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Results from a beam test of a prototype PLT diamond pixel telescope

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ABSTRACT

We describe 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 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 meets all required specifications.

1. Introduction

The Pixel Luminosity Telescope (PLT) is a dedicated luminosity monitor for CMS based on single-crystal diamond pixel sensors. The PLT is comprised of two arrays of eight small-angle telescopes situated one on each end of CMS. The telescopes consist of three equally spaced planes of diamond pixel sensors with a total telescope length of 7.5 cm and are located 5 cm radially from the beam line at a distance of 1.8 m from the central collision point. Fig. 1 shows a sketch of a PLT array and indicates its location within CMS. The telescope planes consist of single-crystal diamond sensors with active area of 3.6 mm $\times$ 3.8 mm that are bump bonded to the PSI46v2 CMS pixel readout chip [1]. The PLT is designed to provide a high-precision measurement of the bunch-by-bunch relative luminosity at the CMS collision point on a time scale of a few seconds and a stable high-precision measurement of the integrated relative luminosity over the entire lifetime of the CMS experiment.

The primary luminosity measurement of the PLT is based on counting the number of telescopes with threefold coincidences formed from the fast-or, column-multiplicity signal output by the PSI46 readout chip. The fast-or signal, clocked at the bunch crossing rate of 40 MHz, indicates the number of double columns with pixels over threshold in each bunch crossing. In addition, the full pixel information consisting of the row and column addresses and the pulse heights of all pixels over threshold is readout at a lower rate of a few kHZ. This full pixel readout provides tracking information and is a powerful tool for determining systematic corrections, calibrating pixel efficiencies and measuring the real-time location of the collision point centroid.

Diamond sensors are crucial for the PLT application since they will operate efficiently with only moderate decrease in signal size over the entire lifetime of CMS [2]. Studies have shown that the PSI46 pixel readout chip will also continue to function at this exposure level [3]. Of equal importance, the radiation hardness of diamond sensors does not require that the sensors be cooled. Single-crystal diamond is used for the sensor material rather than polycrystalline diamond since the pulse height distribution of single crystal diamond is large and well separated from zero, ensuring that any efficiency changes due to threshold drifts will be small. In order to determine the performance of the diamond pixel sensors and the soundness of the PLT design, we carried out a test of a prototype telescope in a 150 GeV/c π^+ beam in the H4 beam line of the CERN SPS in May of 2009. The primary goals of this test were to determine: the yield of good pixel channels that

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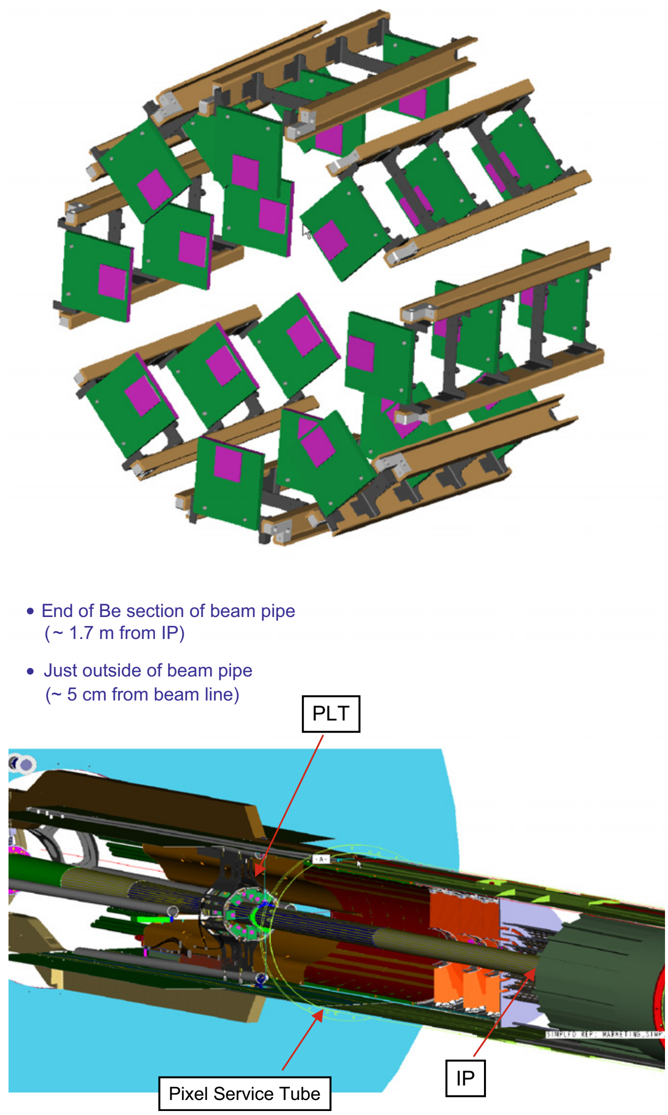

Fig. 1. Sketch of one of the PLT telescope arrays and its location within CMS. The magenta squares on the telescope planes indicate the locations of the diamond sensors.

result from the bump-bonding process; the pulse height response of the diamond sensors for minimum ionizing particles; the fast-or signal efficiency; and the tracking capability of the diamond pixel planes. Although seven days of beam time had been allocated, we had only two days of beam due to accelerator problems. Despite the limited beam time, we were able to complete the core components of the program, although with considerably less statistics and without the benefit of optimization and tuning of parameters that would have been possible with the full beam time allotment.

2. Detector preparation

The diamond sensors were single-crystal Chemical Vapor Deposition (CVD) diamond with nominal thickness of 500 μm supplied by Diamond Detectors Ltd. Their physical area of 4.7 mm × 4.7 mm is the largest size currently available for commercial, single-crystal, detector-grade diamond. Although a larger diamond size would have been preferred for ease of handling during processing, the present area is more than sufficient for the solid angle coverage required for the PLT. The characteristics of each diamond sensor was studied using a ^{90}Sr beta source. We found that 15 out of the 32 sensors measured achieved full charge collection at an applied field between 0.05 and 0.2 V/μm with an additional 13 sensors achieving full charge collection at an applied field between 0.2 and 0.4 V/μm. For the beam test, a bias voltage of 250 V was applied to each of the three diamond sensor planes corresponding to approximately 0.5 V/μm.

Deposition of the pixel electrode pattern on the diamonds and the bump-bonding of the diamond sensors to the pixel readout chips were performed "in-house" at the Princeton Institute of Science and Technology Materials (PRISM) micro-fabrication laboratory. Following surface preparation, electrodes were sputtered onto the diamond surface using a Ti/W alloy target as an under bump metalization (UBM). A 4 mm × 4 mm electrode was deposited on one side of the diamond using a shadow mask. On the other side, a pixel pattern was deposited using a standard lift-off photolithographic process. The pattern covered an area of 3.9 mm × 4.0 mm and consisted of an array of 26 × 40 pixels with pitch of 150 μm × 100 μm matching that of the PSI46 chip. Each UBM pixel electrode was 125 μm × 75 μm with 25 μm gaps between electrodes. The pixelated diamond sensors were then bump-bonded to the readout chip using a flip-chip procedure. Approximately cylindrical indium bumps with diameters of 15 μm and heights of 7−8 μm were evaporated onto the pixel pads on both the readout chip and the diamond sensor. This step required a thick layer of photoresist built up from two layers of intermediate thickness. Depositing the indium bumps on readout chip wafers using this thick photolithographic process was relatively straightforward since chips at the periphery of the wafer could be sacrificed. Depositing the indium bumps on the individual diamond pieces required considerably more development. It was necessary to remove a thick meniscus of photoresist that forms at the edge of the diamond during the photoresist spinning process without compromising the integrity of the pixel pattern close to the edge of the diamond. A procedure was developed for forming a custom-fit frame around each diamond so that the photoresist would fully spin off the diamond onto the sacrificial frame leaving a uniform layer on the diamond. After indium bump deposition, the diamond sensors were then bump-bonded to the readout chip using a Research Devices MA-8 flip-chip bonder with an optically controlled alignment precision of better than 2 μm. The electromechanical bond was formed by applying pressure only. The indium bumps were not reflowed. The readout chip has an array of 52 × 80 channels that is larger in area than the diamond sensors as seen in Fig. 2.

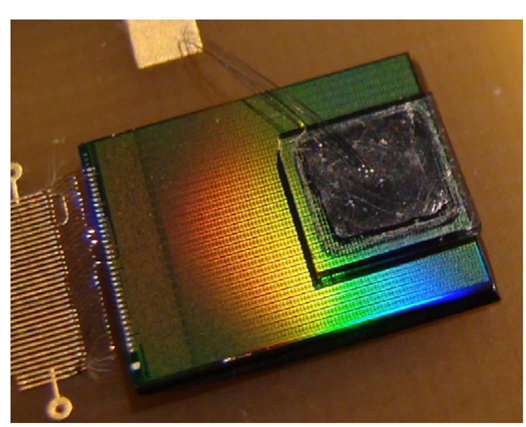

Fig. 2. Bump bonded detector.