Use of Single Crystal Diamond for the Fast Beam Conditions Monitor and the Pixel Luminosity Tracker for CMS at the LHC

Richard Hall-Wilton (CERN/Wisconsin)

On Behalf of CMS-BRM and CMS-PLT Groups

Institutes presently involved: Auckland, Canterbury, CERN, DESY-HH, DESY-Zeuthen, Fermilab, Karlsruhe, Princeton, Rutgers, Tennessee, Vanderbilt, Vienna, Uni Hamburg

CARAT09 Worskhop
14th December 2009
Primarily based upon these 2 papers:

**Fast Beam Conditions Monitor BCM1F for the CMS Experiment**


*Brandenburgische Technische Universität, 03046 Cottbus, Germany*
*CERN, 1211 Geneva 23, Switzerland*
*DESY, 15738 Zeuthen, Germany*
*Rutgers University, 08854 Piscataway, NJ, USA*
*Université de Genève, 1211 Geneva, Switzerland*
*Canterbury University, 8041 Christchurch, New Zealand*
*University of Wisconsin, Madison, WI 53706-1481, USA*

**Abstract**

The CMS Beam Conditions and Radiation Monitoring System, BRM, will support beam tuning, protect the CMS detector from adverse beam conditions, and measure the accumulated dose close to or inside all sub-detectors. It is composed of different sub-systems measuring either the particle flux near the beam pipe with time resolution between nano- and microseconds or the integrated dose over longer time intervals. This paper presents the Fast Beam Conditions Monitor, BCM1F, which is designed for fast flux monitoring measuring both beam halo and collision products. BCM1F is located inside the CMS pixel detector volume close to the beam-pipe. It uses sCVD diamond sensors and radiation hard front-end electronics, along with an analog optical readout of the signals. The commissioning of the system and its successful operation during the first beams of the LHC are described.

**Key words:** LHC, CMS, beam conditions, sCVD diamonds, radiation hard sensors

(Submitted NIM A)

**Results from a Beam Test of a Prototype PLT Diamond Pixel Telescope**

R. Hall-Wilton, R. Loos, V. Ryjov
*CERN, Geneva, Switzerland*

M. Pernicka, S. Schmied, H. Steninger
*Institute of High Energy Physics, Vienna, Austria*

V. Halyo, B. Harrop, A. Hunt, D. Marlow, B. Sands, D. Stickland
*Princeton University, Princeton, NJ, USA*

O. Atramentov, E. Bartz, J. Doroshenko, Y. Gershtein, D. Hits, S. Schnetzer, R. Stone
*Rutgers University, Piscataway, NJ, USA*

P. Butler, S. Lansley, N. Rodrigues
*University of Canterbury, Christchurch, New Zealand*

W. Bugg, M. Hollingsworth, S. Spanier
*University of Tennessee, Knoxville, TN, USA*

W. Johns
*Vanderbilt University, Nashville, TN, USA*

**Abstract**

We describe the results from a beam test of a telescope consisting of three planes of single-crystal, diamond pixel detectors. This telescope is a prototype for a proposed small-angle luminosity monitor, the Pixel Luminosity Telescope (PLT), for CMS. We recorded the pixel addresses and pulse heights of all pixels over threshold as well as the fast-or signals from all three telescope planes. We present results on the telescope performance including occupancies, pulse heights, fast-or efficiencies and particle tracking. These results show that the PLT design concept is sound and indicate that the project is ready to proceed with the next phase of carrying out a complete system test, including full optical readout.

(about to be submitted)
Diagram of Location of BRM+PLT Subsystems

RADMON: 18 monitors around UXC
PASSIVES: Everywhere

BCM1

BCM2+BSC2

BSC1

BPTX: 175m

PLT

BCM1L+F

14.4m

1.8m

10.9m

Monday, December 14, 2009
... and the reality ...
### BRM Subsystem Hardware Summary

<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>

*Emphasis on detectors that are relative flux monitors*

*Systems are independent of CMS DAQ, and on LHC UPS power*
Why do we need beam monitoring?
**Stored Energy**

Large damage potential from uncontrolled beams means that comprehensive protection system is needed.

**BCM Systems perform this role for the experiments**

---

**Damage Potential of High Energy Beams**

Controlled experiment with 450 GeV beam shot into a target (over 5 µs) to benchmark simulations:

- Melting point of Copper is reached for an impact of \(2.5 \times 10^{12}\) p, damage at \(5 \times 10^{12}\) p.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Intensity / p+</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(1.2 \times 10^{12})</td>
</tr>
<tr>
<td>B</td>
<td>(2.4 \times 10^{12})</td>
</tr>
<tr>
<td>C</td>
<td>(4.8 \times 10^{12})</td>
</tr>
<tr>
<td>D</td>
<td>(7.2 \times 10^{12})</td>
</tr>
</tbody>
</table>
Expectation of charged particle flux at nominal LHC luminosity

Location of beam conditions monitors and inner layer pixel detectors ca. 4-5cm radius

At nominal luminosities, fluxes of charged hadrons of $3 \times 10^8$ cm$^{-2}$s$^{-1}$ expected
Diamonds in CMS
Diamond in HEP Experiments

Summary of Diamonds in HEP Experiments

(Plot Courtesy of H. Kagan/RD42)
Fast Beam Conditions Monitor
Fast Beam Conditions Monitor

- **Purpose:** Give bunch-by-bunch (and sub-bunch) MIP-sensitive measurements of losses inside pixel detector volume
- Measure both beam halo losses and collision losses
- Location is very restricted and crowded
  - No cooling or slow control possible
  - Test pulse shares HV lines
  - Needs to be insensitive to environmental conditions
  - Needs to have an optical readout to backend
- sCVD diamond (from DD) used
  - 5x5x0.5mm sensor
  - Choice due to signal size
- Radiation hardness “sufficient” for LHC (…maybe not be SLHC (see Wim’s talk) ..)

---

**$^{90}$Sr results**

[Graphs showing single crystal and polycrystalline results]
Schematic of BCM1F

Tracker volume

Counting Room
BCM1F components in detail - PREAMP + OPTOBOARD

JK16 (CERN) [IEEE TNS 52-2005 2713]:

- 0.25 μm radhard CMOS process
- Transimpedance design
- Charge sensitive preamp + shaper (20 ns peaking time)
- 4 pF input capacitance (open loop)
- 10 mV / fC ⇒ ~ 60 mV / MIP for the sCVD sensor
- ENC ~ 500 e⁻ + 40 e⁻ / pF
- Sensor glued onto PCB and (wire)bonded directly to the preamp
- Leakage currents of < 1 nA achieved
- Supply cable soldered directly to the PCB
- Piggy back connection to the analog optical hybrid (AOH) board
- Optical transmitter supplied via preamp board
Analog optical hybrid:
- Adjustment of laser pre-bias current
- Optimal setting for modulation of signal
  ⇒ Attention paid to possible degradation

…laser, pigtail, patch panel, ribbon…

Optical receiver:
- Adjustment of offset compensation
- Fan-out of electrical signal

Response of whole readout chain
Linear 2.3 MIPs
Saturates >5 MIPs
Final Detectors

- Good separation S/N
- Signal saturates <100V
  - <0.2V/um
Mechanics

Shown is 4 detectors mounted on 1 “end”

Total of 8 detectors
BCM1F Installation

~ 100 mm

beam pipe
First signals 2008 - Beam 1 on scope

+Z side gives signal ~15ns before -Z side (time of flight of particle)
A Closer Look at BCM1F Data

“Fast” System

Based upon Single Crystal Diamond

2008

“Fast” System

Based upon Single Crystal Diamond

2008

About 600 hits/channel recorded with ADC

S:N of better than 10:1

Despite low bunch currents, coincidences about 25% of time

Timing of coincidence hits

Timing resolution ca. 3ns

Uncorrected

Timing difference about 12ns

Channels in Coincidence

Number of Events

Number of Channels

Cable fault on 1 channel during this run (fixed)

Timing of coincidence hits

Timing resolution ca. 3ns

Uncorrected

Timing difference about 12ns

Simultaneity of Signals in Coincidence

Number of coincidences

Integrated Charge [arb. units]

S:N of better than 10:1

About 600 hits/channel recorded with ADC

Monday, December 14, 2009
Detector performance with 2008 beam

• Clear signals seen on all channels
• S/N ranges from 15-28
• Timing shown difference of 12.4ns between hits on either side in agreement with time-of-flight
  • Width of difference is 1.8 ns
  • Implies a single hit timing resolution of 1.3 ns
Beam in 2009

- In good conditions, a few MIPs are seen
- Timing information visible
- With very high losses, see saturation
- (>40 particles/bunch crossing)
- Analysis ongoing
- Clearly a useful tool
- See Steffen’s talk

**Good/Normal Conditions**

**Bad Conditions**

“Aperture Scans”

Monday, December 14, 2009
Pixel Luminosity Telescope

A dedicated “stand-alone” luminosity monitor for CMS
The Pixel Luminosity Telescope (PLT)

- Independent of CMS (self-triggered)
- Relative bunch-by-bunch measurements
- Precision at 1% level (stat, syst)
- Self monitoring/calibrating

⇒ 3 layer particle tracking

- Single-crystal diamond pixel
  - Fast pixel OR readout (3-layer coincidence)
  - Full readout (1-10 kHz)

Count 3-fold coincidences every bunch crossing (40 MHz)
Count “tracks” from the IP
Proportional to luminosity
Mechanics already exists

slides on rails inside of the pixel service cylinder

Fits in BCM1 Carriage
Single-Crystal Diamond Detector (sCVD)

- Radiation hard (survives $> 2 \times 10^{15}$ p/cm$^2$)
- No need for cooling
- Full charge collection at E-field $< 0.2$V/um
- Fast signal collection (~1ns from 500 um)
- Pulse height well separated from pedestal

- 75% drop in charge collected before significant effect on efficiency
Readout

- CMS Pixel chip (PSI46v2) bump-bonded to sCVD
- Fast cluster counting in double-columns built in
- Individual pixel thresholds adjustable
- Individual pixels can be masked
- Self-triggered by fast pixel OR
- Full analog readout of
  - Hit address
  - Charge deposit
- Standard pixel readout (FEC, FED [ADC])
  - Fast-Or Readout (40 MHz)
    - Bunch-by-bunch luminosity
    - Population of abort gap
    - Simulation: 1.6 tracks/BC at nominal luminosity
  - Full pixel readout (1-10 kHz)
    - bunch integrated luminosity
    - IP centroid
    - Beam Halo Measurement

Bump bonded at Princeton micro-fab lab
Detector Fabrication

- Patterned diamond
- Indium bumps
- Bumped ROC
- Bumped detector
Bump Yield

1040 pixels in active area

- $^{90}$Sr beta particles
- Fast-Or used as trigger
- Mostly stopping beta’s
- 3 to 4 pixels hit per beta

Box area proportional to number of hits

Distribution of hits per pixel
Beam Test

- 1 full PLT telescope was successfully tested at CERN SPS
- 150 GeV/c π+
- 2 days of beam time

Small (6x6 mm) Scintillators (used as triggers)
Charge Deposit

- Calibrated using charge injection feature of PSI42
- Require single cluster in all three planes
- Sum over cluster
- Most probable charge deposit: ~18,000 electrons (Si: ~28,000)
Percentage of pixels with no hits:

Plane 1: 1.8%  Plane 2: 2.2%  Plane 3: 0.1%

Fiducial area: masked border rows and columns and columns in shadow of entrance counter
Tracks Observed

Select events with 1 cluster in each plane
(89% of events)
Alignment

- Successfully reconstructed tracks
  - Hit position defined as the “center of charge” (charge sharing)

- Define residual: $x_2 - \frac{(x_3-x_1)}{2}$
- Alignment
  - X offset: $25 \pm 5$ um
  - Y offset: $144 \pm 3$ um
- Rotation: 0.6 degrees
  - 40 um over 4mm
- Even with only a few tracks, a successful alignment was achieved
  - X alignment: 57 tracks
  - Y alignment: 140 tracks
Pulse Heights

- Require single cluster in all three planes
- For Plane c, require hit in regions of Planes a and b such that track is certain to pass through fiducial region of Plane c
- Plot pulse height summed over cluster

Most probable pulse heights:

Plane 1: 16,000 $e^-$  
Plane 2: 18,500 $e^-$  
Plane 3: 18,500 $e^-$
Fast-OR

- Test beam particles arrive at random times with respect to our clock
  ⇒ count ± 1 time bin as the same event
- In CMS, particles arrive at a definite phase of the 40 MHz clock.
  ⇒ fixed to 1 time bin

<table>
<thead>
<tr>
<th>Plane</th>
<th>Measured Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.3%</td>
</tr>
<tr>
<td>2</td>
<td>99.6%</td>
</tr>
<tr>
<td>3</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

Efficiency

Plane 1 AND Plane 2 AND Plane 3 → True

Time bin size = 25ns (40 MHz)

Arrival Time [ns]

Monday, December 14, 2009
Calibration procedure defined for production

Calibration

Readout vs injected charge

$\chi^2$/n.d.f. of a fit of $v_{cal} = f(ADC)$

Readout Threshold

Readout Saturation

Monday, December 14, 2009
Summary

• Outline of 2 MIP sensitive detectors using SCVD diamond for CMS shown
• Fast Beam Conditions Monitor
  - Built, installed and working
  - Meets the required specifications
  - Already proving useful in helping diagnosing beam conditions in the CMS experiment during this LHC run
  - Will prove to be an invaluable diagnostic tool
• Pixel Luminosity Telescope
  - Testbeam results show that design meets requirements
  - Demonstration of a diamond pixel tracker
  - Approved as a CMS project - construction started of 16 (+4) telescopes
  - Installation into CMS early 2011