Development of the ATLAS ITk BCM' system for beam abort and luminosity determination at the HL-LHC based on polycrystalline CVD diamond

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1 Introduction

In the years 2026–2029 the Large Hadron Collider (LHC) at CERN will undergo a high luminosity upgrade (HL-LHC) which will result in the average number of inelastic proton-proton collisions per bunch crossing μ increasing from approximately 40 to 200. To cope with increased particle density, readout channel occupancy and radiation damage the ATLAS experiment will undergo a major upgrade including installation of a new all-silicon Inner Tracker (ITk)[1].

To monitor the background activity in ITk and abort the LHC beam in case of dangerous beam induced particle showers an upgraded Beam Conditions Monitoring (BCM') will be installed within the retractable part of the ITk Pixel system, replacing the existing beam protection system BCM [2]. The system will also complementarily serve as a bunch-by-bunch luminosity meter in ATLAS with a precision of 1 %. BCM' will be based on polycrystalline chemical vapor deposition (pCVD) diamond sensors read out with a new dedicated front end ASIC called Calypso. A slower Beam Loss Monitoring (BLM) developed by the LHC machine will integrate signals over 40 μs and will serve as backup within BCM'.

Due to harsher radiation environment at HL-LHC the radiation specifications will increase by almost an order of magnitude compared to the existing BCM: the fluence equivalent to $1 \cdot 10^{15}\,\mathrm{n_{eq}/cm^2}$ in silicon will increase to $3 \cdot 10^{15}\,\mathrm{n_{eq}/cm^2}$ (neutron fraction of $\approx 15\,\%$), the total ionizing dose (TID) from 0.5 MGy to 3 MGy, and charged particle flux from $60\,\mathrm{MHz/cm^2}$ up to $230\,\mathrm{MHz/cm^2}$ at $\mu = 200$.

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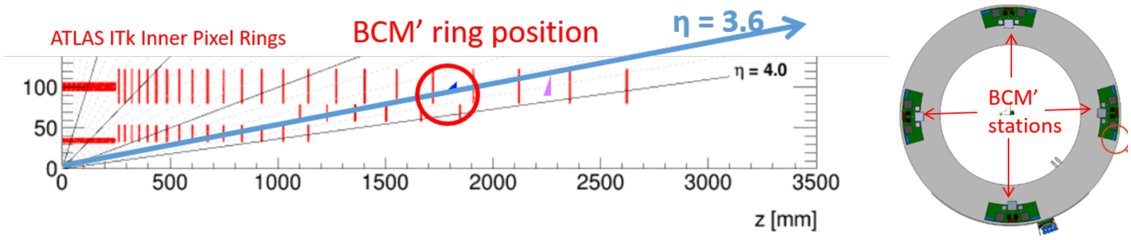


Figure 1: Position of the BCM' ring in ATLAS ITk. Each ring will hold four identical modules (stations).

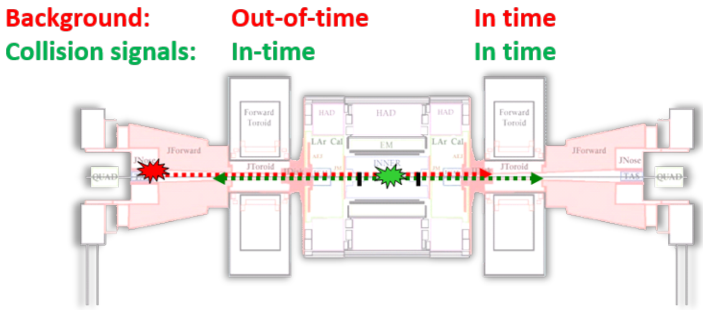
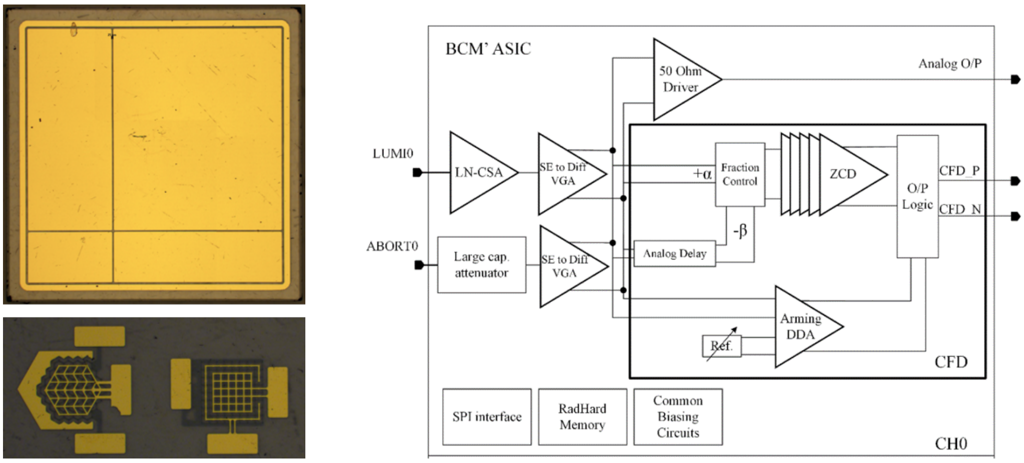


Figure 2: Illustration of time-of-flight concept for discrimination between collision (green) and background signals (red) in BCM and BCM' [2].

BCM' will be installed on two dedicated ITk rings on either side of ATLAS with four identical modules (stations) on each ring. The stations will be located at $r = 10\,\text{cm}$, $z = \pm 1.9\,\text{m}$ from the interaction point at $\eta = 3.6$ (figure 1). The z-position which corresponds to a time-of-flight of 6.25 ns from interaction point is optimized for a time-of-flight based discrimination between collision and background signals and remains unchanged with respect to existing BCM (figure 2). Background particle showers induced upstream of the experiment generate early signals at $t = -2z/c = 12.5\,\text{ns}$ (half LHC clock cycle) in stations on the upstream side, followed by the coincident collision and downstream background signals at the nominal $t = 0$. Out-of-time signals are hence a signature of irregular beam conditions requiring beam abort.

2 Calypso Front End, sensors and BCM' module

BCM' will primarily use 500 µm thick pCVD diamond sensors divided into segments with different surface area, ranging from $1\,\text{mm}^2$ to $50\,\text{mm}^2$ and a maximal capacitance of 5 pF, to adjust the readout rate (figure 3a). In addition, a small 300 µm thick single channel silicon sensor ($C = 5\,\text{pF}$) will be used on each station as an initial reference for luminosity measurement. Each BCM' station will use four pCVD diamond sensors: one



(a) (b)

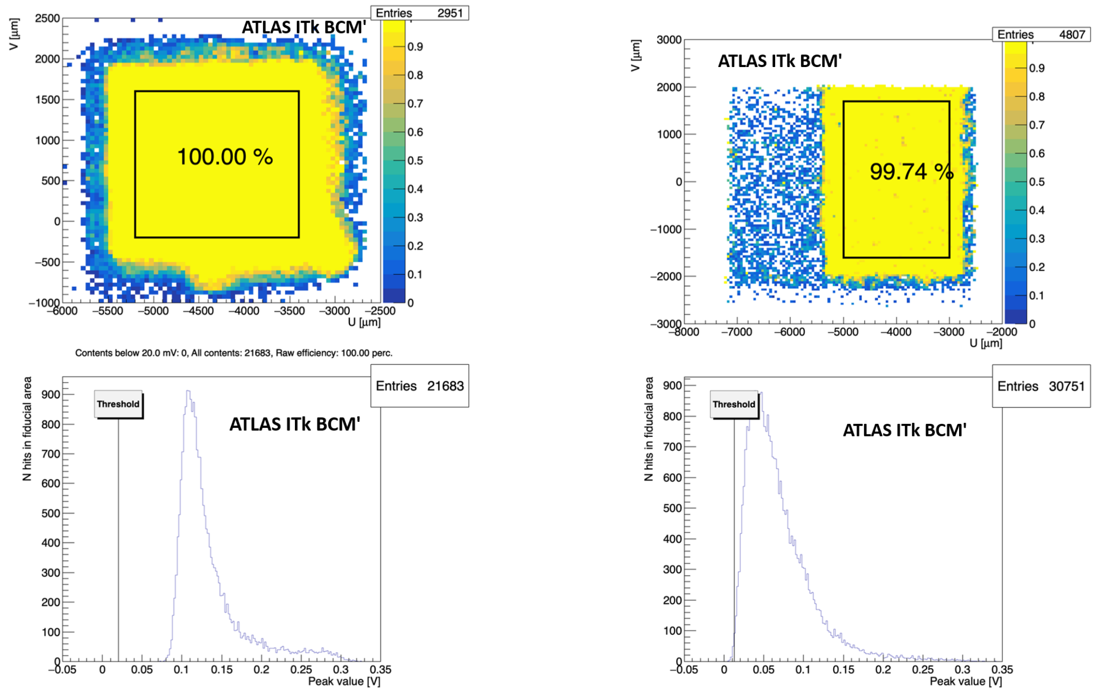
Figure 3: a) pCVD diamond sensor prototypes segmented into four pads (top) and with interconnected 3D electrodes (bottom); b) Schematics of the Calypso front end circuit.

5 mm × 5 mm (4 channels) for abort, two 10 mm × 10 mm (total of 6 pad channels) and one with a single 1 mm^2 channel with 3D electrode geometry for luminosity measurement.

Sensors will be read out with a new custom four channel front end ASIC Calypso (three per station) with a size of 2 mm × 2 mm manufactured in TSMC 65 nm process on a multi-project-wafer. The front end, consisting of a current sensitive amplifier and a discriminator, is designed for a sub-ns hit time resolution for precise time-of-flight measurement, and a fast setting time below 10 ns to prevent pile-up (figure 3b). Each channel is optimized for an input capacitive load of $C_{\rm in}$=2–5 pF and can be configured in luminosity or abort mode of operation.

The luminosity mode emphasizes stable single MIP sensitivity with a good signal-to-noise ratio to mitigate for the degradation of charge collection in the sensor with irradiation. Meanwhile, abort mode relies on a low gain amplifier with a large dynamic range, optimized for large signals typical for dangerous levels requiring abort. Post layout simulations in the luminosity configuration show a noise value of $110\,\mathrm{e}^- + 55\,\mathrm{e}^-/\mathrm{pF} \cdot C_{\rm in}$, a gain of 55 mV/fC and a dynamic range of ±50 ke$^-$, while the abort configurations yields a noise value of 830 ke$^-$, a gain of 8.2µV/fC and a dynamic range of ±750 Me$^-$.

Sensors, front end chips and BLM will be mounted on a module with corresponding power supplies and slow control circuits. Modules will be cooled to −20° C to mitigate TID radiation damage on the ASICs, resulting in a thermal load of 20 W per BCM' ring. Data from the modules will be transmitted asynchronously by a LAPA LVDS driver [3] via 5 m of twinax cable to a generic ATLAS lpGBT transceiver [4], situated in a lower radiation environment, where it will be digitized at 1.28 GHz. Signals will then be optically transmitted to the standard ATLAS FELIX DAQ boards [5] in the counting



(a) Single crystal diamond at 500 V.

(b) pCVD diamond at 1000 V.

Figure 4: Testbeam efficiency and charge spectrum measurement with analog Calypso output with unirradiated a) single crystal diamond sensor; b) pCVD diamond sensor. Small cross talk from neighboring pads is visible.

room. First tests with LAPA and twinax cable have demonstrated no significant signal degradation taking place.

3 Measurement of detection efficiency and SEE susceptibility

Hit detection efficiency of the sensor and Calypso assembly was characterized in a testbeam at CERN SPS H6 beamline with a 120 Gev pion beam using MALTA CMOS beam telescope with tracking resolution of 5 µm [6]. Tests were made with single crystal and pCVD diamond sensors with capacitance up to ≈ 1 pF. Waveforms of analog signals from the first stage amplifier, as well as digital discriminator output signals were recorded with an oscilloscope. Efficiency of the analog signals was calculated offline as the fraction events with signals above a threshold of 5 times noise level. The measured analog signal spectra and detector efficiencies for single crystal and pCVD diamond sensors are shown in figure 4. Both samples have an efficiency above 99.7%, albeit signals in pCVD diamond are significantly smaller. Efficiencies measured with discriminator signals are also similar, but a more systematic threshold study is necessary.

Tolerance of the Calypso ASIC to single event effects (SEE) has been characterized in a proton beam with a particle energy of 230 MeV at PSI Proton Irradiation Facility, with an accumulated proton flux of $3.5 \cdot 10^{13}\,\mathrm{p/cm^2}$. Two chips, one unirradiated and one irradiated with a TID of 3 MGy, were tested. In each sample 30 8-bit registers with triple modular redundancy cells were loaded with a binary pattern and read out every 10 s. In unirradiated sample no beam induced register flips were observed, indicating an upper limit of SEE rate of $10^{-14}\,\mathrm{cm^2}$. In the irradiated sample two events were observed, one with two bit flips, indicating the edge of functionality of the 65 nm technology. This is however not problematic for operation in ITk, since registers can be written at will.

4 Conclusions

The beam protection system BCM' in ATLAS ITk will introduce new pCVD diamond sensors, custom front end ASIC Calypso and a readout chain based on LAPA, lpGBT and FELIX. Different components of the system have been successfully tested in laboratory setups, testbeam and SEE measurements. Further demonstrations of radiation tolerance are still necessary. The project has passed several internal ATLAS reviews and is getting ready for preproduction and production in the years 2022 and 2023.

Acknowledgments

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