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Beam test characterization of an irradiated pixel-strip module for HL-LHC CMS Tracker upgrade

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High Luminosity LHC (HL-LHC)

- Increased instantaneous luminosity from 5 to 7.5 x 10^{34} cm^{-2} s^{-1} [1]
- High Pileup of 140-200 up to 750 kHz L1 trigger rate

Benefits

- Improve precision of standard model measurements
- Improve direct searches for new and rare phenomena

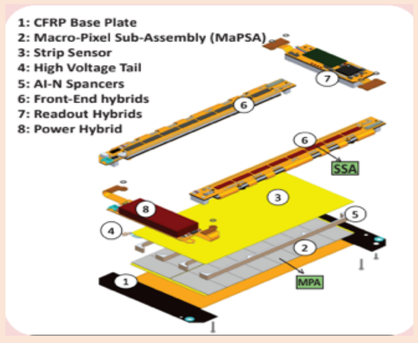
Drawbacks

- Challenging to manage the increased collision rate
- Radiation damage to detector

Outer tracker phase 2 upgrade [2,3]

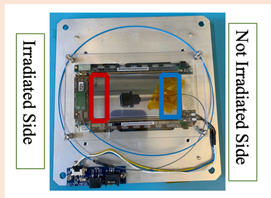
- Silicon PS (pixel-strip) modules and 2S (strip-strip) modules
- On-chip p_T discrimination at 2 GeV
- Trigger information at 40 MHz

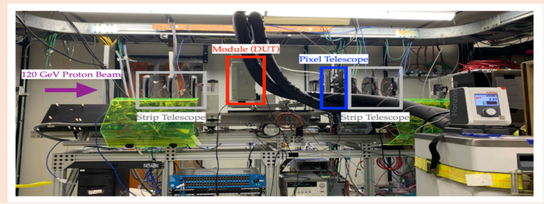
PS Module



Irradiation and test beam at FNAL

- Irradiation of PSs + MaPSA (100 µm pitch,1.6 mm sensors spacing) 400 MeV protons, Beam Sigma ≅ 0.67 cm
- The detector is irradiated (at a higher fluence than expected) on one side at (1.3-1.8) × 10^{15} neq cm^{-2} , while the other side remained not irradiated
- Test beam at 120 GeV proton beam [4], at a 10kHz rate
- Each spill lasts for 4 seconds every minute and deliver ~ 40 k protons
- The telescope [5] consists of 12 strip planes and 4 pixel planes and has a resolution of 7 µm



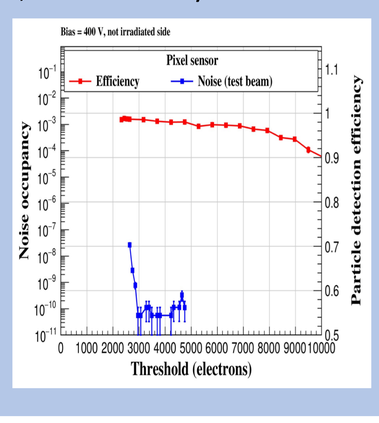


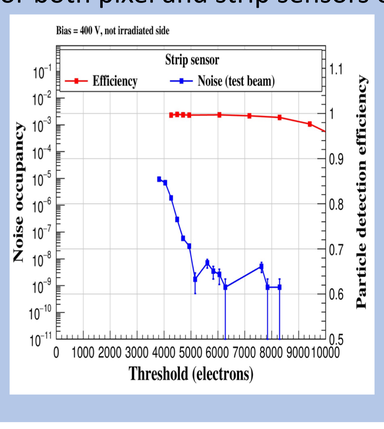
Efficiency and Noise Occupancy as Function of Threshold

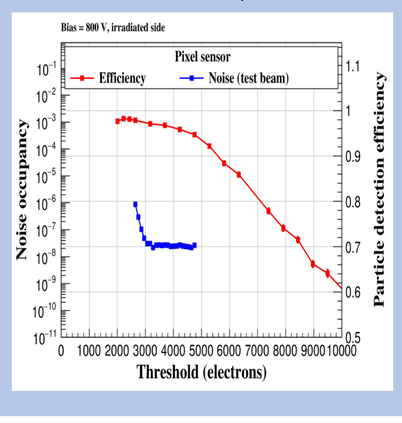
Module Noise Occupancy = $\frac{\text{Total number of dark counts (data without beam)}}{\text{Number of triggers X Number of channels}}$

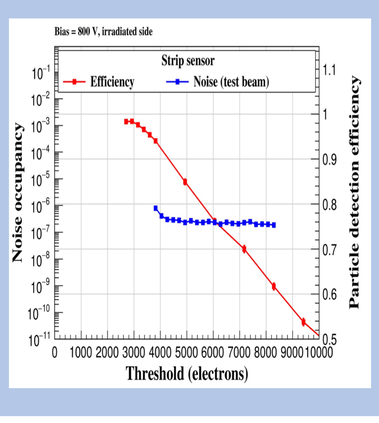
$\varepsilon = \frac{\text{Number of hits on detector matched to the pointing trackswithin a window of } \pm 200\mu m}{\text{Number of tracks pointing to the detector}}$

- At low thresholds, the efficiency of not-irradiated side for both pixel and strip sensors exceeds 99% - 99.6%, while for the irradiated side, it exceeds 98.5% -98.6





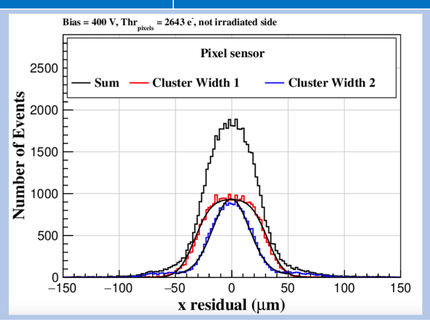


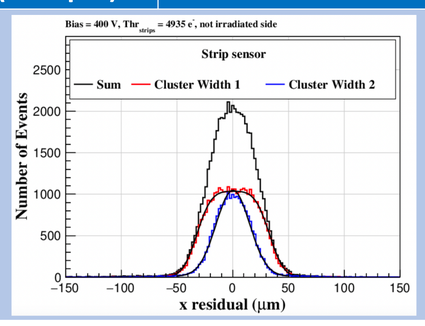


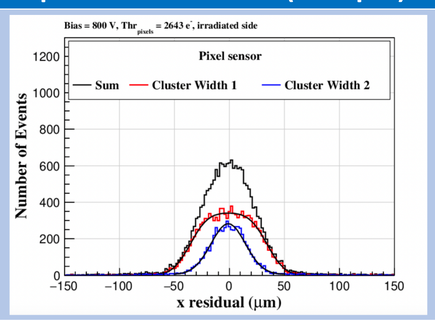
Spatial Resolution

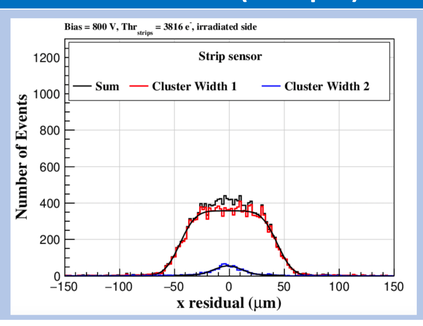
- The residual distribution of clusters of width one is fitted with a uniform distribution convolved with a Gaussian distribution
- The residual distribution of clusters of width two is fitted with a Gaussian distribution summed to a constant
- The table summarizes the fit results for both cluster widths, showing the resolution along the bending coordinate.
- In the table, the resolution for width 1 clusters is the step function width from the fit divided by √12, while for width 2 clusters, it is the Gaussian sigma after subtracting the telescope resolution in quadrature.

Not Irradiated Side	Pixel Cluster Width 1 (18.5 µm)	Pixel Cluster Width 2 (14.7 µm)	Strip Cluster Width 1 (18.8 µm)	Strip Cluster Width 2 (13.3 µm)
Irradiated Side	Pixel Cluster Width 1 (20.1 µm)	Pixel Cluster Width 2 (14.0 µm)	Strip Cluster Width 1 (25.5 µm)	Strip Cluster Width 2 (10.5 µm)





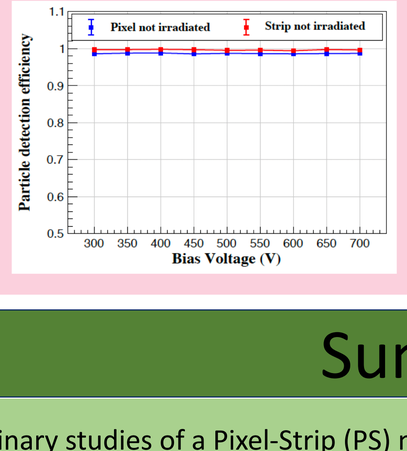




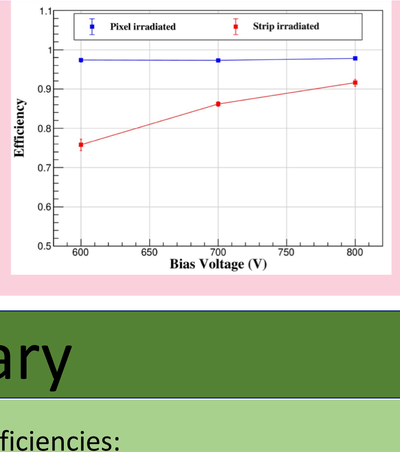
Bias Voltage

- For not irradiated side, pixel and strips are fully efficient already at 300 V
- For the irradiated side, pixels are fully efficient at 600 V, strips reach more than 90% efficiency at the maximum voltage (800 V) that the power supplies of the CMS experiment can deliver

Thr_{pixels} = 2643 e^- Thr_{strips} = 4935 e^- , not irradiated side

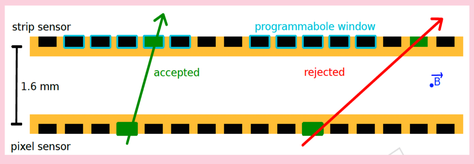


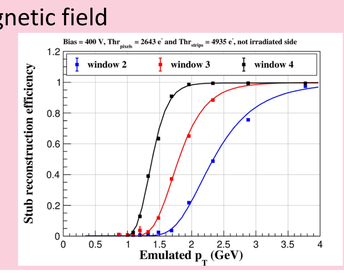
Thr_{pixels} = 2643 e^- Thr_{strips} = 3816 e^- , not irradiated side

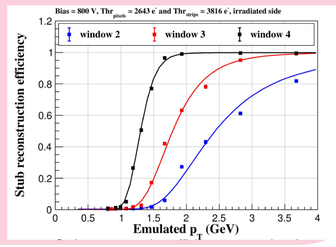


Stub Efficiency

- Short track segments, called stubs, are formed when a hit from the bottom sensor is matched with a hit from the top sensor within a programmable search window
- The relative stub efficiency is calculated with respect to having a cluster in both pixel and strip sensors
- The efficiency was measured for three different widths of the stubs search window, changing the beam incident angle θ by rotating the detector
- Emulated $p_T \left[\frac{GeV}{c}\right] = \frac{0.57 \, . \, R \, (m)}{\sin(\theta)}$, where R = 37.2 cm (layer 2 flat section [6]) the radial distance from the interaction point within the CMS 3.8 T magnetic field







Summary

- Preliminary studies of a Pixel-Strip (PS) module efficiencies:
  Not Irradiated Side : pixels ≈ 99% and strips ≈ 99.6%
  Irradiated Side : pixels ≈ 98.5% and strips ≈ 98.6%
- The expected resolution of detector with binary readouts and sensors pitch is within acceptable limits
- Stub efficiencies with respect to p_T are consistent with geometrical window cut

References

[1] CMS Collaboration, "Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid", CMS-TDR-15-02
[2] CMS Collaboration, "The Phase-2 Upgrade of the CMS Tracker", CMS-TDR-014
[3] The Tracker group of the CMS collaboration, "Selection of the silicon sensor thickness for the Phase-2 upgrade of the CMS Outer Tracker", JINST 16 (2021) P11028
[4] Fermilab, Fermilab test beam facility, http://ftbf.fnal.gov, 2019
[5] S. Kwan et al., "The Pixel Tracking Telescope at the Fermilab Test Beam Facility", NIM A 811 (2016) 162
[6] https://cms-tklayout.web.cern.ch/cms-tklayout/layouts-work/recent-layouts/OT806_IT741/info.html

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