Performance of Silicon n-in-p Pixel Detectors irradiated up to 5×10^{15} n_{eq} /cm^2 for the future ATLAS Upgrades

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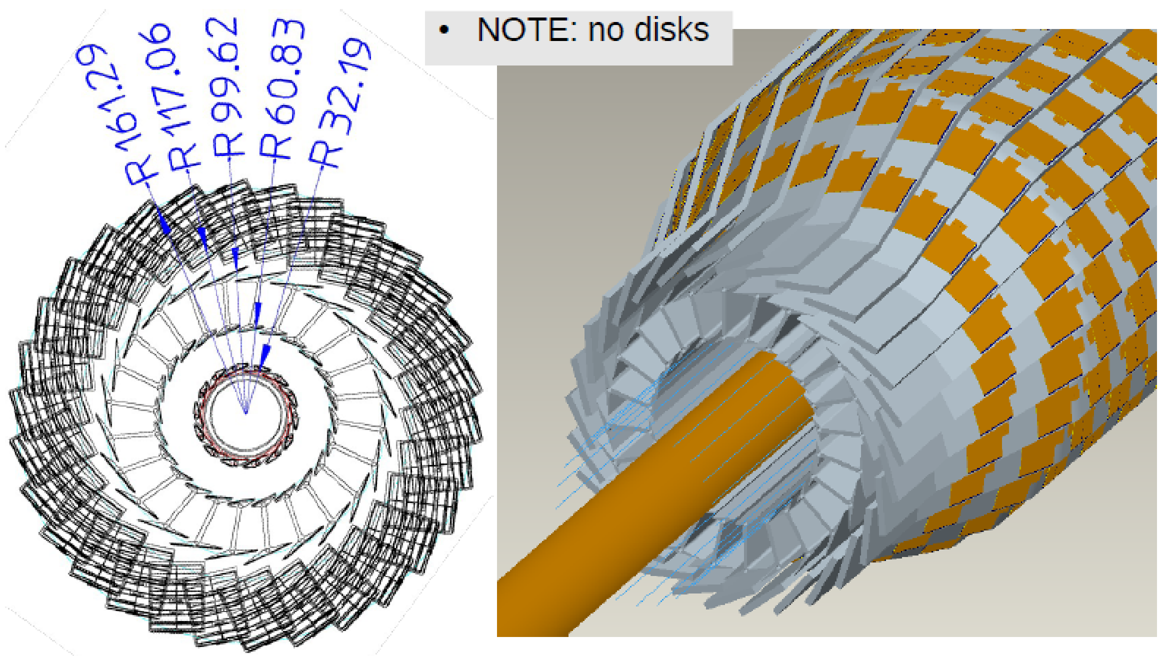
- Motivation
- Advantages and problematic of n-in-p pixel sensors
- n-in-p pixel performance before and after irradiation
- Plans for future n-in-p pixel productions

N-in-p pixels for future ATLAS pixel upgrades

- Insertable B-pixel Upgrade (IBL) advanced to 2013: n-in-n technology and 3D as sensor candidates
- Phase I Upgrade delayed to 2017-2018: replacement of the full ATLAS pixel system under discussion
- Phase II Upgrade foreseen in 2021-2022: fluence up to 1-2x10^{16} n_{eq}/cm^2 in the inner pixel layers



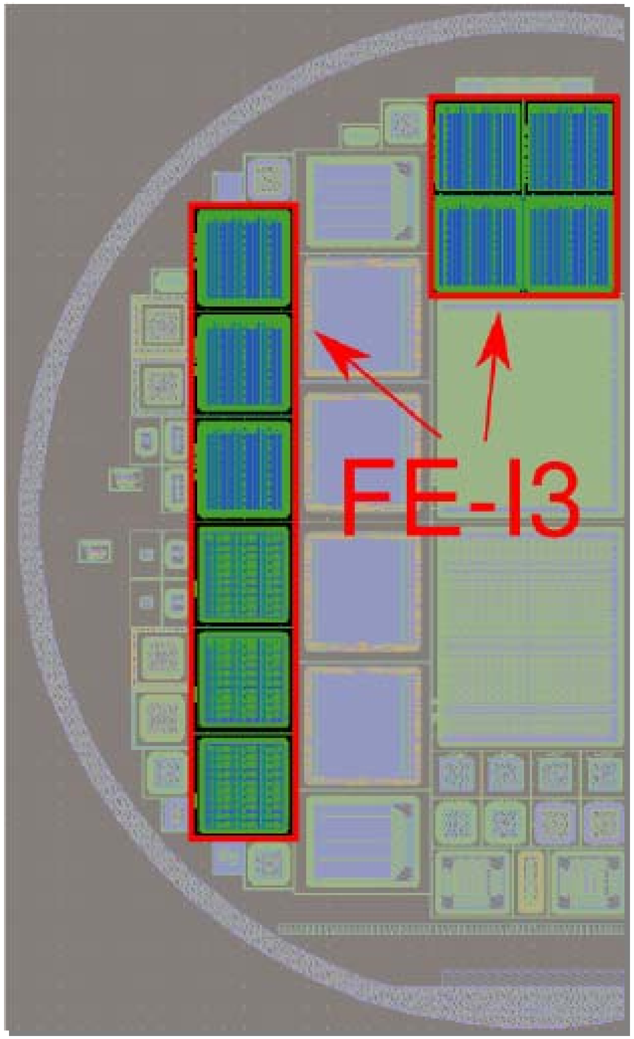
Proposed layout for a possible ATLAS pixel replacement in 2017/2018

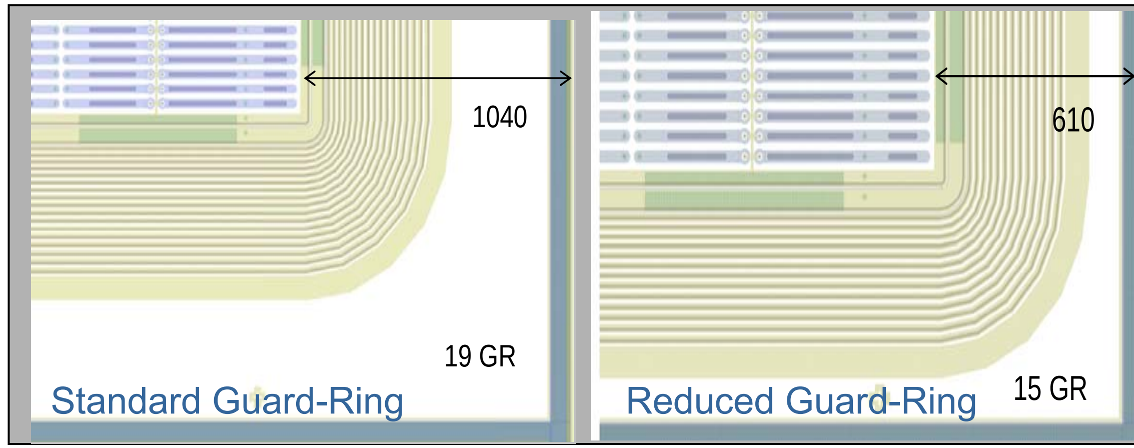
n-in-p pixels good candidates for the outer layers thanks to their radiation hardness and cost effectiveness

M. Garcia Sciveres, ACES 2011, https://aces.web.cern.ch/aces/aces2011/ACES2011.htm

CiS n-in-p pixel production

Common PPS ATLAS -CMS pixel production within RD50



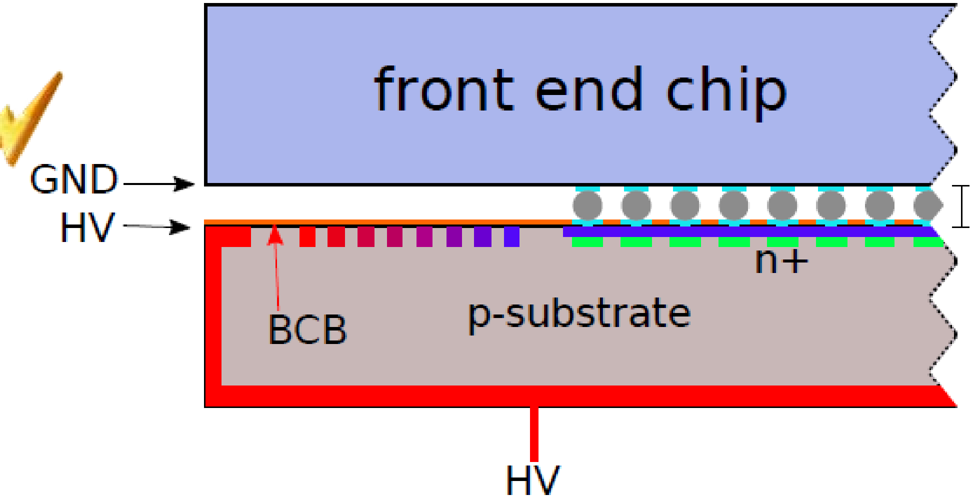


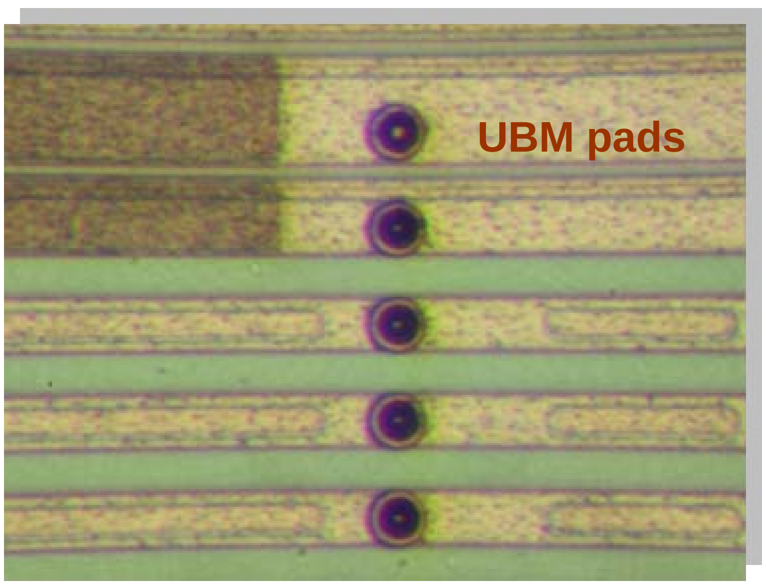
In the n-in-p pixels guard-rings can be implemented on the front-side → single side processing

- FZ p-type material, 285 μm thick
- Inter-pixel isolation:
  - moderated p-spray
  - homogenous p-spray
- Bump bonding to the FE-I3 chips (present ATLAS pixel read-out) performed by IZM-Berlin

High Voltage Stability

Sensor edge at HV facing the chip at ground → n-in-p pixels can suffer from sparks

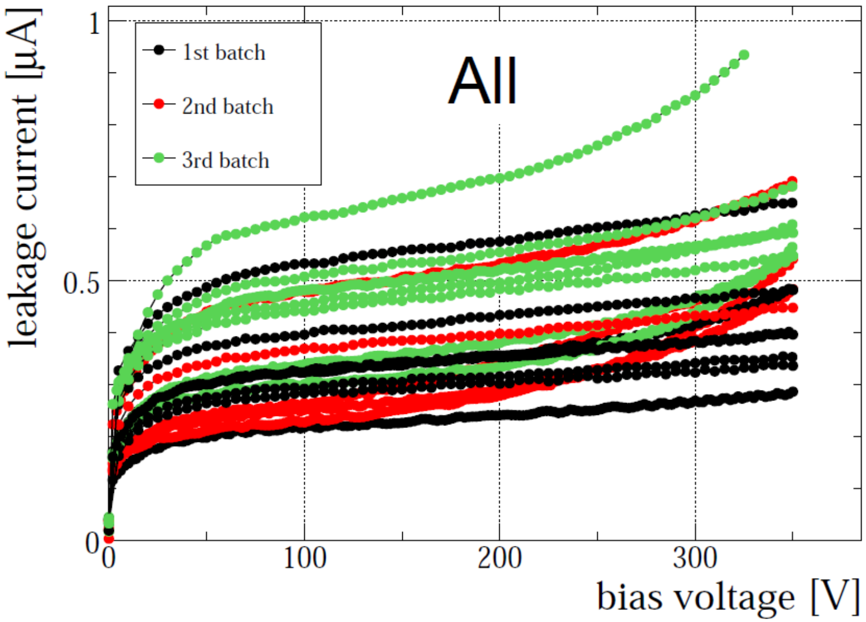




- Sensor surface covered with 3 μm of BCB (Benzocyclobutene ®) during post-processing at IZM Berlin → higher isolation capabilities with respect to normal passivation (for example SiO_2)

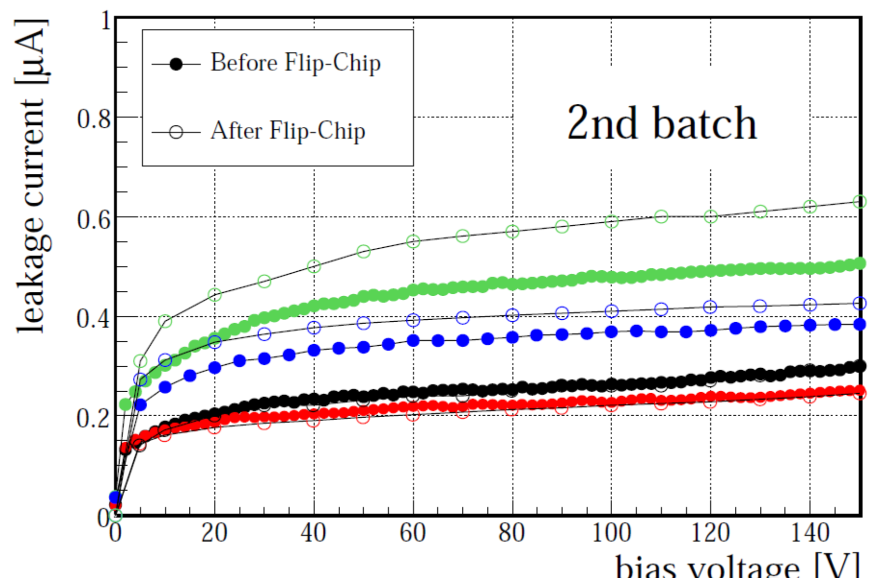
HV Stability observed at 1000V over several hours

Sensor characterization before interconnection



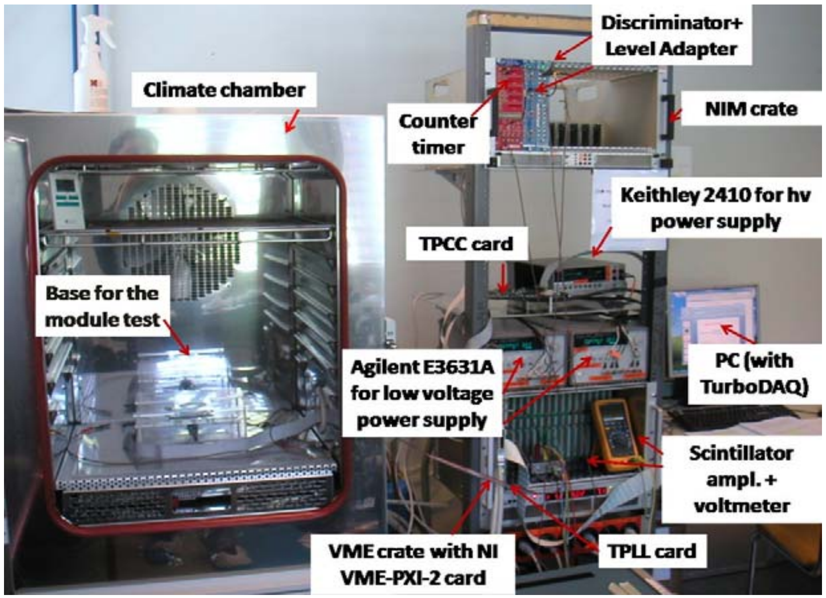
- Breakdown voltages before irradiation much higher then V_{depl}=60V
- Working point for module characterization before irradiation V_{bias}=150V

- Bump-bonding of the sensors to the FE-I3 chip performed in three different batches
- Leakage currents and breakdown voltages not affected by the bump-bonding procedure



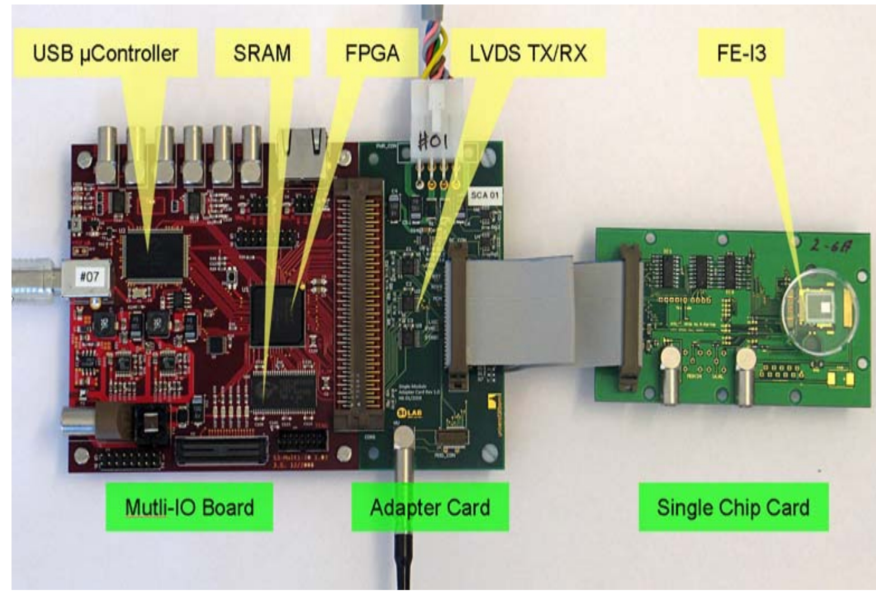
Read-out systems

Turbo DAQ



- PC to VME interface
- Set-up of the CERN ATLAS Pixel group

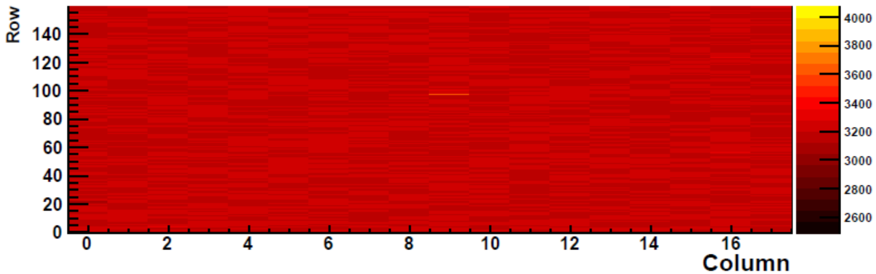
USBPix

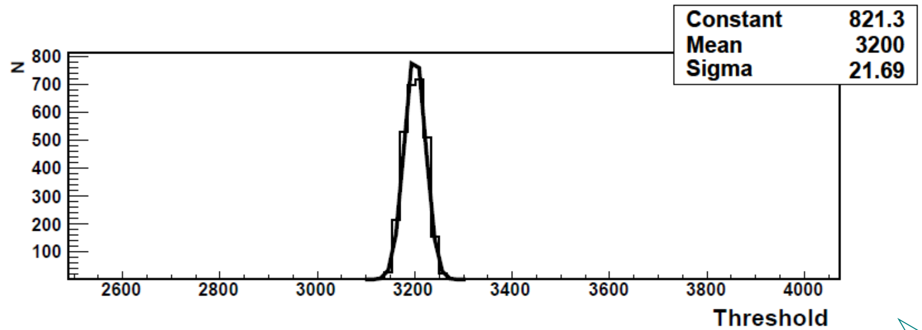


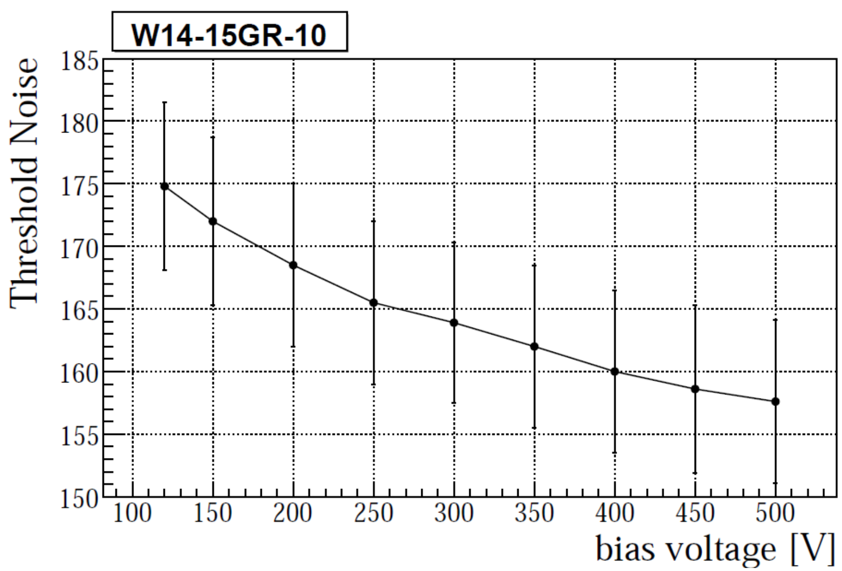
- Modular system with USB interface
- Available at CERN and MPI for Physics

Temperatures of the module measurements cited in the following are always relative to the environmental condition of the climate chamber → no active cooling of the modules

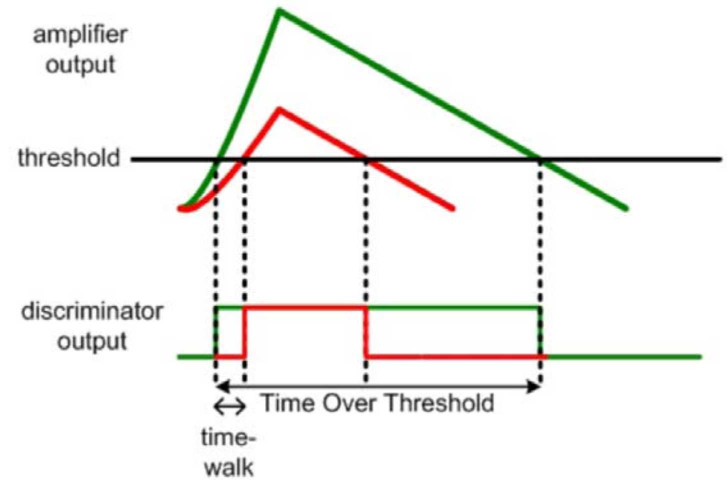
Module characterization before irradiation







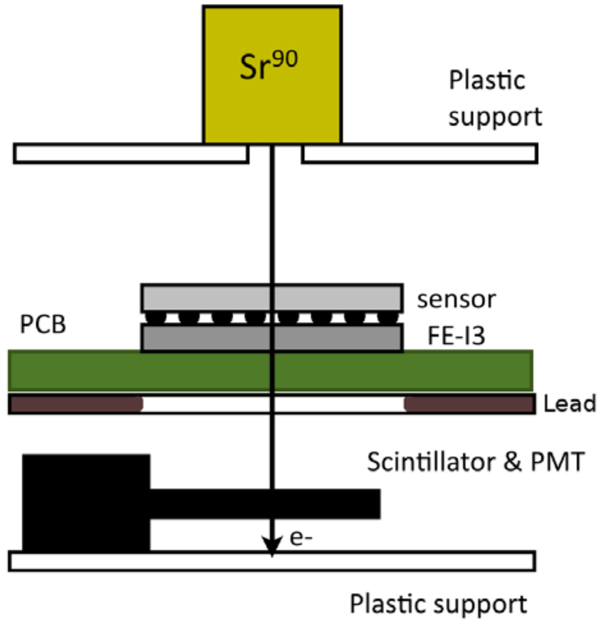
FE-I3 amplifier output and discriminator

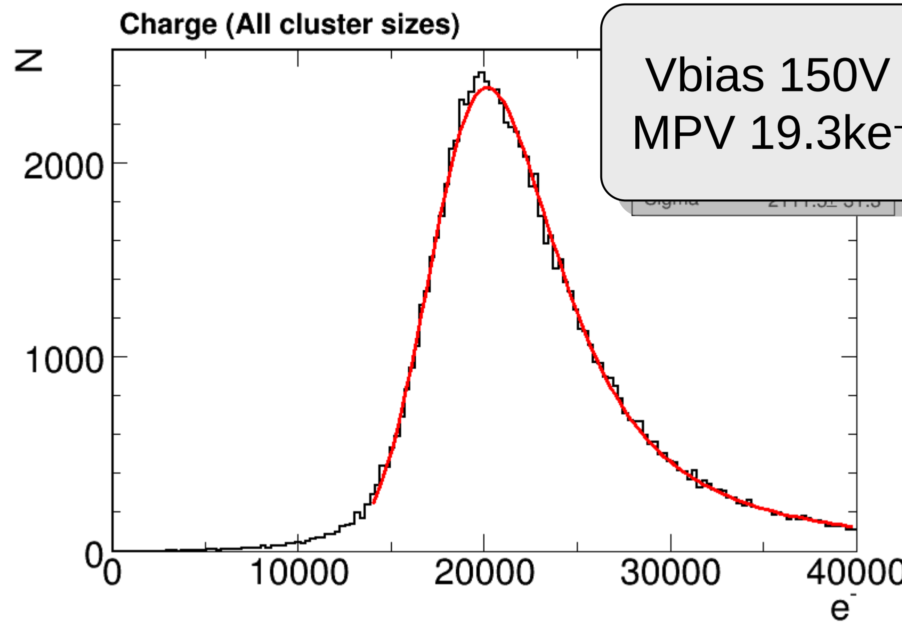


- A very narrow tuning of the threshold can be achieved
- Threshold noise decreasing with Vbias→ better inter-pixel isolation
- Very uniform results over the 19 modules tested

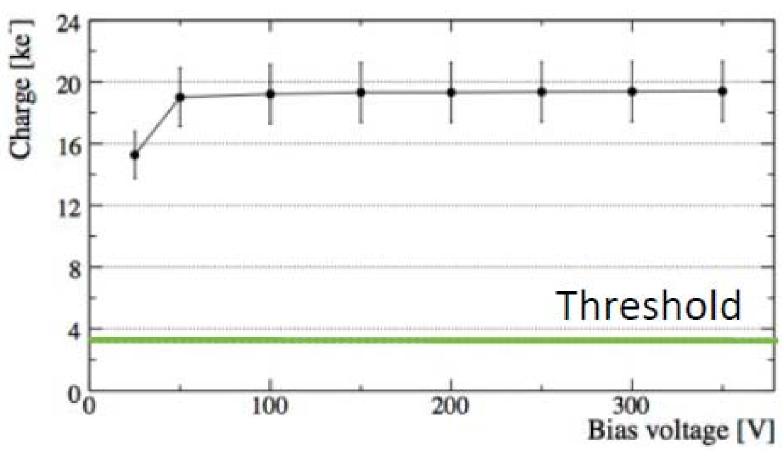
Threshold dispersion and noise fully comparable to values achieved for n-in-n pixels

Module characterization before irradiation





Vbias 150V
MPV 19.3ke$^-$



Charge saturation consistent with the V_{depl}=60V measured on the bare sensors

P. Weigell et al., http://dx.doi.org/10.1016/j.nima.2011.04.049

Irradiation campaign

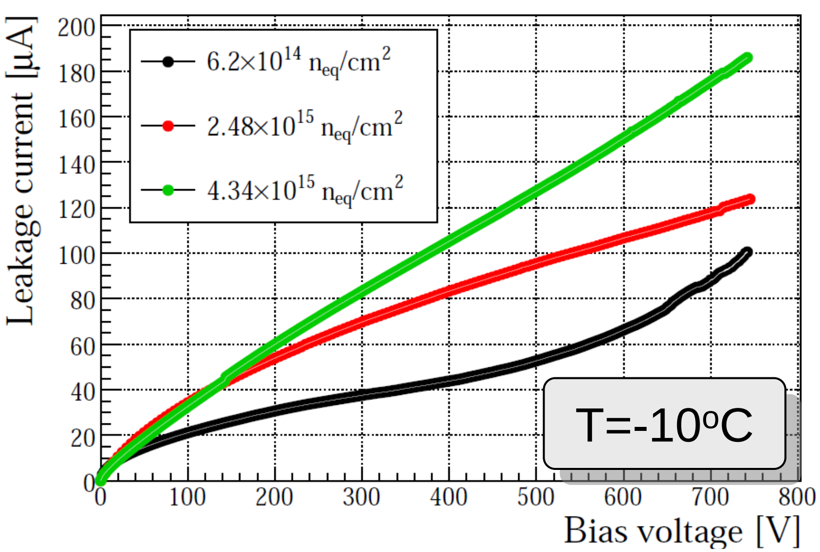
- **CERN** protons at 24 GeV

1 sensor at 6.2 x10^{14} n_{eq}/cm^2
1 sensor at 2.5 x10^{15} n_{eq}/cm^2
1 sensor at 4.4 x10^{15} n_{eq}/cm^2

1 SCM at 2.8 x10^{15} n_{eq}/cm^2
1 SCM at 5 x10^{15} n_{eq}/cm^2

- **Karlsruhe** protons at 25MeV

1 SCM at 10^{15} n_{eq}/cm^2



- **Ljubljana** neutrons

1 SCM at 2x10^{15} n_{eq}/cm^2
1 SCM at 3x10^{15} n_{eq}/cm^2
1 SCM at 5 x10^{15} n_{eq}/cm^2
1 SCM at 10^{16} n_{eq}/cm^2 (ongoing)

- **Ljubljana** neutrons + **Karlsruhe** protons at 25MeV

1 SCM at 10^{15} n_{eq}/cm^2 + 10^{15} n_{eq}/cm^2

For the irradiations we thank:

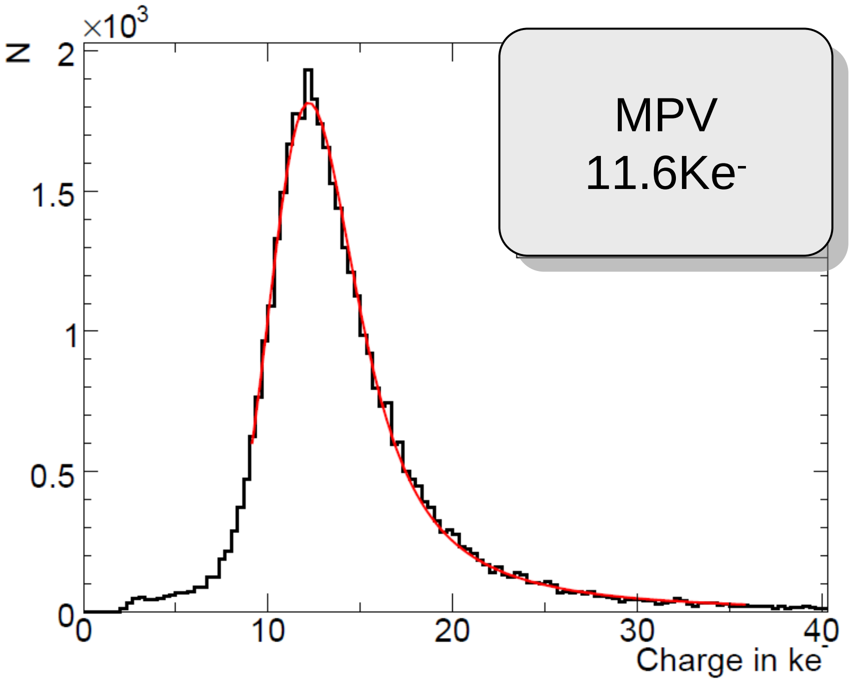
M. Glaser at CERN-PS

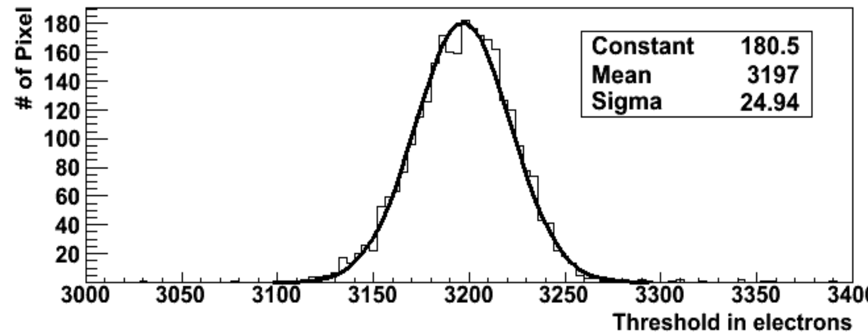
A. Dierlamm and the Helmholtz Alliance at KIT

V. Cindro in Ljubljana

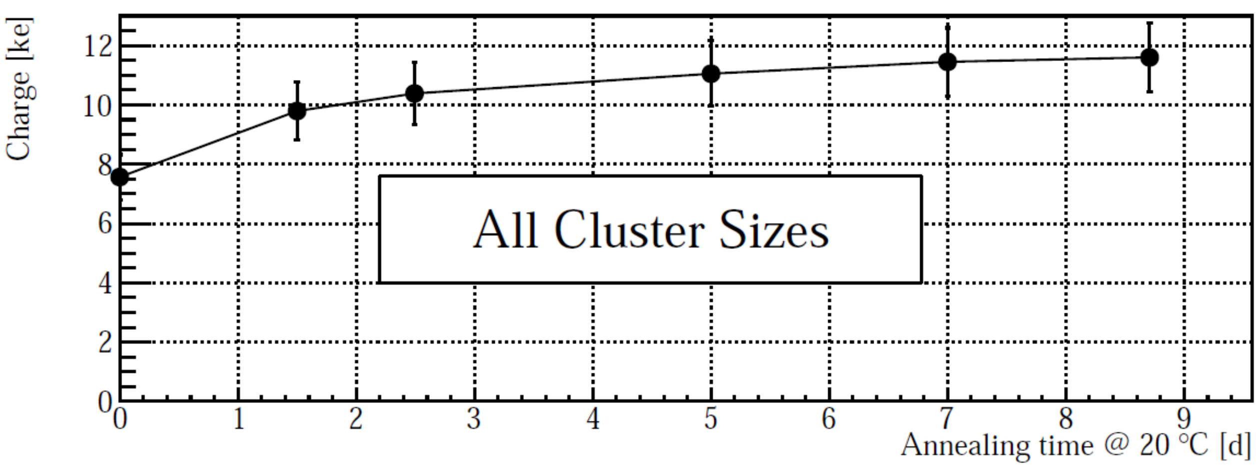
Module characterization @ $10^{15}\ n_{eq}/cm^2$

$10^{15}\ n_{eq}/cm^2$ with 25 MeV p. in Karlsruhe, tuning @ 550V



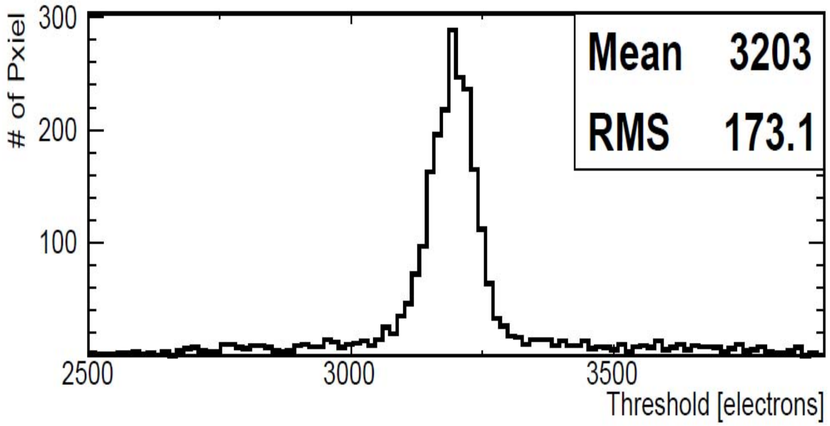


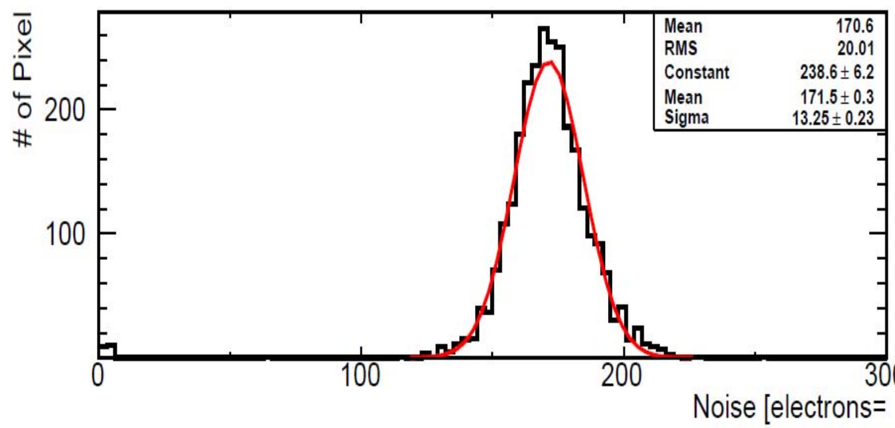
- Still very narrow tuning of the threshold can be achieved at this moderate fluences
- Increase of the collected charge over the first 10 days of annealing at RT



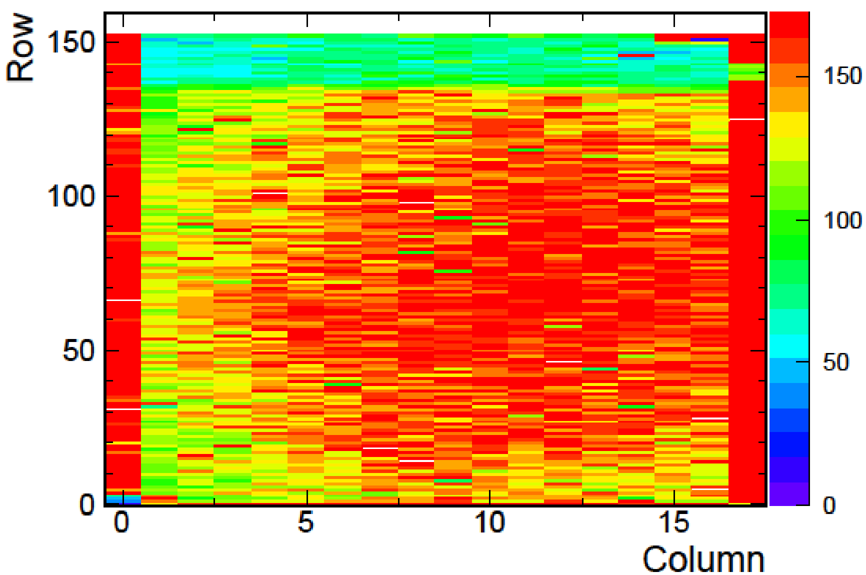
Module characterization @ 5x10^{15} n_{eq} /cm^2

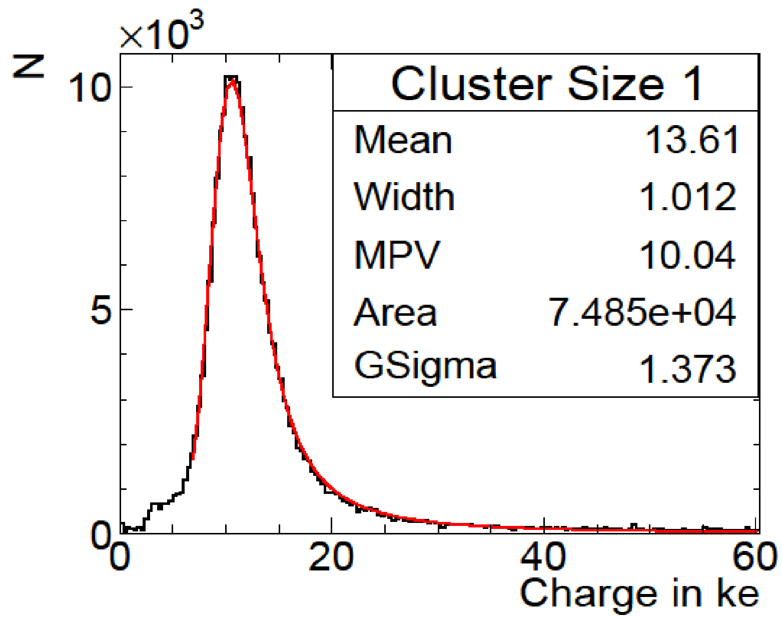
5x10^{15} n_{eq}/cm^2 with reactor neutrons in Ljubljana, Tuning @ 1000V





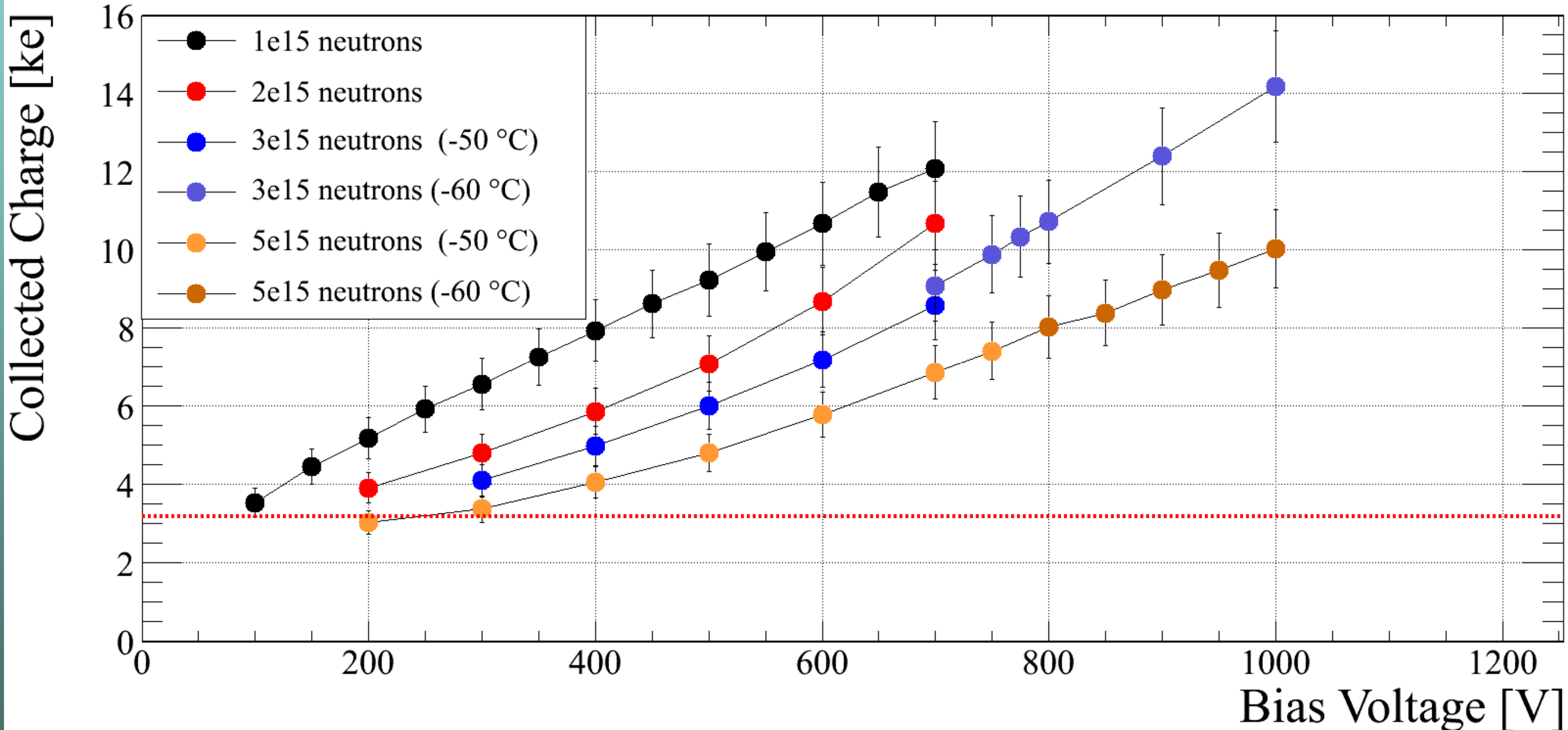
Hit Map ^{90}Sr scan





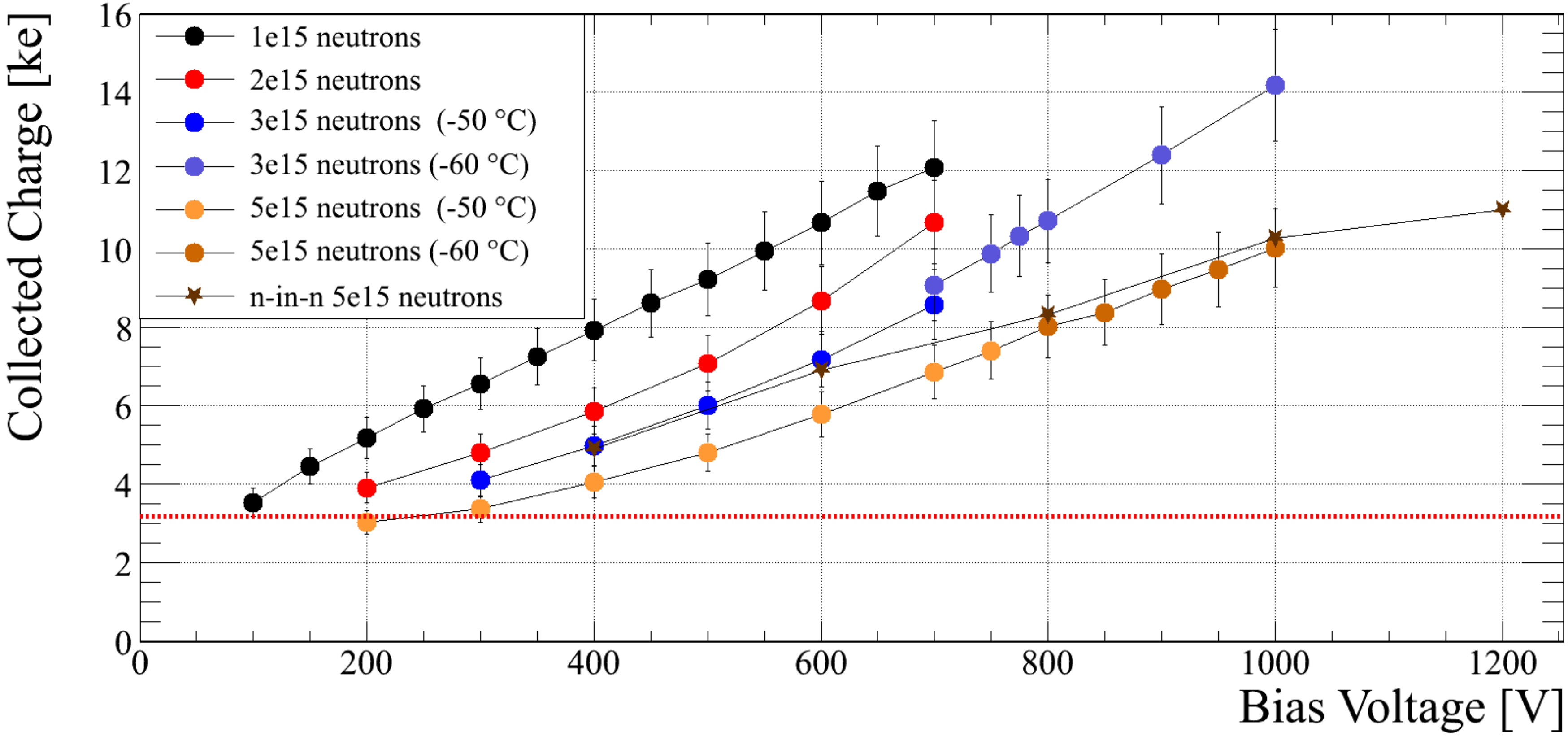
CCE Summary – neutron irradiation

MPV – Cluster Size 1, Threshold=3200 e^-



CCE Summary – Comparison with n-in-n FE-I3 modules

MPV – Cluster Size 1, Threshold=3200 e⁻

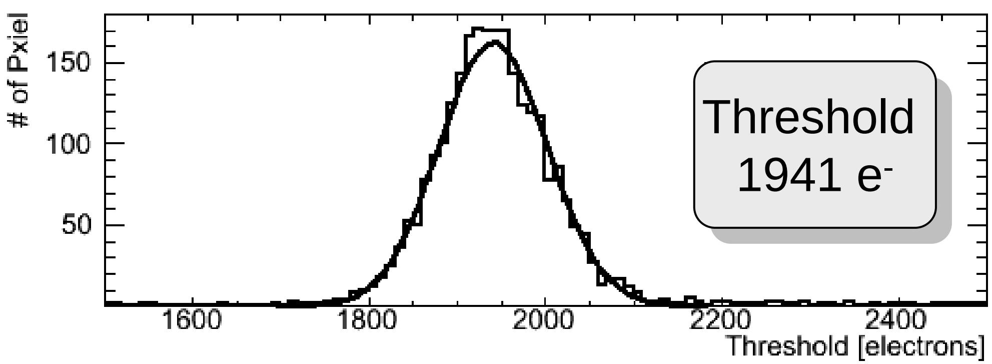


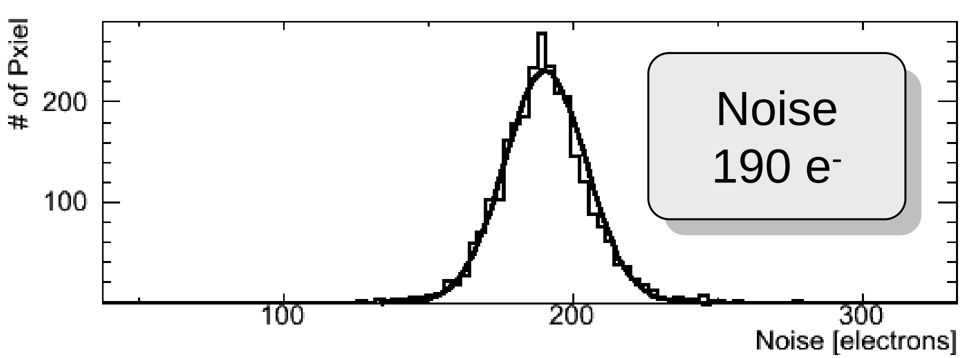
N-in-n data from A. Rummler, 18th RD50 Workshop, http://indico.cern.ch/conferenceOtherViews.py?view=cdsagenda&confId=129737

Investigating lower thresholds

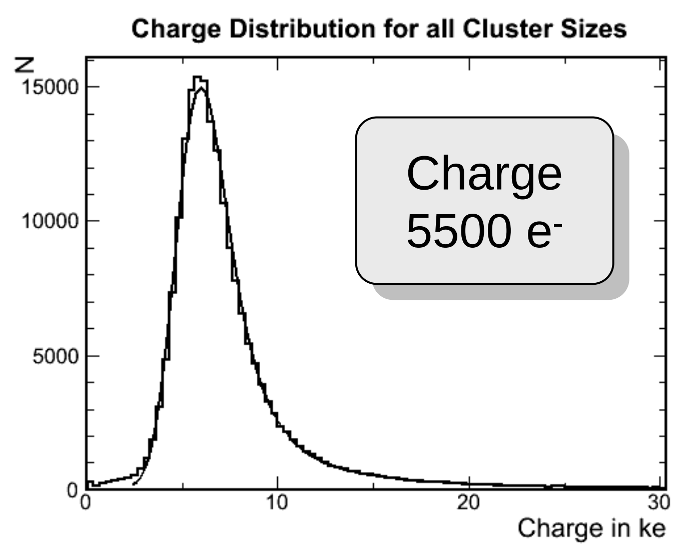
- Lower pixel threshold at equal charge should translate into higher hit efficiency
- Minimum operation threshold in the FE-I3 determined by the corresponding noise and noise occupancy

Fluence=$5\times10^{15}\ n_{eq}/cm^2$, Threshold=2000 e^-, V_{bias}=600V



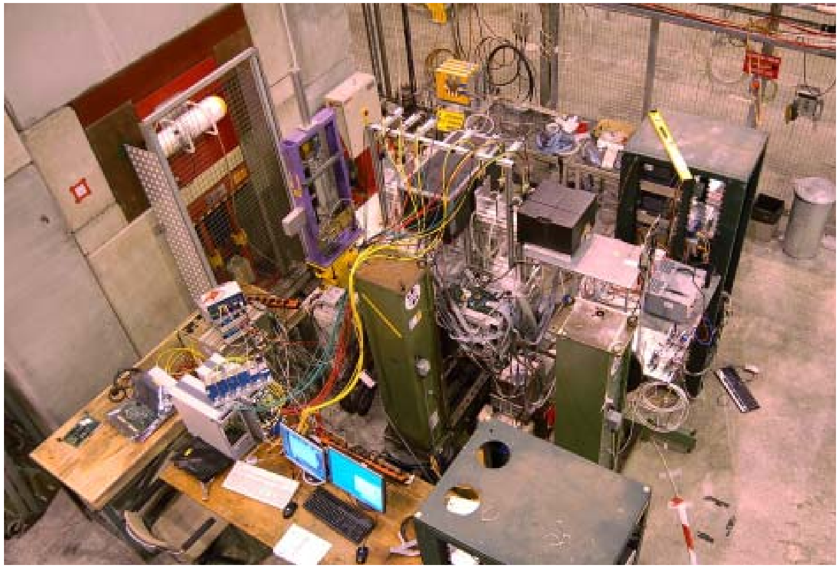


- Charge > 2xThreshold → 600V safe operation voltage to retain good hit efficiency
- Preliminary measurement of the noise occupancy: 10^{-6} per pixel
- Need confirmation from TB



ATLAS Planar Pixel Sensor 2010 Beam tests at CERN SPS

- CERN SPS 180GeV pions beam
- H6/B beam line
- Reference Telescope: EUDET
- DAQ based on TurboDAQ System
- About 9 weeks of beam over July and October

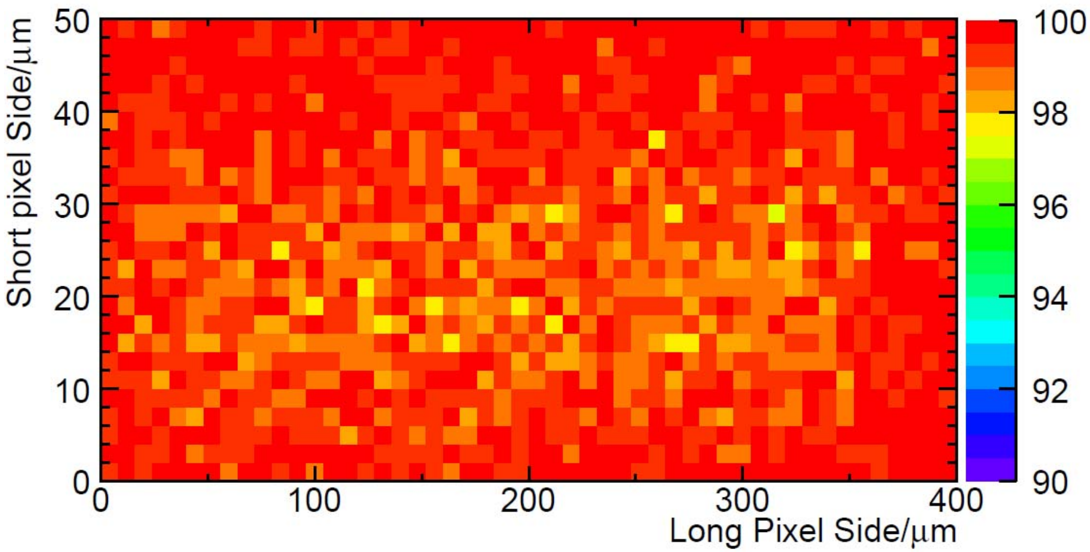


Test beam Crew

M. Beimforde, M. Benoit, M. Bomben, G. Calderini, Ch. Gallrapp, M. George, S. Gibson, S. Grinstein, Z. Janoska, J. Jentzsch, O. Jinnouchi, T. Kishida, A. La Rosa, V. Libov, A. Macchiolo, G. Marchiori, D. Muenstermann, R. Nagai, G. Piacquadio, B. Ristic, I. Rubinskiy, A. Rummler, D. Sutherland, Y. Takubo, G. Troska, S. Tsiskaridze, I. Tsurin, Y. Unno, P. Weigell, J. Weingarten, T. Wittig

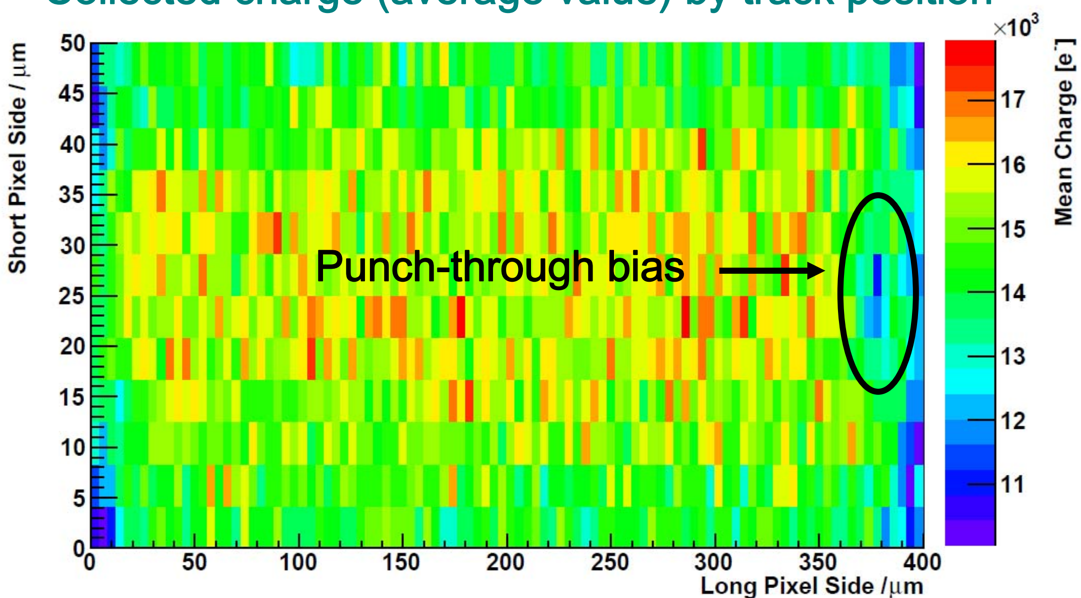
Results from the 2010 test beam

Tracking Efficiency Map



Tracking efficiency before irradiation:
99.3 %

Collected charge (average value) by track position



Proton irradiated sample
$\Phi=10^{15}\ n_{eq}/cm^2$
$V_{bias}=500$ V

MPV= 12.3 ke^-
Mean=15.2 ke^-

Collected charge well above threshold!

Summary and plans

- n-in-p pixels offer a cost effective solution for tracking in high radiation environment
- Potential difference at the sensor-chip edges presents a possible danger of sparks: first countermeasures look very promising, alternative solutions could be explored
- Excellent performance of the n-in-p pixels before and after irradiation in terms of charge collection efficiency and tracking efficiency

New n-in-p pixel production at CIS on 4” wafers

- Pixel sensors compatible with FE-I4 (new ATLAS chip for IBL and outer layers at HL-LHC)
- Thinner bulk: 150 and 200 μm (process without handle wafer) → better CCE expected