Beam Conditions Monitors for the CMS experiment at the LHC

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on behalf of CMS Beam and Radiation Monitoring Group
# BRM Subsystems

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Location</th>
<th>Sampling time</th>
<th>Function</th>
<th>Readout + Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passives TLD + Alanine</td>
<td>In CMS and UXC</td>
<td>Long term</td>
<td>Monitoring</td>
<td>---</td>
</tr>
<tr>
<td>RADMON</td>
<td>18 monitors around CMS</td>
<td>1s</td>
<td>Monitoring</td>
<td>Standard LHC</td>
</tr>
<tr>
<td>BCM2 Diamonds</td>
<td>At rear of HF z=±14.4m</td>
<td>40 us</td>
<td>Protection</td>
<td>CMS + Standard LHC</td>
</tr>
<tr>
<td>BCM1L Diamonds</td>
<td>Pixel Volume z=±1.8m</td>
<td>Sub orbit ~ 5us</td>
<td>Protection</td>
<td>CMS + Standard LHC</td>
</tr>
<tr>
<td>BSC Scintillator</td>
<td>Front of HF z=±10.9,14.4 m</td>
<td>(sub-)Bunch by bunch</td>
<td>Monitoring</td>
<td>CMS Standalone</td>
</tr>
<tr>
<td>BCM1F Diamonds</td>
<td>Pixel Volume z=±1.8m</td>
<td>(sub-)Bunch by bunch</td>
<td>Monitoring + protection</td>
<td>CMS Standalone</td>
</tr>
<tr>
<td>BPTX Beam Pickup</td>
<td>175m upstream from IP5</td>
<td>200ps</td>
<td>Monitoring</td>
<td>CMS Standalone</td>
</tr>
</tbody>
</table>

**Total number of diamonds used:** 32 pCVD and 8 sCVD
RADMON: 18 monitors around UXC
PASSIVES: Everywhere

BCM2 + BSC2

BSC1

BCM1

BPTX: 175m

14.4m

10.9m

1.8m
... and in reality
BRM summary online display – normal conditions

BCM2

BCM1F

Number of bunches in LHC

Beam activity

Background and collisions

LHC intensity

BPTX timing

BPTX timing histogram

% of abort

Steffen Mueller

Carat 09 @ GSI Darmstadt
BCM1F / BCM1L

BCM1F

- Fast diagnostic tool for bunch by bunch monitoring of both beam halo and collision products.
- Located at $Z^+/-$ = 1.8m with a radius of 4.5cm.
- Detectors used are sCVD diamond with a size of 5x5x0.5mm

BCM1L

Leakage current monitor, 8pCVD, 1cm2

Synchronized sampling of beam structure and abort gap
Integration time ~6us

Readout: Standard LHC Beam Loss Monitor

W. Lohmann et al, "Fast Beam Conditions Monitor BCM1F for the CMS Experiment", accepted NIM A (2009)
BCM1 integration

Main challenge was to integrate everything into very little space!
The PLT (Pixel Luminosity Telescope) detector will be installed later into the same carriage by Rutgers.
BCM1 completely installed

Big mechanical challenge!
BCM2 Leakage current monitor
BCM2 Package

BCM2 detector is a 10x10x0.4mm³ polycrystalline CVD diamond with Tungsten-Titanium metallization. The average charge collection distance is 230um@400V.

Baseplate material:
Rogers corp. woven glass reinforced ceramic filled thermoset material.
Installation happened one week before beam, due to CMS schedule. Despite this BCM was ready for first beam. Biggest challenge was to integrate detector in an area where there are three other subsystems (HF, CASTOR, TOTEM).
Front end electronics for BLM and BCM2

- BCM2 uses same readout electronics and data handling as LHC BLM
- Transparent extension of BLM into experimental areas
- Relative Particle Flux Monitor

Data flow and abort in BCM2

- Abort implemented in Hardware
- All 40us readings taken into abort calculation
- Max RunningSums for Monitoring at a 1Hz rate
- Post Mortem analysis

Abort threshold defined by Si-Pixel and Strip tracker, with large safety factor.

Present abort thresholds
- $10^9$ MIPs per cm$^2$ per 1-100ns is expected damage level for detectors
- $3\times10^5$ MIPs per cm$^2$ per digitization (40us) is abort level
- This corresponds to 10uA.
- Slower abort level presently placed at 3 times nominal luminosity.
  (several 100nA= $1\times10^8$ per cm$^2$ per s) “Radiation Budget”

---

BRM Diamond Response, nominal machine

- Energy deposition is scored for diamond region.
- Ionization energy of diamond $E_{\text{ion}} = 13\text{eV}$.
- Non Ionizing Energy Loss (NIEL) is negligible for signal.
- Conversion: $I_{\text{dia}} = \frac{E_{\text{dep}}V_{\text{norm}}C_{\text{CD norm}}L_{\text{unorm}}q_{\text{e}}}{E_{\text{ion}}}$

- Current from energy deposition 7TeV Beam, nominal luminosity:
  - BCM2inner: 394nA (~300e6)
  - BCM2outer: 33nA (~25e6)
  - BCM1F: 24nA (31e6)
  - BCM1L: 91nA (68e6)

- Signal is dominated by Luminosity and not by machine induced background.
Testbeams – excellent correlation with BLM tube

Elbe – Dresden 20MeV electrons
Covered more than 4 orders of magnitude
Good linearity at 200 V bias voltage
Good correlation between ionization chamber and diamond.
Crosscheck between LHCb, Alice and CMS BCM systems
Testbeam kindly organized by LHCb

PS: 2GeV Proton/Pions
Excellent correlation between ionization chamber and diamond.

Louvain la Neuve – 21MeV fast neutrons
Excellent correlation between ionization chamber and diamond.
Almost identical ionization currents in both detectors for 400 um thick diamond
Cyclotron tests 26MeV protons

Test of dynamic range and linearity up to the abort level at different voltages.

Substructure, due to beam scanning.
Sr90 Source tests in cavern

- All Diamonds tested with a 28MBq Sr90 source in Cavern as a final check before closure.
- Checks with what we have seen before in the lab.
- All diamonds responded nicely and as expected from lab measurements.
Noise studies: histogram for 22 days of data

Abort level

Well calibrated electronics

Tolerances of electric components causing mismatch between ADC and integrator count. As the max ADC count is below abort level, not a problem in terms of a false abort!

Intrinsic and normal pickup noise cannot lead to a false abort
BCM2 BLM correlation (Nov 23rd beam trimming)

• Noise is biased due to readout algorithm (only in monitoring, not in abort)
  • Therefore only the signal excess is fitted.
• Shown is just example of ongoing work, correlations to other BLM locations is done at the moment.
• Got more data during the aperture scans, number of correlated detectors and quality will improve.
• A lot of topological information on the losses also available
• Aim: produce a set of correlations for each accident scenario as part of a tool to diagnose losses

Conclusive prove that CMS Beam condition monitors are working!

Signal height scaled
BRM Signals for Dec 3rd (Aperture scans)

BCM1F at 1.8m from IP
BCM2 at 14.4m from IP

Several losses seen

Steffen M.
The maximum reading occurred for the maximums of the RS06 sum (10ms) with a peak of $1.4\,\text{nA} \approx (10^4 \, \text{MIPeq/cm}^2)$.

For the 1s reading (RS09), the maximum was $0.5 \, \text{nA} \approx (400 \, 000 \, \text{MIPeq/cm}^2/\text{s})$.

On shorter timescales than RS06 it was not possible to determine signals above the usual noise level (expected as this was a "slow" loss).
Correlation BCM2 and BCM1F for Dec 3rd

BCM2 at 14.4m from IP

BCM1F at 1.8m from IP

Good correlation, even at low values!

Timing of the detectors slightly different

Graph

$\chi^2 / \text{ndf}$

3.849e-20 / 5483

$p_0$

1.925e-11 ± 3.6e-14

$p_1$

9.268e-15 ± 9.258e-17

BCM1F at 1.8m from IP
BCM2 all inner diamonds

Geometric structure under investigation. Also correlating Signal with several BeamLossMonitors for different loss scenarios.
Outer compared with empty channels

Significant signal seen in all outer Beam Conditions Monitor 2 diamonds
First Correlations between BCM1L and BCM2. Signals clearly in BCM1L

BCM2 –Z top
RS7, 80ms

BCM2 +Z top
RS7, 80ms

BCM1L

BCM1L
First Correlations between BCM1L and BCM2. Signals clearly in BCM1L

+ZTOP

CMS-BRM

Mean 60
Mean y 0.03803
RMS 34.93
RMS y 0.04681

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

First Correlations between BCM1L and BCM2. Signals clearly in BCM1L

+ZNEAR TimeBin02Running Sum 5

CMS-BRM

Entries 111
Mean 65
Mean y 0.1502
RMS 32.04
RMS y 1.689

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

First Correlations between BCM1L and BCM2. Signals clearly in BCM1L

+ZUP TimeBin02Running Sum 5

CMS-BRM

Entries 111
Mean 65
Mean y -0.03233
RMS 32.04
RMS y 2.052

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

40m20 40m40 41m00 41m20 41m40 42m00 42m20
Time

First Correlations between BCM1L and BCM2. Signals clearly in BCM1L
Leakage current in diamond as a function of the magnetic field
Erratic dark currents in diamond detectors

Figure 4. Suppression of erratic dark currents in a magnetic field. At $t = 150$ s a 1.5T magnet was switched on, resulting in the elimination of erratic dark currents in all of the sensors.

Paper: CVD Diamonds in the BaBar Radiation Monitoring System

CDF: magnet trip caused erratic currents

BaBar radiation monitoring

Effects also investigated in multiple test beams during 2006/2007
During CMS magnet ramping 08

Suppression of erratic leakage current, mostly at the pA level, only one diamond shows a leakage current in the nA range. This seems to be the same effect already seen at CDF and BaBar.
During CMS magnet ramping 08 cont.

Increase of leakage current in presence of a magnetic field, seen in 8 out of 24 diamonds. Effects are very small, max difference is one pA.
Lab measurements

- Magnet:
  - Jumbo at ITP, Karlsruhe
  - max. 10.0T @ 4.2K with warm 10cm bore
  - coil currents up to 3000A
  - DUT temperature: 72 – 300K
    - Cooling with cold N₂-Gas

- Diamond used for test:
  - CCD: 231um / 241um (rev.)
  - Leakage Current at 0.5V/um: 230pA /10pA (rev.)

- Measured two different magnetic field angles
  - E parallel B
  - E perpendicular B

Thanks to M. Noe, T. Schneider, KIT/ITP, Karlsruhe, Germany
Results

- **E perpendicular B**
  - Up to 0.8T the leakage current increased, above it starts to decrease again.

- **E parallel B**
  - Current decreases as function of B-field (opposite to perpendicular field).
  - No effect measurable with reversed electric field.

Reproduced with a second diamond!
Drift with isotropic scattering every 1.7µm, good chances to hit a grain boundary where charge carriers recombine.

Drift along small Lorentz angle with scattering every 1.7µm, transversal drift highly suppressed due to magnetic field, smaller chances to hit a grain boundary, higher leakage current.

Drift along larger Lorentz angle, scattering every 1.7µm, higher chances to hit a grain boundary, smaller leakage current.

Leakage current is caused by injected electrons from the electrodes more likely at substrate site.

The number of injected electrons is dependant of:
- the electric field strength
- the metal used for the contact
- temperature

The propagation of the electrons is dependant of:
- Mobility
- Magnetic field
- Grain boundary configuration

S. Mueller, Leakage current of diamond as function of a magnetic field, phys. Stat. sol. (a) 206, No. 9, 2091-2097 (2009)
Conclusion

• CMS Beam condition monitors are working excellently!
  – All systems seeing beam. This was not expected at these very low intensities.

• Good correlations between different detectors

• Diamond is the material of choice for this application.

• Integrating readout electronics of very high dynamic range and low noise available.

• Magnetic field effect observed, does not affect the operation of the safety systems.

• Preliminary model developed, but further tests needed for a conclusive understanding of the effect.