The new Fast Beam Condition Monitor using diamond sensors for luminosity measurement at CMS.

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on behalf of the CMS collaboration
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Introduction

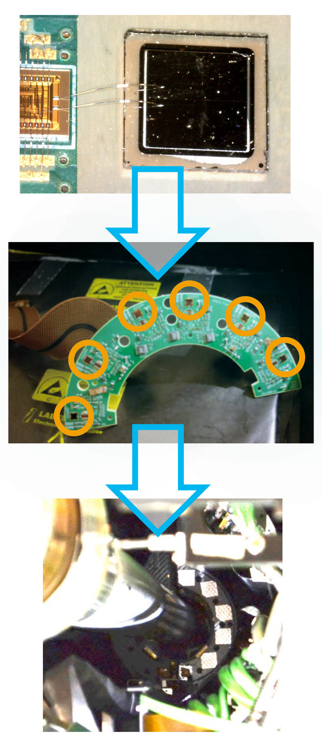
The BCM1F detector is a dedicated beam monitoring device operated by the BRIL group of the CMS experiment [1]. It is used to measure luminosity and beam-induced-background rates. To achieve this a fast front-end amplifier [2] is used, which provides fast recovery to baseline after a particle hit. An analog optical pulse transmission allows the readout to be placed ~100 m away from the detector. A discriminator is used to find pulses, which are counted by the dedicated Realtime Histogramming Unit (RHU), which histograms hits as a function of position in the LHC orbit with 6.25 ns time resolution (4 bins per LHC bunch crossing).

The system in its current form was first installed in 2014 and was in operation during 2015/16, where 500 µm thick single-crystalline diamond (sCVD) sensors were used. In operation, after a small amount of radiation damage, the sensors showed erratic break through behavior, causing the HV to trip after many hours of operation. This instability could only be solved by reducing the operational HV. Operating at HV as low as 100 V (E ~ 0.2 V/µm) resulted in significantly reduced charge collection and minimal ionizing particles could not be discriminated any more.

A replacement using the same electronics was built in 2016 and operated since 2017. Poly-crystalline diamond sensors (pCVD) are used instead. Some sCVD and silicon sensors are also installed for testing and comparison purposes. While pCVD sensors offer less charge collection than un-irradiated sCVD sensors, they provide much better stability at high particle rates and with increasing radiation damage.

Detector concept

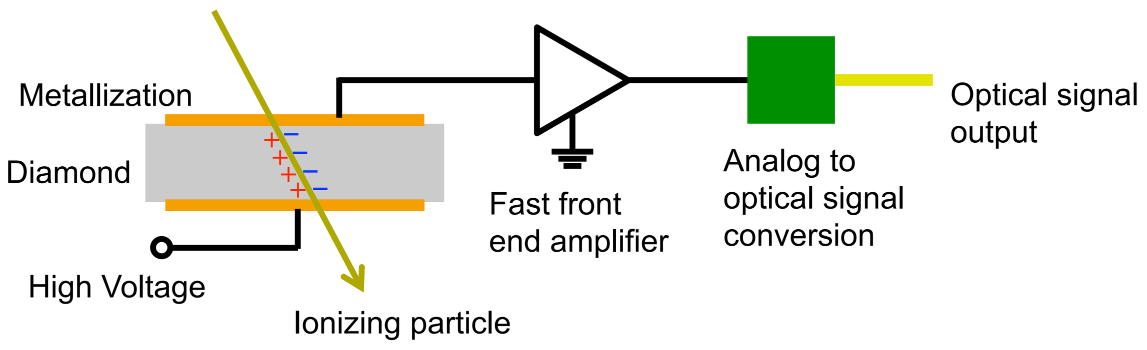
- Single particle detection using 10 poly-crystalline diamond sensors (pCVD), placed around the LHC beam pipe.
- Diamond is used as a solid state ionization chamber. Electron-hole pairs, created by ionizing particles, drift along the electric field induced by the HV and create a current pulse.
- Fast charge sensitive pre-amplifier.
  - 50 mV/fC
  - 7 ns rise time, 10 ns FHWM
  - Pulse recovery within 25 ns
- An analog-to-optical conversion for long distance pulse transmission is used.



Two-pad diamond sensor as mounted on the C-shaped PCB bonded to the amplifier

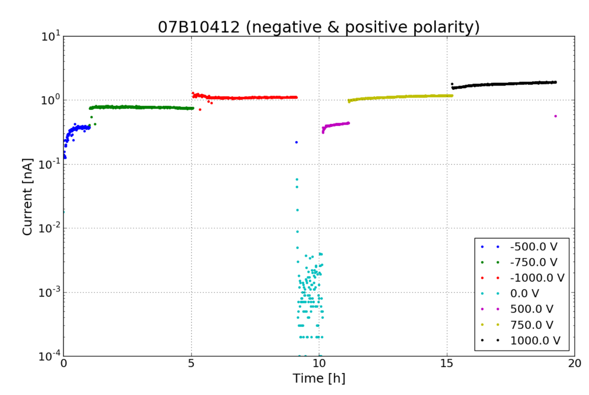
C-shaped detector PCB with 6 detector locations

Detector installed around central CMS beam pipe

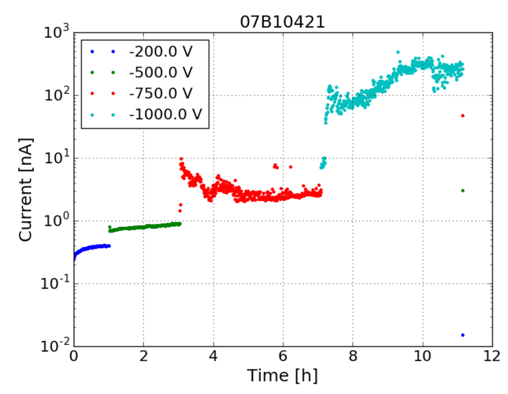


Qualification of diamond sensors

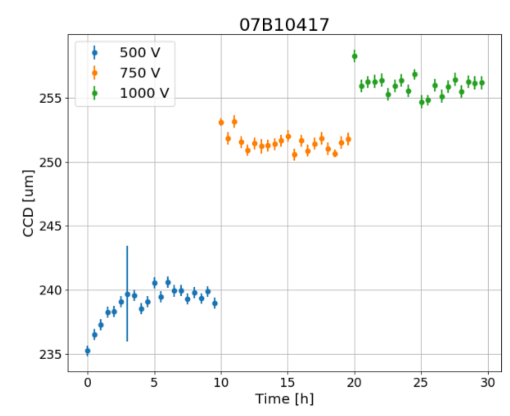
- Various types of defects can be present in diamond, resulting in both deep and shallow traps.
- When sensors are irradiated, charge carriers fill the traps. This process is called pumping.
- Measurements are performed using high rate Sr-90 source to ensure sensors are fully stabilized when taking data.
- Erratic current can occur after many hours. Long exposure time at high particle rate is necessary to predict diamond behavior in operation.
- Charge collection and test beam measurements predict sufficient signal amplitude.



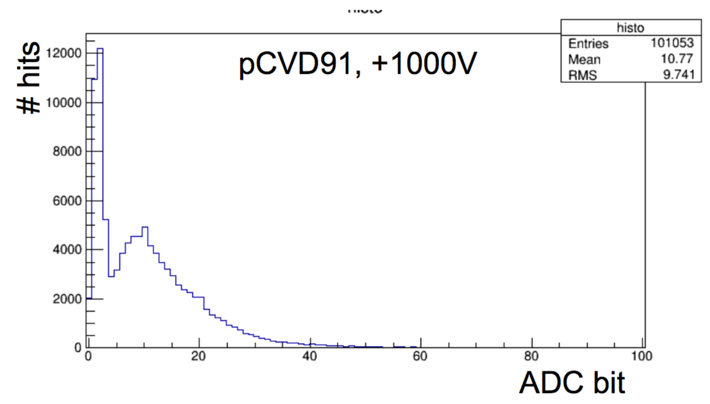
Example current over time measurement. This shows the best achieved behavior with a stable current at 1000 V below 2 nA.



Example of an erratic current developing over time. Unstable behavior above 500 V.



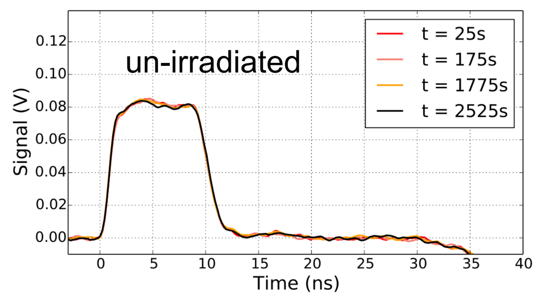
Charge collection expressed as average charge carrier drift length (CCD) measured at different HV values as a function of time. The time dependent measurement ensures stability.

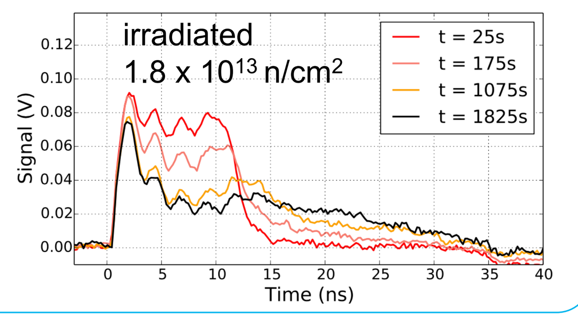


Test beam measurement of the pulse height spectrum of a pCVD diamond sensor, operating at 1000 V in the BCM1F readout. A peak, separated from noise, is visible. A threshold can be placed below the peak promising good stability.

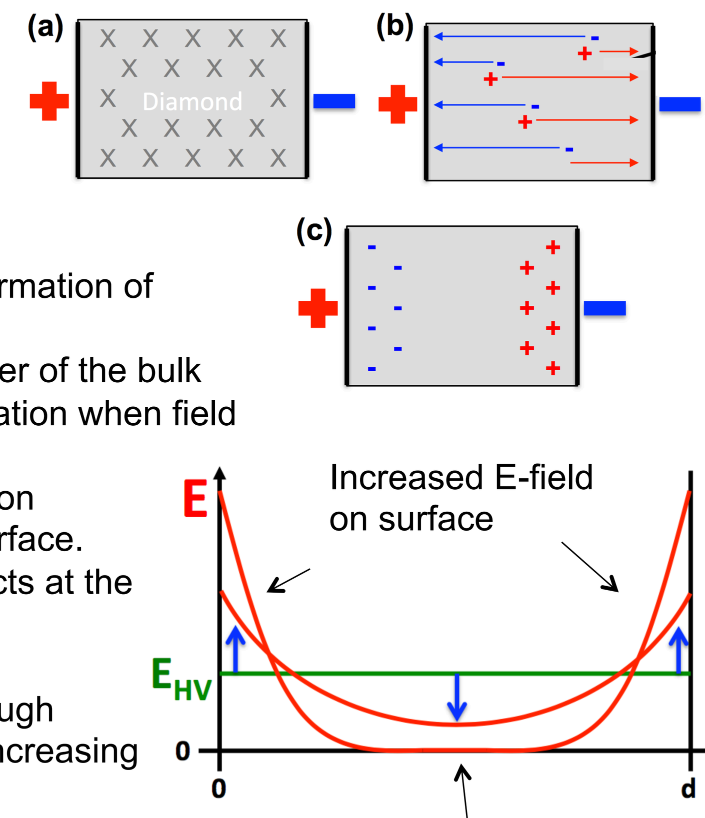
Radiation damage induced polarization

Measurement of the electric field in sCVD diamond using Transient Current Technique (TCT). Un-irradiated sensors show a constant E-field. Irradiated sensors have a constant E-field at the start of measurement, but as charge builds up in the bulk, the E-field deforms. [3]

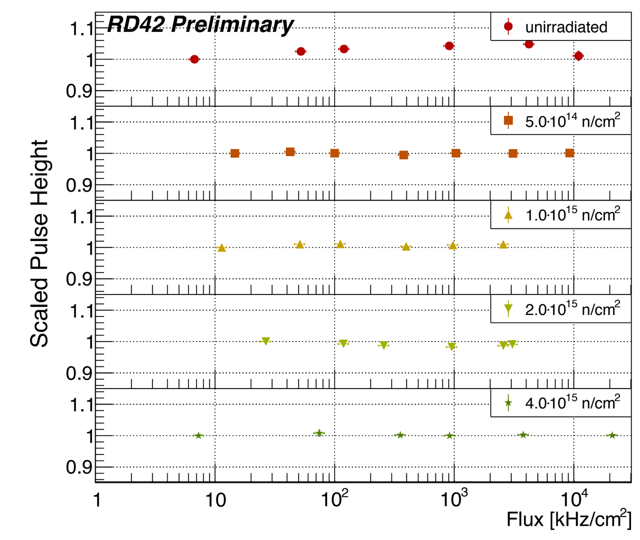




- Radiation damage creates defects in the diamond bulk.
  - These defects are typically neutral vacancies.
- When free charge carriers are trapped at defects they form a fixed space charge.
- Space charge results in a deformation of electrical field
  - Field is reduced in the center of the bulk
    - charge carrier recombination when field is very low.
    - Reduced charge collection
  - Field is increased at the surface.
    - Charge generating defects at the diamond/metal interface become active.
    - HV at which a breakthrough occurs is reduced with increasing polarization.
- Shallow defects lead to a rate dependent polarization.
  - HV trips occur at high rates only



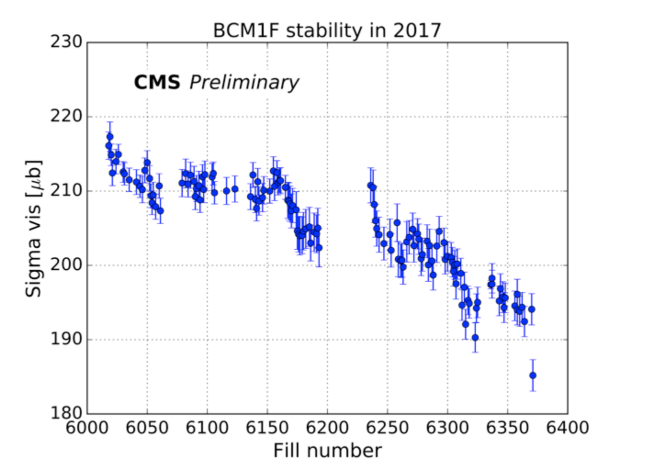
pCVD diamond suffers significantly less from radiation damage induced polarization compared to sCVD sensors. A much better stability with irradiation is expected.



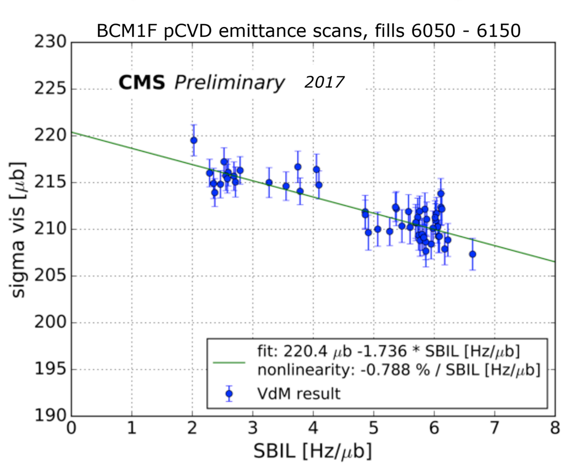
Irradiated pCVD operated at 1000V shows no rate dependency in a dedicated test beam study performed by the RD42 collaboration.

Luminosity performance in 2017

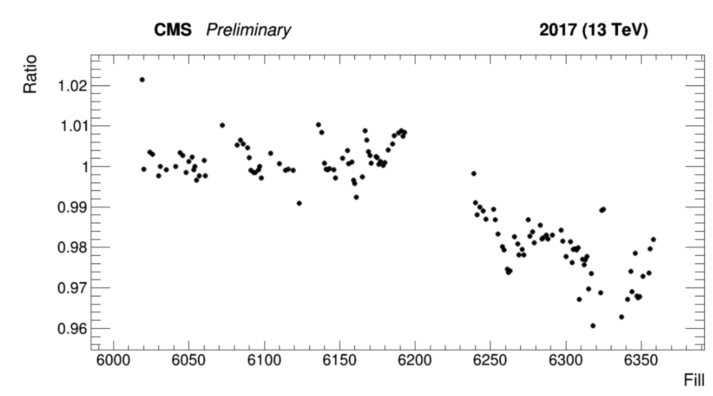
- Calibration of luminosity detectors done with Van der Meer scans. [4]
  - Absolute calibration obtained from yearly dedicated VdM fill.
- Regular short VdM scans in every LHC fill to obtain approximate calibration (so called emittance scans). [5]
  - Measurement of long term stability and linearity (luminosity dependent calibration).
- Offline luminosity including stability and linearity corrections shows good stability.



~ 10 % decrease in calibration over the year. This includes effects from damage to sensor and optical readout, as well as effects from changes in filling scheme.



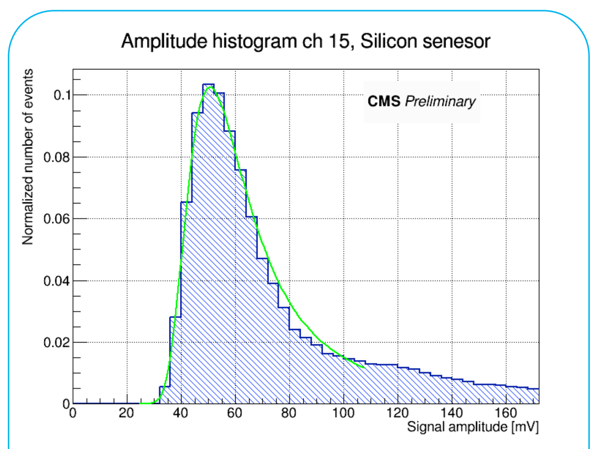
About 2-3 % change in efficiency over the course of an LHC fill. The effect is small and can be corrected for.



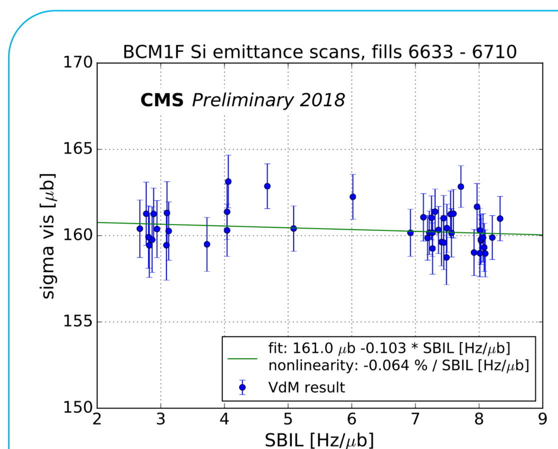
Ratio of BCM1F / HFET
After correction the BCM1F luminosity for 2017 shows a good stability within about 2 % when compared with a reference luminometer. [4]

Silicon sensor alternative

- Prototype silicon sensors are installed instead of diamond.
- Excellent performance
  - Separation of signal and noise.
  - Excellent linearity of luminosity
- Expect life time of about 100 fb^{-1} due to increased leakage current.
  - Future upgrade will use A/C-coupled sensors to mitigate leakage current issues.



Pulse height spectrum of a silicon sensor channel. A clean Landau peak from minimal ionizing particles is visible.



Linearity of silicon sensor based luminosity measurement. No dependency on luminosity found with regular short VdM scans.

Summary

- Modification to use pCVD instead of sCVD sensors in BCM1F provides much better operational stability.
  - Failure of sCVD is consistent with radiation damage induced rate dependent polarization.
  - New pCVD are able to operate at significantly higher HV.
- Rate dependent polarization was shown by TCT measurements in combination with TCAD simulations.
- Small efficiency drifts as function of time and total rate can be compensated for by using CMS emittance scan analysis.
- BCM1F is now successfully used as one of the CMS online luminometers. Luminosity performance will be improved further by further studying the linearity and correction model.

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References

[1] M. Guthoff, on behalf of the CMS collaboration: "Instrumentation for beam radiation and luminosity measurement in the CMS experiment using novel detector technologies", Nuclear Instruments and Methods A, Volume 845, 2017, Pages 565-569, ISSN 0168-9002 , http://dx.doi.org/10.1016/j.nima.2016.06.028.
[2] D. Przyborowski, J. Kaplon and P. Rymaszewski, "Design and Performance of the BCM1F Front End ASIC for the Beam Condition Monitoring System at the CMS Experiment," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 4, pp. 2300-2308, Aug. 2016. doi: 10.1109/TNS.2016.2575781.
[3] F. Kassel, M. Guthoff, A. Dabrowski, W. de Boer: "Description of radiation damage in diamond sensors using an effective defect model", Phys. Status Solidi A, doi:10.1002/pssa.201700162, arXiv:1705.09324 .
[4] CMS collaboration, "CMS Luminosity Measurement for the 2017 Data-Taking Period", CMS-LUM-17-004.
[5] O. Karacheban, P. Tsrunchev on behalf of the CMS collaboration, "CMS emittance scans for luminosity calibration in 2017", AYSS-2018: XXII International Scientific Conference of Young Scientists and Specialists, 23-27 Apr 2018.