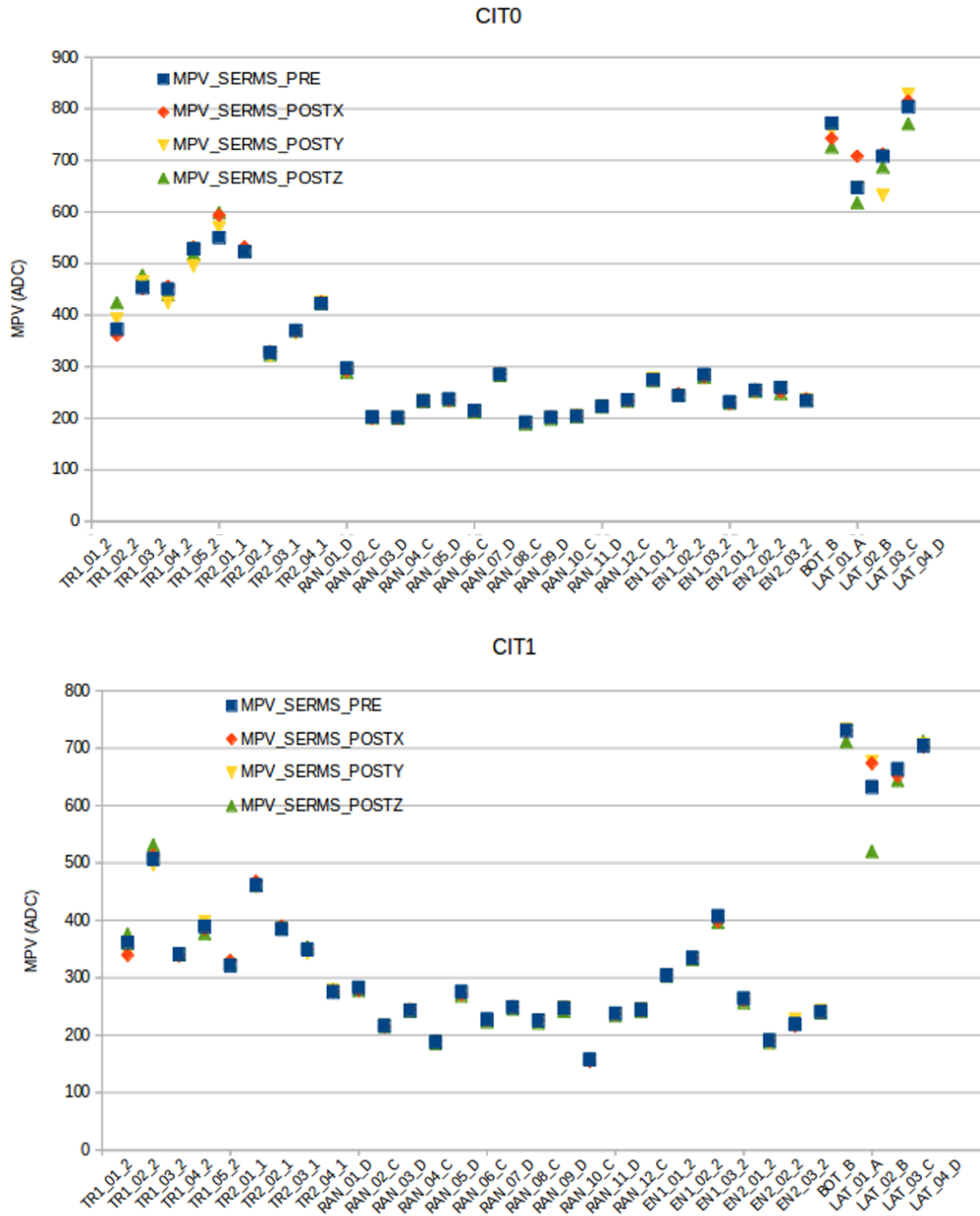
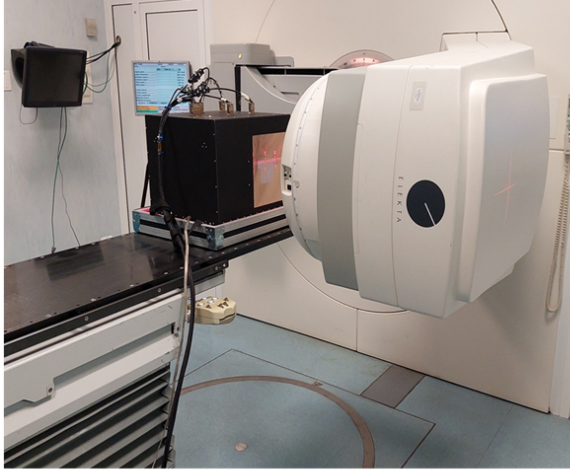


Figure 4.5.4: Verification of the MPV of the signal distribution in each counter with samples of passing-through muons acquired before, between, and after the vibration tests.



Electron test beam at **Linac** Santa Chiara



Carbon test beam at **CNAO**, Pavia.

Figure 4.5.5: HEPD-02 at the electron beam test at LINAC Santa Chiara (left) and at the carbon beam test at CNAO, Pavia (right).

- **Electron Beams**

- from 6 MeV to 12 MeV at the LINAC of the medical center of Santa Chiara Hospital in Trento;
- from 30 MeV to 450 MeV at the Beam Test Facility (BTF) in Frascati;

- **Proton Beams**

- from 30 MeV to 228 MeV at the Proton Therapy Center in Trento;
- 62 MeV and 227 MeV/amu at the National Center for Oncological Hadrontherapy (CNAO) in Pavia.

- **Carbon nuclei** – from 115 MeV/amu to 398 MeV/amu at the National Center for Oncological Hadrontherapy (CNAO) in Pavia.

- **Photons- X.rays** – from 4 MeV to 10 MeV at the LINAC of the medical center of Santa Chiara Hospital in Trento;

In Fig. 4.5.6 are shown examples of the tracker occupancy maps recorded for an electron beam of 450 MeV conducted at BTF, a 64 MeV proton beam at the proton therapy, and a carbon beam of energy 398 MeV/amu at CNAO. To discriminate particle species two different strategies were defined; one based on the tracker information i.e the cluster size (number of close by pixels in a cluster) and the other on the energy deposited (ADC signal) in the trigger and calorimeter, This last is based on the dE/dx approach i.e. the signal deposited on the TR2 plane as a function of the total signal collected in the range calorimeter. The first results of both strategies are shown in Figs. 4.5.7 and 4.5.8, respectively. It can be seen that the cluster size and the ADC signal depend on energy and particle type, allowing clear separation of particles over the investigated energy range.

The linearity of the scintillating counters' response to the deposited energy in the calorimeter has been studied with dedicated runs with protons and carbon nuclei. The first results are given in Fig. 4.5.9, where, on the left panel, the linearity of the

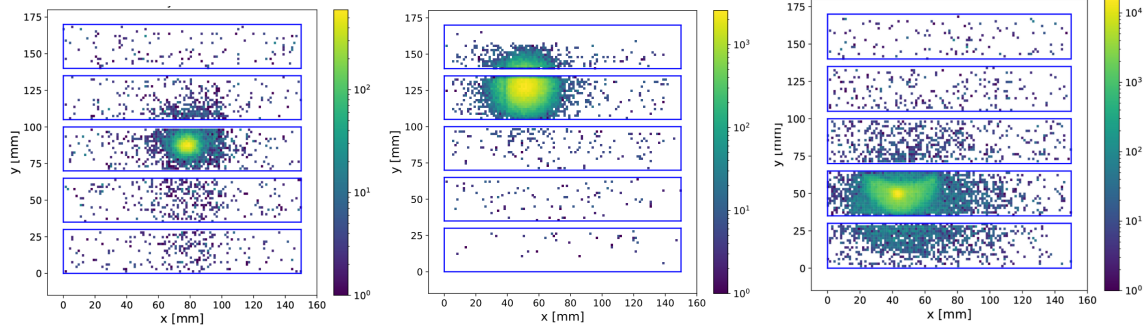


Figure 4.5.6: Figures showing the occupancy map of the incident beam as recorded by the tracker for: electrons of 450 MeV (left), protons of 64 MeV (center), and Carbon nuclei with energy 398 MeV/amu (right).

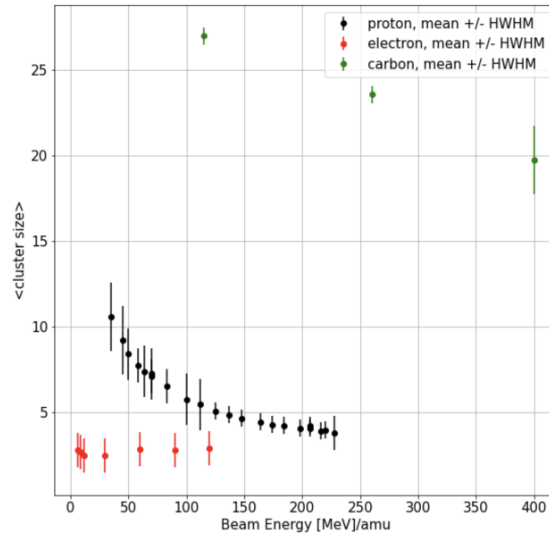


Figure 4.5.7: Cluster size vs beam energy for different ion species. Red dots are for electrons, black dots are for protons, and green dots are for carbon nuclei [61].

High Gain ADC scale versus the beam energy is shown, and on the right panel, the linearity of the Low Gain ADC scale.

The capabilities of the tracker angular reconstruction have also been validated with atmospheric muons and with vertical and inclined particle beams. Figure 4.5.10 shows the preliminary angular resolution obtained for the different ion species as a function of beam energy. Preliminary analysis of beam test data demonstrates scientific performance well beyond expectations.

4.5.3 Tuning of the PMTs High Voltage

As discussed in Sec. 4.4.3, PMTs are assigned to the different counters in a way that ensures that both sides of the same counter are connected with PMTs with nearly the same gain at the 5% level, and that PMTs supplied with the same HV line are within 20%. Each HV line is connected to a block of 2 PMTs, up to 6, interfaced to the same type of counter. However, to achieve the best possible equalization of

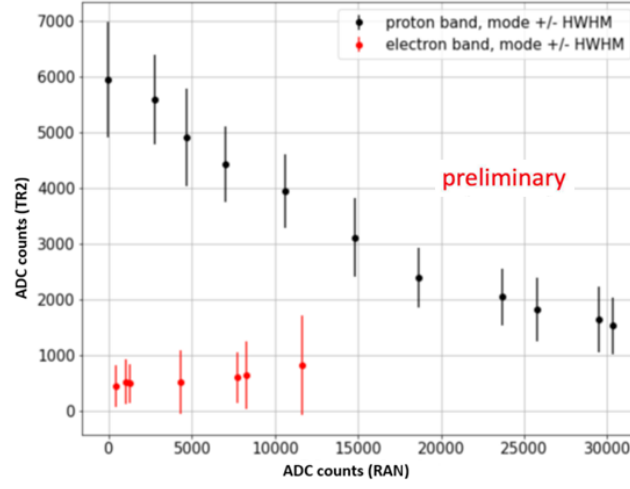


Figure 4.5.8: The TR2 ADC counts versus the total signal deposited in the range calorimeter for protons (black dots) and electrons (red dots) in the HG scale.

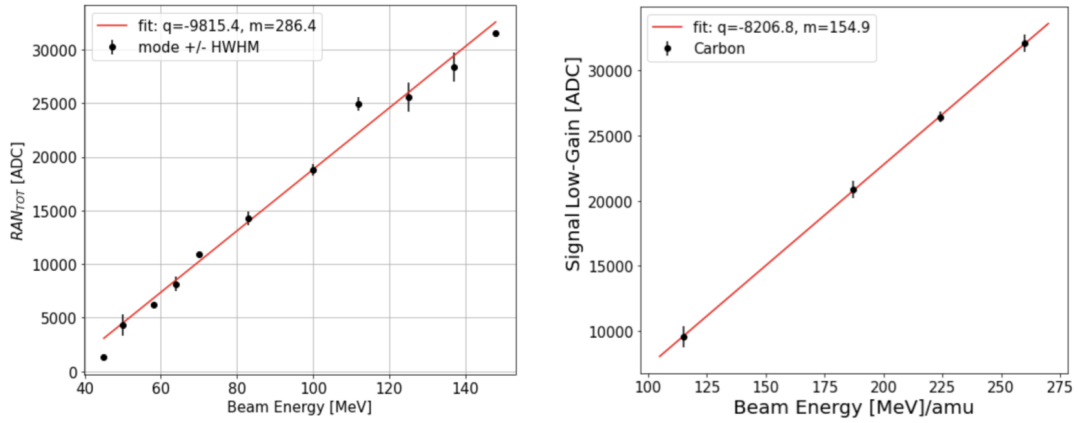


Figure 4.5.9: Energy linearity in the plastic scintillators in the High Gain scale with proton beams (left) and in the Low Gain scale with carbon nuclei (right). Red lines are linear fits [61].

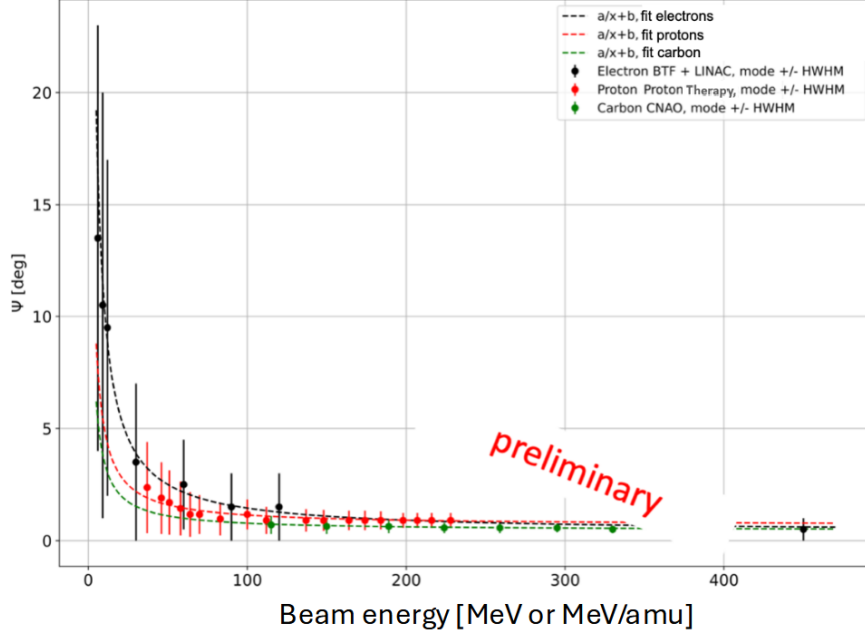


Figure 4.5.10: The angular resolution versus beam energy for electrons (black dots), protons (red dots), and carbon nuclei (green dots).

PMTs across all counters and given the limited number of HV channels (16), further tuning is necessary. The strategy adopted is to simultaneously characterize the gain as a function of HV for each channel and to compute appropriate HV values for optimal PMT equalization. As with everything related to the PMTs and the scintillating system, this adjustment was the responsibility of the Bologna group and it was conducted in close collaboration with the colleagues from INFN Roma Tor Vergata and Naples.

Therefore, HEPD-02 was placed in acquisition under cosmic muons in the clean room of the University&INFN of Roma Tor Vergata, for more than 24 hours, setting all HV lines to the same value consecutively: -750 V, -850 V, and -950 V. Signals were then analyzed for every PMT in every counter, and the MPV of MIP particles was retrieved. The final results showing the MPV of the signal (in ADC) as a function of the high voltage applied are given in Fig. 4.5.11, where all the PMTs from the same HV line have been grouped. HV line optimization is obtained by averaging, in each channel, the PMT HV required to achieve a target MIP signal. The choice of the target signal, or "working point" was based on the need to have signals above threshold and noise with the widest dynamic range for plastic scintillators, and high enough signals for LYSO in order to be above intrinsic radioactivity and allow gamma detection, for GRBs studies. The working point has been settled at 200 ADC for plastic scintillators and 600 ADC for LYSO.

Besides the HV tuning, a scan of the PMT thresholds was also conducted, adjusting the CITIROC HG/LG preamplification during the process.

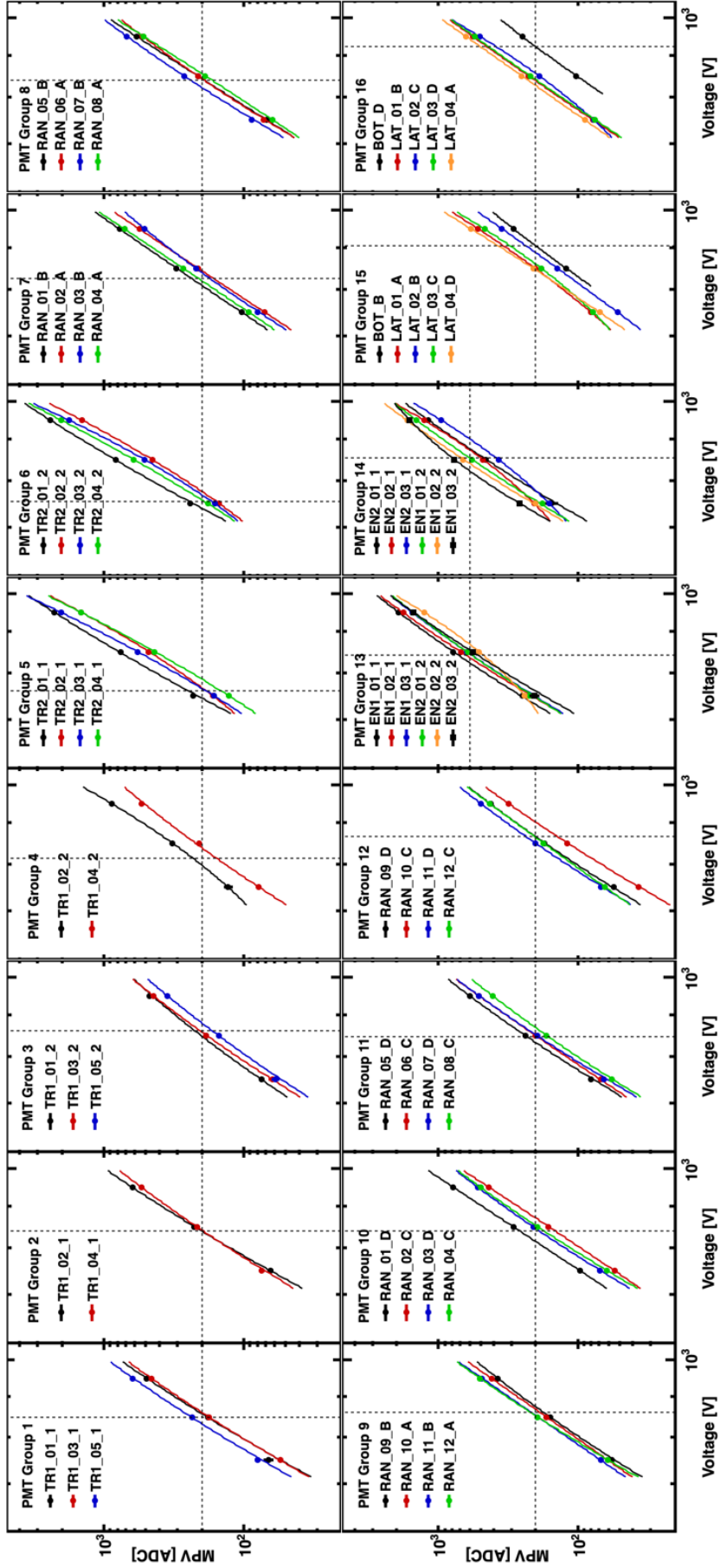


Figure 4.5.11: ADC signal versus HV for all the PMTs of HEPD-02 in groups of HV lines.

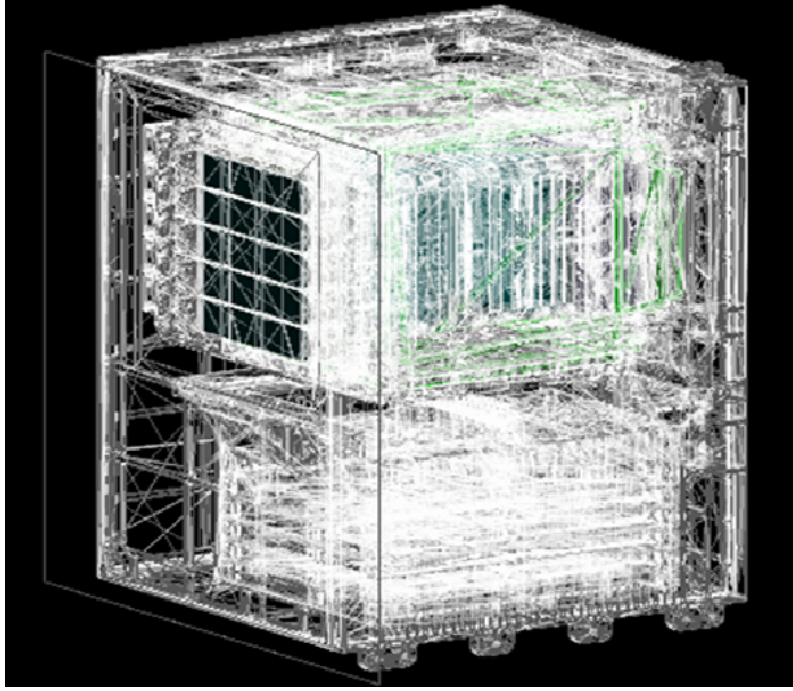


Figure 4.6.1: The HEPD-02 detector with its mechanical structure and the electronic box.

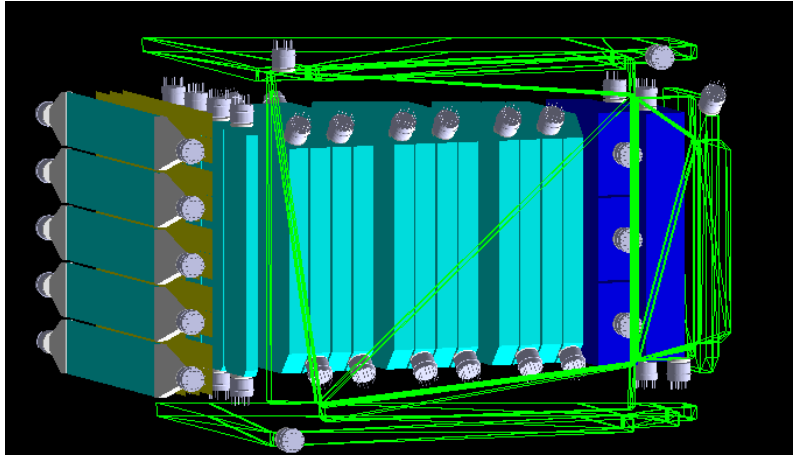


Figure 4.6.2: A detailed view of the HEPD-02 sensitive parts. From left to right, the first trigger plane connected to PMTs through light-guides; the tracker system (dark yellow); the second trigger plane orthogonal to the first one; the three blocks plastic calorimeter tower, and finally the two layers of LYSO crystals (blue). All the plastic scintillators are light blue. The containment panels are shown in transparency and have green outlines. Also shown in light gray are the PMTs.

4.6 HEPD-02 Expected Performance

To evaluate the expected performance of the HEPD-02 detector, a simulation based on the GEANT4 toolkit [45] has been developed. GEANT4 is a framework for simulating the passage of particles through matter. It includes transport code, electromagnetic and hadronic interactions, and optical production, propagation, and interactions. The simulation of HEPD-02 takes a set of GDML files exported from the TCAD model of the detector, including all sensitive counters, inert materials, mechanical structures, and electronic boxes, as shown in Fig. 4.6.1. In Figure 4.6.2 are shown only the sensitive parts of HEPD-02, i.e. scintillation counters with their PMTs and the direction detector.

The simulation is organized in three consecutive layers. The first layer is represented by a truth-level MC of particle propagation and interaction in the detector; the deposited energy, position, and interaction type are recorded in all detector parts with increased precision in the sensitive materials.

Dedicated simulations were used to parametrize the light production processes in the scintillators (LYSO crystals and EJ200 planes), as well as the photon propagation and collection by the PMTs. This semi-empirical approach was developed to speed up the digitization process, as running the full simulation with optical photons, even if possible, would be very CPU-intensive and time-consuming.

Finally, a fast parametric tool, TROPix, that reproduces the output of pixel detectors was used to replicate the pixel signal and generate the clusters produced by the energy deposits in the tracker [62]. This tool has been tuned with data from a test beam realized on the tracker (DD) module used for the integration of HEPD-02.

The simulations used to parametrize scintillation light production are GEANT4-based, accounting for the production of optical photons from the energy released by the incident particle in the sensitive detectors and their propagation through the material to the interface with the PMTs. They include the light-emission spectra of plastic scintillators (EJ-200) and crystals (LYSO), and the PMT's quantum efficiency as a function of wavelength.

For each incident event, the charge collected at each end of a counter was obtained by integrating the total number of photo-electrons converted at the PMT photocathode surfaces and multiplying by the PMT gain. The absorption coefficients of the materials and the wrapper's reflectivity were set as free parameters to be adjusted. The response of each scintillator counter has been simulated individually, and the simulation results compared with the measured data from Sec. 4.2. A further adjustment was made using data from dedicated cosmic-muon runs and during the beam test campaign.

Longitudinal profiles of the MPV and the mean number of photo-electrons recorded by the PMTs were reconstructed as a function of the incident position. A comparison of these profiles with experimental data for TR1, TR2, RAN and EN counters is shown in Figs. 4.6.3, 4.6.4, 4.6.5 and 4.6.6, respectively. It is to be noted that for the RAN counter, the longitudinal profile is built along the diagonal joining the two PMTs. The origin is located at the center of the counter along the axis joining the 2 PMTs.

Bi-dimensional maps of the mean number of photo-electrons / charge relative to the center of a specific counter generated from a certain energy deposit in function

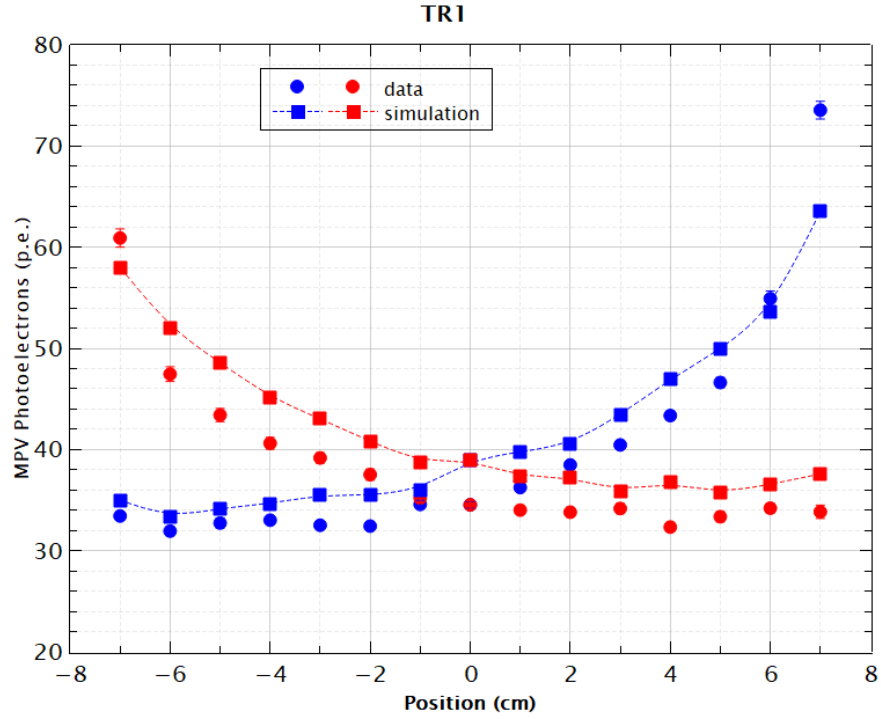


Figure 4.6.3: The MPV of photo-electrons recorded by each PMT versus the longitudinal position for TR1 counter. The MPV is equalized in the center of the bar.

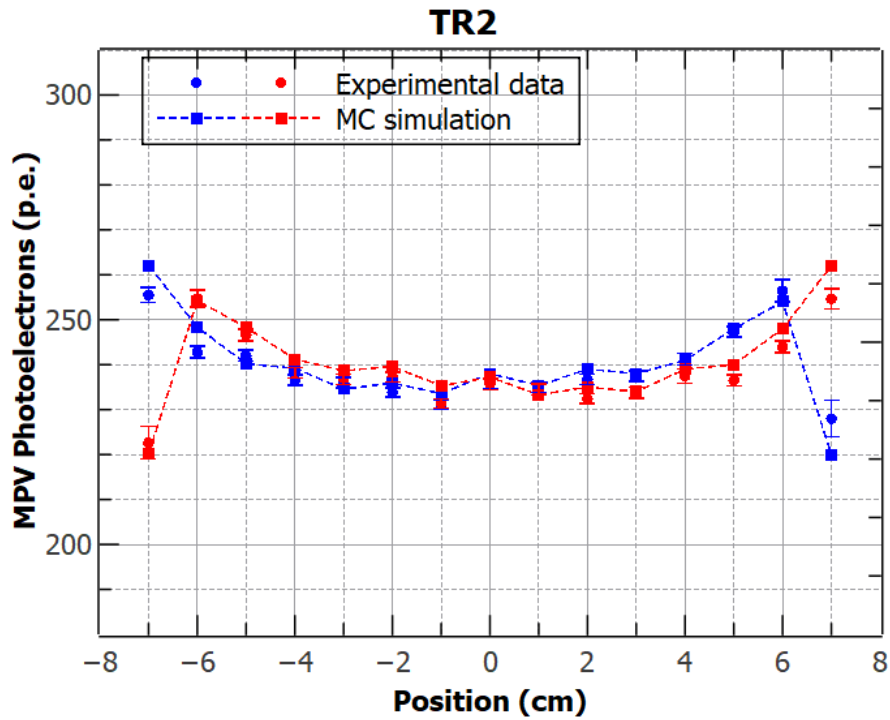


Figure 4.6.4: The MPV of photo-electrons recorded by each PMT versus the longitudinal position for TR2 counter.

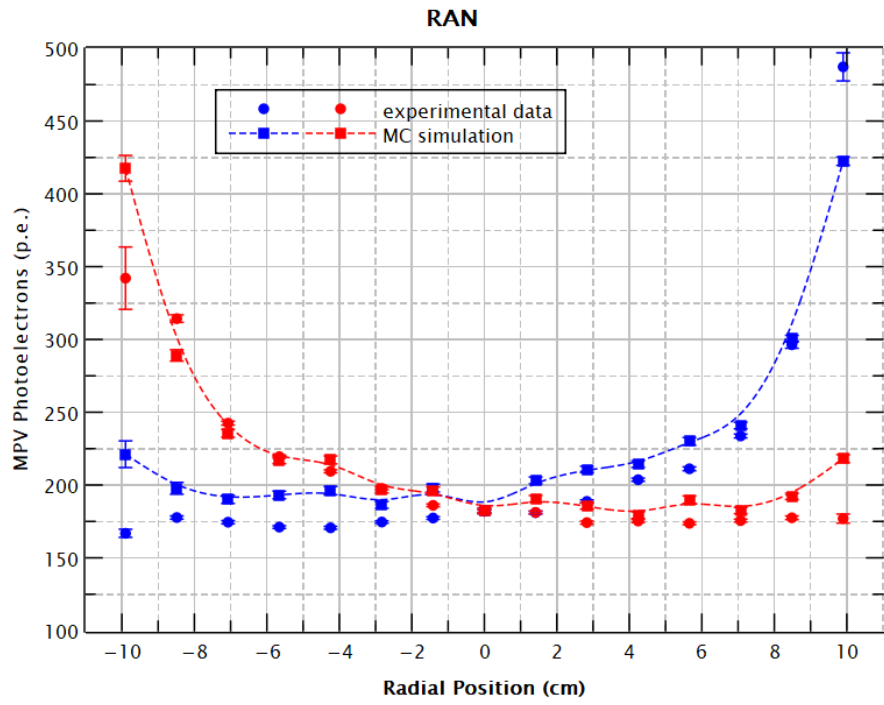


Figure 4.6.5: The most probable number of photoelectrons recorded by each PMT versus the radial position for the RAN counter.

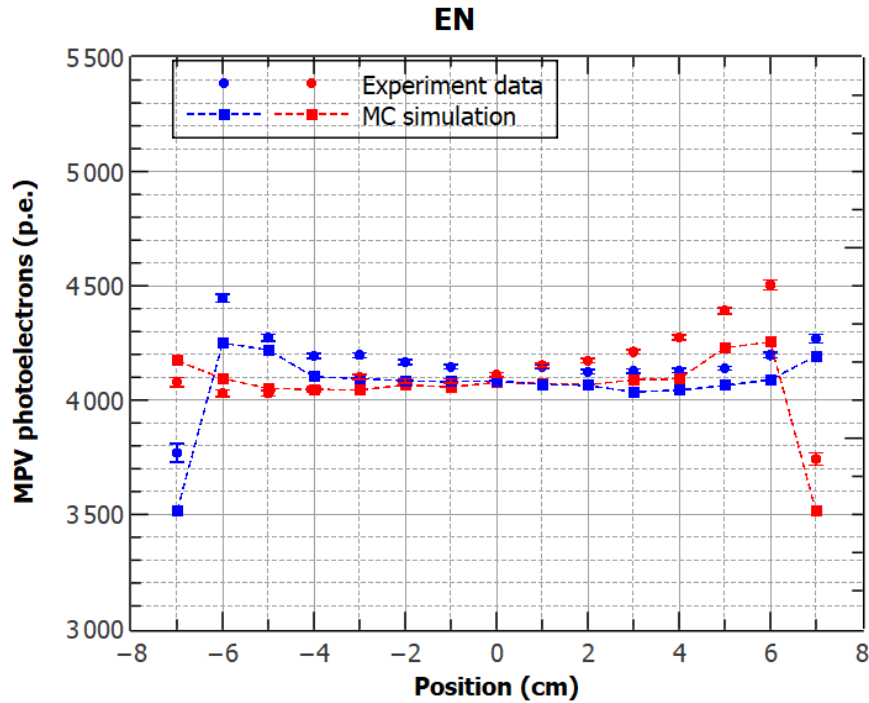


Figure 4.6.6: The MPV of photo-electrons recorded by each PMT versus the longitudinal position for EN counter.

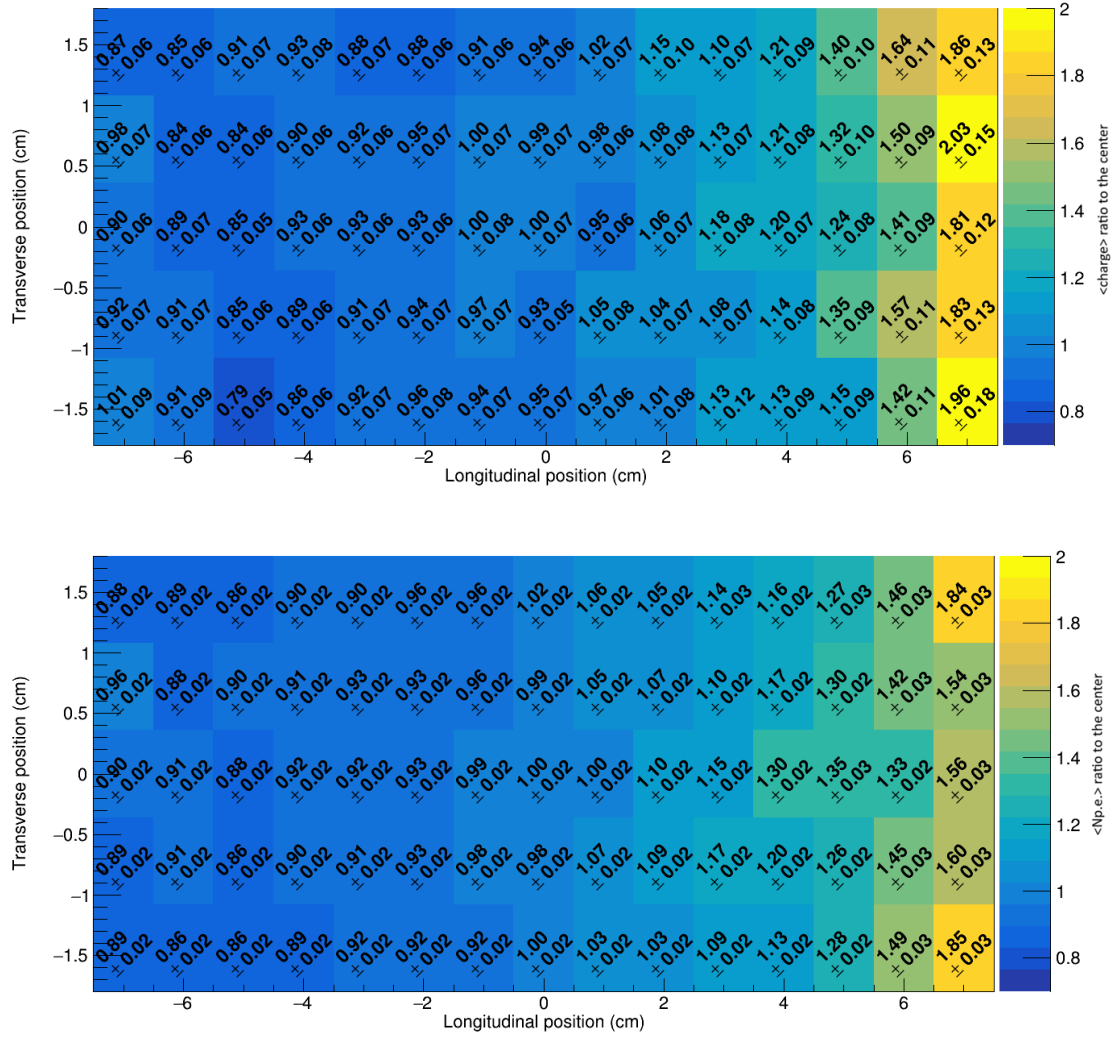


Figure 4.6.7: bi-dimensional map of the mean charge relative to the center recorded by one of the PMTs versus the impact position for the TR1 counter. At the **top** is the map from the experimental data. At the **bottom** is the one from the simulation.

of the impact position (x,y) were also built from simulation and compared to data. These maps, together with the longitudinal profiles, were used to tune the simulations' parameters. The adjusted absorption length was found to be ~ 380 cm for plastic scintillators and ~ 300 cm for LYSO crystals, whereas the reflectivity was found to range from 97% to 98%, depending on the counter.

Figure 4.6.7 shows an example bi-dimensional map of the mean relative charge to the center of a TR1 bar, recorded by one of the phototubes versus the position expressed in 5×15 bins along the transversal $\times$ longitudinal dimensions. The top panel shows the 2D map obtained from experimental data, and the bottom panel shows the simulated map. The simulation results agree with the data within 20%. The remaining discrepancy is probably because the simulation supposes perfect surfaces and perfect optical contacts, as well as constant (i.e., wavelength-independent) reflectivity of the wrapping material. For the other counters, TR2, RAN, and EN, the simulation has an agreement of better than 10%. For these counters, the com-

parison between the data and simulation maps is presented in Figs. 5.4.7, 5.4.8, 5.4.9, 5.4.10, and 5.4.11, 5.4.12 of the Appendix, respectively.

The constructed 2D maps are then used for the implementation of a parametric approach that consists in combining the mean photoelectron number produced in each position for a specific counter, with the distribution of the mean photo-electron number in the center of the counter, as a function of the deposited energy, and the corresponding ADC signal obtained from the PMT readout system calibration curves [63]. In Fig. 4.6.8, an example of the expected mean number of photoelectrons at the center of a specific counter as a function of the deposited energy for different ion species at 3 GeV/nucleon, as obtained from simulation, is given. From top left, clockwise, are shown the curves for TR1, TR2, RAN, and EN counters. Birks' saturation [64] is clearly seen for all the scintillation counters.

Eventually, the full MC simulation has been used to calculate the basic detector performance, including the geometric factor. A dedicated Monte Carlo simulation for electrons, protons, and light nuclei was performed within the apparatus's detection range. Particles have been generated uniformly from a $40 \times 40 \text{ cm}^2$ window (parallel to the x-y plane) right above the detector window with isotropic angles and flat energy spectra. The simulation chain has been executed to produce a final sample containing the digitized information available in real data. The geometrical factor obtained for electrons and protons in different trigger configurations is shown in Fig. 4.6.9. The Simulation also allows for an estimate of the resolution on the reconstruction of energy and angle. As shown in Fig. 4.6.10, the first simulation results yield an energy resolution of around 30% at low energies for electrons, which decreases rapidly at higher energies. For protons, this resolution is $<10\%$ at low energies ($\sim 30 \text{ MeV}$), decreasing steeply at higher energies.

The resolution on the reconstruction of arrival direction for electrons and protons is displayed in Fig. 4.6.11 left and right, respectively. The angular resolution has been estimated as the angular difference between the direction of the reconstructed track ($\vec{d}_{\text{pred}}$) and the true direction ($\vec{d}_{\text{true}}$) and is defined as:

$$\Psi = \arccos(\vec{d}_{\text{pred}} \cdot \vec{d}_{\text{true}}) \quad (4.6.1)$$

with:

$$\vec{d}_{\text{pred}} = (\sin \theta_{\text{pred}} \cos \phi_{\text{pred}}, \sin \theta_{\text{pred}} \sin \phi_{\text{pred}}, \cos \theta_{\text{pred}})$$

$$\vec{d}_{\text{true}} = (\sin \theta_{\text{true}} \cos \phi_{\text{true}}, \sin \theta_{\text{true}} \sin \phi_{\text{true}}, \cos \theta_{\text{true}})$$

where θ is the polar angle, between the particle direction vector and the normal to the detector surface, and ϕ is the azimuthal angle of the projected particle direction vector on the detector plane. The contribution of Coulomb scattering dominates the uncertainty of this observable. The angular resolution for low-energy electrons is $\sim 10^\circ$, while for low-energy protons the error in reconstructing the angle is $\sim 1^\circ$. These results meet the detector's requirements as given in table 2.4.1 in Chapter 2, Sec. 2.4.

Dedicated Monte Carlo simulations [40] were carried out to assess the effective area for photons reaching part of the RAN detectors or hitting the LYSO crystals according to the dedicated GRB masks (see Chapter 2, Sec. 2.4). The preliminary results demonstrate the HEPD-02's capabilities for the detection of gamma-ray burst (GRB) photons with energies in the range from 2 to 20 MeV.

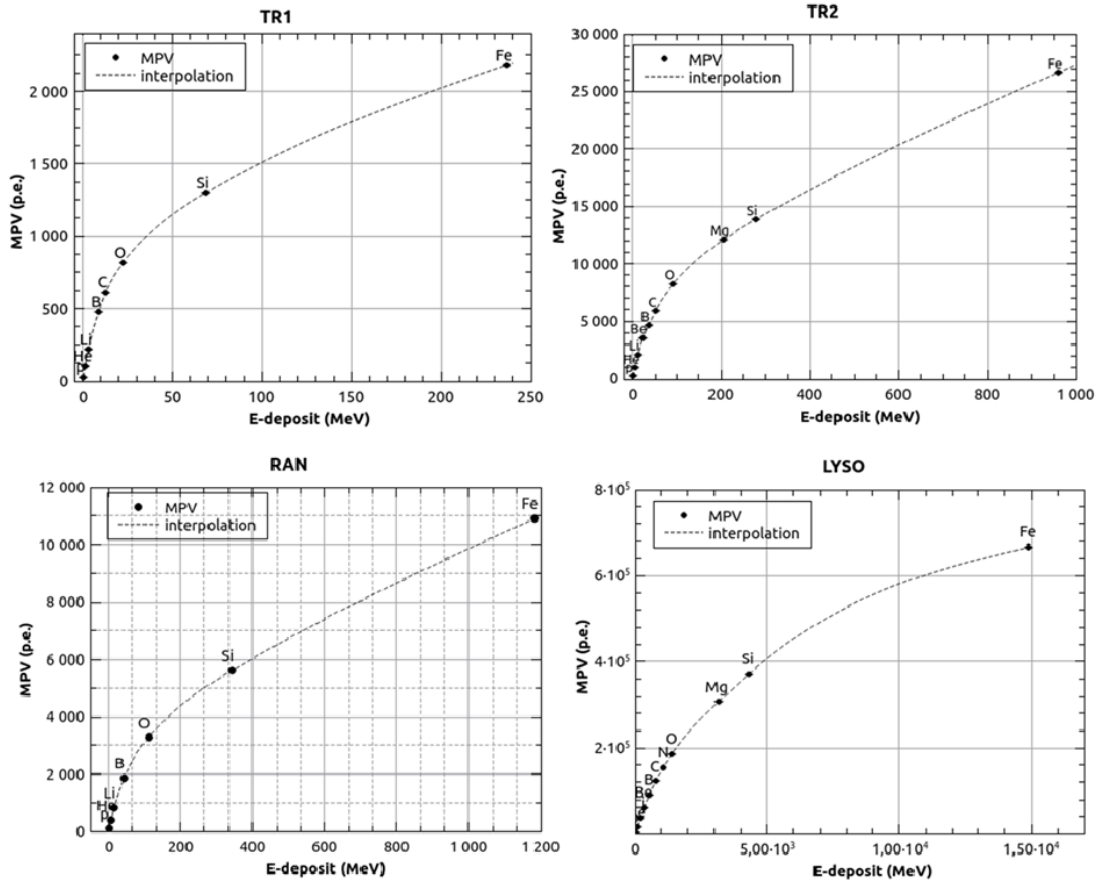


Figure 4.6.8: The MPV of photo-electrons versus deposited energy at the center of TR1 (top left), TR2 (top right), RAN (bottom left), and EN (bottom right) counters. Dashed curves are obtained from an interpolation of data.

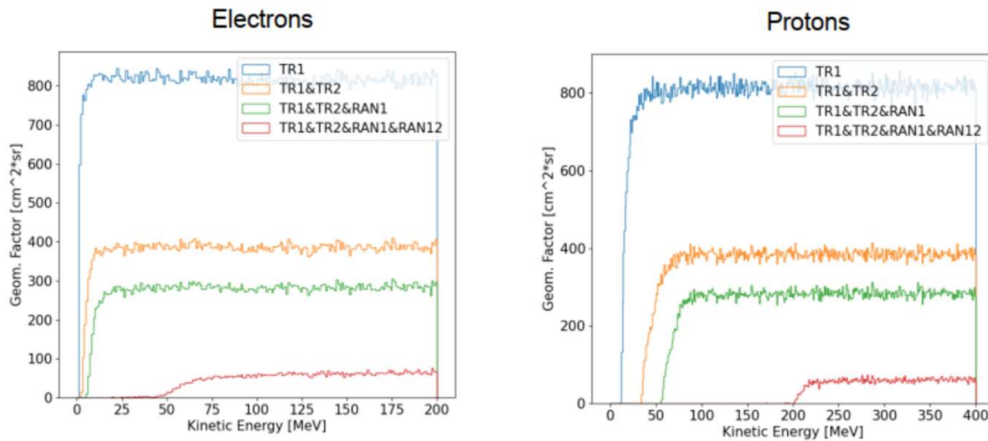


Figure 4.6.9: The HEPD-02 geometrical factor versus energy obtained from the simulation of uniform distributions of electrons (left) and protons (right). Various trigger configurations were considered [65].

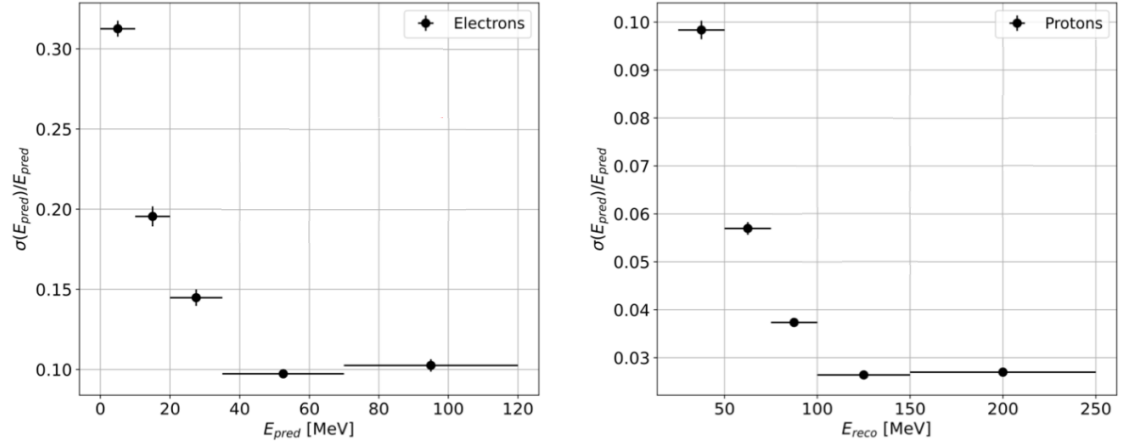


Figure 4.6.10: Reconstructed energy resolution as a function of the true simulated energy for a sample of incident electrons (left) and protons (right) [61].

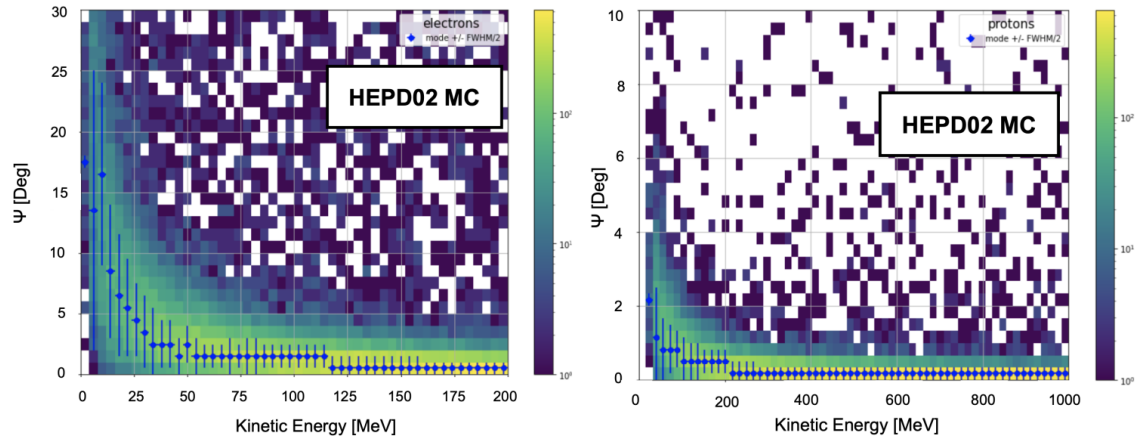


Figure 4.6.11: The HEPD-02 angular resolution for electrons (left) and protons (right) as a function of the initial kinetic energy. Blue points represents the mode of the projection on the y axis and the error bars the HWHM of the distribution [61].

Chapter 5

HEPD-02 Launch and Commissioning

The HEPD-02 Flight Model was shipped to Beijing, China, at the end of 2023. After verification testing, it was integrated into the CSES-02 satellite and underwent a series of tests, starting with the Factory Health Check and complete functional tests, and continuing with space-qualification tests similar to the ones already performed in Italy (see Sec. 4.5.1). The satellite, with all its payloads, was finally transferred to the Jiuquan Satellite Launch Center (JSLC) in April 2025, where factory health checks were repeated for all payloads before the scheduled launch of CSES-02. A team from the Italian collaboration Limadou was involved in all tests performed in Beijing and Jiuquan. I actively participated in data analysis both off-site and on-site during the pre-launch tests. In Tab. 5.0.1, a summary of the various tests conducted on HEPD-02 is given. The HEPD-02 integrated into the satellite is shown in Fig. 5.0.1, and a photograph of one of the Limadou collaboration teams during detector cabling is shown in Fig. 5.0.2.

Table 5.0.1: Tests performed on HEPD-02 and on CSES-02 before the transfer to the launch site.

HEPD-02 verification tests before installation on CSES-02 satellite	
Basic Functional tests	08/01/2024
Inrush Current & Magnetic Cleanliness tests	09-10/01/2024
CSES-02 satellite space-qualification campaign	
Installation on Satellite and Basic Functional tests	11-12/01/2024
Full functional tests	26-28/02/2024
Vibration test (sine and random)	18-21/04/2024
Thermal-Vacuum test	03-10/08/2024
Magnetic Cleanliness test	17-22/08/2024
Aging test	02-06/09/2024
Final tests before CSES-02 transfer to the launch site (JSLC)	
Factory health checking	1/11/2024 and 2/02/2025

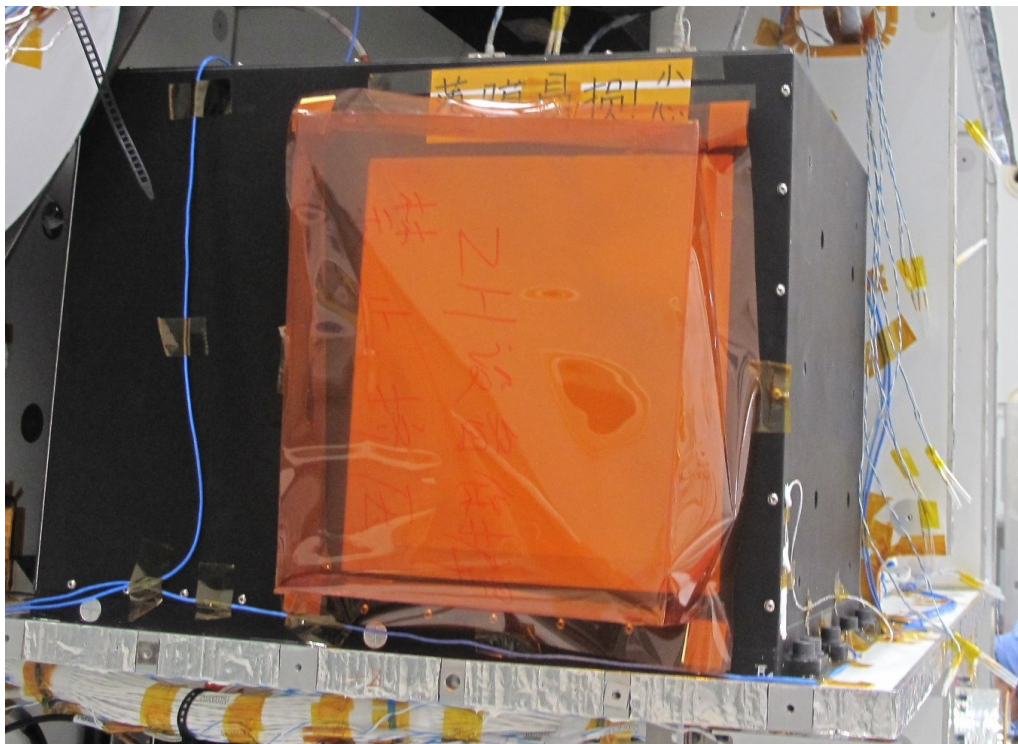


Figure 5.0.1: The HEPD-02 detector integrated into the CSES-02 satellite.

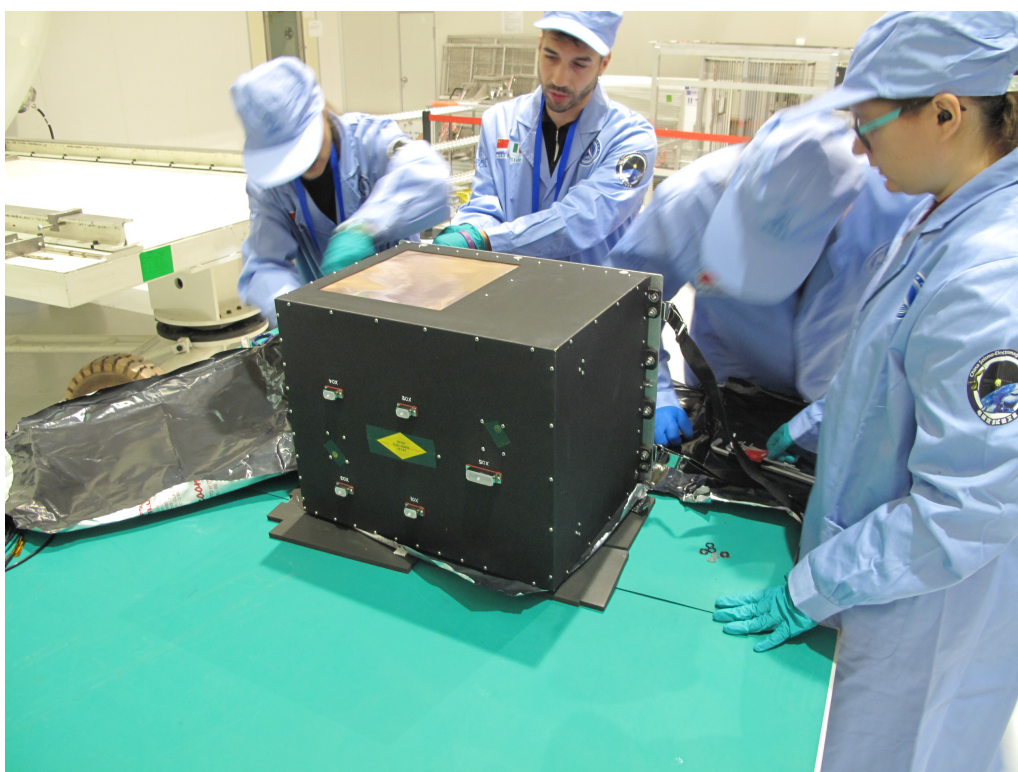


Figure 5.0.2: A team from the LIMADOU collaboration cabling HEPD-02 for testing before its integration into the satellite.

5.1 Launch of CSES-02

On June 14, 2025, the CSES-02 satellite was successfully launched from the Jiuquan Satellite Launch Center (JSLC), see Fig. 5.1.1. CSES-02 is the second satellite in the China Seismo-Electromagnetic Satellite series, a mission carried out in close cooperation between the Italian Space Agency (ASI) and the China National Space Administration (CNSA). In addition to the High-Energy Particle Detector (HEPD-02), the Italian Limadou collaboration also developed a second payload for the mission, the Electric Field Detector (EFD-02).

The HEPD-02 detector was powered on for the first time after launch on June 20, 2025, at 07:50 AM Italian time, and demonstrated full system integrity and functionality. Its operation was monitored by the Italian team at the CSES Scientific Application Center within the National Institute of Natural Hazards (NINH) in Beijing during the first two months of activity. The Bologna group actively participated in this phase, with several people rotating shifts in Beijing. The instrument is now continuously monitored by members of the Limadou collaboration via remote shifts from Italy.

The CSES-02 satellite operates in a sun-synchronous, quasi-polar low Earth orbit, sharing the same orbital plane as CSES-01 but with a phase difference of 180° . It maintains an altitude of approximately 507 km and an inclination of 97.4° , enabling it to pass over any given point on Earth at nearly the same local solar time on each orbit. The orbital period is about 94.6 minutes, corresponding to roughly 15 revolutions per day. An example of the CSES-02 orbital ground track over a full day (specifically June 23, 2025) is shown in Fig. 5.1.2 as displayed by the monitoring tool described in Sec. 5.2. The satellite's position is derived from HEPD-02 data, which records the satellite's broadcast GPS signal at the start and end of each run, each lasting approximately 2 minutes.

Since the beginning of operations, the detector has been undergoing commissioning, which will continue for approximately 6 months. This phase focuses on testing, configuring, and optimizing HEPD-02 for scientific operations and in-flight performance verification. All commissioning activities completed so far have been successful, and no significant issues have been identified.

5.2 Scintillator System Monitoring

The HEPD-02 is controlled by a main Data Processing and Control Unit (DPCU) board. The DPCU manages power distribution, communicates with HEPD-02 boards (the tracker board T-DAQ, the trigger board TRIG, the low-voltage control board LV-CTRL, and the high-voltage control board HV-CTRL), performs data acquisition and calibration, manages additional data, and communicates with the satellite to transmit and receive data.

The HEPD-02 collects data continuously during the orbit. Data acquisition is initiated by a trigger signal from the TRIG board. The DPCU then constructs an event from data provided by the T-DAQ board, which is responsible for the Tracker system information, and the TRIG board, which provides trigger information and scintillator system information.



Figure 5.1.1: Launch of CSES-02 satellite from the Jiuquan launch center, on June 14, 2025.

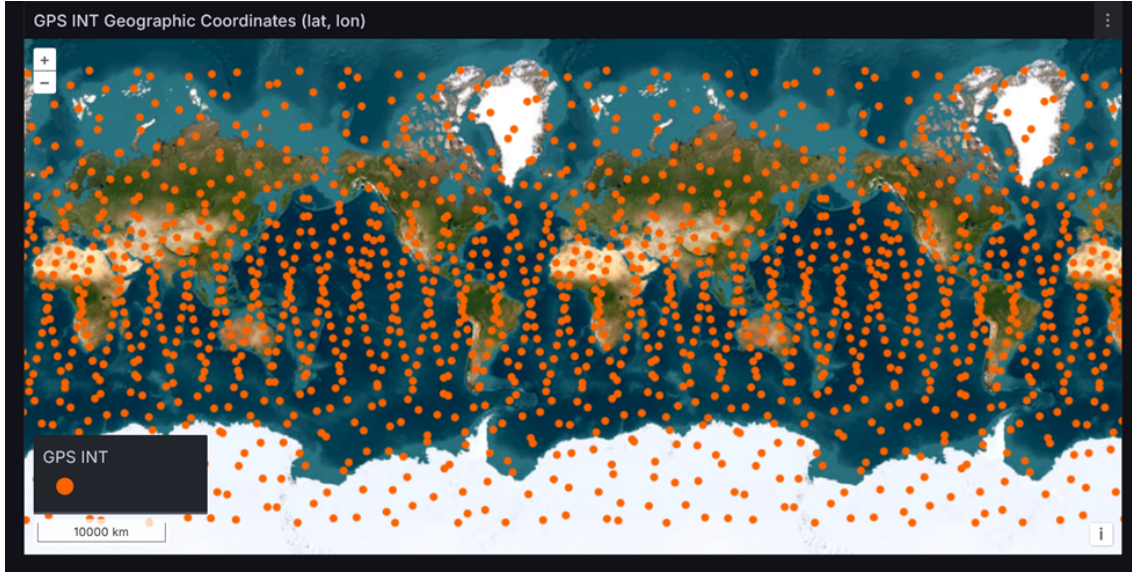


Figure 5.1.2: HEPD-02 orbital positions as on June 23, 2025 as given by the GPS broadcast.

During operations, the HEPD-02 transmits various types of data packets at different periodicities:

- **Run Header/Tail packets** - Event data acquisition is performed continuously, with each data acquisition run lasting 2 minutes. At the beginning/end of each run a header/trailed data packet is transmitted. This packet contains general information such as: a unique identifier of the current run (DPCU reboot number and current run number), the *DPCU time* (the time elapsed since the last power-on measured with the DPCU internal clock), configuration of the current run mode (trigger configuration, pre-scaling factors, ...), satellite broadcast data (satellite time and attitude, GPS data, Star Sensor data), timestamp of satellite broadcast, last command sent, status of all HEPD-02 main boards (LV-CTRL, HV-CTRL, TRIG, T-DAQ, DPCU).
- **Run Event packet** - Within the run, each triggered event generates the acquisition of the scintillator and tracking systems. The acquired data, ADC measurements from each PMT (both low- and high-gain), and the tracker pixels that have fired are transmitted in this packet. The packet also contains the progressive trigger number, the event time from both the trigger and Tracker boards, the time difference relative to the previous event, and the measured dead time.
- **Scientific Periodic Data packet** - On the TRIG board are present rate meters that are used to monitor the acquisition rate of single PMTs (even the ones that are not in the trigger), and of all the channels belonging to the trigger mask. After transmission, the counters are reset to zero. This data packet is transmitted every 10 seconds during acquisition. The data packet also includes the DPCU time.
- **PMT Calibration Event packet** - Calibration of the PMT system is a

special type of run in which the triggers are generated by an internal 100 Hz pulser. For each PMT, the mean, i.e. *pedestal*, and width, i.e. *noise*, of the signals recorded with the pulser are collected and sent to the ground in this data packet. Calibration of the PMT is performed only once every few hours when the satellite is passing through the equator, where the cosmic ray flux is expected to be minimum. Other information, such as the DPCU time and the satellite's orbital position at the start/stop of the calibration, is transmitted to the ground in this packet.

- **ALTAI Calibration Event packet** - Several specific calibration procedures exist for the tracker, for the optimization of the system thresholds, and for the online masking of noisy pixels. Relative information is sent to the ground in this packet.
- **Diagnostic packet** - This packet is sent every 10 seconds and contains a complete diagnostic of the detector: status of boards, measured current and voltages from DPCU, tracker, and low- and high-voltage systems, temperatures from sensors installed on boards and on various points of the calorimeter volume, counters of anomalies registered. This data packet is sent during an event acquisition run, a calibration run, or a dedicated housekeeping run. The data packet also includes the DPCU time.
- **Configuration packet** - This data packet contains the HEPD-02 configuration (run configuration, calibration configuration, trigger configuration, prescaling factors, ...). This data packet is sent at the main board's boot. The data packet also includes the DPCU time.

A suite of dedicated software tools has been developed within the Italian collaboration to continuously monitor the configurations, statutes, and responses of the various HEPD-02 subsystems, enabling the prompt detection of potential anomalies. The satellite data, downloaded from DFH Company, is distributed to the collaboration and promptly processed at the ASI Space Science Data Center (SSDC). The data are initially produced in Level 0 (L0) format, containing raw quantities, and subsequently converted into Level 1 (L1) and Level 2 (L2) products, which include reconstructed and calibrated physical parameters. Data production at ASI is managed through a MySQL database that tracks all generated datasets.

The L0 data are used immediately to produce quick-look plots, which are made available to operators on shift for verification and early identification of potential issues in the data-acquisition process. Copies of the L0, L1, and L2 datasets are also transferred to CNAF, INFN's national computing center, where they are archived and made available for scientific analysis.

A dedicated fast monitoring system has been developed by the Bologna group, based on the automated processing of L0 data and their ingestion into an **InfluxDB**¹ time-series database, visualized through a **Grafana**² interface. This system operates within the INFN Cloud infrastructure, ensuring continuous and efficient monitoring. An example of this monitoring is shown in Fig. 5.2.1, which displays the measured

¹<https://www.influxdata.com/>

²<https://grafana.com/>



Figure 5.2.1: Example of HV monitoring. 3 months are shown from July. 29th to October 26th.

high-voltage (HV) of all PMTs over time. The HV remains stable throughout the observation period, with minor fluctuations observed during system reboots and in early September 2025, when a dedicated scan of different HV settings was performed to fine-tune the HV line and equalize the PMT responses.

Periodically, during the satellite’s passage through the equatorial region, a calibration of all PMTs is performed. The PMT calibration involves determining the pedestal and electronic noise by calculating the mean and RMS of signals recorded from events triggered by a 100 Hz pulser in the absence of particles passing through the detector, as described before. The signal pedestals of all PMTs are continuously monitored in both the high-gain (HG) and low-gain (LG) scales, see Fig. 5.2.2. Occasional irregularities appear as sudden peaks that correlate with simultaneous calibration of the tracker’s ALTAI system and are now well understood. Consequently, it was decided to disregard PMT calibration data obtained simultaneously with ALTAI calibrations. Apart from these isolated events, the pedestals exhibit remarkably stable behavior, consistent with the values measured on the ground, as illustrated in Fig. 5.2.3.

The temperatures of the various subsystems are also continuously monitored with the diagnostic. Each electronic board (DPCU, TRIG, T-DAQ, LV-CTRL, and HV-CTRL) is equipped with 2 temperature sensors, while each tracker turret contains 18 sensors. In the scintillation system, 8 sensors are installed, 4 on the first RAN block and 4 on the third block, with 2 sensors installed on opposite sides. All sensors exhibit nominal and stable behavior, consistent with expectations. An example of the temperature evolution measured by the calorimeter sensors over time is shown in Fig. 5.2.4.



Figure 5.2.2: Example plots of PMTs’ pedestals measured during calibration. On top 2 panels: the pedestals measured in the HG scale for PMTs read-out by CITIROC-1 and CITIROC-2, and on bottom 2 panels are the pedestals measured in the LG scale for PMTs read-out CITIROC-1 and CITIROC-2.



Figure 5.2.3: Plots showing the stability of PMTs' pedestals over time. This time range excludes calibrations performed concurrently with the tracker calibration.

5.3 Scintillator System Commissioning

After the CSES-02 launch and successful basic health checks of HEPD-02 on the MAIN side, a 6-month commissioning phase started. HEPD-02 is a complex detector with several novel data-acquisition modes, and some of its innovative features cannot be fully tested or configured during the ground test campaign. Two notable examples are the *variable prescaling factor* that depends on orbital position, which optimizes data acquisition by avoiding rate saturation; and the *GRB algorithm* that, whenever a GRB signal is detected, enables GRB acquisition mode in parallel with the standard data acquisition mode.

The scheduled procedures applied during the commissioning on MAIN side are:

- **Orbital Zone Trigger Optimization** – optimization of the trigger mask, prescaler values, and tracker acquisition stave masks for each defined orbital



Figure 5.2.4: RAN sensors measured temperatures versus time. Different colors are for different sensors.

zone (128 cells, each spanning 11.25° in latitude and 47.5° in longitude).

- **High Voltage Scan** – optimization of the PMT high-voltage settings to equalize the response of the 64 PMTs.
- **Threshold Scan** – optimization of the PMT thresholds to avoid the acquisition of false triggers.
- **GRB Algorithm** – optimization of the GRB algorithm parameters to fine-tune its performance.

At the time of writing this thesis (October 2025), the first three phases have been completed, and the fourth, dedicated to optimizing the GRB algorithms, is in progress. Next steps will be dedicated to the SPARE side, with a reduced version of the commissioning procedure already concluded on the MAIN side. The time reduction of the procedure is possible thanks to the availability of analysis tools already optimized for flight data and the expectation that most of the configuration parameters (such as HV values, or optimization of thresholds for GRB algorithm, ...) are not expected to change between the two sides.

In the following, we focus primarily on the steps related to the scintillator system, which has been the main responsibility of the Bologna Limadou group.

5.3.1 High Voltage Scan

During commissioning, an HV scan was performed to equalize PMT responses and optimize the operating points of the scintillation counters. The procedure followed the same approach used during ground calibration (see Sec. 4.5.3). Six HV settings were tested, ranging from -950 V to -700 V in steps of 50 V. The sequence of operations performed during the scan is illustrated in Fig. 5.3.1, and follows:



Figure 5.3.1: The HV monitor showing the scanning procedure featuring the 6 stages with equal HV for all the PMT lines.

PMT Group	HV _{flight} (V)	HV _{ground} (V)	Relative Diff. (%)
1	837.7	848.2	-1.2
2	839.8	840.5	-0.1
3	924.7	862.8	7.2
4	829.9	818.2	1.4
5	760.7	769.7	-1.2
6	759.7	763.9	-0.6
7	825.6	825.9	0.0
8	840.8	838.5	0.3
9	855.5	859.9	-0.5
10	845.7	837.6	1.0
11	848.8	846.3	0.3
12	862.5	864.7	-0.3
13	837.5	841.4	-0.5
14	852.0	853.1	-0.1
15	900.0	903.5	-0.4
16	916.6	921.9	-0.6

Table 5.3.1: Table of the optimized HV values found with flight data for each PMT group compared to the nominal ones calculated on ground. In the last column is given the relative difference computed as $100 \times (\text{HV}_{\text{flight}} - \text{HV}_{\text{ground}})/\text{HV}_{\text{ground}}$.

- **Step 1:** -750 V for 5 orbits;
- **Step 2:** -850 V for 10 orbits;
- **Step 3:** -950 V for 5 orbits;
- **Step 4:** -800 V for 10 orbits;
- **Step 5:** -700 V for 5 orbits;
- **Step 6:** -900 V for 5 orbits.

For each HV step, the MPV of the ADC distribution for each PMT was derived using passing-through particles (i.e., events with signals in all detectors, including the bottom veto), along with additional selection criteria similar to those described in Sec. 4.5.3. Furthermore, orbital data cuts were applied to exclude regions such as the South Atlantic Anomaly.

Figure 5.3.2 shows the MPV values of the signals as a function of the applied HV for all PMTs, grouped according to their respective HV lines. As illustrated, four HV points were sufficient to characterize the PMT gain dependence on HV and to derive the equalization curves. The lowest and highest HV settings (−700 V and −950 V) were excluded due to insufficient statistics.

The equalization voltage for each channel was determined by matching the average ADC signal to reference values of approximately 200 (600) for the TR, RAN, and BOT (EN) counters. The resulting equalization voltages were found to agree with the nominal ground settings within 10%, as reported in Tab. 5.3.1. Consequently, it was decided to maintain the nominal HV configuration at least until the next scheduled scan, planned every 6 months. Indeed, it is planned to periodically conduct an HV scan even after the completion of commissioning, in order to check for any degraded response of the PMTs and aging of the scintillation counters. If necessary, a corrective configuration may be applied.

5.4 Flight Performances of HEPD-02

The data collected by the HEPD-02 detector during the commissioning phase are valuable data used also to monitor performances of the detectors subsystems and the reconstruction algorithms as example for tracks reconstruction with data from the direction detector, and the preliminary evaluation of the reconstruction of the particle angle, deposited energy, etc. Figures 5.4.1, 5.4.2, and 5.4.3 show the event display of preliminary reconstructed single and multi- tracks events.

The monitoring of the events acquisition rates triggering the various masks enable the simultaneous acquisition and study of different populations of particles along the orbit. For instance, the TR1And mask allows the detection of electrons and protons with energies above 1 MeV and 15 MeV, respectively, with a maximum rate of ~ 3.2 MHz, significantly reducing the experiment's threshold compared to its predecessor HEPD-01, and enhancing the capability to analyze trapped particles and outer belts. As the trigger pattern moves deeper into the detector, the energy threshold for the particles detected increases and the frequency of events decreases. As an examples for the $\text{TR1} \wedge \text{TR2}$ trigger mask the threshold increases to 3 MeV

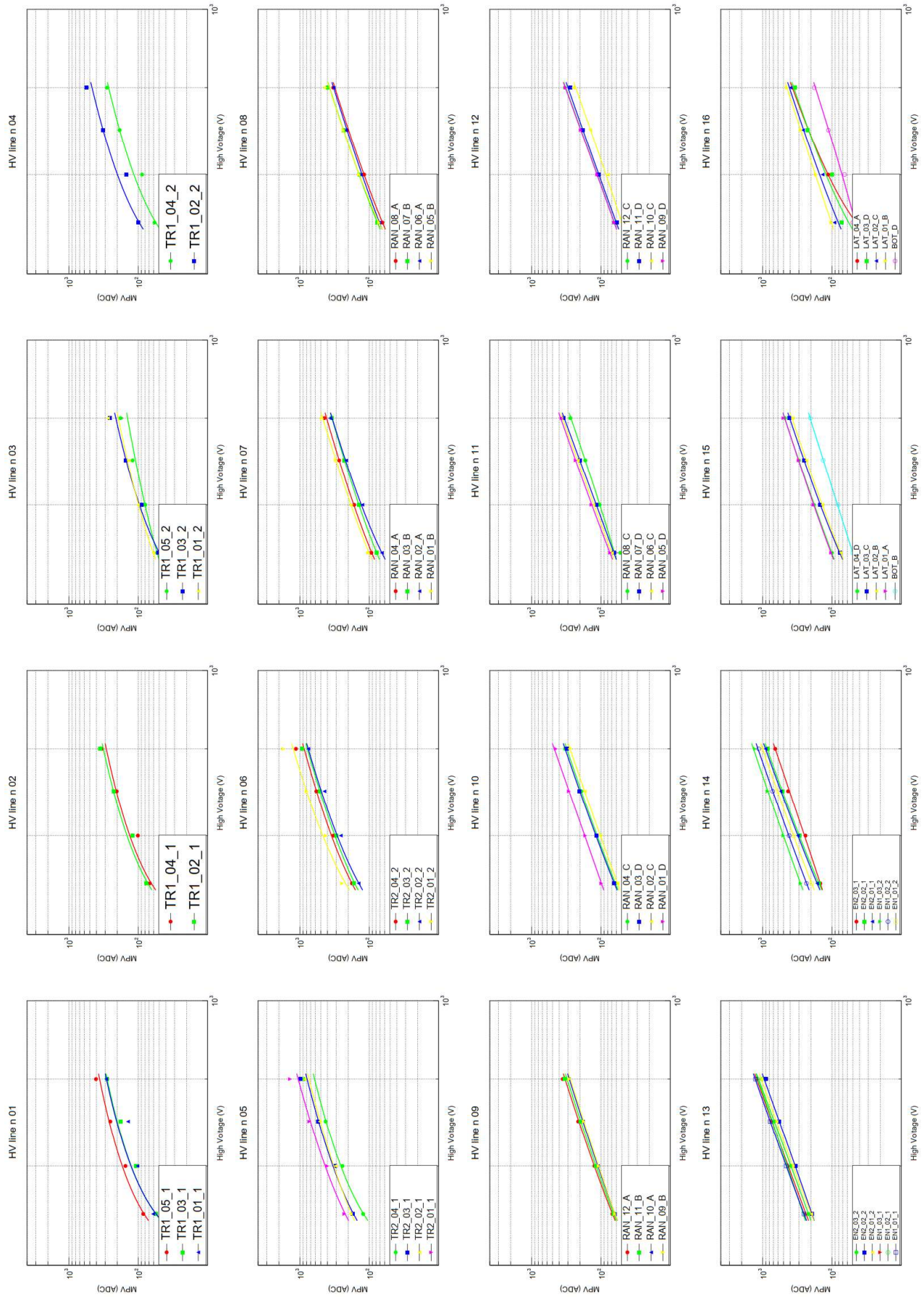


Figure 5.3.2: ADC signal versus HV for all the PMTs of HEPD-02 in groups of HV lines obtained during in-flight HV scan.

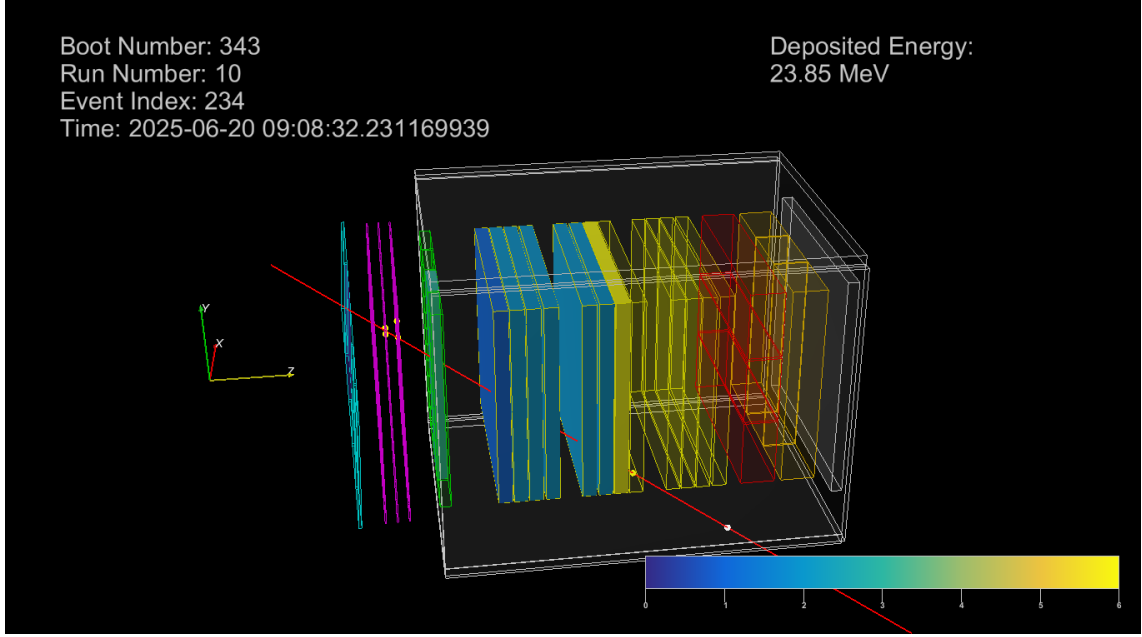


Figure 5.4.1: Display of the first reconstructed track from HEPD-02 flight data.

for electrons and 30 MeV for protons while the maximum rate goes to around 100 kHz. These thresholds increase to > 7.5 MeV and 50 MeV for protons for the $TR1 \wedge TR2 \wedge RAN$ trigger mask. The event rate maps for these masks are given in Fig. 2.4.2, see caption for more details. The trigger pattern dedicated to calibration of the detector, $TR2 \wedge RAN$ is also shown. This trigger pattern is an innovation in the same way as the GRB trigger logic or the Upward and Lateral masks, not present in HEPD-01, and not shown here. Also, besides a wider latitude coverage, these maps show an improved resolution compared to the maps obtained with HEPD-01 [26, 66].

Finally, a preliminary study was initiated to investigate the change in the PMT gain over time. Considering about 3 and a half months of data beginning from June 23rd, 2025 (after the Health checks), and avoiding calibration periods, the MPV of the signal recorded by each PMT for passing-through particles at the center of the scintillating counters under consideration was monitored every 15 days. To accumulate sufficient statistics, data were collected for a full day and for orbits outside the SAA. The first results show a decrease in the signal over time for most of the PMTs, with an average of 7 to 10% and a maximum of 20%, as can be seen in Fig. 5.4.5. However, this overall decrease seems to be slowing down and reaching a plateau, see Fig 5.4.6 for some examples. Further analysis in the coming months will likely provide more insight. If the signal continues to decrease, a possible retuning of high voltage can be foreseen after a new HV scan.

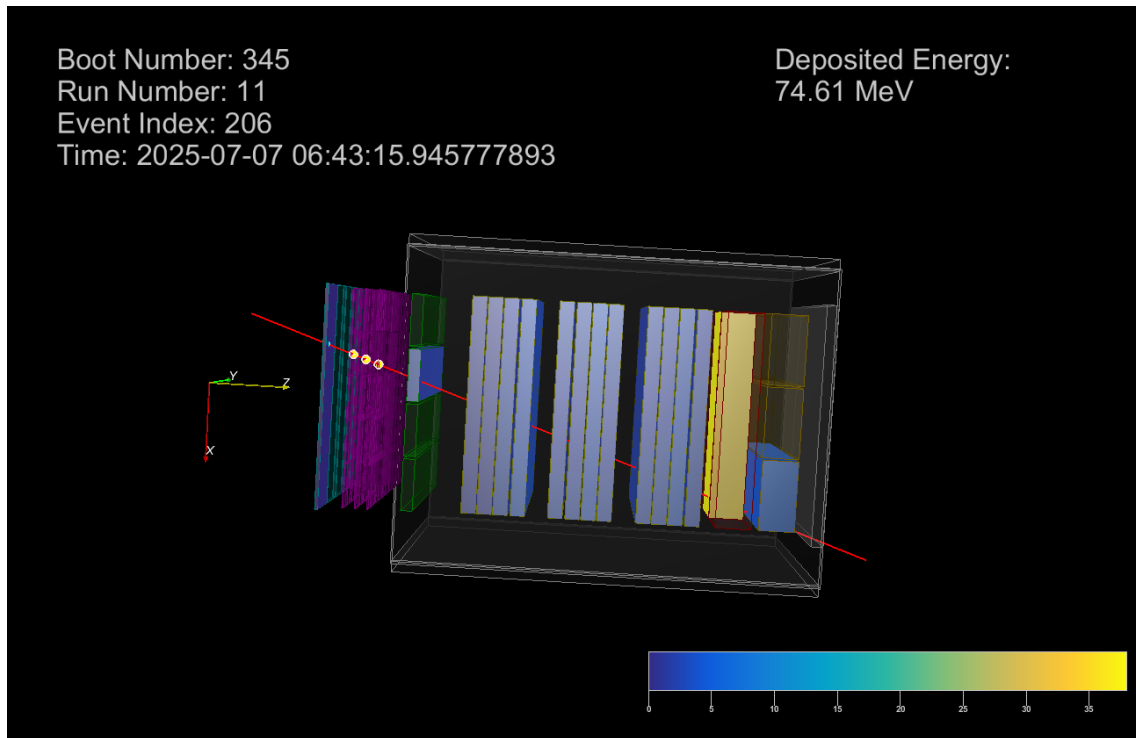


Figure 5.4.2: Event display of an example reconstructed track.

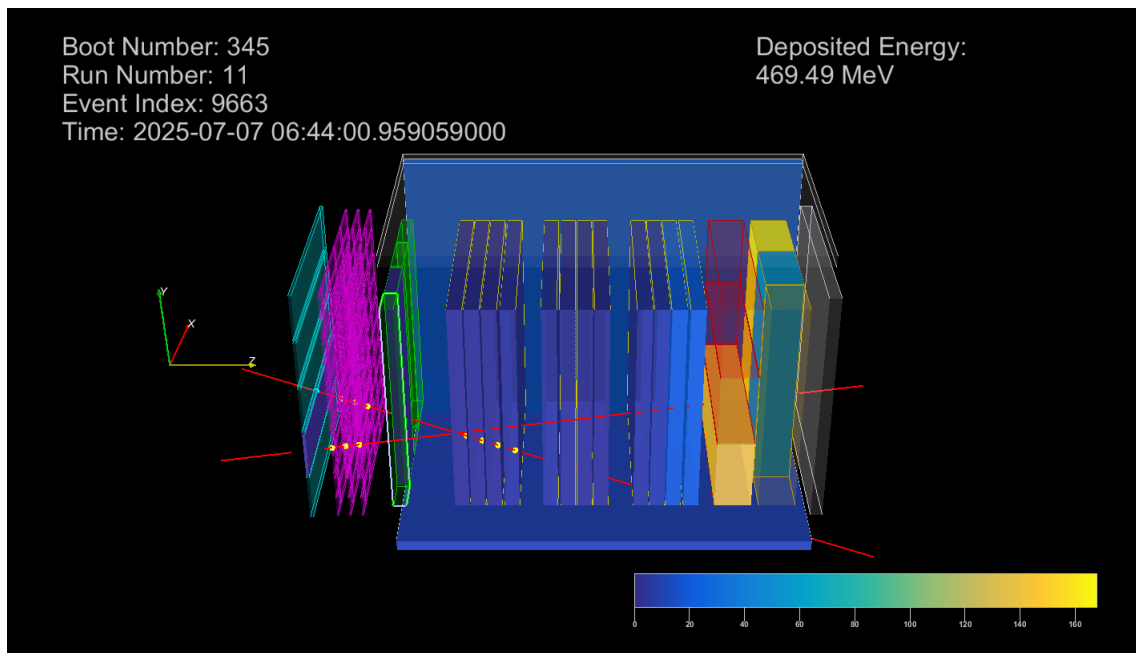


Figure 5.4.3: An example reconstructed multi-tracks.

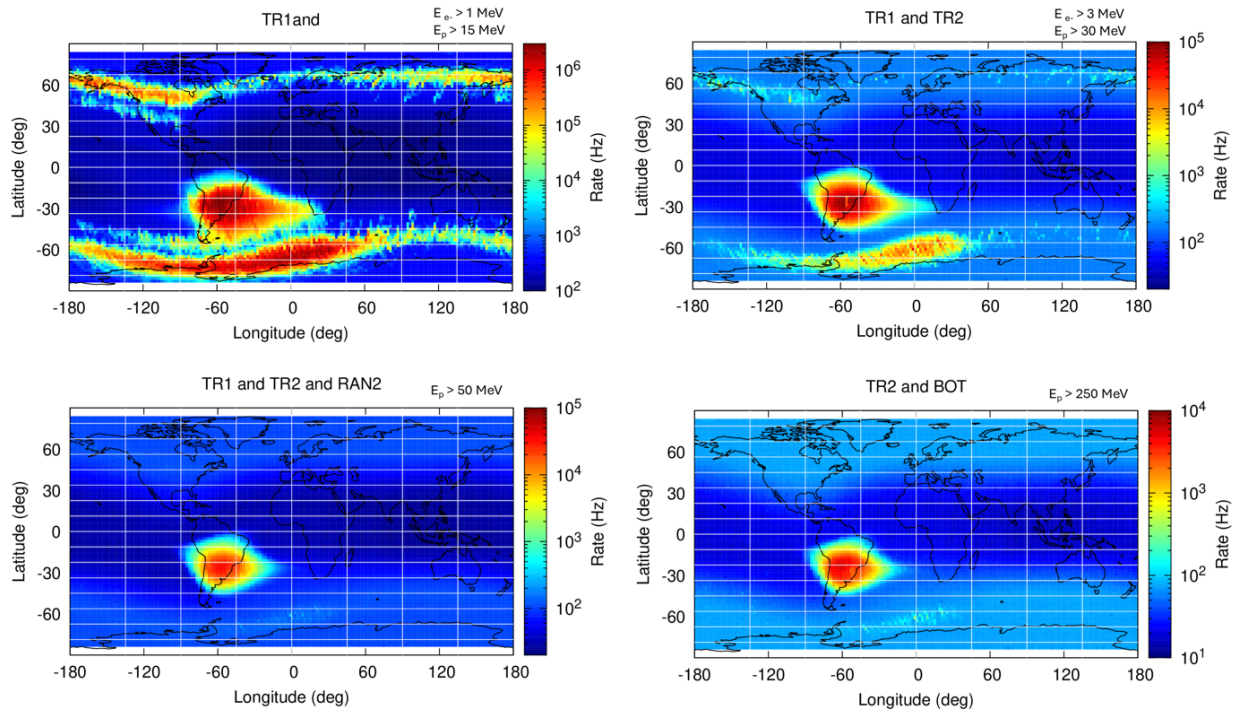


Figure 5.4.4: Smoothed orbital maps of the event rate measured by HEPD-02 for four different trigger masks: TR1and (top left), TR1 and TR2 (top right), TR1 and TR2 and RAN2 (bottom left), and TR2 and BOT (Bottom right). Rates are given for ascending semi-orbits.

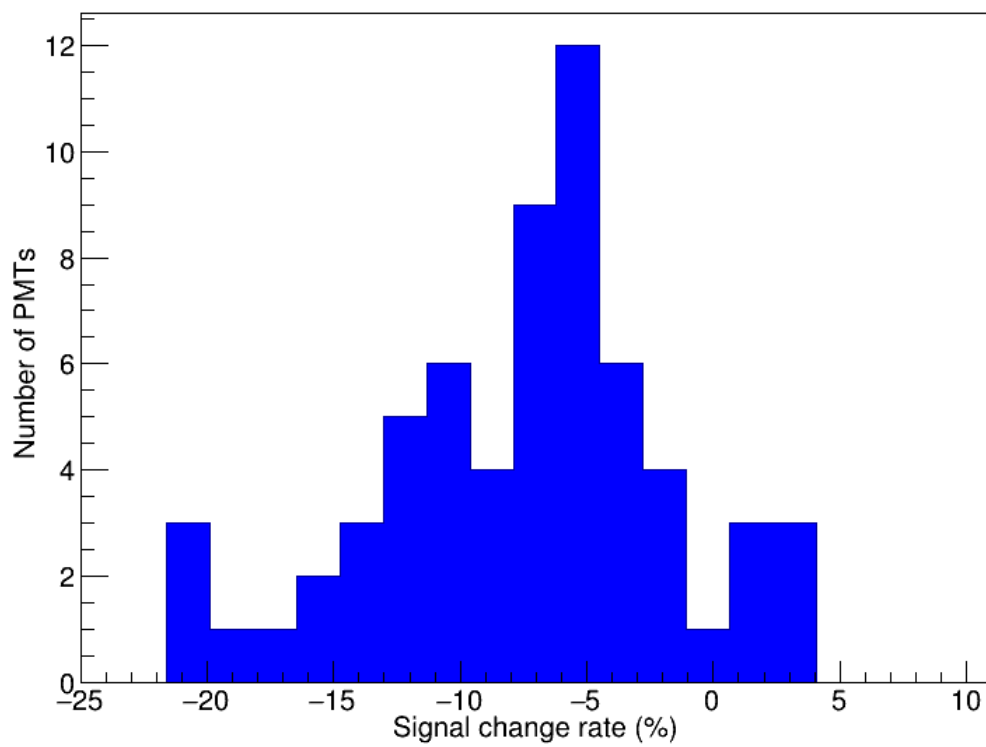


Figure 5.4.5: Histogram representing the loss rate of PMT gain after approximately 3.5 months of operation. The reference date being June 23 2025.

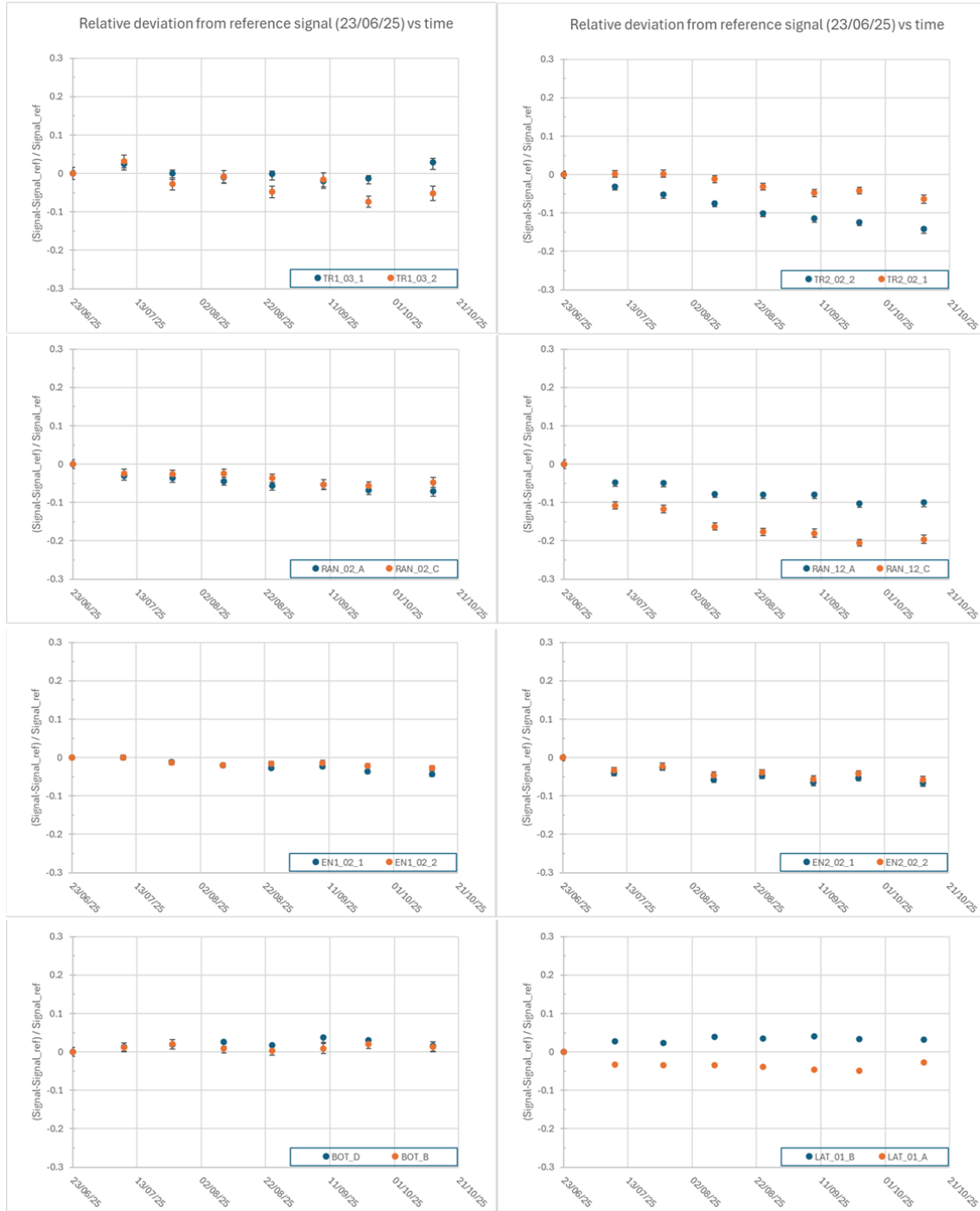


Figure 5.4.6: Example change over time of the PMT signal of different counters relative to a reference date set to the 23 June 2025. Top panels are example PMTs of TR1 (left), and TR2 (right) counters. The second row panels are for RAN counters, third row panels are for EN1 and EN2, and bottom panels are for BOT and LAT counters.

Conclusions

The CSES (China Seismo-Electromagnetic Satellite) program is dedicated to studying the near-Earth environment to detect electromagnetic and particle perturbations potentially associated with seismic activity, as well as to investigate Earth–ionosphere–magnetosphere coupling phenomena. In addition, the mission contributes to a broader understanding of space weather, cosmic-ray modulation, and ionospheric dynamics through continuous measurements of electromagnetic fields, plasma parameters, and energetic particles.

Two satellites of the CSES constellation are currently in orbit. CSES-01 was launched on February 2, 2018, from the Jiuquan Satellite Launch Center (JSLC) aboard a Long March 2D rocket, and has been operating nominally since then. The second satellite, CSES-02, was launched on June 14, 2025, also from JSLC, to continue and enhance the mission’s scientific objectives through improved instrumentation and expanded measurement capabilities.

Among the different instruments onboard the CSES satellite, the High Energy Particle Detectors (HEPD-01 on CSES-01, and HEPD-02 on CSES-02) are the two instruments with capabilities of measuring the particle environment in the magnetosphere, distinguishing electrons in the range 3–100 MeV, protons from 30–200 MeV, and light nuclei up to about 300 MeV/nucleon.

In this thesis, I conducted a detailed study of the HEPD-01 detector, developing an analysis to measure proton fluxes as a function of geomagnetic latitude during both quiet and an intense solar flare period. The analysis revealed a trapped particle population at low geomagnetic latitudes, with only a slight latitude dependence and similar behavior under both quiet and active solar conditions. At higher latitudes, distinct populations of solar-origin particles (observed during solar flare events) and galactic cosmic rays (dominant during quiet periods) are clearly identified. The results of this thesis confirm previous HEPD-01 publications and extend AMS-01 measurements to a range of low rigidities not previously observed. The HEPD-01 data analysis has been developed as a preparatory step for understanding the instrumentation, data analysis, and physics topics of its successor, HEPD-02.

A significant portion of my work has been dedicated to the design, prototype testing, performance characterization, integration, space qualification, and commissioning of the HEPD-02 detector. The HEPD-02 is an enhanced version of HEPD-01, developed to extend the measurable energy range and improve the detector’s overall response and performance. Prototypes of all counters were produced in Bologna, where their signal response and efficiency were thoroughly evaluated. The photomultiplier tubes (PMTs) were fully characterized in Bologna, and a comprehensive calibration procedure was developed before assigning them to specific HV lines. Once integrated into the detector, the PMT high voltages were fine-tuned using

a dedicated procedure. Extensive verification tests were conducted to confirm the linearity and high efficiency of the scintillator counters. My participation spanned all phases of detector integration and testing, and following the launch of CSES-02 in June, I also took part in the commissioning of HEPD-02 in orbit contributing to the definition and verification of flight operations as well as to the analysis of the data collected for the detector optimization and in-flight performances verification.

While writing this thesis, many exciting developments have been taking place with HEPD-02, with numerous activities ongoing to transition the instrument to scientific observation mode. In this context, a particularly interesting study would be to apply a HEPD-01-like analysis to HEPD-02 data, potentially extending the work to additional particle species. Such an analysis would provide valuable confirmation of observations made with HEPD-01 and demonstrate the capabilities and performance of HEPD-02.

Acknowledgments

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Appendix

In this section are provided the 2D simulated maps of the mean number of photoelectrons/charge relative to the center of the counter as a function of the impact position for TR2, RAN and EN counters together with the measured ones. Maps are binned in 5×15 cells on the X×Y plan for TR2 and EN counters, and 15×15 cells for RAN counters. The simulated maps presented here were obtained after the individual tuning of the simulation parameters (scintillators absorption length, wrapper reflectivity) to the experimental data obtained for each counter. They show an agreement of the order of 10% in most impact positions, with the exception of the position located closely in front of the PMT for which simulation gives signals up to 20% above data. For all counters only one PMT response is shown in these maps, as data were averaged between PMTs and the simulated response of the PMTs is perfectly symmetric.

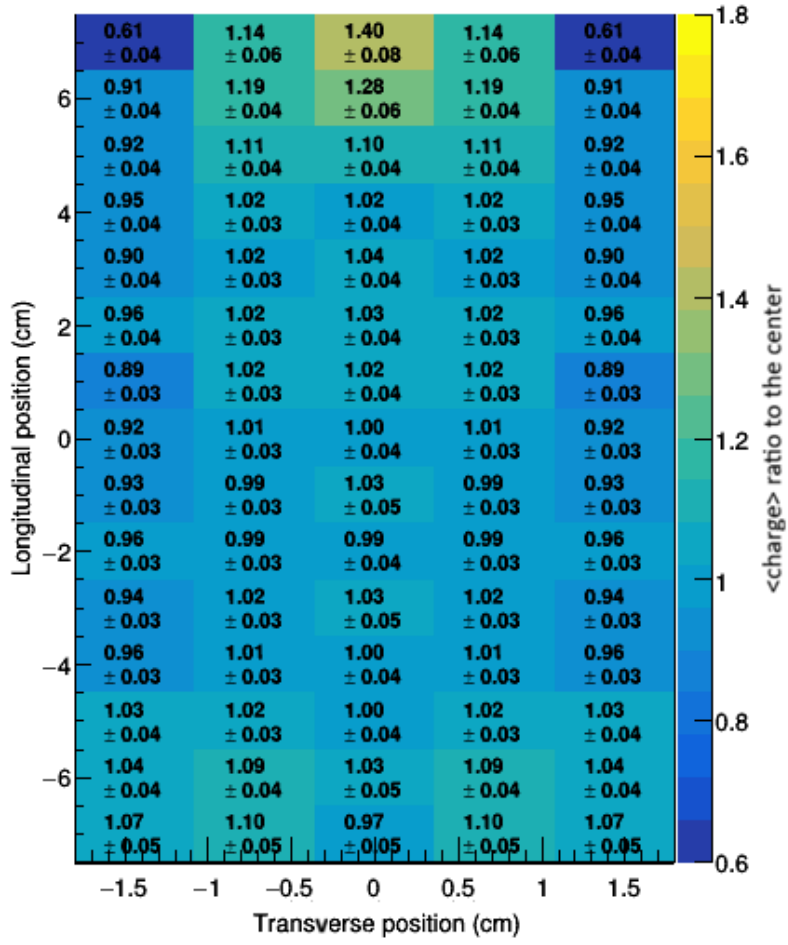


Figure 5.4.7: The measured 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the TR2 counter.

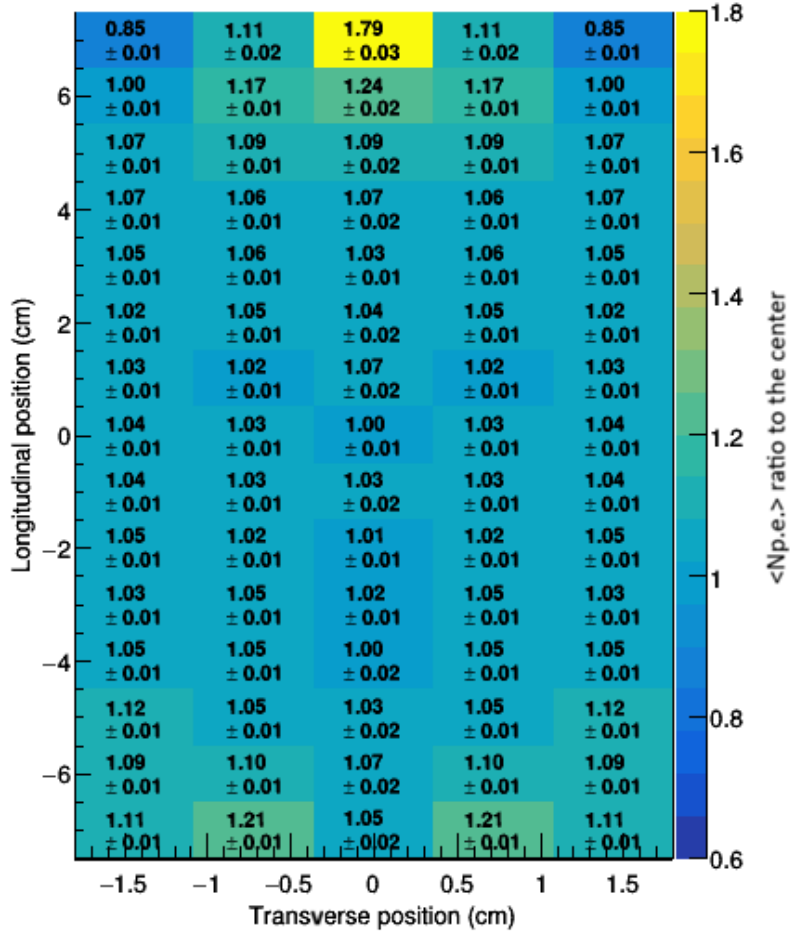


Figure 5.4.8: The simulated 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the TR2 counter.

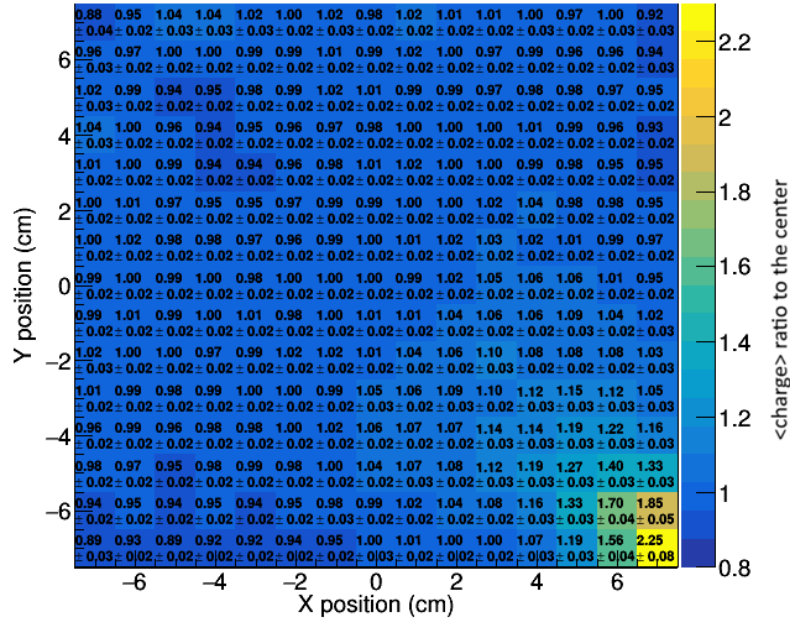


Figure 5.4.9: The measured 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the RAN counter.

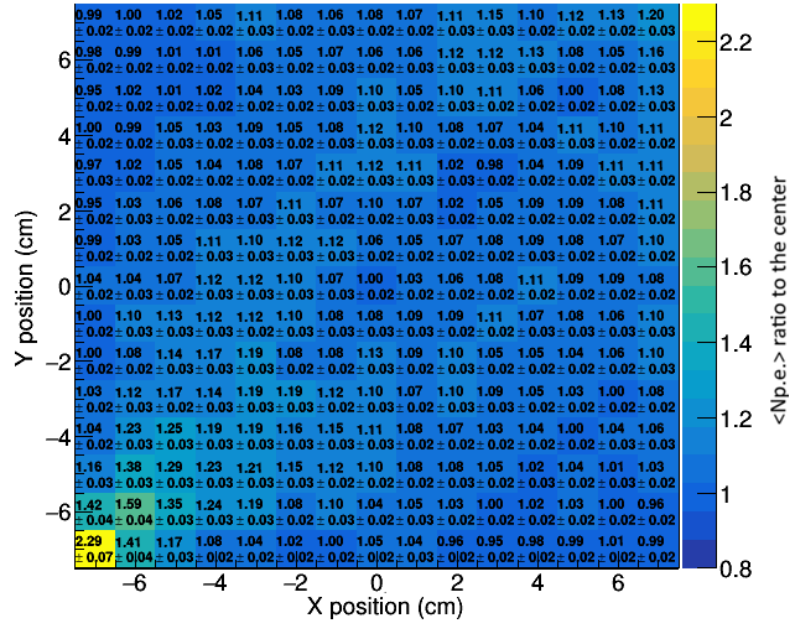


Figure 5.4.10: The simulated 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the RAN. counter.

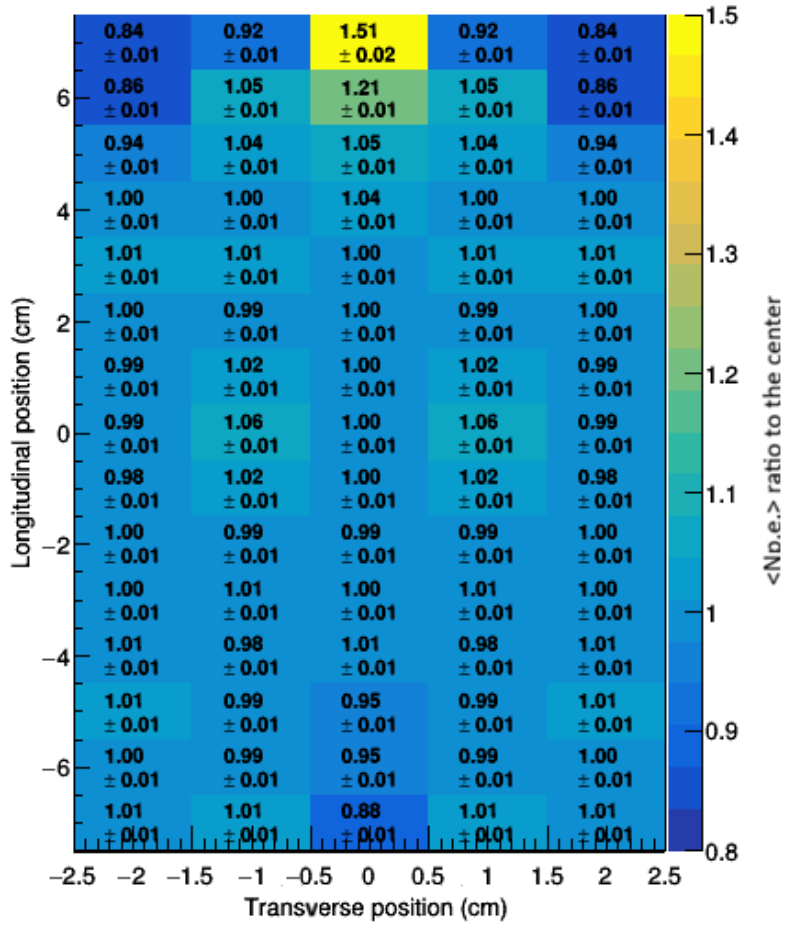


Figure 5.4.11: The measured 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the EN counter.

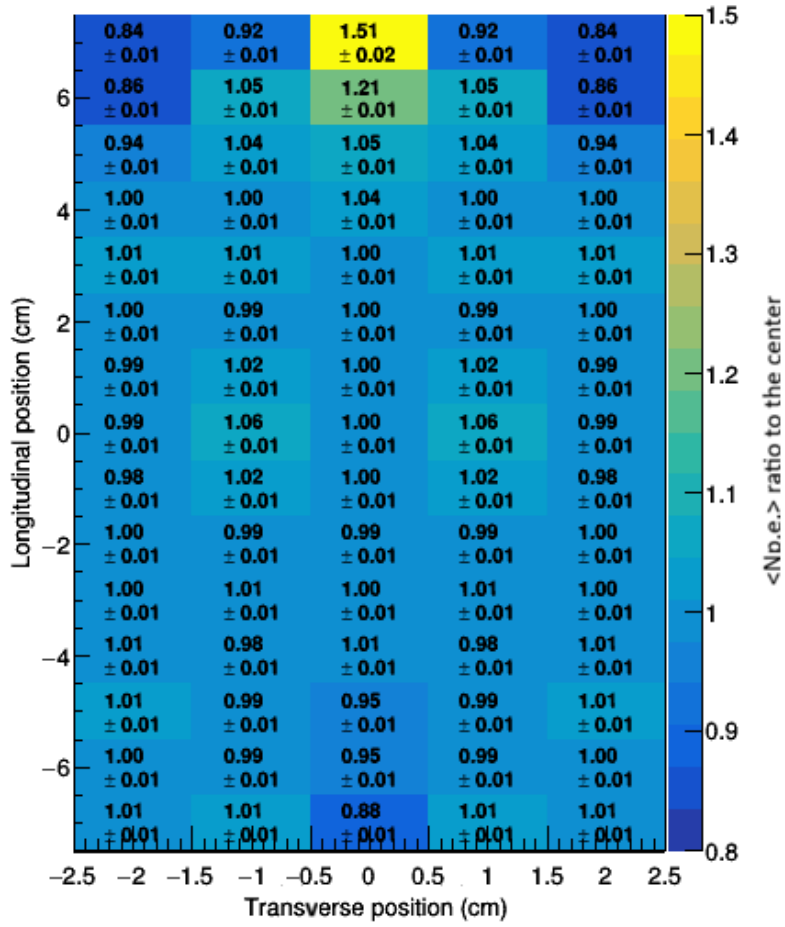


Figure 5.4.12: The simulated 2D map of the ratio to the center of the number of photo-electrons recorded by each PMT for the EN counter.

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