Instrumentation for beam radiation and luminosity measurement in the CMS experiment using novel detector technologies

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on behalf of the CMS collaboration

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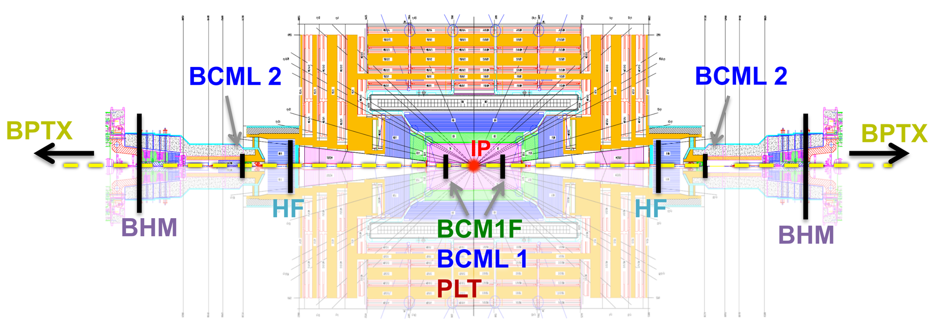
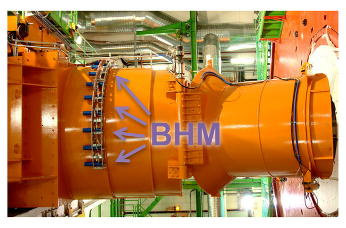
Beam Instrumentation at CMS

The Beam Radiation Instrumentation and Luminosity (BRIL) project of the CMS experiment is responsible for:

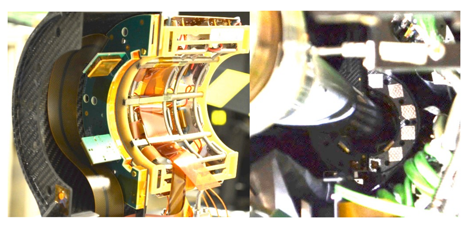
- Measuring the luminosity for online visualization and beam tuning, and offline data processing as part of many physics analyses.
- Measuring machine induced background (MIB) to quantify operational conditions and safe operation for the silicon tracker of CMS. [1]
- Provide active protection in case of intense beam loss events as part of the LHC beam loss monitoring system. The main objective is to protect the silicon Tracker at CMS from potentially damaging radiation levels. [2]
- Measuring the beam timing: The precise time of the incoming bunches with respect to the LHC orbit clock and in comparison of both beams. The position of the luminous centroid can be predicted and monitored, as important beam quality criteria.
- Input the CMS trigger system BRIL detectors can be used as part of the CMS trigger system.
- Radiation simulation of the CMS detector [3,4]: While for physics analyses of CMS data, Geant4 based simulations are used, there are many questions that have to be answered with non-event based simulations. Example applications are detector hit rates, radiation damage, activation of material. The simulation codes used for these applications are FLUKA [5,6] and MARS [7]. Proton-proton and heavy ion collisions can be simulated, as well as machine induced background simulations following a simulation of the LHC performance and the particle showers inside the LHC tunnel [8].

To achieve the goals a variety of detectors, operated outside of the central CMS data acquisition, are used. All detectors are operated during the whole LHC cycle, including the injection phase.

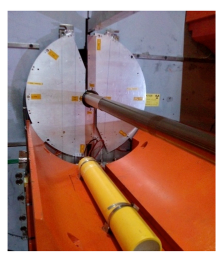




The BHM detectors, placed around the forward shielding



PLT, BCM1F and BCML1 mounted on a common carriage, placed around the beam pipe inside the pixel detector volume

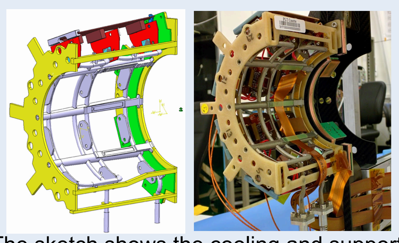


The BCML2 wheel placed around the beam pipe in the forward section

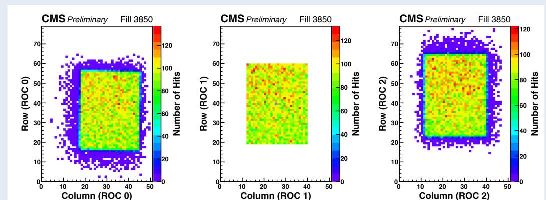
Detector systems and technologies.

Pixel Luminosity Telescope (PLT) [9]

- 16 small angle particle tracking telescopes.
- Each telescope is build from 3 planes of hybrid silicon pixel detectors developed for the phase-0 CMS Pixel detector. The detector backend readout has been adopted from the Forward Pixel system.
- A fast cluster counting signal (Fast-OR) transmits the number particles passing through a sensor plane on a 25 ns basis. Threefold coincidences of the fast-OR output are used to count luminosity particles as function of the bunch crossing number (BXID).
- The position sensitive pixel readout, operating at a trigger frequency of 2 kHz, is used to record tracking information to correct for systematic detector effects. From the reconstructed tracks in the PLT the size and position of the beam spot can be computed.



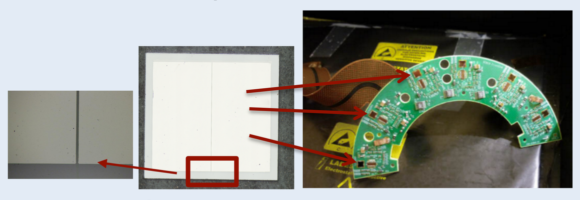
The sketch shows the cooling and support structure with one telescope. On the picture a fully assembled PLT "quarter".



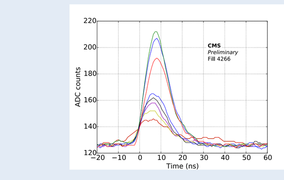
Occupancy of each plane of one telescope. The center plane has a 4x4 mm^2 mask applied to remove edge effects. The mask shadows on the other planes.

Fast Beam conditions monitor (BCM1F)

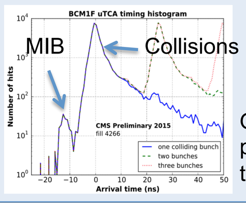
- 24 single-crystalline diamond detectors with two pad metallization
- Dedicated fast ASIC pre-amplifier in 130 nm technology
- Response to particle hits with ~10 ns FWHM
- Placed at the strategic location of Z=1.8m, where incoming machine induced background particles and outgoing luminosity products are separated in time by 12.5 ns (alternating between background and collisions in 25ns operation).
- Fast timing to discriminate machine induced background particles from luminosity products.
- Signals are discriminated and histogrammed as function of time with 4 bins per bunch crossing in a dedicated Real-time Histogramming Unit (RHU).
- A μTCA based readout system is used to process the analog pulses [10]. A modified FMC125 ADC board with 1.25 GS/s digitizes the pulse information. The GLIB carrier board is equipped with a Xilinx Virtex-6 FPGA. A peak finding algorithm measures the peak height and timing with respect to the LHC orbit clock. Both values are histogrammed dead time free in the FPGA. Advanced peak filtering will be implemented to mitigate pile-up. This system will also be used to process BPTX information in the future.



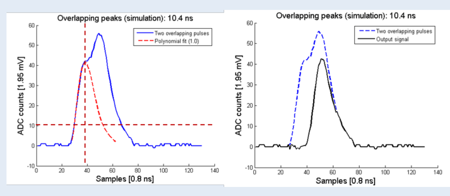
Split metallized sCVD diamond sensors and their placement on the C-shaped carrier PCB holding also the preamplifier.



Several pulses from particle hits recorded with the FMC7 ADC.



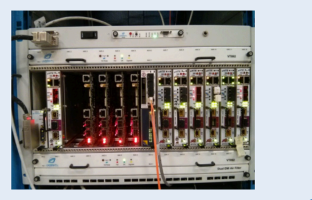
Offline processing of the bunch timing



Proposed pile-up mitigation by pulse subtraction

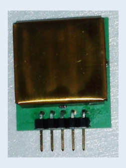
Hadron Forward calorimeter for Luminosity (HFlumi)

- Uses the hadron forward calorimeter (HF): Steel absorber with quartz fibers to detect Cherenkov light.
- uTCA based readout system of the HF detector includes a secondary readout chain used for Luminosity measurements.
- Detector hits are histogrammed as function of bunch crossing.
- Triple buffering allows dead time free readout, independent of the CMS DAQ

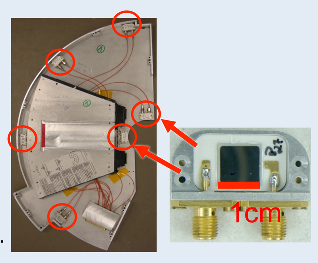


Beam Condition Monitor for Loss monitoring (BCML)

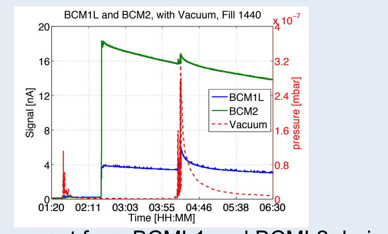
This system is part of the LHC Beam Loss Monitoring system of the LHC, using 1x1 cm^2, 400 μm thick, poly-crystalline diamond sensors instead of ionization chambers of the LHC. Since the detector current is measured directly, the low dark current of the diamond sensors are an important feature. If the current in one of the 16 channels exceed the pre-defined abort threshold, the LHC beams are automatically dumped.



BCML1 detector module. Two are mounted on each BCM1F c-shape



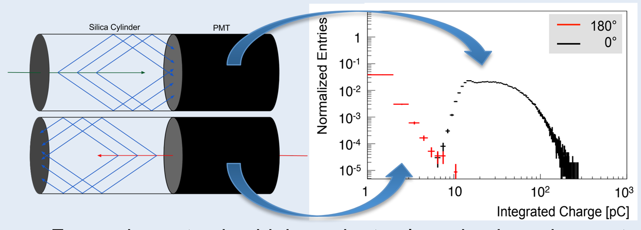
BCML2 detector module and placement on support wheel.



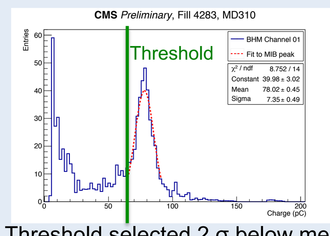
Detector current from BCML1 and BCML2 during a LHC fill. Here, bad vacuum conditions lead to beam loss and increased detector signal.

Beam Halo monitor (BHM) [11]

- Measures muons created in beam loss events, so called muon halo.
- Directional Cherenkov light created in quartz bars.
- Photomultiplier for light detection inside magnetic shielding.
- 20 detectors per beam pointing towards the LHC tunnel
- Fas timing allows additional separation of MIB hits from collision products



Forward events give high readout values, backwards event are suppressed.



Threshold selected 2 σ below mean charge of background events

Beam Position for Timing at the Experiments (BPTX)

This system uses LHC beam position monitor detectors to measure the exact timing of the incoming bunches. The detectors are placed 175 m away from the interaction point.

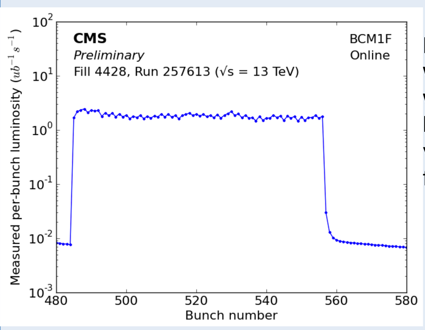
The signals are analyzed together with the orbit clocks in an oscilloscope to compute the time difference between the two beams, deltaT(B1-B2), and phases between beams and CMS clock. The signal are also discriminated and send to a logic unit to compute various technical trigger signals.

Measurement of bunch intensity is also possible and will be done in the future.

Detector performance and deliverables

Luminosity is a key measurement at CMS, influencing the results of many studies. The systems used for luminosity measurements are: PLT, BCM1F and HFlumi. An online luminosity value is reported every ~1.4 seconds (2x10^{14} LHC turns), including bunch-by-bunch values. Luminosity values are visualized in the CMS control room, and sent to the LHC control room. The online luminosity is used by the LHC to optimize the beam overlap and increase the collision rate, and bunch-by-bunch values are used to compute the emittance of the beam. For offline analyses, all luminosity values are stored in a database allowing CMS collaborators to download luminosity information and apply the latest offline calibration constants.

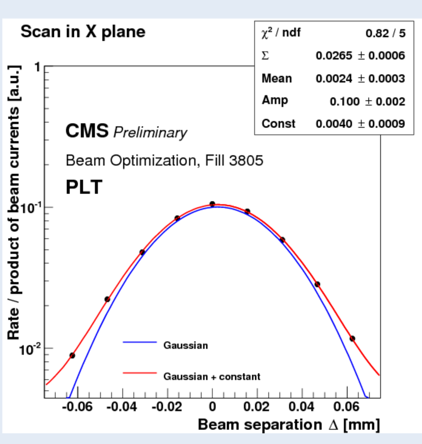
The absolute calibration of a luminometer is performed in a Van der Meer (VdM) scan. The absolute luminosity can be calculated, if the width of the beam overlap and the beam intensity is known, and put into relation with the detector readings. To measure the width of the beam overlap, both beams are offset and scanned across. The detector rate as function of beam separation is parameterized to compute the visible cross-section of this detector.



Bunch-by-bunch luminosity as measured with the BCM1F detector and recorded with the RHU system, zoomed in on one bunch train. Few out of time hits are visible after the train, which are likely from radioactivity of short lived isotopes.

Rate Luminosity relation	$R = L \cdot \sigma$
Expected Luminosity	$L = N_1 N_2 f n_b / A_{eff}$
Area of beam overlap	$A_{eff} = 2\pi \Sigma_X \Sigma_Y$
Visible cross section as function of measured parameters	$\sigma_{vis} = \frac{2\pi \Sigma_X \Sigma_Y}{N_1 N_2 f n_b} \left(\frac{Peak_X + Peak_Y}{2} \right)$

Peak: detector rate at maximum
Σ: width of beam overlap
N: bunch intensities
f: revolution frequency
n_b: number of bunches



Example of VdM scan analysis for one dimension of the PLT detector.

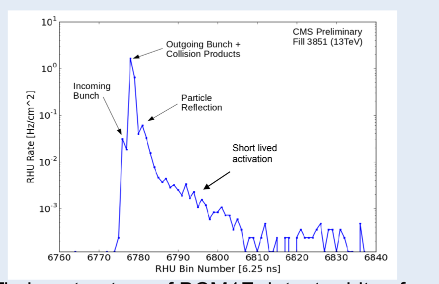
Machine induced background (MIB) particles are several order of magnitude rarer than collision products. A measurement of this background is desirable since an increase of such background is an indication for bad beam quality that may affect data taking performance. The systems used for machine induced background measurements are BCM1F, BCML and BHM.

The BCM1F is placed at low radii and most sensitive to MIB originating from local beam gas interactions. BCM1F background measurements are well correlated with the local vacuum pressure. [1]

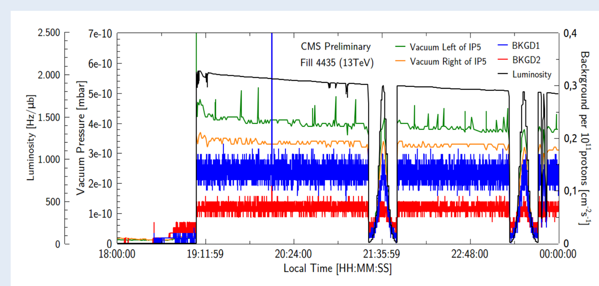
As the BHM detector measures long ranging muons, it is more sensitive to MIB originating further upstream in the LHC. In the muon halo, MIB particles originating from beam halo hitting the tertiary collimators are more dominant.

BCM1F and BHM give complementary information allowing to study the nature of beam loss events, and separate contributions from beam gas and beam halo interactions.

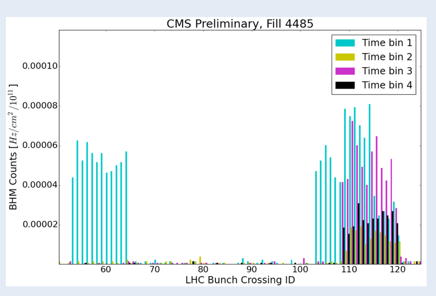
The BCML system uses different integrating windows that allow to study the timing structure of fast beam loss events like UFOs [2,3].



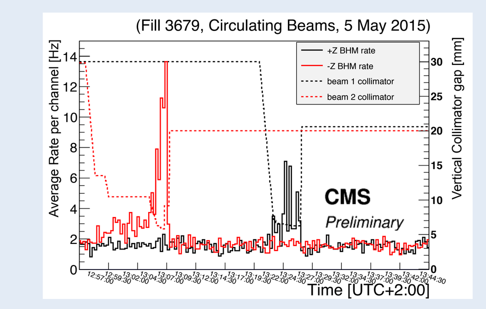
Timing structure of BCM1F detector hits of one colliding bunch as measured with the RHU



Luminosity, vacuum and normalized background during a fill. The increase in vacuum pressure leads to an increase in MIB.



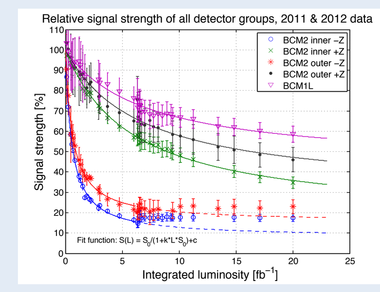
BHM timing histogram with a non-colliding and a colliding bunch train. Time bin 1 contains the background particles, which come earlier in time than the collision products



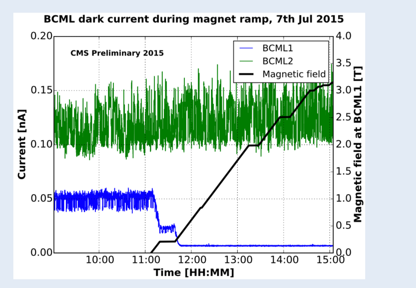
BHM readings during collimator scan. When the collimator scrapes the beam, the beam loss is measured. Beam 1 and beam 2 events are measured separately.

Active protection of the silicon detectors inside CMS is achieved by the BCML system. The data acquired by the system is used for checks of functionality and stability. Most important for this system is an availability of 100%. Radiation induced signal degradation was observed during Run 1 [12], due to the relatively low operational HV. Increased HV is desirable, however only achievable in the presence of a magnetic field, since erratic currents are suppressed.

A proper functionality of the BCML system, together with reasonable values of the measured MIB, is a requirement to allow the CMS Tracker to switch on the HV, and is therefore a key ingredient in the CMS data taking.



Degradation of the signal output of different detector groups in the BCML system as function of integrated luminosity during Run 1. The detectors were operated at 200 V (~0.5 V/μm), to achieve a better radiation hardness more HV has to be applied.



Erratic dark currents in two example detectors, one from BCML1 and BCML2 each, during the ramp up of the CMS magnet. Erratic dark currents are suppressed by the magnetic field. In BCML2 there is no sufficient fringe field and no visible suppression.

Beam timing is checked before the LHC goes into collisions. A stable position of the collision point is the key to a good tracking reconstruction. The precision of deltaT(B1-B2) measurement in BPTX is about 50 ps, which corresponds to a precision on the position of the collision point of about 7.5 mm.

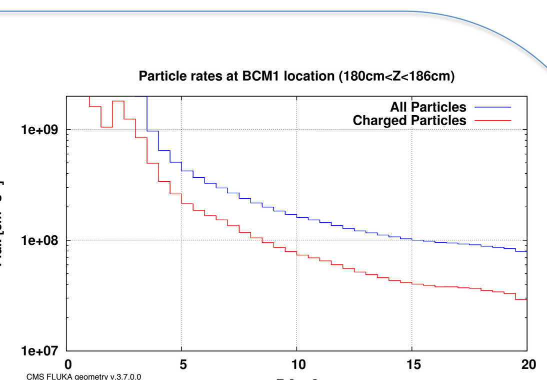
The number of bunches, paired and un-paired, can be cross-checked with the filling scheme

Signals from BPTX are used as **technical triggers** in CMS. These are: single bunch triggers, zero bias (AND), unpaired bunches (XOR), pre-collision (AND, 1 BX advanced), pre-train (1 BX before).

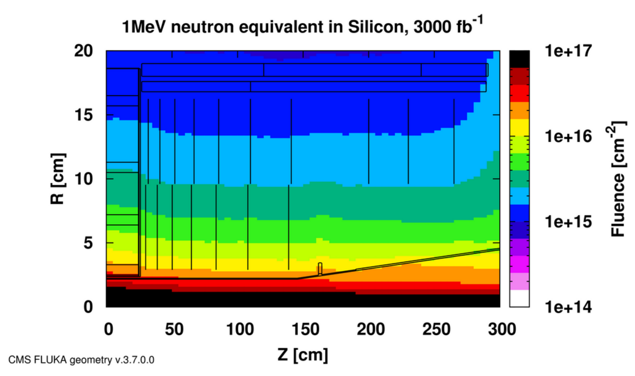
Outlook for High Luminosity - LHC

The phase-2 upgrade of CMS [13] is to prepare for the intense conditions of the HL-LHC. Most relevant for BRIL is the change of the machine interface, where the diameter of the beam pipe and absorbers have to be increased. This results in an increased level of MIB particles entering the CMS detector. The modification of the beam pipe also requires a re-design of the beam instrumentation in the forward detector region, where the BCML2 system is placed. The phase-2 upgrade of CMS also includes a complete replacement of the Tracker requiring a modification of the BCM1 and PLT systems. All systems have to be designed to operate at a pileup of 150 and with a radiation hardness to survive an integrated luminosity of 3000 fb^{-1}. Especially luminometers require a high dynamic range and good linearity. Specific modifications proposed to all beam instrumentation systems are:

- **Beam abort system:** With detectors in two different locations, the requirements are different for BCML1 and BCML2. For BCML1, pCVD diamond detectors are a viable option. Alternatively sapphire based detectors are an interesting alternative [14]. Likely the diamonds will not survive the intense radiation at the BCML2 region. While sapphire detectors could be viable, ionization chambers similar to the LHC BLM system are the most promising. The readout electronics will follow any changes done for the LHC BLM system.
- **Dedicated luminosity telescope:** The current concept of the PLT is still a viable option for phase-2, however the CMS Pixel detector will be extended to eta=4 and with it, more volume is needed. A luminosity system could be more integrated into the Pixel detector system by including a readout chain dedicated for luminosity measurement.
- **Fast background and luminosity detector:** A replacement for BCM1F has to be able to cope with increasing pileup. A higher granularity for high rate and similar total detector area for low rate measurements make single channel readouts increasingly difficult. A pixelated readout using a fast front-end chip that supports a readout frequency > 80 MHz could be a solution.
- **Large radius muon halo detector:** The BHM system is expected perform well in HLLHC conditions and does not have to be modified
- **Calorimeter based luminometer:** Similar to HFlumi, a calorimeter based readout system could be included into the upgrades of any of the calorimeter systems. The performance of the phase-2 detectors have to be studied.



FLUKA simulated particle rates at the BCM1/PLT location expected at HL-LHC conditions.



FLUKA simulated 1MeV-n-eq fluence inside the Pixel volume after 3000 fb^{-1}.

References

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