# Lab measurements and testbeam results of irradiated n$^+$-in-n planar pixel sensors for IBL and beyond

18th RD50 Workshop

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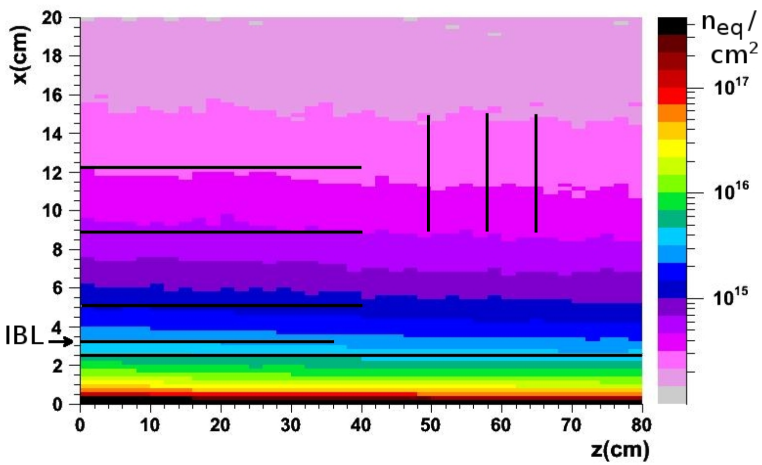
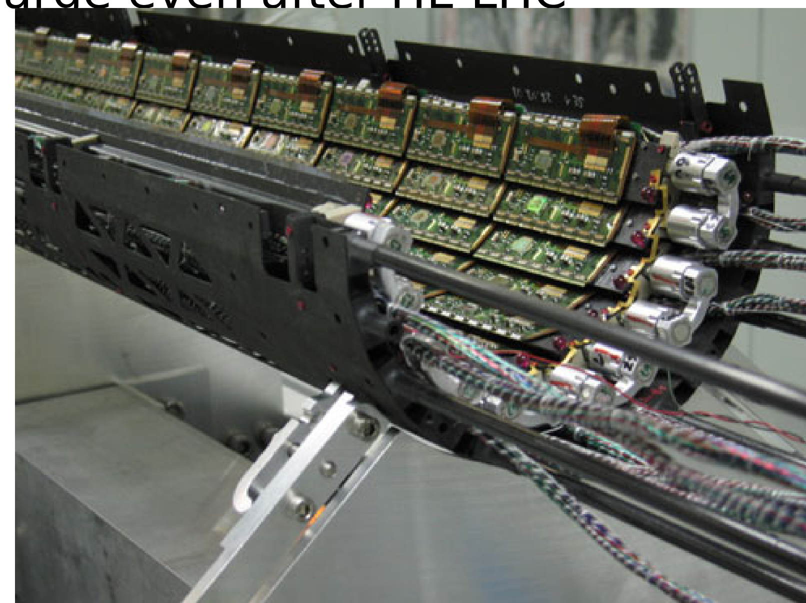
# Why planar Pixel R&D – Upgrade Plans for LHC

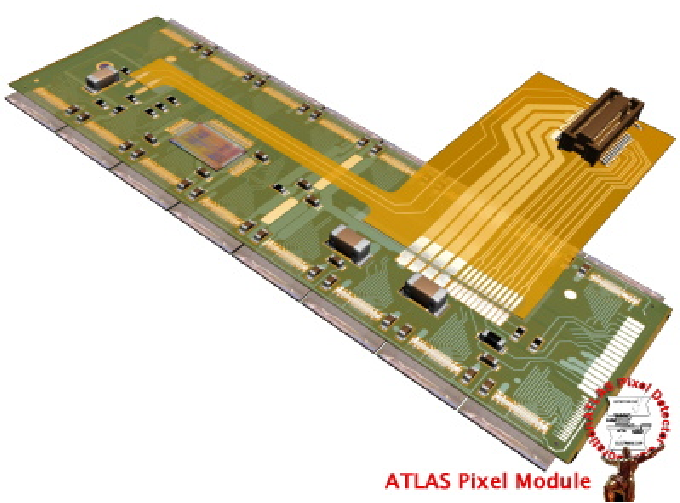
- Two phased upgrade plan on the path to sLHC:
  - Phase 1: $5 \cdot 10^{15}\ n_{eq}/cm^2$ → IBL
  - Phase 2: $2 \cdot 10^{16}\ n_{eq}/cm^2$ → sLHC
- Current ($n^+$-in-n) pixel detector has been shown to be rad hard up to $1 \cdot 10^{15}\ n_{eq}/cm^2$
- Planar $n^+$-in-n technology is proven and reliable
- Results gained with strip sensors show promising results with regard to collected charge (charge amplification!)
- First results with real pixel taken this year confirm the capability and rad-hardness of planar sensors



# Planar Sensors: Basic Information

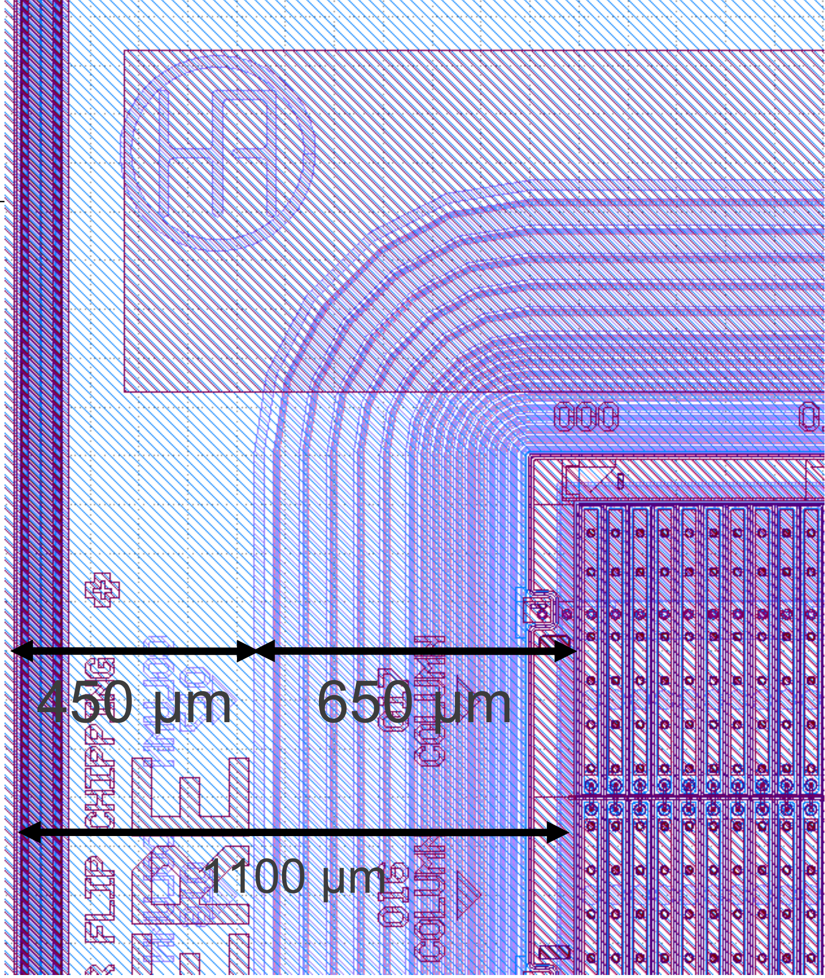
- The current ATLAS Pixel detector is based on planar sensors
- Planar sensors were already shown to yield charge even after HL-LHC fluences of $2 \cdot 10^{16}$ $n_{eq}/cm^2$
- IBL specifications to qualify:
  - Power dissipation < 200 mW/cm$^2$
  - Leakage current < 100 nA/pixel
  - Operation temperature -15°C on sensor
  - Inactive edges < 450 µm
  - Thickness between 150 and 250 µm
  - Sufficient hit efficiency
    - after a benchmark fluence of $5 \cdot 10^{15}$ $n_{eq}/cm^2$
    - at a maximum bias voltage of 1 kV



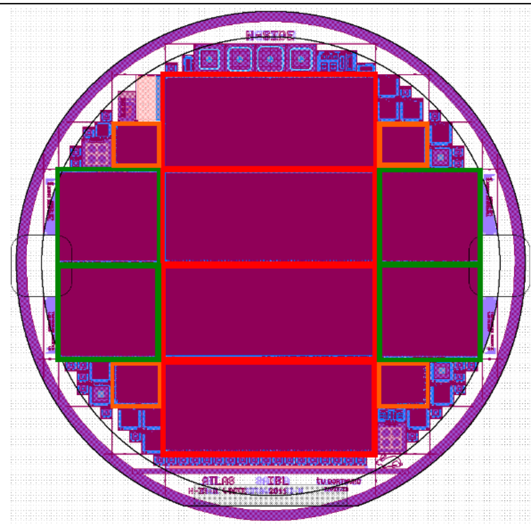


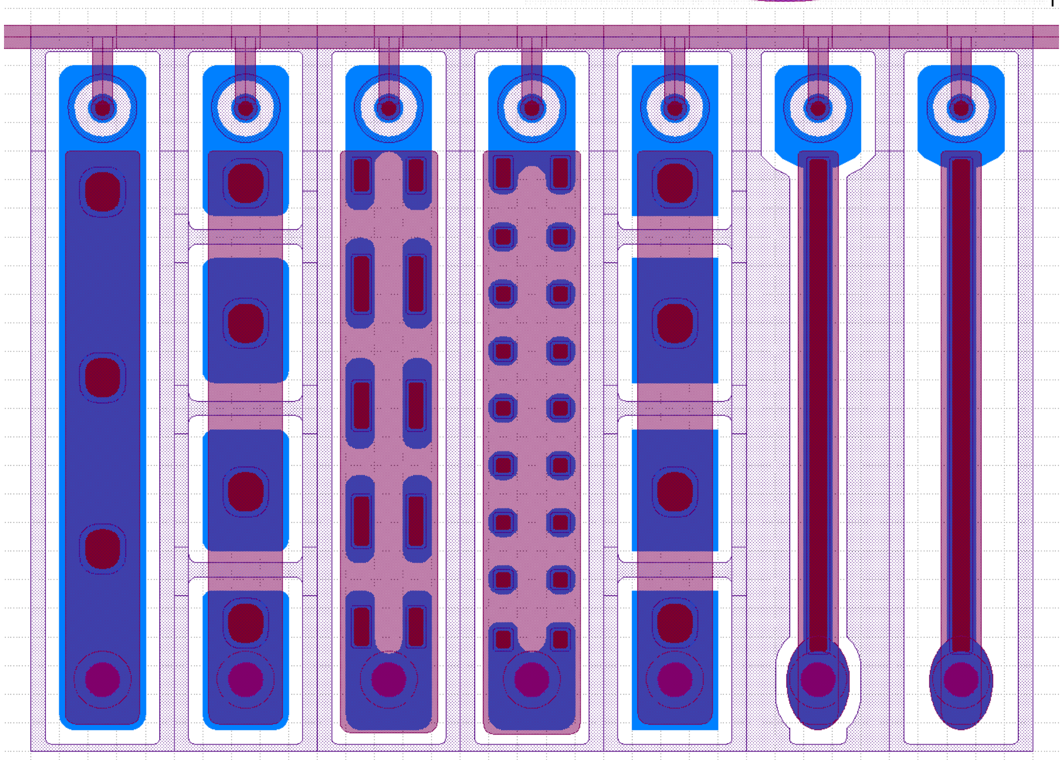
# Initial point and progress

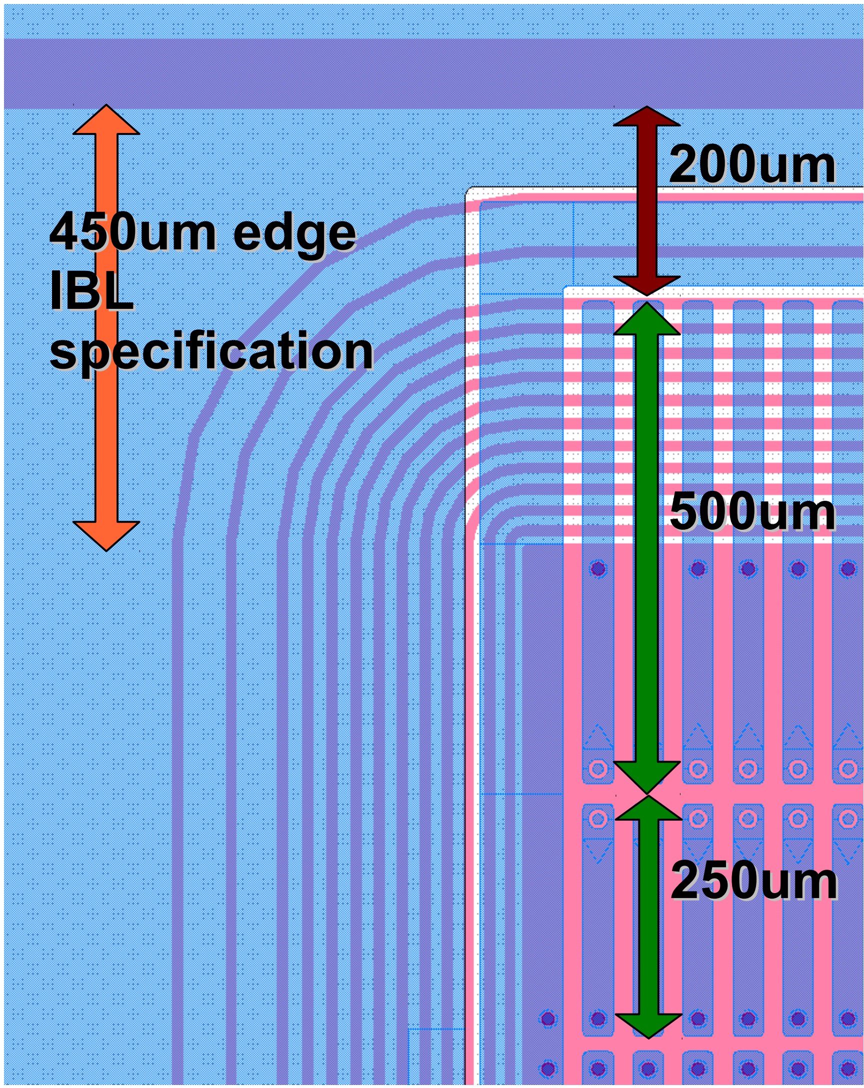
- Standard SingleChip Sensors taken from ATLAS Pixel production wafers
- $n^+$-in-n design produced by CIS
- 16 guard rings with overhanging metal
- 250µm thick DOFZ bulk
- 400µm by 50µm pixel cells
- 2880 pixel cells!
- New production in 2009:
  - MCz and FZ in 285µm
  - Joint RD50 and PPS production
- New Production in 2010:
  - PPS production with structures contributed by several RD50 member institutes
  - varied bulk thicknesses (150µm – 285µm)
- several special layouts (e.g. w/o bias grid) and FE-I4 compatible sensors on all production wafer
- IBL pre-production 2011

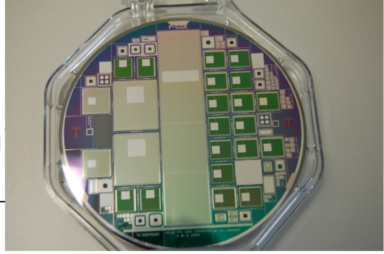


# New layouts



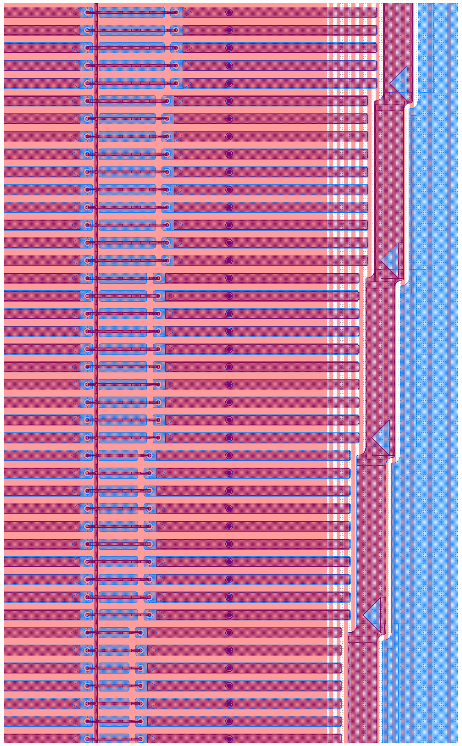


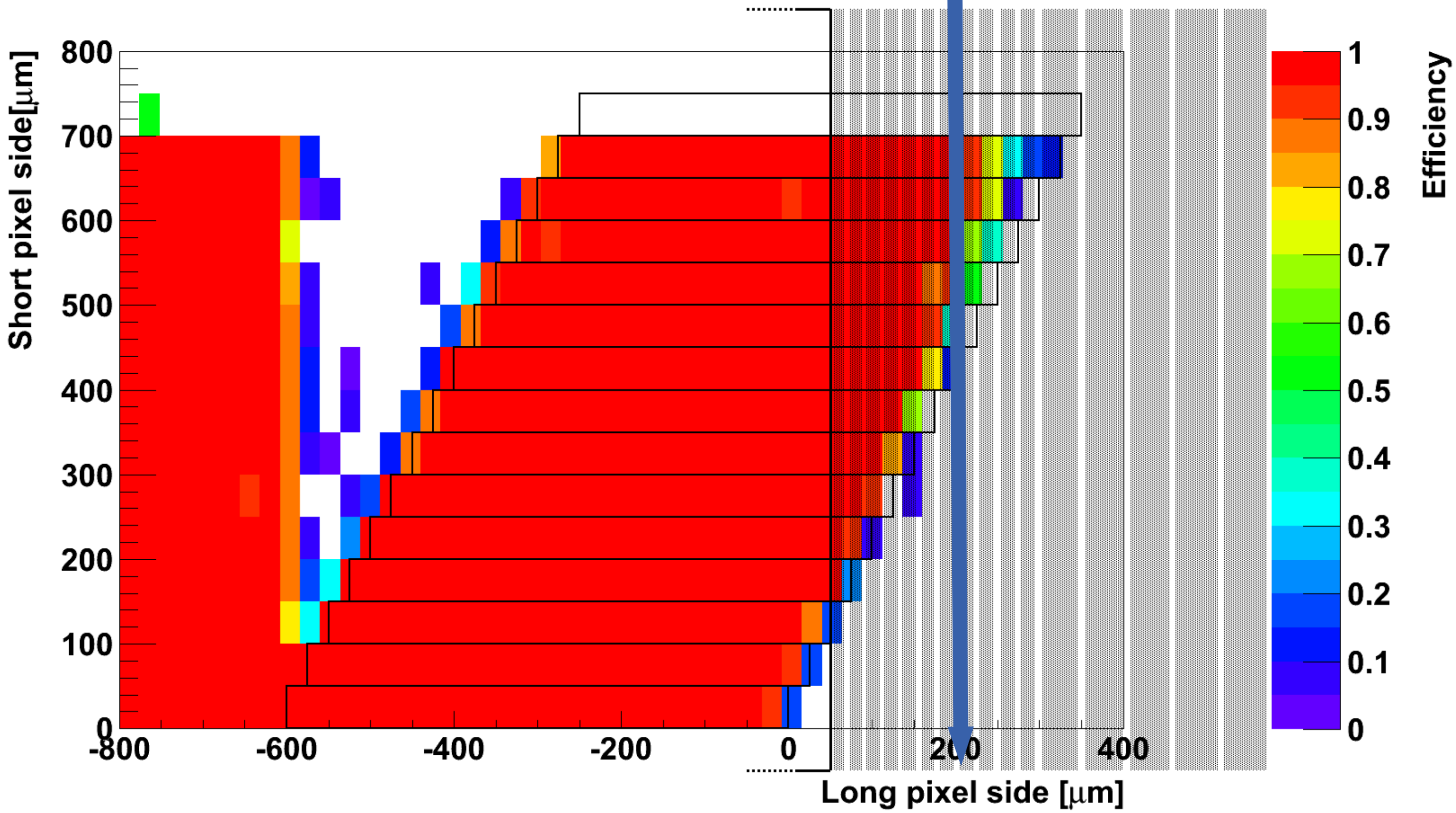




# Slim-edge: testbeam results available up to now

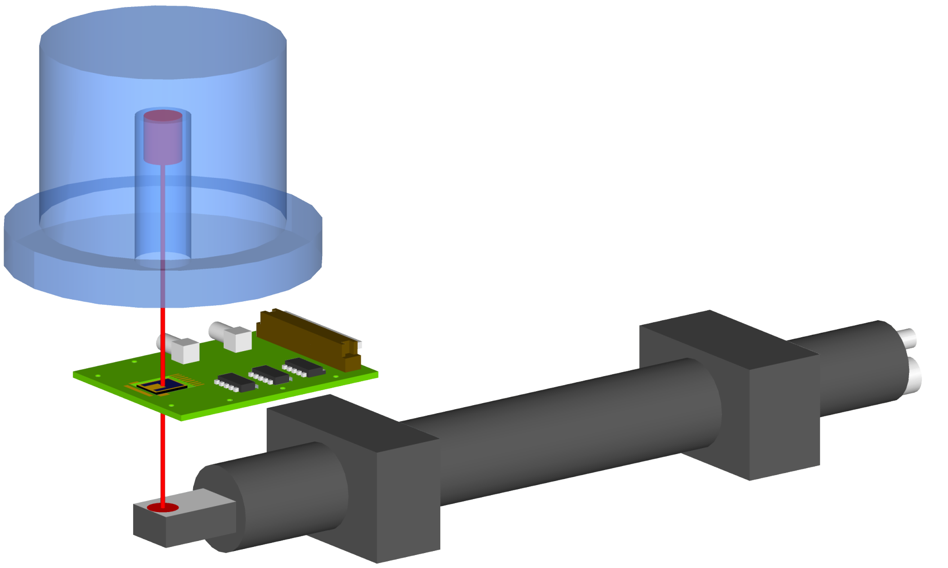
- dedicated test structure ('pixel shifted stepwise') confirms that charge is collected opposite of the guard rings
- estimated region of high (>99%) efficiency before irradiation: up to ~200 µm from the HV implant (i.e. ~250 µm inefficient edge)
- looks promising (strongly supported by simulation results at LAL by M. Benoit)





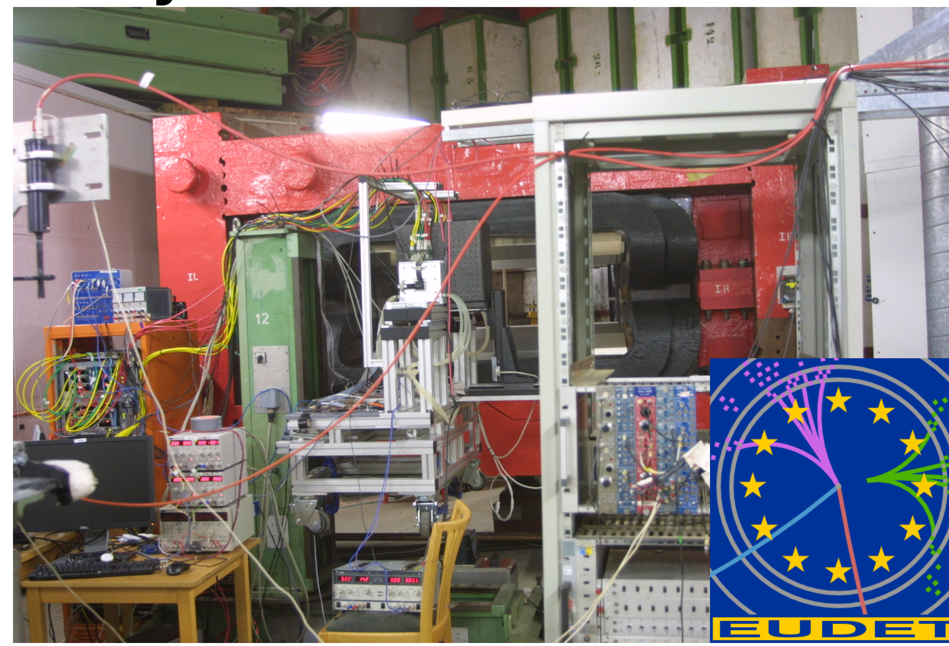
# Experimental Methods: electrons

- $^{90}$Sr beta electrons:
  - Charge Collection Efficiency measured with a Sr-90 source (landau expected)
  - Operation temperature below -55°C with dry ice in a insulated box
  - Standard ATLAS TurboDAQ readout (already used during the production process)
  - Two possible triggers:
    - trigger scintillator beneath the sensor, only through-going electrons
    - (internal) hitbus trigger, all electrons
- Advantages:
  - easily accessible
  - study of many parameters possible
- Disadvantages:
  - much scattering
  - “no real MIPs”



# The IBL Testbeam in February 2011

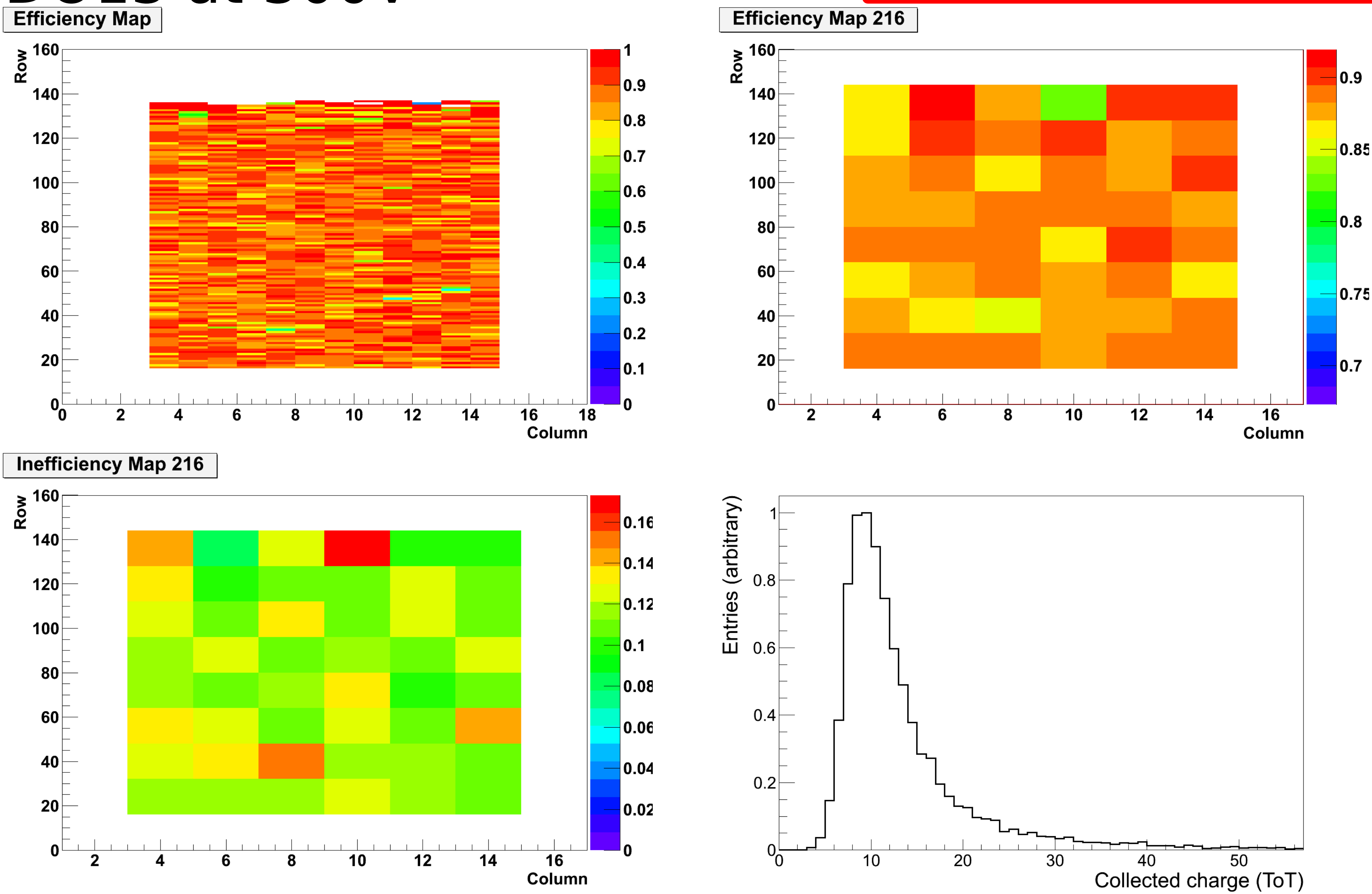
- Testbeam data taken in February 2011 at DESY
- Allows to take space resolved data
- Samples were mounted in the DOBOX which uses a lab proven dry ice system capable of cooling heavily irradiated sensors
- New readout system USBpix used for FE-I3 and FE-I4
- Despite still existing trouble with irradiated FE-I3 much more amicable
- 4 GeV electrons




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

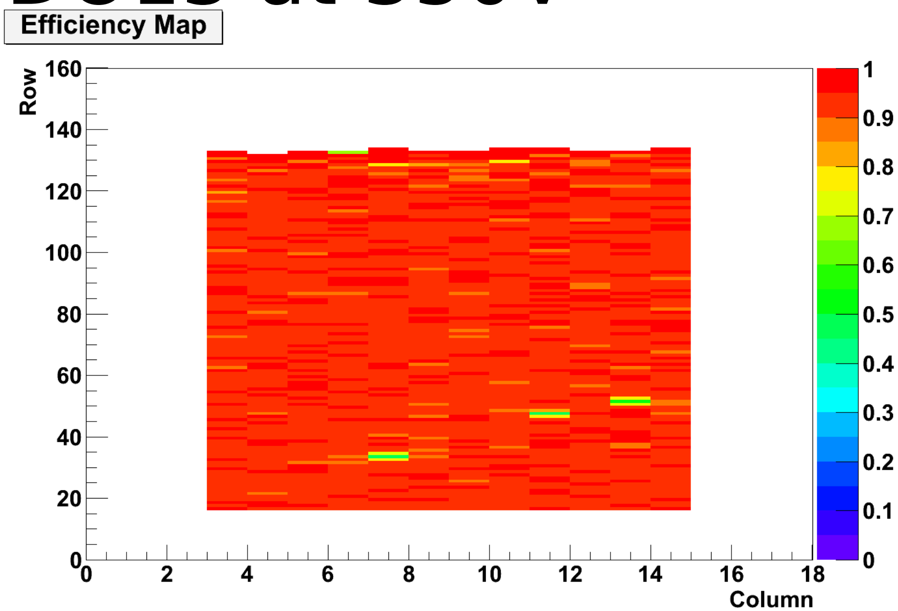
# DO13 at 300V

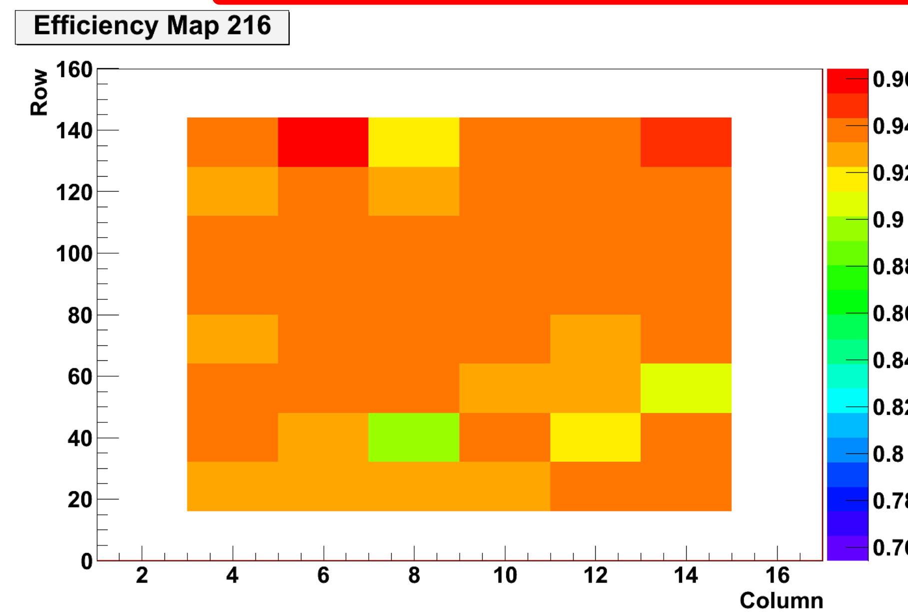
**Efficiency: 88.1%±0.1%**

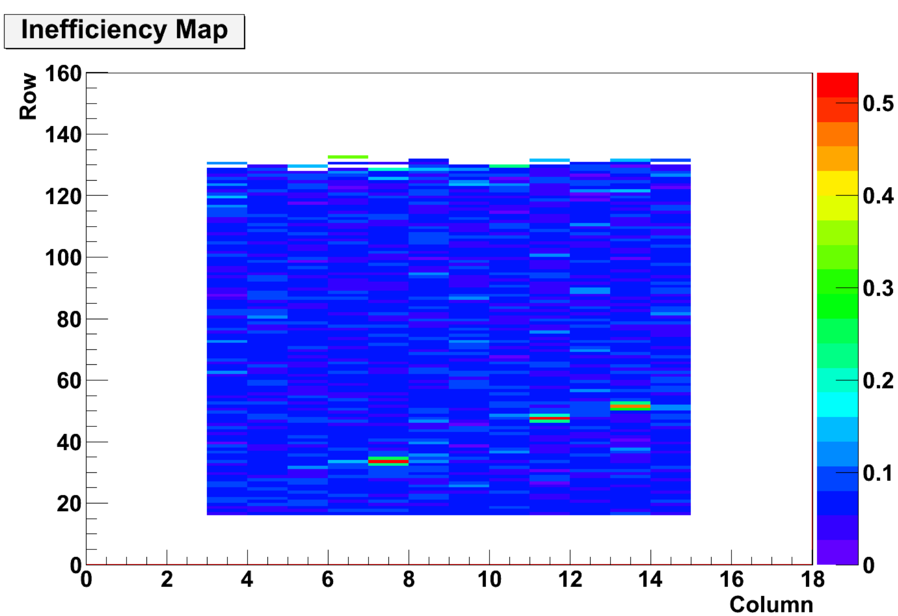


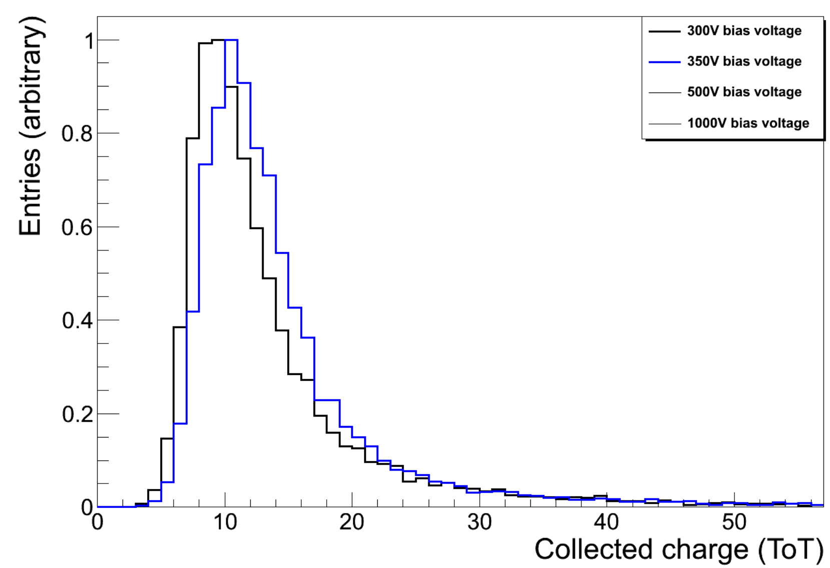
# DO13 at 350V

**Efficiency: 93.2%±0.1%**



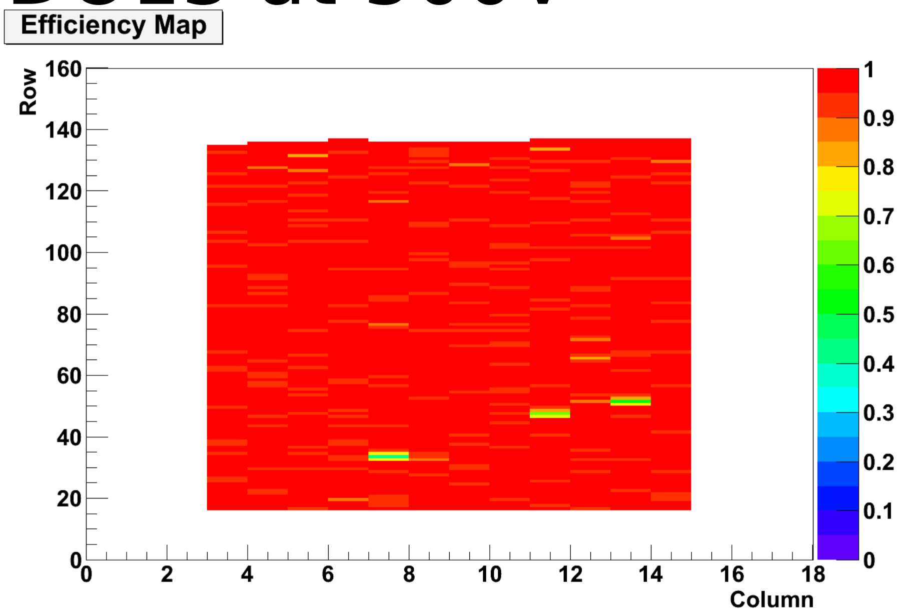



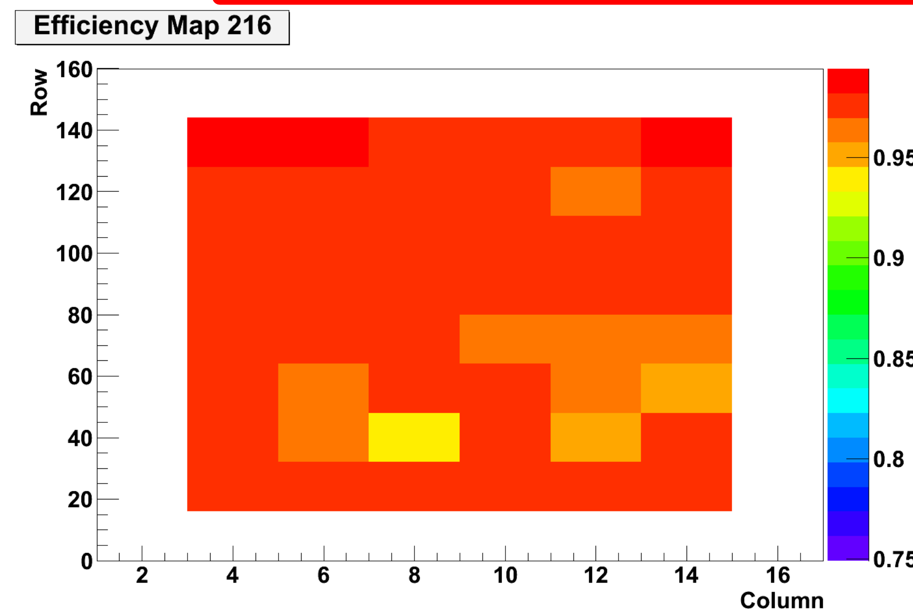



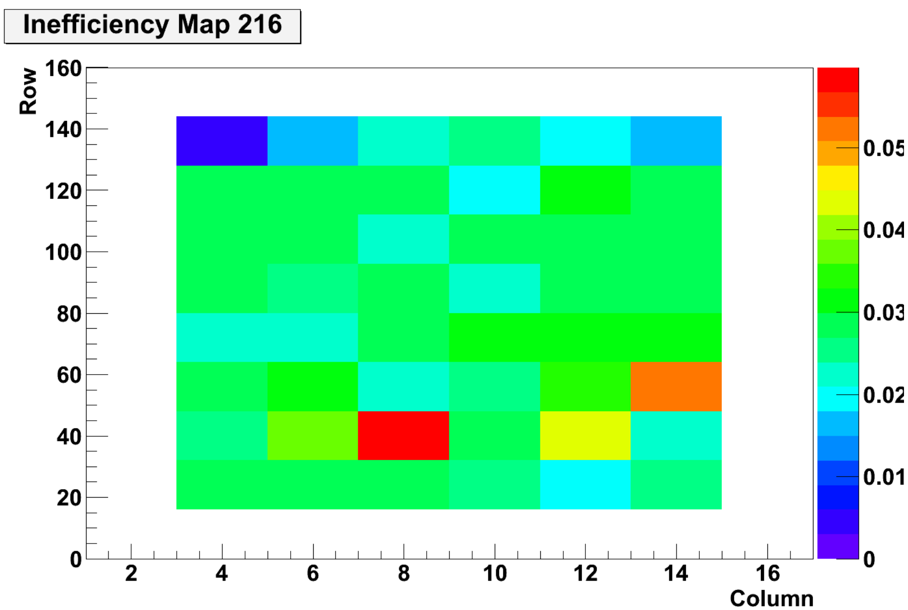



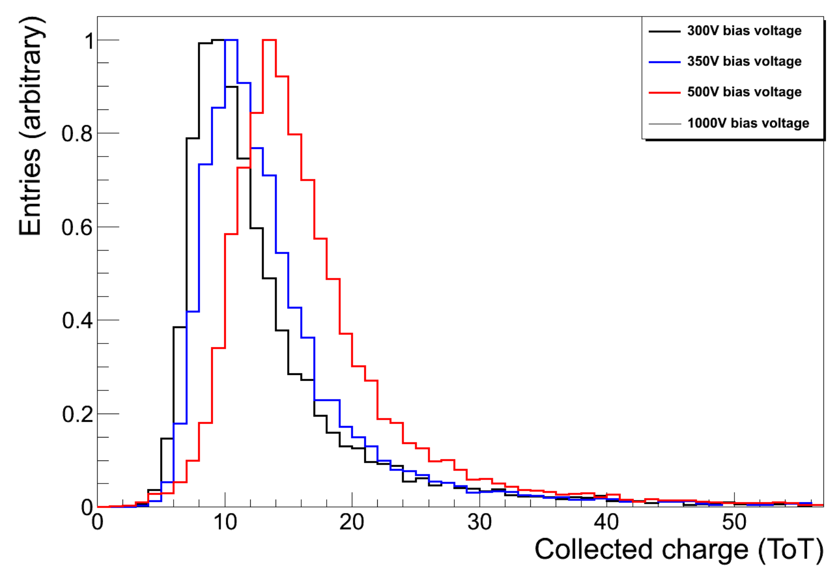
# DO13 at 500V

**Efficiency: 97.3%±0.1%**



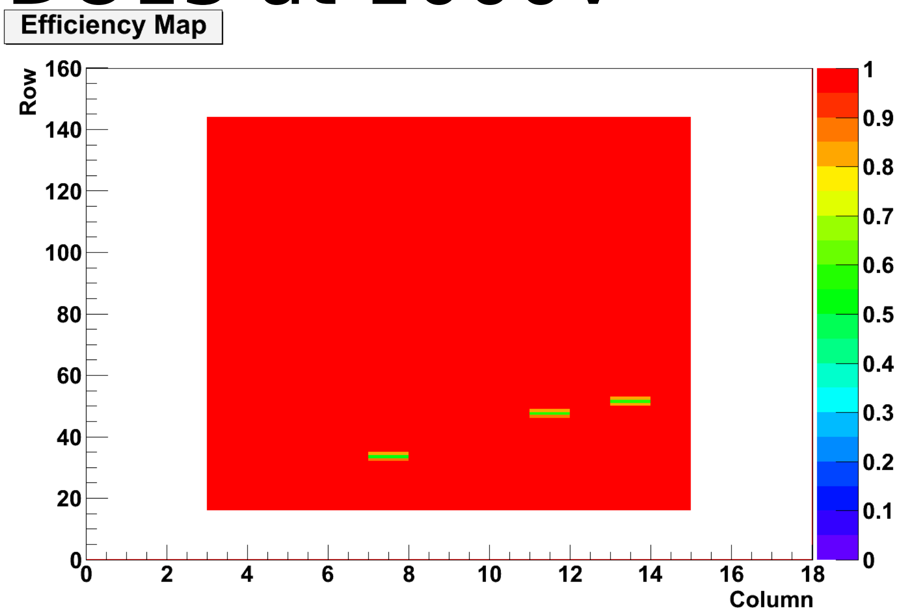



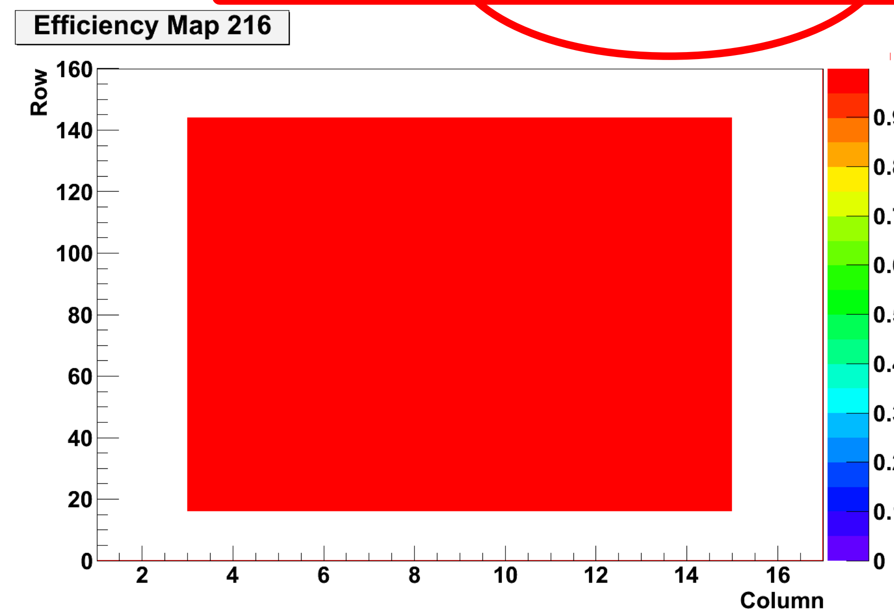



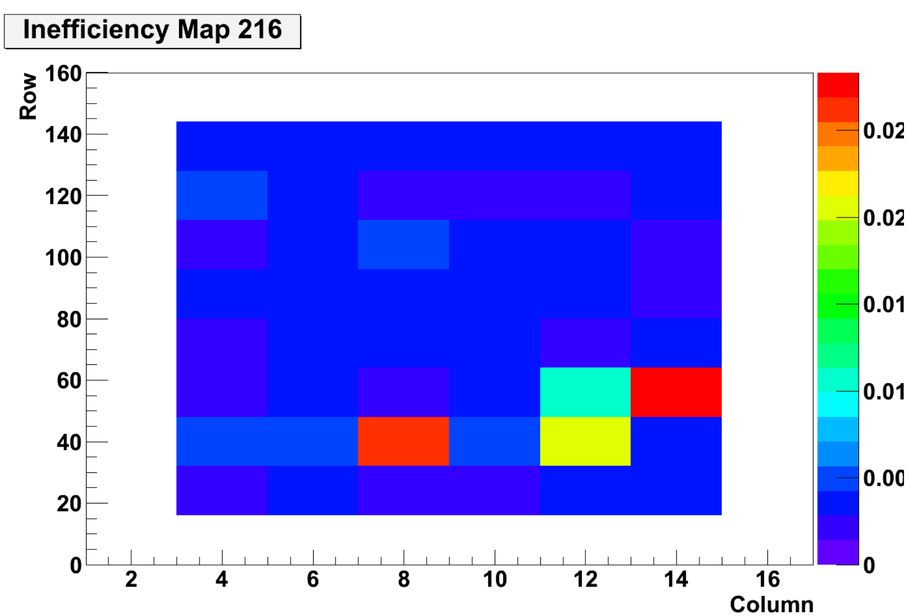



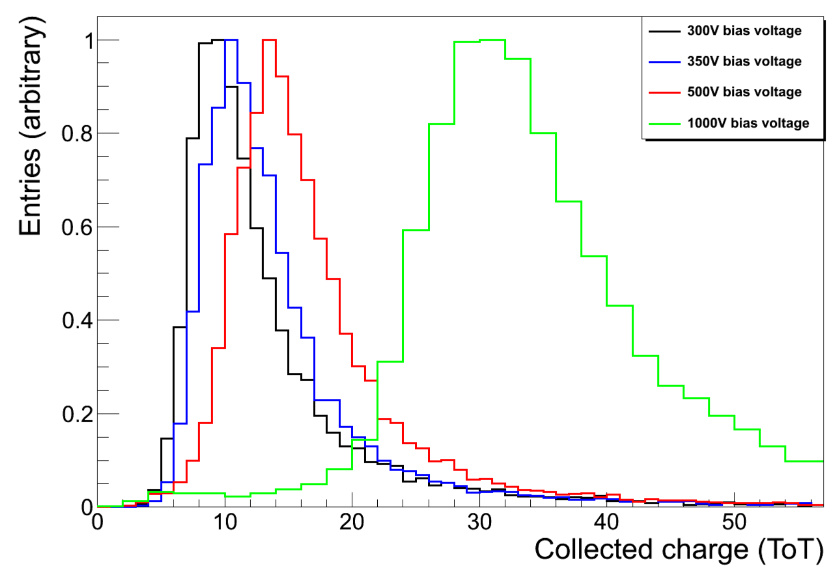
# DO13 at 1000V

**Efficiency: 99.6%±0.1%**

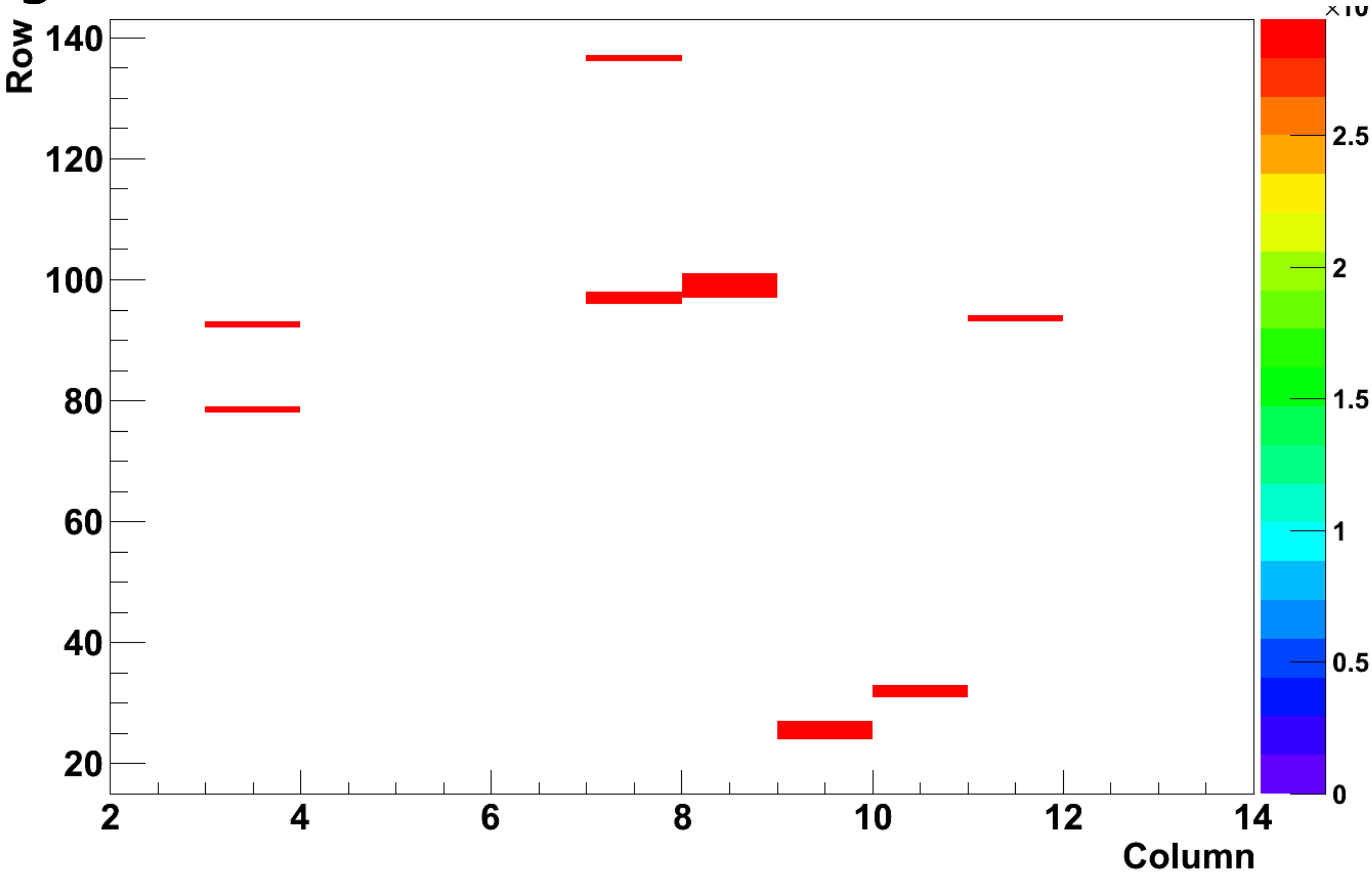


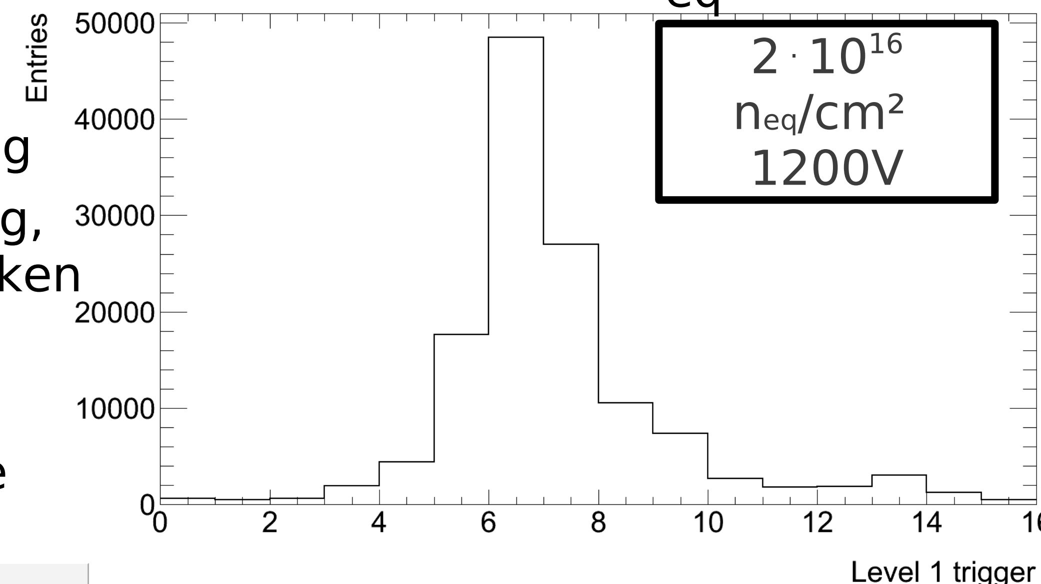



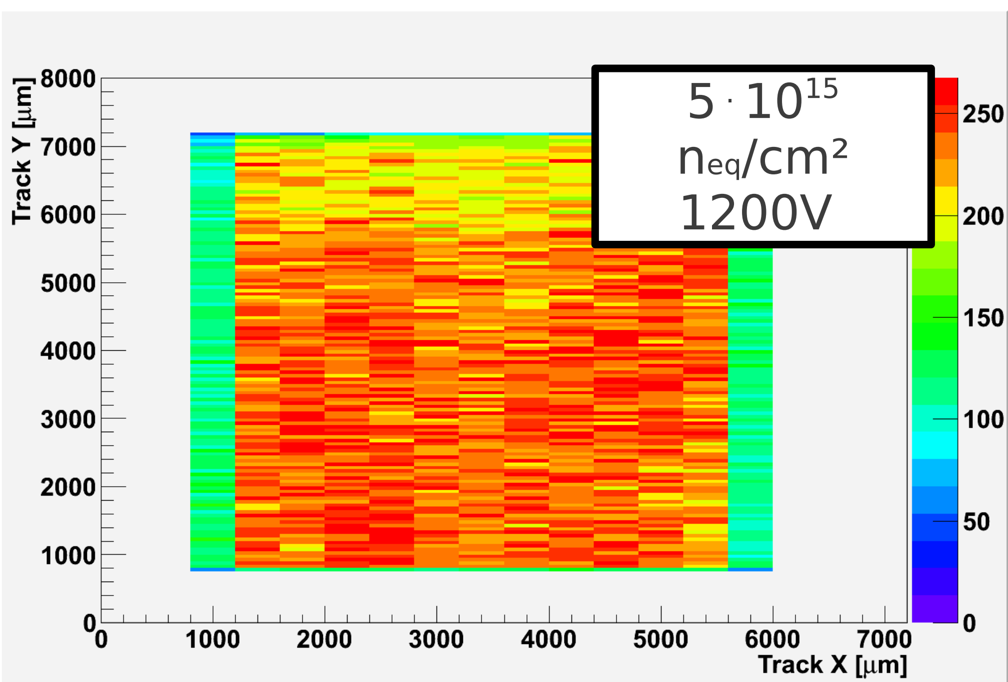
# Peek at noise occupancy at 1000V in central region

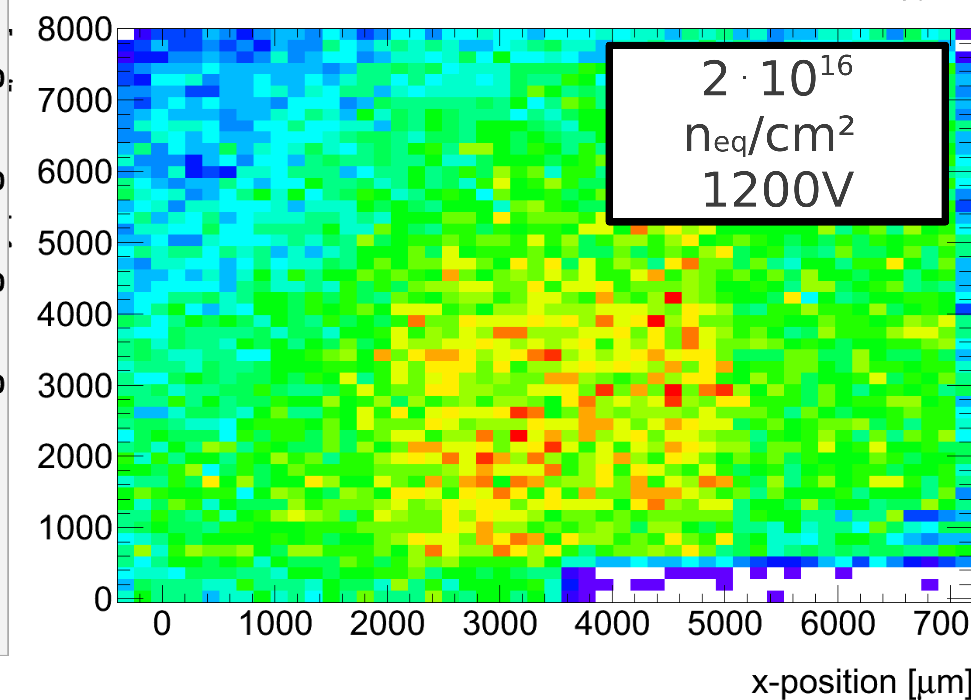


# A challenge: $5 \cdot 10^{15}\ n_{eq}/cm^2$ and $2 \cdot 10^{16}\ n_{eq}/cm^2$

- Operation at below -50°C to exclude self-heating effects
- $2 \cdot 10^{16}\ n_{eq}/cm^2$ sample always working
- $5 \cdot 10^{15}\ n_{eq}/cm^2$ sample mostly working, data with more such samples was taken and is currently being analysed
- Testbeam hitmaps look good
- Trigger-distribution shows little noise

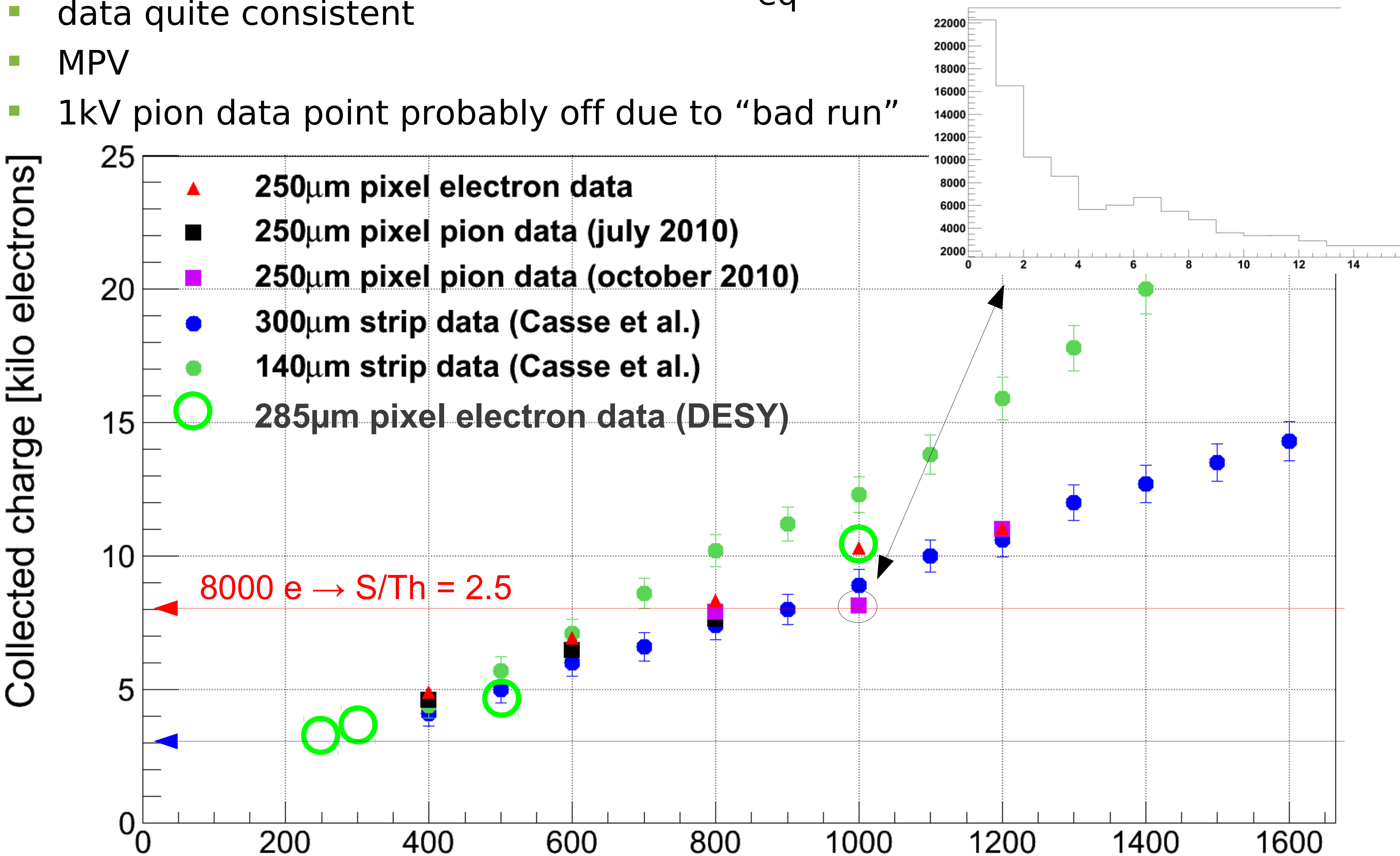


# Charge Collection $5 \cdot 10^{15}\ n_{eq}/cm^2$ summary

- data quite consistent
- MPV
- 1kV pion data point probably off due to “bad run”

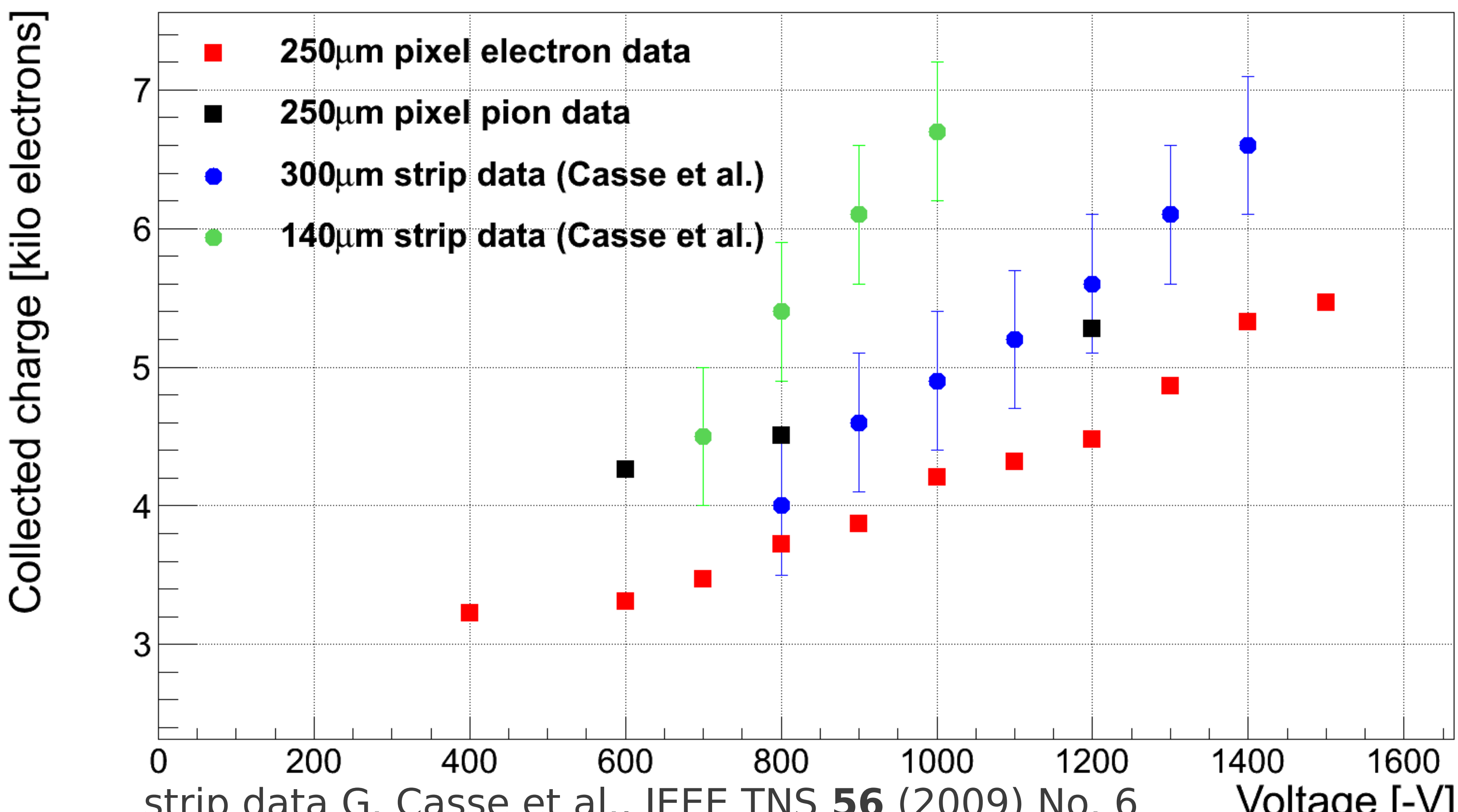



strip data: G. Casse et al., doi:10.1016/j.nima.2010.02.134

# Charge Collection $2 \cdot 10^{16}$ $n_{eq}/cm^2$ summary

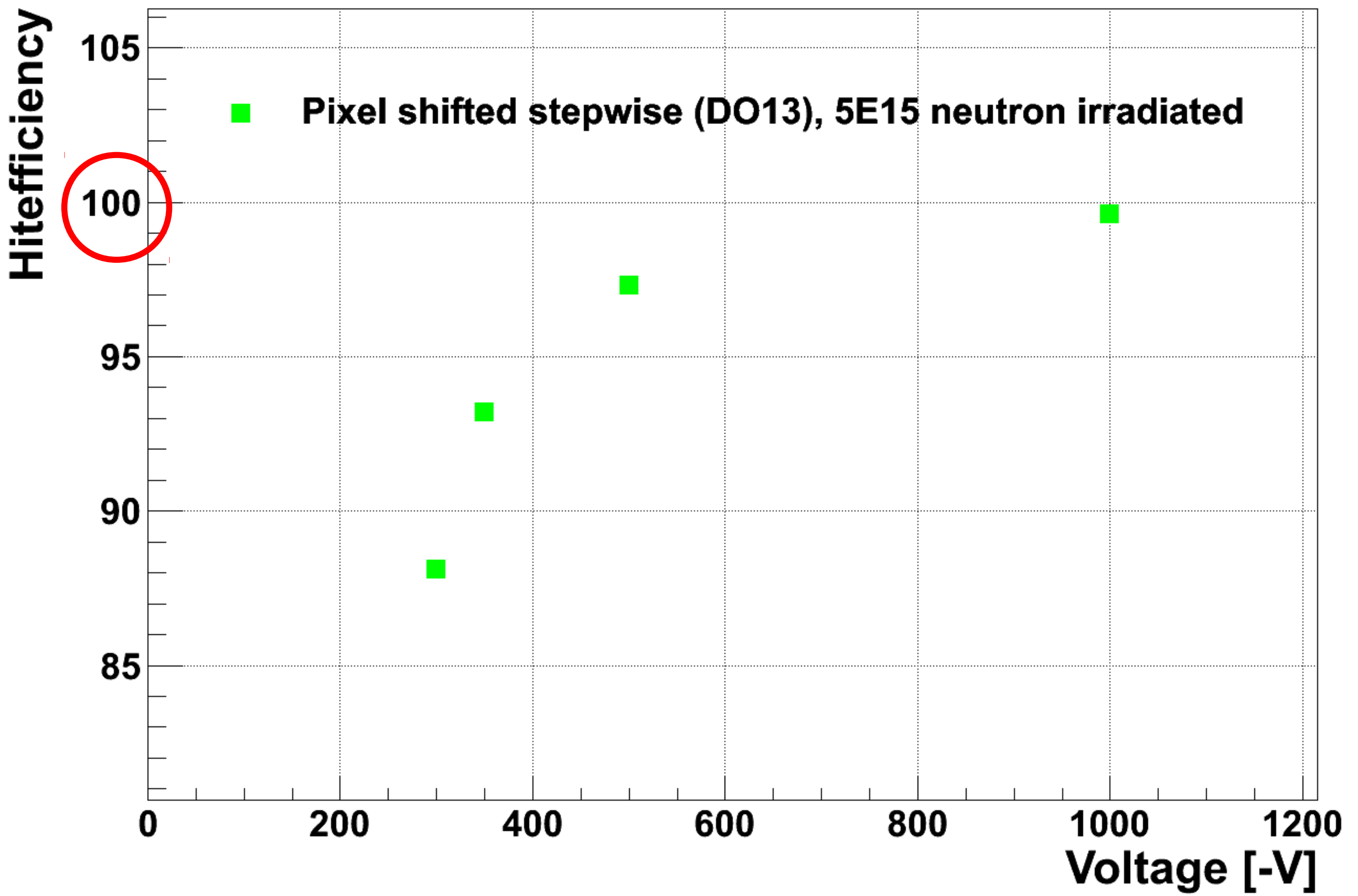
- Pixel electron data lower than pion data and lower than strip data
- Might be a charge-sharing effect

doi:10.1016/j.nima.2010.11.186



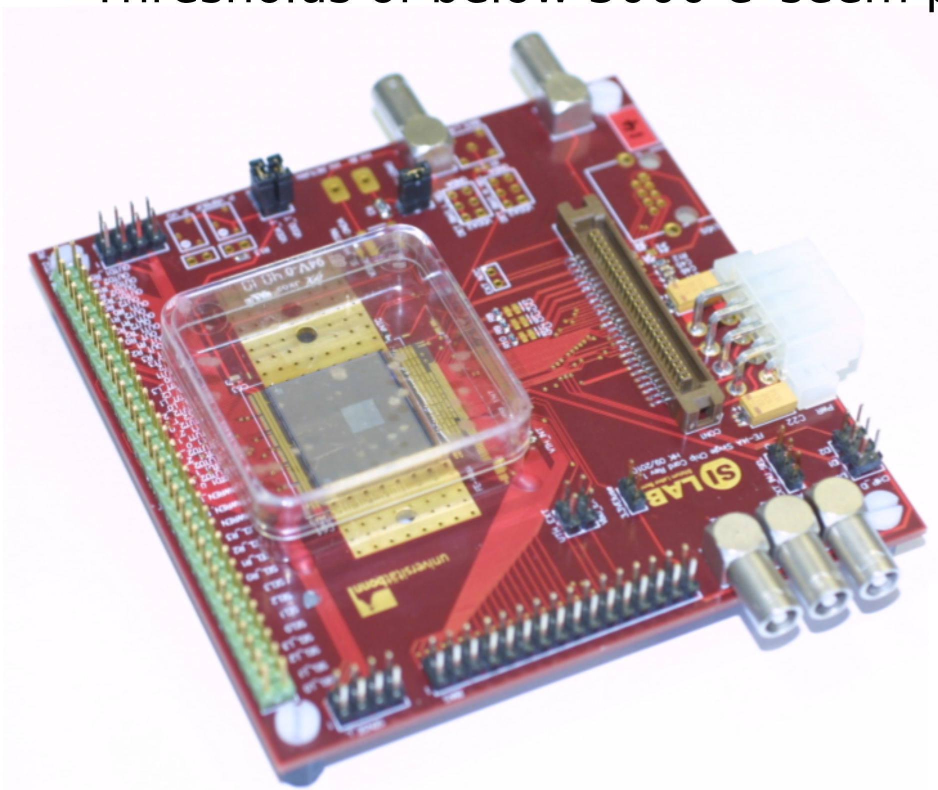

strip data G. Casse et al., IEEE TNS **56** (2009) No. 6

# Hitefficiency at $5 \cdot 10^{15}\ n_{eq}/cm^2$ - Overview

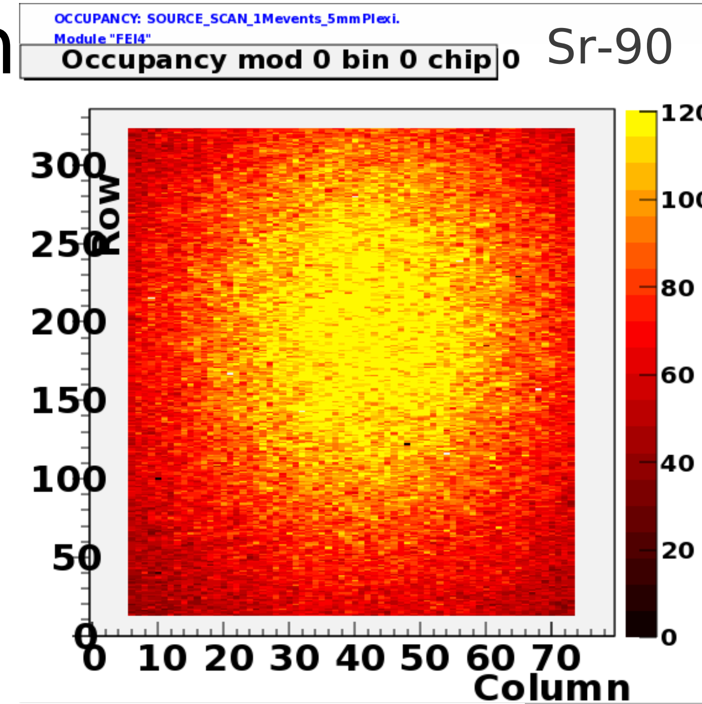


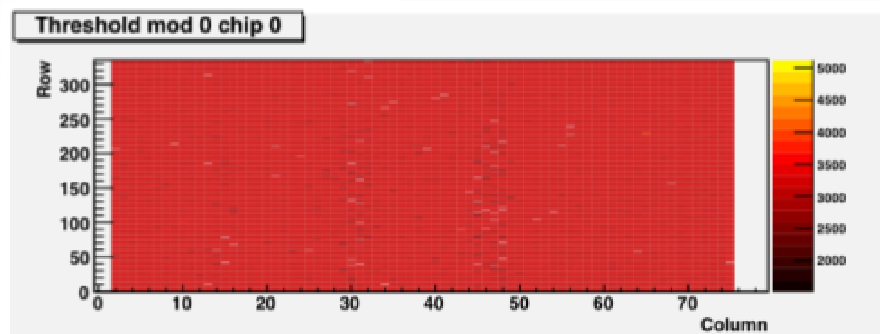
# First 250 µm sensor FE-I4 assem

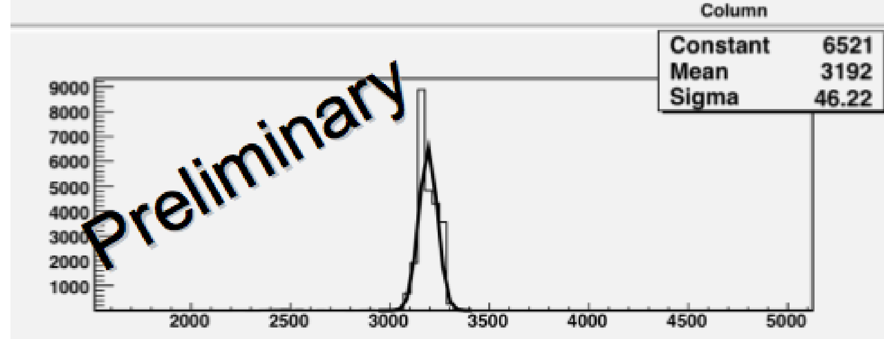
- Thresholds of below 3000 e$^-$ seem possible



J. Jentzsch



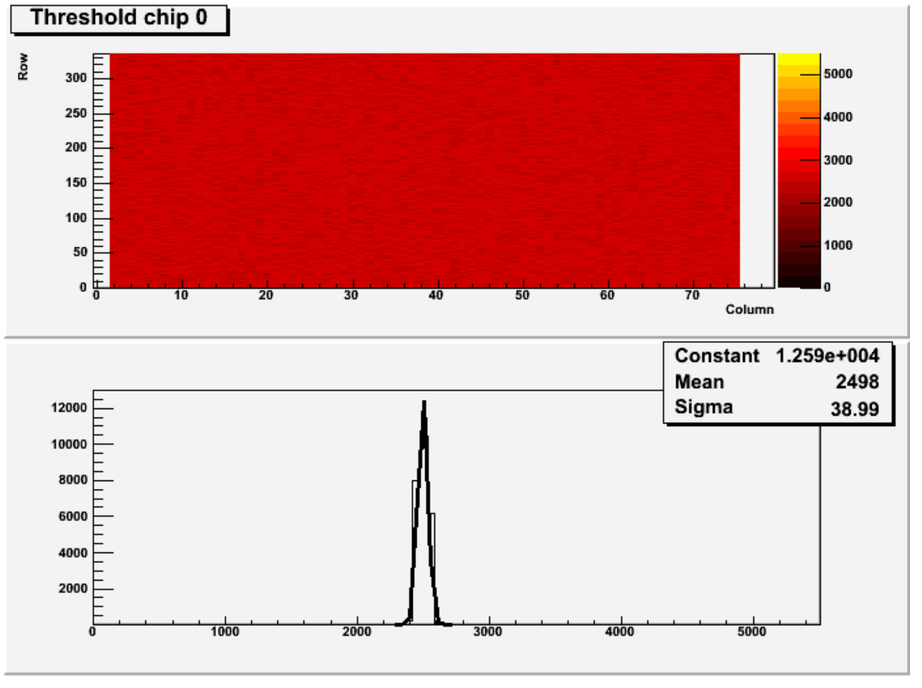



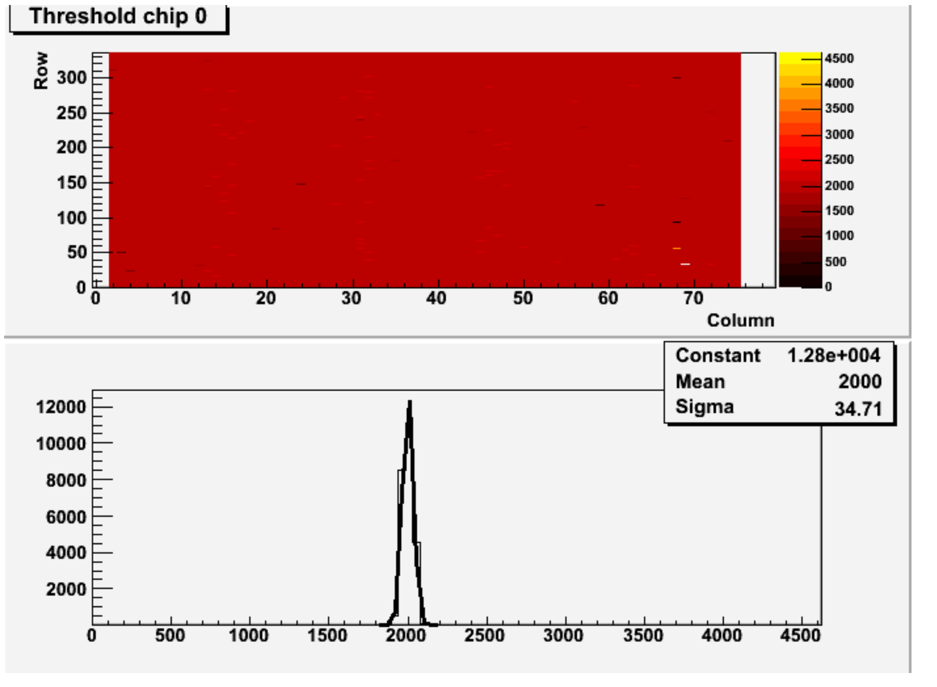




- Testbeam with unirradiated assemblies at DESY in February
- Immidiately after irradiation testbeam in April at DESY as well

# Tuning of neutron irradiated FE-I4 assemblies

- Tuning seems to be very successful
- Very painless after teething troubles

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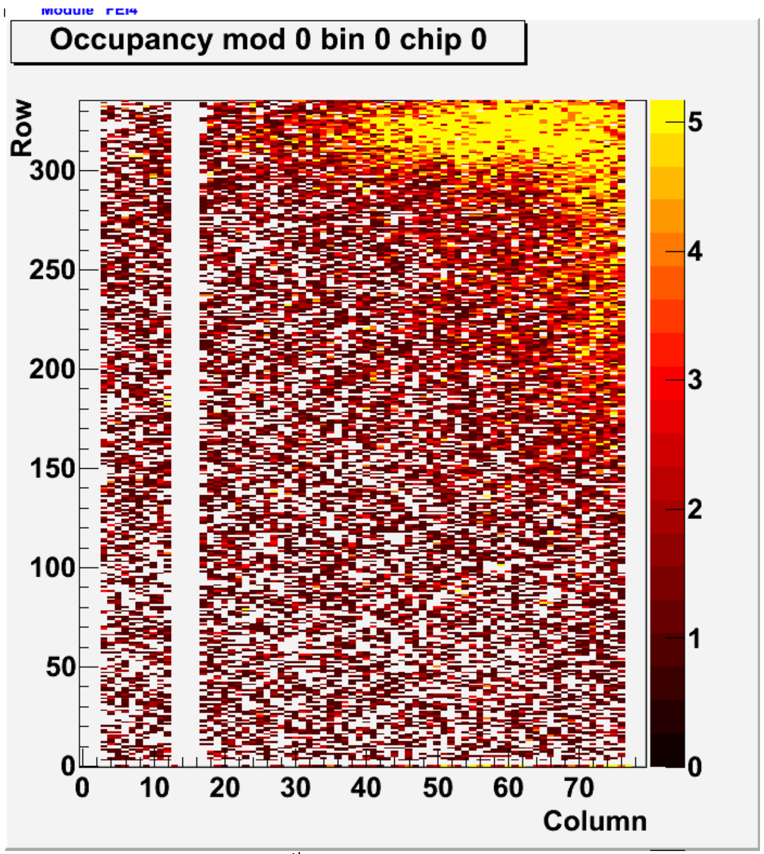
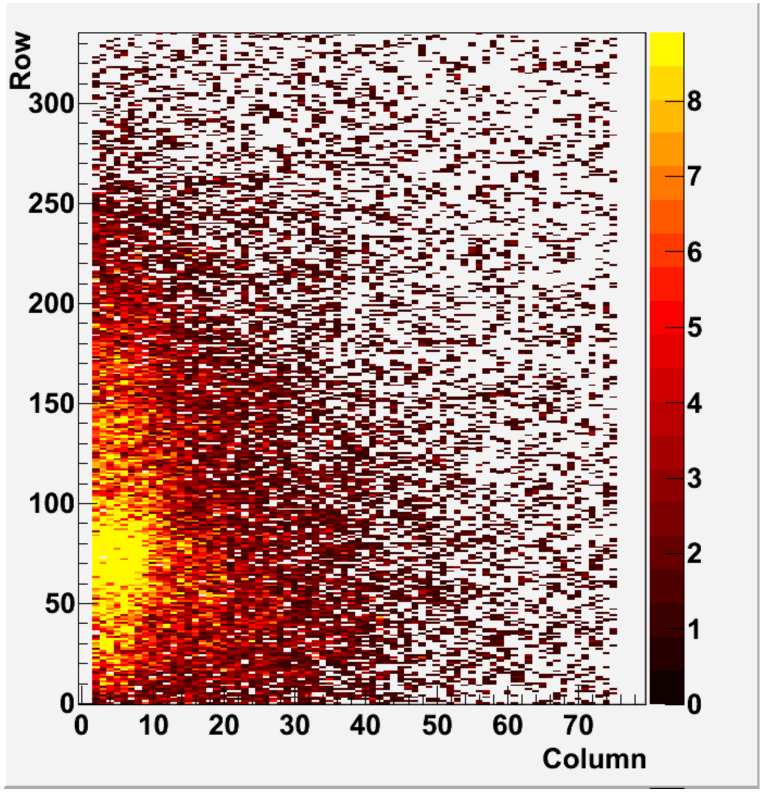
# First source scans with neutron irradiated FE-I4 assemblies

- New readout electronic and
- New frontend
- First (neutron) irradiated samples
- Activated (acts as its own source)

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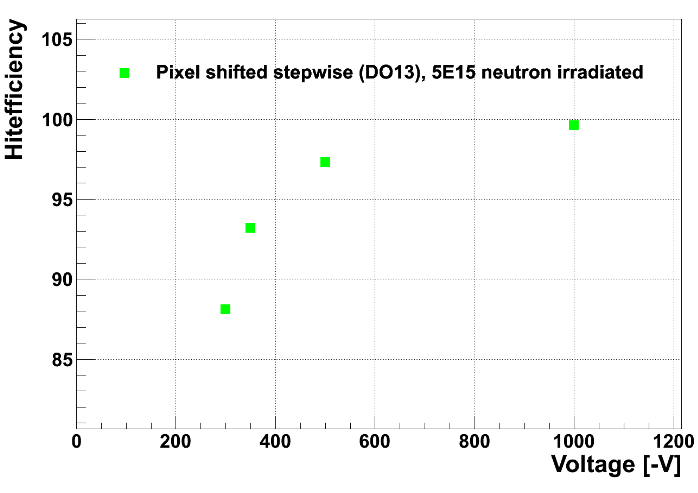
But nevertheless it works very well!

# Conclusions and Outlook

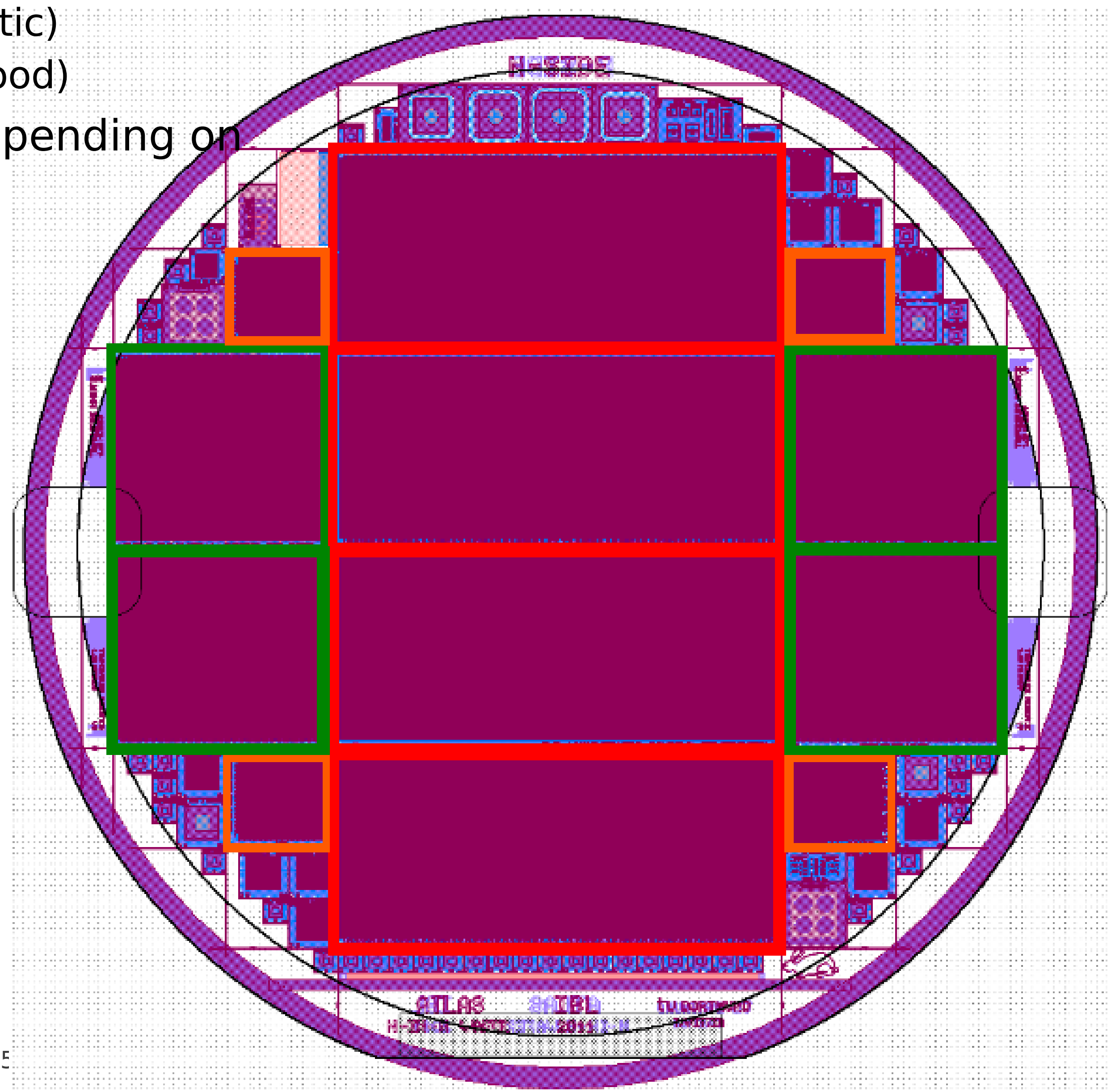
- Lot of progress in the last three years
- Planar pixel sensors still yield charge at 'SLHC innermost layer' conditions
- The n-bulk IBL sensor qualification production was very successful
  - high yield (~80% for 2-chip modules)
  - slim-edge design (~200-250 µm inactive edge) working well
- Planar sensors have been shown to yield more than 10 $ke^-$ after $5 \cdot 10^{15}$ $n_{eq}/cm^2$ at 1 kV
- Hit efficiency with a FE-I3 based readout is at 99.6% → excellent
- Data with FE-I4 were taken and are currently analyzed
- Operation of irradiated pixel detectors still tricky as FE-I3 not rad-hard enough but new DAQ seems to behave much better under testbeam conditions
- Planar IBL (pre-)production is under way



# Backup

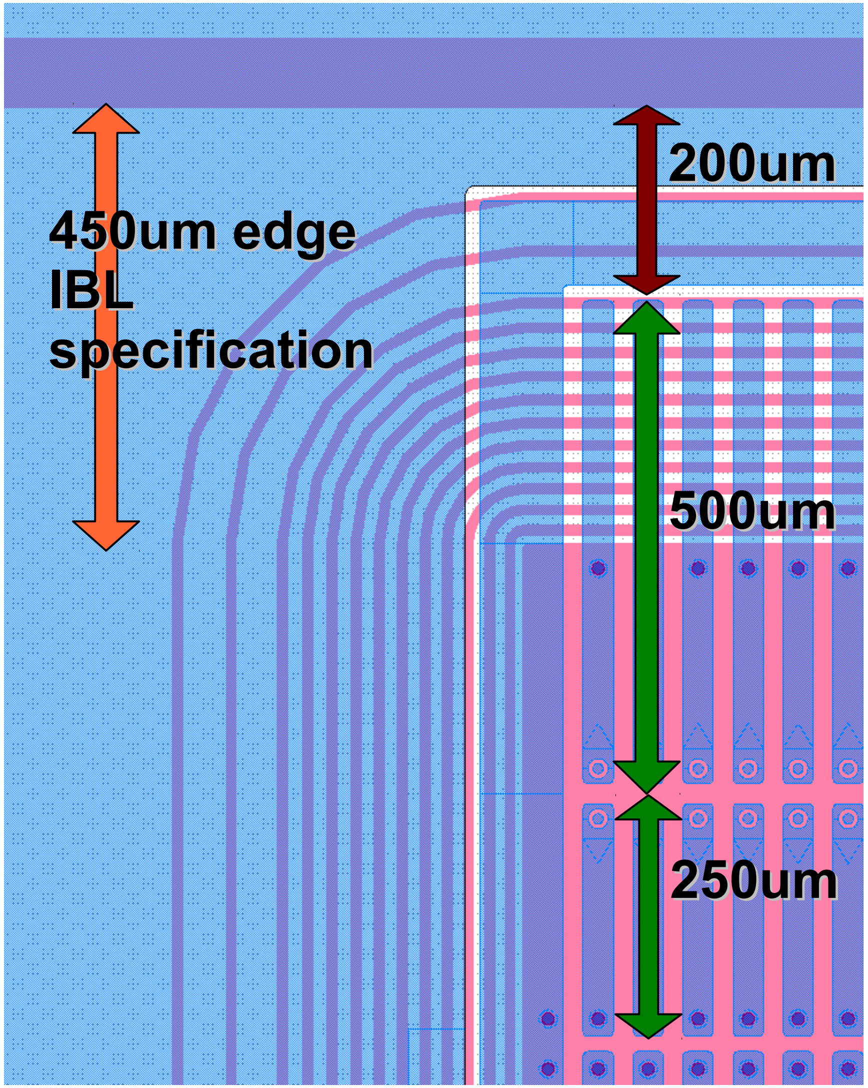
# The planar IBL production wafer

- thinning and polishing of raw wafers is outsourced:
  - 250um – 100 wafers (Okmetic)
  - 200um – 50 wafers (Rockwood)
- will decide by mid-march depending on
  - thinning results
    200 µm UBM/flipping experience
- 4” n-bulk wafer
  - slim-edge design
  - 4 FE-I4 2x1 MCMs
  - 4 FE-I4 SCs
  - 4 FE-I3 SCs
  - diodes
  - test structures



# FE-I4 sensor design

- we decided to use the “slim edge” design:
  - with long pixels (500um)
  - 13 guard rings shifted 250um beneath the pixels to reduce the inactive area
  - no disadvantage in comparison to the conservative design
  - only ~200-250um inactive edge expected
- same design for the MCMs and for the SCs
  - for comparability



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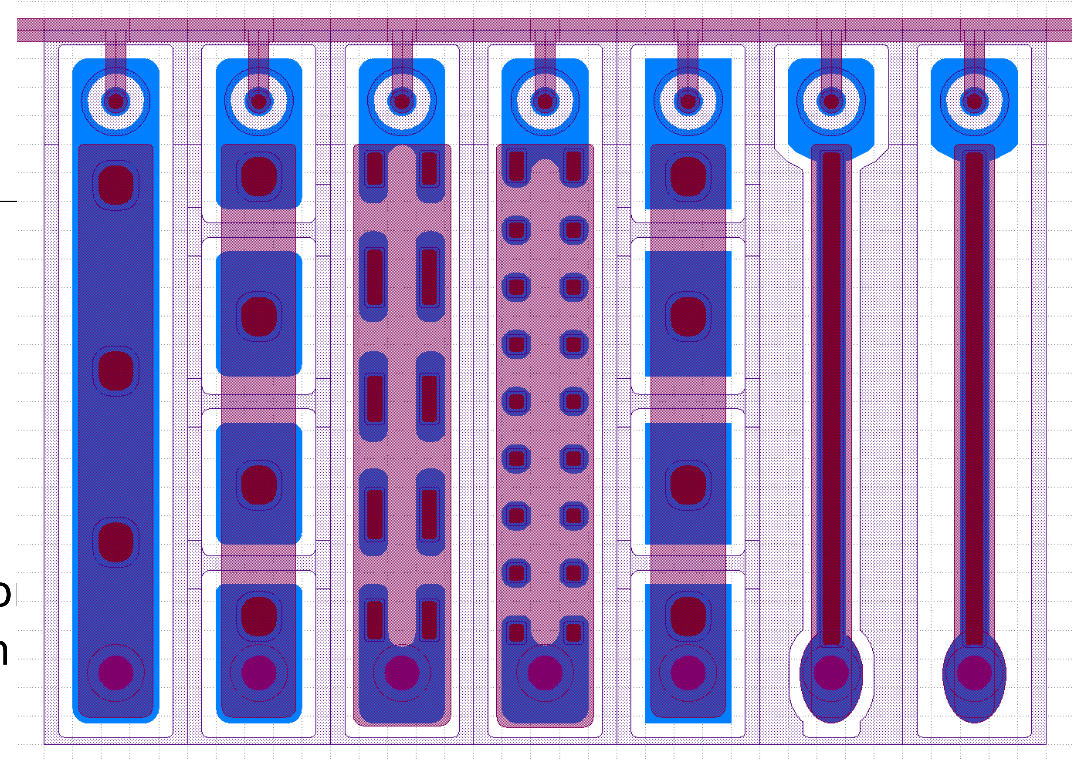
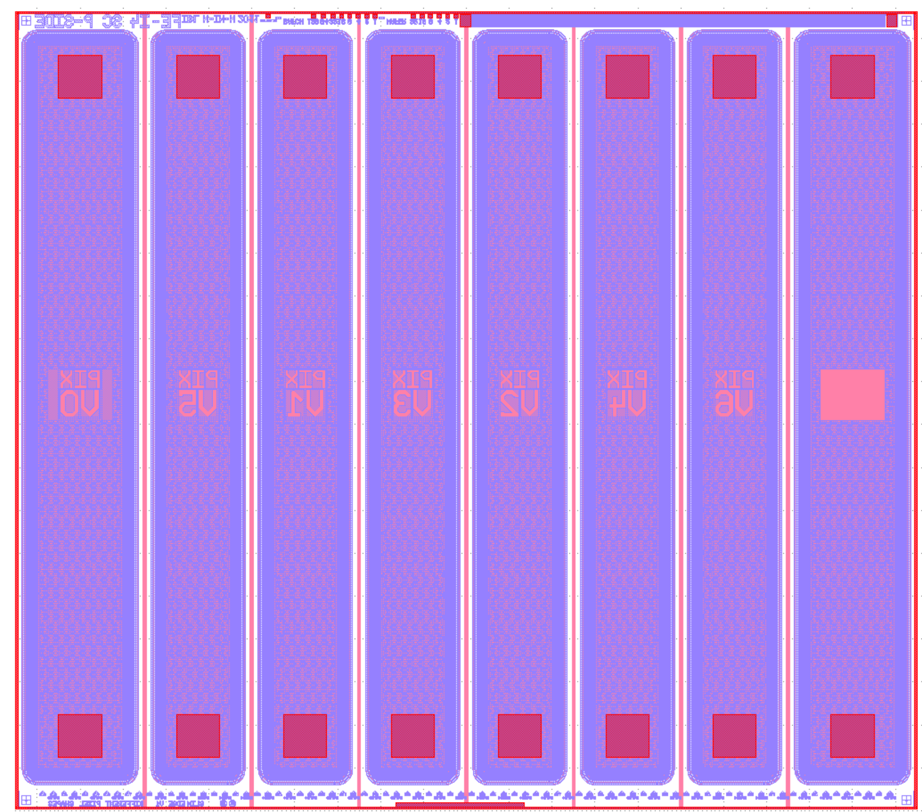
# segmented FE-I4 SC



- on one FE-I4 SC we implemented pixels with different shaped implantations
  - to enforce different field configuratio
  - study of charge amplification at high fluences
- always 5 double columns contain same pixel version
  - every double column will only see one sort of pixels (same capacities)
- The HV-pad is segmented into strips
  - the different pixel versions can be operated seperately
  - possibility to do slim edge studies with two double columns (of each version) opposite of guard rings



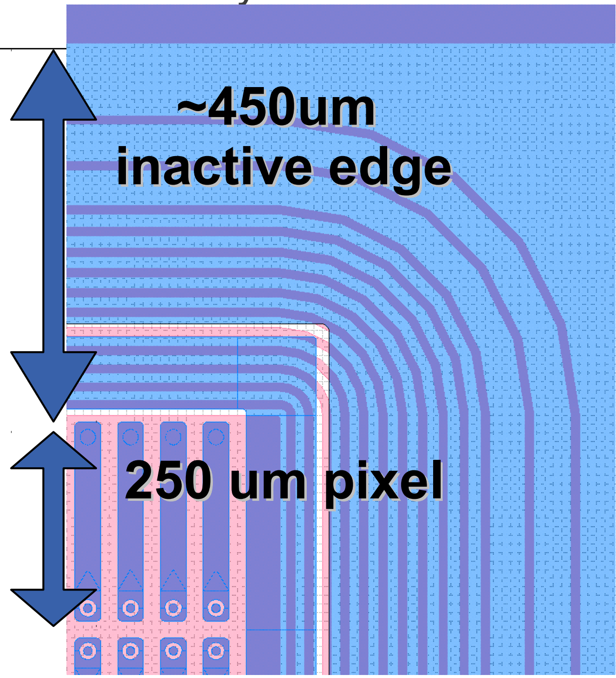
# Time schedule

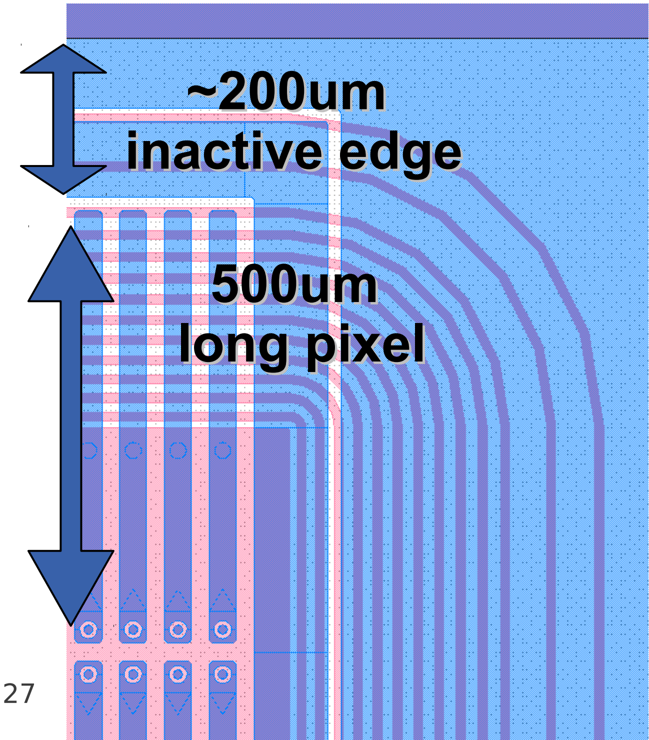
- final design review was held on January 28th
- after final changes the design was submitted to CiS in the begin of February
- 50 wafers will be ordered in March
- time table:
  - Mid-January the wafer-thinning was ordered
    - 4-6 weeks delivery time
  - ~ mid-March: start processing at CiS
    - 16-18 weeks processing time
  - ~ mid-July: wafers delivered from CiS
    - start UBM & dicing at IZM, ~4-6 weeks
  - -> ~ end of August: ~150 2-chip sensors available for flip chipping

- Subsequent order of ~100 wafers could (should?) be placed soon
  - would allow to get ahead of schedule

# Inactive edge widths

- 2 official n-bulk designs produced:
  - n-in-n: mature technology
  - double sided processing, 4” wafers
  - CiS one of the ATLAS Pixel production vendors
- Conservative design
  - as similar as possible to current ATLAS design
  - ~450 µm inactive edge width
  - electric field at edges homogenious
- Slim edge design
  - guard rings on p-side are shifted beneath the outermost pixels
    → least possible inactive edge (< 200 µm)
  - less homogenious electric field, but charge collection after irradiation dominated by region directly beneath the pixel implant
    → only moderate deterioration expected
- Three parameters:
  - Safety margin (doi:10.1016/j.nima.2010.06.004)
  - Number of guard rings
  - Pixel opposite guard rings



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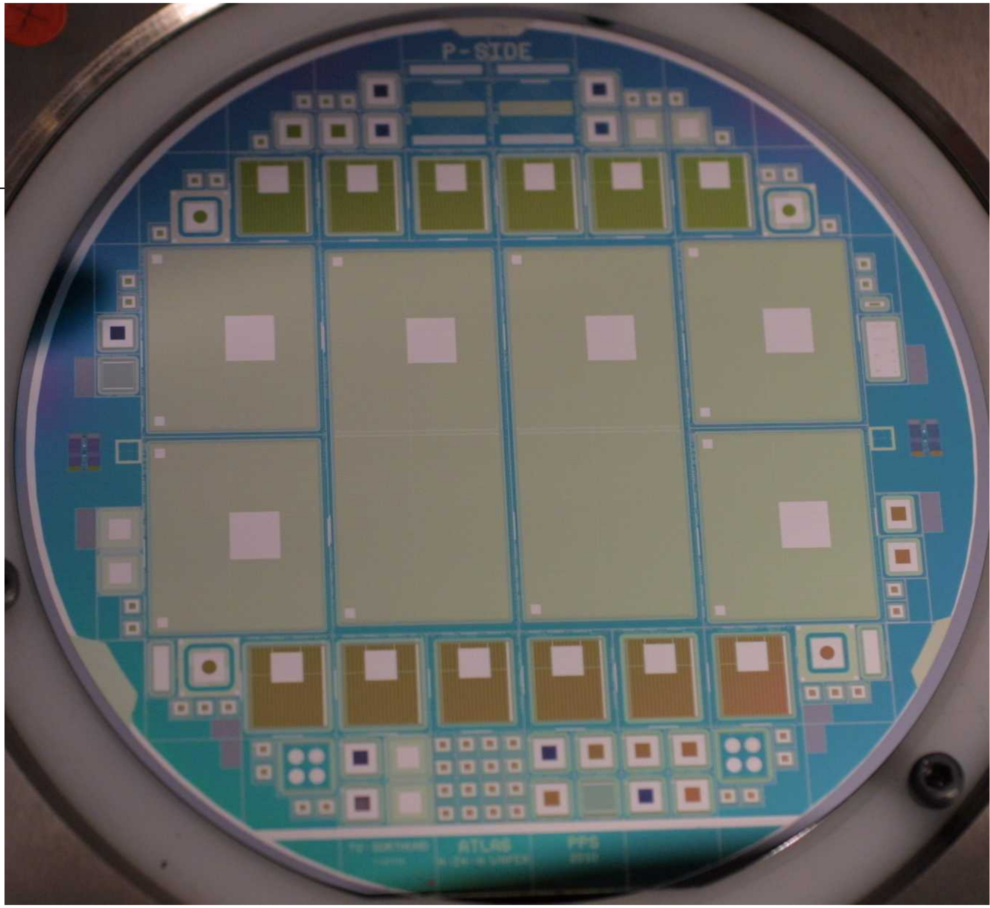
# n-bulk qualification wafer

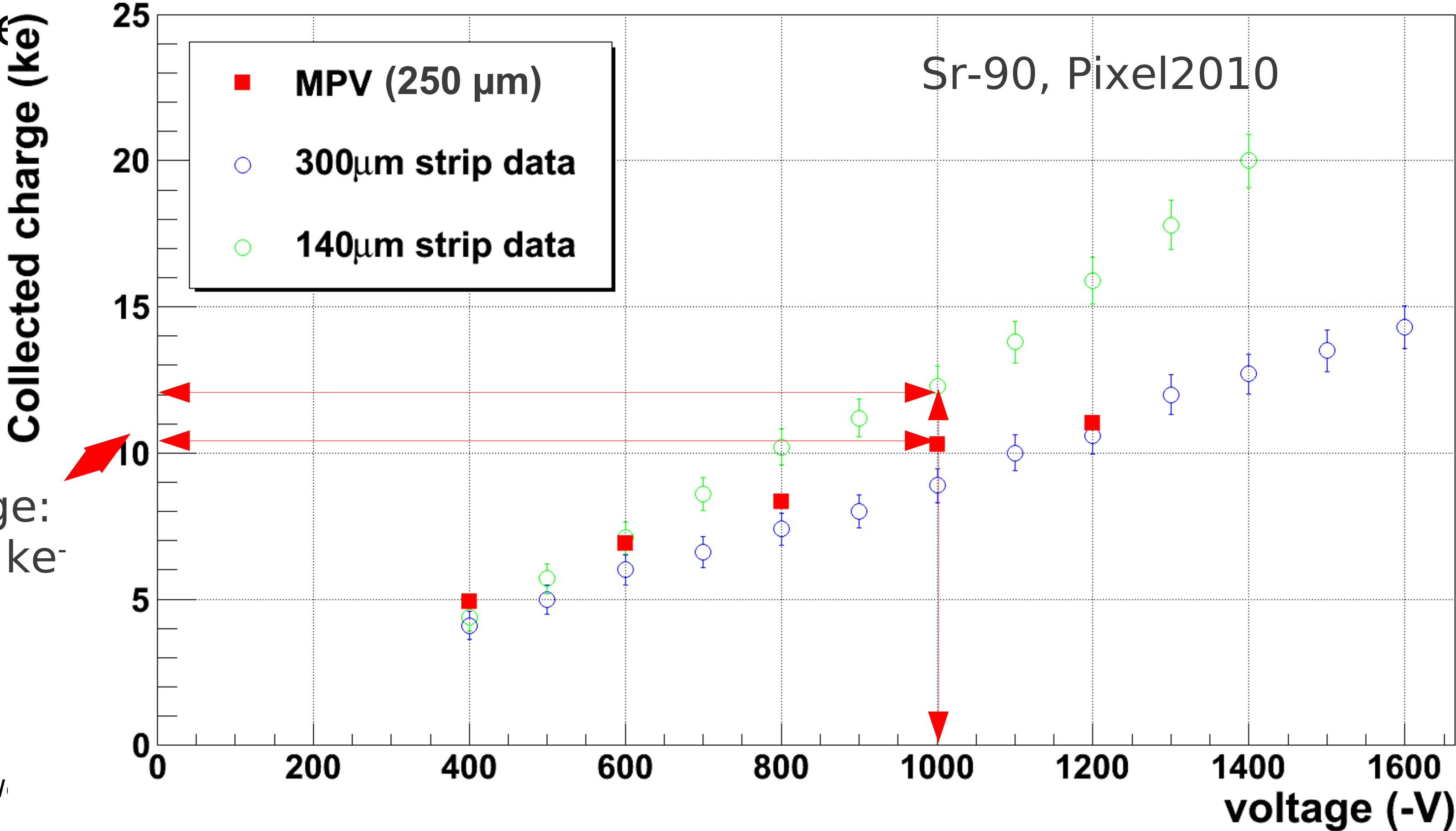



- 6 FE-I4 sensors:
  - conservative (no long pixels, no pixel overlap)
  - slim edge (long pixels (500um), pixels shifted over guard rings)
  - 1 2-chip and 2 1-chip sensors of each design
- 12 FE-I3 SCs
  - various guard ring designs
- diodes, test structures...
- vendor: CiS
- 5 thicknesses:

| thickness | wafers ordered | wafers received |
|---|---|---|
| 250um | 12 | 18 |
| 225um | 6 | 11 |
| 200um | 6 | 10 |
| 175um | 6 | 11 |
| 150um | 6 | 8 |

# Wafer thickness

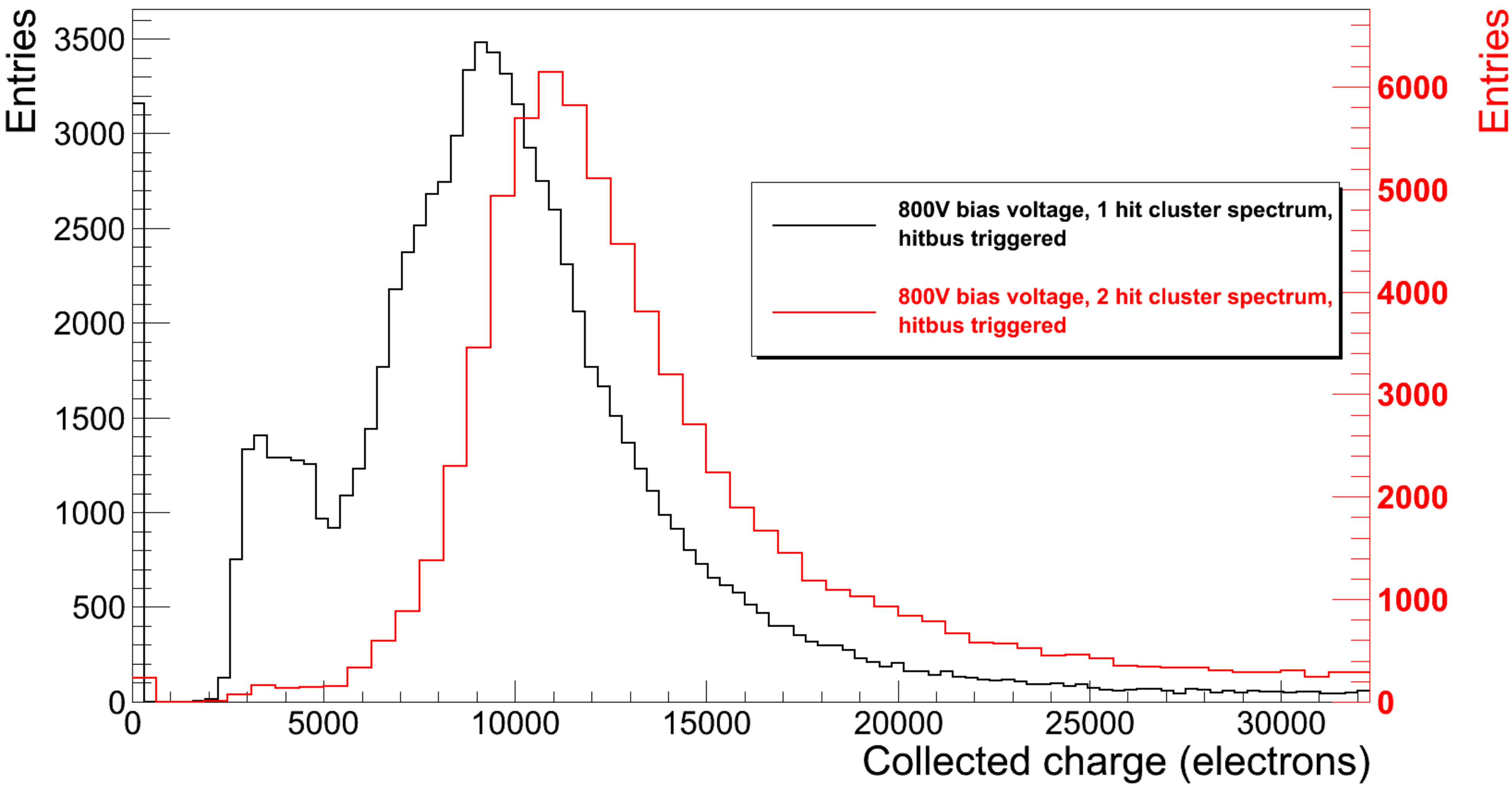
- Thinner sensors
  - generate about 1-2 ke⁻ more charge after $5 \cdot 10^{15}$ $n_{eq}/cm^2$ at 1 kV
  - have less radiation length
- Baseline: 250 µm (ATLAS production)
- Extreme: 150 µm
- Compromise




Expected charge:
10-12 ke⁻

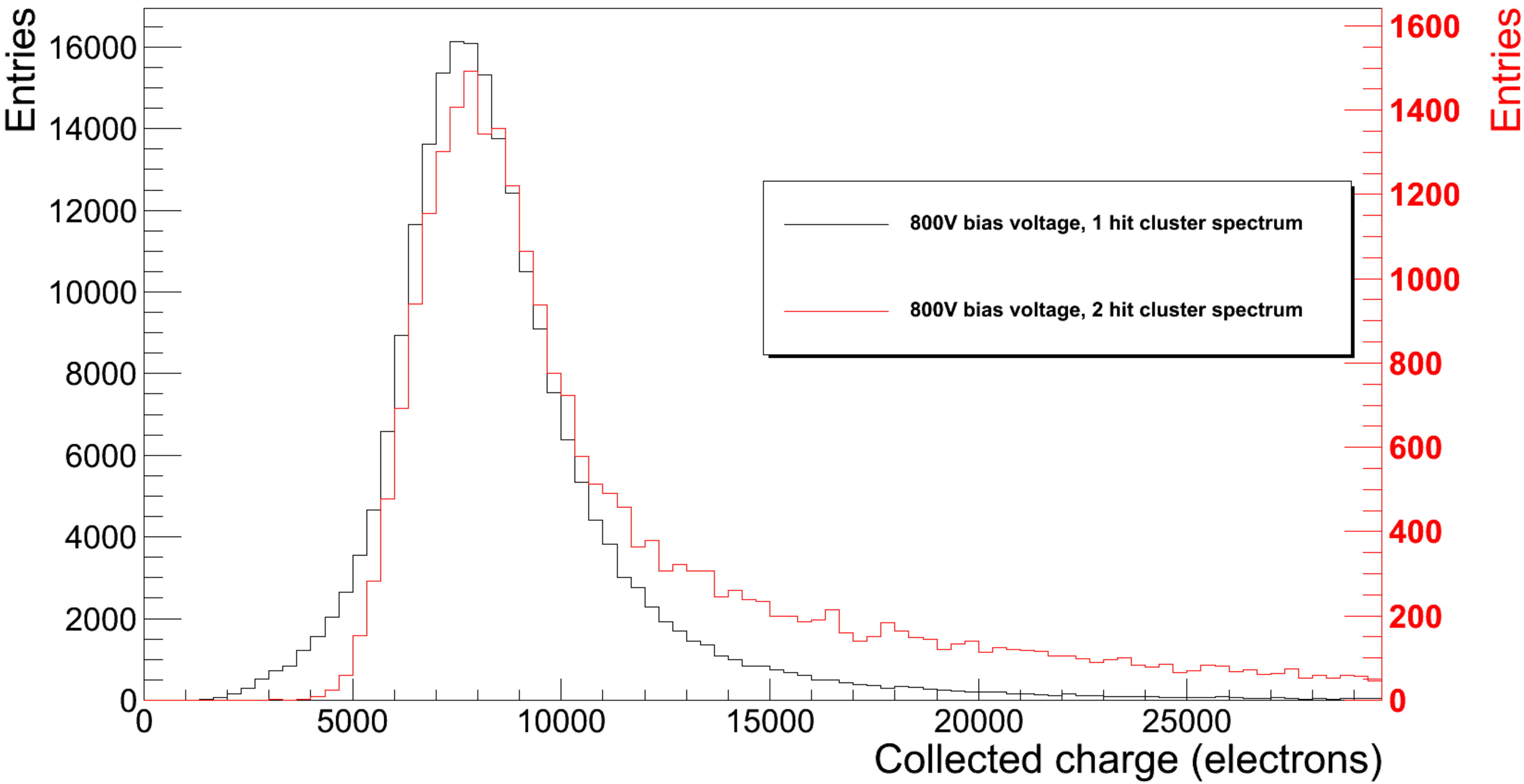
# $5 \cdot 10^{15}\ n_{eq}/cm^2$ @ 800V, Sr-90 electrons

- Difference between cluster charge of 1-hit and 2-hit clusters:



# $5 \cdot 10^{15}\ n_{eq}/cm^2$ @ 800V, pions

- With pions, this effect is negligible



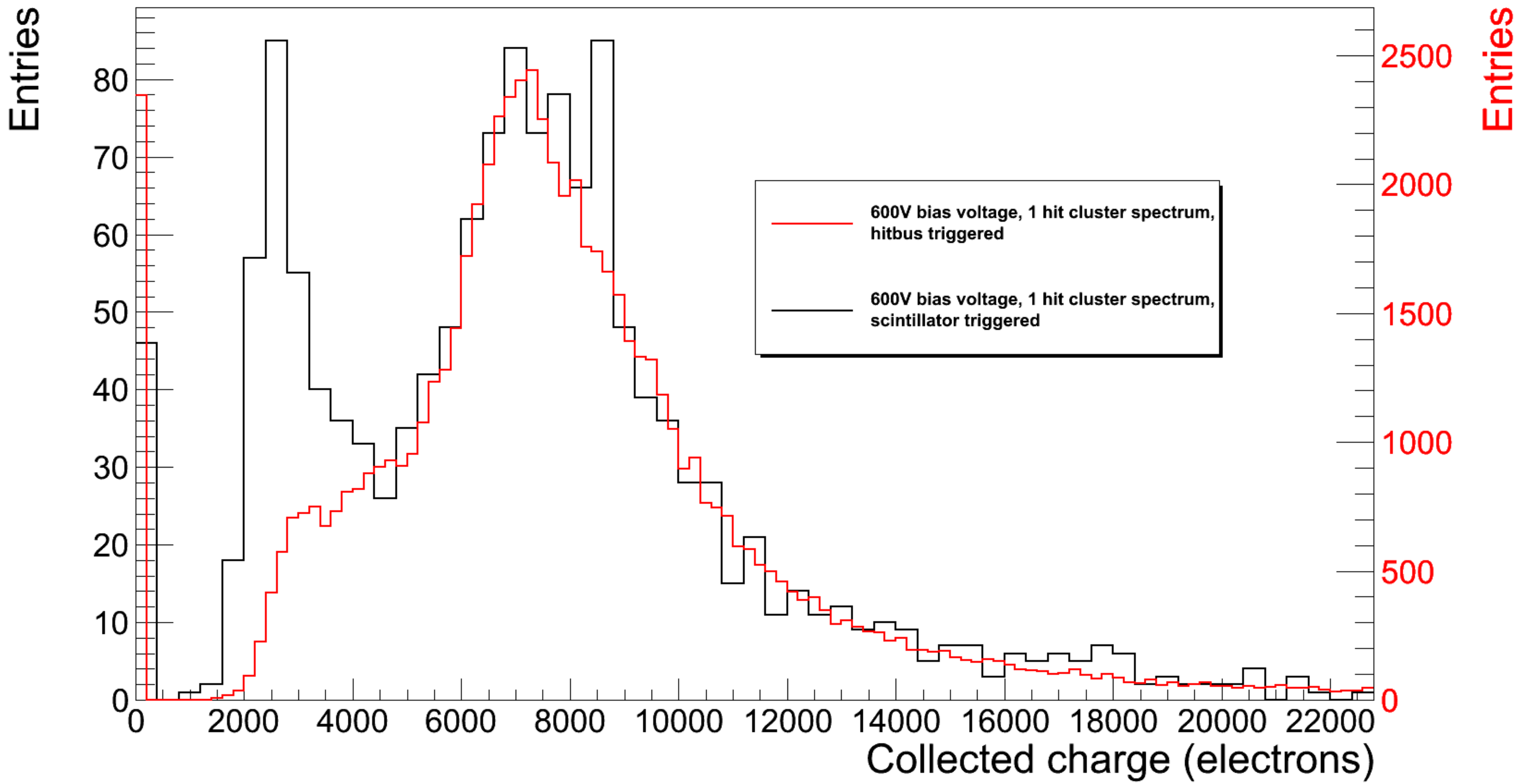
# 1 hit vs. 2 hit clusters

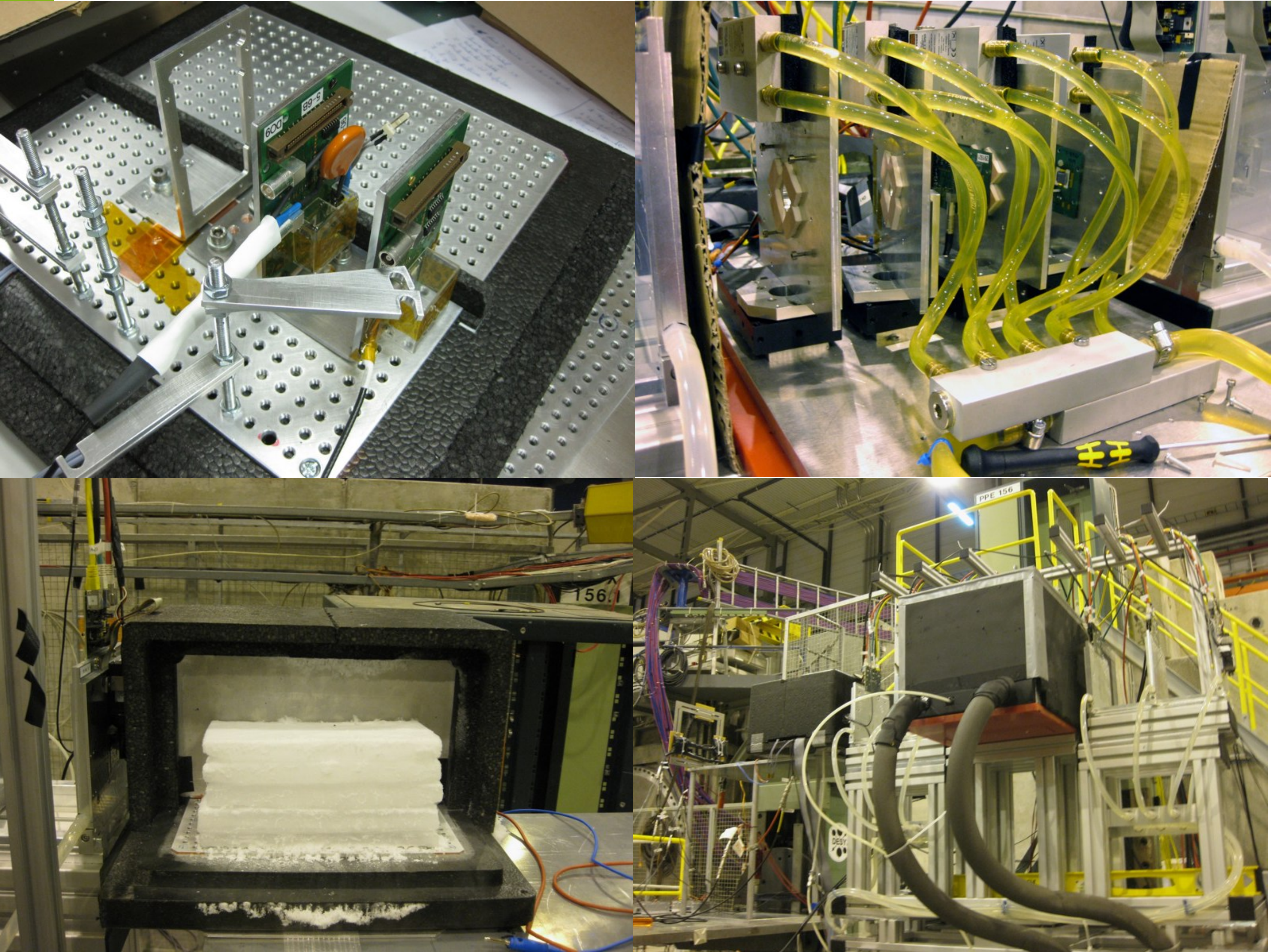
- For testbeam data with high energy pions there seems to be little difference between the charge spectra of 1-hit and 2-hit clusters.
- Low energy electrons (Sr-90) show increased charge deposition for two hit clusters

  → Only 1 hit clusters regarded for Sr-90 data, conservative choice

# Trigger: $5 \cdot 10^{15}$ $n_{eq}$/cm² 600V electrons

- No visible difference for MPV between scintillator and hitbus-triggered data

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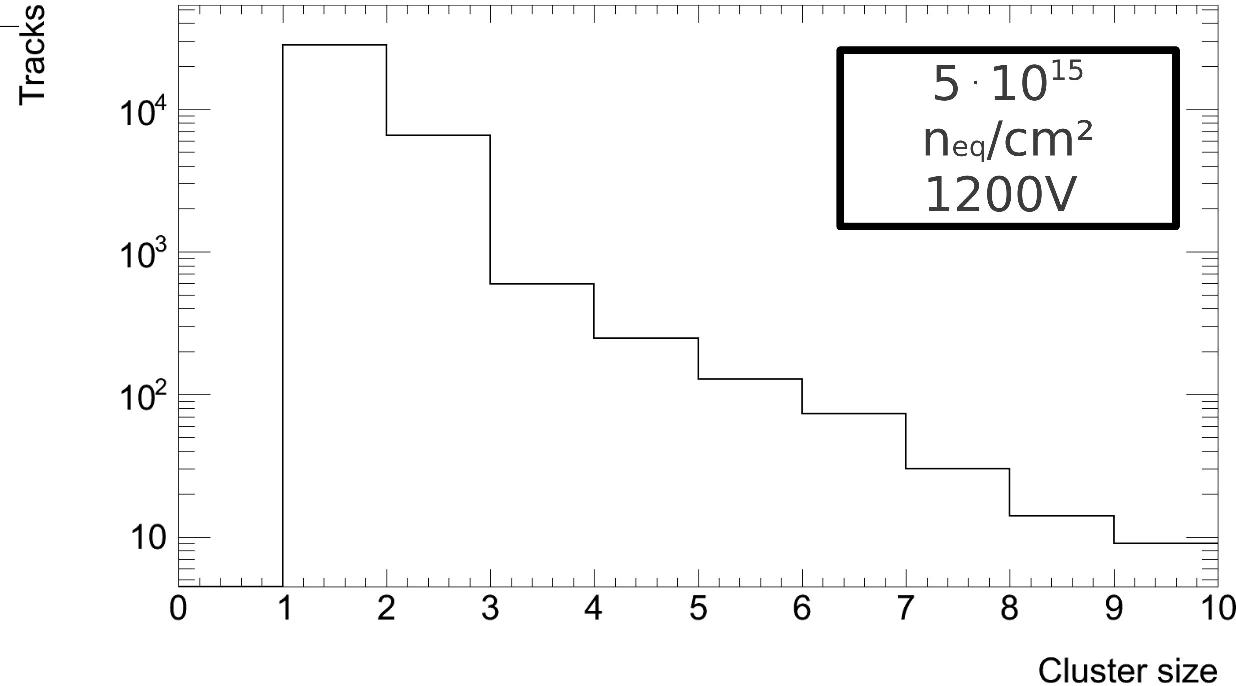
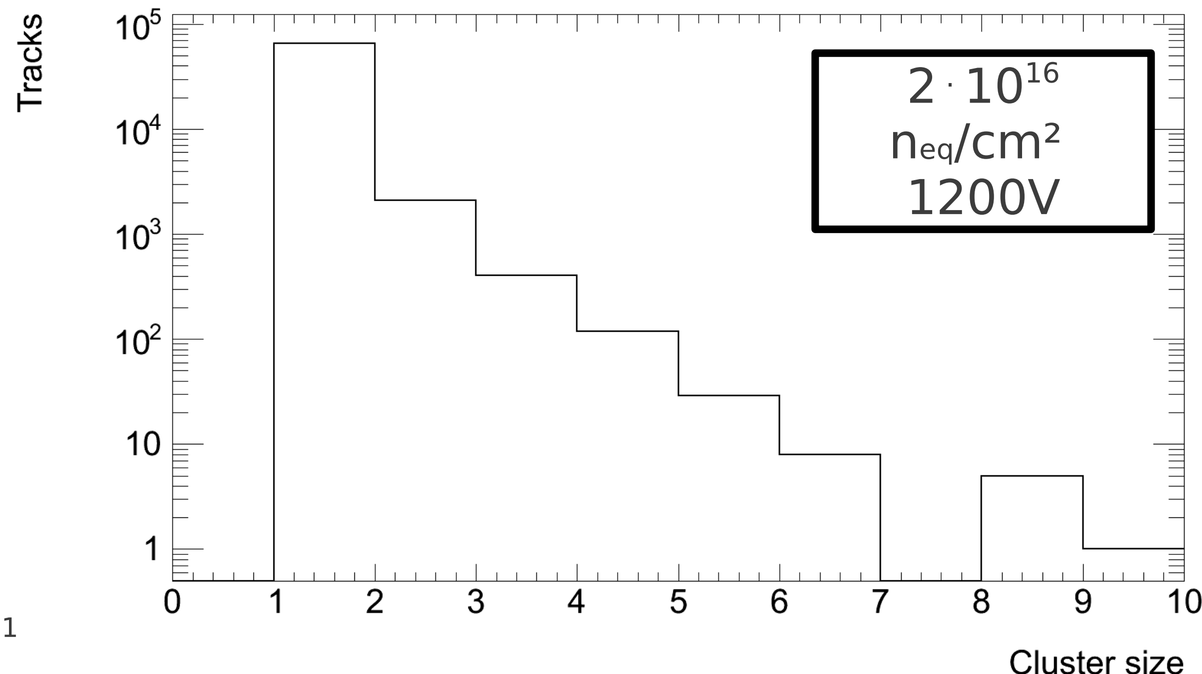
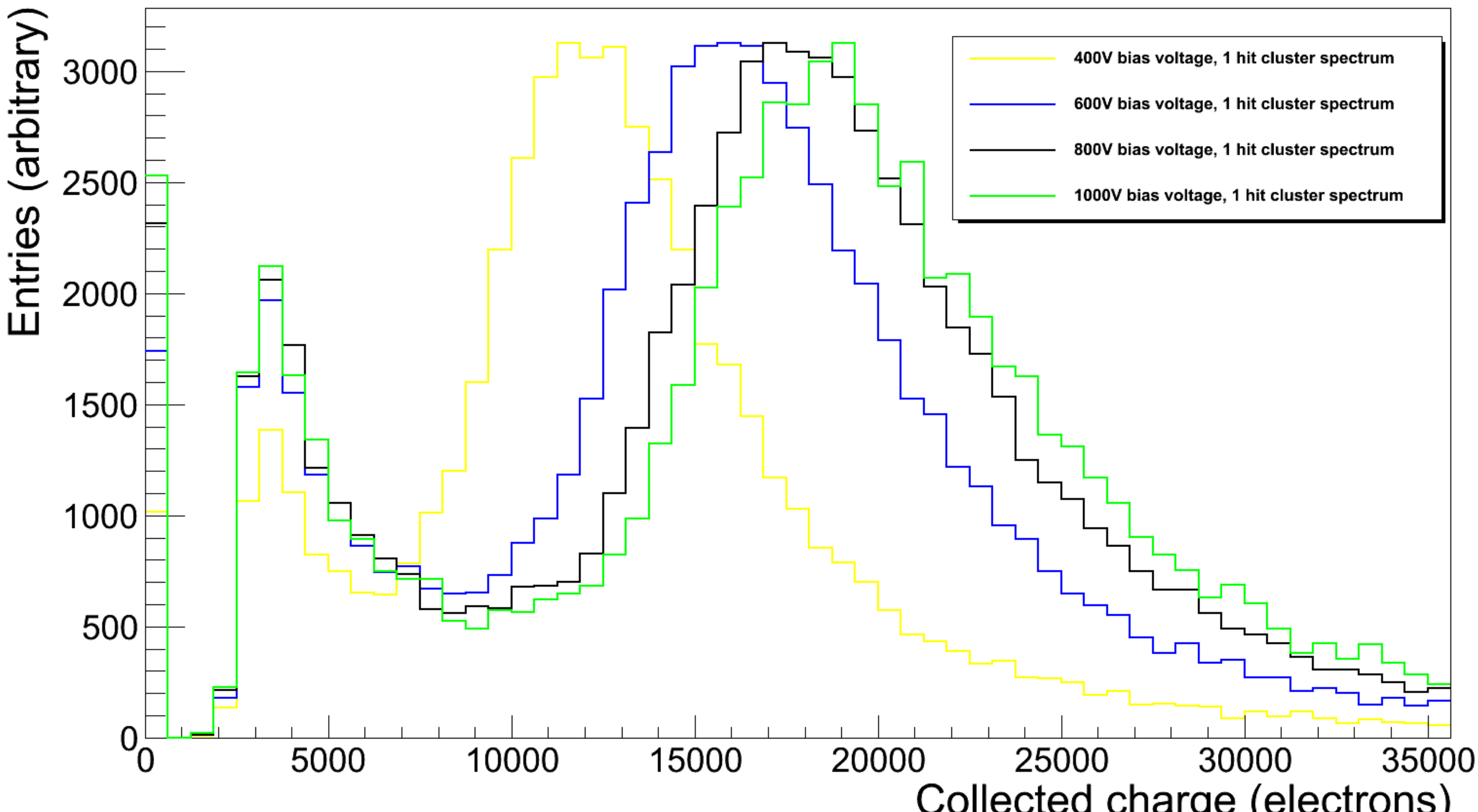
# Charge sharing?

- Single-hit cluster fraction grows with fluence (as expected)
- (Much) more shared charge not seen due to threshold effect in the neighbouring pixel
- Scattering is larger with electrons, might (partially) explain lower observed charge with electrons



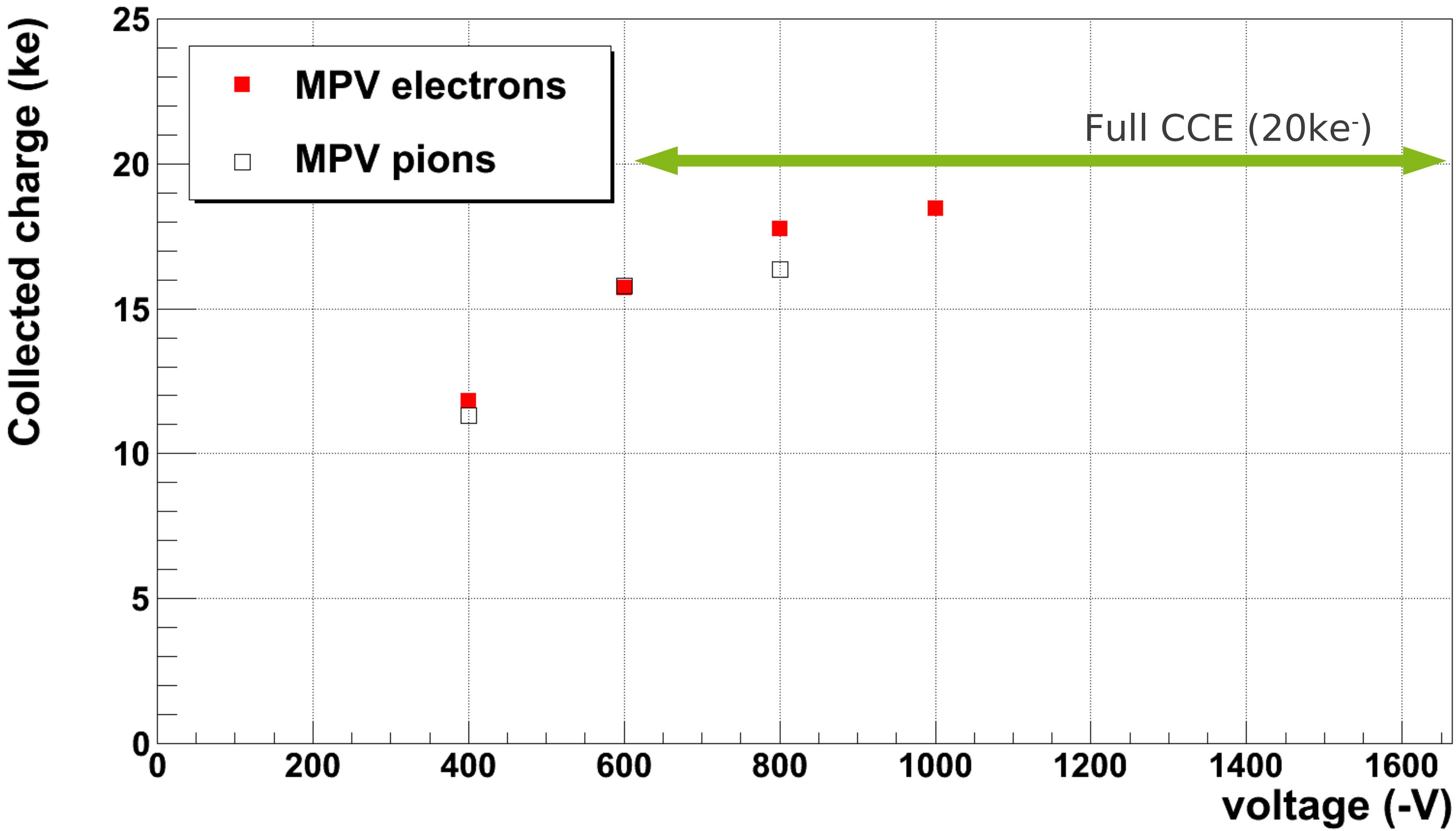



# $1 \cdot 10^{15}\ n_{eq}/cm^2$ with Sr-90 electrons

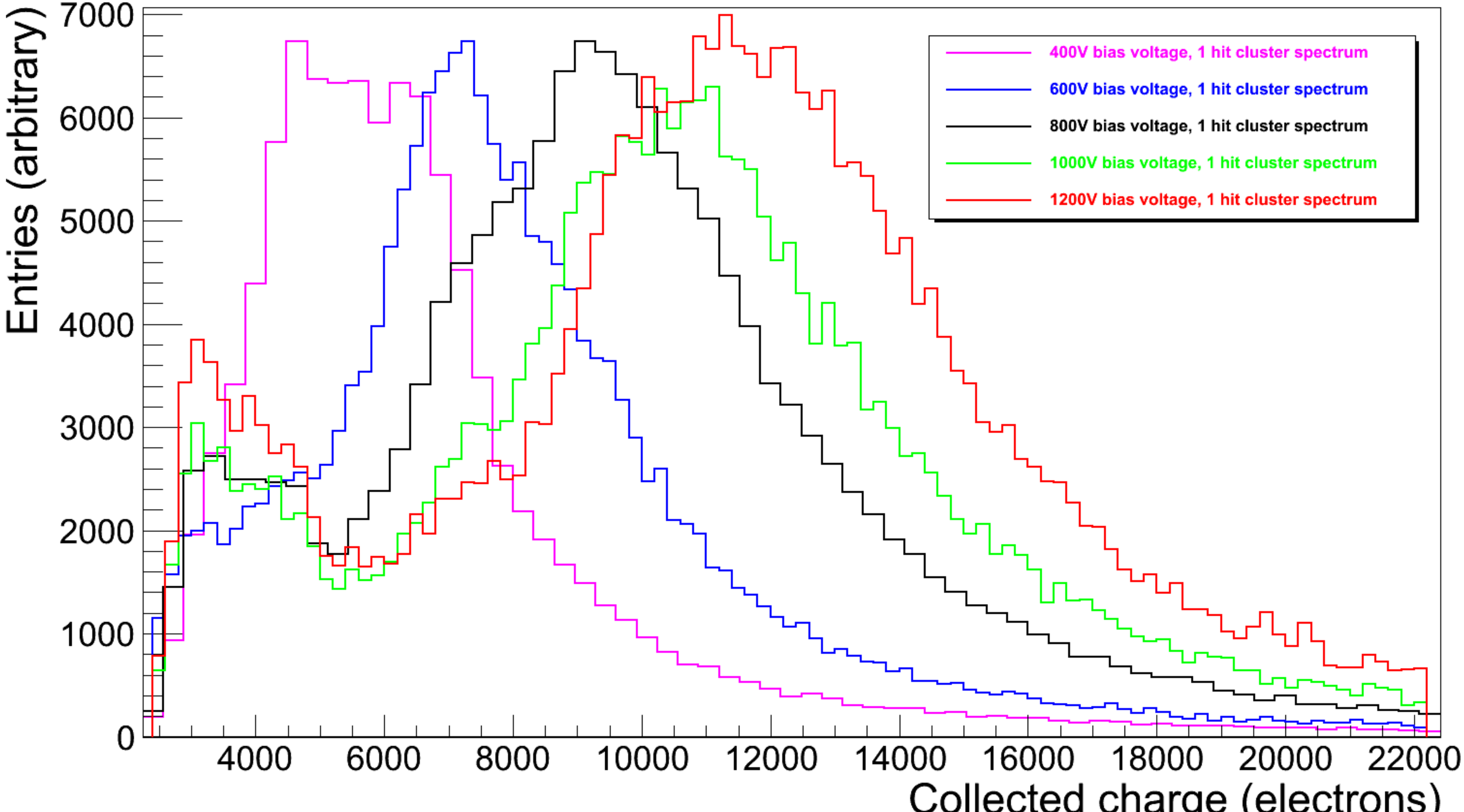


# $1 \cdot 10^{15}$ $n_{eq}/cm^2$ charge collection summary

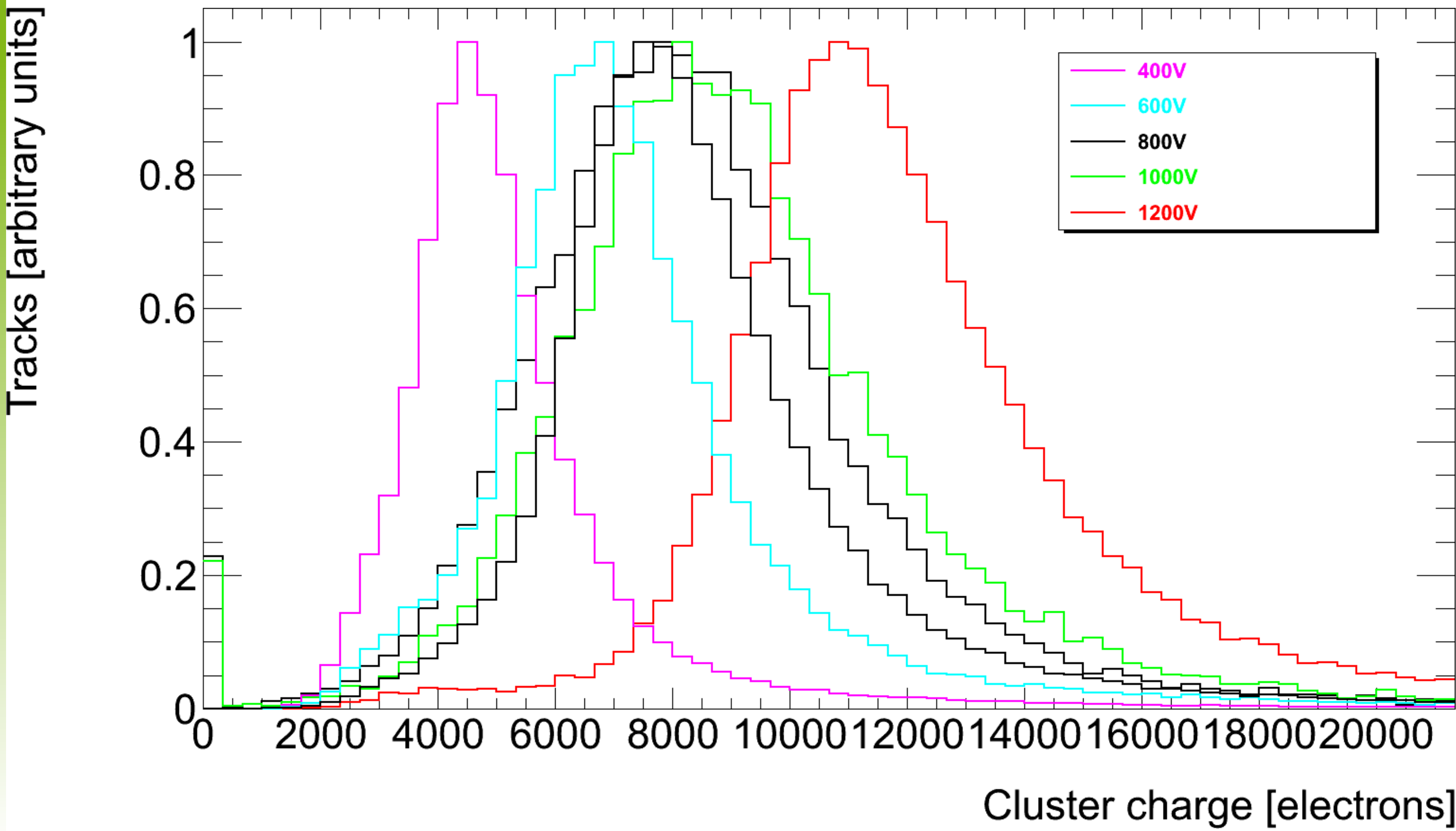
- satisfactory results: 16 $ke^-$ at 600V, almost full CCE at 1kV
- agreement with pion measurements



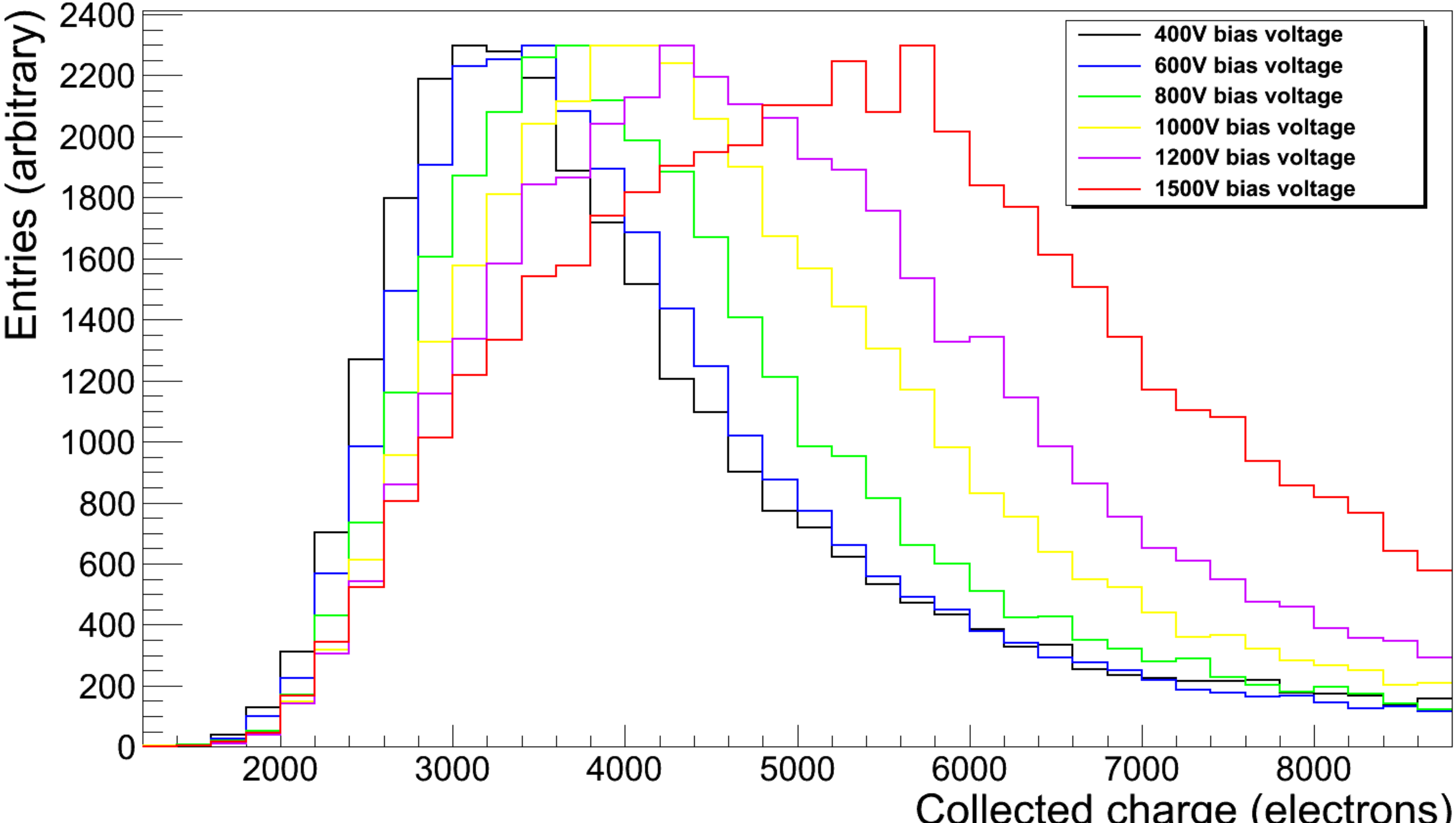
# $5 \cdot 10^{15}\ n_{eq}/cm^2$ with Sr-90 electrons



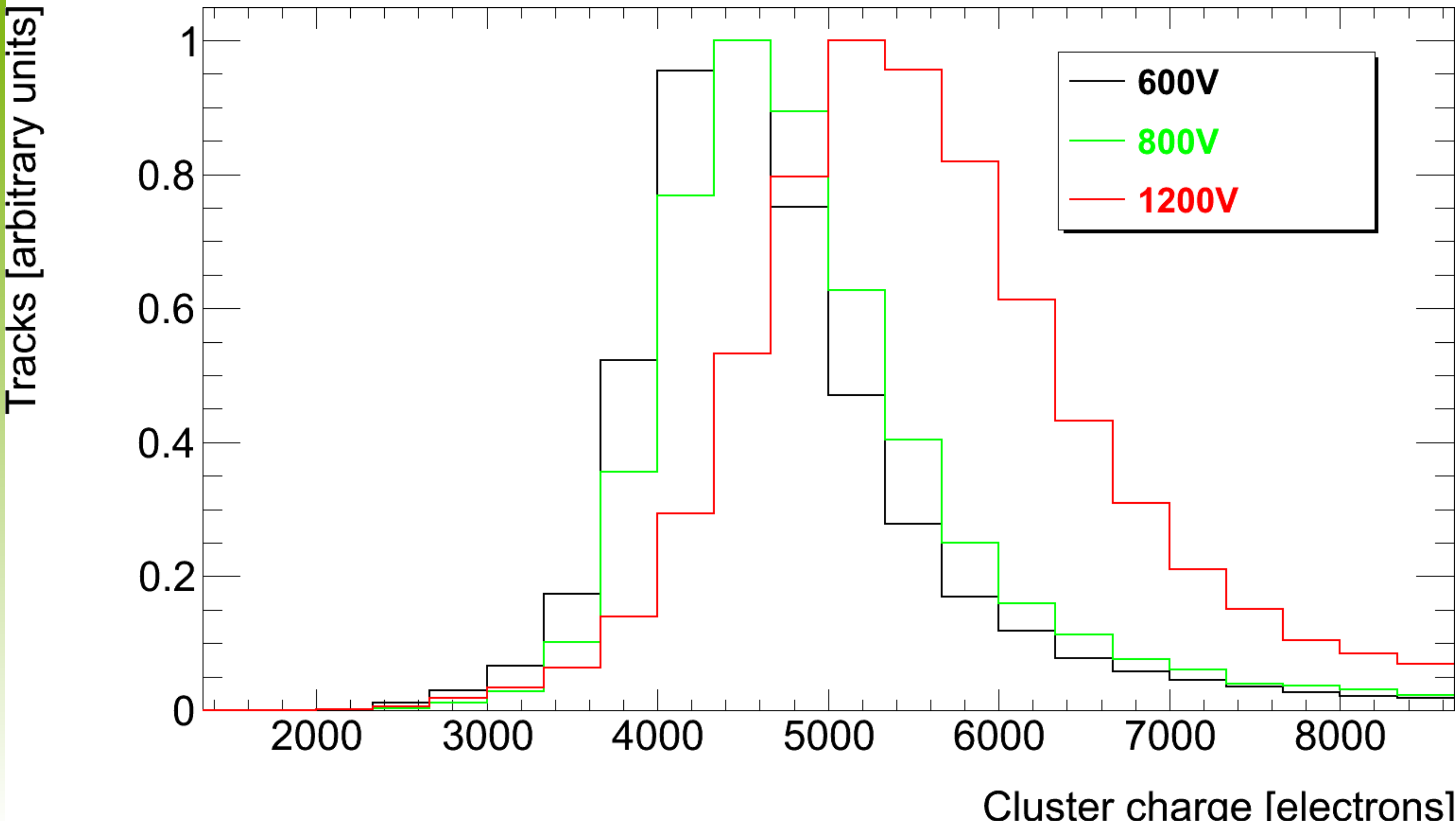
# $5 \cdot 10^{15}\ n_{eq}/cm^2$ with pions



# $2 \cdot 10^{16}\ n_{eq}/cm^2$ with Sr-90 electrons



# $2 \cdot 10^{16}\ n_{eq}/cm^2$ with pions



# Integrated temperature sensors

- next to all 4 FE-I4 SC sensors a loop of metal conductor is implemented on the p-side
- possibility to determine the sensor temperature via measurement of (temperature depending) resistance
- length of ~1.2m
  - resistance in the order of ~1-10k ohms
- two dicing streets to have the possibility of cutting away the loop or leave it attached to the sensor
- on three FE-I4 SCs and one MCM a shorter loop (~21cm length) is implemented in the edge of the sensor (within the dicing streets)