Performance characterisation of ALPIDE after 2.7 Mrad proton irradiation at NPI

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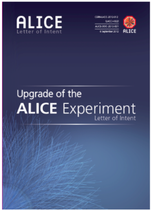
Motivation for the ALICE upgrade

Increase of delivered luminosity of Pb-Pb (100$\times$ w.r.t. current state) [1]

Physics Goal $\rightarrow$ high-precision measurements of QGP properties

- Open HF hadrons, quarkonia down to zero p_{T}
  Thermalization, hadronization, recombination, temperature evolution of the QGP
- Vector mesons and low-mass di-leptons
  Chiral symmetry restoration, thermal radiation from the QGP
- High-precision measurements of the light (anti-)nuclei and hypernuclei
  nucleosynthesis, exotics

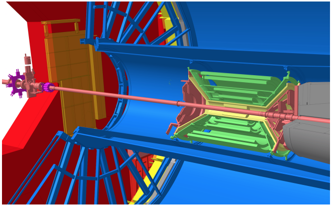


ALICE Upgrade LoI
Mar 2013

[1] K. Aamodt et. al.(ALICE collaboration), *Phys. Rev. Lett.***105** 252301(2010)

ALICE Inner Tracking System Upgrade

- Improve impact parameter resolution by factor of $\sim 3(5)$
  - Get closer to IP (position of first layer): 39 mm→23 mm
  - Reduce pixel size 50 μm×425 μm → 29 μm× 27μm
  - Reduce material budget: 1.14% → 0.3% X_0 per layer in IB
- Improve tracking efficiency and p_{T} resolution at low p_{T}
  - 6 layers → 7 layers
  - Silicon pixel, drift, strip → only pixels (ALPIDE)
- Fast readout
  - readout Pb–Pb interactions at > 100 kHz
- Fast insertion/removal for yearly maintenance



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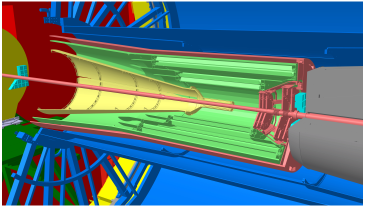
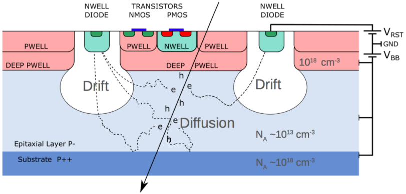
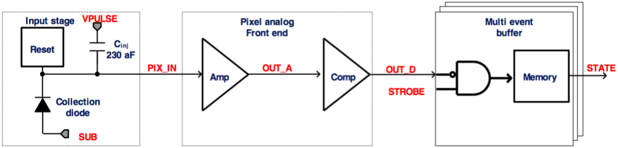


ALPIDE Sensor

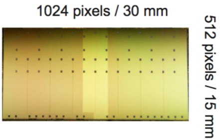


- Monolithic Active Pixel Sensor (MAPS) 180 nm CMOS Imaging by Tower Jazz, each ALPIDE pixel contains sensitive volume, amplification and discrimination
- High resistivity $> 1k\Omega$ cm p−type epitaxial layer 25 μm thick on p−type substrate; deep p-well shielding PMOS transistors
- Small n−well diode 2 μm diameter, much smaller than pixel
- Threshold is regulated by global DACs: V_{CASN}, I_{THR}



ALPIDE requirements and performance

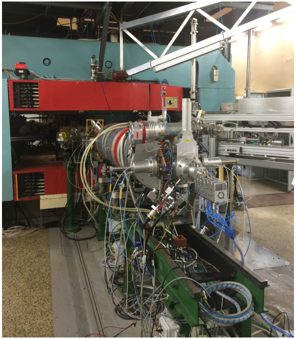
	Inner Barrel	Outer Barrel	ALPIDE performance
Thickness [μm]	50	100	OK
Spatial resolution [μm]	5	10	~ 5
Chip dimension [mm]	15×30	15×30	OK
Power density [mW/cm^2]	< 300	< 100	<40
Event-time resolution [μs]	< 30	< 30	~ 2
Detection efficiency [%]	> 99	> 99	OK
Fake-hit rate [event^{-1}pixel^{-1}]	$< 10^{-6}$	$< 10^{-6}$	$< 10^{-10}$



Radiation load for the Inner Barrel:
TID 270 krad (Total Ionizing Dose)
NIEL 1.3×10^{12} 1MeV $n_{eq} \cdot cm^{-2}$
(Non-Ionizing Energy Loss)
Chip is tested with a safety factor of 10

Radiation Hardness Tests at NPI

- Cyclotron provides protons with $E = 35$ MeV
- Beam current $I \approx 50\,\mathrm{pA}$
- On-line monitoring using ionization chamber 30100 PTW Freiburg
- TID and NIEL are calculated using stopping power of material (S) and fluence (F)



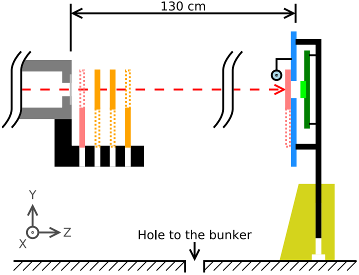
$$\mathrm{TID}\,[\mathrm{krad}] = 1.602 \times 10^{-8} \times \mathrm{S}\,[\mathrm{MeV}\cdot\mathrm{cm}^2\cdot\mathrm{mg}^{-1}] \times \mathrm{F}\,[\mathrm{cm}^{-2}]$$

$$\mathrm{NIEL}\,[1\,\mathrm{MeV}\,\mathrm{n_{eq}}\,\mathrm{cm}^{-2}] = 2.346 \times \mathrm{F}\,[\mathrm{cm}^{-2}]$$

[2] F. Křížek, ... V. Raskina, ... , Nuclear Inst. and Methods in Physics Research, A 894 (2018) 87–95.

[3] Non Ionizing Energy Loss (NIEL), https://rd50.web.cern.ch/rd50/NIEL/default.html

Setup



Energy degrader plates (0.5 - 2 mm Al)

Beam stop plates (8 mm Al)

Shielding (8 mm Al)

Ionization chamber

Irradiated sample (FPGA chip)

Shielded part of target (circuit board)

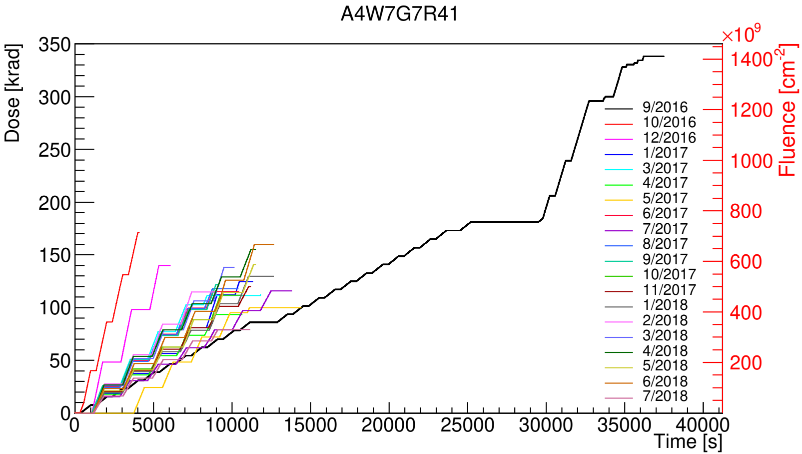
X-Y positioning mechanism (MCL)

Beam pipe and its exit window

Proton beam

Irradiation of the chip

- Threshold and DAC scans are made when beam is stopped
- Each time chip receives TID $\approx$ 100 krad ($\approx 1/3$ of the total dose in Run3)

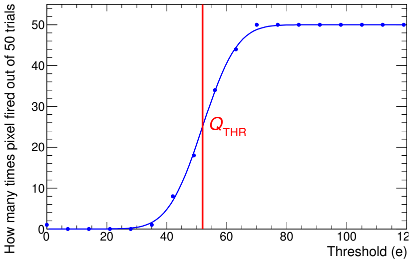


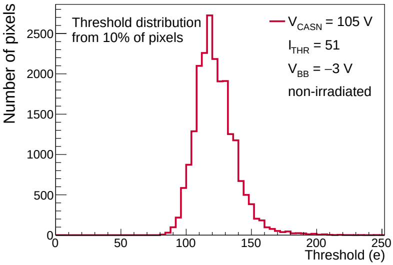
Charge threshold and temporal noise measurement

Firing probability of a pixel is tested by inducing a given charge 50 times on the analog part of pixel. The firing probability is described by S-function:

$$S(Q) = \frac{1}{2}\left(50 + 50 \times erf\left(\frac{Q - Q_{\mathrm{THR}}}{\sqrt{2}\sigma}\right)\right),$$

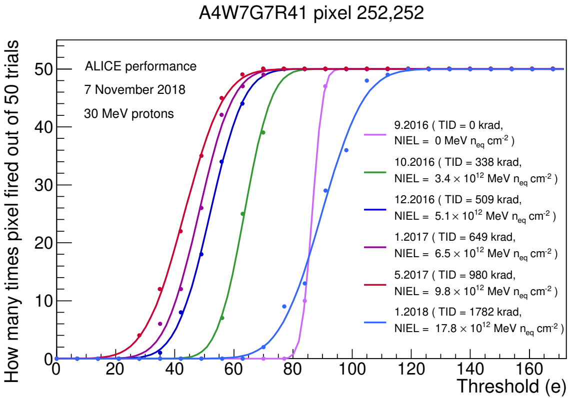
Q - induced charge, Q_{THR} - threshold, σ - noise.





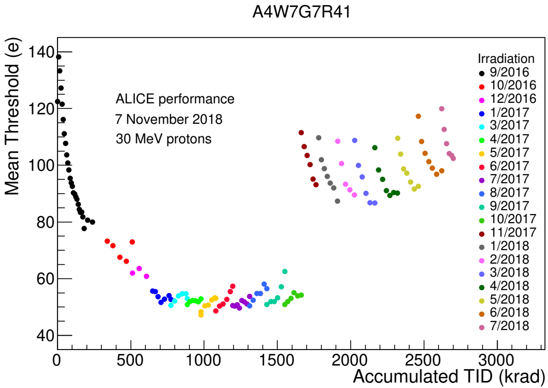
S curves for different time periods for chosen pixel

Shift of the S curve to the left/right corresponds to decrease/increase of threshold.
Broadening of the transition region corresponds to increase of noise.



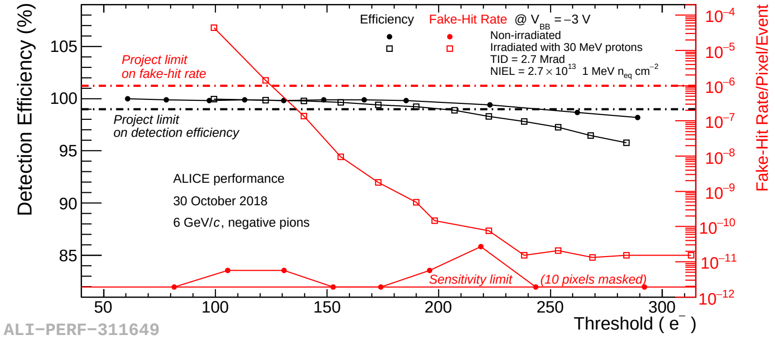
Mean threshold vs. TID

- Average threshold over 10% of 0.5 M pixels
- With initial settings of I_{THR} and V_{CASN} → threshold decreased
- Since Nov 2017, running with decreased V_{CASN} settings → since then we observe annealing



Fake-Hit Rate and Efficiency

- Irradiated chip obtained TID of 2700 krad and NIEL of 2.7×10^{13} 1 MeV $n_{eq}cm^{-2}$
- ALPIDE chip was tested at CERN PS with 6 GeV pion beam
- Limit on detection efficiency $> 99\%$
- Limit on fake - hit rate $< 10^{-6}event^{-1}pixel^{-1}$

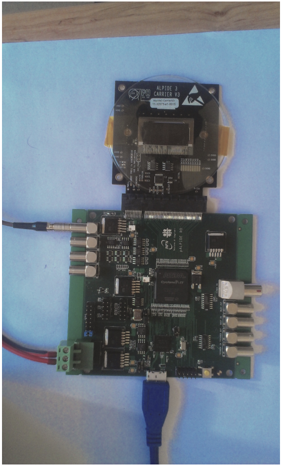


Summary

- ALICE will upgrade its Inner Tracking System (ITS) detector in LS2
- The radiation hardness tests of the ALPIDE sensors were done at U-120M cyclotron with 30 MeV proton beam
- ALPIDE chip which obtained TID of 2700 krad and NIEL of 2.7×10^{13} 1 MeV $n_{eq}cm^{-2}$ meets the requirements for the new ITS

Backup

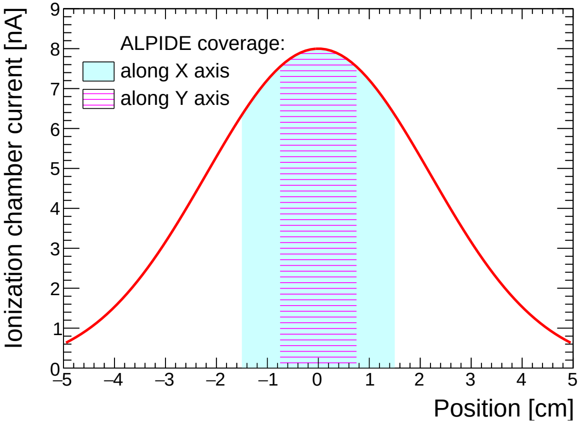
Ionization chamber and ALPIDE



DAQ board (read-out) and
Carrier card with ALPIDE chip

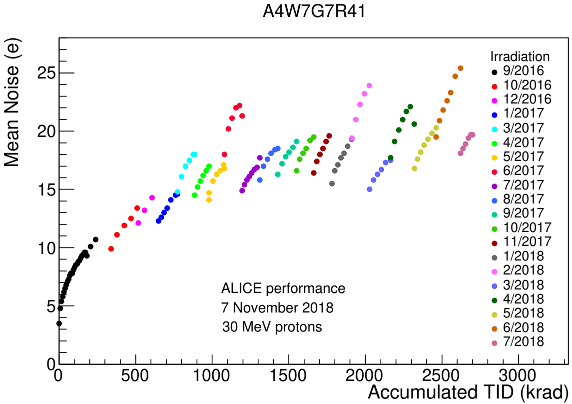
Proton beam profile

- Beam profile is a 2D symmetric gaussian
- 0.56 mm thick Al degrader plate is used to increase its width to $\sigma \approx 22\,\mathrm{mm}$



Mean noise vs. TID

- Average noise over 10 % pixels out of 0.5 M
- Noise is continuously increasing with TID
- Annealing is present but small



Resolution and Cluster size of irradiated and non-irradiated chip

The required spatial resolution is $\sim 5\,\mu m$