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The new Beam Halo Monitor for the CMS experiment at the LHC

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Introduction

The Large Hadron Collider (LHC) [1], at the European Laboratory for Nuclear Research (CERN) in Geneva, is a hadron-hadron collider, designed to work at a center of mass energy of 14 TeV and with a peak instantaneous luminosity of $1 \cdot 10^{34}$ cm⁻² s⁻¹.

The *Compact Muon Solenoid* (CMS) [2] is one of the four main experiments designed to study high energy particle collisions generated by the LHC.

LHC and CMS have been operating at a beam energy of 3.5-4 TeV from 2011 to early 2013, collecting about 30 fb⁻¹ of integrated luminosity, enough to discover, together with ATLAS, the Higgs boson [3, 4], one of the most important discoveries in fundamental physics.

One of the many sources of background during data taking for the measurements performed by CMS is the *Machine Induced Background* (MIB), which is the combination of backgrounds originating from the accelerator itself, and is typically produced along the beamlines.

The LHC has undergone significant upgrades during the so-called *Long Shutdown 1* (LS1) in 2013 and 2014, that will allow it to eventually reach its target beam energy of 7 TeV and possibly an instantaneous luminosity of $2 \cdot 10^{34}$ cm⁻² s⁻¹, a factor of two higher than was foreseen in the LHC technical design report. The changes made to several machine parameters are expected to produce an increase in the production of MIB, which may cause undesired effects during data taking.

In parallel, the CMS detector was also upgraded, and among other changes, several sub-detectors were improved or built ex-novo with the objective of measuring luminosity and machine background. These new sub detectors are responsibility of the *Beam Radiation Instrumentation and Luminosity* (BRIL) project.

In the context of this project, a new detector, called the *Beam Halo Monitor* (BHM), has been designed and will be installed before the LHC is restarted at a higher energy. The BHM detector is a device that uses Cherenkov radiation to detect MIB, mostly composed of muons produced by the interaction of beam particles.

This thesis describes the BHM detector, after two introductory chapters on LHC and CMS, which include details of the origin and the effects of the Beam Halo as well as an introduction to beam monitoring in CMS. Several different detectors are dedicated to

this monitoring, with BHM being the outermost, largest in radius (1.8 m from the beam axis) and acceptance.

The third chapter is focused on the design of the BHM detector front-end, with an overview of the operating principle, based on Cherenkov radiation, and the detailed description of the detector units.

The fourth chapter is a description of the electronics used to readout the detector, with emphasys on the work I carried out to adapt for BHM the electronics designed for the upgrade of the CMS forward hadronic calorimeter (HF).

The fifth chapter presents the design of the monitoring and calibration system of BHM, that I developed with the objective of monitoring the performance of the detector units over time.

The last chapter concludes this work by presenting data acquired during the characterization of the basic detector components and of the assembled detector units, before their installation in CMS which is foreseen in the first months of 2015.

Chapter 1

The Large Hadron Collider

The Large Hadron Collider (LHC) at CERN near Geneva is the world's newest and most powerful tool for Particle Physics research. It is designed to collide proton beams with a centre-of-mass energy of 14 TeV and an unprecedented luminosity of $2 \cdot 10^{34}$ cm⁻² s⁻¹. The aim of the LHC is to study the Standard Model physics at the TeV energy scale (in particular the Higgs mechanism) and possibly reveal physics beyond the Standard Model. In this chapter, a description of the LHC machine will be presented, based mostly on [1] and [5], emphasizing aspects relative to beam induced background which is the subject of this thesis.

1.1 Overview

The LHC is a two-ring-superconducting-hadron accelerator and collider installed in the existing 26.7 km tunnel that was constructed between 1984 and 1988 for the CERN Large Elctron Positron collider (LEP). In 1989, CERN started LEP, the world's highest energy electron-positron collider. In 2000, LEP was closed to liberate the tunnel for the LHC, whose construction had been authorized by the CERN Council in 1994.

The LEP tunnel has eight straight sections and eight arcs and lies between 45 m and 170 m below the surface under the Franco-Swiss border near Geneva (Fig 1.1). There are two transfer tunnels, each approximately 2.5 km in length, linking the LHC to the CERN accelerator complex that acts as injector. The LHC is a particle-particle collider and it has two rings with counter-rotating beams, unlike particle-antiparticle colliders that can have both beams sharing the same space in a single ring.

The tunnel geometry was originally designed for an electron-positron machine, and there were eight crossing points flanked by long straight sections for RF cavities that compensated the high synchrotron radiation losses. A proton machine such as LHC does not have the same synchrotron radiation problem and would, ideally, have longer arcs and shorter straight sections for the same circumference, but accepting the tunnel "as



Figure 1.1: Location of the LEP/LHC tunnel. The straight sections are centered around the 8 "Points" shown on the map.

built" was the cost-effective solution.

Four main experiments are installed in the interaction regions of LHC:

- ALICE A Large Ion Collider Experiment [6], devoted to the study of Heavy Ion collisions, located in Point 2 in Fig 1.1
- ATLAS A Toroidal Lhc ApparatuS [7], a "general purpose" experiment (Point 1)
- CMS Compact Muon Solenoid [2], a "general purpose" experiment (Point 5)
- LHCb LHC beauty [8], an experiment devoted to CP-violation measurements with b-hadrons (Point 8)

The high centre-of-mass energy and luminosity make the LHC a perfect "discovery" machine. The use of protons, which are not elementary particles, allows to simultaneously explore a range of collision energies (of the internal constituents) with a fixed beam energy. This is in contrast with lepton colliders, which operate at a single energy and are more suitable for precision measurements, also thanks to the lower number of background processes. The LHC can also accelerate and collide Heavy Ions, which allows the study of Quark-Gluon-Plasma, a state of matter whose existence is predicted by quantum chromodynamics at extremely high temperature and density.



▷ p (proton) ▷ ion ▷ neutrons ▷ p̄ (antiproton) → H→ proton/antiproton conversion ▷ neutrinos ▷ electron

Figure 1.2: The CERN accelerator complex. The injection chain of the LHC strarts from LINAC2 and proceeds into PSB, PS and SPS

1.1.1 The CERN accelerator complex

The LHC accelerator takes advantage of a series of pre-existing CERN accelerators (shown in Fig. 1.2) to obtain an injection energy of 450 GeV per beam. The injection chain is critical in generating a beam of high intensity and low emittance, and the existing accelerators had to be modified to allow for LHC operation. More upgrades in this pre-acceleration chain will be necessary in the future to achieve higher luminosity in LHC.

In the first step the protons are produced by hydrogen ionization and then accelerated to the energy of 50 MeV by a linear accelerator (LINAC2). Protons are then injected into the Proton Synchrotron Booster (PSB), a four ring synchrotron that accelerates single bunches up to 1.4 GeV. Two batches of protons are transferred to the Proton Synchrotron (PS), the oldest CERN accelerator still in service. In the PS, the large PSB bunches are split into smaller bunches and accelerated to 25 GeV, before being split again to achieve the final 25 ns bunch spacing that will be maintained up to the LHC.

The last step of pre-acceleration is made by the 6.9 km Super Proton Synchrotron (SPS), where the beams reach the injection energy of 450 GeV. The SPS is filled with 3 to 4 cycles of the PS (out of the 11 that would fit), as it is not capable of accelerating more than $4 \cdot 10^{13}$ protons at a time. After acceleration, the proton bunches are then transferred to the LHC ring for acceleration up to 7 TeV. It takes 12 cycles of the SPS

in order to fill the LHC. A 3 μ sportion of the 88 μ sorbit is left empty to allow for the rise time of the beam dump kicker magnet; it is known as the *Abort gap*.

When LHC operates as a heavy ion accelerator, lead ions are first accelerated by the linear accelerator LINAC 3, and the Low-Energy Ion Ring (LEIR) is used as an ion storage and cooler unit. The ions then are further accelerated by the PS and SPS before being injected into LHC ring, where they will reach an energy of 2.76 TeV per nucleon (or 575 TeV per lead ion).

1.1.2 LHC design goals

The main aim of the LHC was to discover the Higgs Boson (a result that was successfully achieved [3]) and possibly to reveal physics beyond the Standard Model with centre of mass collision energies of up to 14 TeV. The number of events per second generated in the LHC collisions is given by:

$$N_{event} = \mathcal{L}\sigma_{event} \tag{1.1}$$

where σ_{event} is the cross section for the event under study and \mathcal{L} the machine luminosity. The machine luminosity depends only on the beam parameters and can be written for a Gaussian particle distribution within the beam as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F \tag{1.2}$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ the relativistic gamma factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the collision point, and F the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP).

The nominal values for the parameters above are listed in Table 1.1. Not all of these parameters have achieved their nominal values in the first years of operation of LHC.

Beams were circulated for the first time in LHC on 10 September 2008, but just 8 days later, a major technical incident forced a long stop. Investigations showed that cause of the incident was a faulty electrical connection between two of the accelerator superconducting magnets. This fault resulted in mechanical damage and release of cryogenic coolant (liquid helium) into the tunnel. In order to operate the accelerator safely, it was decided to limit the maximum beam energy to 4 TeV after the repair works were completed. Only with the conclusion of the consolidation works in the first Long Shutdown (LS1, 2013-2014), the LHC will be able to reach the nominal beam energy.

On 23 November 2009 the accelerator produced the first proton-proton collisions. After a few pilot runs at energies of 450 GeV and 1.18 TeV per beam, the energy was ramped up to 3.5 TeV, reaching the first collision at a centre-of-mass energy of 7 TeV on 30th March 2010, the highest ever reached at a particle collider.

Number of particles per bunch (N_b)	$1.1 \cdot 10^{11}$
Number of bunches per beam (n_b)	2808
Circulating beam current	$0.582 \ {\rm A}$
Proton energy	$7 { m TeV}$
Relativistic Gamma (γ)	479.6
Stored energy in each beam	$362 \mathrm{~MJ}$
Luminosity (\mathcal{L})	$1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Beta function at IP (β^*)	$0.55 \mathrm{~m}$
Normalized transverse beam emittance (ϵ_n)	$3.75~\mu{ m m}$
Geometric luminosity reduction factor (F)	0.836
Luminosity lifetime	10 h
Time between collisions	$24.96~\mathrm{ns}$
Bunch crossing rate	$40.08 \mathrm{~MHz}$

Table 1.1: LHC design parameters for collisions at ATLAS and Compact Muon Solenoid (CMS).

The luminosity was then gradually increased up to $2 \cdot 10^{32}$ cm⁻² s⁻¹ with a maximum of 400 bunches spaced down to 150 ns. The proton-proton operation continued smoothly also in 2011 when a record instantaneous luminosity of $3.6 \cdot 10^{33}$ cm⁻² s⁻¹ was reached, with up to 1380 bunches of $1.4 \cdot 10^{11}$ protons spaced down to 50 ns. By the end of the 2011 run, more than 5 fb⁻¹ of integrated luminosity has been delivered to CMS and ATLAS. The centre of mass energy was increased from 7 to 8 TeV in 2012. The bunch spacing of 50 ns had to be maintained due to difficulties achieving the 25 ns design goal, but the bunch intensity was increased beyond the nominal value to compensate in part, at the cost of a higher pile-up. n 2012 there were 1368 bunches per beam and the intensity was 1.6 to $1.4 \cdot 10^{11}$ protons per bunch, delivering a total integrated luminosity in collisions at 8 TeV of about 20 fb⁻¹ (Fig 1.3).

1.2 The LHC machine

The high beam intensity required for a luminosity of $2 \cdot 10^{34}$ cm⁻² s⁻¹ excludes the use of antiproton beams, and hence excludes the particle-anti-particle collider configuration of a common vacuum and magnet system for both circulating beams, as used for example in the Tevatron [9]. To collide two counter-rotating proton beams requires opposite magnetic dipole fields in both rings. The LHC is therefore designed as a proton-proton collider with separate magnetic fields and vacuum chambers in the main arcs and with common sections only at the interaction regions (IR) where the experimental detectors are located. The two beams share an approximately 130 m long common beam pipe



CMS Integrated Luminosity, p

Figure 1.3: Integrated luminosity delivered to the CMS experiment during the three years of proton-proton run.

along the IRs.

There is not enough room for two separate rings of magnets in the LEP/LHC tunnel and, for this reason, the LHC uses twin bore magnets that consist of two sets of coils and beam channels within the same mechanical structure and cryostat. The peak beam energy depends on the integrated dipole field around the storage ring, which implies a peak dipole field of 8.33 T in the curved sections and therefore the use of superconducting magnet technology.

Aside of the obvious limit to the maximum energy imposed by the diameter of the ring and the peak field of the dipoles, the performance of LHC is limited by a number of factors, mostly related to nonlinear effects and defects in the beam optics and interaction between beam particles and the surrounding structures.

1.2.1 Machine layout

The basic layout of the LHC follows the LEP tunnel geometry: see Fig. 1.4. The LHC has eight arcs and eight Long Straight Sections (LSS). Each straight section is approximately 528 m long and can serve as an experimental or utility insertion. The two high luminosity experimental insertions are located at diametrically opposite straight sections: the ATLAS experiment is located at Point 1 and the CMS experiment at Point 5. Two more experimental insertions are located at Point 2 and Point 8, which also include the injection systems for Beam 1 and Beam 2, respectively.



Figure 1.4: Schematic layout of the LHC (Beam 1: clockwise; Beam 2: anticlockwise).

The beams cross from one magnet bore to the other at four locations. The remaining four straight sections do not have beam crossings. Insertions at Points 3 and 7 each contain two collimation systems. The insertion at Point 4 contains two RF systems: one independent system for each LHC beam. The straight section at Point 6 contains the beam dump insertion, where the two beams are vertically extracted from the machine using a combination of horizontally deflecting fast-pulsed (*kicker*) magnets and vertically-deflecting double steel septum magnets. Each beam features an independent abort system.

The arcs of LHC lattice are made of 23 arc cells. The arc cells are 107 m long and contain six long dipole magnets, powered in series. The LHC arc cell has been optimized for a maximum integrated dipole field along the arc with a minimum number of magnet interconnections and with the smallest possible beam envelopes.

1.2.2 Magnets

The Large Hadron Collider relies on superconducting magnets that are at the edge of present technology. The LHC magnet system, while still making use of the well-proven technology based on NbTi cables, cools the magnets to a temperature below 2 K, using superfluid helium, and operates at fields above 8 tesla. Space limitations in the tunnel



Figure 1.5: Cross section of a dipole magnet.

and the need to keep costs down have led to the adoption of the *twin-bore* design for almost all of the LHC superconducting magnets. The two-in-one design accommodates the windings for the two beam channels in a common cold mass and cryostat, with magnetic flux circulating in the opposite sense through the two channels.

The LHC ring accommodates 1232 identical main dipole magnets, which provide the curvature of the particle orbit. The core of the dipole is the cold mass, which contains all the components cooled by superfluid helium (Fig 1.5). The dipole cold mass provides two 56 mm apertures for the cold bore tubes (i.e. the tubes where the proton beams will circulate) and is operated at 1.9 K in superfluid helium. It has an overall length of about 16.5 m , a diameter of 570 mm (at room temperature), and a mass of about 27.5 t. The superconducting coils are formed by flat cables made of several strands of 1 mm thick wire composed of thousands of NbTi filaments.

In addition to the dipoles, about 400 main quadrupoles, also built with superconducting NbTi coils, provide strong focusing for the beams. Mounted together with the quadrupoles are thousands of smaller correction magnets, that compensate for the many higher order effects experienced by the beams. Of special importance are the three quadrupoles placed in the LSS on each side of an experiment, also known as *inner triplet*, which provide the final focusing at the collision point.

Approximately 96 tonnes of liquid helium is needed to keep the magnets at their

operating temperature of 1.9 K, making the LHC the largest cryogenic facility in the world at liquid helium temperature.

1.2.3 The origin of beam background

Each of the two LHC rings will handle a stored beam energy of more than 350 MJ, concentrated in a very small cross section, making the beams potentially destructive. At the same time the superconducting magnets in the LHC would quench at 7 TeV if small amounts of energy (on the level of 30 mJ/cm^3 , induced by a local transient loss of $4 \cdot 10^7$ protons) are deposited into the superconducting magnet coils. Any significant beam loss into the cold aperture must therefore be avoided. However, beam losses cannot be completely suppressed.

A so-called *primary beam halo* will continuously be filled by various beam dynamics processes. Important known mechanisms of particle diffusion include Touschek scattering, synchrotron radiation, intrabeam scattering, the nonlinear motion due to the long-range beam-beam collisions at top energy, persistent-current field errors during injection and at the start of acceleration, and Coulomb scattering off the residual gas [10]. The handling of the high intensity LHC beams and the associated high loss rates of protons requires a powerful collimation system.

The collimation system [11] is mainly located in two dedicated insertions: IR3 for momentum cleaning and IR7 for betatron cleaning. Most collimators consist of two movable jaws, with the beam passing in the center between them.

The collimation system is composed of several stages, with the Target Collimator Primary (TCP) closest to the beam, followed by secondary collimators (TCS) and absorbers. For optimal performance, the halo particles should first hit a TCP, and the TCS and absorbers should only catch the losses that are scattered out of other upstream collimators. Tertiary collimators (TCTs) made of tungsten are installed in the experimental IRs about 150 m upstream of the collision points, in order to provide local protection of the quadrupole triplets in the final focusing system and to decrease experimental background. In front of each experiment, there is one TCT in the horizontal plane (TCTH) and one in the vertical plane (TCTV).

In spite of the sophisticated design and high efficiency, a small number of protons hitting the TCPs are not absorbed by the downstream cleaning system. Some of them are intercepted by TCTs. Elastic beam-gas interactions far from the detectors can also kick protons directly onto the TCTs without passing through other collimators. Parts of the high-energy showers induced by these losses can propagate into the detectors and cause background, even though the experiments are surrounded by a heavy shielding. This is true in particular for high-energy muons, for which the shielding is less efficient.

Beam-gas interactions occur continuously around the ring during stored beam operation. The showers from very distant inelastic events do not reach the experimental



Figure 1.6: Comparison of simulated particle rates as a function of radius from local beam-gas, global beam-gas and beam halo, for all particles and muons, entering the interface plane in IR1 as simulated with FLUKA for the 2011 machine configuration. [12]

detectors but protons scattered with a small variation in energy and angle can traverse long parts of the ring before they are lost (global beam-gas). These particles, if lost close to the detector, contribute to the machine induced background, as well as the showers from close-by inelastic beam-gas events (local beam-gas).

The beam-gas interactions can occur downstream of the primary and secondary collimators, leaving only the TCT in a position to block them. The beam-gas interaction give a higher overall contribution to machine background with respect to beam halo, Fig. 1.6.

Chapter 2

The CMS Experiment

The Compact Muon Solenoid is one of the two general pourpose experiments that operates at the LHC. It is a detector designed to investigate the physics phenomenology coming from pp-collisions, but it operates also in heavy ions mode. The experiment is located 100 m underground along the LHC tunnel near the french village of Cessy. The CMS design is driven by the requirements of good reconstruction of charged particles, high electromagnetic energy resolution, precise missing transverse energy and jet measurements and good muon identification and p_T reconstruction. To achieve these goals, and maintain the detector compactness at the same time, a high solenoidal magnetic field of 3.8 T has been chosen to provide large bending power.

2.1 Overview of CMS

The CMS detector [2] consists in a cylindrical barrel, built of five slices (*wheels*), each comprising multiple layers, and two disk-like endcaps, also built in multiple stacked layers (Fig. 2.1). The overall detector length is 26.7 m, its diameter is around 15 m and it has a total weight of approximatively 14000 tons. Due to the challenging operational environment, high-granularity detectors with good time resolution must be used in order to reduce occupancy. Moreover the high radiation flux expected at LHC design luminosity (1-2 kGy/year) implies the use of radiation-hard components, especially in the central tracking system.

The compactness of the detector is ensured by using a high field NbTi superconducting solenoid, 16 m long and of 6 m aperture, able to generate a field up to 3.8 T in the inner tracking region. The 2 T residual field present inside the iron provides enough bending power in the muon system as well (Fig 2.2).

A silicon-based, inner tracking system, an homogeneous lead-tungstate electromagnetic calorimeter and a high hermeticity brass/scintillator sampling hadron calorimeter are accommodated in the solenoid bore. The magnetic field outside the solenoid is strong



Figure 2.1: Overview of the CMS detector.



Figure 2.2: A transverse cross section of the CMS detector, showing the subdetectors dedicated to each particle type.

enough to saturate the iron return yoke where a muon spectrometer, based on four layers of Drift Tubes detectors and Cathode Strip Chambers, respectively positioned in barrel and endcaps, is placed. Resistive Plate Chambers complement the other muon subdetectors ensuring redundancy and improving trigger abilities.

Coordinate System

The CMS coordinate system used to describe positions in the detector is a right-handed Cartesian frame, centred in the interaction point and with the z-axis along the beam line (this direction is referred to as *longitudinal*). The positive z end is towards the West, or the direction of the anticlockwise beam (Beam 2). At both ends of CMS, the beampipe is covered by a thick steel and concrete cone, the rotating shielding. The x-axis is chosen to be horizontal and pointing towards the centre of the LHC ring, and the y-axis is vertical and pointing upwards. The positive x is also known as near side. The x - y plane is called *transverse* plane.

A cylindrical coordinate system is also defined, with the ϕ angle lying in the transverse plane. $\phi = 0$ along the positive x-axis and $\phi = +\pi/2$ along the positive y-axis (upwards). An additional coordinate, known as pseudorapidity, is defined starting from the other polar angle, θ , as:

$$\eta = -\log\left(\tan\frac{\theta}{2}\right) \tag{2.1}$$

2.1.1 Inner detectors

The tracker [13] is the innermost subdetector of the CMS experiment and has a total length of 5.8 m and a diameter of 2.5 m. It is designed to efficiently detect and measure the trajectory of charged particles whose p_T is above 1 GeV/c, furthermore it has to precisely reconstruct their secondary vertices in order to provide jet-flavour tagging. Together with the electromagnetic calorimeter and muon spectrometer it has a crucial role in the reconstruction of electron and muon tracks respectively. Moreover, due to these characteristics, the tracking system is heavily used in the high level trigger.

At LHC design luminosity around 1000 charged particles coming from pp interactions (with an average pileup of 25) will be produced every 25 ns, leading to the need to develop a high granularity and radiation hard system. In order to keep track occupancy low enough to perform efficient and precise measurements, and considering that particle flux quickly decreases with radius, three detection regions have been defined. The CMS tracker is therefore subdivided in a fine granularity *pixel detector* system in its innermost parts, and in silicon strips modules of different pitch in its central and external part. This design allows to keep occupancy around 1% everywere during high luminosity ppcollisions and still ensure reasonable occupancy levels during PbPb ones (1% in the pixels and around 20% in the silicon microstrip detector).



Figure 2.3: Layout of the CMS Pixel Detector

The high granularity of the system, however, implies elevated power consumption and, together with the low temperature needed to allow good functioning and mitigate radiation damage (around -10°C), this leads to the need for an efficient cooling infrastructure. The total amount of material in the tracker however has to be kept as low as possible in order to reduce multiple-scattering and secondary interactions, therefore a compromise in the tracker design had to be found.

Pixel detector

The pixel system is the innermost tracking detector; it consists of finely segmented silicon pixels, whose cell size is 100 µmby 150 µm, placed on a high-resistivity *n*-type substrate. It is built to ensure precise 3D vertex reconstruction to allow efficient τ and b jets identification and it covers a pseudorapidity range up to $|\eta| < 2.5$. The small pixel size allows to keep single channel occupancy per bunch crossing around 10⁻⁴ even in the expected high flux scenario (10⁷ particles/s at 10 cm radius).

The layout of the pixels, shown in Fig. 2.3, consists of three barrel layers, located at a mean radius of 4.4, 7.3 and 10.2 cm, and two endcap disks, located in a radial region extending from 6 to 15 cm. The total number of pixel channels is 66 million.

During the LS1 upgrade, the old beampipe passing through the pixel detector has been replaced with a new one, with thin berillium walls that reduce particle scattering and improve vertex resolution. The new beampipe also has a reduced diameter, and will allow a future upgrade of the pixel detector to have the first layer closer to the IP.

The detector uses an hybrid construction with separate, bump bonded readout electronics. An analog readout is used in order to take advantage of the charge sharing between adjacent pixels, which allows to interpolate the hit position. The resulting hit resolution depends on the cluster size and position, and is in general between 10



Figure 2.4: Performance of the CMS pixel detector in early runs.

and 25 μ m(Fig. 2.4a). In the first two years of operation the detector has shown a hit reconstruction efficiency of about 99%, as shown in Fig 2.4b.

Microstrip detector

The pixel system is surrounded by the Silicon Strip Tracker (SST). With its more than 9.3 million detector channels, 15000 silicon modules and a total active detector area of about 200 square meters, it is the largest silicon tracker ever built.

The SST consists of four main subsystems, shown in Fig. 2.5: the four-layer Tracker Inner Barrel (TIB), the six-layer Tracker Outer Barrel (TOB) and, on each side of the barrel region, the three-disk Tracker Inner Disks (TID), and the nine disk Tracker End Caps (TEC). Each TID disk is made of three rings of modules, while TEC disks have seven rings.

The active detector elements, the silicon modules, consist of a carbon or graphite fibre frame, which supports the silicon sensor and the associated front-end readout electronics. The entire system is operated at a temperature below 10°C. The silicon sensors are made up of single-sided p+ strips on n-bulk sensors with two different thicknesses: 320 µmand 500 µmin the inner four and outer six layers of the barrel, respectively; 320 µmin the inner disks, and 320 µmand 500 µmin the inner four and outer six layers four and outer three rings of the end cap disks, respectively.

More than 20 different module geometries exist, with differences in terms of strip length, pitch and material resistivities, to ensure that the single strip occupancy is low even at full LHC luminosity. Both single-sided and double-sided modules (two singlesided modules mounted back to back with a stereo angle of 100 mrad) are used. The



Figure 2.5: Layout of the CMS Silicon Strip Tracker Detector



Figure 2.6: Silicon strip hit resolution as a function of strip pitch.



Figure 2.7: Longitudinal view of one quarter of the ECAL subsystem

final single hits resolution depends on the type of sensors and their position, and has been measured to be between 15 and 45 μ m, in accordance to the design expectation (Fig. 2.6).

2.1.2 Calorimeters

Electromagnetic Calorimeter

The Electromagnetic Calorimeter [14] (ECAL) is designed to accurately reconstruct electron and photon position and energy, as well as to perform, in conjunction with the Hadron Calorimeter, precise measurement of hadronic jets. The main driving criteria that lead to its design is the goal to reconstruct invariant mass with a resolution of 1% in order to investigate the $H \rightarrow \gamma \gamma$ decay channel.

To match this requirement, a lead tungstate (PbWO₄) homogeneous, finely segmented, hermetic calorimeter has been developed. PbWO₄ has been chosen because of its radiation-hardness, as well as for its small Moliere radius (22 mm) and short radiation length $X_0 = 8.9$ mm, which ensure good shower containment and compactness. These crystals are characterized by a very short scintillation-decay time, that allows to collect about 80% of the light in the read out electronics within a 25 ns time period. On the other hand, the low (4.5γ /MeV) emitted light output, forces to use photodetectors with high intrinsic gain that can operate in a high magnetic field. Therefore solutions based on Vacuum Photodiodes (VPT) and Avalanche Photodiodes (APD) have been adopted in the endcaps and barrel respectively. As the APD and crystal response are sensitive to temperature, thermal stability up to 0.1°C is required to preserve energy resolution.

The crystals have a length of 230 mm in the barrel and 220 mm in the endcaps,

corresponding respectively to 25.8 and 24.7 X_0 . They are trapezoidal in shape with a square front size of 22 mm in the barrel and 28.5 mm in the endcaps. The barrel crystal axes are inclined at an angle of 3° relative to the direction of the nominal IP, in both the azimuthal (ϕ) and η projections (Fig. 2.7). The two ECAL endcaps (EE) are located at a distance of 314 cm from the vertex and are constructed from four half-disk dees, each consisting of 3662 tapered crystals, arranged in a quasi-projective geometry. The crystals are focused at a point 1.3 m farther than the nominal IP along the beam line, with off-pointing angles between 2° and 8°. The crystals in each dee are organised into 138 standard 5 by 5 supercrystal units, and 18 special shaped supercrystals that are located at the inner and outer radii.

In order to allow π^0 identification and improve photon and electron position measurements, a preshower detector is installed in front of both endcaps. It consists of a two-layer sampling calorimeter, where lead radiators are alternated to silicon strip detectors, for a total material thickness of about 3 X_0 .

For energies below an approximate value of 500 GeV, where shower leakage starts to be significant, the ECAL energy resolution can be parameterized as follows:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + c^2 \tag{2.2}$$

where S refers to the stochastic term due to fluctuations in lateral shower containment, photostatistics and energy deposit in the preshower (where present), N is the noise term related to electronics, digitization and pile-up, and C is a constant contribution due to ECAL calibration, non uniformity of longitudinal light collection and leakage from the back of the crystals. Studies performed during test beams allowed to estimate these parameters to be S = 2.8%, N = 0.12% and C = 0.3%.

Hadronic Calorimeters

The Hadron Calorimeter (HCAL) [15] is used, together with the ECAL, to perform measurements on direction and energy of hadronic jets and to estimate the amount of missing transverse energy (missing E_T) of each event. Furthermore HCAL is also used to improve identification of electrons, photons and muons. The request to perform precise missing E_T measurement implies the development of a very hermetic system, whose design is constrained by compactness requests and by the high magnetic field.

In order to fulfill these requirements a sampling calorimeter system based on brass absorber layers alternated to active plastic scintillators has been built. The signal coming from active scintillators is read out with embedded wavelength-shifting fibers (WLS) and conveyed via clear fiber wave-guides to hybrid photodiodes. The choice of brass as absorber material has been driven from its short interaction length λ_I and its non-



Figure 2.8: Longitudinal view of one quarter of the HCAL subsystem.

magnetic nature.

A longitudinal view of the HCAL layout is shown in Fig. 2.8. The barrel calorimeter (HB) covers an η region up to 1.4 and its readout segmentation ($\Delta\phi \times \Delta\eta = 0.087 \times 0.087$) is fine enough to allow proper di-jet separation and mass resolution. The HB total depth increases as a function of η , raising from 5.15 λ_I at $\eta = 0$ to 10.15 λ_I at $\eta = 1.3$. In order to improve hadron shower containment within the barrel an outer calorimeter (HO) is placed outside the magnet coil. It consists of scintillator tiles and serves as a "tail catcher", increasing the effective thickness of HB over 10 λ_I everywhere, thus improving missing E_T resolution. As part of the LS1 upgrade projects, the original readout photodetectors of HO have been replaced with Silicon Photomultipliers [16].

An endcap calorimeter (HE) is also placed inside the magnet bore, covering the $1.4 < |\eta| < 3.2$ region. Its segmentation overlaps with the HB one and its average depth is about 10.5 λ_I . Outside the magnet a forward calorimeter (HF) covers the η region up to 5.2. Due to the harsh conditions at high η , radiation hard quartz fibers, embedded in a steel absorber, have been chosen as active medium.

2.1.3 Muon System

Muons are characterized by a great penetrating power, so they can easily go through the calorimeters and are easy to detect being charged particles. Many of the interesting physical processes in the LHC program are characterized by final states which will involve the presence of high p_T muons. Hence a robust and redundant muon spectrometer is needed to provide precise muon identification, high resolution p_T measurements and



Figure 2.9: Longitudinal view of one quarter of the Muon Detctors (DT, CSC, RPC).

effective trigger capabilities.

The muon system [17] is the outermost group of subdetectors of the CMS experiment, it covers an η region up to 2.4 and is located in the iron yoke for the return of the magnetic field, as shown in Fig. 2.9. It consists of three different types of gaseous detectors, chosen in function of the large surface to be covered, and whose design is driven by the differences in the radiation environment and magnetic field at different values of η .

Drift Tubes Chambers (DTs) are used in the barrel (up to $|\eta| < 1.2$) where low track occupancy and residual magnetic field are expected. The endcaps (0.8 < $|\eta| < 2.4$) are instead equipped with Cathode Strip Chambers (CSCs), chosen to cope with the high particle flux and non uniformity of the magnetic field at large η .

In order to ensure redundancy and improve trigger capabilities, Resistive Plate Chambers (RPCs) complement DT and CSC based detectors, both in barrel and endcaps, covering an η region up to 2.1. RPCs allow only coarse spatial resolution measurements, however they are characterized by fast response and their excellent time resolution provides unambiguous BX identification to the muon trigger. For muons up to a p_T of about 200 GeV/c the system resolution is limited by the multiple scattering of the particle before reaching the first spectrometer station, at higher p_T the precision of the chamber measurements dominates due to the larger bending radius.

The resolution is directly proportional to the square root of the amount of material

in the muon system in units of X_0 (radiation length) and inversely proportional to the magnetic field. For high p_T (1 TeV/c or more) the momentum resolution is proportional to the spatial resolution of the muon chambers. Up to the last muon station the thickness of the absorber is 16 interaction lengths. Good muon identification is achieved by absorption of charged particles before the muon system in ECAL and HCAL, and in the muon system by the iron yoke. Moreover, the muon system is able to measure the charge of the muons up to about 1 TeV. The muon system can withstand the harsh radiation environment produced by high rate interactions.

An important issue for the muon system is its alignment, both internally and with respect to the inner tracker. The misalignment originates from imperfect assembly, temperature instabilities or deformations related to the magnetic field. It is important to monitor the alignment, as the measurement of muons is based on the combination of data from muon chambers and from the tracker.

Drift Tube Chambers

The Drift Tubes (DT) are used for the barrel of the CMS muon system because of the large dimensions of the surface to be covered. The CMS regions inside the return yoke of the magnet have the lowest particle rate and radiation doses. The DT system is segmented in 5 wheels along the z direction, each about 2.5 m wide and divided into 12 azimuthal sectors, covering 30° each. Drift tubes are arranged in 4 concentric layers (called stations) within each wheel, at different distances from the IP, and interleaved with the iron of the yoke. Each station consists of 12 chambers, with the exception of the outermost station MB4, whose top and bottom sectors are equipped by two chambers each (instead of only one), yielding a total of 14 chambers in that station. The overall CMS detector is thus equipped with a total of 250 DT chambers. The dimensions of each chamber are station-dependent. Each chamber is azimutally staggered with respect to the preceeding inner one, in order to maximize the geometrical acceptance.

The basic detector element of the DT muon system is a drift tube cell, whose section is shown in Fig. 2.10a. The dimensions of a cell are 42 mm by 13 mm and it has a stainless steel anode wire with diameter 50 µmand length varying from 2 to 4 m. A layer of cells is obtained by two parallel aluminum planes within which a series of I-shaped aluminum beams (1.2 mm thick and 9.6 mm high) define the boundaries among adjacent cells. Aluminum strips, deposited on either faces of each I-beam and electrically isolated from the I-beam body using Mylar tape, serve as cathodes. Anode wires and cathodes are put at positive and negative voltage respectively, and provide the electric field within the cell volume.

The distance of the traversing track to the wire is measured by the drift time of ionization electrons; for this purpose, two additional positively-biased strips are mounted on the aluminum planes (with an insulator in between) on both inner surfaces in the



(a) Cross section of a Drift Cell

superlayers

Figure 2.10: Details of DT chamber construction

center of the cell itself, just in correspondence of the anode wire, in order to provide additional field shaping to improve the space-to-distance linearity over the cell (which is crucial for triggering purposes). Typical voltages are +3600 V, +1800 V and -1800 V for wires, strips and cathodes respectively. The tubes are filled with a 80%-20% gas mixture of Ar-CO₂, which provides good quenching properties.

A cross-sectional view of a muon chamber is shown in Fig. 2.10b. Each muon station is instrumented in the transverse plane and in the longitudinal $\theta - z$ plane. The drift cells are assembled in layers, the number of cells depending on the chamber dimensions. Four layers are assembled together to form a quadruplet called superlayer (SL), with neighbouring planes staggered by half a tube, allowing to resolve the left-right ambiguity of a single layer. Each DT station is composed of 3 superlayers, two of which are devoted to the position measurement in the bending plane $r - \phi$ (the wires are parallel to the beam line), and one to the measurement of the z-coordinate in the longitudinal plane $\theta - z$ (the wires are disposed orthogonally to the z-direction). The only exception is the outermost station MB4, which lacks the SL in the θ view. In addition, a 128 mm thick honeycomb plate, acting as a rigid but light spacer, is inserted between the inner ϕ view SL and the outer one. It increases the lever-arm in the bending plane, improving the angular resolution.

Cathode Strip Chambers

In the two endcap regions of CMS, where the muon rates and background levels are high and the magnetic field is large and non-uniform, the muon system uses Cathode Strip Chambers. CSC chambers are multi-wire proportional chambers with fast response time, fine segmentation, and radiation resistance, so that they can operate at high occupancy



Figure 2.11: A Cathode Strip Chamber module (*left*) and internal details (*right*).

levels and in the presence of a large inhomogeneous magnetic field. CSC chambers identify muons between $|\eta|$ values of 0.9 and 2.4, and are arranged in four stations placed between the iron disks of the yoke. The innermost station consists of three concentric rings, the first (ME1/1) being closer to the IP than the other two. The other stations are composed by two disks only.

The rings are formed by 18 or 36 trapezoidal chambers, which, with the exception of the outermost ring of ME1, are staggered with a small overlap in ϕ . Chambers are composed of six layers, each consisting of an array of anode wires between two cathode planes, as sketched in Fig. 2.11. The gap is 9.5 mm thick and is filled with a 30%-50%-20% mixture of Ar-CO₂-CF₄. One of the two cathode planes is segmented into strips orthogonal to the wires. The avalanche produced in the gap by a crossing charged particle induces a charge in several adjacent strips, an interpolation of the signals gives a precise spatial measurement. Strips are radial and measure the ϕ coordinate. The orthogonal coordinate (r) is measured by the wires which, to reduce the number of channels, are read out in groups of 5 to 16. The resolution is of the order of 0.5 cm, to be compared with about 150 µmof the strip measurement.

Resistive Plate Chambers

For improving the ability of muon system trigger and measuring the correct beam crossing time when the LHC reaches full luminosity, a complementary, dedicated trigger system consisting of resistive plate chambers (RPC) was added in both the barrel and



Figure 2.12: Cross section of a double-layer Resistive Plate Chamber.

endcap regions. The RPCs provide a fast, independent, and highly-segmented trigger with a sharp p_T threshold over a large portion of the rapidity range ($|\eta| < 1.6$) of the muon system.

The RPCs are double-gap chambers (as shown in Fig. 2.12), operated in avalanche mode to ensure good operation at high rates. They produce a fast response, with good time resolution but coarser position resolution than the DTs or CSCs. They also help to resolve ambiguities while reconstructing tracks from multiple hits in a chamber. A total of 6 layers of RPCs are embedded in the barrel muon system, two in each of the first two stations, and one in each of the last two stations. The redundancy in the first 2 stations allows the trigger algorithm to work even for low p_T tracks that may stop before reaching the outer 2 stations. In the endcap region, there is a plane of RPCs in each of the first 3 stations in order for the trigger to use the coincidences between stations to reduce background, to improve the time resolution for bunch crossing identification, and to achieve a good p_T resolution.

2.1.4 Trigger

When running at its design luminosity, the LHC will deliver bunch crossings every 25 ns, each causing multiple particle interactions. Most of these events are "soft", i.e. no high p_T particles are produced during the collision. Storing the data of all of these events is neither practical nor necessary. In order to select only interesting events and thus to reduce the event rate which has to be processed and stored, a trigger system has been developed for CMS. It consists of two logic stages:

• The Level 1 trigger (L1 [18]) is a system of hardware based online triggers, operating in hardware. They use simplified algorithms and partial information from calorimeters and muon detectors to produce a triggering decision (L1 accept, L1A) within 3 μ sof each bunch crossing, the maximum time for which the whole event data can be stored. The L1 triggers lead to a reduction of the event rate from 40 MHz to 100 kHz, which is low enough to be readout and transferred to a computer farm.

• The High Lvel Trigger (HLT [19]) is a software based set of algorithms that is run on a large computing farm. It uses all of the available detector information, including that of the inner tracking detectors, to reach a triggering decision. It achieves a reduction of the event rate down to a few hundred Hz, resulting in a manageable data rate.

Both trigger stages employ different algorithms to select events from different categories, for example events with high energy muons or significant amounts of missing (undetected) energy, which are signatures of different types of particle interactions. These algorithms are undergoing continuous upgrades to maintain their performance with increasing luminosity and pileup.

2.2 Beam Monitoring in CMS

In the first run of LHC, CMS used a set of small detectors to monitor the conditions of the beam. The silicon tracking detectors are very sensitive to even small amount of beam losses, and a safety system prevents them from turning on unless the beam monitoring detectors are measuring good beam conditions.

These monitoring detectors, such as the Beam Condition Monitor (BCM) [20], and the Beam Scintillation Counters (BSC) [21], were not intended for operation at full LHC luminosity, and had started to show aging and saturation effects due to the increasing particle rates. An upgrade of the BSC had been installed in the technical stop between 2011 and 2012, but this was only a stopgap solution.

It was therefore decided to consolidate and improve the entire beam monitoring infrastructure during the LS1 upgrades [22]. The Beam Radiation, Instrumentation and Luminosity (BRIL) group was formally established with the goals of developing, installing and maintaining detectors to perform monitoring of the beam conditions. The BRIL group is also responsible for the calculation of "online" luminosity and the simulation and measurement of background radiation in the CMS cavern.

In the second run of LHC, the machine will eventually operate at its designed 25 ns bunch spacing, aiming at a luminosity of $2 \cdot 10^{34}$ cm⁻² s⁻¹, twice as much as was foreseen in the initial design. The new fast monitoring detectors will be able to measure both the beam background and the luminosity on a bunch-by-bunch basis.

The luminosity is a key parameter of a collider experiment and its precise measurement is necessary to determine cross sections. The new online luminometers in



Figure 2.13: An overview of the upgraded CMS beam instrumentation sub-systems and their location in the CMS detector.

BRIL include the Pixel Luminosity Telescope (PLT), the Fast Beam Conditions Monitor (BCM1F), and the luminosity based on a dedicated readout of the Hadron Forward (HF) Calorimeter. These online luminometers are independent and together with the offline luminosity measurement based on pixel cluster counting, allow for a cross check and reduction of the systematic errors.

The higher beam intensity in the second LHC run implies tighter settings of the collimator systems and an increased susceptibility to electron cloud effects contributing to a higher potential rate of MIB for CMS. The upgraded BCM1F is designed to have sensitivity at low radius where it will be possible to detect beam gas interactions happening in the vicinity of CMS. The Beam Halo Monitor (BHM), subject of this thesis, will be sensitive towards beam gas interactions happening further away as well as beam halo interactions with the upstream collimators.

2.2.1 Beam condition monitors

BCM1F

The BCM1F detector has been successfully operating in CMS since the beginning of data taking in 2008 [20]. It was originally based on eight single crystalline Chemical Vapor Deposition (scCVD) diamond detectors mounted at 1.8 m from the IP at a radius



Figure 2.14: Drawing of the PLT/BCM support carriage. A quarter of the system is shown.

of 50 mm.

The need for an upgrade arised mainly from the reduction in bunch spacing, as the old electronics was based on a preamplifier Application Specific Integrated Circuit (ASIC) with a peaking time of 25 ns, that would not be able to separate pulses from two consecutive BXs.

The upgrade of the detector comprises two-pad sensors, dedicated frontend ASICs and the design of dead-time free backend electronics, with flexible Field Programmable Gate Array (FPGA) for signal processing and sub-bunch histogramming capabilities. To improve the time resolution of the detector, a new dedicated front-end ASIC has been developed at CERN in collaboration with the University of Science and Technology AGH Krakow. The ASIC is based on IBM CMOS-8RF 130 nm technology and includes a fast trans-impedance preamplifier with an active feedback, a shaper stage and a fully differential output buffer.

The upgraded BCM1F detector acceptance is increased by a factor of three from an active area of 8 5.0×5.0 mm² sensors to 24 5.0×5.0 mm² sensors, to allow for additional statistical sensitivity to monitor the Machine Induced Background. Each sensor is metalised into two pads to decrease the count rate per channel, and maintain linearity with increased pileup. The width of the gap between the two pads is 25 µm.

Six BCM1F sensors are mounted on a specially designed PCB composed of a rigid C-shaped section that is mounted around the beampipe and a flexible part with a rigid end that acts as a cable for bias, signal, power and control lines. This PCB is mounted on a carbon fiber support carriage that allows this detector to be inserted along the beamline inside the tracker volume. The same carriage also supports the PLT and BCM1L detectors (Fig. 2.14).

BCM1L and BCM2

The Beam Condition Monitor "Leakage" (BCM1L [23]) and Beam Condition Monitor 2 (BCM2 [24]) are a part of the beam loss monitoring system of the LHC. These systems were designed to protect the silicon tracking detector of CMS from catastrophic beam loss events. The current generated in silicon detectors in one of these events could be so intense that the electronics would get damaged.

These detectors operate in a simple and robust way, by measuring the average current of CVD diamond sensors over a short period of time. If the current exceeds a safety threshold, the electronics automatically initiates a beam dump of the LHC to protect the CMS tracker. Both these detectors have undergone upgrades in LS1, with a replacemnt of many of the diamond sensors.

The BCM1L detector is positioned, together with BCM1F, close to the beampipe at $z = \pm 1.8$ m from the IP, while BCM2 is located inside the rotating shielding, behind the hadron forward calorimeter.

2.2.2 Beam halo monitors

A novel Beam Halo Monitoring system has been designed to provide an online bunchby-bunch measurement of MIB arriving in CMS at a radius of 1.8 m from the beam axis, separately for the two beams. At this radius, particles of the beam halo (mostly muons) can cause large radiative energy deposits in calorimeters, inducing errors for example in the reconstruction of missing energy. They can also interfere with the muon detectors in the endcap region, producing false triggers that decrease the effectiveness of the system.

The Beam Halo Monitor is described in detail in the following chapters.

2.2.3 Online luminosity

PLT

The Silicon Pixel Luminosity Telescope (PLT) is a dedicated luminometer monitor for CMS based on silicon pixel sensors. It uses a sensor and a readout electronics similar to that used by the main Pixel Tracker of CMS.

The PLT is comprised of two arrays of eight small-angle telescopes situated one on each end of CMS, 1.75 m from the CMS interaction point (IP). Each telescope consists of three planes of pixel sensors with a total telescope length of 7.5 cm, located 5 cm radially from the beam line. The PLT is designed to provide a measurement of the bunch-bybunch luminosity at the CMS collision point on a time scale of a few seconds and a high-precision measurement of the integrated luminosity. The luminosity information is provided by a bunch-by-bunch count of the number of telescope columns with a threefold coincidence.

HF Luminosity

During the fist run of LHC, the HF tower occupancy method was the primary method used to perform high statistics, real-time bunch-by-bunch luminosity measurements for CMS. It is based on zero counting, in which the average fraction of empty towers is used to infer the mean number of interactions per bunch crossing.

During LS1, the HF readout Photomultipliers were replaced with a superior model, offering more stable gain and less spurious signals, thereby improving the luminosity measurement. The back-end electronics of HF was also replaced, and hardware developed for this upgrade has been adapted for use in the Beam Halo Monitor, as described in Chapter 4.
Chapter 3

The Beam Halo Monitor detector

In this chapter a detailed description of the BHM detector will be presented, starting from the operating principle and continuing with all the details about the components, the design of the mechanics of detector modules and final assembly, including aspects of the integration with CMS.

3.1 Operating principle

The BHM is designed to be able to detect and correctly identify MIB particles in the context of an intense particle flux, dominated by products of high energy pp collisions. Detection and identification are based on techniques that exploit differences between MIB and other particles, combined into a single instrument.

First of all, there is an obvious difference in the general trajectory of beam background, which travels towards CMS parallel to each beam, and collision products, that, to first order, propagate outwards from the Interaction Point. Sensitivity to direction of propagation is therefore a crucial property for the detection technique that has to be used.

Second, it is known (see Section 1.2.3) that the beam background is composed mainly of charged particles, with a predominance of muons. Insensitivity to neutral particles is therefore a desirable property, as it would allow to disregard neutrons and γ -rays that are abundant in the CMS cavern.

A third, less obvious but nevertheless important characteristic that differentiates the beam background from other particles is its arrival time with reference to the machine timing. This time strongly depends on the positioning of the detector along the z-axis of CMS.

While many detection techniques can be used in order to achieve the features described above, the use of Cherenkov radiiation is the most immediate way of satisfying these requirements.



Figure 3.1: Emission of Cherenkov radiation (blue arrows) caused by the passage of a charged particle (red arrow).

3.1.1 Cherenkov Radiation

While c, the speed of light in vacuum, is constant, the speed of light in any other medium is given by v = c/n where n is the refractive index of the medium. When n is greater than 1, it is possible for a highly energetic charged particle to be travelling through a medium at a speed that is greater than the speed of light in the same medium. When this happens in a dielectric, part of the energy lost by the particle in its interactions with the surrounding atoms is emitted in the form of electromagnetic radiation in the visible and near UV part of the spectrum.

This phenomenon was first observed by Pavel Cherenkov in 1934 as blue light coming from a bottle of water undergoing bombardment by particles from a radioactive source [25]. This discovery of the process earned him the Nobel Prize in Physics in 1958, together with Ilya Frank and Igor Tamm that developed the theoretical explanation.

Unlike scintillation light, Cherenkov radiation is emitted with a preferential direction with respect to the direction of the originating particle. In the framework of classical electrodynamics, the direction can be explained by assuming that radiation is emitted isotropically by the charged particle as it passes through the dielectric polarizing it. In a given time t, the particle will have traveled a distance βct , while the electromagnetic radiation will only have traveled ct/n.

If these distances are taken as the sides of a triangle, as shown in Fig. 3.1, it follows that the angle θ between the particle trajectory and the plane where radiation interferes

constructively is given by

$$\cos\theta = \frac{c}{v_p n} = \frac{1}{\beta n}.$$
(3.1)

An explanation according to quantum physics is presented in [26]; the formula derived there for θ reduces to 3.1 in the classical limit.

According to the Frank-Tamm theory, the spectrum of Cherenkov radiation by a particle is given by the formula:

$$\frac{dN}{dx} = \frac{2\pi\alpha}{\lambda^2} \cdot \left(1 - \frac{1}{\beta^2 n^2}\right) \tag{3.2}$$

where α is the fine structure constant.

The total emitted energy per unit length dx, integrated over all the frequency (ω) spectrum is:

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{v > \frac{c}{n(\omega)}} \mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega$$
(3.3)

where $\mu(\omega)$ and $n(\omega)$ are the frequency-dependent permeability and index of refraction of the medium and q is the electric charge of the particle.

The emission begins to be significant in the visible part of the spectrum and becomes more intense at shorter wavelengths, peaking in the UV. There is however a cutoff at higher frequency in the X-ray region, when n becomes less than unity.

3.1.2 Directionality

Cherenkov radiation is widely used in experimental High Energy Physics, and many types of detectors are designed around it. The BHM *detector unit* is perhaps the simplest detector configuration, which directly couples a material where Cherenkov radiation is emitted with a single photodetector, as shown in Fig. 3.2.

In this configuration, light emitted in a cone around the particle axis reaches either directly or after a few internal reflections the sensitive surface of the photodetector. The orientation of the radiating material and photodetector defines the axis along which the detector is more sensitive to particles. Particles travelling from the material (*front*) side towards the photodetector (*back*) side will produce a large signal; while particles travelling in the opposite or orthogonal directions will produce a smaller or even zero signal (provided total internal reflection is blocked on the front face).

The shape and size of the detector unit, as well as the number and positioning of units, have been optimized thanks to simulations and testing with particle beams. Simulations of the fluxes of MIB and *pp*-collision products at the detector location have been carried out [27] to estimate the expected ratio between the two. While the detector location has been chosen for its relatively high MIB rate of $\mathcal{O}(1)$ Hz/cm², the flux of



Figure 3.2: Simplified view of the Cherenkov light propagation. In the top view, light emitted by a particle travelling *forward* reaches either directly, or through total internal reflection, the photocathode. In the bottom view, light emitted by a particle travelling *backward* is absorbed at the front face by a layer of matte black paint.

pp-collision products is higher by almost three orders of magnitude, as can be seen in Fig 3.3.

It is therefore necessary for the BHM detector unit to suppress the pp-collision signal by a factor of 10^3 in order to have a meaningful measurement of the MIB flux. Additional simulations provide information about the type, direction and energy of the particles reaching the detector location, and the results are summarized in Fig 3.4.

The difference in signal amplitudes for muons travelling forward and backward in the detector unit allows to discriminate between MIB and pp (see next section), but it is not sufficient to suppress other sources of background such as low energy electrons and positrons that are also present in the CMS cavern (also shown in Fig. 3.4). There are however other ways of suppressing these backgrounds, such as the use of timing information and passive shielding, as described below.

3.1.3 Timing

The MIB can be assumed to be travelling almost parallel to the beam bunch that originated it, at the same speed. The same applies to the pp-collision products; even though the propagation angle is somewhat larger, the difference in the arrival time at a given z-coordinate is still small.

Several points along the beam axis, shown in Fig 3.5, are characterized by having the highest possible separation in time (12.5 ns) between the bunches of the two beams, and anything parallel to them. The z-coordinate that defines these points (Golden Locations)



Figure 3.3: Charged particles fluxes arriving at the detector location from *pp*-collisions (black) and from MIB (red) as a function of the radial distance from the beam axis [27], with nominal beam conditions. The detector is at a radius of approximately 190 cm.

is:

$$GL_{k+1} = \left(\frac{1}{4} + \frac{1}{2}k\right) \cdot (BX \text{ spacing}) \approx 1.875m + 3.75m \cdot k$$
 (3.4)

The emission of Cherenkov radiation is prompt, i.e. there is no decay time as in the scintillation process. Combining this fact with the fast signal rise time of the Photomultiplier Tube, it is possible to discriminate particles that are *in time* with the incoming beam from other sources of background, which are either in time with the opposite beam, as is the case for some collision products, or have a more uniform time distribution.

3.2 Detector design

The Beam Halo Monitor consists of forty independent detector units, positioned around the CMS rotating shielding, twenty per each end. The combined geometrical acceptance of the detector units is considered sufficient to accumulate adequate statistics for the purpose of beam monitoring.

Ten units per side are distributed uniformly in ϕ from the top of the rotating shielding to about 30° below the beamline as shown in Fig. 3.6. There are no detector units below this position as the MIB flux becomes lower due to absorb from the tunnel floor. This effect is shown in the simulation in Fig. 3.7.

The z coordinate is determined by the choice of using a Golden Location (Fig. 3.5). Golden Locations are equivalent in terms of time separation, but they differ in other



Figure 3.4: Simulations of several particle fluxes at the BHM location as a function of energy and angle. 0° is the direction of the incoming beam, 175-180° is the direction of the IP. Muons from MIB (top) are our signal, while muons (middle) and e^+/e^- (bottom) originating from pp-collisions are the background for BHM



Figure 3.5: Golden Locations in CMS



Figure 3.6: CAD rendering of the BHM support structure on one side of the rotating shielding, corresponding to a quarter of the detector.



Figure 3.7: Normalized distribution of beam background in the x - y plane around the rotating shielding [27].

practical parameters. GL_6 was chosen for BHM as it is characterized by a relatively high MIB flux, it has sufficient free space to mount the detector at an interesting radius, and it is already outside of CMS, which will shield it from most of the collision products. It also has a relatively low residual magnetic field (from the CMS solenoid) and a rather low total radiation dose.

The ten units of each quarter are firmly attached to an aluminum support structure. This structure is composed of two main arcs manufactured with water-jet cutting, with additional spacers and stiffeners; it is attached to the rotating shielding with welded bolts. The structure has sufficient strength to prevent the magnetic force created by the CMS solenoid from moving the detector units.

3.3 Detector unit

The active element of each detector unit is a cylindrical piece of fused silica, 100 mm long and 52 mm in diameter, coupled to a Photomultiplier Tube. The side facing the photomultiplier is polished for optimal transmission, while the opposite side is only ground and then covered with a thick layer of matte black paint to absorb light emitted by particles travelling *backward*. The material is SQ0 synthetic fused silica with high OH content, manufactured by J-Plasma, it has very good transmission in the UV, down to less than 200 nm, good resistance to radiation damage and is free of defects and



Figure 3.8: A picture of the fused silica cylinder and PMT assembled together with the silicone disk.



Figure 3.9: Simulated flux (all particles combined) in the CMS cavern [30].

impurities [28].

The fused silica piece is coupled with the photomultiplier thanks to a soft silicone disk (1 mm thick DC93-500 [29]) that ensures a matched refraction index with the quartz window of the photomultiplier, avoiding loss of light. The optical coupling is treated in vacuum after being assembled, in order to remove air bubbles. The finished optical assembly is shown in Fig. 3.8.

The expected dose at the detector location has been estimated, from the CMS radiation simulation [30], to be less than 50 krad for the planned operating period (Fig. 3.9). Samples of the fused silica and silicone disk were irradiated with 100 krad of γ rays from a ⁶⁰Co source, and their light transmission was measured to be essentially unchanged (Fig 3.10).

The Photomultiplier Tube (PMT) used in BHM is the R2059 manufactured by Hamamatsu [31]. This PMT features a large circular bialkali photocathode of 47 mm diameter,



Figure 3.10: Optical transmission of samples of natural quartz, fused silica and optical coupling material, before (dashed) and after (continuous) 100 krad irradiation with a 60 Co source.

which is sensitive to UV down to 160 nm thanks to its fused silica window (see Fig. 3.11). It is a conventional, linear focused PMT with 12 dynodes, and has a very high gain, up to $2 \cdot 10^7$, and a fast signal rise time of 1.3 ns.

The PMT is coupled to a standard resistive divider base, supplied by Hamamatsu itself. This base allows for DC-coupled signal connection through BNC and requires negative high voltage supplied through an SHV connector. This device was modified by Hamamatsu to use radiation resistant insulating material (PE) instead of the Teflon that was used in the original product.

The core elements of the detector units are arranged in a simple and straightforward configuration, but complications arise due to the need of shielding the sensitive photomultiplier from the residual magnetic field while allowing the passage of signal and high voltage (HV) cables and optical fibers for the calibration system (see Chapter 5).

3.3.1 Shielding

The detector units are exposed, in their installation position, to the residual field of the superconductiong solenoid at the core of CMS. The field value at the BHM installation position has been measured to be between 15 and 19 mT, forming an angle between 15° and 20° from the z axis. A complex shielding configuration is necessary due to the orientation of the magnetic field, whose direction forms a small angle with the longitudinal axis of the detector unit.¹

Extensive testing has been carried out on several prototypes before the design of a

¹A transverse field would be easier to shield.



Figure 3.11: Characteristics of the Hamamatsu R2059 PMT [31].

Field	Proto 1	Proto 2	Proto 3
0 T	1.00	1.00	1.00
1 T	0.98	1.00	0.98
2 T	0.99	0.99	1.00
3 T	0.99	0.96	0.95
3.8 T	0.81	0.94	0.85

Table 3.1: Relative gain at different values of the CMS solenoid field. An uncertainty of approximately 0.03 can be inferred by the fluctuations in repeated measurements. Prototype 2 has the best performance at full field.

simple yet effective shielding configuration was finalized. Three prototypes with different shielding configurations were tested in the real CMS solenoid field in november 2014, very close to the final installation position (see Fig. 3.12).

The gain loss of the three prototypes was measured by injecting a constant amplitude light pulse using some of the components of the calibration system that had already been installed (see Chapter 5), and the results are summarized in Table 3.1.

In all the prototypes, the magnetic shielding is based on three layers of different materials. The three prototypes differed in some details, such as the lengths of the shielding cylinders and the types of endcap, but were fairly similar and all of them offered adequate shielding. Despite being slightly more complex than number 1, prototype number 2 was chosen due to its higher performance; its drawing is shown in full detail in Fig 3.13.

The innermost layer is a cylinder with one end closed by a welded cap and the other



Figure 3.12: The three prototypes installed on the z+ side of CMS in November 2014, during a test of the solenoid up to full field.

open, made of Permalloy [32] and supplied directly by Hamamatsu. It is 0.8 mm thick, with an inner diameter of 60 mm and a length of 280 mm; the front face has a 3 mm hole that allows light from the calibration system optical fiber to reach the inside.

This inner cylinder is also the mechanical piece supporting the PMT and fused silica: the PMT is firmly inserted into its socked, which is secured to the permalloy cylinder with three screws. The fused silica is pushed against the PMT by an elastic O-ring acting between the front face of the permalloy and a polyethilene spacer, ensuring that the optical elements do not separate.

The intermediate shielding layer is a similar, slightly larger, cylinder which completely covers the inner shielding. It is made of mu-metal alloy [33], 1.5 mm thick with an inner diameter of 67 mm; it is manufactured by the CERN workshop. A second polyethilene spacer is interposed between the two cylinders at the front face, isolating them electrically and magnetically. This spacer also provides alignment for the threaded connector for the calibration optical fiber. Further isolation is included along the cylinder walls by means of a thick tape.

The final layer of shielding is a 10 mm thick steel tube, 400 mm long with 80 mm inner and 100 mm outer diameter. This tube is closed at both ends with 8 mm thick endcaps, machined in soft iron with very smooth surface to ensure good contact with the tube. The front endcap has a single hole in the centre for the calibration fiber, while the back endacp has two holes, one for the signal connector and one for the HV connector. Two more polyethilene spacers separate the outer shield from the internal parts; these spacers are held in place along the longitudinal axis by means of headless screws.



Figure 3.13: Longitudinal cross section of the BHM detector unit, showing all the internal components, shielding layers and spacers.

The three layers of shielding ensure a progressive reduction of the magnetic field from the outside value to a couple of millitesla inside the outer shield, down to less than 0.1 mT around the photocathode, which is the most sensitive part of the PMT. The layered construction ensures that each layer can operate in an optimal field intensity: mu-metal and permalloy, while having very high permeability and being able to reduce the field to a very low level, share the disadvantage of a low saturation point, unlike the steel which can sustain much higher fields without saturating.

The thick steel shielding also serves as a low energy particle absorber, and it is able to stop most of the electrons and γ s that would mimic a MIB signal in the detector, at least up to 10 MeV for the electrons. Additional spacing is available inside the front endcap to insert more shielding material, should the current thickness prove insufficient. A third, side effect of the shielding material is that of reducing the total absorbed dose on the detector components, possibly extending their useful life beyond the expected limits.

3.3.2 Cabling and services

Given the difficulty in developing radiation tolerant electronics that can successfully operate in the CMS cavern (UXC), it was decided to have the readout for BHM in the adjacent service cavern (USC). This is possible given the large amplitude of the PMT signals, which do not require active amplification at the source and can be transmitted by coaxial cables over significant distances with acceptable attenuation.

A high quality coaxial cable is however required to cover the distance between the PMTs and the readout electronics, which is around 100 m taking into account the path around obstacles and into existing passages. The cable chosen for BHM is CKC50 [34], a rather large high performance coaxial with double braid, using Type N [35] connectors with a maximum bandwidth of more than 6 GHz. The attenuation of a signal pulse peak amplitude over the cable has been measured to be about 20%, which is not an issue as the PMT signal is very large (a few volts on a 50 Ω load) at the 2500 V bias.

Every R2059 PMT has to be biased with an adjustable high voltage. The normal operating range of this PMT is between 1500 V and 2700 V, and BHM will bias them at around 1800 V, to keep their gain and their output signal in a range that is compatible with the readout electronics.

The high voltage is provided by a CAEN power supply, based on the SY1527 mainframe [36]. Two A1535SN [37] modules, with 24 individually adjustable channels each, provide up to -3.5 kV high voltage, with common floating return. The power supply output features individual SHV connectors, but in order to save on cabling, groups of ten channels have been merged into a single multicore cable using a patch panel. At another patch panel, located on the blockhouse close to the detector, the multicore cable splits back into individual SHV cables that are connected to each detector unit.



Figure 3.14: The grounding scheme of BHM, for signal and HV paths.

Both signal and HV cables, as well as the calibration optical fibers, are routed from the blockhouse around the hinges of the rotating shielding on a flexible support, allowing the shielding structure to move without having to disconnect every cable.

The grounding scheme of the detector, which is important for signal quality reasons, is presented in Fig. 3.14. Inside the detector unit, the PMT, socket and inner shield are electrically connected. The socket in particular shorts the HV and signal shields together. They are however fully isolated from the outer shielding layer, which is in electrical contact with the support, the rotating shielding and ultimately the UXC ground. The signal cable shield is connected to ground in USC, while the HV shield, which acts as return, is floating with respect to USC ground thanks to isolation in the power supply.

3.4 Detector prototype testing

In an effort to to find the optimal configuration of the detector, a number of tests have been carried out with particle beams and cosmic rays. Early measurements with cosmic rays failed to produce enough statistics due to limitations in the trigger acceptance, and the only cosmic measurements with sufficient statistics have been carried out for validation purposes after the final design had been completed (see Chapter 6).



(a) Signal amplitude for forward and backward particles

(b) Full Width at Half Maximum of the forward signal

Figure 3.15: Results from the 2012 Test Beams at CERN

3.4.1 Early results

A first set of test beam measurements was carried out at the CERN PS T9 beam line in 2012. These tests confirmed the viability of the detector concept, by demonstrating a fast (Fig. 3.15b) and directional (Fig. 3.15a) response [27].

An important lesson learned in this test concerned relative sizes of the Cherenkov radiator and the PMT photocathode. Originally, they were made of the same size, but it was found that Cherenkov light could be produced in the PMT window, which extends a few millimeters outside the photocathode. Forward particles crossing the border of the PMT window outside of the main radiator would produce a small signal, and would be misidentified as backward particles. It was therefore decided to increase the diameter of the Cherenkov radiator by a few mm to the size of the PMT window, rather than just the photocathode.

3.4.2 Test Beam at DESY

In early 2014 a set of prototypes of the active components of the detector was brought to DESY in Hamburg to find the optimal configuration. By that time, the PMT model and the dimensions of the Cherenkov radiator had alrady been established, and have remained the same of the final detector design. The tests were aimed at confirming that this final configuration was capable of suppressing backward particles by a factor of at least 10^3 with a simple threshold on signal amplitude. Details such as the thickness of the optical coupling disk, the polishing grade of the fused silica and the type of black paint were also finalized during this testing campaign.

An assembled detector prototype was placed on an electron beamline operating at an energy of 5 GeV. The detector was aligned with small beam trigger scintillators



Figure 3.16: The prototype detector installed in the test beam area at Desy. One of the trigger scintillators is visible on the bottom left.

and it could be rotated horizontally to change the particle direction relative to its axis (Fig. 3.16). Data was acquired with an oscilloscope in coincidence with the beam trigger.

If the distributions of signal amplitude for particles travelling at 0° and 180° relative to the detector axis are normalized to unity they can be regarded as the probability distribution for the random variable x (signal amplitude) given either a *Forward* (P(x|F)) or *Backward* (P(x|F)) particle. A likelyhood-ratio test can then be used to find the value of x that best discriminates between F and B:

$$\frac{P(F|x)}{P(B|x)} = \frac{P(x|F)}{P(x|B)} \cdot \frac{P(F)}{P(B)}$$
(3.5)

the value of x for which the ratio is one is the optimal threshold, that minimizes identification errors, according to the Neyman-Pearson lemma.² The constant P(F)/P(B) is the ratio of the a priori probabilities of detecting a Forward or Backward particle, and it is estimated in this case, by the ratio of the simulated fluxes (Fig. 3.3), to be about 1/200. We have chosen to add a safety margin to this ratio and use a more conservative factor of 10^{-3} .

In Fig. 3.17 a graphical representation of the likelyhood-ratio test is plotted. The Forward distribution shape is characterized by a very long tail, which is due to the use of an electron beam. Muon data collected with cosmic rays, such as shown in Section 6.2, do not have such tails.

 $^{^2\}mathrm{A}$ cost factor can be added to represent the different importance assigned to the two possible misidentification errors.



Figure 3.17: The experimental Forward and Backward distributions (P(x|F)) and P(x|F)) are plotted in both linear and logarithmic scale, along with a fit to the Backward distribution, and the same scaled by $P(B)/P(F) = 10^3$. The fit curve is a combination of a gaussian with an added exponential tail. The *x* coordinate of the intersection between scaled fit and Forward distribution is the optimal discrimination amplitude. With a cut at approximately 0.42 pC, the efficiency for Backward particles is only about $6 \cdot 10^{-5}$, while for Forward particles it remains very high at 0.98.

Chapter 4

Electronics and DAQ

This chapter will describe in detail the readout electronics used by the BHM detector. The requirements that were set for this readout system will be briefly described in the first section, along with an overview of the implementation. Later sections will describe in more details the individual elements that compose the readout electronics. The chapter will be concluded by an overview of the data acquisition software and the description of a temporary system used in the commissioning phase.

4.1 Overview

The readout electronics used for the BHM is adapted from the system developed for the Phase I Upgrade of the CMS Hadron Calorimeter [16]. The hardware developed by the HCAL group, after some modifications, satisfies all the requirements of BHM.

4.1.1 Requirements

The electrical signal produced by the photomultiplier in each detector unit carries both timing and amplitude information, as discussed in Sec. 3.1. They are both necessary to discriminate a signal produced by a beam halo particle from those produced by other background sources. It is therefore critical for the BHM readout electronics to be able to measure both the signal amplitude and the timing.

It is not necessary to have very high resolution on the signal amplitude, but a large dynamic range is useful as the MIB signals can be two orders of magnitude larger than those produced by other background sources. A fairly good time resolution, of the order of 1 ns, is also required.

While the expected MIB rate with good beam conditions is quite low, just a few counts per second per channel, the electronics must remain sensitive continuously, i.e. without any deadtime.

The electronics must be able to discriminate MIB particles from every other signal in real time, based on cuts (thresholds) on the amplitude and timing information. It is however not necessary to record all the information related to an individual MIB particle after this information has been used to perform the discrimination. For the purpose of beam monitoring, it is in facts sufficient to measure the rate of MIB particles, subdividing them by channel, amplitude and bunch crossing (BX). This information can be stored in binned form in histograms, which are then read out by the data acquisition software on a regular basis.

4.1.2 Implementation overview

The electronics developed for the CMS Hadron Calorimeter (HCAL) is subdivided in a front-end system, mounted close to the detector in UXC, and a back-end system placed in USC. The two parts are then linked by a set of high speed optical links. The front-end system is specialized for the parts that compose the Hadron Calorimeter, the Barrel (HB), Endcap (HE) and Forward (HF) calorimeter. The back-end system, on the other hand, is common.

The Phase I upgrade will replace both the front-end and the back-end, but the HCAL group decided to upgrade their readout in multiple steps. The back-end was upgraded first, starting with the part dedicated to HF, during Long Shutdown 1 [16]. The front-end of HF will be replaced one year later, during the 2015-16 winter shutdown. The readout of HB and HE will be replaced last.

The HF front-end has been developed with a timescale compatible with the installation of BHM, as well as a more standard hardware form factor, and was preferred to the HB/HE one for these reason.

An overview of the entire system is presented in the scheme of Fig. 4.1, which also shows the data, clock and control paths.

The front-end system is based on a custom designed crate, which houses up to 16 Readout Modules, one calibration module and a crate controller. The back-end system is based on a commercial Micro Telecommunications Computing Architecture (μ TCA) [38] crate, which contains either data readout cards or control cards.

Data flow

The Readout Module (RM), has 24 analog input channels, each coupled to an ASIC that serves both as an ADC and as a TDC. The board and ASIC are described in detail in Section 4.2.2. The digitized data are read by an FPGA, which assembles them into frames and serializes them into an high speed optical link. The optical fiber is connected to a receiver in the μ HTR board (Section 4.3.3) which decodes the frame and recovers the digitized data. In the BHM implementation, unlike in HCAL, these digitized data are



Figure 4.1: Scheme of the readout electronics. On the left side is the front-end crate, on the right the back-end. Arrows show the main paths of the different signal classes.

used to determine whether or not the signal was generated by a beam halo particle, and histograms are filled accordingly. The readout software periodically reads the histograms through a regular *ethernet* link.

Clock and control flow

A clock signal synchronous with the LHC bunch crossings is made available to the backend through the TCDS (Trigger, Control and Distribution System [39]). The control software also sends configuration commands to the back-end system through ethernet. The back-end next-generation Front End Controller (ngFEC), described in Section 4.5, combines the clock and control commands in a single data stream that is transmitted to the front-end crate with an optical link. In the front-end, the next-generation Clock Control and Monitoring (ngCCM) card (Section 4.5.2) decodes this data stream recovering the clock and control commands, which are then distributed to the RMs through the crate backplane. The backplane signals are received by the RM where they are directed to the appropriate component by a dedicated FPGA, allowing to configure each component, set thresholds, run debug sequences,

4.1.3 Implementation choice

The requirements set for the BHM readout electronics could have been satisfied by several possible implementations. The choice of adapting the electronics developed for the HCAL Phase I upgrade was motivated chiefly by the desire of exploiting synergies within the CMS community and secondly by budget reasons. While the HCAL hardware fulfils BHM requirements completely, it is designed for an application of a fairly different scale, which pushed its complexity well beyond what is required by BHM.

In order to mitigate risks typically involved in such complex systems, several alternative options have been investigated in more or less detail. For completeness, some of these will be presented quickly below, along with the reasons for which they were abandoned.

VME readout

Given the relatively low number of channels, it was considered to employ fast digitizer cards in Versa Module Eurocard (VME) standard [40]. Devices such as the CAEN v1721 [41] offer multiple channel readout at 500/1000 MSps, enough to achieve the desired time resolution.

While the VME bus would not be fast enough to read out digitized data at full speed, the low rate of physical events would make it possible, via adequate zero suppression, to readout all the interesting events and perform final analysis and processing in software.

The downsides of this solution were the relativley high cost of the digitizer modules themselves and the fact that they were somewhat unflexible with regards to triggering and clock frequencies. VME electronics is also considered outdated and CMS is pushing for the adoption of the newer μ TCA [38].

µTCA digitizer readout

A similar solution, based on μ TCA hardware rather than VME, had been devised and is still under development for the readout of the BCM1F detector [42]. It is based on the standard μ TCA crate and controllers (which are the same used in HCAL and is thouroughly described later), and is centered around a generic μ TCA FPGA-based card.

An high speed (1.25 Gbps), 4-channels digitizer [43] on an FPGA mezzanine card (FMC) would be mounted on the FMC connector of the carrier card. A powerful, feature-rich FPGA is able to read multiple digitizer channels at full speed, integrating into a single device all the functions that the HCAL implementation delegates to multiple cards and chips.

This solution offered the highest flexibility, as it would have been possible to perform sophisticated on-line analysis on the digitized signal, but would have also required significant development time. Furthermore, the cost per channel, while justified for the fast BCM1F detector, was too high for the low-rate BHM detector.

4.2 Front-End electronics

4.2.1 Crate and Backplane

The HF crate is a standard "Eurocard" chassis, 6U tall, designed to house 160 mm deep cards. This is effectively the same mechanical standard used by most commercial VME [40] cards and crates. Like VME, each board is connected to the backplane with two DIN41612 connectors, but the pin assignement of these connectors is very different from the VME standard.¹

The backplane distributes eletrical power and a set of control signals to all the cards plugged in it. The clock and control signals are either direct point to point links from the ngCCM slot (in the centre) to all other slots, or bussed signals, typically spanning one half of the crate. Two main classes of signals exists, *fast signals* and *slow signals*. The first class includes the system clock (called MClk) running at 40.08 MHz, and a set of control signals that are synchronous to this clock. *Slow signals* include for example Inter-Integrated Circuit (I²C) [44] and Joint Test Access Group (JTAG) [45], which run at much lower speeds (100 kHz and 1 MHz respectively). Critical backplane signals are protected from electrical noise by using LVPECL differential signals (Low Voltage Positive Emitter Coupled Logic).

4.2.2 Readout Module

The Readout Module (RM) is the main board of the front-end electronics, and is dedicated to signal acquisition. The RM has been developed by Fermilab, and features a rather complex and dense circuit board, composed by as many as 18 layers.

At the time of writing, only the pre-production cards are available, and two will be used in the BHM readout system. Preproduction cards have passed a preliminary review, and no major changes are foreseen for the actual production cards.

The main components of this board are shown in Fig. 4.2:

- 1. QIE10 ASIC The integrated circuit that digitizes the analog signal. There are 24 Charge Integrator and Encoders (QIEs) on each board, each serving one channel.
- 2. Readout FPGAs These two large FPGAs receive data from the QIEs (12 each) and serialize them for transmission via optical links.

¹Even power and ground pins are different; shorts may happen if a VME card is mistakenly plugged into this crate or viceversa.



Figure 4.2: The RM pre-production board, fully assembled. Marked in the picture are: 1) QIE10 - 2) Readout FPGA - 3) VTTx - 4) Bridge FPGA. On the front panel (left), starting from the top: auxiliary clock input, readout fiber connector, two 24-coaxial signal connectors.

- 3. VTTx Versatile Twin Transmitters, CERN developed radiation hard laser drivers, working at up to 5 Gbps. There are three of them, each driving two fibers.
- 4. Bridge FPGA A smaller FPGA which is responsible for control and monitoring of the card.

The board power is supplied by the backplane and regulated by DC-DC converters developed by CERN for use in a radiation environment [46].

The QIE card features a mezzanine connector to allow the installation of an LED pulse generator, used to calibrate the detector. The mezzanine used by HCAL is not compatible with the calibration system of BHM, therefore a different mezzanine card had to be developed (see Section 5.2).

4.2.3 QIE10 ASIC

The Charge Integrator and Encoder version 10 (QIE10) is the latest version of a family of devices designed at Fermilab to measure signals from photo-detectors [47]. The QIE integrates input charge pulses (or current) in 25 ns periods, and digitizes at 40 MHz using four phases of operation in pipelined fashion. It has a dynamic range of five orders of magnitude, which are encoded into 6 bits of mantissa and 2 range bits, or 256 codes. The response is approximately logarithmic, with approximately constant resolution over the full dynamic range.

The device also has a built-in 6 bit time-to-digital converter (TDC), with 0.5 ns resolution for each time slice.

The QIE10 is fabricated in a 350 nm SiGe process, providing intrinsic hardness against ionizing radiation. Its configuration register is also protected from Single Event Upsets.

Functional description

The device receives charge from a photo-detector (PMT), and splits the current into four ranges using different weights. Each range then integrates the resulting current fractions onto separate capacitors, with the integration period set to 25 ns. The input stage with the current splitter and integration stage is shown in Fig. 4.3.

After the integration period, subsequent circuitry selects the range that lies within the dynamic range of the digitizer circuit. The voltage on the selected range is then multiplexed to the on-board flash analog-to-digital converter (FADC). The 6 bit flash ADC also has a nonlinear transfer function, shown in Fig. 4.4, helping to achieve a constant 1% resolution over the whole dynamic range.

The FADC output (*mantissa*), along with the two bits identifying the integration range (*exponent*), is thus capable of representing a wide dynamic range (equivalent to



Figure 4.3: The input stage of the QIE10.



Figure 4.4: The transfer function of the 6 bit ADC inside the QIE10. Four subranges are clearly visible.



Figure 4.5: The complete, simplified scheme of a QIE10, showing the replicated capacitors and range selector circuits.

17 bits when linearized), in just 8 bits. A look-up table can be used to convert the 8 bit output code to a linear charge value.

The pipelined operations described above require more than one clock cycle to be completed. In order to achieve zero dead time, parts of the circuitry are replicated four times, namely the integrating capacitors and range selectors, as can be seen in Fig. 4.5. At any time, one capacitor bank will be integrating, one will undergo range selection, one will be digitized and the last one will be cleared. Each clock cycle will rotate the active capacitor by one, with one being always ready to accept the signal charge. Two bits identifying the active capacitor (*CapID*) are included in the data output, allowing to correct for small mismatches in the hardware.

Independently of the charge integration, one extra output from the current splitter is sent to a fixed-threshold discriminator. The discriminated signal is processed by a TDC, which has a 500 ps resolution. The 50 valid output codes from the TDC are encoded into 6 bits, with some extra codes indicating the absence of an edge or the presence of multiple edges.

Performance evaluation

The various iterations of QIE10 prototypes have been extensively characterized at Fermilab [47], [48]. The latest results indicate that all the design goals have been met, and the chips are fully functional.

Fig. 4.6 shows the reconstructed charge as a function of the output code, demonstrating the high dynamic range. The linearity of the TDC is shown in Fig. 4.7.

At the time of writing, full scale production for HCAL is not completed, but BHM



Figure 4.6: Charge vs. QIE output. The different colors indicate the four ranges.



Figure 4.7: Performance of the TDC: output code vs. pulse time delay

will take advantage of the large quantity of chips produced in the last Engineering Run.

4.2.4 Readout FPGAs

Reading out the data and formatting it for transmission on the optical link is the main task of the two readout FPGAs. Other features include the QIE individual clock phase adjustment and a falling-edge TDC to complement the rising-edge found in the QIE. These devices are *IGLOO2* FPGAs from Microsemi, part number M2GL050T-FGG896 [49].

As the system is designed to transmit all the raw data from the front-end to the back-end, a significant amount of bandwidth is required for the links between the two parts.

Serial Links

The preferred way of achieving high bandwidth in modern electronics is a very fast serial connection over optical fibers, which offers many advantages over a parallel transmission, especially over longer distances. Transmission over high speed² serial links requires however specialized hardware and protocols.

A ser-des, or serializer-deserializer, is a device designed to convert a stream of data on a parallel interface to a serial transmission with a higher frequency and viceversa. A ser-des also includes sophisticated analog electronics to drive and receive a differential signal in a way that compensates for the losses associated with the transmission medium (cable or fiber), which normally behaves as a low-pass filter. The differential signal is then either directly connected from transmitter to receiver (in the same board or crate) or is used to modulate a laser driver for transmission over fiber, with the light at the receiving end being converted back to an electrical signal by a fast photodiode. For the correct operation of a ser-des, it is crucial to provide a *reference* clock, with very good frequency and phase stability, and very low jitter. This clock can be used for the parallel interface and is internally multiplied to operate the serial part.

As the receiver does not typically have access to a clock identical to that used by the transmitter, the receiving end of a serializer needs to reconstruct a clock from the data stream itself. This requires the data stream to have frequent transitions, or equivalently no more than a few ones or zeroes in a row. Furthermore, the low level encoding used for serial links typically needs to ensure that the transmission is DC-balanced; on average, an equal number of ones and zeroes has to be transmitted.³

²Higher than a few hundred Megabit per second.

³A number of practical considerations leads to the links being AC-coupled rather than DC-coupled. An average DC component in the data stream, caused by predominant ones or zeroes, would be filtered out, worsening the signal quality.

Byte	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0			
0	Alignment comma (K28.5)										
1	TDCE3	TDCE2	TDCE1	TDCE0	Reserved			BC0			
2	CAPID3		CAPID2		CAPID1		CAPID0				
3	ADC0										
4	ADC1										
5	ADC2										
6	ADC3										
7	RTDC	C3[5:4]	RTDO	C2[5:4]	RTDC1[5:4]		RTDC0[5:4]				
8	RTDC	C3[3:2]	RTDO	C2[3:2]	RTDC1[3:2]		RTDC0[3:2]				
9	RTDC	C3[1:0]	RTDO	C2[1:0]	RTDC1[1:0]		RTDC0[1:0]		RTDC0[1:0]		
10	FTDC1			FTDC0							
11	FTDC3			FTDC2							

Table 4.1: The frame format of the data link. One such frame is transmitted every 25 ns, containing information for four channels. BC0: Bunch Crossing 0 alignment marker (orbit signal); RTDC: Rising Edge TDC; FTDC: Falling Edge TDC; TDCE: Error in Falling Edge TDC

One of the first and still very common encoding that guarantees both frequent transitions and average DC-balance is the 8B/10B [50]. This encoding translates each byte into one of two possible 10 bit encodings, which are selected from time to time based on their relative content of ones and zeroes. Encodings which would result in sequences longer than five consecutive ones or zeroes are not used, and some encodings are decoded as special control signals (*K*-characters) instead of data bytes. While this protocol is effective, it also adds a 25% overhead to the data; superior encodings have been developed that have less overhead, a few also offering some protection against transmission errors, at the cost of a more complex implementation.

Data formatting and serialization

Each readout FPGA receives data from half of the QIE chips found on a RM. The data from four consecutive QIEs is encoded into one serial stream for transmission via optical link. Each QIE generates 16 bits of information every bunch crossing (25 ns), to which the readout FPGA adds 5 bits (4 data and one status) of falling-edge TDC. Four channels then generate a total of 84 bits, to which 4 status bits are added. The data frame, shown in Table 4.1, also includes a special *K*-character which is used by the receiver to identify the beginning of the frame. The whole frame is then encoded using the 8B/10B scheme, bringing the total size to 120 bits.

In order to transmit 120 bits every 25 ns, a link speed of 4.8 Gbps is required. The

high speed serializer included in the IGLOO2 FPGA supports speed of up to 5 Gbps, but with a serialization factor of 20 at most [51]. Since the maximum data rate is given by the base clock frequency multiplied by the serialization factor, a base clock frequency higher than 40 MHz is required to serialize data. This means that the data first has to be converted from 120 bits at 40 MHz to 20 bits at 240 MHz.

Two ways of generating a faster clock exist: multiplying the existing 40 MHz clock or using a fast standalone oscillator. The former method, which would have to produce a 240 MHz clock, has the advantage of being *synchronous* to the base clock, simplifying the internal logic in the FPGA. This choice was preferred in the HCAL TDR; it is however nontrivial to multiply a clock producing a low jitter output with a radiation tolerant circuit. It was therefore decided to use a fixed frequency oscillator that would produce a clean clock at a higher frequency (250 MHz) with the sole purpose of driving the serializer.

Since the actual data rate is only 4.8 Gbps, while the data rate resulting from the 250 MHz clock is 5.0 Gbps, it becomes necessary to insert *pad words* in the data stream, to keep the frame synchronous with the 40 MHz clock. These pad words, which have a specific encoding using 8B/10B K-characters, are transmitted along the link and discarded at the receiver. In agreement with the HCAL group, and because this feature was extremely important for BHM, I implemented part of the transmitter side of this mechanism in the IGLOO2 firmware.

Separate beam clocks

The asynchronous link feature is an optimization from the HCAL point of view; it is however a necessity for BHM. Most subdetectors, including HCAL, start the data acquisition only after the LHC beams are declared stable, and receive a constant frequency machine clock, oscillating at exactly 40.079 MHz⁴. This is not the case for BHM, which must operate also during the injection and ramping of the LHC beams. During ramp, the machine clock frequency is slightly increased from about 40.077 MHz up to the nominal value, and each beam uses a potentially different clock phase.

For HCAL, the clock that operates the front-end and back-end is derived from the same source and is fixed at 40.079 MHz. In the case of BHM however, only the back-end operates from a fixed frequency source (TCDS, see Section 4.3.2), whereas the RM receives the real machine clock on a front panel input (on a LEMO connector visible in the top left in Fig. 4.2). Since the detector channels are divided between the two RMs according to the relevant beam, each RM can be connected to the appropriate Beam clock.

 $^{^4\}mathrm{Whenever}$ "40 MHz" is mentioned in this chapter, it is actually 40.079 MHz; the same applies to muliplied clocks deriving from it.

This difference in clock frequency can only be allowed thanks to the data link being operated asynchronously. The potential mismatch in the number of clock cycles between front-end and back-end is avoided by resetting the relevant logic every orbit, before the difference becomes large.

QIE clock phase adjustment

The QIE charge integration gate and rising edge time measurement both use as starting point an edge of the input 40 MHz clock. However in the case of HCAL, it is desirable to provide a small phase offset to QIE for each channel, in order to compensate for the different time of flight of particles from the IP to each calorimeter region. Due to all detector units being at the same z, BHM does not expect time of flight differences, however phase tuning allows to compensate for different lengths of the signal cables.

Clock phase offset adjustment per channel is provided by the readout FPGA. A multiple of the 40 MHz system clock is used to output a repeating pattern of strings of ones and zeroes, simulating a clock. By changing the pattern, it is possible to change the phase of the output clock in steps of 1/8 of the system clock period.

Falling Edge TDC

In order to complement the information on the rising edge, the readout FPGAs implement a second TDC, using the discriminator signal produced by the QIE10. This TDC is implemented using the FPGA fabric, using a technique that relies on oversampling the input signal with a fast clock. This method results in a somewhat crude, yet effective TDC, with a resolution of about 1 ns.

The information on the falling edge is produced relative to a clock phase that is not adjusted for each channel, therefore the measured value needs to be compensated for the phase offset, which is constant and known.

Control and debug features

The readout FPGAs implement a set of control registers accessible through an I^2C interface that I implemented. Through these registers it is possible to set the QIE clock phase offset and to read several debug counters.

The data formatting code includes a *link test* feature, also developed by me, that allows to verify the correct operation of the optical link by transmitting a known data pattern.

The readout FPGA can enable and trigger the Charge Injection mode of the QIE, which forces it to integrate a known signal pulse for testing and calibration purposes.

4.2.5 Bridge FPGA

The Bridge FPGA is responsible for control and monitoring of the RM. As part of my contribution to the development of HCAL electronics, I implemented the Bridge FPGA firmware using the *Verilog* HDL [52]. The Bridge FPGA is a ProASIC3L from Microsemi [53], part number A3P1000L-FGG256.

A complete up-to-date technical documentation of the Bridge is available as part of the firmware release [54]; a summary of the current version is in Appendix A.

Configuration and monitoring

The RM implements a number of different configurable devices, including for example the QIE chips, the two large FPGAs and the VTTx chips. These and other devices offer an interface for configuration and/or monitoring. With the exception of the QIEs, the interface used is I^2C [44].

 I^2C is a widely used standard suitable for configuration and monitoring of integrated circuit within the same board or short distances. Its main advantage over competing standards is the small number of signal lines required, only one clock (*SCL*) and one data (*SDA*) line. The I^2C bus is by design a multipoint communication system, featuring any number of *master* and slave *devices*.

In order to connect more than one master or slave to the same bus, two conditions need to hold: the devices must have the same I/O voltage and they need to have unique addresses. This is not the case for the RM: the board includes several devices with different I/O voltages and six identical devices with the same hardcoded address (the two halves of each VTTx count as separate devices here). In order to interface all the incompatible I^2C devices, as well as the QIE chips, with a single connection coming from the backplane, it was decided to include an FPGA to provide the appropriate protocol translation.

Part of the philosophy of the HCAL design was to have as little sophistication as possible in the front-end system, to make the design more robust. The bridge FPGA follows this philosophy in the way it handles translation of the I^2C protocol. Since the only problems with I^2C concerned the I/O voltage level and the address incompatibility, it was decided that the Bridge would only act as a (de-)multiplexer with respect to the I^2C bus, as shown in Fig. 4.8. In this way, no logic is necessary to handle I^2C transactions, other than those addressed to the Bridge itself.

The QIE chips on the other hand require a special treatment. Each QIE has a 64 bit configuration register, accessible for both reading and writing through a custom serial interface. Due to limitations in the number of pins available on the Bridge, the serial interfaces of the QIE chips are daisy-chained in four groups of six. This configuration makes each daisy-chain appear to the bridge as a single 384 bit shift register. In order to



Figure 4.8: Block diagram of the Bridge Firmware: the internal I^2C slave controls the I^2C and JTAG multiplexer.

access a daisy-chain, the control software executes an access via I^2C to a virtual internal register on the Bridge. The Bridge then translates this operation to the appropriate protocol for accessing the QIE.

Other features

In a similar fashion to that used for I^2C , the Bridge FPGA also acts as a (de-)multiplexer for the JTAG signals that can be used to reprogram the readout FPGAs online. This feature was deemed necessary as the readout firmware will most likely need to be updated during operations. No remote reprogramming is however foreseen for the Bridge itself, which can only be programmed through a JTAG header on the board. Unlike the HCAL case, this connector remains accessible on a live system thanks to the BHM front-end crate having many free slots.

The Bridge also controls the operation of the pulser mezzanine card, where installed, by sending trigger pulses at a programmable delay from the global triggering signal (coming from the backplane). The Bridge will support both the original HF mezzanine and the custom one developed for BHM (more details in Section 5.2).

4.3 Back-End electronics

The bulk of current CMS off-detector electronics is based on the VME architecture. It was however decided, at a collaboration level, that all upgrades should try to abandon this aging technology in favor of a more modern alternative. The standard that was identified as a substitute is the μ TCA [38]. Beside the HCAL and BHM back-end, this standard will be used for the TCDS system, for the upgrade of the Level-1 trigger [55], for the readout of BCM1F [42] and for other future upgrades.

4.3.1 µTCA

The μ TCA is a modern, high density and high performance architecture, developed primarily for use in the telecom industry. It is derived from the even higher performance Advanced Telecommunications Computing Architecture (ATCA), as a more compact and self-contained alternative. The ATCA standard defines a set of card form factors and an interconnection that together form the Advanced Mezzanine Card (AMC) specification. These AMCs were originally intended to be used as mezzanines on the very large ATCA *blades* that compose an ATCA shelf. Since the AMC standard allows these cards to feature substantial computing and communication resources, the μ TCA standard was created to allow their use in a more compact platform.⁵

Both ATCA and μ TCA offer much more flexibility than VME, since they only specify the card mechanical and electrical interface, but leave the choice of interconnection and protocols used on the backplane to the user. The configuration chosen in CMS is fairly typical for a μ TCA crate: 12 AMC slots and two MCH (μ TCA Controller Hub) slots. Only the management part of the interconnection is specified in μ TCA: the low level (power, thermal, etc...) management is carried out via Intelligent Platform Management Interface (IPMI) [56] while the user management goes through a regular Gigabit Ethernet network.

The backplane offers several point-to-point connections from each MCH to the AMCs, in what is called a *dual-star* topology. These connections are based on differential pairs, and can therefore support many high speed link protocols, with PCI Express being one of the most common. Multipoint connections from the MCHs are also available, and can be used to broadcast high quality clocks and other signals to all the AMCs.

Fig. 4.9 shows the backplane configuration used in CMS; as the data throughput requirements of BHM are relatively low, many of the links will not be used.

4.3.2 The AMC13 and TCDS

The new TCDS [39] replaces the previous TTC (Timing, Trigger and Control [57]) system starting from Long Shutdown 1. The TCDS is responsible for distributing the LHC clock and Level-1 Accept (L1A) signals to all electronics subsystems in CMS, as well as receiving back throttling information.

L1As are generated by the global trigger system for all of CMS, but local triggers can be generated for each subdetector as well. Both clock and L1As are encoded in

⁵A full size ATCA shelf can be up to 14U high, while µTCA crates are typically 6-7U.



Figure 4.9: Typical *dual-star* μ TCA Backplane. Each interconnection shown represents a *star* connection from each MCH to up to 12 AMCs. The Fabric connections are bidirectional (one pair each direction). Only the green connections are strictly required for operation in CMS.

a single digital signal that is transmitted over optical links at 160 Mbps. This signal originates in the Central Partition Manager card, and is distributed (Fig. 4.10) to various subsystems through the Local Partition Manager and the Partition Interface cards, all of which are implemented in μ TCA hardware. Each subdetector in CMS is assigned at least one *partition*, and BHM is no exception.

The TCDS signal is backwards-compatible with the TTC signal, and will be received by the legacy receivers for those subdetectors that are not being upgraded starting from LS1. For the new or upgraded detectors however, the TCDS signal will be received by the AMC13 card.

The AMC13 card [58] is a generic μ TCA card that has been developed mainly by Boston University as a secondary crate controller and data aggregator for μ TCA electronics. This role is accomplished by placing this card in the slot where the redundant crate controller (MCH) would be, instead of a regular crate slot. The AMC13 card therefore gains access to several multi-Gbps links to each slot, allowing it to distribute control signals and collect readout data.

When used in CMS, the AMC13 card receives and decodes the TCDS clock and signals, and distributes them to each slot in the crate. In most subdetectors, it would also aggregate the event data and transmit it to the central DAQ computers, but this feature is not used in BHM in the current implementation.

The current version of the AMC13, whose overview is shown in Fig. 4.11, features a large Xilinx Kintek 7 FPGA that handles high speed data links (up to 10 Gbps each), and a smaller Spartan 6 FPGA that takes care of the signals associated with TCDS. BHM is not a triggered detector, and it will not make use of the L1A signal, but it will use other TCDS signals such as the orbit start (also called *BC0* for Bunch Crossing Zero).


Figure 4.10: An overview of the Trigger, Control and Distribution System



Figure 4.11: An overview of the AMC13 showing all the available links.



Figure 4.12: Block diagram of the μ HTR card highlighting the serial links.

4.3.3 µHTR board

The μ TCA HCAL Trigger and Readout (μ HTR) [59] is the back-end card that receives the raw data from the front-end electronics, processes it and makes it available for readout.

Hardware

The μ HTR is a μ TCA board developed by the University of Minnesota. This board offers high density optical interconnects and abundant FPGA resources in order to receive multiple data links form the front-end RMs. An overview of the board is presented in Fig. 4.12. The receivers for the optical links from the front-end are two 12-fibers Avago PPODs (Pluggable Parallel Optics Device, [60]). These are connected to the *front* FPGA, which is a large Xilinx Virtex 6 [61]. This FPGA also drives a 12-fiber transmitter and can be connected to two single fiber transmitters for connection with the calorimeter trigger. The front FPGA is connected to the *back* FPGA, which is directly connected to the backplane.

Many auxiliary functions of the boards are delegated to pluggable mezzanine cards, including power management and FPGA configuration through JTAG. The board however, unlike many other of similar design, does not integrate any large memory chips, relying exclusively on the comparatively small amount embedded in the two FPGAs. This proved to be a limitation for the implementation of features specific to BHM.

Firmware

The μ HTR firmware is one of the aspects of this electronics system that requires substantial modifications for BHM with respect to the original HCAL implementation. This firmware is in fact responsible for the processing of the raw data generated by the frontend and its translation to actual physical quantities.

In the HCAL implementation, the front FPGA decodes the data received on the optical links. It then applies calibration constants to translate the raw QIE encoded charge into a linearized quantity representing energy deposited in a calorimeter tower. This information, in aggregated form, is first transmitted to the calorimeter trigger for processing, and is stored on the μ HTR for the time necessary for the trigger to take a decision. If a L1A is received through TCDS, the relevant event is read out through the backplane links to the AMC13, otherwise it is discarded.

At the same time, a summary representing the total deposited energy in a portion of the calorimeter, and a total of the channels crossing a particular threshold, are calculated every bunch crossing on the front FPGA and sent to the back FPGA. In the back FPGA, this information is saved in histogrammed form, with each bin representing one particular bunch crossing in the repeating orbit, and an integration period of a few thousand orbits. These histograms are then periodically read out by the data acquisition software, and are used to compute the instantaneous luminosity at CMS.

The BHM is not designed to record collision data, and its measurements are not read out as part of either the trigger or the main data acquisition of CMS. Therefore, most of the functions existing in the front FPGA are unused; only the link decoding is left unchanged. In BHM, the raw data has a different meaning, and a different set of charge linearization constants must be applied.

For each channel, one sample is processed by comparing it against an amplitude threshold and determining its delay with respect to the beam clock. The result of this processing is then sent to the back FPGA, where it is stored in an time-domain histogram. This histogram, whose bins represent a quarter of a bunch crossing, will therefore count the number of events above threshold, integrated over a period of $2^{12}(4096)$ orbits or more.

A different set of histograms is created, directly in the front FPGA, to represent the amplitude spectrum of each channel, helping in identifying the correct amplitude threshold. The third set of histograms is also saved, again an amplitude spectrum that is only filled in correspondence of a pulse generated by the calibration system.

As is the case in HCAL, the acquisition of these histograms through the backplane must be free of dead time. To solve this issue, the technique of *double-buffering* is employed: while an histogram is being read out and cleared, the data accumulation takes place on a different histogram; once the integration period is completed, the two histograms are swapped instantaneously preventing a loss of data.

For use in BHM, the μ HTR card is the most significant performance limitation. Its lack of fast SRAM memory chips limits the amount of per-channel histograms that can be accumulated on a single card at the same time, forcing us to spread the 40 channels over two cards (in HCAL, which only computes aggregate histograms, each μ HTR handles 96 channels). The μ HTR card could, in principle, be replaced by a different μ TCA card with less optical I/O and more on-board memory; this replacement is being considered as an upgrade.

4.4 Data Acquisition

Data is collected in the μ HTR in the form of histograms, which are integrated for a period of time equivalent to 2¹²(4096) orbits, called a *lumi-nibble*, or a multiple thereof. This produces, for every channel, an histogram which represents the average signal rate as a function of the position in the orbit, with a quarter-of-BX (6.24 ns) resolution. Under normal beam conditions, the orbit profile of the beam background should reflect the profile of the LHC filling pattern, with trains of 25 ns spaced bunches separated by gaps left free for the injection and dump kicker magnets. Every lumi-nibble, the daq software reads the time-domain histogram for each channel and processes the data in order to obtain a value for the MIB rate.

The data acquisition software for BHM is developed as a module of LumiDAQ. LumiDAQ is a collection of software that is used for the readout of all the detectors of the BRIL group. It is responsible for collecting and storing all the information related to machine luminosity and beam background, as well as producing online monitoring information for the CMS and LHC control room operators.

LumiDAQ is built on the XDAQ framework [62] and is based on the publishersubscriber concept. In this concept, a central process takes the role of *eventing* bus, and forms the backbone of LumiDAQ. Sources of data, such as the actual readout processes, *publish* information to this eventing bus on a regular basis, classifying them with a *topic* name. Data processors and storage managers *subscribe* to one or more topics, and are notified by the eventing bus when new data becomes available. Results generated by data processors are published back to the eventing bus for use by other processors or storage.

The advantage of this modular framework is the decoupling of different tasks into different applications, which can be developed and maintained by different people. The dependencies on external software libraries are also better isolated.

In BHM, the data source process uses IPbus to configure and then readout data from the back-end electronics. While this protocol is designed for slow control and is not optimized for data throughput or latency, the amount of data that has to be read



Figure 4.13: Overview of the BHM data acquisition in the LumiDAQ framework.

out is small compared to the actual bandwidth offered by Gigabit Ethernet. Histograms occupy approximately 32 kbytes each, with a new one being produced for each channel at most every 0.36 s, leading to a total bandwidth lower than 4 Mbyte/s. Amplitude and calibration histograms are smaller, and can be readout less often, requiring a negligible amount of extra bandwidth. All histograms transmitted to the software have a header that includes, among other information, the lumi-nibble and run number that identify the histogram.

The BHM data source publishes the histograms on the eventing bus without any further processing (Fig. 4.13). The BHM data processor application collects histograms from bus and, in normal operating conditions, merges all the channels for a few consecutive nibbles into two histograms, one for Beam 1 and one for Beam 2. These histograms

are published for storage and monitoring. More detailed information, such as data for individual channels, or data from the amplitude histograms, is only displayed when abnormal conditions are detected, or for monitoring the BHM detector itself.

4.5 Slow Control

The term *Slow Control* is typically used to indicate the hardware and software responsible for the configuration commands and monitoring requests that are executed before, during and after data taking. Many parameters need to be properly configured before data acquisition can start, and several quantities need to be monitored to ensure proper operation of the whole system. Typically slow control is accomplished through read and write operation to individual registers, operations that requires relatively small bandwidth and can therefore use a slow transmission system.

4.5.1 The Back-End and IPbus

The slow control in the back-end is implemented through the Ethernet link that exists in the μ TCA backplane for this specific purpose. The protocol used over this link is called *IPbus* [63], and was developed specifically for slow control applications over Ethernet in ATCA and μ TCA.

Hardware devices are reached through a standard UDP or TCP connection managed by the software. Software accesses hardware based on a virtual flat 32 bit address space, with 32 bit data width. The IPbus protocol allows for individual register read and write operations, as well as memory block access of up to 1 kByte.

Both the AMC13 and the μ HTR boards are controlled through IPbus, using specific software applications. In BHM, the histograms produced by the μ HTR are also read out through the IPbus link, since the required bandwidth is very small.

The front-end is controlled by the back-end through a card called ngFEC. The ngFEC functionality requires only a generic μ TCA AMC with a sufficiently large FPGA and a few standard optical transceivers. In BHM, a CERN made GLIBv3 card [64] will be used.

4.5.2 The Front-End ngCCM

The front-end crate is managed by a crate controller card placed in the central slot, the ngCCM. The ngCCM receives, encoded on a single optical link from the back-end, the system clock, the fast control signals and the slow control commands. It then distributes these signals to the appropriate RM through the backplane.

The development of the ngCCM, and the RM as well, was initially based on the planned Gigabit Transceiver (GBTX) [65], a radiation hard ser-des chip developed by CERN. With the delays in the production of this device, it was decided to switch to an

FPGA with an integrated Ser-Des, such as the *IGLOO2* from Microsemi [49]. While the FPGA would be capable of more sophisticated operations, it was decided to program it only to emulate the GBTX chip. The link is run at 4.8 Gbps, and protocol that is used is the same that would be employed by the GBTX, which offers better reliability than 8B/10B with a slightly larger overhead.

For most of its functions, the ngCCM acts merely as a relay between the ngFEC and the individual backplane slots. The logic to handle for example I²C transactions used to communicate with the RM is implemented in the ngFEC, and the ngCCM simply translates electrical levels on the backplane to bits in the optical link frame and viceversa. While this is not an efficient use of the optical link bandwidth it is extremely robust, as very little logic is implemented in the IGLOO2 FPGA, where it could be exposed to radiation induced Single Event Errors.

4.6 Commissioning Electronics

The implementation of the electronics derived from HF is, at the time of writing, insufficiently mature to be reliably used in data taking. For this reason, it was decided to complement the main readout system with an auxiliary one, that offers increased reliability but lower performances. This auxiliary system is similar to the one that will be used temporarily by BCM1F.

The analog signal from the photomultipliers is split using a simple passive splitter integrated in the signal patch panel in USC. The outputs connected to the QIE board are AC-coupled, in order to block the DC offset generated by the QIE itself. The other outputs, which are DC-coupled, are connected to VME discriminators (CAEN v814 [66]). The discriminator digital outputs are connected to Readout and Histogramming Units (RHU [67]), which generate time domain histograms similar to those generated by the main electronics.

A small number of channels is also connected to a fast VME digitizer (CAEN v1721 [41]) in order to study the signal waveform and measure amplitude information. Calibration pulses will also be acquired for these channels.

Chapter 5

The calibration and monitoring system

An important part of my contribution to the BHM detector was the design and construction of a calibration and monitoring system. This system allows continuous evaluation of the performances of each detector unit, enabling the monitor of possible degradation due to aging and radiation damage. While variations are expected to be small, if not negligible, for the first years of operation, it is planned to operate BHM throughout the rest of the lifetime of the LHC, including its high luminosity upgrades.

The calibration system will periodically inject pulses of light with known intensity and evaluate the response of the photomultipliers. An overview of the system is presented in Fig. 5.1. The system uses a light signal produced by UV emitting LEDs and driven to each detector unit through quartz optical fibers and splitters. The light is injected on the front of the quartz bar, and the resulting PMT signal is compared with that of a reference photodetector that receives the same light signal (through the splitter). The LED Pulser circuit is housed on a mezzanine card mounted on the QIE front-end card, and the reference photodetectors is read out by spare input channels.

The calibration and monitoring system will also be used during the commissioning of BHM, assisting with the tuning of the PMT bias and the signal timing. In order to offer a precise timing reference, the light pulse will have a fast rise time and a duration contained within one bunch crossing.

5.1 Light distribution system

The light pulse used for calibration is distributed to the detector units thanks to a system of optical fibers. Each quarter of BHM has a dedicated light source and feedback detector, along with a passive light splitter. Light from the source is transmitted to the



Figure 5.1: Overview of the calibration system (for one quarter of BHM).

splitter by the *source* fiber.

The splitter distributes the light to its eleven outputs, ten of which are connected to individual detector units. The eleventh output is connected to the *feedback* fiber, which carries the light back to the feedback detector. Using the feedback from the splitter, instead of relying on a local feedback, allows to monitor not only variations in the source intensity, but also attenuation along the fibers.

One cable per each end of CMS carries four fibers from the electronics rack in USC to the rotating shielding area, following the same path of the signal cables. The cable carries two pairs of source and feedback fibers; before reaching the rotating shielding, the cable bifurcates, taking one pair to each side. Source and feedback fibers are connected with inline joiners with two of the splitter fibers.

5.1.1 Fibers

The choice of optical fiber for the calibration system was dictated by the requirement of transmitting near-UV wavelength (330–380 nm) in a moderate radiation environment. As a secondary constraint, the cabling material had to be sufficiently fire resistant to comply with safety regulations in the underground experimental cavern, and also protect the fibers from mechanical damage.



Figure 5.2: Attenuation at different wavelengths for an Optran UV fiber.

Synthetic fused silica fibers¹ were a natural choice, given their very high radiation tolerance and good transmittance. An estimation of the expected dose along the fiber path is of the order of 50 krad at the worst position, for an integrated luminosity of 3000 fb^{-1} . This estimation was obtained from the CMS Radiation Simulation online tool [30].

All the fibers in the system are Ceramoptec $Optran^{(R)}$ UV [68]. Fig. 5.2 shows the attenuation at different wavelengths as measured by the manufacturer. The chosen fiber type has a 200 µmdiameter silica core, a 220 µmdiameter Fluorine-doped silica cladding, and a thin Polyimide jacket. The numerical aperture (NA) for this fiber is 0.22, measured by the manufacturer at the 95% surface of the acceptance/emission cone.

While we had no chance of irradiating the fibers that we use, extensive irradiation tests have been carried out over many different types of quartz fibers. Results from [69] indicate small to negligible damage to silica fibers with polyimide jacket, especially in terms of light attenuation, up to at least one Mrad.

5.1.2 Light Splitter

A passive light splitter is used to distribute light to multiple outputs. This splitter is composed of a fiber bundle cable and a mirror placed at the common end of the bundle.

The light from the centre fiber in the bundle, connected to the source fiber, is reflected off the mirror and enters the other fibers in the bundle, as shown schematically in Fig. 5.3. This arrangement, similar to that used in the CMS ECAL [14], produces a slightly more uniform distribution on the outputs compared to a direct illumination. It also has the advantage of a simpler mechanical construction. Since the source and outputs are already aligned into the bundle, there is no need to precisely control the axial alignement of the mirror, as it can be made much larger than it needs to be. The only parameters that

¹Commonly called quartz fibers, even though they are made of amorphous silica.



Figure 5.3: Schematic view of the light splitter (not to scale). Light enters the splitter from the source fiber, is reflected off the mirror and exits through the remaining fibers.

need to be controlled precisely in this assembly are the angle of the mirror with respect to the bundle axis, which should be zero, and the distance.

The mirror assembly is formed from optical components manufactured by Thorlabs [70]. An aluminum-coated mirror, with reflectivity higher than 90% at UV wavelength [71], is fixed inside a threaded tube by two retaining rings. In front of the mirror, an adapter for the optical fiber SMA905 [72] connector is also mounted in the threaded tube. The distance between the fiber bundle and the mirror is fixed by the thickness of the front retaining ring (3.9 mm), which was selected to ensure an optimal light distibution. The mirror assembly and its components are shown in Fig. 5.4.

From the numerical aperture (NA) of the fiber we can derive the angle of the emission cone for the source fiber:

$$NA = n\sin(\theta) \quad \Rightarrow \quad \theta = \arcsin\left(\frac{NA}{n}\right) \approx 8.5^{\circ}$$
 (5.1)

where n is the refractive index of the fused silica fiber core (1.458). This leads to a light spot on the mirror with a radius of

$$r_m = d\tan(\theta) + \frac{1}{2}r_{core} \approx 700\mu m \tag{5.2}$$

Assuming an ideal reflection, the spot reflected back to the fiber bundle has a radius of

$$r_b = 2d\tan(\theta) + \frac{1}{2}r_{core} \approx 1300\mu m \tag{5.3}$$

Due to manufacturing contraints, the fiber bundle is not ideally built, with one central fiber surrounded by 11 at identical radius. It has instead three fibers closer to the centre and nine arranged on a larger radius, as can be seen in Fig. 5.5.



(a) The components of the mirror assembly. From left to right: threaded tube, rear retaining ring, mirror, front retaining ring, SMA connector adapter. The diameter of the mirror is 25.4 mm. Not shown is a black plastic disk protecting the rear of the mirror from dust and light.



(b) Partially assembled

(c) Fully assembled

Figure 5.4: The mirror assembly.



Figure 5.5: Picture of the common end of the fiber bundle, taken through a microscope. The black circles are the twelve optical fibers. The visible aberration on the outer side of the image is a camera effect, all the fibers appear circular to the naked eye.

It was therefore decided to use one of the three centre fibers as source and a second one as feedback, leaving the third for one of the Detector Units. The diameter of the common end of the bundle is approximately 900 μ m, which is covered entirely by the reflected spot, even though the center is offset by about 100 μ m.

It should be pointed out that the light distribution within this cone is not uniform, but rather close to a Gaussian, with the cone being defined at the two sigma point. While reducing the distance, and the reflected spot size, helps in transmitting more power through some fibers, it also reduces the amount received by other fibers, which is undesirable.

The fiber bundle has been manufactured by Ceramoptec based on a customized design (Fig 5.6). Twelve fibers, 250 cm long, are inserted in a single ferrule of an SMA 905 connector on the common end of the bundle. Each fiber is individually connectorized at the other end, also with SMA 905. The epoxy used for the connectorization is Epo-Tek[®] 350, whose radiation characteristics are briefly presented in [73]. Fibers are routed through a corrugated metal tubing (2.5 mm in diameter) which protects them from excessive bending and other mechanical stresses.

The bundle legs are connected to the front of the detector unit, through an opening in the shielding layers. The fiber SMA connector is screwed to a threaded element that is part of the intermediate Polyethilene spacer and is aligned with an hole in the inner



Figure 5.6: Production drawing of the fiber bundle. The details show the view of the common and individual connectors.

shielding layer (Fig. 5.7). The light passes through a small air gap in the inner spacer and enters the fused silica cristal through a small hole (1-2 mm) in the black paint covering the front face. The light has a roughly normal incidence angle and is mostly transmitted through the air-silica boundary, after which it travels straight towards the PMT.



Figure 5.7: Detail of the cross section of the BHM detector unit, showing the fiber SMA connector in light grey and the UV light in violet.

5.2 Calibration electronics

The calibration system requires the generation of a pulse of UV light with precise timing and amplitude characteristics in order to fulfil its requirements. A dedicated electronics board, which will be integrated in the front-end readout electronics (Section 4.2), is being developed for this purpose by INFN Bologna.

The board will be mounted as a mezzanine card on the HF Readout Module, which has a dedicated connector for this purpose.² One mezzanine will feature two adjustable pulse generators, each connected to an UV emitting LED. The mezzanine will also have two Silicon Photomultipliers (SiPM [74, 75]) acting as reference photodetectors. Two mezzanines will be mounted, one on each RM, for a total of four channels.

The mezzanine card design is being completed at the time of writing. The performance of LEDs from different manufacturers is being evaluated; we have measured optical power and switching speed and at least two viable models have been identified. During the early commissioning phase, a temporary system will be used, with a pulser circuit similar to the final one, assembled on a breadboard. No feedback detector will be installed.

5.2.1 Pulser circuit

The pulser circuit configuration is shown schematically in Fig. 5.8. The operating principle is based on RF transistors acting as fast switches. Two digital trigger pulses, coming from the Bridge FPGA on the motherboard, activate the two transistors with a short delay. When the top transistor (Q3 in the figure) is driven, it becomes conducting and connects the anode of the LED to the positive power rail, switching it on. The bottom transistor (Q2) is activated shortly afterwards, and it shorts the anode to ground. Since the LED cathode is held at an intermediate constant voltage, the voltage between anode and cathode is characterized by a fast positive pulse, followed by a negative pulse before returning to zero, as shown in Fig. 5.9. The negative pulse is necessary as the internal capacitance of the LED would produce a slow decay of the output light, instead of the desired sharp pulse.

A configurable delay implemented in the Bridge FPGA allows to trigger the generation of the pulse at the desired moment, including for example the possibility of firing one pulse during the abort gap of each LHC orbit, as well as making dedicated calibration runs when no beam is present. The pulse amplitude can be controlled through an I^2C DAC which sets the intermediate voltage level applied at the LED cathode.

 $^{^2\}mathrm{A}$ mezzanine card is being developed for use in HF as well, it is however incompatible with our calibration system.



Figure 5.8: Simplified schematic of the pulser circuit.



Figure 5.9: An oscilloscope picture of the pulser circuit output (pink). Also shown are the two trigger pulses and the light output of the LED viewed with an R2059 PMT (blue).



Figure 5.10: The amplitude spectrum of a SiPM showing peaks corresponding to an integer number of photoelectrons.

5.2.2 Feedback

Even with constant settings, pulse amplitude produced by the LED is sensitive to a number of factors, including for example temperature, aging and drift in power supply. Rather than implementing sophisticated correction circuitry to keep the average amplitude constant, it is easier to measure the light that is produced with a reproducible photodetector and use its signal amplitude to normalize the values measured during calibration.

The photon counting characteristics of SiPMs, coupled with simplicity, small volume and low cost, allow them to be used as feedback detectors in this application. At any time, a SiPM can be calibrated by injecting low amounts of light and obtaining a charge spectrum similar to the one shown in Fig. 5.10. Each peak in this spectrum corresponds to an integer number of photons detected in the integration gate: 0, 1, 2, ...

While at higher amplitudes the gaussian peaks become wider and begin to overlap, it is still possible to extrapolate their position as the distance between them is constant (and proportional to the device gain). This calibration procedure allows to unambiguously convert a measured amplitude into a number of photons, ignoring at least to first order variations in the SiPM itself due to temperature effects and power supply variations.

Fiber	Amplitude	Normalized	Distance from
	[a.u.]	Splitting Fraction	average $[\sigma]$
C3	3.05	0,110	1,43
E4	2.97	0,107	1,03
E5	2.51	0,091	-1,31
E6	2.79	0,101	0,11
E7	2.60	0,094	-0,85
E8	2.80	0,101	0,16
E9	2.66	0,096	-0,55
E10	2.75	0,099	-0,09
E11	3.02	0,109	1,28
E12	2.53	0,091	-1,21
Average	2.77	0,100	0
RMS	0.20	0,007	

Table 5.1: The splitting fraction of one of the four splitters used in the system. The raw amplitude measurement is normalized so that the sum of all outputs is 1. Fibers C1 and C2 were used as source and feedback fibers, respectively.

5.3 Characterization of the calibration system

The effectiveness of the calibration system for the measurement of signal amplitudes relies on the precise knowledge of several calibration parameters. It is further assumed that some of these parameters are constant over time, and do not change with aging effects, radiation damage or mechanical disturbances (such as when opening the rotating shielding).

5.3.1 Splitter parameters

The most important parameter to know is the splitting fraction, that is the relative amount of light that the splitter distributes to each output. By construction, this parameter should depend only on geometrical effects and on the polishing quality of the common end of the fiber bundle. The splitting fraction has been measured prior to installation, and the results of one such measurements are shown in table 5.1. The splitter achieves a reasonaby homogenous output, with an RMS deviation less than 10% between different fibers.



Figure 5.11: The splitting factors for two fibers, measured over several hours. The first points may be disregarded as the PMTs used for the measurement had been just turned on. After those, the stability of the ratio is very good, within 1%.

Stability

Is is assumed that once the system is assembled in place, the splitting fraction will remain constant. This assumption was verified by repeating several times the measurement of the splitting fraction for an assembled system. The measurement was performed by selecting two central fibers (C1 and C2) as source and feedback, respectively. The feedback fiber was connected to one PMT (to ensure that the LED was stable) and the other fibers were connected in turn to a second PMT. An LED pulse was generated and the average PMT signal amplitude was measured with an oscilloscope.

The results for one of the measurements are shown in Fig 5.11; no significant variation occurs over a period of time of a few hours. Thanks to its robust steel case and precise construction, moving or shaking the mirror assembly also has no measurable effect on the splitting fraction.

Once installed, the mirror assembly will not be subject to large mechanical shocks or stresses, as the opening and closing of the rotating shielding is a very slow and carefully controlled operation. The temperature in the cavern is also kept stable to within one degrees Celsius and no other local heat source exists that could result in thermal expansion or contraction of the assembly. It was however observed that disassembling the mirror, or disconnecting the fiber bundle from it, does have a measurable effect.

Fiber	Delay]	Jitter	Rise time	Rise time σ
	[ns]	[ns]	[ns]	[ns]
Near 1 (source)	652.4	1.0	11.8	1.6
Near 2 (feedback)	1170	4	-	-
Far 1 (source)	658.6	0.8	11.3	1.2
Far 2 (feedback)	1183	2.2	-	-

Table 5.2: Timing measurements for the two fiber pairs on the Z- end of CMS. Note that the source measurement does not include the final signal cable length, while the feedback does include the return fiber length. Rise time was not measured on the feedback detector. This measurement was carried out with a pulser different from the one that is used in the final sytem, which is designed to produce sharper edges.

5.3.2 Timing

As the calibration system is also going to be used to study the timing characteristics of the signals, its light pulses must have well defined rising edges and durations.

The system is designed so that the distance covered by the light, and therefore the delay, is identical for all channels in one quarter of the detector. The four quarters can then be synchronized by an appropriate delay in the generation of the LED pulse.

The travel time along the entire fiber distribution system, including the long fiber cables, as well as the timing characteristics of the pulse have been measured prior to installation. An LED pulse was injected at the source fiber and two PMTs were connected, one at one of the bundle outputs and another one after the feedback fiber. The results for the two quarters on the Z- end of CMS are reported in Table 5.2.

5 The calibration and monitoring system

Chapter 6

Detector characterization and testing

At the time of writing, the BHM detector units are being assembled and will be ready for installation by the end of January 2015.

6.1 Characterization of PMTs

Prior to assembly into the detector units, all the forty Hamamatsu PMTs have been characterized. The characterization procedure included measuring their Quantum Efficiency, their gain and their dark count rate as a function of the operating High Voltage.

Quantum Efficiency has been measured at CERN with a specialized device. The measurements for the forty PMTs (Fig. 6.1) show good uniformity and agreement with the manufacturer specified value.

6.1.1 Dark Count Rate

The Dark Count Rate (DCR) of a photomultiplier is defined as the rate of signal pulses exceeding half the amplitude of a single photon signal, recorded when no light is incident on the photocathode. Dark counts are caused primarily by spontaneous emission of electrons from the photocathode material and are highly dependent on the applied high voltage.

Measurement of Dark Count Rate is straightforward and fast, and was carried out using readily available VME electronics as a readout. Batches of eigth PMTs each were connected to a CAEN V814 discriminator [66], whose ECL output was fed to a CAEN V560 scaler [76]. I wrote a C++ application that configured the discriminators with a threshold and acquired data for a fixed amount of time. The application loops



Figure 6.1: Quantum Efficiency Measurements for the R2059 PMTs.



Figure 6.2: Setup used for gain and DCR measurements.



Figure 6.3: Dark Count Rates for a sample of the PMTs.

over different thresholds repeating the acquisition in order to find the half-photoelectron point. The acquisition then stops and allow to set a different bias voltage.

Measurements for some of the forty PMTs are shown in Fig. 6.3. The curves are not uniform between different devices, but the absolute count rate is low and is not a concern. In most devices, a relatively flat part of the curve can be found, where the behaviour is more stable with respect to variations of the bias voltage.

6.1.2 Gain Measurement

Measuring the absolute gain of a photomultiplier requires a calibrated light source (or reference photodetector) that was not available to us. It is however sufficient for our purposes (make the gain approximately uniform over all detector channels) to measure the relative gain of all the PMTs with respect to a reference device.

The relative gain measurement was carried out for all forty PMTs using the working principle and some of the parts of the detector calibration system (Fig 6.2). An UV LED was connected to one leg of the fiber bundle, and the others were connected to individual PMTs using a simple and reproducible coupling. One of the PMTs, a spare that is not going to be installed in the detector, was connected to a leg assigned as feedback. This particular PMT was kept at a constant voltage (2000 V) and it provided a reference value, while the others were measured in the range 1400 V to 2000 V.

The LED was pulsed with 500 ns square pulses of adjustable amplitude by an Agilent pulse generator and the PMT outputs were digitized by a CAEN v1721 ADC [41] and acquired by a Labview application. The relative gain of the PMTs under test, shown



Figure 6.4: Relative Gain Measurements for the 40 R2059 PMTs.

in the plots of Fig. 6.4, was computed by dividing the absolute charge measurement for the value of the reference PMT, and applying the splitting fraction coefficient measured previously (Section 5.3.1).

While some significant differences were found within the 40 PMTs, they fall in acceptable range of variation, and it is possible to operate them all at an homogenous gain through an appropriate setting of the bias voltage.

6.2 Characterization of detector units

In order to complement test beam measurements and validate the final assembly procedure, a sample of detector units was tested with cosmic rays in Bologna. More measurements are foreseen before the installation to accumulate statistics.

The use of cosmic rays, which are predominantly muons at sea level, reflects more accurately the particle composition of MIB with respect to the test beam data from DESY. Despite the smaller statistics, the analysis procedure used for cosmics is the same used for test beam data, already described in Section 3.4.2. The first two measurements with cosmics confirmed the directional discrimination capabilities of the detector units, as shown in the plots in Fig. 6.5.

6.2.1 SiPM based cosmic ray telescope

The measurements with cosmic rays have been carried out with the use of a versatile cosmic ray telescope developed by INFN Bologna. This device is based on a set of plastic scintillator tiles readout with Wavelength Shifting fibers and Silicon Photomultipliers; one such tile, partially disassembled, is shown in Fig. 6.6.

The telescope planes are optimized to allow simultaneous measurement of two units using only three scintillator tiles, as can be seen in Fig. 6.7. The units are mounted back-to-back, with one measuring forward particles and the other measuring backward particles. After sufficient statistics has been collected, the units are exchanged.

The readout electronics is a custom board that provides tunable bias voltage, signal amplification and digitization for up to eigth channels [77]. The board includes an FPGA with fully programmable trigger logic, allowing any combination of the eigth channels. This telescope was originally developed for measurements of scintillation detector proto-types, and I contributed by developing the FPGA firmware and the DAQ software library. The software interface has been developed using LabVIEW [78] and its user interface is shown in Fig. 6.8.



Figure 6.5: The experimental Forward and Backward distributions are plotted along with a fit to the Backward distribution, and the same scaled by $P(B)/P(F) = 10^3$. The fit curve is a combination of a gaussian with an added exponential tail. The x coordinate of the intersection between scaled fit and Forward distribution is the optimal discrimination amplitude. The scale is different with respect to test beam data due to a different bias voltage applied to the PMT. Low amplitude entries in the Foward data are due to imperfect trigger geometrical acceptance and should be disregarded.



Figure 6.6: One of the tiles of the cosmic telescope. The SiPM housing is visible at the top.



Figure 6.7: The cosmic telescope installed in a standard 19" rack in Bologna.



Figure 6.8: The LabVIEW based Graphical User Interface of the SiPM versatile readout card.

6 Detector characterization and testing

Conclusions

After the successul discovery of the Higgs Boson, the LHC has been upgraded in 2013 and 2014, allowing it to reach eventually its target beam energy of 7 TeV and luminosity of $2 \cdot 10^{34}$ cm⁻² s⁻¹. The CMS experiment has been upgraded as well, in order to maintain it highly efficient in the presence of increased luminosity and backgrounds.

The changes made to LHC parameters are expected to produce an increase in the production of MIB, and the CMS detector has been equipped with a new set of subdetectors with the objective of measuring luminosity and machine background. The *Beam Radiation Instrumentation and Luminosity* (BRIL) project has been established with the objective of operating and maintaining the new systems.

Among these detectors is the new *Beam Halo Monitor*, a device that uses Cherenkov radiation to detect MIB particles at high radius (1.8 m). This detector is capable of reliable identification of beam related background in the context of high particle flux generated by pp collisions in CMS. To achieve this performance, it makes use of the directional nature of the Cherenkov emission, as well as the timing information associated with the signal. The detector design has been validated with testing campaings at particle beam facilities and with the use of cosmic rays.

As part of my work on this detector, I collaborated with the CMS HCAL group for the development of the readout electronics which has been adapted to work for BHM. I also developed and built a calibration system that will allow to monitor the detector performance over time.

All the issues related to installation inside the CMS cavern have been solved and the detector will be installed in the first months of 2015. This time scale will allow BHM to be ready to take measurements when the first beams after the machine upgrades will start circulating in the LHC, which is currently planned for March 2015.

Appendix A

Bridge FPGA implementation details

This Appendix is the latest version of the Bridge FPGA documentation as of this writing. Newer versions are available online [54].

A.1 Introduction

The main purpose of the Bridge FPGA is providing access to status and configuration parameters of the different components mounted on the HF QIE Board. These include the QIE10 chips, the two main FPGA, the GBTX and the VTTX chips.

The Bridge FPGA implements an I^2C slave that receives commands from the ngCCM board via an I^2C bus on the crate backplane. These commands can be directed to the Bridge itself or to other I^2C slaves on the board. The Bridge translates the I^2C commands that it receives into the appropriate format for devices that use different protocols, such as the QIE10.

Since the real I^2C devices have conflicting addresses and different voltage levels, they are not attached to a traditional I^2C bus topology; instead each device has its own I^2C bus connected to the Bridge. An internal register on the Bridge selects the active I^2C bus, as shown in Fig. A.1. The slave present on the Bridge FPGA itself is always connected.

To address a real I^2C device, it is necessary to write first the correct value to the I^2C select register; it is then be possible to communicate directly with the addressed device. The selected I^2C bus remains connected until a different one is selected. On the other hand, devices which are not I^2C , such as the QIE and the temperature sensor, are controlled through the slave on the Bridge, and do not require this preliminary operation; their registers are mapped as if they were internal registers of the Bridge and should be



Figure A.1: Block diagram of the Bridge Firmware: the internal I^2C slave controls the I^2C and JTAG multiplexer.

accessed as such (the only difference is in the access time).

A.2 Interface with ngCCM

The ngCCM can either address the I^2C slave on the Bridge FPGA or one of the other slaves connected to the Bridge. All these slaves have slightly different cycle formats.

The description below applies only to the slave on the Bridge itself. Write operations are straightforward; only one I^2C cycle is required:

- Master (ngCCM) transmits Start command.
- Master transmits 7-bit address of the Bridge FPGA (0001000).
- Master transmits 1 bit logic 0, indicating I²C write.
- Slave (Bridge) transmits ACK if the address is correct otherwise it transmits NACK and the remainder of the cycle is ignored.
- Master transmits 8 bits of the register address [7:0].
- Slave transmits ACK if the address is recognized as valid, otherwise it transmits NACK and the remainder of the cycle is ignored.
- Master transmits 8 bits of data.

- Slave transmits ACK. Data is not checked for correctness or consistency. The last two operations should be repeated depending on the target register length, up to a maximum of 48 times. The first byte transmitted is the least significant.
- Master transmits Stop command.

Upon a successful completion of a write cycle, the Bridge either updates its own internal register or issues a write operation to the specified register on the specified component, using the required protocol. The operation is assumed to be successful and no feedback is provided directly (although it is generally possible to read-back the register contents later).

The write operation to the targeted register requires a variable amount of time to complete, depending on which component is being addressed. If a second write cycle is initiated by the ngCCM while the Bridge is still busy, the Bridge will send a NACK and ignore the cycle. The maximum amount of time required for a write is approximately 10 ms. The I²C master on the ngCCM does not support clock stretching, therefore read operations require two separate I²C cycles. The first cycle is an I²C write that specifies the desired component and register addresses, while the second cycle is the actual data read. The sequence is the following:

- Master (ngCCM) transmits Start command.
- Master transmits 7-bit address of the Bridge FPGA (0001000).
- Master transmits 1 bit logic 0, indicating I²C write.
- Slave (Bridge) transmits ACK if the address is correct otherwise it transmits NACK and the remainder of the cycle is ignored.
- Master transmits 8 bits of the register address [7:0].
- Slave transmits ACK.
- Master transmits Stop command.

The data value is read from the target register with a fixed time delay after the completion of the first cycle, and it is then kept available for readout with the second cycle. After the first cycle, the ngCCM must wait for at least 10 ms, before issuing the second cycle, with the following format:

- Master (ngCCM) transmits Start command.
- Master transmits 7-bit address of the Bridge FPGA (0001000).
- Master transmits 1 bit logic 1, indicating I^2C read.

- Slave (Bridge) transmits ACK if the address is correct otherwise it transmits NACK and the remainder of the cycle is ignored.
- Slave transmits 8 bits of data.
- Master transmits ACK. The last two operations should be repeated according to the target register length, up to a maximum of 48 times. The first byte transmitted is the least significant.
- Master transmits Stop command.

Address	Component	Register	Mode	Data size
0x00	Bridge	ID string	R	32 bits
0x01	Bridge	ID string continued	R	32 bits
0x04	Bridge	Firmware Version	R	32 bits
0x08	Bridge	Ones	R	32 bits
0x09	Bridge	Zeroes	R	32 bits
0x0A	Bridge	OnesZeroes	R	32 bits
0x0B	Bridge	Scratch	R/W	32 bits
0x10	Bridge	Status	R	32 bits
0x11	Bridge	I2C select	R/W	32 bits
0x12	Bridge	Clock Counter	R	32 bits
0x13	Bridge	RES_QIE Counter	R	32 bits
0x14	Bridge	WTE Counter	R	32 bits
0x15	Bridge	BkPln_Spare_1 Counter	R	32 bits
0x16	Bridge	BkPln_Spare_2 Counter	R	32 bits
0x17	Bridge	BkPln_Spare_3 Counter	R	32 bits
0x22	Igloo	Main FPGAs controls	R/W	32 bits
0x24	Bridge	Pulser A Configuration	R/W	32 bits
0x25	Bridge	Pulser B Configuration	R/W	32 bits
0x30	QIE	Daisy Chain 0	R/W	384 bits
0x31	QIE	Daisy Chain 1	R/W	384 bits
0x32	QIE	Daisy Chain 2	R/W	384 bits
0x33	QIE	Daisy Chain 3	R/W	384 bits

A.3 Registers accessible through the Bridge FPGA
ID String (0x00-0x01 - R)

The Identification String registers contain 4 ASCII chars each, reading "HFRM" and "Brdg".

Firmware version (0x04 - R)

31:24	23:16	15:8	7:0
Major Version	Minor Version	SVN	revision

Status (0x10 - R)

31:10	9	8	7:4	3:0	
Reserved	BkPln_RES_QIE	BkPln_WTE	Reserved	BkPln_GEO	

The Status register includes information picked up from the Backplane lines. The BkPln_GEO lines identify the slot within a crate.

I^2C select (0x11 - R/W)

This register selects the active I^2C slave according to the following table.

I2C bus ID	Component
0x00	VTTX 1
0x01	VTTX 2
0x02	VTTX 3
0x03	VTTX 4
0x04	VTTX 5
0x05	VTTX 6
0x06	Top Readout FPGA
0x07	Bottom Readout FPGA
0x08	Unique ID chip
0x09	Pulser Mezzanine

Main FPGA controls (0x22 - R/W)

This register is used to control the reset and configuration of the two Main FGPAs.

31:10	9	8	7	6	5	4:1	0
Reserved	Top	Bottom	Top	Bottom	JTAGsel	Board	FPGA
	Reset	Reset	TRST	TRST		Select	Select

The JTAG Select fields allow programming the two Main FPGAs by connecting them to the backplane JTAG lines. The Board field is matched against the slot number picked up from the Backplane (and available as BkPln_GEO in the status register). The FPGA field chooses between Top (0) and Bottom (1) FPGA. The other fields are directly connected to the respective FPGA pins.

Pulser A Configuration (0x24 - R/W), Pulser B Configuration (0x25 - R/W)

These registers are used to configure the parameters of the pulse generator for the A and B channels respectively.

31:16	15:14	13:2	1:0
Trigger Delay	Reserved	Pulse Pattern	Trigger Select
Trigger Select Trigger Source			
0b00	None - Pu	llser disabled	
0b01	Co	ounter	
0b10	BkPln_	RES_QIE	
0b11	BkPl	n_WTE	

The Pulse Pattern field is the pattern that is output: the pattern is loaded in a shift register after the Delay counter has elapsed, and is then shifted out (msb-first) by a 240 MHz clock. Each bit therefore corresponds to one sixth of a clock cycle. It is possible to create pulses from a minimum of about 4 ns (only one bit set to one) up to 50 ns wide (all ones).

The Delay field is a 16 bit unsigned integer that specifies how many 40 MHz clock cycles the pulse must be delayed w.r.t. the trigger signal.

QIE registers

The QIE chips are connected to the Bridge using a custom serial protocol; there is only one 64 bit register on the QIE [47]. The 24 QIE chips mounted on the board are arranged in 4 daisy chains of 6 chips each; each chain must be programmed in a single serial operation. The bridge FPGA presents the daisy chain as a single 384 bit register.

The daisy chains are connected in order of increasing QIE number, and the data is shifted in lsb-first. The mapping between the bits of the Bridge register and those of the individual QIE registers is shown below for the first daisy chain, the others follow the same order.

Register	383:320	319:256	255:192	191:128	127:64	63:0
QIE	QIE 1	QIE 2	QIE 3	QIE 4	QIE 5	QIE 6

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Glossary

- ASIC Application Specific Integrated Circuit. 29, 52, 55, 57
- FPGA Field Programmable Gate Array. 29, 52–57, 61–66, 69–71, 74, 75, 84, 95, 101–106
- I²C Inter-Integrated Circuit. 55, 64–66, 75, 84, 101–103, 105
- JTAG Joint Test Access Group. 55, 66, 70, 102, 105
- QIE10 Charge Integrator and Encoder version 10. 55–59, 64, 101
- QIE Charge Integrator and Encoder. 55, 57, 60-62, 64, 65, 71, 75, 77, 101, 104, 106
- VME Versa Module Eurocard. 54, 55, 66, 67, 75
- µHTR µTCA HCAL Trigger and Readout. 52, 69–74
- µTCA Micro Telecommunications Computing Architecture. 52, 54, 66–68, 70, 71, 73, 74
- ngCCM next-generation Clock Control and Monitoring. 53, 55, 74, 75, 101-103
- ngFEC next-generation Front End Controller. 53, 74, 75
- BHM Beam Halo Monitor. 28, 33, 35, 36, 38–42, 45, 46, 51, 52, 54, 55, 57, 59, 63, 64, 66–74, 77, 78, 83, 91, 99
- CMS Compact Muon Solenoid. 4, 7, 8, 13–18, 22–24, 26–31, 33, 36, 37, 39–44, 46, 51, 52, 54, 66–69, 71, 72, 78, 79, 89, 99
- LHC Large Hadron Collider. 3-11, 13, 15, 17, 21, 25-31, 53, 63, 68, 72, 77, 84, 99

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