

Radiation Tolerance Evaluation of P-Type Silicon Sensors for FoCal Detector in ALICE

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VECC, Kolkata

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- Introduction to FoCal @ ALICE
- Experimental setup
- Results:
 - Electrical characterization
 - MIP response
- Outlook



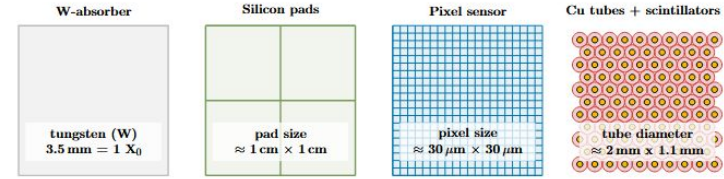
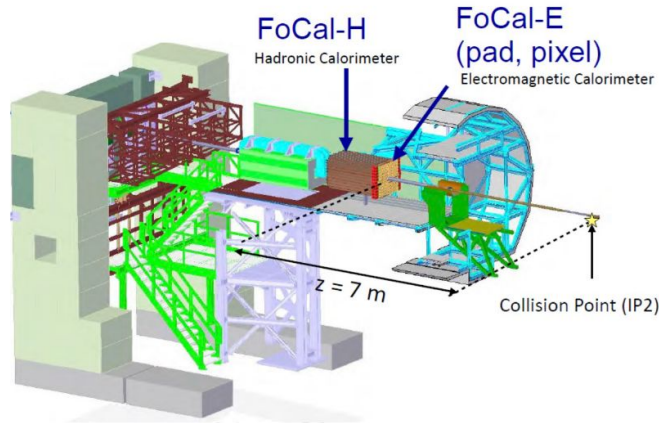
Technology & Instrumentation in Particle Physics Conference

TIFR, 2026

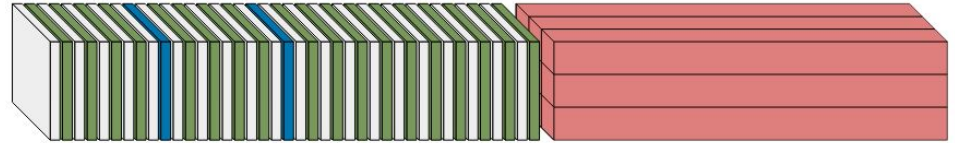
<https://indico.cern.ch/event/1542844/overview>



Introduction to FoCal at ALICE



*Dimension not in scale



FoCal-E

- 20 tungsten layers, with thickness of 3.5 mm = $1 X_0$
- 18 layers of silicon pad sensors, pad size $\approx 1 \times 1 \text{ cm}^2$
- 2 layers of silicon pixel sensors, pixel size $\approx 30 \times 30 \mu\text{m}^2$

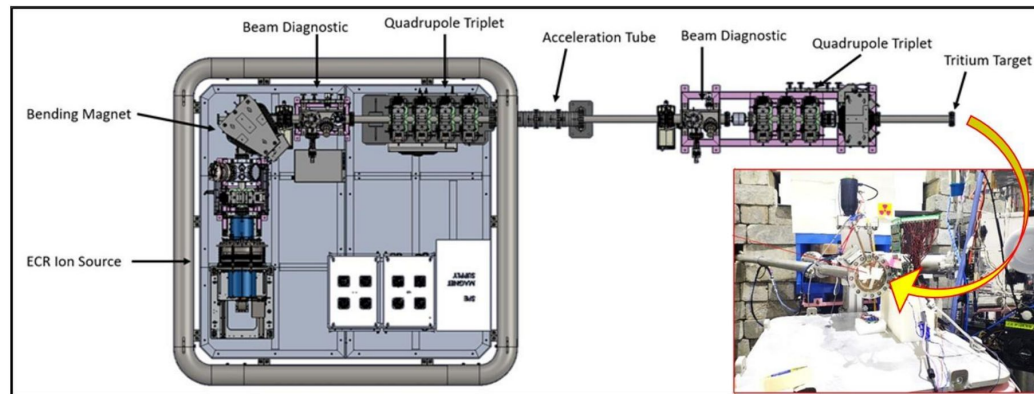
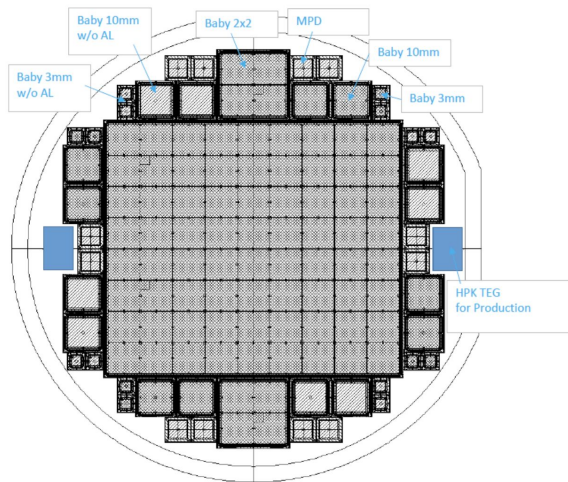
FoCal-H

- length of 110 cm
- copper "strawtubes" with 2.0 mm diameter
- scintillating fibre with $\approx 1.1 \text{ mm}$ diameter

Forward Calorimeter (FoCal): $3.4 < \eta < 5.8$

- To provide unique capabilities to measure low-x gluon structure of protons and nuclei, via forward measurements of direct photons
- Si+W electromagnetic calorimeter to discriminate single photons from pairs of photons originating from π^0 decays.
- A conventional sampling hadron calorimeter for jet measurements and the isolation of direct photons.

Experimental setup



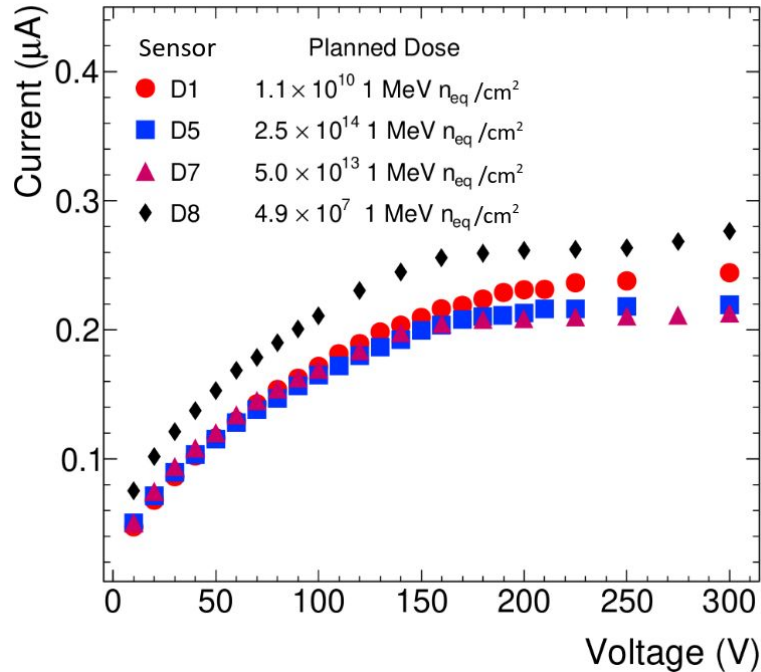
Schematic of the neutron irradiation facility at IPR.

Sensor label	Accumulated fluence (1 MeV n_{eq}/cm^2)
D9	0
D8	4.9×10^7
D1	1.1×10^{10}
D7	5.0×10^{13}
D5	2.5×10^{14}

- Two types of damages:
 - Bulk damage: Silicon lattice (neutron, proton, hadron)
 - Surface damage: Si-SiO₂ interface (x-rays, gamma, electrons)
- Radiation Hardness measured metrics:
 - Leakage current increases → dependence on fluence, Sensor-to-sensor uniformity
 - Depletion voltage evolution → charge collection vs bias
 - Noise to signal ratio, Annealing studies

Electrical characterization (1/2)

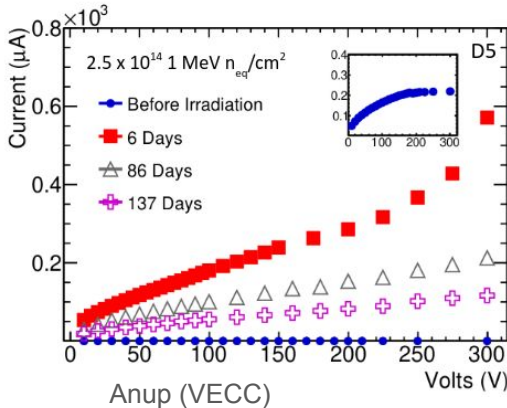
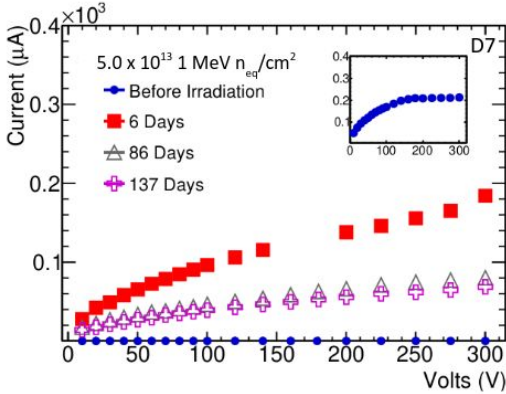
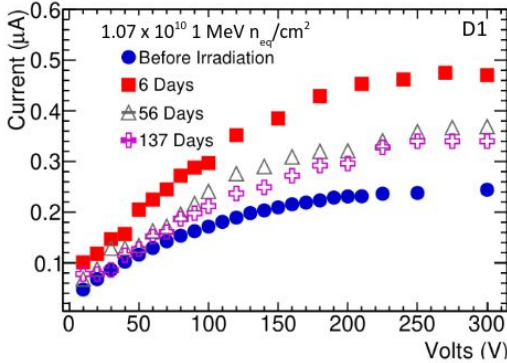
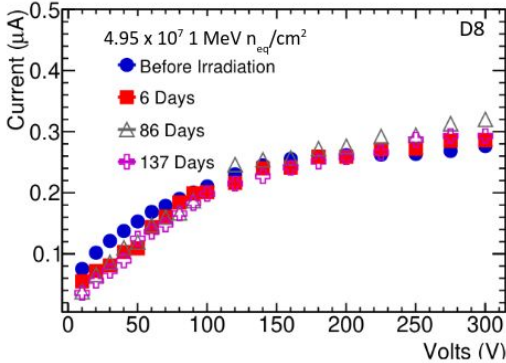
I-V before Irradiation



- Uniform leakage current before irradiation ($\sim 10^{-6}$ A)

Electrical characterization (2/2)

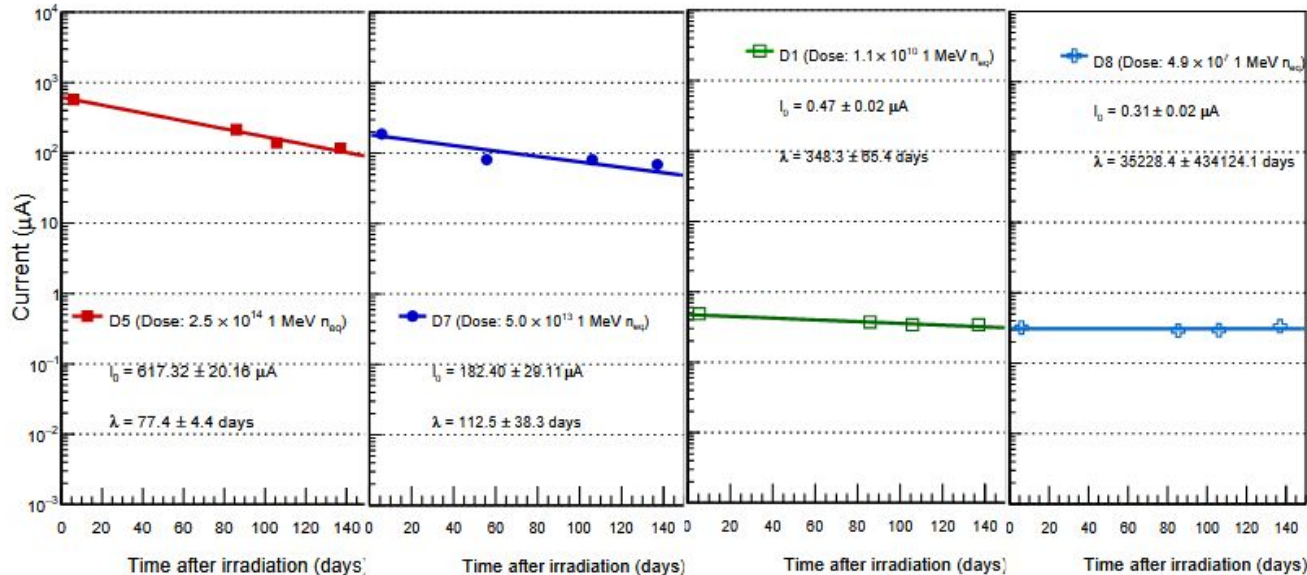
I-V after Irradiation



- More leakage current with more irradiation
- Beneficial annealing (short-term improvement) & Reverse annealing (long-term degradation)

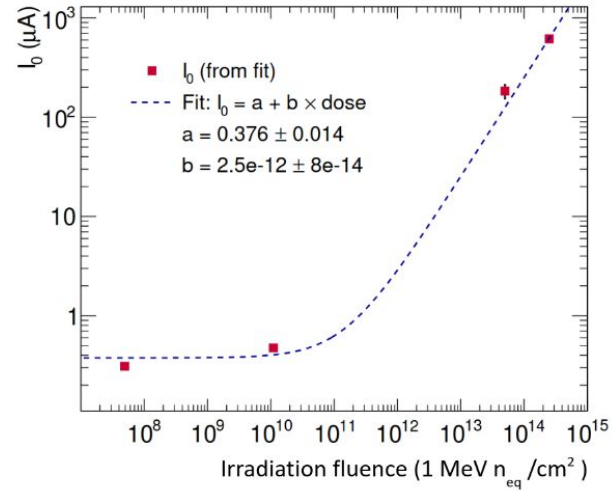
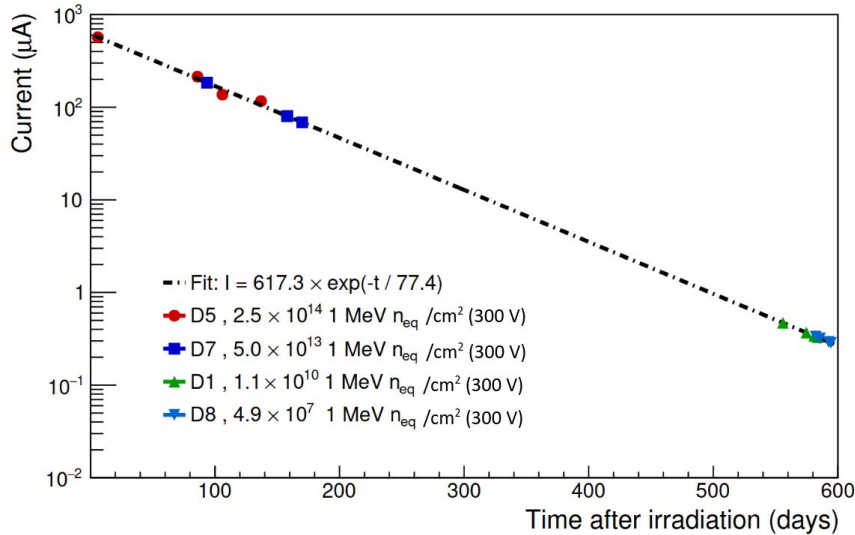
Comparison of leakage current

Leakage current (at 300 V) as a function of time after irradiation for the test sensors



- D8 ($10^7 n_{\text{eq}}/\text{cm}^2$) exhibits negligible effect
- D5 ($10^{14} n_{\text{eq}}/\text{cm}^2$) showed more than 3 order of magnitude increase in leakage current
- Leakage current benefits from beneficial annealing, while long-term re-verse annealing increases the effective space charge and the depletion voltage

leakage current with time

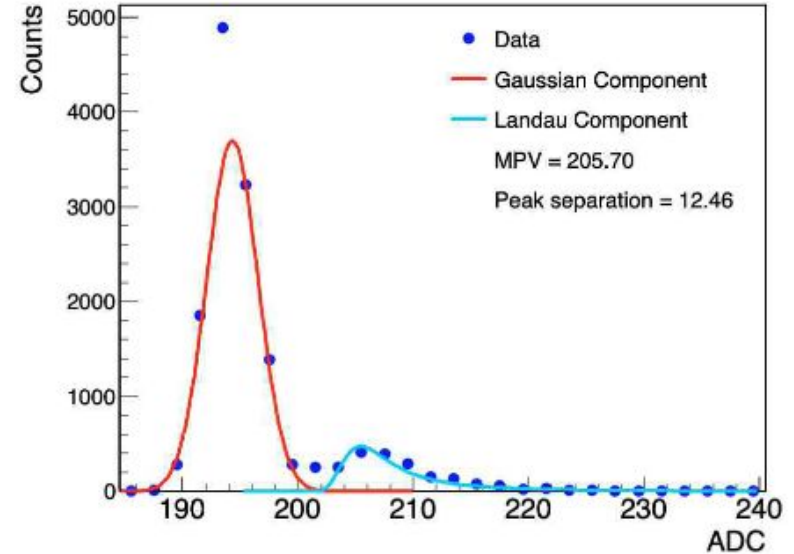
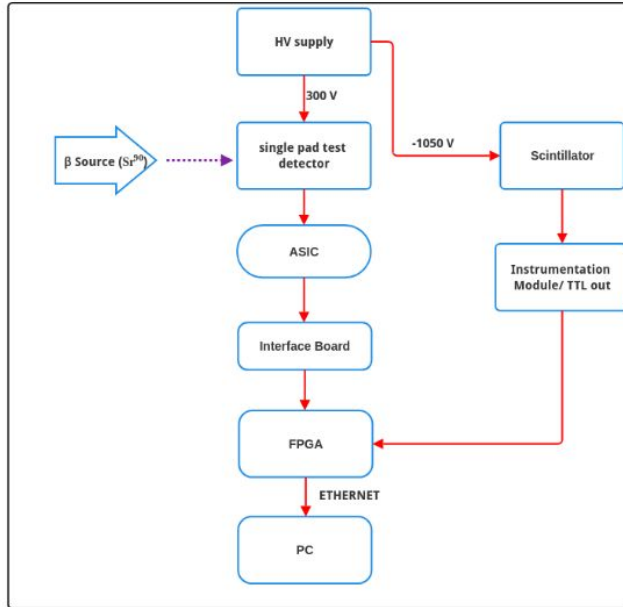


- Leakage current and dose with the recovery rate at a fixed dose, we estimate both the time required to reach a target leakage-current level and the evolution of the current under continued irradiation

Sensor label	Accumulated fluence (1 MeV n_{eq} / cm^2)	Time (day)
D8	4.9×10^7	500
D1	1.1×10^{10}	460
D7	5.0×10^{13}	80

<https://arxiv.org/abs/2511.03573>

MIP response setup



- peak-to-peak separation between the mean of the Gaussian pedestal and the Landau MPV for different irradiation levels.

MIP response at different irradiation

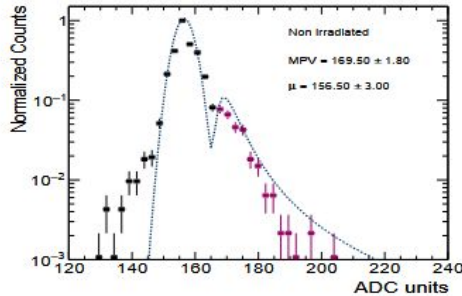


Figure 6: D9

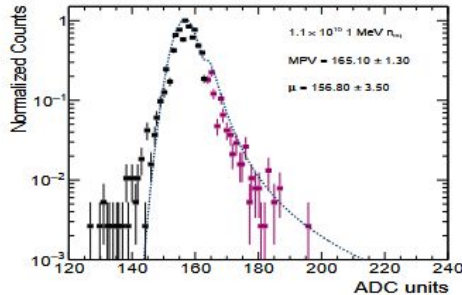


Figure 8: D1

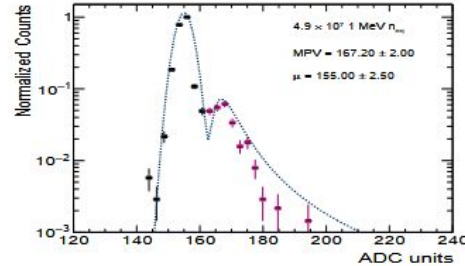


Figure 7: D8

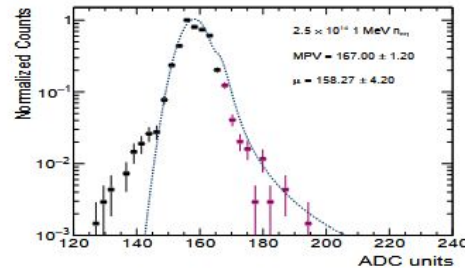


Figure 9: D5

- MIP detection response measured with a ^{90}Sr β source for sensors with different irradiation levels
- peak-to-peak separation is larger for the lower-dose sensor (D8) than for the higher-dose devices
- Radiation-induced increases in leakage current, broaden the noise (σ), reducing signal to noise separation

Outlook

- 4 test detectors were irradiated with different neutron fluences and compared with unirradiated one
- Electrical characterization were compared before and after irradiation
- A significant degradation in signal-to-noise ratio (SNR) was observed post-irradiation for D5 ($10^{14} n_{\text{eqv}}/\text{cm}^2$)
- Leakage current recovery shows a clear dependence on radiation dose
- Recovery behavior exhibits a fast initial component followed by slower beneficial annealing
 - D5 ($10^{14} n_{\text{eqv}}/\text{cm}^2$) took around 500 days to reach same level of leakage current of D8 ($10^7 n_{\text{eqv}}/\text{cm}^2$)

Thank you!

References

- S. Mukhopadhyay, M. Sukhwani, S. Muhuri, Z. Ahammed, S. Chattopadhyay, A. Das, and R. Laha, “Design of indigenous large area P-type silicon pad sensor on a 6-inch wafer,” in *Proc. DAE-BRNS Symposium on Nuclear Physics*, vol.67, Indore, India, 9–13 Dec 2023.
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