PROCEEDINGS OF SCIENCE

Performance analysis of phase 2 Tracker upgrade PS module before and after irradiation

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The Large Hadron Collider will undergo a luminosity upgrade targeting a peak instantaneous luminosity ranging from 5 up to 7.5×10^{34} cm^{-2}s^{-1}. The ambitious goal of the High Luminosity LHC is to achieve a total of 3000–4000 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13–14 TeV by 2041. To cope with such challenging environmental conditions, the outer tracker of the CMS experiment will be upgraded using closely spaced silicon sensors (pixels and strips) to survive in the harsh radiation environment. A PS module, composed of a pixel and a strip sensor was tested at the Fermilab Test Beam Facility to evaluate its ability to provide accurate tracking information, p_T discrimination, and optimal performance at the irradiation levels expected after being exposed to the harsh conditions of the High Luminosity LHC. The results of the test and the comparison of the module performance before and after irradiation will be presented in this paper.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

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1. Introduction

The Large Hadron Collider (LHC) at CERN is undergoing an upgrade to increase its luminosity, known as the High Luminosity LHC (HL-LHC) [1]. The CMS detector is planning a Phase-2 upgrade [2] to address the challenges of higher collision rates, increased detector occupancy, and more significant radiation-induced damages up to 4000 fb^{-1}. The upgraded CMS tracker consists of an Inner Tracker (IT) with silicon pixel modules and an Outer Tracker (OT) featuring modules that combine strip-strip (2S) and pixel-strip (PS) silicon sensors, to provide on-detector transverse momentum (p_{T}) discrimination for particles with momentum greater than 2 GeV. The PS module's sensors, made using n-on-p technology on high resistivity float zone silicon, will be installed at radii from 200 to 600 mm. The PS module has been tested under various conditions, and the results are presented in this paper. The PS module has 2 silicon sensors with a $10 \times 5\,\mathrm{cm}^2$ active area: the strip sensor (PSs) has 2×960 strips, each around 2.5 cm long, wire-bonded to 16 Short Strip ASICs (SSA), while the pixel sensor (PSp) has an array of 32×960 macro-pixels, each approximately 1.5 mm in length, bump bonded to 16 macro pixel ASICs (MPA). Both strip and pixel sensors have a pitch of 100 μm. The pixel sensor bump bonded to the MPAs form the Macro Pixel Sub Assembly (MaPSA). The MPA chips correlate hits in the pixel (bottom) sensor with hits on the strip (top) sensor within a programmable active search window to form a short track segment called a stub, which is transmitted to the L1 trigger at 40 MHz.

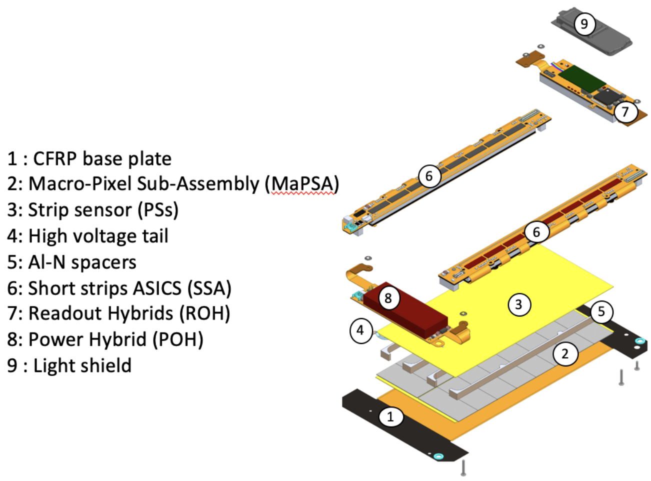

Figure 1: Exploded overview of a PS module

2. Irradiation Test Area (ITA) at Fermilab

The sensor sandwich (PSs + MaPSA) without readout hybrids underwent irradiation at the Fermilab Irradiation Test Area (ITA). The irradiation used a 400 MeV proton beam from Fermilab's linear accelerator (LINAC), which delivered 8 pulses per minute with a sigma of 1 cm. Only a specific portion of the sandwich was irradiated to allow a direct comparison between not-irradiated and irradiated areas on same module. The irradiation focused on the Readout Hybrid (ROH) side. The targeted uniform fluence was 1.4×10^{15} neq/cm^2, but the total mean accumulated fluence exceeded the target, reaching 1.55×10^{15} neq/cm^2.

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3. Fermilab Test Beam Facility (FTBF) Setup

After irradiating the sandwich, the PS module was completed by attaching the hybrids, and then tested at the FTBF. The module was tested with a 120 GeV bunched proton beam at a rate of about 10 KHz. The PS module was mounted in the FTBF telescope set up, which provided precise tracking information [3]. The telescope consists of four pixel planes and twelve strip planes. The telescope's resolution is $\approx 7\ \mu$m. To maintain low humidity, the DUT box was purged with nitrogen gas. A chiller was used to maintain a temperature of -20 °C to prevent thermal runaway and minimize sensor annealing.

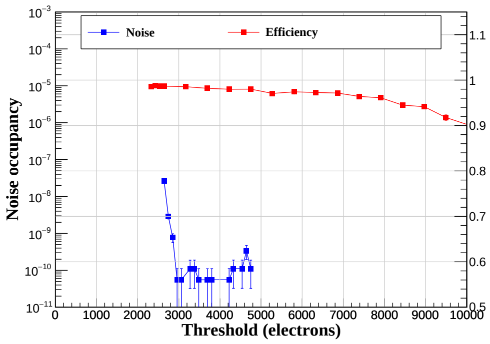
4. Performance

4.1 Noise Occupancy and Threshold Optimization

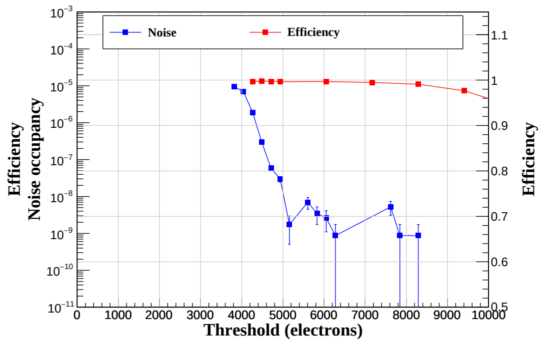
The optimal threshold maximizes efficiency while keeping the noise hit occupancy below 10^{-5}. The noise occupancy is defined as:

$$\epsilon = \frac{\text{Number of hits in one cell of pixel/strip}}{\text{Number of triggers}} \tag{1}$$

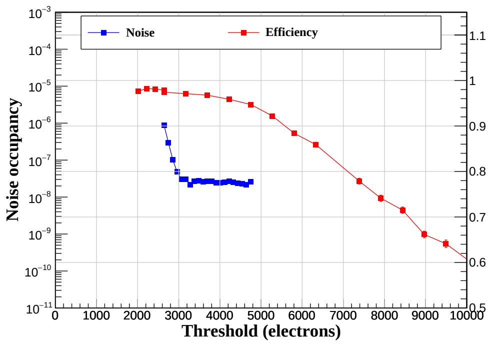
Figure 2 shows plots of efficiency and noise hit occupancy as a function of the threshold.



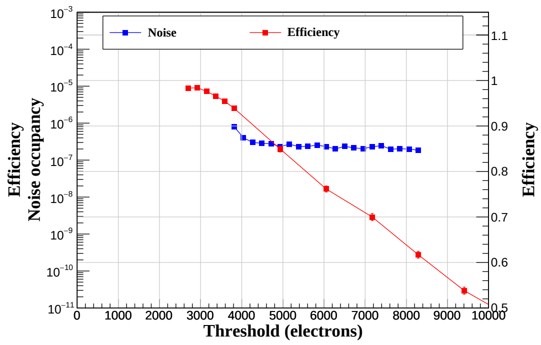
(a) Not-irradiated pixels



(b) Not-irradiated strips



(c) Irradiated Pixels



(d) Irradiated Strips

Figure 2: Efficiency and noise occupancy as function of threshold (electrons).

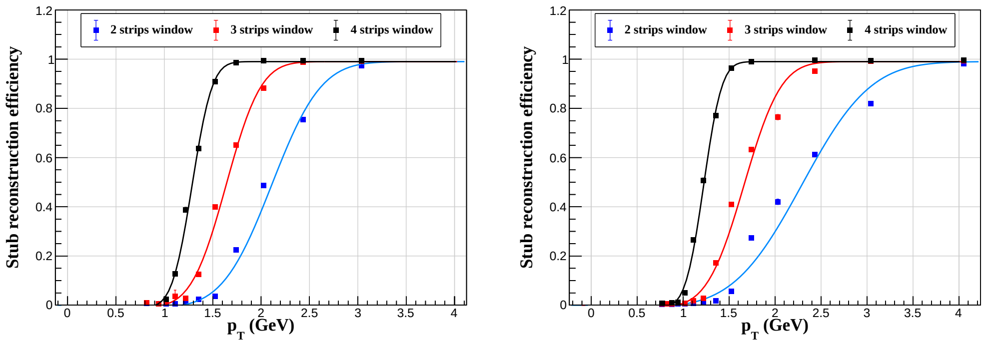
4.2 Stub Reconstruction Efficiency

The MPA and SSA chips required geometrically matching hits to construct a stub. Without a magnetic field, the PS module's correlation logic was tested by rotating the module to simulate track bending in the CMS magnetic field.

For an incident angle β, the beam simulates a charged particle track with a transverse bending radius r_T and magnetic field B = 3.8 T, for a module placed in the CMS detector at a distance R from the interaction point. The relationship between β and r_T is given by $\sin(\beta) = R/(2r_T)$, where $r_T = p_T/(qB)$. So p_{T} becomes:

$$p_T[\mathrm{GeV}] \approx 0.57 \cdot R[\mathrm{m}]/\sin\beta.$$

The beam incident angle β is related to the stub direction $\Delta X = X_{\mathrm{seed}} - X_{\mathrm{correlated}}$, where seed is pixel sensor and correlated is strip sensor. The sensors separation d = 1.6 mm, via $\tan(\beta) = p\Delta X/d$, where p is the strip pitch (100μm). The SSAs were configured to generate stub triggers within windows of size of ±2 , ±3, and ±4 strips.



(a) Not-irradiated side

(b) Irradiated side

Figure 3: Stubs reconstruction efficiency for different window sizes, given in half channel as function of p_T.

5. Conclusions

A PS module was selectively irradiated on one portion to enable a comparison between the irradiated and not-irradiated sides. The irradiation was conducted at the ITA facility at Fermilab, followed by testing at the FTB facility, also located at Fermilab. The not-irradiated side achieved the efficiency of ≈99.6% for strips and ≈98.5% for pixels at a bias voltage of 400 V. However, the efficiency on the irradiated side was ≈94% for strips and ≈98% for pixels at a bias voltage of 800 V. The low efficiency measured on the strip detector was caused by a non optimal choice of the threshold. Finally, by emulating, via a rotation of the PS module, its p_{T} discrimination capabilities when installed in CMS, the stub logic was tested successfully and it worked as expected. Overall, the performance of the PS module met the requirements to operate in the CMS Outer Tracker detector at the HL-LHC.

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References

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