Measurements of highly irradiated ATLAS planar pixel sensors with unirradiated readout electronics

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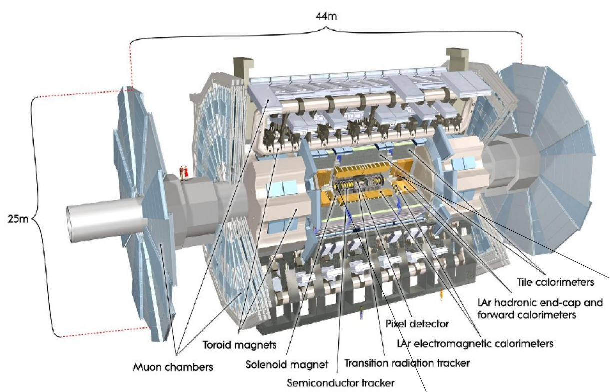
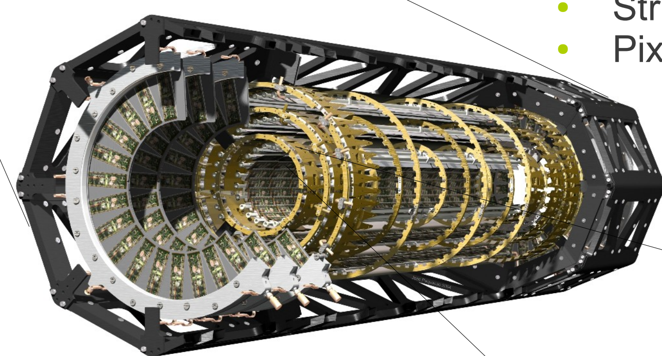
The pixel detector of the ATLAS experiment

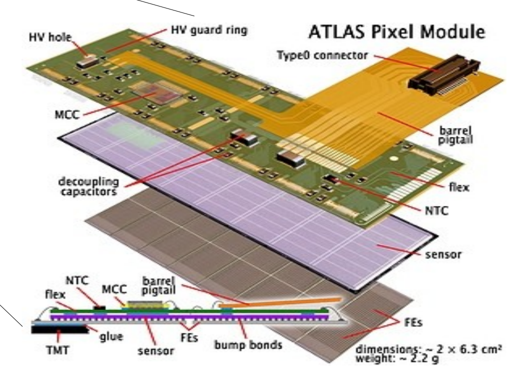


- ATLAS is one of the four experiments at LHC
- 44 meters long, diameter about 25 meters
- Weight 7000t
- Sub-detectors
  - Muon spectrometer
  - Hadron calorimeter
  - Electromagnetic calorimeter
  - Inner detector
    - Transition Radiation Detector
    - Strip Detector
    - Pixel Detector

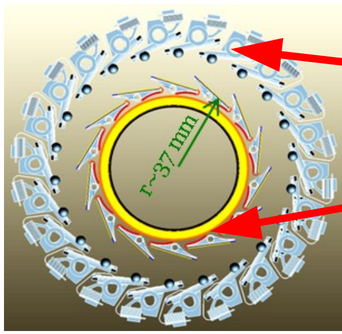


- Current pixel detector:
  - 80 million readout channels
  - 3 barrel layer
  - 6 end caps

- Current pixel module:
  - planar n-in-n FZ sensors
  - 250µm thick
  - Read-out chip Front-End I3



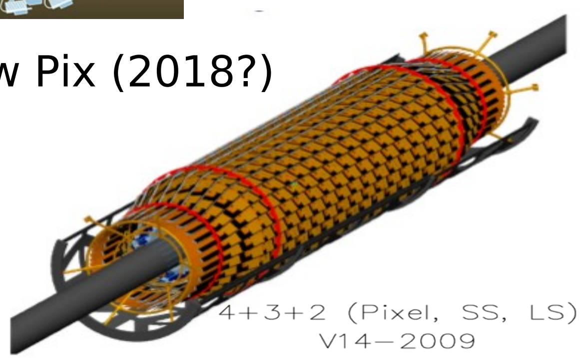
Future upgrade of the ATLAS pixel detector

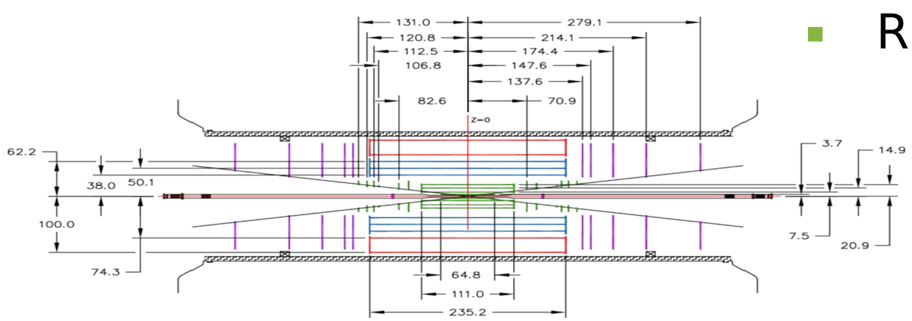


Existing B-layer

IBL (mounted on the New beam pipe)

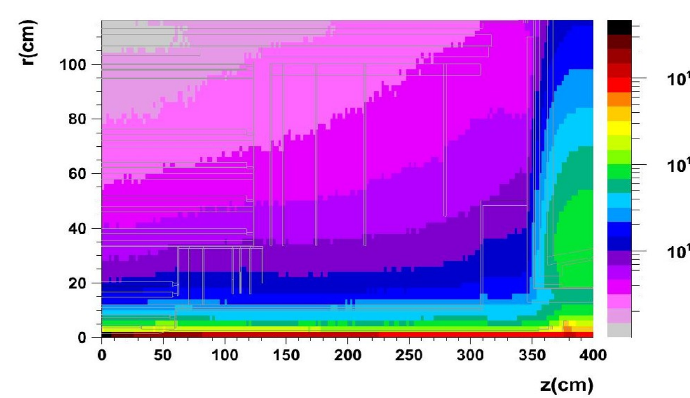
New Pix (2018?)





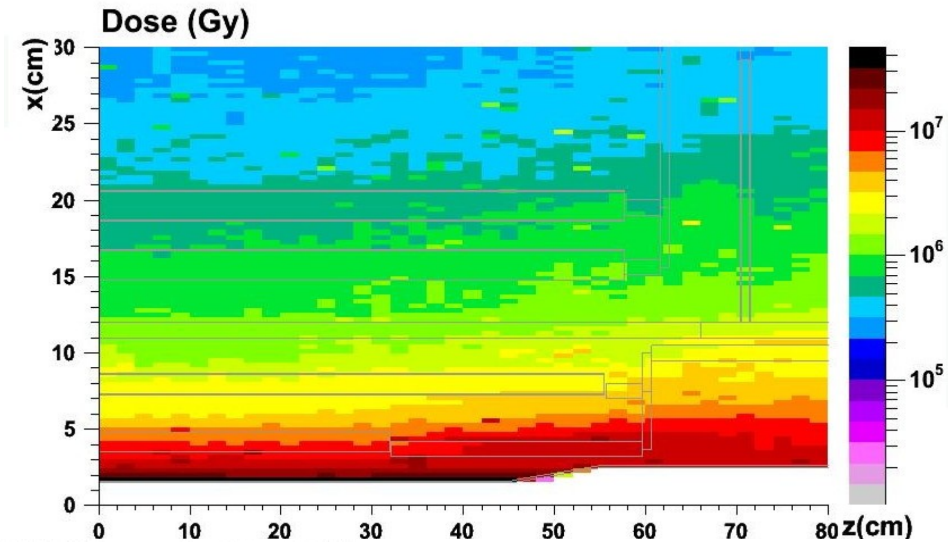
4 layers of pixel to larger radius than now
Approx. 400 Million pixels (80 Million now)

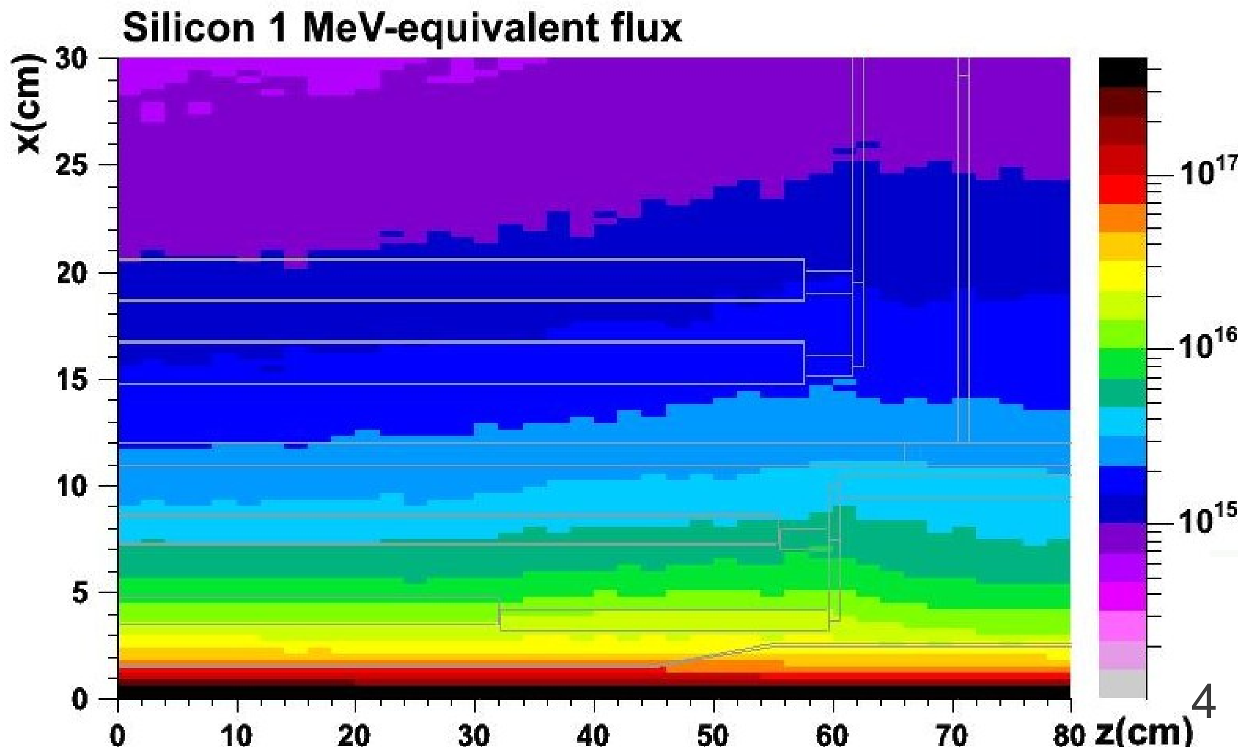
- Twofold upgrade
  - Insertable b-layer (IBL)
    - IBL conditions:
      - Maximum bias voltage: 1000V
      - Cooling -15°C
      - Radiation hard up to $5 \cdot 10^{15} n_{eq} cm^{-2}$
  - Full replacement in 2018 or 2021-2022 depending on the performance
- Luminosity: $(2\text{-}3) \cdot 10^{34}\text{-}10^{35} cm^{-2}s^{-1}$
- Radiation dose: $10^{15}\text{-}10^{16} n_{eq} cm^{-2}$

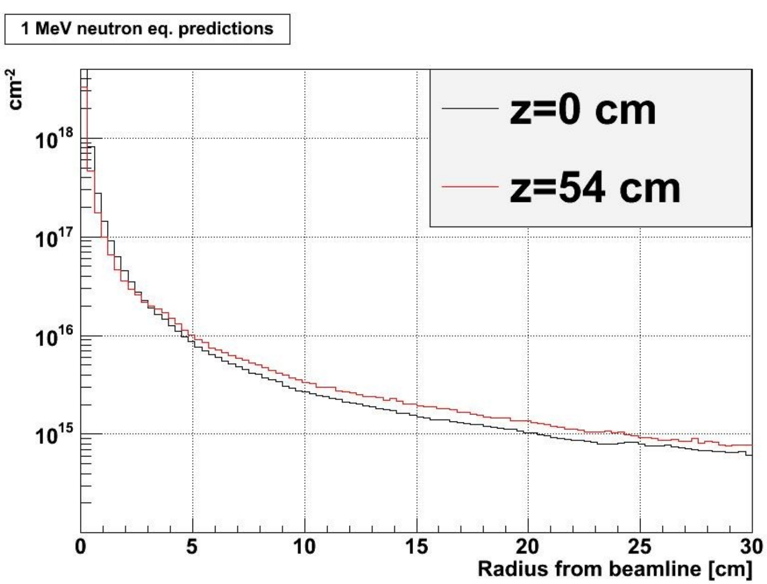


Fluences at HL-LHC

- integrated luminosity for sLHC: 3000 fb^{-1}
- including a safety factor of 2 to account for all uncertainties this yields the following fluences:
  - $2 \cdot 10^{16}$ n_{eq} cm^{-2} at 3.7 cm radius
  - up to 10^{15} n_{eq} cm^{-2} at 30 cm radius
  - > 10^{14} n_{eq} cm^{-2} at the outer tracker radius

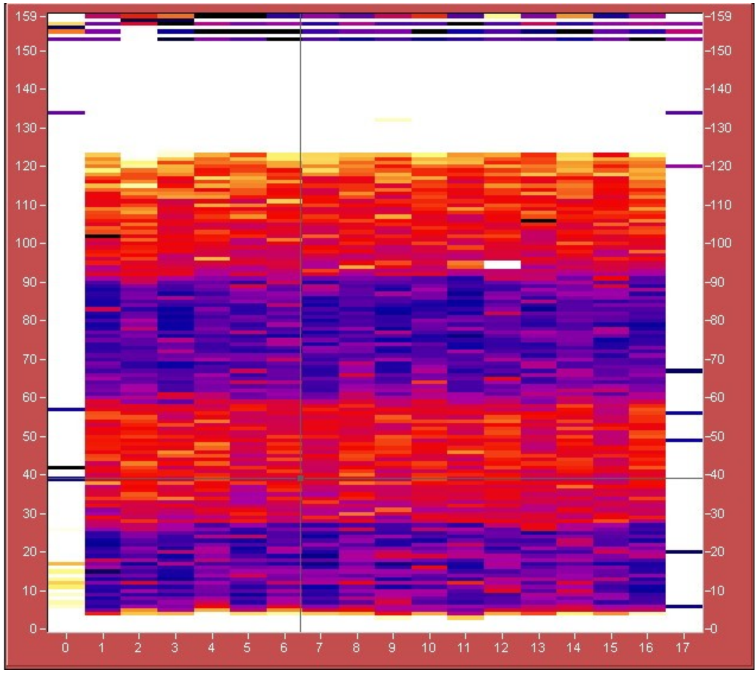


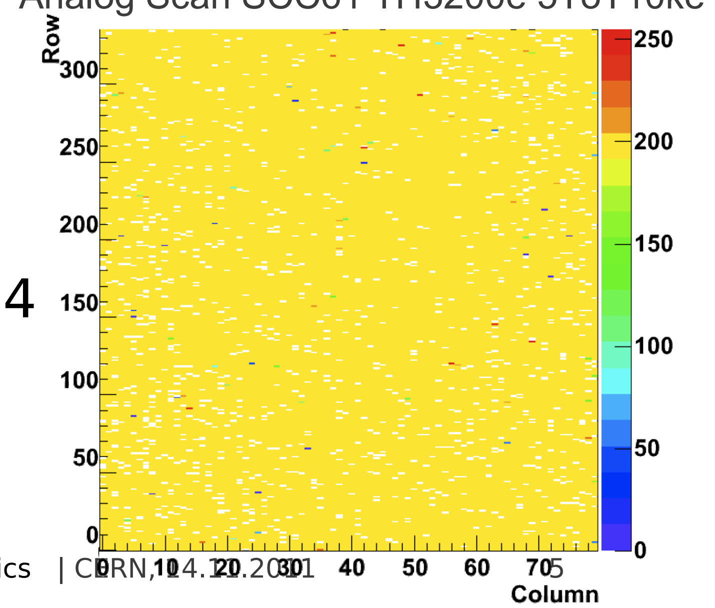




FE damage – FE-I3 after severe irradiation with neutrons

- Experience after very high fluences with neutron-irradiated assemblies:
- threshold tuning and digital communication always work
  - **but**: erratic behaviour observed, even with assemblies from the same irradiation batch:
    - on some days, source scans only yield noise/empty events/stripes
    - on some days, chip works fine
    - some chips never work
    - some chips always work
- Low energy proton irradiation → no longer working beyond $1 \cdot 10^{15}\ n_{eq}\ cm^{-2}$
- High ionising dose means trouble also for FE-I4
- See Claus Goessling's talk at last AUW

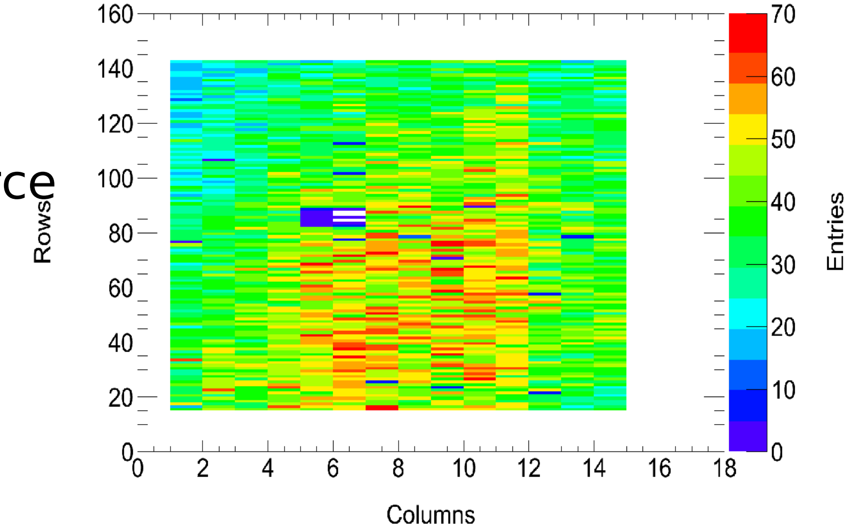


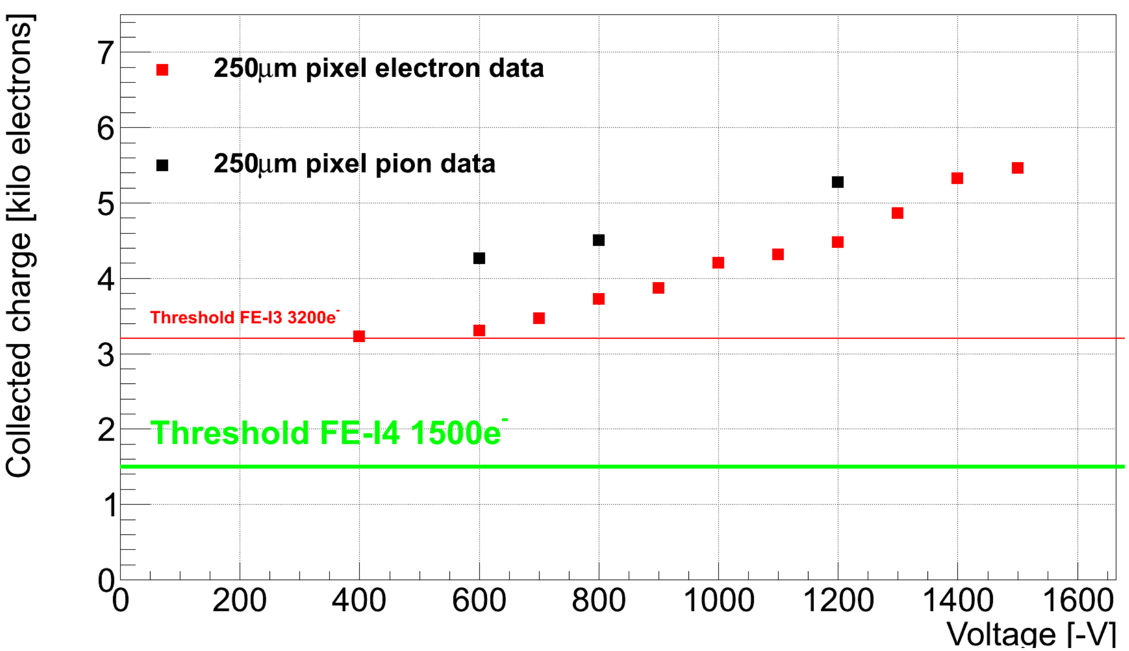


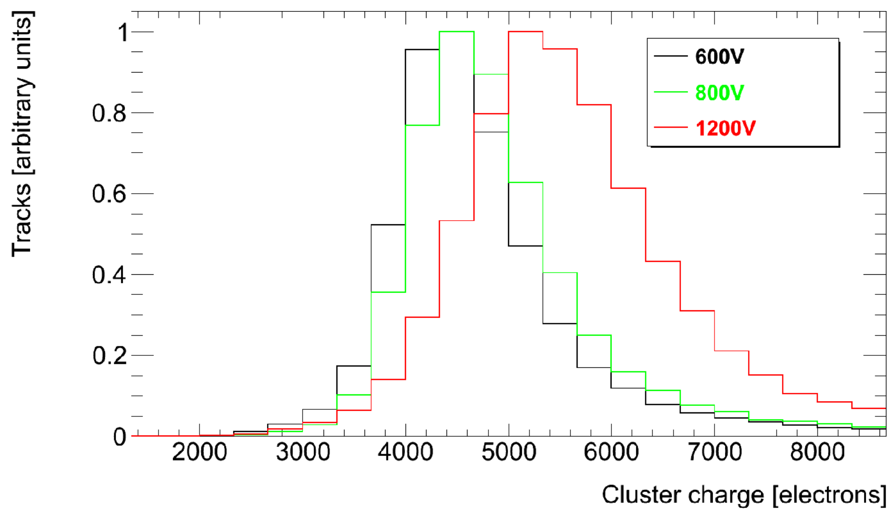
It is still possible: first results

- FE-I3 assemblies were irradiated in Ljubljana with reactor neutrons up to $2 \cdot 10^{16}\ n_{eq}\ cm^{-2}$
- Collected charge measured with a Sr-90 source (electrons) and with pions at CERN-SPS
  - beamspot
  - landaus
  - collected charge vs. bias voltage

$2 \cdot 10^{16}\ n_{eq}\ cm^{-2}$ 1200V







doi:10.1016/j.nima.2011.05.074
doi:10.1016/j.nima.2010.11.186
more forthcoming

Deconvolution of the effect of radiation on sensor and chip

FE-I3 chip

- Present ATLAS front-end
- 250nm IBM CMOS technology
- Radiation hard up to ~100Mrad
- Still widely used for the R&D thanks to its larger availability and better understood TOT-Charge conversion

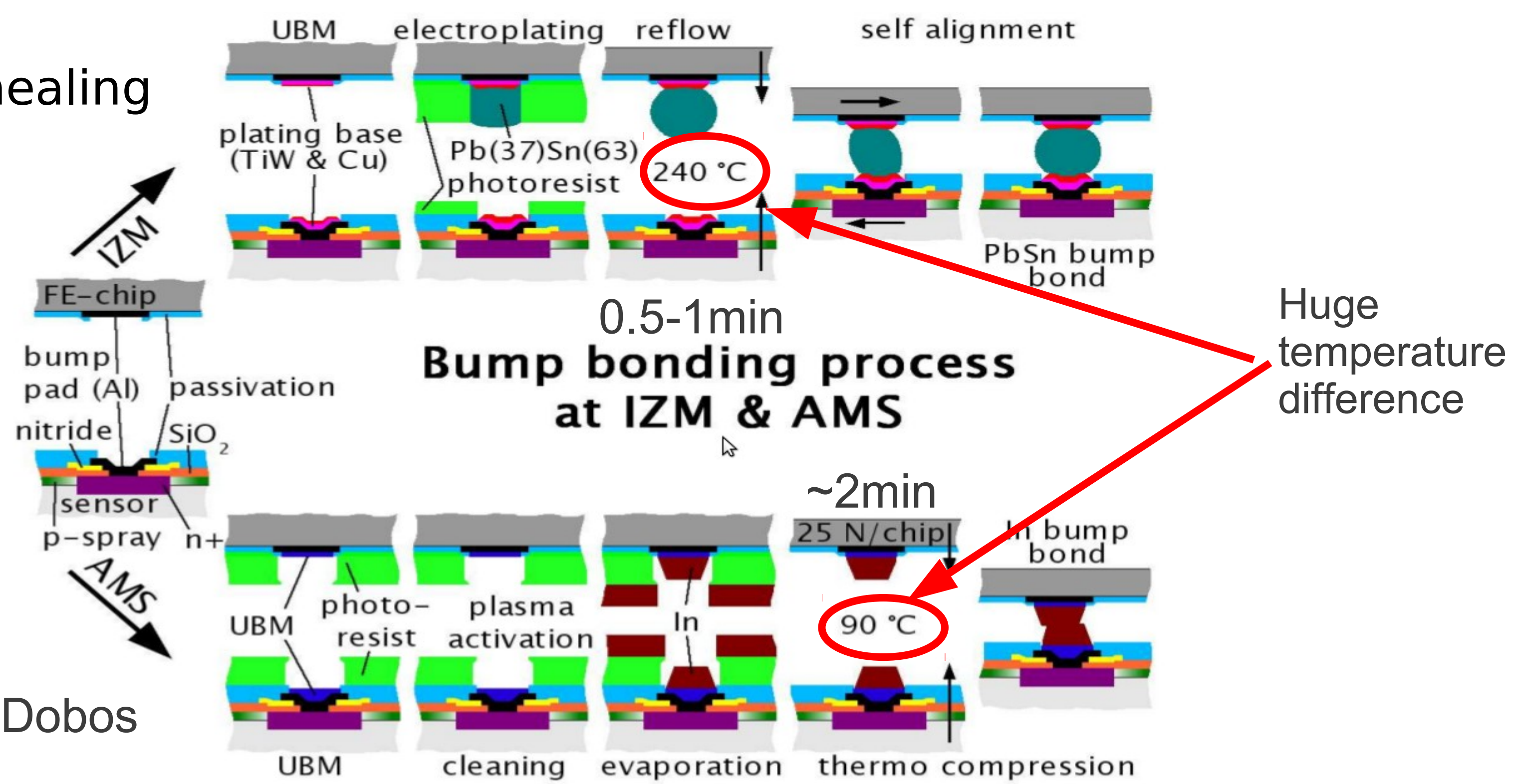
FE-I4 chip

- New front-end for IBL upgrades
- 130 nm IBM CMOS technology
- Radiation hard up to ~250Mrad
- Will be used in the outer layers of upgraded pixel detector
- A more radiation resistant chip will be needed for the pixel inner layer in 2022

Solution to investigate sensor radiation hardness in the full HL-LHC range: Irradiate sensor before connection to the front-end chip and afterwards interconnect the chip with indium bump-bonding, a technology requiring a low temperature budget

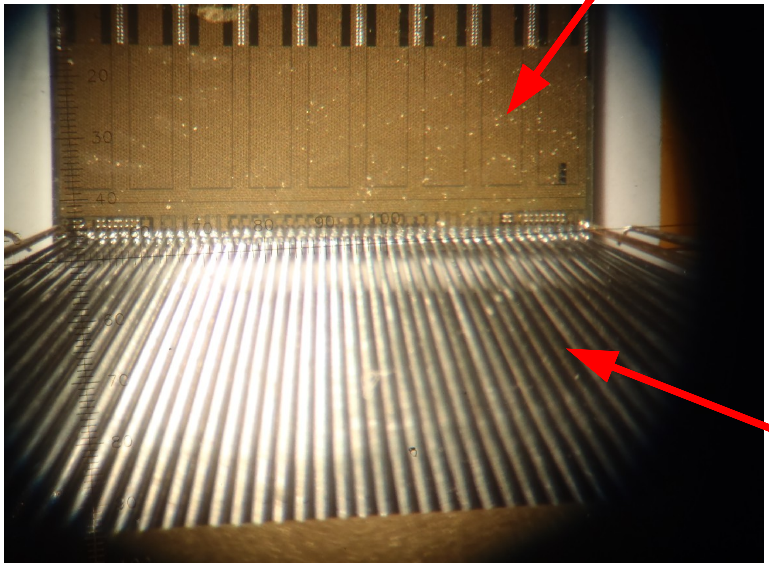
Flip chip procedure

- Samples were flip chipped successfully at Selex (AMS) in Italy
- Thermo compression bonding with indium bumps
- Flip chip procedure is much colder (80°C – 90°C, 2min) than the IZM (SnAg-3-5, 250°C-260°C, 0.5 – 1min) procedure.
- This roughly equals the annealing time 2h @ 60°C
- No additional annealing needed

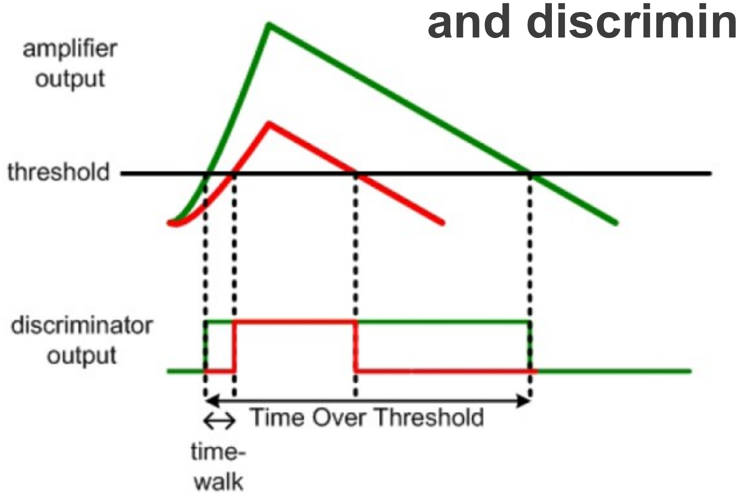


Pre-testing the unirradiated front-ends

- unirradiated FE-I3s were tested before flip chipping with a testcard (needle comb) in order to assert their working condition
- Successfully passed tests:
  - Digital test
  - Analog test
  - Threshold scan

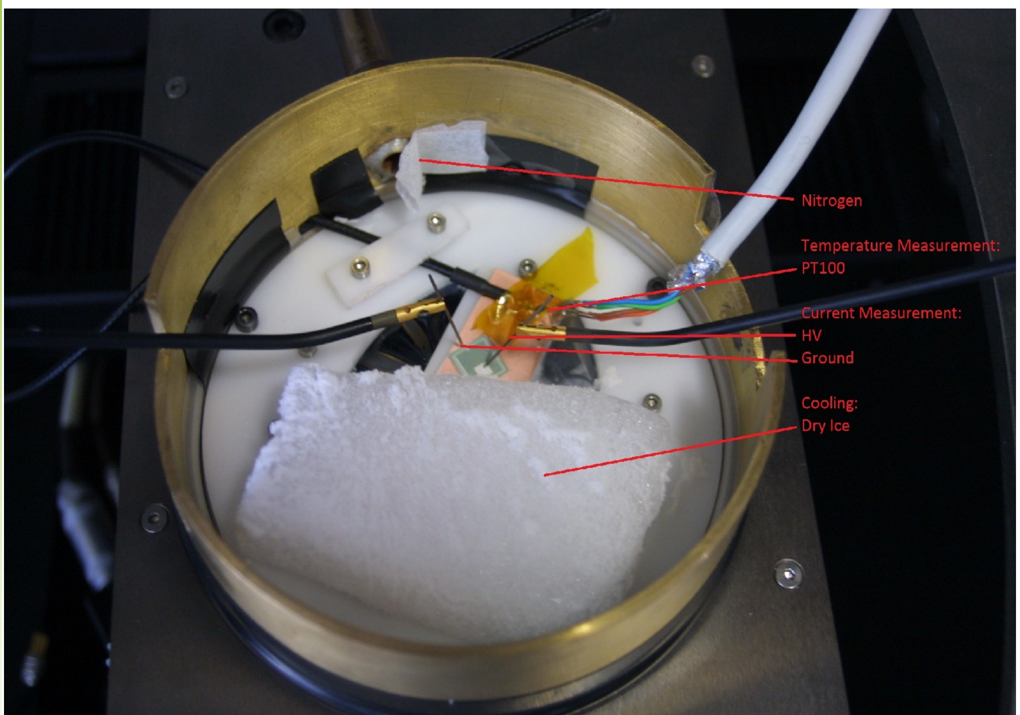


FE-I3 amplifier output and discriminator

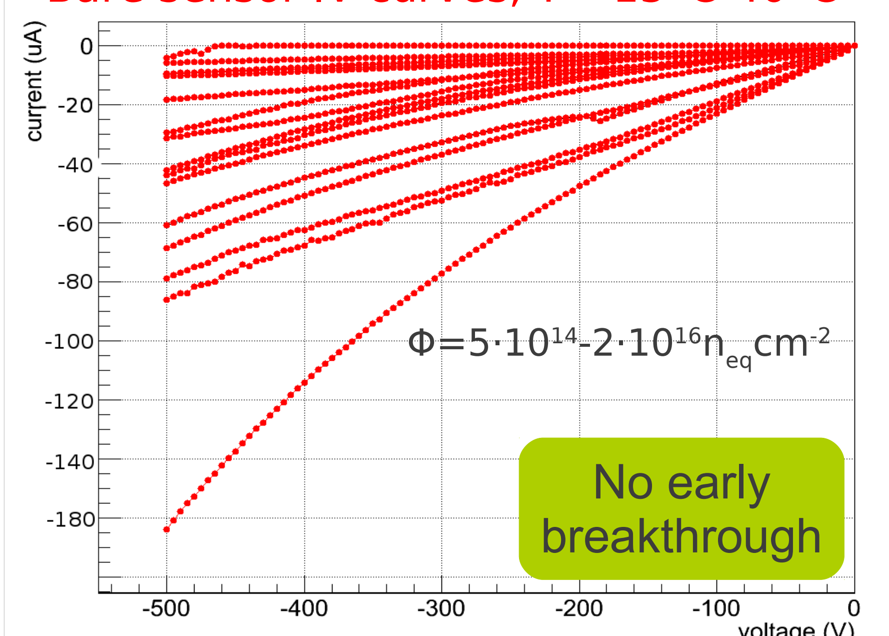


Testing the irradiated sensors

- Sensors in n^+-in-n design on 250µm thick Fz-bulk from the original ATLAS production
- tested before and after irradiation by IV measurements (ATLAS QA criteria applied, best samples selected)
- Irradiated with 26 MeV protons in Karlsruhe ($5 \cdot 10^{14} n_{eq} cm^{-2}$ to $2 \cdot 10^{16} n_{eq} cm^{-2}$)
- After irradiation the sensors were cooled with dry ice (temperature between -15°C and -40°C, all currents corrected to -15°C)

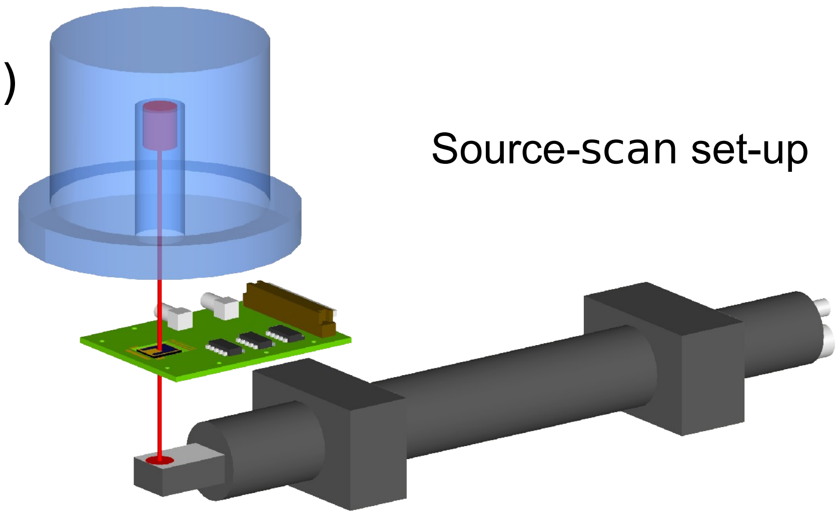


Bare sensor IV curves, T=-15°C-40°C

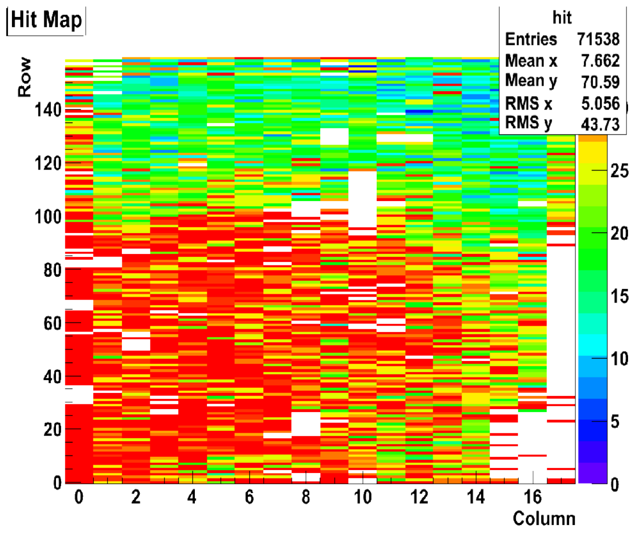


Lab Measurements

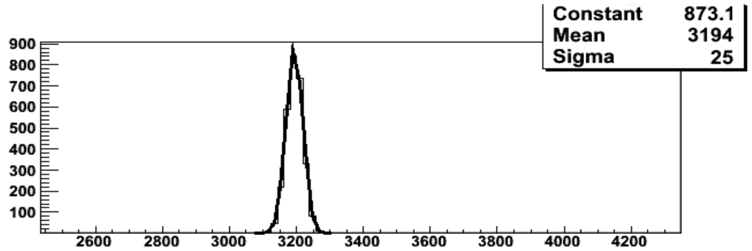
- Source scans with ^{90}Sr (~1MeV electrons)
- External trigger: scintillator coupled to a photomultiplier
- Sensor bias voltage up to 2000V
- Cooling with dry ice (about -45°C on at the aluminum carrier plate)
- Copper tape was used to realize the heat conductive connection between dry ice and the backside of the aluminum
- All temperatures were measured with a PT1000 on the aluminum carrier
- Read-out realized with new ATLAS common read-out system (USBPix)



Source-scan set-up



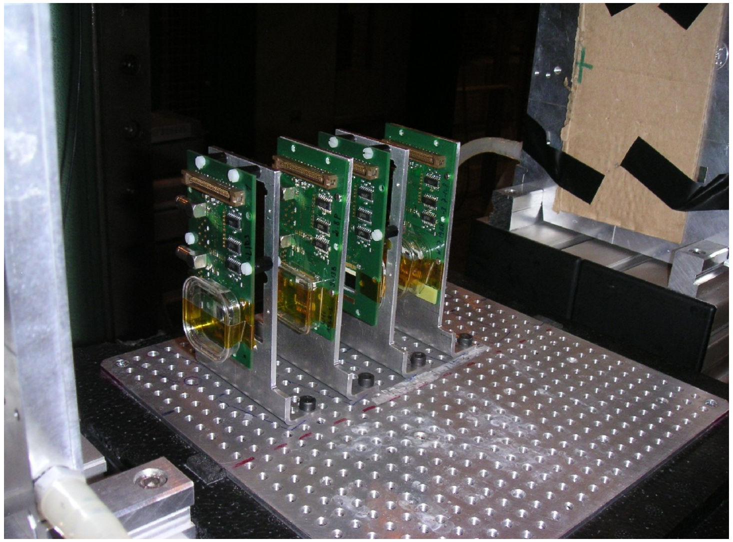
1200V, $2.2 \cdot 10^{15}\ n_{eq}/cm^2$



Threshold distribution after tuning

Test beam measurements

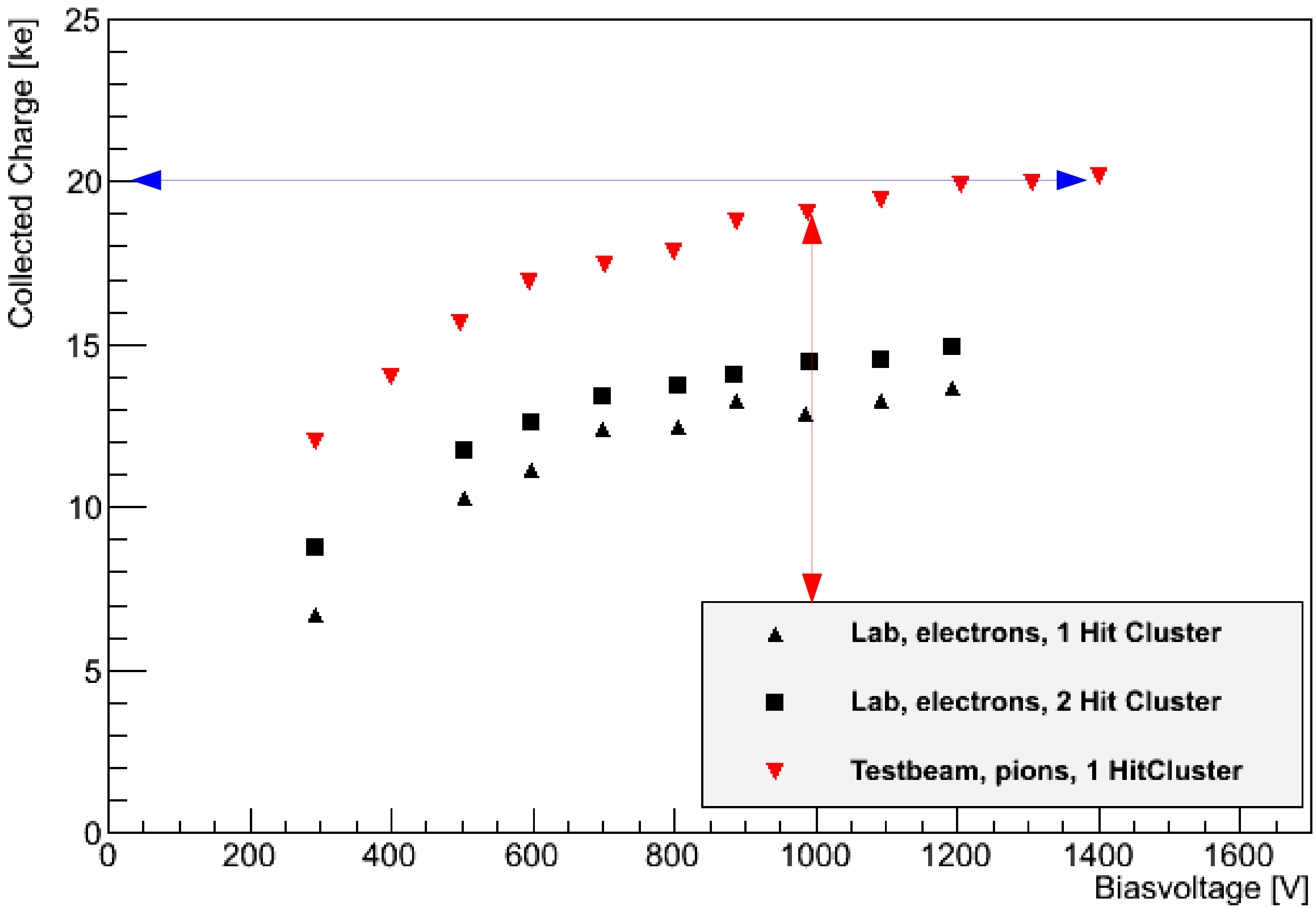
- Beam from SPS with 120GeV pions
- cooling with dry ice (about -45°C on the aluminum plate) measured with a PT1000
- fast bias scan → just enough statistics to measure the correlation between the collected charge and bias voltage
- 5 voltage steps up to 1800V with sufficient statistics for space resolved analysis (e.g. efficiency)



Many thanks to the PPS collaboration and in particular to the PPS Testbeam group and all people involved in the data taking and analysis

Name	Fluence	Voltage	Voltage	Voltage	Voltage	Voltage	“fast bias scan”
DO-I-7	$2.2 \cdot 10^{15}$ n_{eq} cm^{-2}	500	600	1000	800	1200	300-1500
DO-I-11	$1 \cdot 10^{16}$ n_{eq} cm^{-2}	600	1000	1500	1300	1800	500-1700
DO-I-5	$1.4 \cdot 10^{16}$ n_{eq} cm^{-2}	600	1000	1500	1300	1800	500-1700
DO-I-12	$1.4 \cdot 10^{16}$ n_{eq} cm^{-2}	600	1000	1500	1300	1800	500-1700

$2.2 \cdot 10^{15}\ n_{eq}\ cm^{-2}$



- Collected charge decreases with the fluence but is still above the threshold (3200e /4000e)
- Collected charge increases with the bias voltage
- Threshold 3200e
  ToT calibration: 60 ToT = 20ke

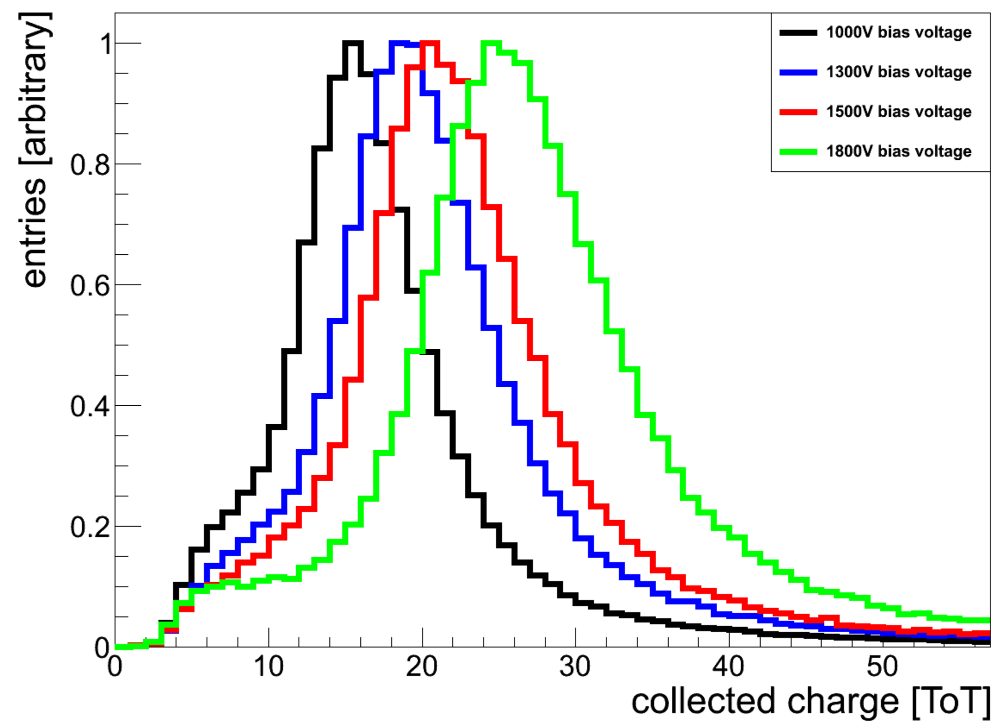
ToT to charge conversion with mean values for calib constants

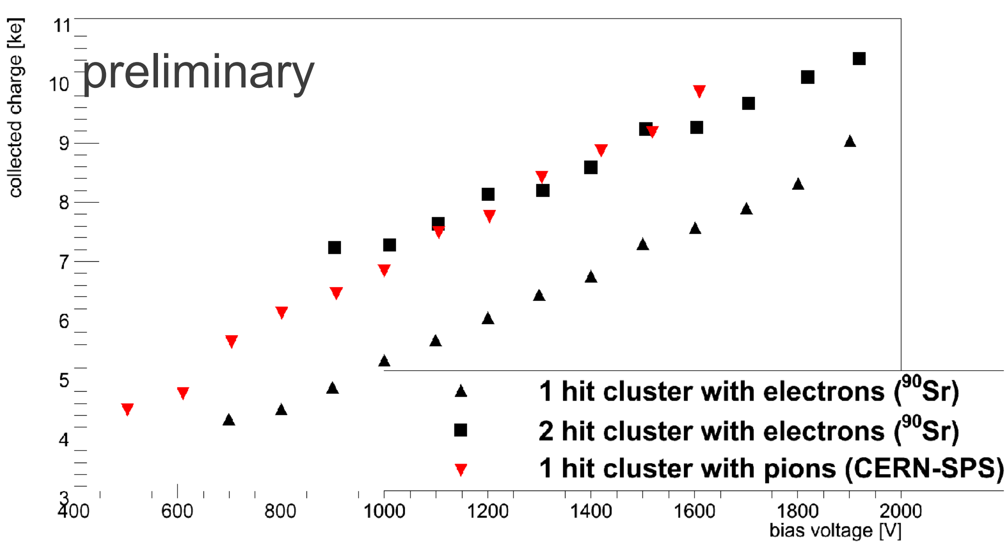
$1 \cdot 10^{16}\ n_{eq}\ cm^{-2}$

- collected charge increases linearly with the applied bias voltage
- at 1900V an MPV of about 10ke
- Threshold 4000e

ToT calibration:

60 ToT = 20ke



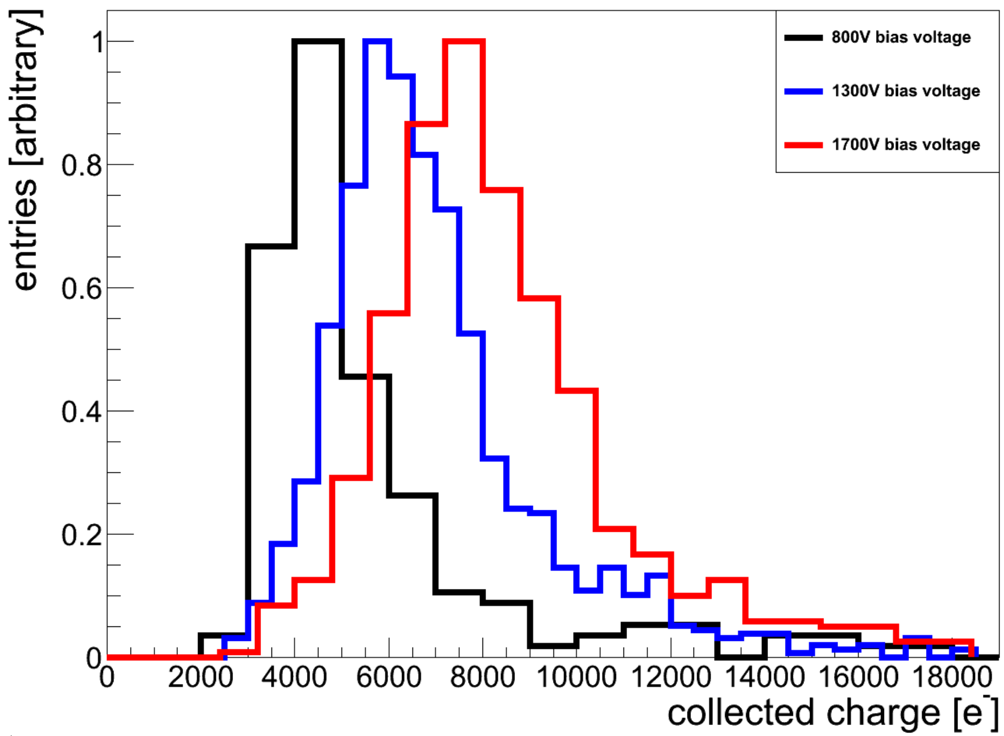


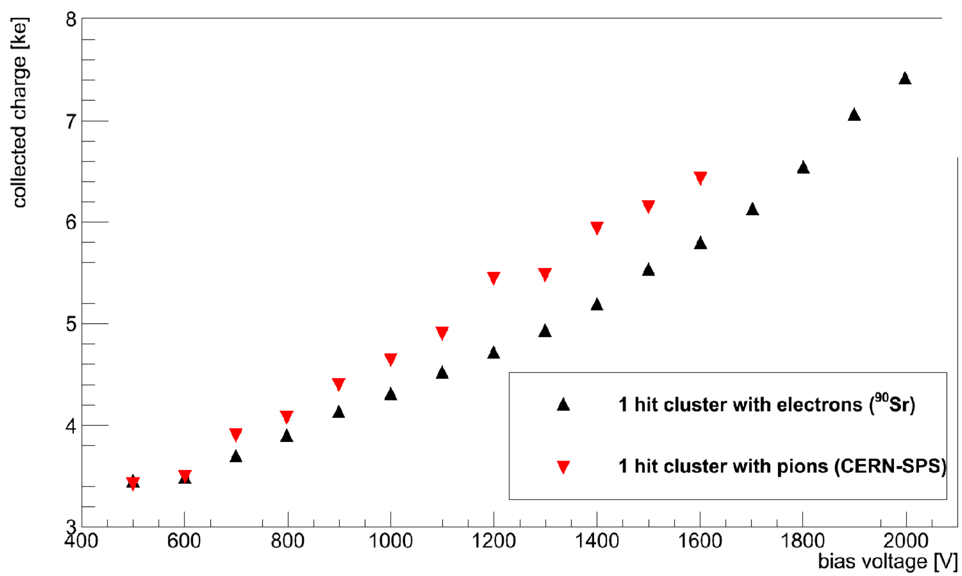
ToT to charge conversion with mean values for calib constants

$1.4 \cdot 10^{16}\ n_{eq}\ cm^{-2}$

- Threshold 4000e
- T0T calibration

  60 ToT = 20ke

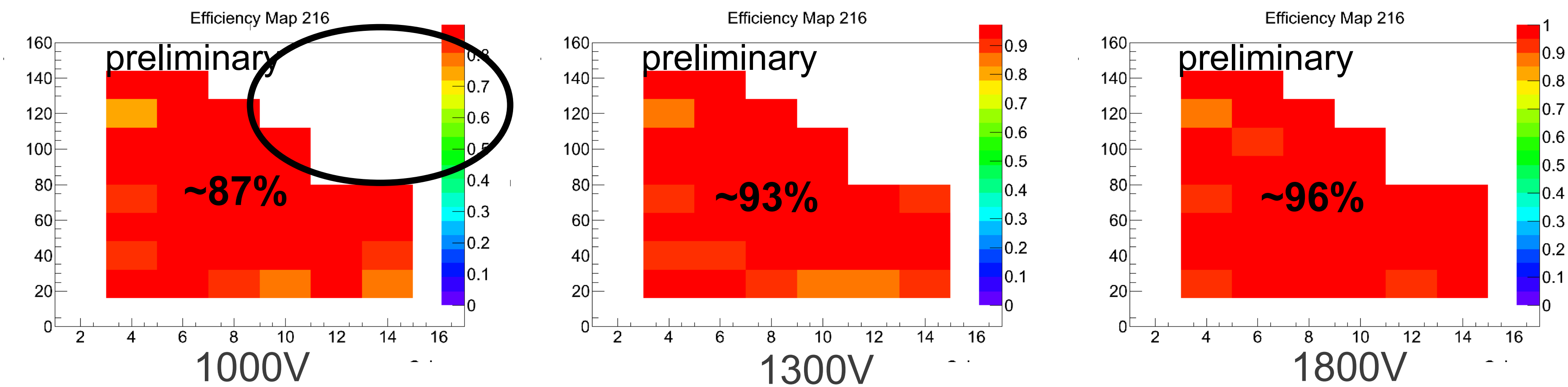




ToT to charge conversion with mean values for calib constants

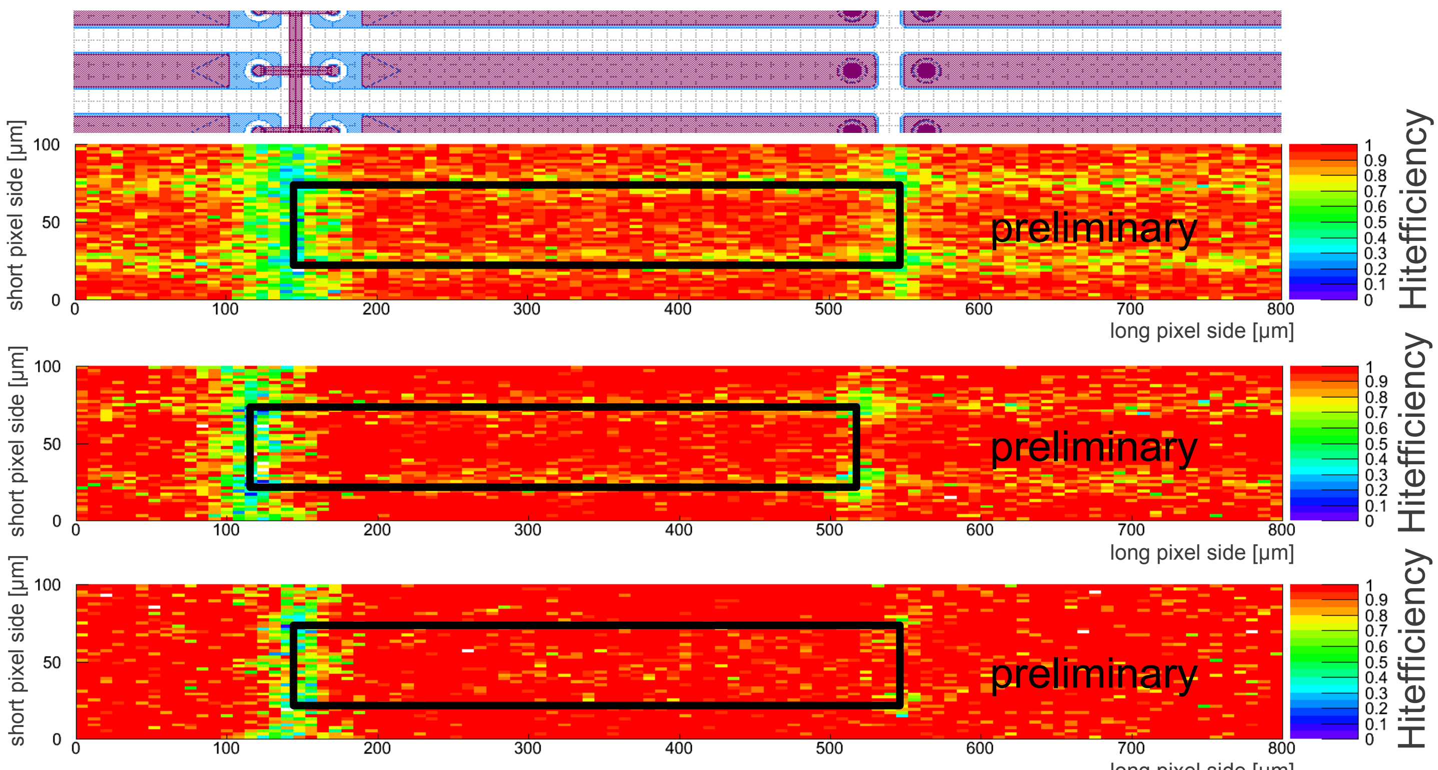
Tracking efficiency maps $1.4 \cdot 10^{16}\ n_{eq}\ cm^{-2}$

- Some disconnected bumps due to aging



Charge loss and possible improvements

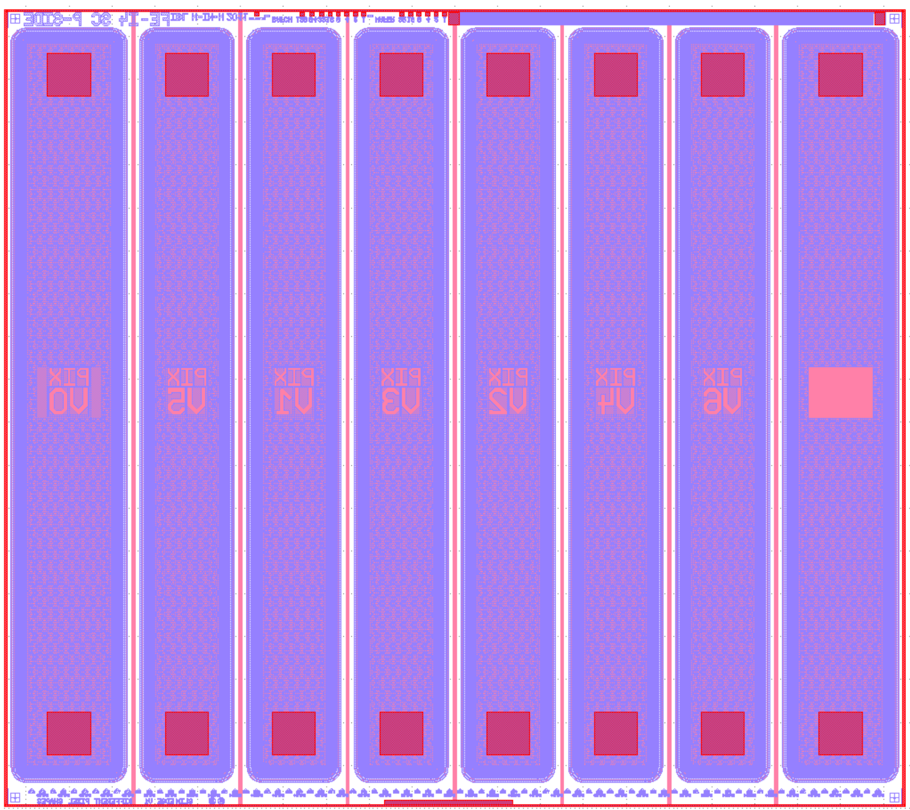
- Most of the pixel has much higher efficiency than 97% – charge loss seems to occur mainly under the bias grid
- Ideas:
  - No bias grid? → No testing before flip chipping
  - Bias grid running over pixels instead of between them → currently being produced, first results soon

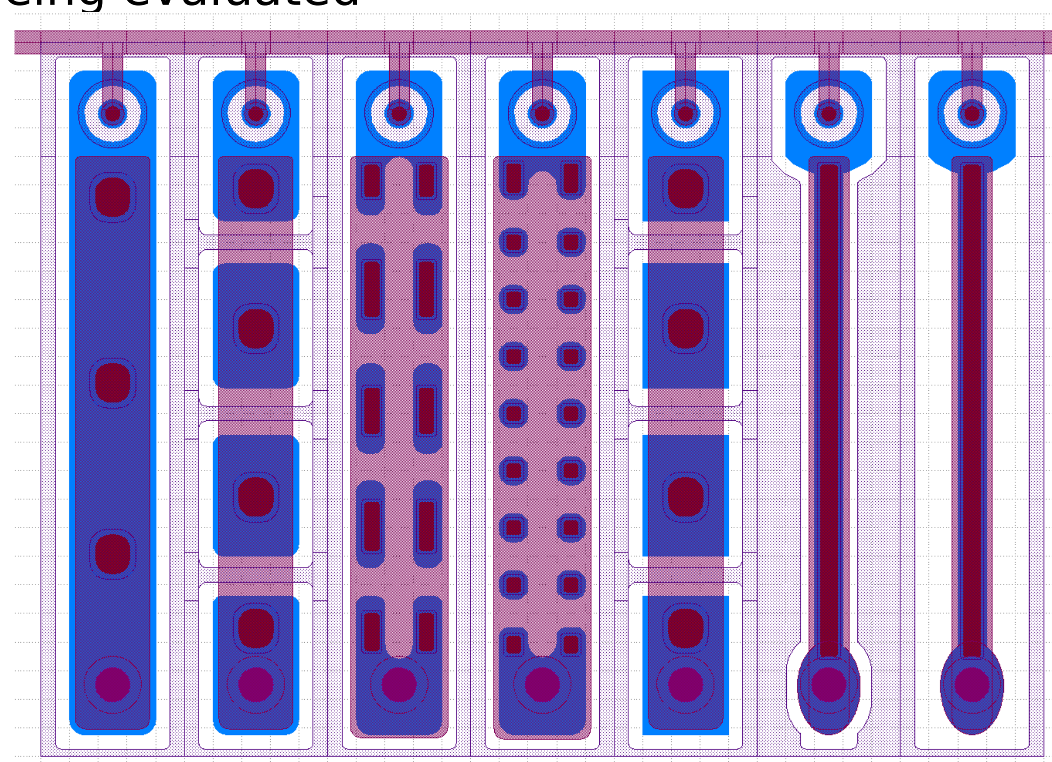


$1.4 \cdot 10^{16}$ n_{eq} cm^{-2} proton irradiated: Tracking efficiency projected into one single pixel cell

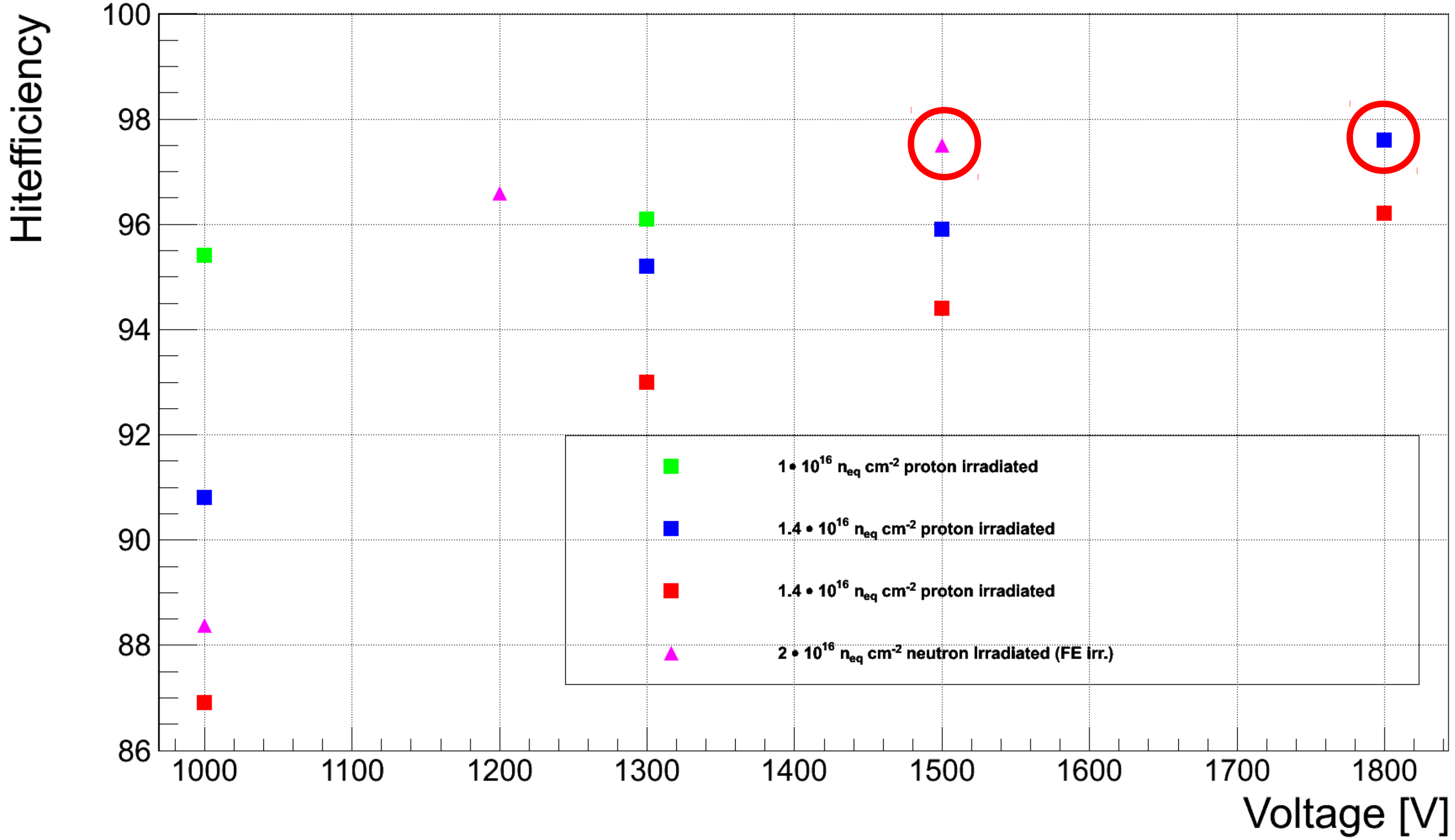
Charge loss and possible improvements

- In addition: improve collected charge
  - reduce thickness to increase field: 150 µm thick planar sensors available from several vendors, 75 µm has also been produced
  - try to improve the charge multiplication effect by employing special field forming implant geometries
  - special structures dedicated to this task were already produced
- New materials like n-type MCz are being evaluated





Tracking efficiencies at HL-LHC fluences



Conclusion

- Strong indication that the planar sensor are sufficiently radiation hard for the inner most layer under HL-LHC conditions
- Sensors irradiated to a fluence about $1.4 \cdot 10^{16}$ n_{eq} cm^{-2} yield 4-5ke at 1000V and about 7-8ke at 2000V
- Good tracking efficiencies measured with beam-test data: 97% at 1800V
- Results are comparable between samples with and without irradiated front-end
- Bias Voltages and environmental temperature not far away from IBL conditions: max. bias voltage of 1000V, T=-25°C-30°C on the modules
- Successful and stable operation up to 2 kV at -45°C

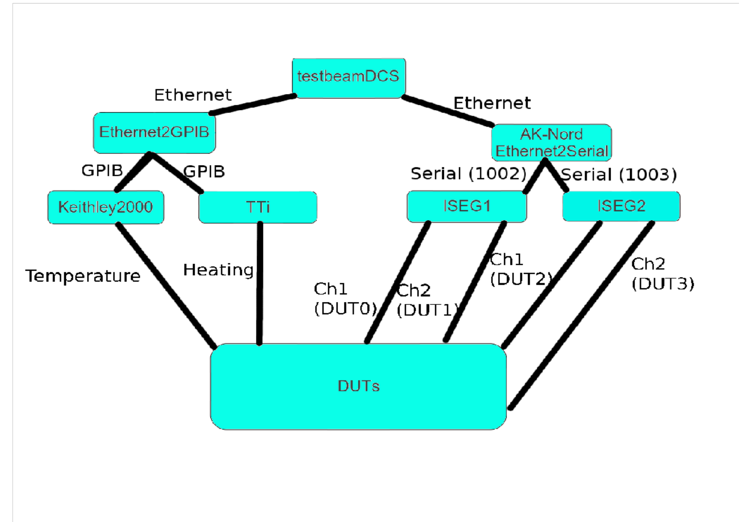
Outlook

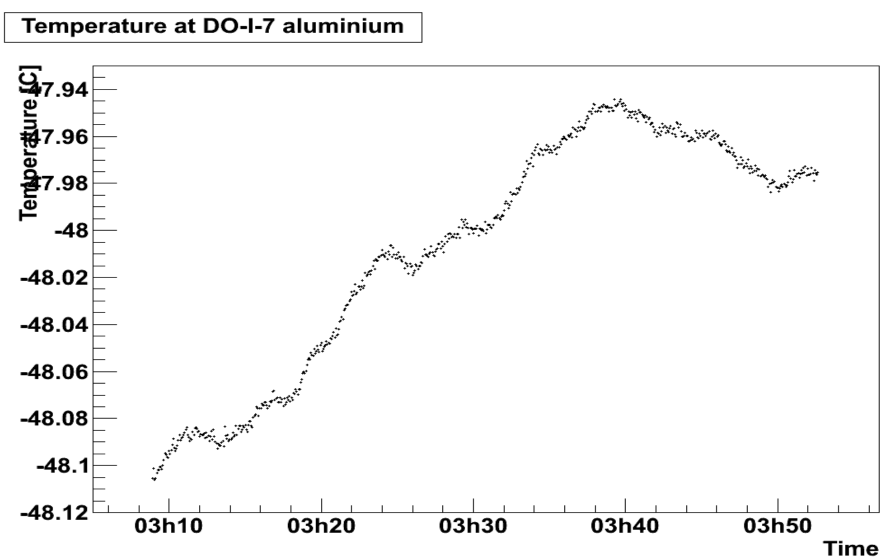
- More detailed analysis of the data taken / Annealing
- More studies will be carried out with new Indium samples irradiated with reactor neutrons
- Would also be possible in the future with FE-I4 as soon as Indium-bumps with Selex are qualified
- Even at moderate (IBL like) bias voltages the highest irradiated assembly shows charge collection fully compatible with the FE-I4 threshold (1500e)

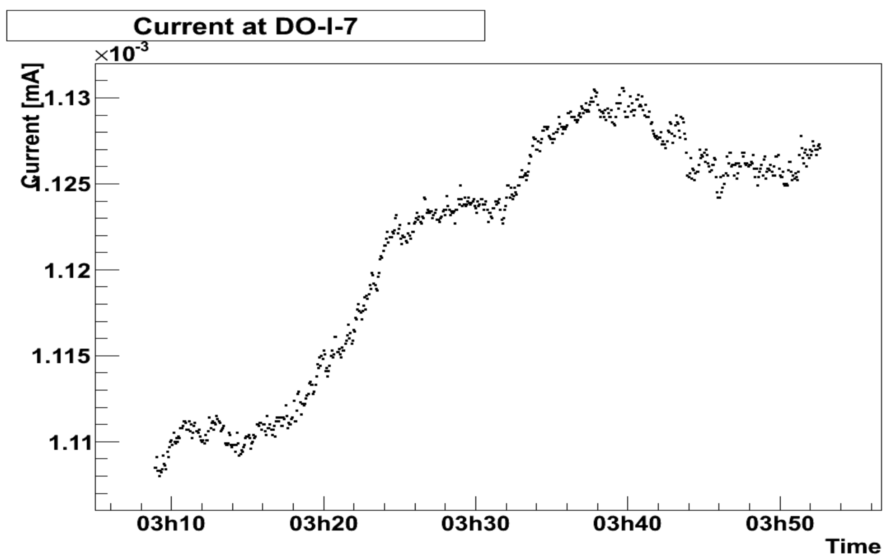
Backup

TestbeamDCS -an environment monitoring program

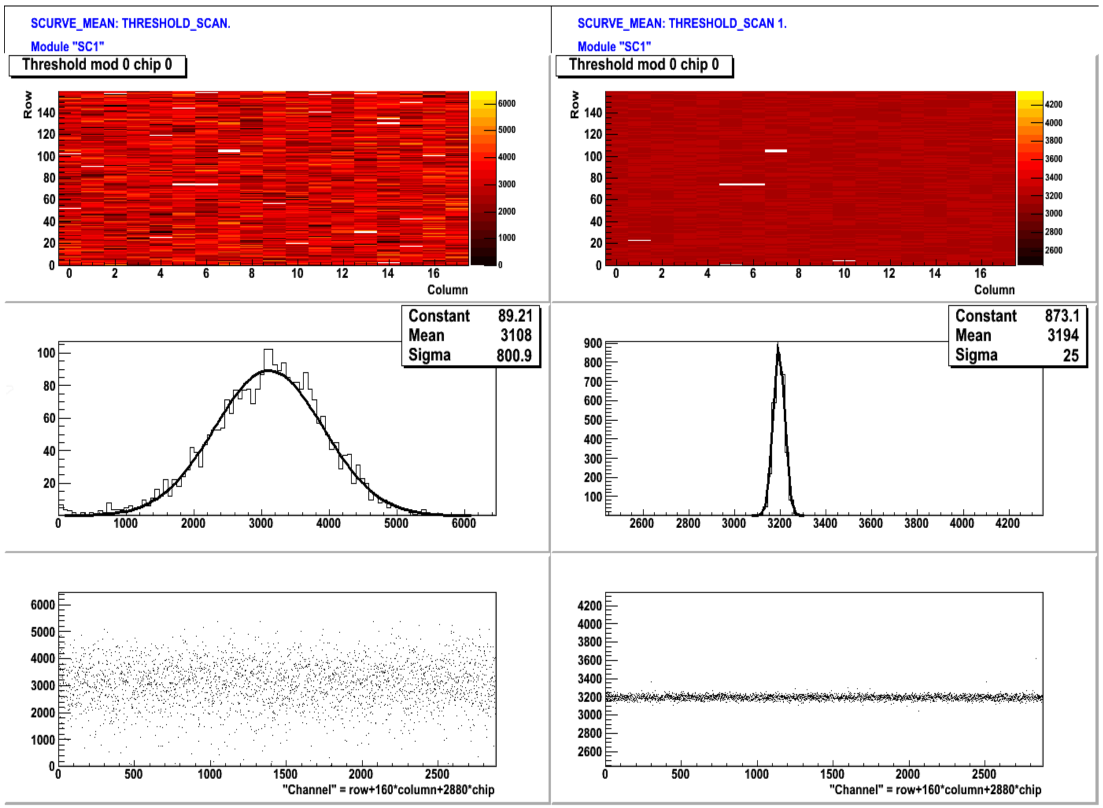
- Monitoring temperature, currents and high voltage
- Control temperature with heating resistor
- Synchronize information with the run control
- Possibility to see for example the strong correlations between temperature and leakage current



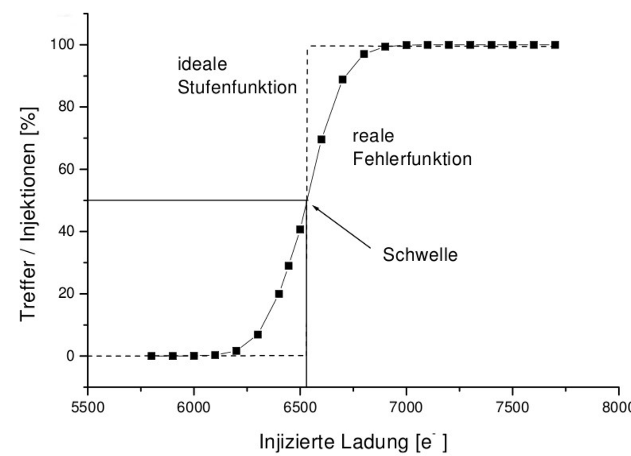




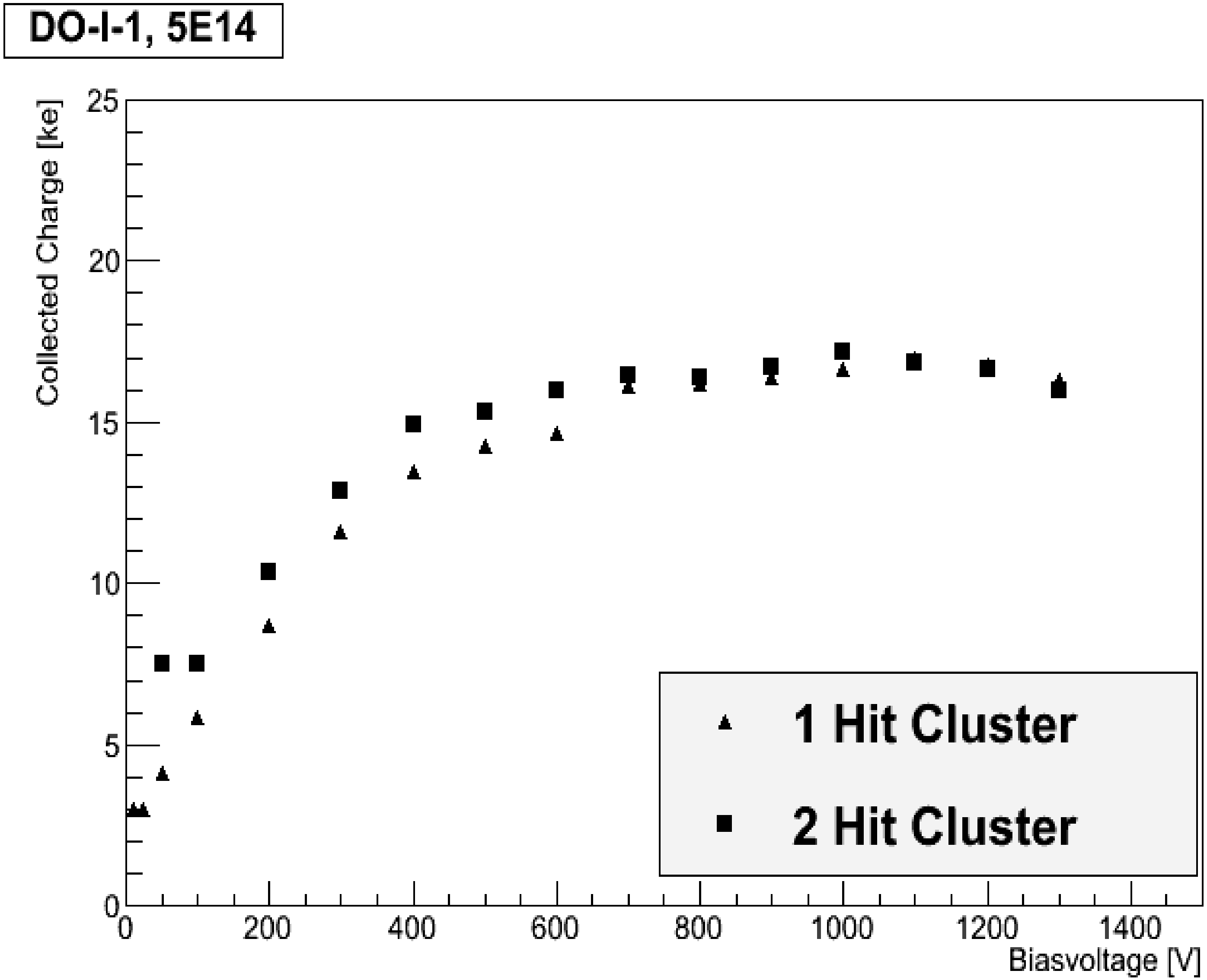
Tunings



- Each pixel has its own threshold
- Before testing the samples with a source they have to be tuned to a specific threshold
- After tuning the pixel have a similar threshold

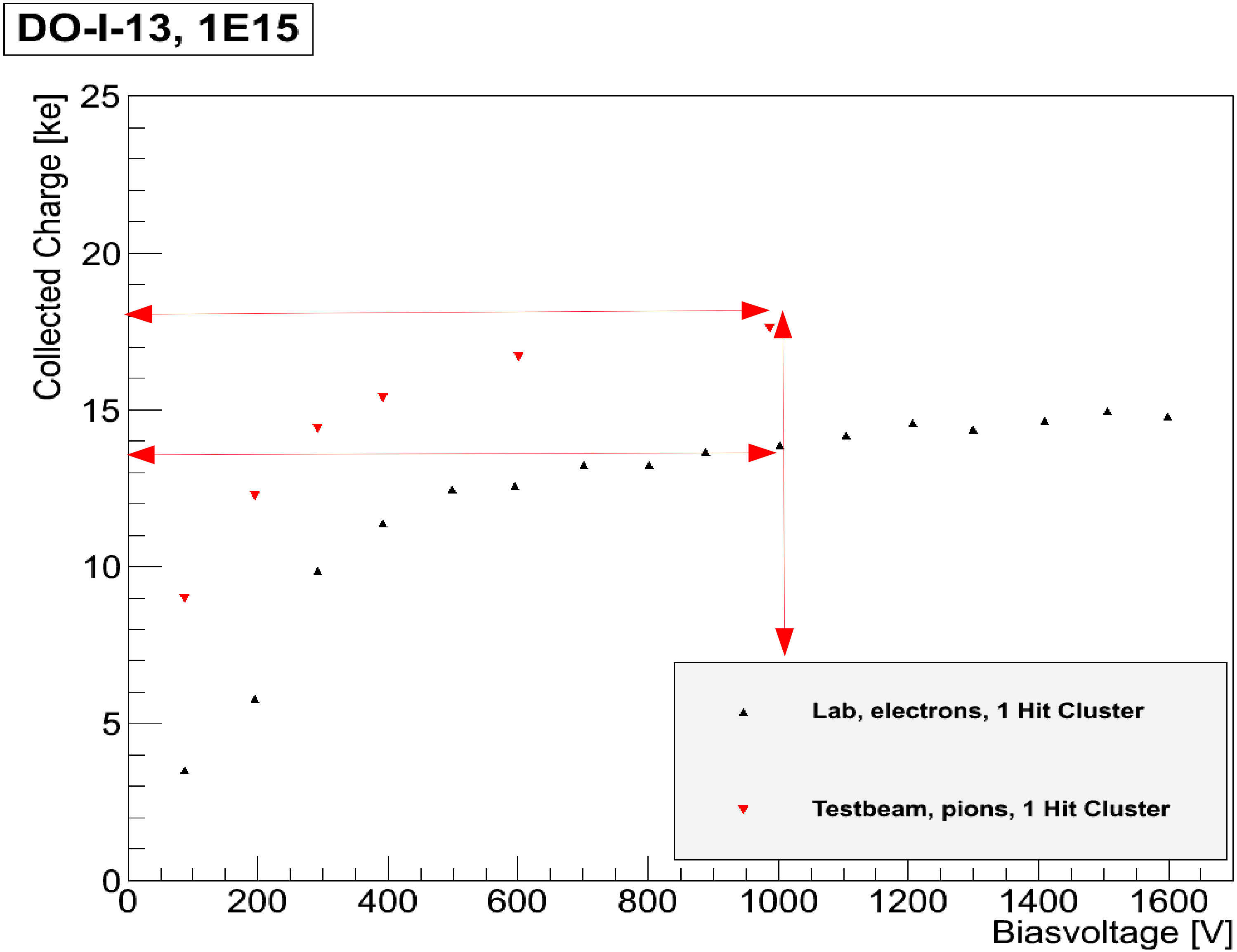


$5 \cdot 10^{14}\ n_{eq}/cm^2$, measured with Sr90



- Collected charge increases with the bias voltage
- Maximum MPV is about 17ke
- Threshold 3200e
- TOT calibration 60TOT=20ke

$1 \cdot 10^{15}\ n_{eq}/cm^2$



- at 1000V one can observe a collected charge of about 14ke with electrons and 17.5ke with pions
- Threshold 3200e
- TOT calibration 60TOT=20ke

Results of lab measurements

- Collected charge decreases with the fluence but is still above the threshold (3200e /4000e)
- Collected charge increases with the bias voltage
- Above 500V the noise contribution grows with bias voltage at low charge values

Fluence=$2.2 \cdot 10^{15} n_{eq} cm^{-2}$