PROCEEDINGS OF SCIENCE

Development of the BCM' System for Beam Abort and Luminosity Monitoring at the HL-LHC

Andrej Gorišek[a,*], Mo'men Abusareya[b], Ignacio Asensi[c], Bojan Hiti[a], Harris Kagan[b], Helmut Frais-Kölbl[d], Boštjan Maček[a], Miha Mali[a], Marko Mikuž[a], Alexander Oh[e], Aleksandra Onufrena[c], Alice Laura Porter[e], Ismet Siral[c], Dale Shane Smith[b], Carlos Solans[c], Kirsty Veale[c]

a J. Stefan Institute, Ljubljana, Slovenia

b Ohio State University, Columbus, Ohio, USA

c CERN, Geneva, Swizerland

d FH Wiener Neustadt, Wiener Neustadt, Austria

e University of Manchester, Manchester, UK

E-mail: andrej.gorisek@ijs.si

The High Luminosity upgrade of Large Hadron Collider (HL-LHC) will increase the LHC Luminosity and with it the density of particles on the detector by an order of magnitude. For protecting the inner silicon detectors of the ATLAS and other experiments and for monitoring the delivered luminosity, a radiation hard beam monitor is being developed. We are developing a set of detectors based on pCVD diamonds and a new dedicated rad-hard front-end ASIC. Due to the large range of particle flux through the detector, flexibility is very important. To satisfy the requirements imposed by the HL-LHC, our solution is based on segmenting diamond sensors into pixel devices of varying size and reading them out with new multichannel readout ASICs divided into two independent parts - each of them serving one of the tasks of the system. In this talk we describe the proposed system design including detectors, electronics, mechanics and services and present preliminary results from the first detectors fabricated using our prototype ASIC with data from beam tests at CERN.

10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (Pixel2022), 12-16 December 2022 Santa Fe, New Mexico, USA

[*] Speaker

1. Introduction

Over the next few years, the Large Hadron Collider (LHC) at CERN will be undergoing a high luminosity upgrade (HL-LHC) which will result in an increase of the average number of inelastic proton-proton collisions per bunch crossing from 40 to 200. To handle the increased particle density, the ATLAS experiment will receive a major upgrade, including the installation of a new all-silicon Inner Tracker (ITk).

To ensure that the background activity in the ITk is monitored and to abort the LHC beam in case of dangerous particle showers, the ATLAS experiment will be fitted with an upgraded Beam Conditions Monitoring Prime (BCM’) system. This system will replace the existing beam protection system BCM and will be installed within the retractable part of the ITk Pixel system. In addition to its protective function, the BCM’ will also serve as a luminosity meter for ATLAS. The BCM’ system will be based on polycrystalline Chemical Vapor Deposition (pCVD) diamond sensors, read out by a newly developed front-end ASIC called Calypso. A slower Beam Loss Monitoring (BLM) system, with readout developed by the LHC machine, will be used as a backup for the abort function of the BCM’.

The HL-LHC’s harsher radiation environment will require the BCM’ system to meet higher radiation specifications. The neutron equivalent fluence of 1 x 10^{15} n_{eq}/cm^2 in silicon will increase to 3 x 10^{15} n_{eq}/cm^2 (with a neutron fraction of approximately 15%), the total ionizing dose (TID) from 0.5 MGy to 3 MGy, and the charged particle flux from 60 MHz/cm^2 to 230 MHz/cm^2 at μ = 200.

2. The Concept

The current Beam Conditions Monitoring (BCM) detector [1] in the ATLAS experiment is a reliable and well-established system. During the LHC's Run 1, it served as the primary online luminosity monitor for ATLAS and was responsible for monitoring the safety of the Inner Detector. In the event of any dangerous particle showers, the BCM was responsible for triggering a beam dump, thereby protecting the Inner Detector. To further improve the system, the team behind ATLAS BCM is developing a new and improved version, known as ATLAS BCM'. This new system will build on the legacy of the BCM, incorporating the latest advances in pCVD diamond sensors and a novel dedicated Front-End Calypso ASIC built using radiation-hard 65nm technology [2].

The BCM' system is a crucial component for the upgraded ATLAS Experiment at the Large Hadron Collider (LHC) at CERN. Set to undergo a high luminosity upgrade between 2026 and 2029, BCM' serves as a primary safety system for the experiment, detecting dangerous particle showers with a fast response time and aborting the LHC beam in case of danger to the all-silicon Inner Tracker (ITk) [3, 4]. Moreover, BCM' also serves as a bunch-by-bunch luminosity meter with a precision of 1% and as a background activity monitor in the ITk. The system uses time-of-flight (TOF) discrimination to separate background signals from collision signals.

PoS(Pixel2022)040

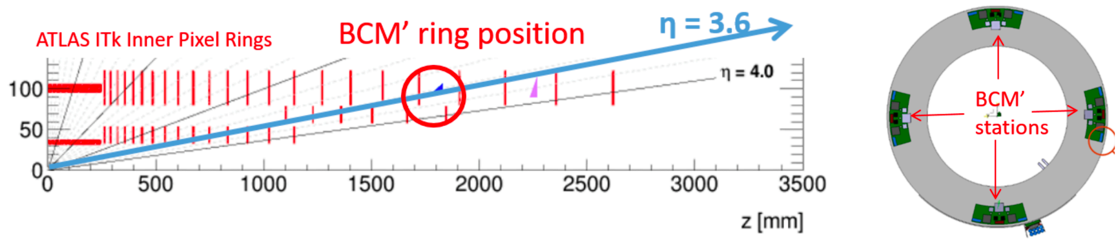

Figure 1: Position of the BCM' ring in ATLAS ITk. Each ring will hold four identical modules

BCM' will be installed on two dedicated ITk rings, located at r ≈ 10 cm and z ≈ ±1.9 m from the interaction point at η ≈ 3.6, near the optimal spot at the carbon fiber cooled ring structure, known as the "R1 Pixel ring." Each ring will have four identical modules on either side, each capable of detecting multi-minimum ionizing particles (MIPs) signals for abort and single-MIP signals for luminosity measurement and background monitoring. Additionally, the system includes the slower Beam Loss Monitoring (BLM), which integrates signals over 40 microseconds as a backup protection system. With a z-position optimized for TOF discrimination, BCM' is designed to operate in the harsher radiation environment at the HL-LHC with increased radiation tolerance specifications. The z-position, which corresponds to a time-of-flight of ≈ 6.25 ns from the interaction point, is optimized for time-of-flight-based discrimination between collision and background signals and remains unchanged from the existing BCM. Background particle showers generated upstream of the experiment generate early signals at t ≈ -2z/c ≈ 12.5 ns (half LHC clock cycle) in the upstream stations, followed by coincident collision and downstream background signals at the nominal t = 0. Excessive out-of-time signals are a signature of irregular beam conditions, which require beam abort.

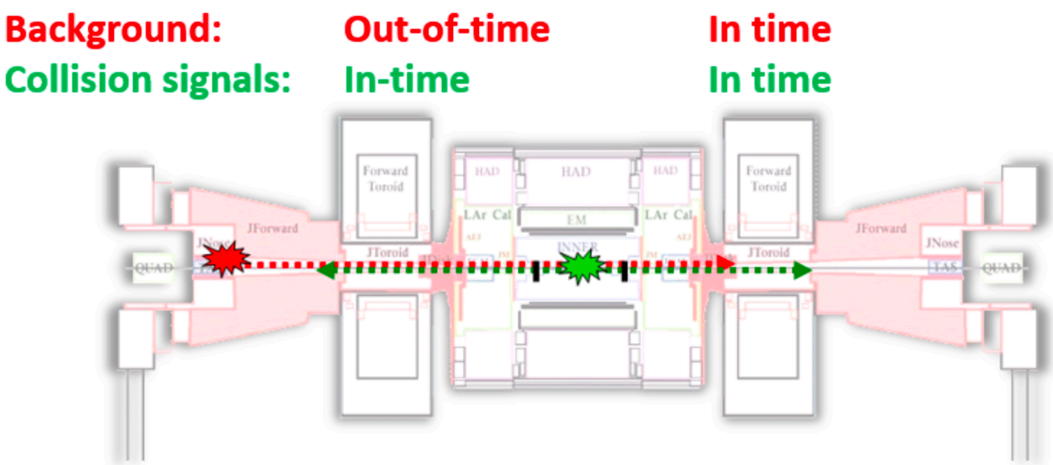

Figure 2: The time-of-flight concept for the discrimination of collision (represented in green) and background signals (represented in red) in the upgraded Beam Conditions Monitoring (BCM') is demonstrated through a graphical illustration. This concept allows for the effective differentiation between the two signals, which are otherwise indistinguishable. By using the time-of-flight principle, the BCM' system is able to accurately determine which signals correspond to collisions and which ones correspond to background activity.

1.1pCVD Diamond Sensors

The BCM’ upgrade at the ATLAS experiment at CERN will feature pCVD diamond sensors from US vendor II-VI [9]. These sensors will be made from newly grown wafers and will come in two sizes - 10x10 mm^2 for luminosity measurement with three pad design and 5x5 mm^2 for abort with four pads. The maximum size of these pads is expected to be about 25 mm^2 and the minimum size is 1 mm^2 . The pCVD diamond sensors have successfully passed bench tests of charge collection distance (CCD) at 1000 V, and the beam test data from five 10x10 sensors from two different wafers (H0, S0 S7, S8, S9) connected to the Calypso-C ASIC on single chip boards have shown promising results. The pad mask for these tests was arranged in strips of 4:2:1:8 size, with the 8-pad being about the largest single pad area that will be connected to a single readout channel. Additionally, single pad sensors (3D pCVD diamond, Si diode) will also be used for luminosity measurements.

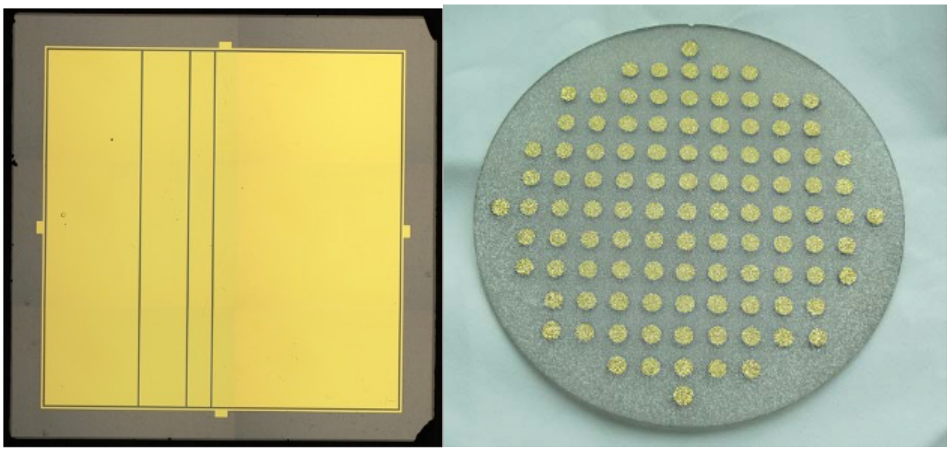

Figure 3: Illustration of the 4-pad test version of the 10x10 mm^2 pCVD Diamond Sensor, where a guard ring can also be seen (left). This design was used throughout the 2022 beam test campaign. On the right, we can see the as-grown pCVD Diamond wafer with dot metalization for testing purposes (Courtesy of II-VI Inc.).

1.2 FE ASIC – Calypso

The Calypso ASIC is a front-end designed in TSMC 65 nm process with a minimal die size of 2x2 mm^2 [2]. The ASIC is affordable to purchase through Europractice/IMEC's Multi Project Wafer. The Calypso ASIC has two types of channels, luminosity and abort, which have been optimized for 2-5 pF detector capacitance. The ASIC has a peaking time of 1.5 ns and a settling time of 15 ns at 2 pF. The time jitter is 100 ps at 2 pF for 3.6 ke signals, which provides a luminosity channel with a noise level of (110+55/pF) e and a dynamic range of 50 ke. The abort channel has a dynamic range of 750 Me, where the signal to noise ratio is not an issue. The 3rd iteration of Calypso, Calypso_C, was received in December 2020 and has been extensively tested, and the 4th iteration, Calypso_D, was submitted in October 2022, and will be tested in 2023.

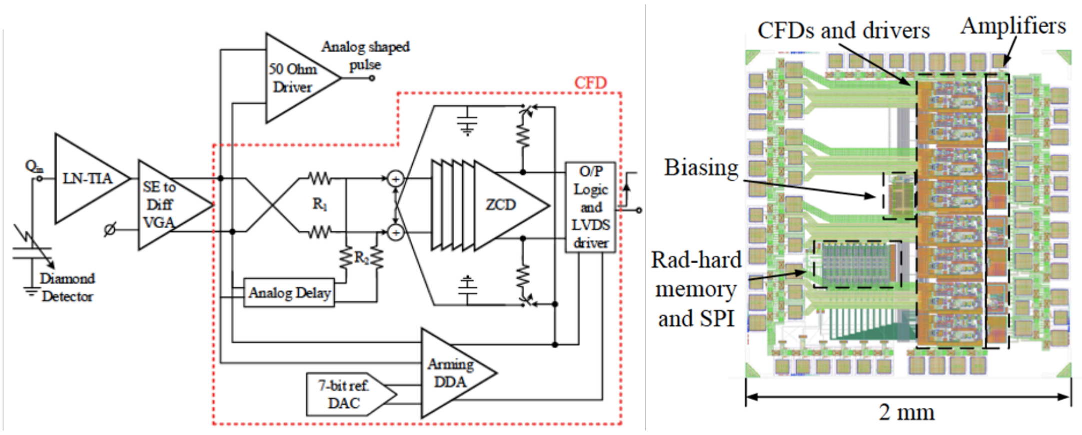

Figure 4: Diagrams of the Calypso ASIC are presented on the left and right. The schematic diagram on the left shows the design of the ASIC, while the layout on the right illustrates the physical arrangement of the ASIC dice.

1.3 BCM' System Overview

The BCM' system is an integral part of the ATLAS Inner Tracker (ITk) Detector. It is a self-contained and fully functional system that includes several key components, such as Low Voltage (LV), High Voltage (HV), Data, Command, Detector Control System (DCS), Interlock, and Cooling. All these components work together in the BCM' system to monitor the background activity in the ITk Detector and to abort the LHC beams in case of dangerous particle showers.

The BCM' system is complex and involves various, distributed services. The services baseline largely follows the ITk Pixel Inner System [3] with some notable differences. For example, the LV system uses DC-DC converters (bPOL [5]) instead of the serial powering scheme in the Pixel system, and the HV operates at 1000 V as opposed to 750 V in the Pixel system. The DCS, Interlock, Cooling, and PP3 design are largely based on the Pixel system, while the PP2, PP1, and PP0 designs have minor modifications.

The printed circuit board (aPCB) and modules in the BCM' system are unique to the system and have specific requirements. Complex grounding and shielding scheme will be implemented in accordance with the ATLAS recommendations.

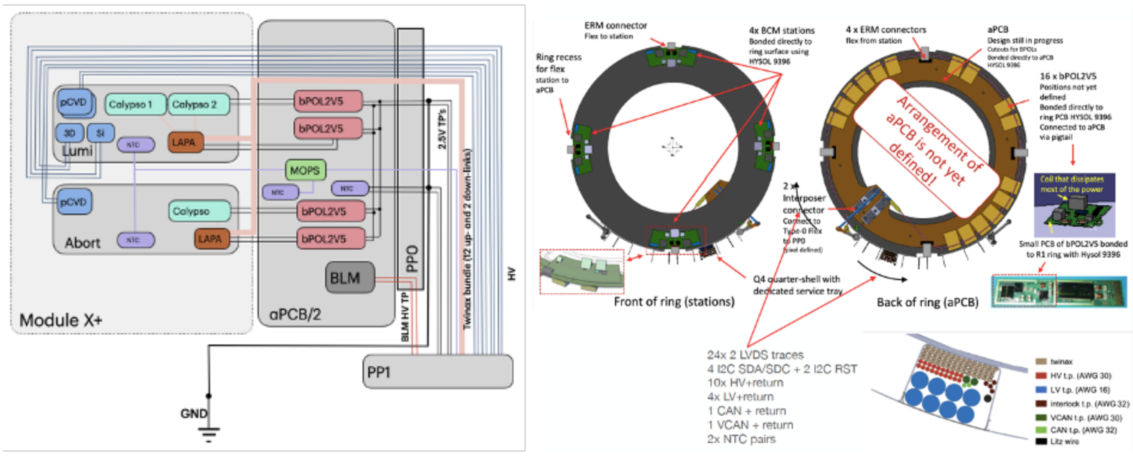

Figure 5: A schematic illustration of the BCM' system is depicted on the left, while the right diagram highlights key components of the system.

3. Results

1.4 Electronics Tests with Calypso Prototype Modules

The Single chip test boards for the BCM' system were assembled at Ohio State University (OSU) and Jožef Stefan Institute (JSI). The basic functionality tests have returned positive results, however, a larger offset spread than expected from simulations was noted and has been addressed in the Calypso_D version. The results from both OSU and JSI were consistent with each other. The bare chips were irradiated with X-rays up to 300 Mrad, and the chip still functioned after the radiation exposure. A variation of less than 20% was observed in the analogue parameters. To fully understand the effects of radiation damage, the chips need to be irradiated while powered and while cold to test before and after the exposure. The I2C configuration has been fully tested, where the BCM' system is equipped with a Triple Modular Redundant memory for all 240 registers.

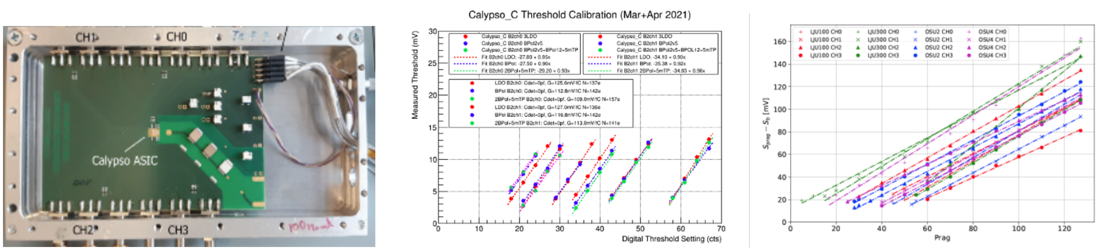

Figure 6: The left picture shows a single chip test board featuring the Calypso ASIC. The middle and the right plots display the linearity measurement of the threshold in mV in relation to the DAC setting for a number of channels. It has been observed that the threshold spread is wider than anticipated and measures are being taken to address this issue in the Calypso_D version.

1.5 System Test Setup

The base-line readout for BCM' utilizes a LAPA driver for the ToA and ToT digital LVDS level signal [6]. This is connected to the optical system via a 5 meter "Twinax" twisted pair cable, which is similar to the one used in the Pixel system. The signal is then sent into the lpGBT and sampled at 1.28 Gbs, with the option to split and delay for a 2.56 Gbs signal. The full chain has been tested up to the FELIX readout test setup at CERN and has shown no transmission errors at 1.28 Gbs. The BCM' readout is also bi-directional, allowing for both data uplinks and command (I2C) downlinks. The BCM' opto readout consists of a single opto-box within the Pixel opto-panel, and is designed to fit the minimal configuration of sampling at 1.28 GBs into one BCM' dedicated opto-box.

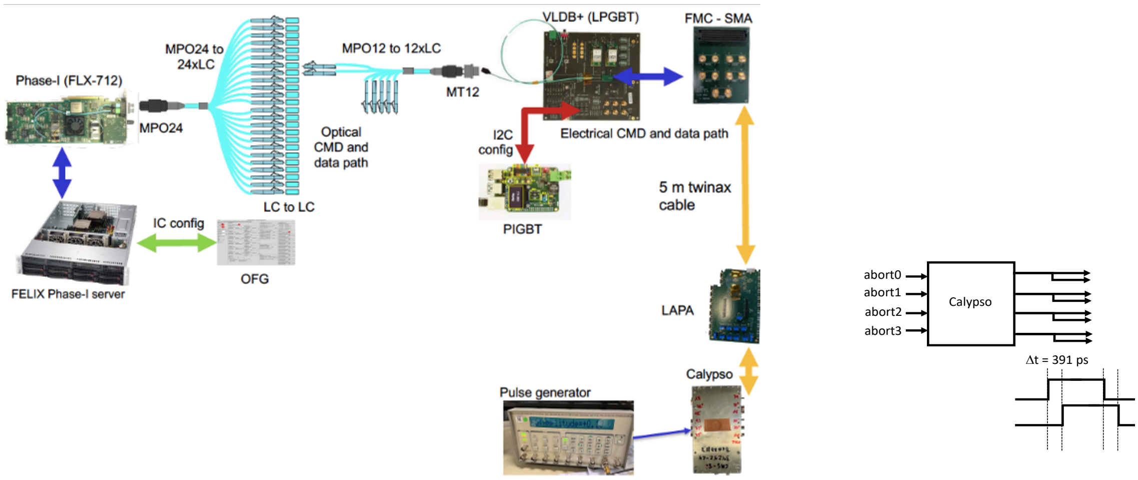

Figure 7: A schematic illustration of the BCM' system test setup is shown on the left. The right sketch depicts an optional 2.56 Gbs sampling configuration.

1.6 Single Event Effect Test at PSI

The tests at PIF facility at PSI in October 2021 aimed to evaluate the performance of the Calypso_C ASIC under the effects of radiation searching for occurrence of SEE. The tests involved exposing the ASICs to 230 MeV total protons flux of 3.5 x 10^{13} p/cm^{2}. One ASIC was left unirradiated, while another was passively exposed to 300 MRad prior to the tests at PSI. The test procedure involved loading 240 bits into the Triple Modular Redundancy (TMR) registers and reading them out every 10 seconds. If a change was detected in two consecutive reads, the chip was reloaded and the reading process was restarted. The results showed that the unirradiated ASICs performed without any issues, which was consistent with the ITk Pixel's upper limit of 10^{-14} cm^{-2}. On the other hand, two events were detected in the irradiated ASIC. However, these events can be mitigated in the experiment by reprogramming the ASIC registers periodically, such as during the LHC inter-fill periods.

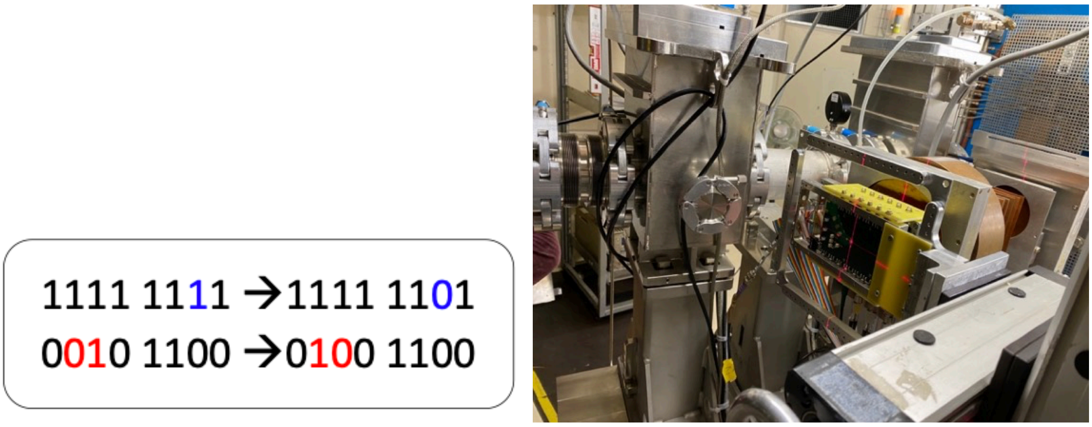

Figure 8: During the Single Event Effect (SEE) tests at PSI in October 2021, two events were recorded in the passively irradiated Calypso ASIC (left image). The experimental setup at PSI, including the positioning of the modules with a laser alignment system to the proton beam, is shown on the right photo.

1.7 Sr-90 Laboratory Tests

In the laboratory, the bench tests were conducted using a Sr-90 source with a activity of 2.2 MBq. The readout was performed using a DRS4 oscilloscope, which has a bandwidth of 700 MHz and a sampling rate of 4 GHz [7]. The tests were triggered by the scintillator and the collimator was positioned above the 4-pad to ensure that relatively pure samples could be collected. During the tests, it was challenging to bias the samples, especially to a positive high voltage due to the erratic currents. However, despite these difficulties, it was possible to select a set of events with a high probability of hitting the selected pCVD diamond 4-pad and fit the distribution reliably through the use of a convolution of Landau and Gaussian functions. This allowed for accurate measurement and analysis of the test results.

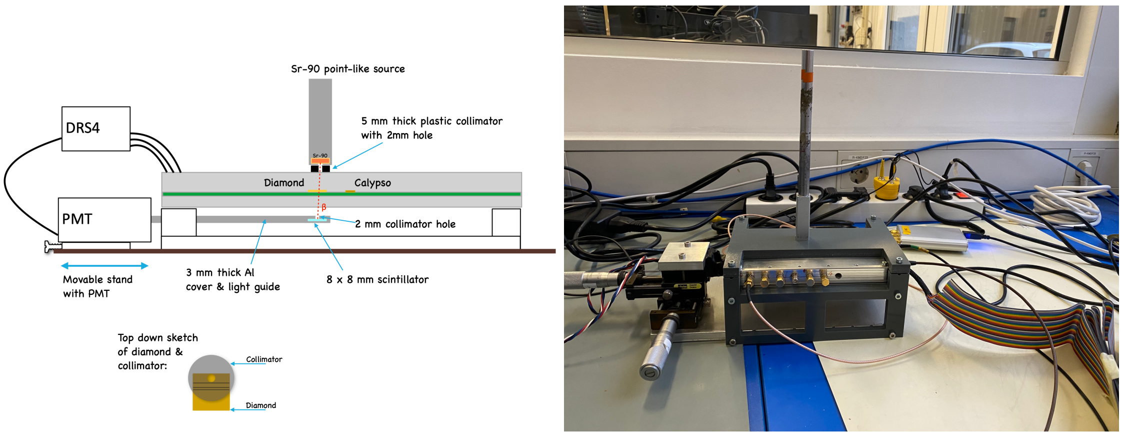

Figure: 9: The schematic view and a photo show the setup of the Sr-90 source used in the bench tests conducted in the laboratory.

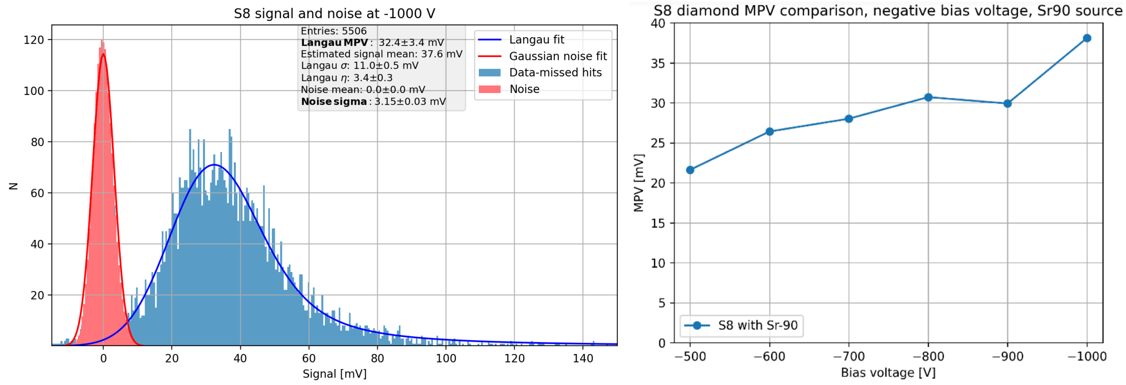

Figure 10: The left image depicts a spectrum of signals produced by electrons passing through the pCVD diamond sensor and triggering the scintillator. The signals are fitted with a convolution of Gaussian and Landau functions, represented by the blue line in the plot. The red distribution represents a noise pedestal. The right plot displays a voltage scan of the most probable value of the fit, ranging from 500V to 1000V.

1.8 Beam Test Results

The MALTA monolithic pixel detector, based on TowerJazz 180 nm CMOS technology developed at CERN [8], was used as the beam telescope for the tests. The active area of the sensors measures 2x2 cm^2 and it consists of 512x512 pixels with a 36.4 μm pitch. The detector has 6 planes. The tracking cuts applied include a requirement for number of tracks reconstructed to equal 1, slopes of the tracks in X and Y to be less than 0.00025, chi^2 to be less than 10, and the track to be within the fiducial area, with a loose timing cut for hits in individual planes of ±10 ns applied on 3 planes.

Data was collected from multiple Calypso modules during multiple test beam campaigns throughout 2022. The modules tested included H0, S0, S7, S8, and S9. The results showed that the noise measured was dependent on the input capacitance, as predicted. However, difficulties were encountered in ramping up to the nominal voltages of ±1000V due to an increase in leakage currents, which were not seen in the bare sensors. To resolve this issue, cleaning of the PCB prior to mounting the diamond and changes to the design of the PCB to increase clearance to the HV will be attempted for Calypso_D version of the PCB. The mean signal was found to decrease with input capacitance at the upper design limit of a few pF. Despite this, the signals were still large enough to provide a working range for the choice of threshold.

The results of the measurements for the Sr-90 setup and the H6 at SPS beam test have been compared and shown to be consistent. The signals were renormalized to account for the approximately 10% higher value of MIP signal expected with Sr-90 electrons and the sqrt(2) higher signals in the beam test due to the 45 degree angle. The usable Signal to Noise (S/N) ratio has been confirmed at both the Sr-90 setup and the beam test measurements at SPS, CERN. The results obtained in the beam test and the Sr-90 lab setup are comparable and consistent.

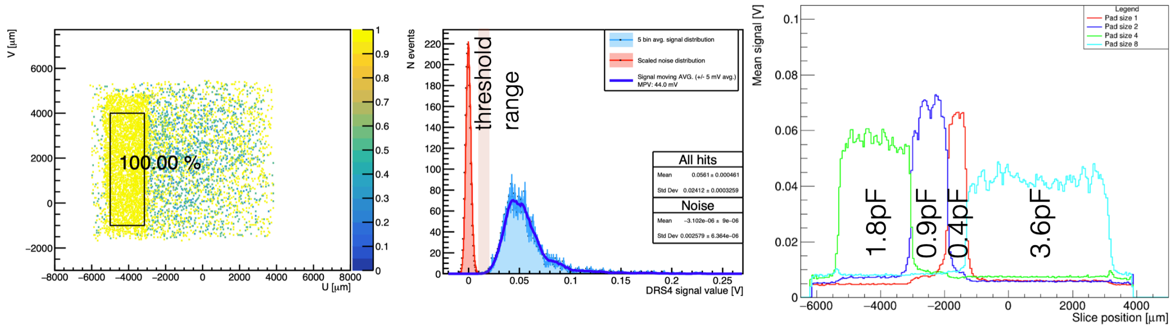

Figure 11: The left plot demonstrates that the ability to detect a minimum ionizing particle (MIP) in a 4-pad is almost perfect, as determined through beam test measurements at CERN. The middle plot displays the distribution of signals in blue, in conjunction with a noise pedestal in red. Usable threshold range is also indicated. For the plot on the left a threshold of 12.5mV was used. The right plot displays the average signal value for 4 different pads, revealing that for the 8-pad with the highest capacitance, signals are approximately 30% smaller compared to the 1 and 2-pads.

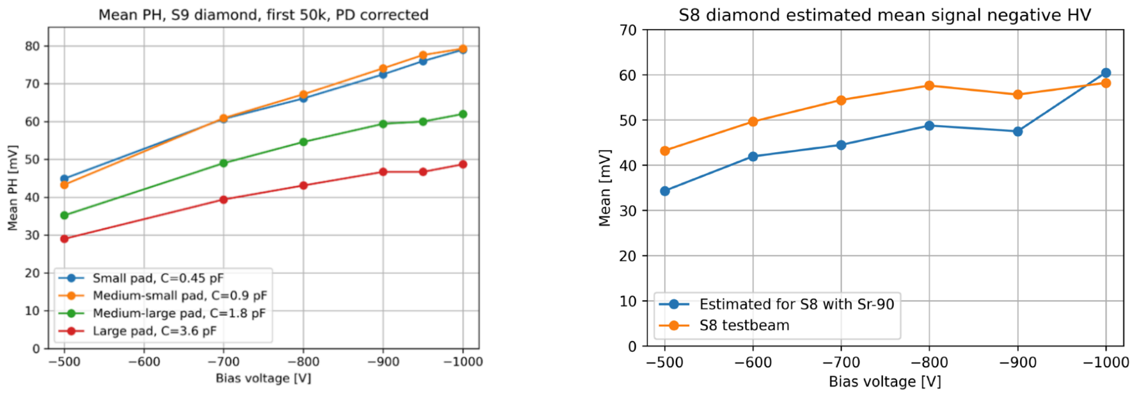

Figure 12: The left plot presents a voltage scan of the average signal for four different pads. The right plot compares the voltage scan from both the beam test and the bench test, after re-normalizing the data. The results demonstrate that the results are comparable.

4. Summary

The BCM' detector is an advanced system that is currently being developed for the upcoming ATLAS High-Luminosity upgrade. The design proposal was presented, showcasing the status of the project, as well as preliminary results from various beam tests and bench tests. These preliminary results have been found to be satisfactory, meeting the goals that the BCM' aims to achieve. The main purpose of the BCM' detector is to measure and monitor the luminosity of the ATLAS experiment, as well as to protect the delicate inner parts from potential damage. While there is still a challenging period ahead, the team is working hard to secure all necessary components and develop any missing pieces in order to have the system fully installed by 2025.

References

[1] V. Cindro et al., *The ATLAS Beam Conditions Monitor, 2008 JINST 3 P02004*

[2] Mo'men Mansour et al., *A Fast, Low Jitter, and Low Time-Walk Multi-Channel Front-End IC for Diamond and Silicon Radiation Detectors*, submitted to *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*

[3] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Pixel Detector, CERN-LHCC-2017-021,* http://cds.cern.ch/record/2257755

[4] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector, CERN-LHCC-2017-005,* http://cds.cern.ch/record/2257755

[5] F. Faccio et al., *The bPOL12V DCDC converter for HL-LHC trackers,* PoS(TWEPP2019)070.

[6] R. Cardella et al., *LAPA, a 5 Gb/s modular pseudo-LVDS driver in 180 nm CMOS with capacitively coupled pre-emphasis,* PoS(TWEPP-17)038.

[7] S. Ritt, DRS4 *Evaluation Board User's Manual*, https://www.psi.ch/sites/default/files/import/drs/DocumentationEN/manual_rev51.pdf

[8] H. Pernegger et al., *Radiation hard monolithic CMOS sensors with small electrodes for High Luminosity LHC, Nuclear Inst. and Methods in Physics Research, A 986 (2021) 164381*

[9] II-VI Inc., 375 Saxonburg Blvd., Saxonburg, PA 16056. https://ii-vi.com/product/cvd-diamond-substrates/