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A novel Beam Halo Monitor for the CMS experiment at the LHC

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Abstract: A novel Beam Halo Monitor (BHM) has been designed and built for the CMS experiment at the LHC. It will provide an online, bunch-by-bunch measurement of background particles created by interactions of the proton beam with residual gas molecules in the vacuum chamber or with collimator material upstream of CMS. The BHM consists of two arrays of twenty detectors that are mounted around the outer forward shielding of the CMS experiment. Each detector is comprised of a cylindrical quartz radiator, optically coupled to a fast ultraviolet-sensitive photomultiplier tube from one end and painted black at the opposite end. Particles moving towards the photomultiplier tube will be detected with time resolution of a few nanoseconds, allowing to measure the flux of background particles produced upstream of CMS and suppress signals from collision-induced products. Monte Carlo simulations were performed to optimise the detector design. Prior to installation, the performance of the prototype detectors was measured in test beams quantifying the detector’s direction-sensitive response and time resolution. The BHM was installed during the first LHC long shutdown (LS1) and is currently being commissioned. Design considerations, results from the test-beams supporting the design and the installation of the BHM in the CMS are presented.

Keywords: Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Cherenkov and transition radiation; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc)
1 Introduction

The performance of the Compact Muon Solenoid (CMS) detector [1] at the CERN’s Large Hadron Collider (LHC) [2] depends most notably on the quality of the delivered beams to the experiment. Machine-induced background (MIB) [3] has an impact on the efficiency of the CMS trigger and the quality of the data recorded. MIB is generated by interactions of beam particles with residual gas molecules in the vacuum chamber or with the aperture restricting components of the accelerator, such as the tertiary collimators (TCTs).

The former component of the MIB is known as ‘beam gas’, whereas the latter component is known in the experiments’ community as ‘beam halo’ or ‘collimators tails’. All of these expressions refer to the produced secondary particles that reach the experimental cavern from the LHC tunnel and their direction of motion is almost parallel to the incoming beam. Nonetheless, it should be clarified that the primary ‘beam halo’ is actually the population of beam protons characterized by offsets in the transverse coordinates i.e. travelling in large radial amplitude around the beam axis.
and being captured mostly by the LHC collimation system. In every step of the multi-stage cleaning system of the LHC, more halo particles are captured but also secondary showers are created by the interaction of the beam particles with the collimator material. The term ‘beam halo’ will be used in this article as the type of MIB consisted of secondary particles (mostly muons) that stem from the interactions of the beam halo particles at the tertiary collimators and arrive in large radius into the CMS cavern.

During the first years of the LHC operation, the CMS was equipped with the Beam Scintillation Counter (BSC) [4]. The BSC was designed for the measurement of the luminosity up to $10^{29}$ cm$^{-2}$s$^{-1}$ and for the purpose of monitoring MIB rates and triggering scattering events. The system was based on scintillators. Towards the end of Run I, the flux of particles saturated the BSC. In addition, the time resolution was not sufficient for LHC beams with 25 ns bunch spacing.

After the first scheduled long LHC maintenance period, the Long Shutdown 1 (LS1), the LHC is expected to exceed the nominal luminosity of $1.0 \times 10^{34}$ cm$^{-2}$s$^{-1}$, with bunches of intensity $O(10^{11})$ protons, separated by 25 ns and an energy of 6.5 TeV per beam [5]. The rate of beam particle interactions with residual gas molecules will be enhanced due to larger beam currents and cross sections. The increased potential of electron cloud [6] due to the 25 ns bunch spacing may lead to a higher vacuum pressure resulting in an increased number of interactions with residual gas molecules. In addition, tighter collimator settings will be needed to absorb beam halo and potential beam losses [7], hence protecting the superconducting final focus magnets from additional heat load. All these effects motivate a high performance monitoring of the MIB at the CMS.

The Beam Halo Monitor (BHM) has been designed, built and installed in the CMS during LS1, as part of the upgrade of the CMS background monitoring instrumentation [8]. It will provide a measurement of the MIB arriving at high radius from the LHC tunnel, which is mainly beam halo muons, originating from the interactions of the beam halo of the LHC beams with the tertiary collimators and travelling almost parallel with the incoming beam. The BHM is installed about 20.6 m away from the CMS interaction point (IP) at a radius of 1.8 m from the beam axis, parallel to the beam axis.

The BHM is designed to be more sensitive to the MIB than to the collision-induced particles. This feature is achieved by detecting the Cherenkov light in a quartz bar produced by the MIB particles with a photomultiplier tube coupled at the one end of the radiator and absorbing most of the light produced by the collision-induced particles with black paint at the opposite end. Therefore, the BHM overcomes the limited performance of the BSC by exploiting the prompt and directional nature of Cherenkov light. In addition, it is designed to be sufficiently radiation hard to operate efficiently during the full LHC lifetime, including the High Luminosity LHC [10].

The MIB measurement by the BHM will complement the one by the Fast Beam Conditions Monitor (BCM1F) detector, installed at lower radius (r=7.2 cm) and closer to the IP (1.83 m from the IP) [9]. The BCM1F is based on diamond detectors, operated as solid-state ionization chambers and is equally sensitive to both collision products and MIB particles. The BCM1F is able to distinguish the two components thanks to its fast response (better than 12.5 ns) and location and hence, it is used as both luminosity and MIB monitor. Due to low radius acceptance, the BCM1F is more sensitive to the products of local beam gas interactions of beam protons in the Long Straight section of the LHC tunnel and its measurement serves mostly the inner parts of the CMS detector, such as the pixel and the outer tracker. The BHM installed at high radius is designed to provide valuable
information for the rate of the beam halo component of MIB and has an overlapping acceptance with the CMS sub-detectors at higher radius, such as the muon chambers and the calorimeters, which get contaminated by the beam halo muons.

In this article, the BHM design is introduced. First, the detector concept and its design requirements are presented along with a study of the properties of the particles fluxes at the detector location as estimated based on FLUKA [11] simulations. The choice of the components and the mechanics are described in detail. Special emphasis is given on the direction-sensitive response of the detectors based on Geant4 [12] simulations, followed by the validation of the performance of prototype units during test beams. To conclude, an overview of the new system is presented.

2 Detector concept

The technology choice for the BHM is a Cherenkov radiator read out by a photomultiplier tube. The signal from Cherenkov radiation is prompt, directional and produced only by relativistic charged particles. As a radiator, quartz was selected because of its large photon yield, robustness and radiation hardness. As a photodetector, a fast photomultiplier tube with a quartz window, matching the size of the quartz radiator, is used.

2.1 Choice of location

The MIB flux arrives in the CMS experimental cavern in time with the incoming beam bunches and can be distinguished from the intense flux of collision-induced particles also based on the time of arrival at the detector location. At the LHC, the bunch spacing of 25 ns imposes a maximum time separation between the incoming MIB fluxes and prompt collision products of 12.5 ns. There are seven locations in the CMS cavern that correspond to this maximum time separation and they are depicted at the sketch as planes numbered from 1 to 7. The BHM is installed in one of these locations, at a distance of 20.6 m (68.75 ns) from the IP at a radius of 1.8 m with respect to the beam axis shown in figure 1. This sketch shows a sagittal view of the positive end of the CMS and the directions of the fluxes arriving at the selected BHM location.

In figure 1, another feature of the selected location is explained. The blue numbered arrows represent the bunches of beam 1 and the red numbered arrows the bunches of beam 2. The number in each arrow corresponds to the number of the bunch within an orbit. These bunches would collide at the IP, indicated by the yellow plane. This figure shows the products of the first collision, travelling with the outgoing beam, arriving at the detector location only 68.75 ns after the first collision. This feature offers the additional asset of performing a background measurement for the first six bunches of each orbit without the presence of collision products.

To estimate the expected flux from MIB and collision-induced particles, FLUKA simulations were performed using the CMS geometry. The program DPMJET-III [13] was used to generate proton-proton collision events at 7 TeV. An inelastic cross-section of 85 mbarn and a luminosity of $10^{-34} \text{cm}^{-2} \text{s}^{-1}$ are assumed. The MIB particles were generated using the output of MARS code simulations [14] for LHC nominal settings of $1.15 \times 10^{11}$ protons/bunch, 25 ns bunch spacing and a pressure profile as described in ref. [15], and transported into the CMS cavern using FLUKA.
**Figure 1.** A schematic of a quarter of the CMS showing the candidate locations (red planes) and the directions of the different fluxes arriving at the chosen BHM location, indicated by number 6: the products originating from collisions (yellow), the outgoing beam 2 (red) with the beam 2 halo muons (red dots), the incoming beam 1 (blue) with the beam 1 halo muons (blue dots).

**Figure 2.** The sketch shows the time structure of incoming and outgoing beams and their beam halo muons and the collision-induced particles. Time equal to 0 ns corresponds to the time of the first collision within an orbit. The yellow band at position 0 ns corresponds to the IP. In blue, the incoming bunches and beam halo muons of beam 1. In red, the incoming bunches and beam halo muons of beam 2. The yellow-framed bunches are the ones that are outgoing and the prompt collision products are travelling in time with them.

All charged particles, with energy above the Cherenkov radiation production threshold for quartz, were counted.¹

¹The Cherenkov thresholds for each particle type for a quartz material of n=1.46 are: electrons/positrons 190 keV, muons 39 MeV, protons 350 MeV, charged pions 52 MeV.
The MIB flux as a function of the distance from the beam axis and the ratio of the MIB flux to the flux of collision-induced products are shown in figure 3 (left). The flux of collision-induced products is almost three orders of magnitude larger than the flux of MIB particles. Hence, the BHM should be able to suppress particles originating from collisions to better than $10^{-3}$, in order to have a higher sensitivity towards MIB particles.

![Figure 3. Left: the particles fluxes for charged particles, with energy above the threshold for Cherenkov radiation production, arriving at the chosen detector location as a function of the radial distance from the beam axis; particles induced by from proton-proton (pp) collisions (black) and from MIB (red). Right: the ratio of the two distributions.](image)

The rate of MIB particles arriving at the detector location for nominal LHC beam conditions is about one particle per cm$^2$ per second. In order to provide a measurement for all 2808 filled bunch crossings, for an integration period of a so-called luminosity section of $2^{18}$ LHC orbits, corresponding to about 23 seconds, a total acceptance of more than 300 cm$^2$ per beam is required.

### 2.2 Properties of the expected particle fluxes

A substantial fraction of the MIB flux consists of muons, originating from pion decays. Pions are produced copiously by beam halo particles impinging on the tertiary collimators or in proton interactions with residual gas molecules in the vacuum chamber. These muons arrive almost in time with the incoming bunches. Muons are also produced in collisions. In figure 4, the angular and energy distributions of muons arriving at the BHM location are shown. As can be seen in figure 4 (left), MIB muons move almost parallel with the incoming beam and their energy distribution peaks at about 10 GeV. Muons stemming from collisions move towards the BHM in the opposite direction, and their energy distribution is softer, as shown in figure 4 (right).

In addition to muons, other collision-induced products produce secondary particles and activate the material in the cavern, leading to electrons and positrons randomly distributed in angle. The angular and energy distributions of these particles are shown in figure 5 (left). In contrast to the muons, the electrons/positrons arrive from both directions with large angular spread, due to Coulomb interaction with the atoms of the material in the cavern. Their energy is less than 1 GeV.

A large fraction of these particles with energy below 15 MeV, is suppressed by a 1 cm thick mild steel shielding, as explained in section 5.2. For the electrons/positrons moving in a polar angle range between 0° and 90° the relative impact of this shielding is illustrated in the arrival time.
distribution shown in figure 5 (right). Prompt muons from the primary interaction are expected at about 69 ns. The delay of the electrons/positrons is due to multiple scattering, spiral paths in the magnetic field and in the case of activation, by a delayed decay.

Figure 4. Muon fluxes at the position of BHM as a function of the energy and the polar angle with respect to the incoming beam. Left: muons from MIB. Right: muons from collision products.

Figure 5. Left: electron/positron flux at the position of BHM originating from collision-induced products as a function of energy and polar angle with respect to the incoming beam. Right: the time of arrival of the electrons/positrons moving with polar angles between 0° and 90° at the BHM location with respect to the time of the collision.

2.3 Environmental conditions

Based on the FLUKA simulations, the expected dose at the detector location is less than 20 rad per fb$^{-1}$. At the end of the LHC program an integrated luminosity of 3000 fb$^{-1}$ is planned. Therefore, after applying a safety margin, the detector components are chosen such that their performance does not deteriorate significantly after a dose of 100 krad.

For the mechanical design of a detector unit the magnetic fringe field at the BHM position must be considered. To avoid a performance loss of the photomultiplier tube, a proper shielding for the detector has been developed.
3 Design choices

3.1 Choice of components

3.1.1 Quartz as a Cherenkov radiator

Fused quartz is an amorphous form of silicon dioxide (SiO$_2$). Two types of fused quartz were examined: natural fused quartz and synthetically fused silica or synthetic quartz. The former is produced by the electrical fusion process, which uses resistance heating to melt highly refined quartz crystalline silica sand. The latter is obtained by flame hydrolysis of silicon tetra-chloride, SiCl$_4$.

![Figure 6](image-url)

**Figure 6.** Left: the transmission coefficients for natural and synthetic fused quartz as a function of the wavelength before and after irradiation with a dose of 100 krad. Right: the transmission coefficient as a function of the wavelength before and after irradiation with a dose of 100 krad, for the optical coupling materials.

Quartz is transparent for near ultraviolet light where a fraction of the Cherenkov radiation is sufficient for detection. The transmission coefficient was measured as a function of the wavelength with an integrating sphere, which was associated with a spectrometer, by comparing the intensity of the direct incoming radiation with the intensity of the transmitted radiation. The results are shown in figure 6 (left) for natural and synthetic fused quartz samples (3 cm long) before and after irradiation with $\gamma$ rays of a dose of 100 krad. As can be seen, the transmission coefficient of the natural fused quartz drops at low wavelength from almost 90% to 50% after irradiation. No significant deterioration was observed for the synthetic quartz, in agreement with results given in ref. [16]. Hence, synthetic fused quartz, produced by J-plasma$^{\textregistered}$ [17] with an interstitial hydrogen content approximately $1.0 \times 10^{18}$ mol/cm$^3$ [18], is used as the radiator.

3.1.2 Optical coupling and black paint

An optical coupling was used to join the quartz bar and the tube to avoid any reflections from the quartz-air interface between the radiator and the photomultiplier tube window. Two coupling schemes are investigated, using either optical glue, RTV 3145$^{\textregistered}$ [19], or optical gel, DC-93500$^{\textregistered}$ [20]. Both of them are silicone-based, matching the refractive index of the quartz bar and the photomultiplier tube window.
In figure 6 (right), the transmission coefficient as a function of the wavelength is shown for each scheme before and after irradiation with a dose of 100 krad. For this measurement, the integrating sphere setup was also used and the samples consisted of two polished quartz disks of 1 mm thickness coupled with the material under test. For both coupling schemes, no change after irradiation was observed. To keep flexibility, for the optical coupling a 1 mm disk made of silicon optical gel is used.

To ensure air-free contacts, the contact surfaces were covered with silicon oil, Rhodorsil® [21]. Then, the detector units were put in a vacuum chamber, as shown in figure 7 (left), where possible air bubbles from the contact surfaces are removed and hence a flawless path for the Cherenkov light produced in the radiator to the photocathode was achieved.

The end surface of the quartz bar, opposite to the photomultiplier tube, was painted black to minimize the reflections of the Cherenkov light emitted by particles of opposite flight direction. A black paint with reflection coefficient of less than 1% for the wavelength range of interest was chosen [22]. To allow the injection of light pulses for the calibration via an optical fiber [23], a hole of 3 mm in the centre of the end surface was left unpainted. To align the hole with the centre of the detector unit, a lathe machine was used to mark the point that should remain unpainted, as shown in figure 7 (middle). A complete detector unit is shown in figure 7 (right).

### Figure 7.
Preparation of a detector unit. Left: the unit is placed in a vacuum chamber to outgas any unwanted air bubbles present in the contact surfaces of the optical coupling both to the quartz radiator and the PMT. Middle: the alignment of a hole in the foreseen black painted surface to allow for light injection by the calibration system. Right: black paint is applied to the front face of the radiator, excluding the marked hole that remains unpainted.

#### 3.1.3 Photodetector

The photodetector chosen is a Hamamatsu® [24] R2059. The spectral response spans from 160 nm to 650 nm. The quantum efficiency was measured and verified. A maximum value of 27% around 400 nm, as shown in figure 8, was found. The rise time of the photomultiplier tube is 1.3 ns, allowing a sufficient time resolution in comparison to the 12.5 ns time difference expected between signals from incoming MIB and collision-induced products. The diameter of the quartz bar was chosen to match the quartz window of the PMT tube of 51 mm. To ensure full coverage of the photomultiplier window, the nominal quartz bar diameter was increased by 1 mm (52 mm).

Simulations were performed using Geant4 transporting 4 GeV muons through the quartz radiator, generating and transporting the Cherenkov light in the radiator, and mapping it with the quantum efficiency of the photocathode. The spectrum of the Cherenkov light produced is shown in figure 9 (left). The spectrum of photons generating a photoelectron is shown in figure 9 (right) spanning
mostly from 300 nm to 600 nm, covering a relatively large fraction of the produced Cherenkov radiation spectrum.

Figure 8. The quantum efficiency of the R2059 as measured at CERN.

Figure 9. The wavelength of the light as simulated, when a muon of 4 GeV crosses the 10 cm long quartz radiator, entering from the centre of the front face of the bar. Left: the wavelength of the Cherenkov light produced. Right: the wavelength of the light detected by the photocathode.

3.2 Optimization of the length of the radiator

Geant4 simulations were performed to estimate the necessary length for the Cherenkov radiator. Muons of 4 GeV energy are directed to the cylindrical radiator of 51 mm diameter under a different angle $\varphi$ with respect to the cylinder axis, as sketched in figure 10. Inside the radiator, Cherenkov photons are generated and transported to the photocathode. The number of photoelectrons was determined as a function of the angle $\varphi$ and the length of the radiator $l$.

A quantity, the directional gain $D$, is defined as:

$$D (l, \varphi) = \frac{\text{Number of photoelectrons (} l, \varphi \text{)}}{\text{Average number of photoelectrons}(l)},$$

(3.1)
where the Average number of photoelectrons(l) is the average value of photoelectrons integrated over \( \varphi \). The simulation was performed for radiator length of 2 cm, 10 cm and 20 cm and several \( \varphi \) angles.

As can be seen in figure 11 (right), the directional gain increases for smaller angles and longer radiators. The length of the radiator was chosen to be 10 cm, as a good balance between directionality and compactness. The expected signal is large for small values of \( \varphi \), pointing to a high sensitivity for particles moving towards the cathode and a suppression of signals moving at larger \( \varphi \).

### 4 Performance measurements with beam

Prototypes of the BHM detectors, consisting of quartz radiators coupled to the photomultiplier tube R2059 were studied in two test-beam campaigns to verify the required performance. The first measurements, using 20 cm radiator length and 30 mm diameter, were done in the T9 area of CERN in 2012, using 4 GeV muons. Later, an electron beam of 5 GeV at the DESY II Synchrotron in Hamburg was used to study 10 cm radiator length with a 51 mm diameter.
The setup consisted of a detector unit on a frame that allowed orienting precisely the detector axis with respect to the beam axis, as shown in figure 12. Beam particles were triggered by a coincidence of signals from two scintillators placed before and after the detector. A third scintillator was used in the trigger to define a beam-spot small in comparison to the diameter of the radiator.

Two examples of photomultiplier signals obtained from muons passing through a 20 cm long quartz bar, under 30° and 150° impact angles, are shown in figure 13, demonstrating the sensitivity of the detector response with respect to the angular direction.

The waveform of the photomultiplier tube signals has an almost Gaussian shape. As a measure of its length the full width at half maximum (FWHM) is taken. For signals obtained from muons moving in the direction of the photocathode, the FWHM is distributed in figure 14 (left). From a fit with a Gaussian a mean value 3.09 ns and sigma of 0.20 ns are determined. An estimate of the time resolution is obtained by distributing the difference between the arrival times of the signal from the BHM detector and the arrival time of the signal from a fast trigger scintillator. The arrival times of the signals were defined by fixed threshold discriminators. This distribution is shown in figure 14 (right). A fit with a Gaussian results in a combined time resolution of 0.6 ns.
During the DESY test-beam, the directional response was measured varying the $\varphi$ angle from $0^\circ$ to $180^\circ$. The analogue signal of the photomultiplier was readout by a fast scope and the waveforms were stored with a 1 ns time resolution. The integrated charge was calculated by summing all the voltage values (in V) over a time window of 20 ns that included the photomultiplier waveform. The result was then multiplied by 1 ns (time resolution) and divided by the 50 $\Omega$ value of the photomultiplier channel termination in the scope to convert it to integrated charge. The distribution of the integrated signals for $\varphi$ angles of $0^\circ$ and $180^\circ$, expressed in pC, is shown in figure 15 (left). As can be seen, there is only a very small overlap between these distributions. The cumulative integrals are shown in figure 15 (right). By setting a proper threshold the efficiency to detect electrons at $0^\circ$ amounts to 99.99% and the efficiency to detect electrons at $180^\circ$ to 0.01%, a suppression factor of $10^{-4}$ for these angles.

The study, as shown in figure 11 for muons, was repeated for 5 GeV electrons, and compared to the data taken in the electron beam. The results, shown in figure 16, demonstrate the good description of the data by the Monte Carlo simulation, supporting the validity of the design study. The calculations of the ratio for the directional gain are based on eq. (3.1). The number of photoelectrons is used for the simulations, while for the data the measured signal charge is converted into the number of photoelectrons using the gain of the photomultiplier tube.
5 Integration considerations

5.1 Acceptance and rates

The cross section area of a detector unit amounts to 21.2 cm$^2$. To achieve the minimum required acceptance of 300 cm$^2$ per beam, twenty detector units were installed per CMS end, leading to an instrumented area of 424 cm$^2$ for each beam. The units were distributed azimuthally around the outer forward shielding, having an overlapping acceptance with the CMS muon chambers [25]. The expected distribution of the flux of MIB in the x-y plane in a ring covering the position of the detectors is shown in figure 17. For nominal operation conditions, as listed on page 6, each detector is expected to detect about 10–20 particles per second. The detector units positioned near the horizontal plane are expected to detect slightly higher rates than the others, as the rate of the MIB arriving is higher due to the way the beam is treated by the beam optics prior to its arrival in the CMS cavern. In addition, the flux on the y < 0 plane is lower than the one on the y > 0 because of the presence of the tunnel and cavern floor that are considered to absorb part of the MIB particles.

5.2 Shielding of the magnetic field and of low energy particles

At the location of the BHM in the CMS cavern, a fringe field less than 20 mT was measured, with axial and transverse components. The relative magnitude of these components depends on the phi-location of the detector units. The photomultiplier tube operates efficiently with a field of less than 0.01 mT [26]. To shield the photomultiplier tube from the magnetic field a three-layer structure, as shown in figure 18, is used. The outer layer is made of a mild carbon steel tube of 1 cm thickness. The outer end-caps on both sides are made of soft iron (ARMCO) of the same thickness. The intermediate layer is a 1.5 mm thick mu-metal tube, and the innermost a 0.8 mm thick permalloy tube.

Each layer is made of material with different magnetic permeability and its thickness is optimized in order to achieve maximum magnetic shielding efficiency without saturation. Simulations

Figure 16. The directional gain, D, determined from 5 GeV electron data (blue) and obtained from simulations (red) using a 10 cm long cylindrical quartz radiator.
using the Opera package [27] were performed to simulate the magnetic shielding behavior in a magnetic field of 20 mT with axial and transverse components as measured at the BHM location.

Figure 17. The flux distribution in the XY plane of the MIB flux at the detector location (Z=20.6 m).

Figure 18. Scheme of the shielding of a BHM detector unit. The mild steel tube in shown in blue, the mu-metal tube in grey and the permalloy in yellow. The radiator, the photomultiplier tube and the socket are shown in white, light green and dark green, respectively.

The reduction of the magnetic field as a function of the radius is shown in figure 19. In the presence of the external field of 20 mT, the mild steel layer (40–50 mm) attracts a magnetic flux of more than 1 T, the mu-metal layer (33.5–35 mm) attracts more than 350 mT and the permalloy layer (30–30.6 mm) less than 10 mT. The design of the magnetic shielding had to take into account also the holes in the end-caps. These holes serve as feed-through for the calibration fiber on the radiator side and for power and signal cables on the photomultiplier tube side. The estimated value of the magnetic field at the photocathode was obtained to be less than 0.001 mT, as shown in figure 19.

The magnetic shielding efficiency of the design was measured during the ramp-up of the CMS magnet in November 2014, using a BHM prototype. The prototype was installed at the BHM location parallel to the beam with an angle of 48° with respect to the horizontal plane. The shielding efficiency, defined as the ratio of the integrated signal with magnet on and off, was measured using the light pulse from the calibration system to be 98%. In addition to the shielding of the magnetic field, the mild steel tube also serves as a shielding of the radiator from electrons and positrons with
Figure 19. Opera results showing the effect of the three layers of the magnetic shielding as a function of the radial distance from the photomultiplier tube axis at the location of the photocathode.

energy below 15 MeV, being about 97% of the particles that arrive at the detector in the direction of the MIB, as shown in figure 5 (left).

5.3 Calibration system

A calibration system has been installed to monitor the long-term performance of the detector units and to provide a time reference during the commissioning phase. Figure 20 shows a sketch of the installed calibration system. A mezzanine is installed on the foreseen readout card in the service cavern equipped with UV LEDs as a light source. A fast pulser circuit drives the LEDs. The light pulse is injected into the source quartz optical fiber [28]. Each source fiber is coupled to a
twelve-fiber bundle close to the detectors. At this location, the source light is reflected by a mirror into the fibers of the bundle [29, 30]. One of the fibers is routed back to the service cavern and is readout by a reference silicon photomultiplier (SiPM), mounted on the calibration mezzanine. The choice of the SiPM as a reference photodetector was based on the easiness of mounting on the calibration mezzanine and its cost effectiveness for reading out the feedback fibers. Ten fibers are distributed to the detectors for a quarter of the BHM. SMA-type connectors are used to connect the calibration fiber to the detector [31]. The light is injected through the small hole left unpainted on the front face of the quartz bar.

![Graph of signal fit with entries 10000, mean 62.8, RMS 4.759 and pedestal mean 3.523, RMS 0.04186](image)

**Figure 21.** An example of a charge distribution from the detector acquired during the injection of a calibration light pulse.

The ratio of each detector signal to the corresponding reference silicon photomultiplier signal will be monitored throughout the lifetime of the system. In figure 21, the charge measured for the calibration pulses from a detector is shown. The average charge of about 60 pC is matching the expected charge from a signal induced by a forward MIB particle, as shown in figure 15 (left).

5.4 Installation

The BHM detector and services have been installed at the end of LS1. In figure 22, a quarter of the system is shown. The detectors were installed on an aluminium structure around the outer forward shielding of the CMS. Each photomultiplier front face position has been surveyed to be at ±20.20 m from the IP at an average radial position of 1.84 m. All of the service cables and calibration fibers in the experimental cavern were routed from the blockhouse around flexible hinges, such that there is no risk during the movement of the shielding.

The photomultiplier tube analogue signals are transmitted via high bandwidth cables [32] over 80 m to the service cavern, where the readout electronics are installed. The readout cables are double braided, with an additional mu-metal shield, coaxial cables which were chosen in order to maintain the signal quality and avoid potential electromagnetic interference and pickup along their path.

Each R2059 photomultiplier tube is supplied independently with high voltage of about 1.8 kV corresponding to a nominal gain of $10^6$. For the powering of the forty detector units, two remotely
Figure 22. A picture of a quarter of the system, with the detectors being painted blue, as installed around the CMS forward rotating shielding.

controlled modules, CAEN A1535SN [33], are installed in the service cavern. Each module has 24 individually adjustable channels, up to 3.5 kV per channel and is using SHV connectors. The photomultiplier socket is also using SHV connectors. To minimize the number of cables, a multicore cable combined with patch panels was used for delivering the high voltage from the service cavern to the experimental cavern, as shown in figure 23.

Figure 23. The BHM cabling scheme from the experimental CMS cavern to the service cavern where the readout electronics and the power supplies are installed.
6 Conclusions
A new beam halo monitor, BHM, has been designed and built for the CMS experiment. The BHM will provide feedback to the CMS experiment and the LHC on the machine-induced background. The BHM detectors exploit the characteristics of Cherenkov radiation. Being positioned at an optimal location along the beam-line, an efficient discrimination of machine-induced background particles from particles originating from collisions will be performed. Signal characteristics, time resolution and directional sensitivity of the system have been studied in test-beams and found to match the requirements for the suppression of collision-induced products of better $10^{-3}$. The time resolution of 0.6 ns will allow a bunch-by-bunch measurement of the machine-induced background. The BHM has been recently installed in the CMS and is being commissioned with first LHC beams in Run II.

Acknowledgments
We gratefully acknowledge the support for the construction of the BHM provided by CERN, INFN Bologna and University of Minnesota. We would like to thank the excellent technical and engineering support from V. Giordano, V. Cafaro, G. Torromeo, E. Albert, M. Abbas, I. Ahmed, C. Farrow, P. Trapani, S. Kilchakovskaya, A. Kurenkov, D. Dattola and the CMS integration engineering office. We would also like to thank the operation and technical teams of both the CERN accelerator division and the DESY accelerator division for their support of the test-beam facilities at CERN and DESY. We thank S. Mallows, M. Guthoff and W. Lohmann for the useful discussions.

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