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.

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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 $3.6 \times 3.8$ 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 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 $\pi^+$ 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 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 optimiza-
tion 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 dia-
mond 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 90Sr 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 sput-
tered onto the diamond surface using a Ti/W alloy target as an
under bump metallization (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 develop-
ment. 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.

The bonded detectors were mounted onto hybrid boards
consisting of flex circuits with a ceramic filled fiberglass backing

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.

Fig. 2. Bump bonded detector.
varying by about 50 μm in thickness from one edge of the diamond to the other. This caused difficulty in the flip-chip bonding. In the first attempt nine columns did not form bonds. The sensor and readout chip were separated and in a second bonding attempt all columns bonded except for left-most five. This wedging was due to a temporary defect in the diamond polishing procedure that has since been corrected.

3. Detector readout

The front-end part of the readout chain consisting of the readout chip, hybrid board and HDI circuit represents closely the circuitry that will be used in the PLT. The hybrid board was described above. The three hybrid board planes that make up a telescope are connected by pigtails to the HDI, a four-layer flex circuit. The HDI houses a CMS pixel Token Bit Manager (TBM) chip that communicates with the three readout chips in the telescope and orchestrates readout of the full pixel information. These data are output by the TBM onto a single analog line. The HDI also houses a custom PLT driver chip that amplifies and outputs the three fast-or signals onto separate analog lines. The HDI also distributes low voltage power and sensor bias voltage to the hybrid boards.

In the PLT, the HDI circuits will connect to a semi-circular port card board located at the end of the support carriage with one port card for each half carriage (four telescopes). The port card will be connected to the opto board, another custom circuit, located at the foot of the carriage. The opto board will house the optical hybrid circuits for the outgoing analog signals (pixel readout and fast-ors) and for the digital control signals. From the opto board the analog signal fibers will connect to a Front End Driver (FED) [4], a VME flash ADC module, located in the CMS underground service cavern. The PLT will use two types of FED, a standard CMS pixel detector FED for the full pixel analog readout and a custom FED with an identical hardware configuration but with customized firmware for processing the fast-or signals.

The port card and opto board are closely coupled to mechanical design constraints of the PLT support structure and along with the rest of the optical part of the readout chain are currently under design. For the beam test, the readout downstream of the HDI was, therefore, electrical rather than optical. The HDI was connected to a telescope test stand board that played the role of the port card. This board produced four amplified, single-ended analog signals from four differential analog signals: one full pixel readout signal from the TBM and three fast-or signals, one from each of the three readout chips. These signals were sent on coaxial cables, approximately 30 m long, to the electronics control room. The test stand board also output a digital TTL signal for each of the three fast-or signals for use in triggering. A Front End Controller (FEC) test stand board provided functions similar to those of the FEC module of the CMS pixel detector [4]. It programmed the registers in the TBM and readout chips and set the pixel threshold trim values. It also sent clock and trigger signals to the TBM. The telescope test stand board was located in the beam line next to the telescope while the FEC board was located 30 m away in the electronics control room. The full readout pixel analog signal and the three fast-or signals were input to the FED flash-ADC module. This FED was a modified version of the CMS pixel system FED that accepted electrical rather than optical inputs. The module was otherwise identical to the FED used for the CMS pixel systems.

The whole system including readout chips, TBM chip and FED was clocked at 40 MHz.

Fig. 4 shows the setup in the beam line. Small scintillators each 6 mm × 6 mm, seen in the figure, were positioned just upstream and downstream of the telescope. All of the results reported here are based on events triggered by a coincidence of these two scintillators. When a trigger coincidence occurred a signal was sent to the FED via a CMS Timing Trigger and Control Interface (TTCci) module initiating digitization. In order to have a wide time view of the event, the digitization started three clock periods before the event and continued for 960 clock periods.

Before taking data, a procedure, similar to that for the CMS pixel detectors, was used to lower the pixel thresholds as much as possible. This was a multiple-step procedure that involved...
adjusting three DAC settings in the readout chip: the overall coarse threshold, the trimming range around this setting and the trimmed threshold for each individual pixel. The pixel thresholds achieved were in the range of 2500–4500 electrons.

The telescope planes were calibrated using the built-in pulsing capability of the PSI46 readout chip. Internally the readout chip could be programmed to deposit known amounts of charge into selected pixel channels. One-by-one each pixel was calibrated by ramping this charge through the full input range while reading the output signal into the FED. The input charge was plotted vs. the FED ADC value and fit to a second-order polynomial to obtain a mapping from ADC count to pulse height in electrons.

4. Results

4.1. Plane occupancies and pixel yield

Fig. 5 shows the occupancy of each of the three telescope planes for events triggered by a coincidence of the two 6 mm × 6 mm scintillators. The area of each pixel box in the figure is proportional to the number of hits on the pixel. As noted above, the first five columns of Plane 1 were disabled because of bonding problems caused by the wedge shape of this sensor. Due to several noisy pixels, the rightmost column of Plane 1 was also disabled. All of the rest of the columns in all three planes were enabled. Because of limited beam time, we were not able to fully iterate the alignment of the telescope and scintillators with beam. As a result, the leftmost columns of the telescope planes were not covered by the scintillators, as can be seen in the figure. The outermost rows and columns collect charge from particles over a region extending outside of the pixelized region and, therefore, have more hits than other rows and columns. In the PLT, these outermost rows and columns will be masked in order to define a sharp fiducial region given by the boundary between the outermost rows (columns) and their neighboring row (column). Fig. 6 shows the same plots but with the outermost rows and columns and the columns not covered by the scintillators left blank. The six empty pixels in column 37 of Plane 1 were noisy and were also masked off.

Except for shadowed and disabled columns, nearly all pixels were active. Fig. 7 shows the distribution of the number of hits per pixel for those pixels in the indicated regions in Fig. 6. Due to limited beam time, only about 12 hits per pixel, on average, were accumulated over the period of good data runs. As a result, the distributions are not well separated from zero. They, nevertheless, allow an upper limit on the number of non-functioning pixels to be determined. The number of pixels without any hits are 1.8%, 2.2% and 0.1% for Planes 1, 2 and 3, respectively, indicating that, for these planes, the yield of good pixel bump connections was
98% or better. Since the time that these sensors were bump-bonded, we have continued to improve and gain experience with the process and currently percentage yield of good bump connections is even higher.

4.2. Tracking

In order to reconstruct tracks in the telescope, we first found the clusters associated with particle hits in each plane. Pixels above threshold that were nearest neighbors in either the row or column direction were merged. The resulting clusters consisted of one, two, three or four nearest neighbor pixels. The cluster position was calculated as the average of the positions of its constituent pixels weighted by their collected charge. Fig. 8 shows a sample of tracks reconstructed from the cluster positions. For this plot, events were selected in which there was one and only one cluster in each of the three planes. Events of this type constitute 89% of events that have an in-time fast-or signal in all three planes. Each line represents a track from a separate triggered event. The lines shown are linear fits to the cluster hit positions. Fig. 9 shows a similar sample of tracks in a three-dimensional display.

The tracking information allowed us to readily determine the relative alignment of the three planes. Using the difference between the hit cluster position in Plane 2 and the average of the hit cluster positions in Planes 1 and 3, we determined the relative offset of Plane 2 with respect to Planes 1 and 3. This offset was $25 \mu m \pm 5 \mu m$ in the column direction and $146 \mu m \pm 3 \mu m$ in the row direction. Although it is only one data point, it gives an indication of the accuracy of the positioning of detectors onto the telescope planes and of the planes onto the telescope during the assembly process. The accuracy indicated here is well within that required for the PLT. In addition, the difference of the hit cluster positions in two planes vs. the hit cluster position in the orthogonal direction allowed us to determine the relative rotation of the three planes about the beam direction. The largest was a rotation of Plane 2 by $0.6^\circ$ with respect to Planes 1 and 3. This alignment of the telescope planes was done readily with only a small amount of data indicating that the alignment of the PLT will be straightforward and quick once data comes.

In the PLT, particles from the interaction point will have nearly normal incidence on the telescope planes. They will also have very small curvature since they are nearly parallel to the solenoidal magnetic field. As a result, digital spatial resolution, pixel width divided by $\sqrt{2}$, is adequate for the operation of the PLT. In the test beam, the measured hit residuals indicate that the spatial resolution is somewhat better than digital as would be expected.

![Fig. 7. Distribution of the number of hits per pixel for each of the three telescope planes.](image1)

![Fig. 8. A sampling of tracks reconstructed in the telescope. The lines are linear fits to the cluster hit positions. (Each line represents a track from a separate triggered event.)](image2)
from charge sharing in the fraction of events with two-pixel clusters. While precise spatial resolution is not a key aspect for the functioning of the PLT, in a future beam test we plan to determine the improvement in spatial resolution obtained when the planes are rotated by 20° with respect to the beam.

4.3. Pulse height distributions

For determining pulse height distributions, we defined an acceptance region in each of the three planes such that if a beam particle were incident on this region in two of the planes it was certain to also be incident on the enabled area of the third plane. Fig. 10 shows these acceptance regions. The very small number of hits on pixels outside of the delineated regions are beam related and not due to electronic noise. They are the result of particles produced from beam particle interactions in the telescope material. Because the telescope was at a slight angle with respect to the beam, there was an approximately 8 row offset between Planes 1 and 3 in particle hit position. Fig. 11 shows the summed pulse height distributions in units of collected electrons for each of the three planes where for a given plane a cluster within the acceptance region of the other two planes was required. We also required that there be one and only one cluster in each of these two planes. The pulse height plotted is the sum over all pixels within the hit cluster. The most probable signal is approximately 16,000 electrons for Plane 1 and approximately 18,500 electrons for Planes 2 and 3. There is a 10% systematic uncertainty in calibration from plane to plane. For comparison, the most probable signal for a 300 µm thick silicon sensor is 22,000 electrons. The most probable pulse height in Plane 1 is about 15% lower than that for Planes 2 and 3. This is

Fig. 9. A three-dimensional display of tracks. The lines drawn connect the cluster hit positions.

Fig. 10. Acceptance regions of the three planes.

Fig. 11. Distribution of the summed pulse height for each of the three telescope planes.

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largely due to the fact that the average thickness of the diamond sensor for this plane was less than that of the other two. Planes 2 and 3 were 499 and 496 μm, respectively, while Plane 1 was wedge-shaped and had an average thickness of 457 μm with a variation of 50 μm from one side to the other. The small bump in the pulse height distribution of Plane 2 at around 5000 electrons is not yet fully understood but seems to be due to about 15 pixels that have anomalously low pulse heights. The low pulse height turn on of single pixels indicates that the pixel thresholds are 3500–4500 electrons, 3000–4000 electrons and 2500–3500 electrons for Planes 1, 2 and 3, respectively. Although these thresholds are low, lower values could likely have been achieved if there had been more time to tune and iterate the threshold trimming.

4.4. Fast-or efficiencies

The fast-or signals form the basis for the primary luminosity measurement of the PLT. Clocked at the LHC bunch crossing rate of 40 MHz, they will allow the threefold coincidence rate within each telescope to be formed for each LHC bunch crossing, thereby, determining the relative bunch-by-bunch luminosity. Understanding these fast-or signals and measuring their efficiency are key to establishing the performance of the PLT. While the fast-or output of the PSI46 chip was originally implemented for possible application in the CMS Level 1 trigger, the current results are the first systematic study of their efficiency.

For determining the fast-or efficiencies, we imposed the same requirements as for the pulse height measurement above in order to ensure that a particle passed through the enabled area of the plane under test. For the two planes other than the one under test, we required that there be only one cluster and that the cluster position be in the delineated acceptance regions indicated in Fig. 10. In the test beam, the arrival time of beam particles was uncorrelated with the clock phase. Due to time walk, a particle that arrived shortly after the leading clock edge and that had a large pulse height might be output one clock period earlier than the clock time of the trigger. Similarly, a particle that arrived shortly before the trailing clock edge and that had a small pulse height might be output one clock period later than the clock time of the trigger. For the PLT running at the LHC, the clock will be synchronized with the bunch crossing and particle arrival times will be fixed to within a few nanoseconds relative to the clock edge. The clock phase at the readout chips can then be adjusted so that all of the fast-or signals will occur in the “in-time” clock pulse. In order to correctly determine the fast-or efficiency using the test beam data, it is necessary to count fast-or signals that occur one clock period early or one clock period late as well as those that occur in-time. The fast-or efficiencies and the percentage of events with early-only or late-only fast-or signals are shown in Table 1. All three planes have a fast-or efficiency greater than 99%. Plane 2 had a significantly larger percentage of early fast-or signals than did Planes 1 and 3. This is most likely simply an adjustment issue. Given the abbreviated beam time, we were not able to fully tune the adjustment of the fast-or timing in the pixel readout chips and, as a result, for beam particles arriving near the clock edge, the fast-or from Plane 2 was more apt to fire on the earlier clock pulse than were those for Planes 1 and 3. In any case, as noted above, early fast-or signals will not be an issue during actual operation of the PLT in CMS.

5. Conclusions

We have completed an analysis of beam test data of a prototype PLT telescope. The fraction of active pixel channels is high, 98% or more, in all three planes. The pulse height distribution for the high energy beam pions is large with a most probable value of about 18,000 electrons and well above the pixel threshold range of 2500–4500 electrons. The efficiency of the fast-or signals that form the basis of the primary PLT luminosity measurement is high, greater than 99% for all three planes. Clear and well defined tracks are readily reconstructed in the telescope. These results show that the PLT design concept is sound and that the project is ready to proceed with the next phase of carrying out a complete system test, including full optical readout, of a set of PLT telescopes.

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