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Fast Luminosity Diamond Monitor for CEPC

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Introduction

A fast luminosity monitor using diamond strip detectors is proposed to detect small-angle Bhabha scattering electrons from e^+e^- collisions at 10 mrad (in the CMS frame), boosted by 33 mrad due to beam crossing (CMS +16.5 mrad in the lab frame). It is designed to be placed in the MDI volume, close to the beam-pipe wall along the lab frame's boosting direction. Multiple electronic-grade diamond strips will be integrated into a diamond slab detector, positioned in front of the quadrupole at $|z|$ = 855~1110 mm, with x = – 27 mm and y from – 12 to 12 mm beside the beam-pipe. By measuring symmetric event rates on the $-z/+z$ sides, it will monitor luminosity at a high rate. It will also provide real-time feedback on interaction point (IP) offsets in the z and y directions, based on the shower profile in diamond slab from Bhabha scattering electrons.

Fast Luminosity Diamond Monitor

Two diamond slabs are designed to be installed close to the beam pipe, represented as yellow blocks in Figure 1:

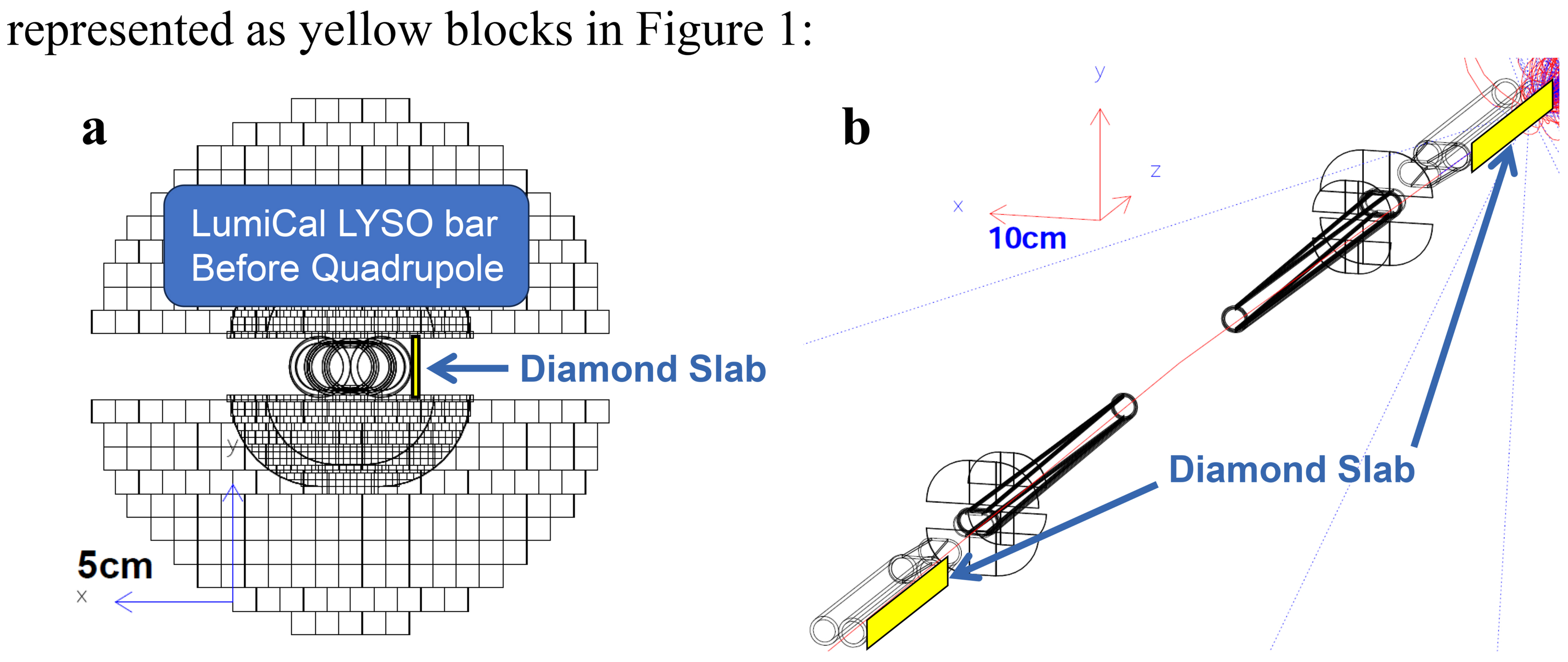

Fig. 1a: x-y view of the Diamond at x=-27mm between the LumiCal detector of LYSO bars in 10×10 mm² blocks. The project of LumiCal in front of Flange are also projected. 1b:The MDI is shown with a race-track pipe, the LumiCal Si-wafers, and the Diamond slabs on the side of the boost direction.

Each diamond slab is composed of dozens of diamond strip electrodes stitched together, segmented with a 2 mm pitch to measure Bhabha electron showers passing through the 3 mm thick Cu beam-pipe. Schematic diagram and specific location coordinates are shown in Figure 2:

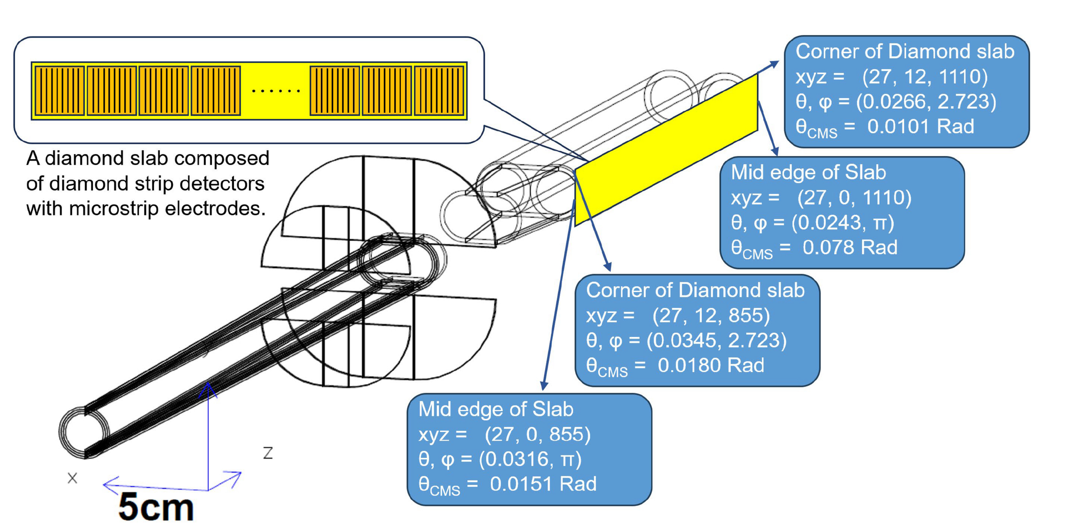

Fig. 2: The coordinates of the diamond slab and the preliminary layout of the diamond strip electrodes. The strip electrodes can be arranged in different orientations.

Shower profile, Sensitivity to θ and IP offset

The Bhabha cross sections covered by the diamond detector are estimated to be on the order of 100 nb, corresponding to a trigger rate of 100 kHz at an instantaneous luminosity of $1x10^{36}/cm^2{\cdot}s$. Simulations of the shower profile for a 50 GeV electron at θ = 10 mrad (CMS), boosted to 26.5 mrad in the x-direction passing through the copper beam pipe and hitting the diamond, are presented in Fig. 3a. For comparison, shower profiles for electrons at 9 to 12 mrad are also displayed in Fig. 3b. The fast monitoring functionality can be achieved with several thousand diamond strips, each with a 2 mm pitch, and a 100 kHz readout system.

The sensitivity of diamond shower profiles to interaction point (IP) offsets has also been simulated. An IP offset in the x-direction is equivalent to a shift in θ, which is not detectable. However, offsets in the y and z directions can be obtained through the cross-sectional patterns of the shower in different directions. With a 2 mm strip pitch, the diamond detector is sensitive to an angular resolution of 0.1 mrad, and can detect IP offsets of 0.1 mm in the y-direction and 1 mm in the z-direction.

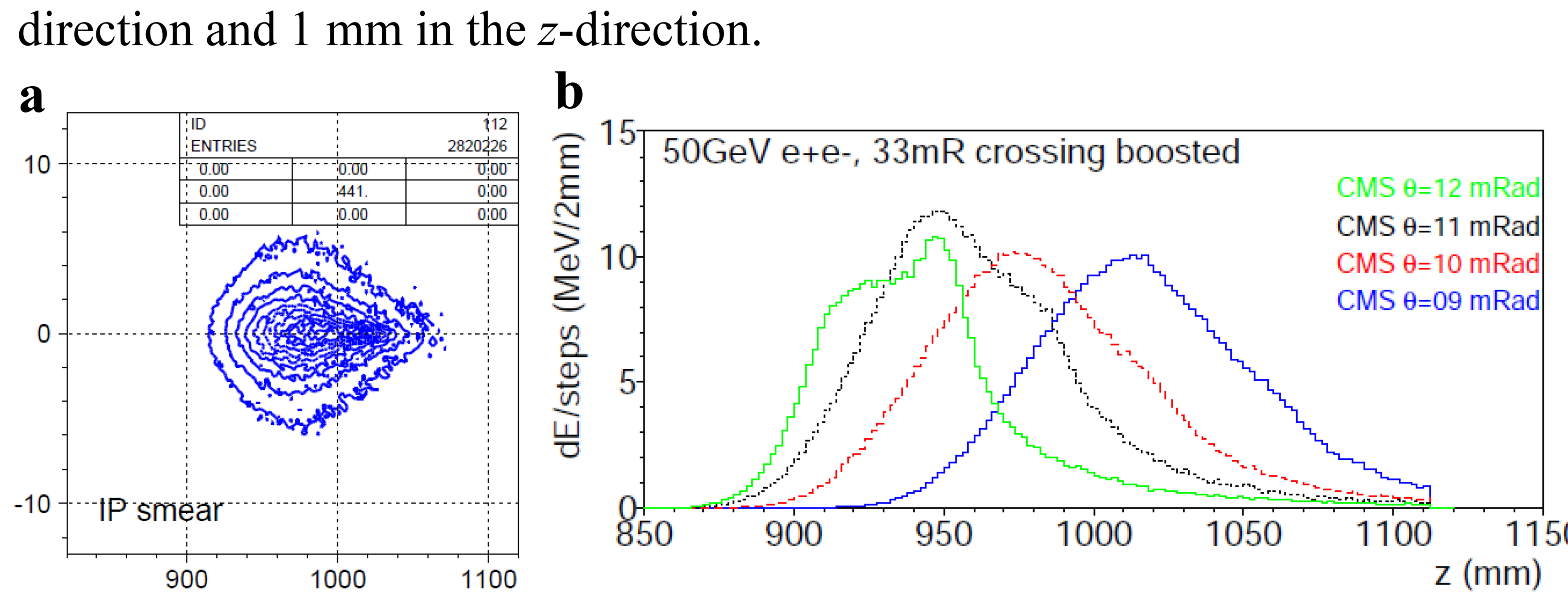

Fig. 3a: for a 50 GeV electrons at θ= 10 mRad (CMS), boosted in x at 26.5 mRad. 3b: Comparison of shower profiles on diamond at 9 to 12 mRad.

Fabrication of Diamond sensors

Based on the research for calorimeters in the forward region of the HL-LHC-ATLAS, high-quality, electronic-grade single-crystal diamond sensors have been fabricated at Nanjing in collaboration with various institutions. The diamond materials were synthesized using 30 kW direct current (DC) arc plasma chemical vapor deposition (CVD), and metal electrodes were deposited onto the diamond surface through magnetron sputtering. The resulting single-crystal diamond sensors have a thickness of 300-500 μm and a surface area around 0.5 cm². The sensors are mounted on a ceramic-based high-frequency Rogers board, providing secure support for the diamond and facilitating effective integration with the readout electronics. They achieve a dark current in the range of tens of picoamperes at an electric field of 2.5 V/μm, resulting in a high signal-to-noise ratio.

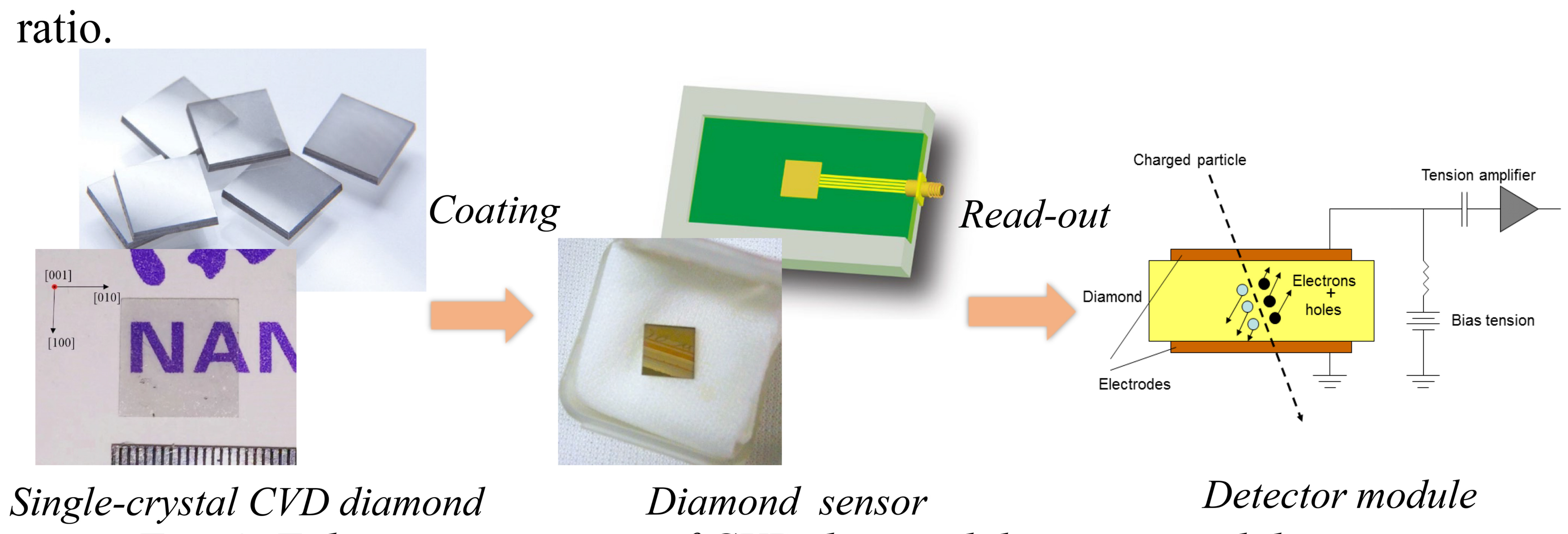

Fig. 4: Fabrication process of CVD diamond detecting module

Radiation tolerance test of diamond sensor

- Fast neutron irradiation was conducted at the IBR-2M reactor in Dubna, Russia, with a total of 280 hours, a total dose of 3.3×10^{17} n/cm²;
- 100 MeV proton irradiation was conducted at CIAE for a total of 47 hours, accumulating a dose of 1.6×10^{17} p/cm²;
- Radiation tests reveal that, at an expected radiation level of 3×10^{17} n/cm² (~10 MGy), diamond sensors demonstrate the ability to maintain low noise operation and signal attenuation can be corrected through calibration.

Electrodes design on Diamond sensor

To meet the requirements for fast luminosity and IP offset monitoring, diamond sensors have been designed with microstrip electrodes. Advanced electrode techniques are also being explored to further improve resolution.

Microstrip Electrodes :

- Microstrip electrodes with a width of 1 mm (and a minimum achievable of 10 μm) can be fabricated through photolithography and coating techniques.
- Readout strip could be directly wire bonded from the diamond strip detector to a VA2.2 readout channel;

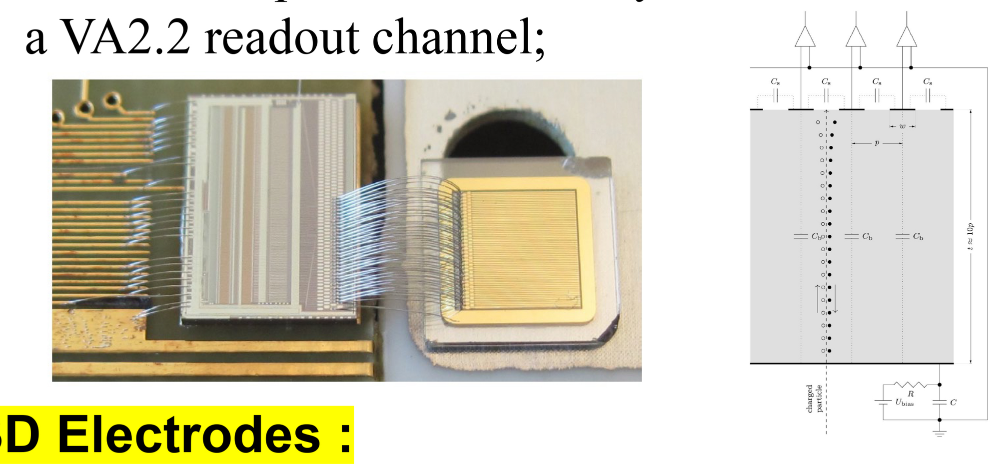

Fig. 5: Schematic diagram of a 50 μm pitch diamond microstrip detector prototype[1] and its principle.

3D Electrodes :

- Proposed scheme for fabricating cutting-edge 3D electrodes in diamond;
- Utilizing femtosecond pulsed laser to induce the transformation of the sp³ phase in diamond to a conductive sp² phase, serve as the electrodes;
- Improves both time and spatial resolution by 30%;
- Enhancing radiation resistance by improving CCE.

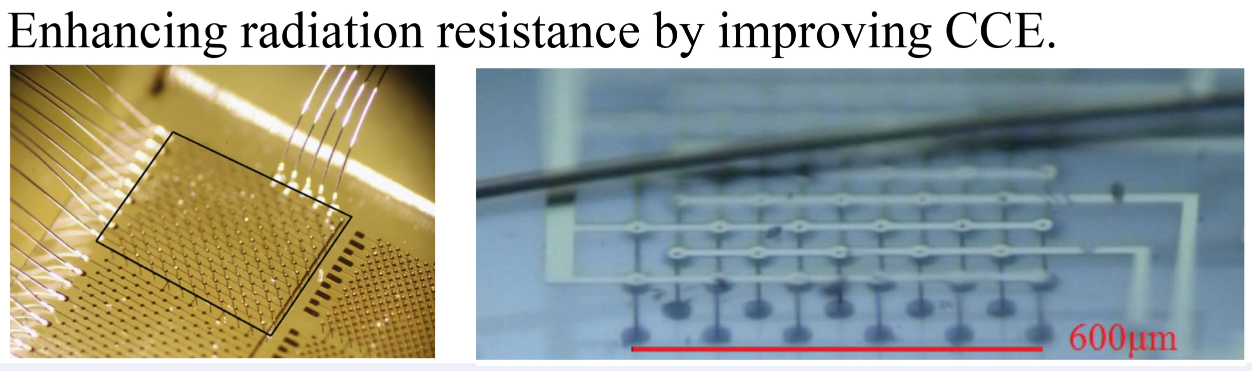

Fig. 6: 3D electrodes[2] inside the diamond bulk

Conclusion

By integrating radiation-resistant diamond sensors with a pitch of 2 mm or less, a diamond slab positioned adjacent to the beam pipe can facilitate fast luminosity monitoring through real-time feedback on event rates from the –Z and +Z sides. Additionally, with pattern recognition, the system can achieve a resolution of 0.1 mRad for detecting scattered electrons, a resolution of 1 mm for shifts in the interaction point (IP) in the z direction, and 0.1 mm for shifts in the y direction, given an appropriate electrode configuration. The production of diamond materials and various advanced electrodes can be conducted in laboratories in Nanjing.

References

[1] CERN RD42, J. Phys. D: Appl. Phys. 52 (2019) 465103
[2] CERN RD42, 38th International Conference on High Energy Physics

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