Measurements of highly irradiated ATLAS n$^+$-in-n planar pixel sensors

7th Trento Workshop on Advanced Radiation Detectors

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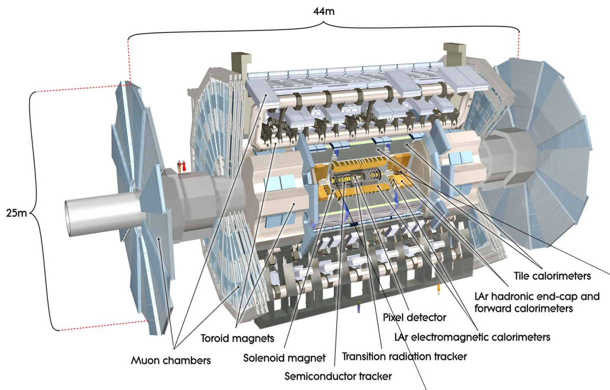
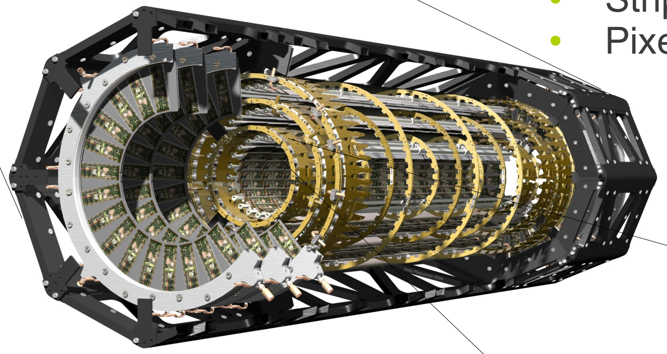
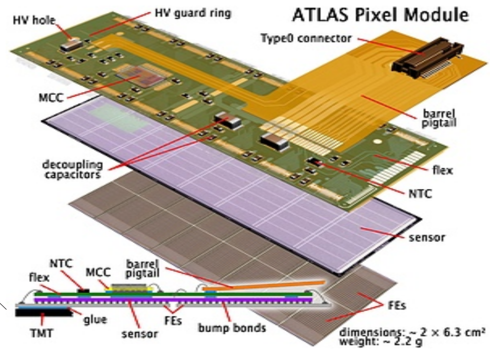
The pixel detector of the ATLAS experiment



- 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



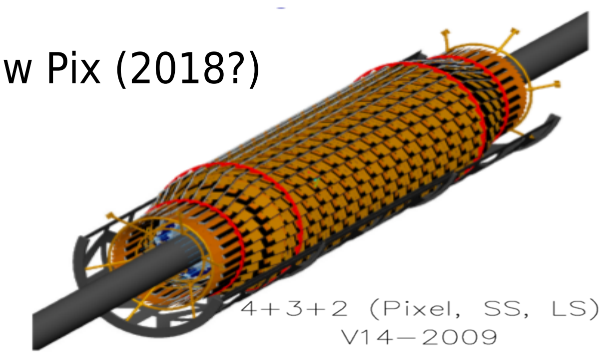
- Current pixel module:
  - planar n-in-n FZ sensors
  - 250µm thick
  - Read-out chip Front-End I3

Future upgrade of the ATLAS pixel detector

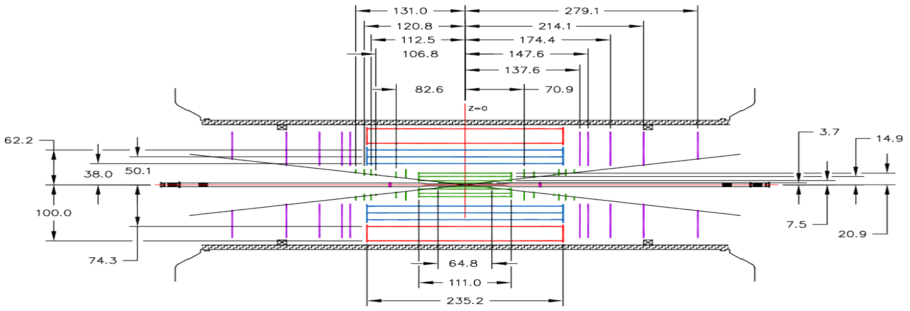
Existing B-layer

IBL (mounted on the New beam pipe)

New Pix (2018?)



- 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: $10^{15}\text{-}10^{16} n_{eq} cm^{-2}$



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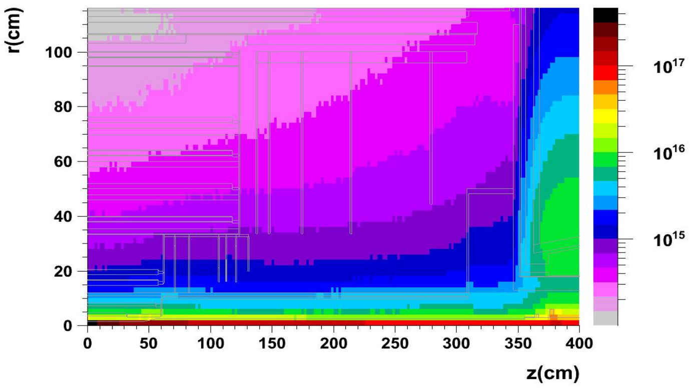
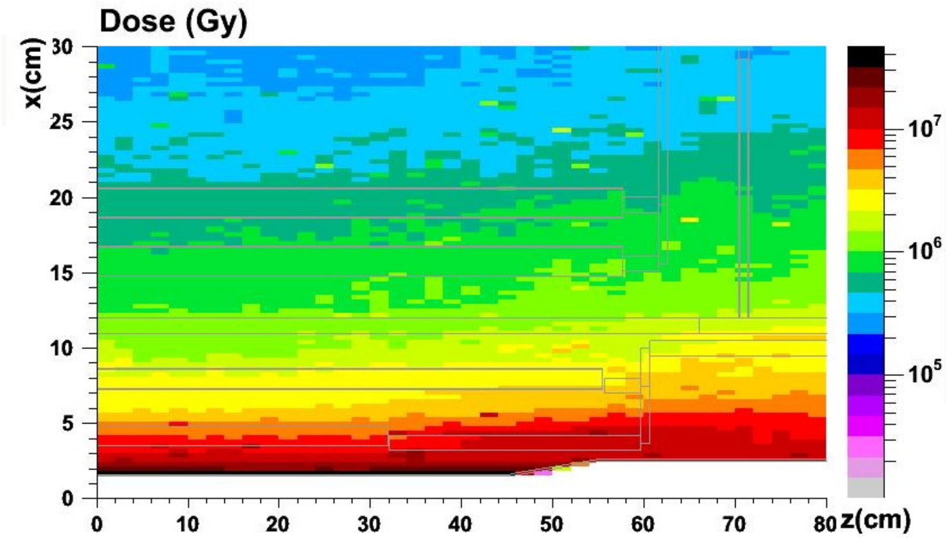
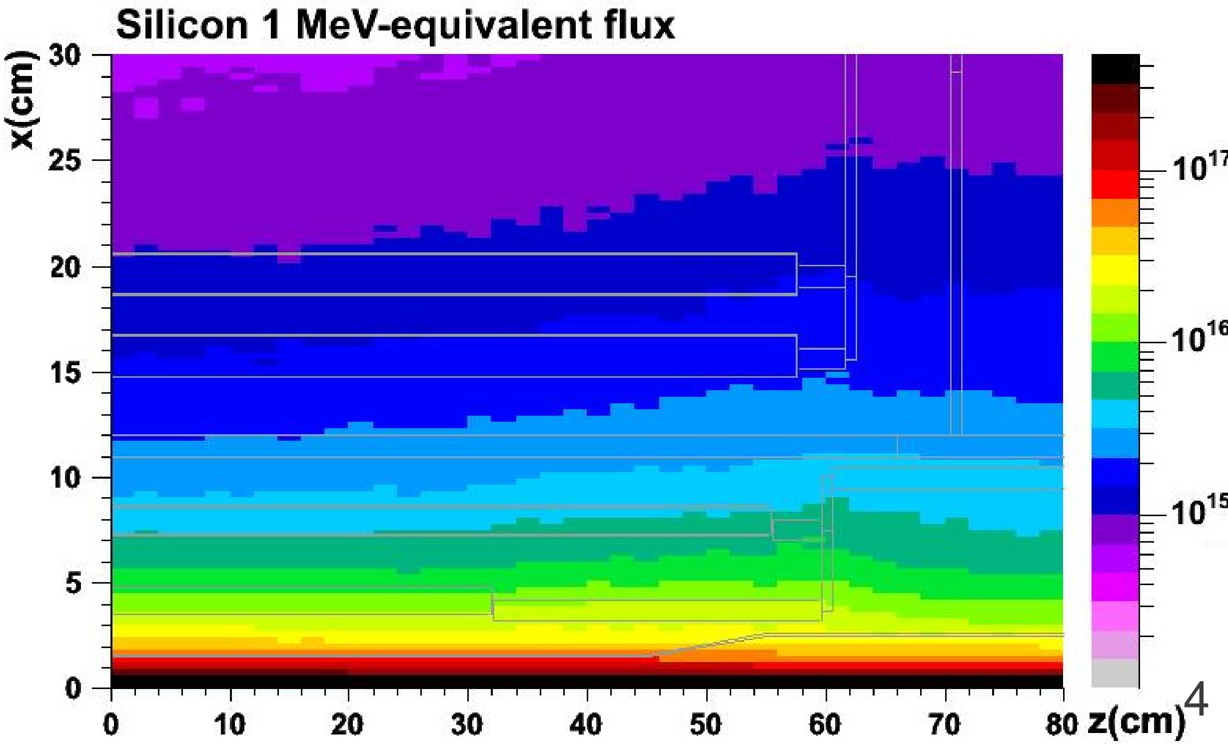
4 layers of pixel to larger radius than now
Approx. 400 Million pixels (80 Million now)

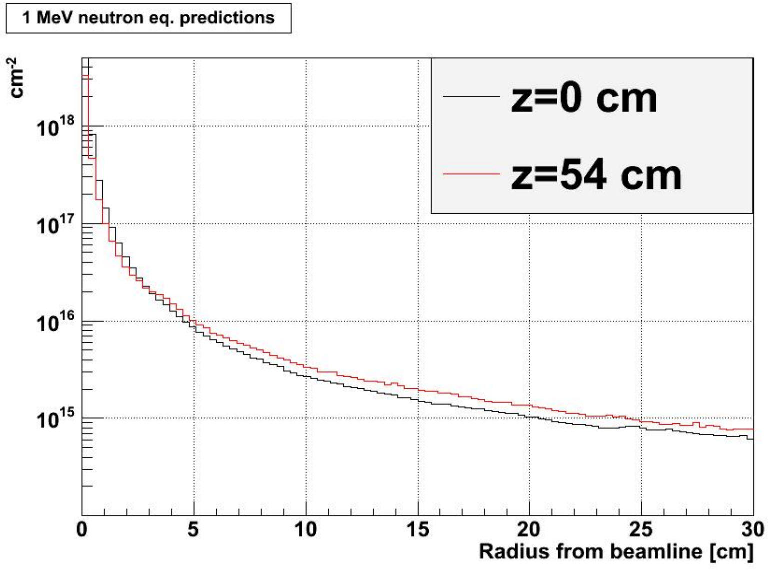


Fluences at HL-LHC

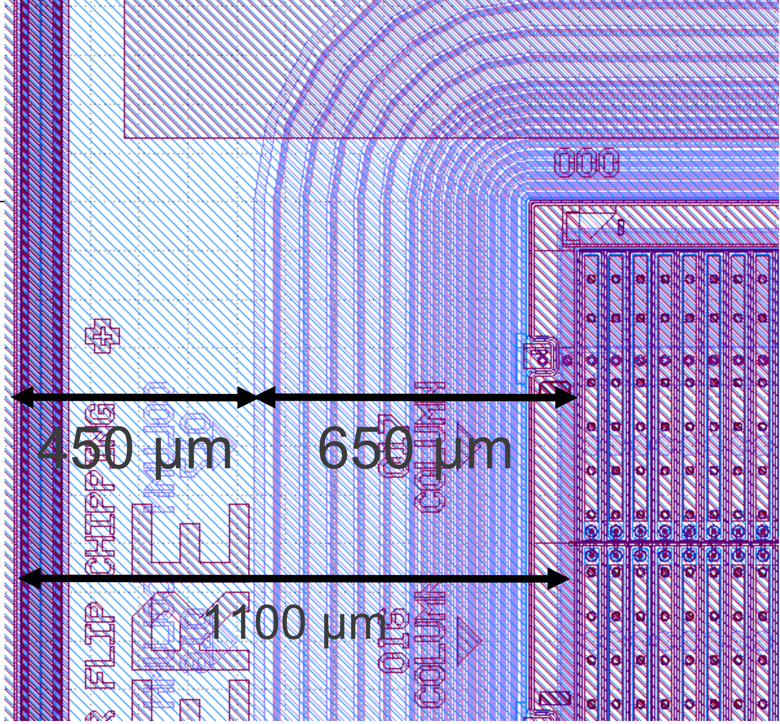
- integrated luminosity for sLHC: 3000 fb^{-1}
- including a safety factor of 2 to account for all uncertainties this yields the following fluences:
  - 2•10^{16} n$_{eq}$ cm^{-2} at 3.7 cm radius
  - up to 10^{15} n$_{eq}$ cm^{-2} at 30 cm radius
  - > 10^{14} n$_{eq}$ cm^{-2} at the outer tracker radius



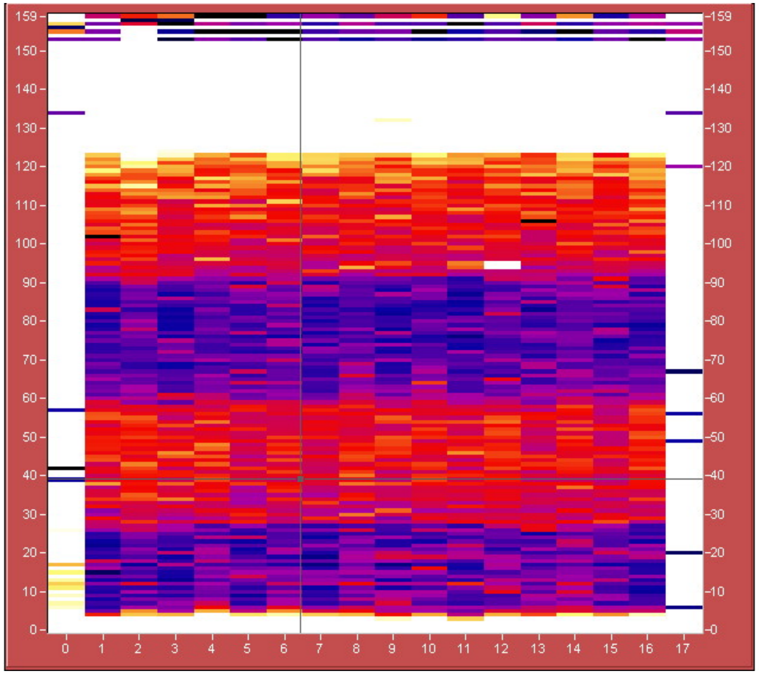




Sample overview – irradiated and unirradiated FE

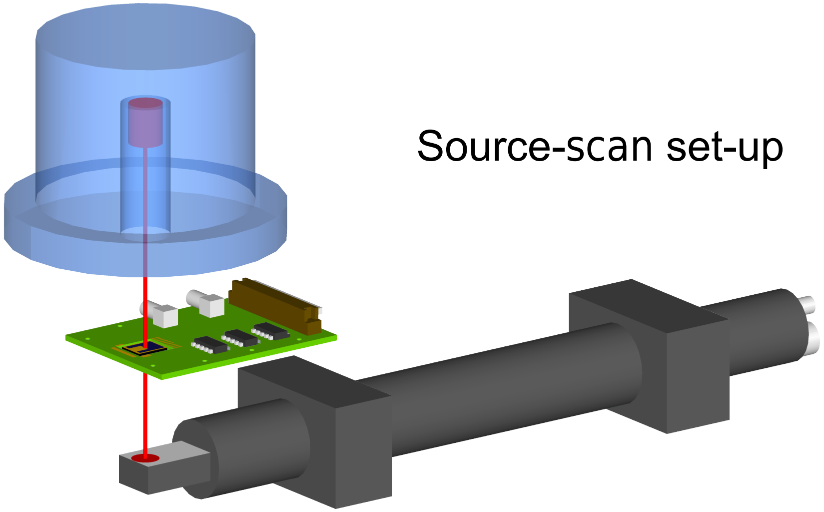


- Standard SingleChip Sensors taken from ATLAS Pixel production wafers
- n^+-in-n design produced by CIS
- 16 guard rings with overhanging metal
- 250µm thick DOFZ bulk
- 400µm by 50µm pixel cells, FE-I3 read out
- Neutron irradiated up to $2 \cdot 10^{16} n_{eq} cm^{-2}$ in Ljubljana
- Trouble with irradiated electronics: threshold tuning and digital communication always work
    - **but**: erratic behaviour observed, even with assemblies from the same irradiation batch:
- Cross checked with indium bump bonded assemblies (80°C-90°C, 2 min)
- Proton irradiated up to $1.4 \cdot 10^{16} n_{eq} cm^{-2}$ with 26 MeV protons in Karlsruhe

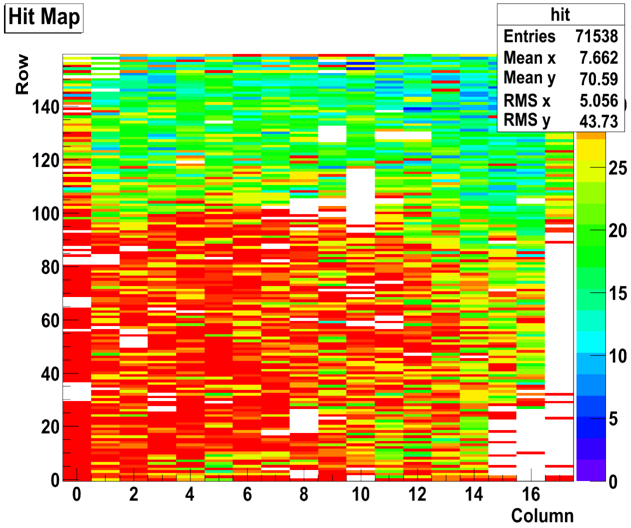


Lab Measurements

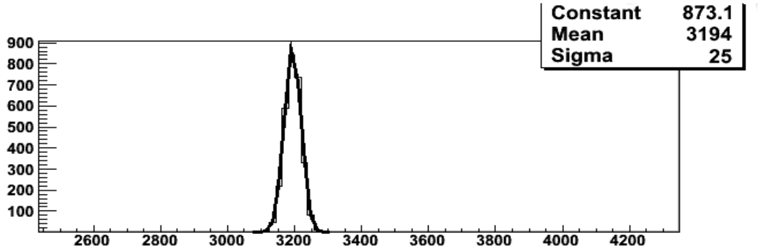
- Source scans with ^{90}Sr (~1MeV electrons)
- External trigger: scintillator coupled to a photomultiplier
- Sensor bias voltage up to 2000V
- Cooling with dry ice (about -45°C on at the aluminum carrier plate)
- Copper tape was used to realize the heat conductive connection between dry ice and the 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



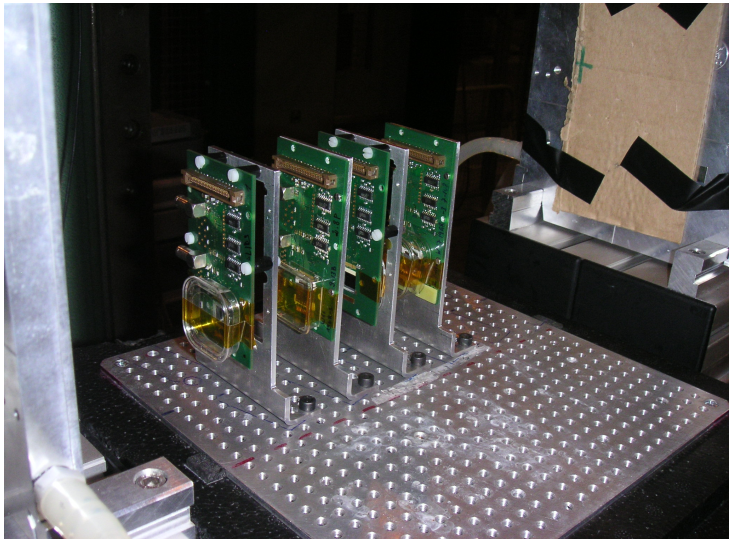
$1200\text{V}, 2.2 \cdot 10^{15}\ n_{eq}/cm^2$



Threshold distribution after tuning

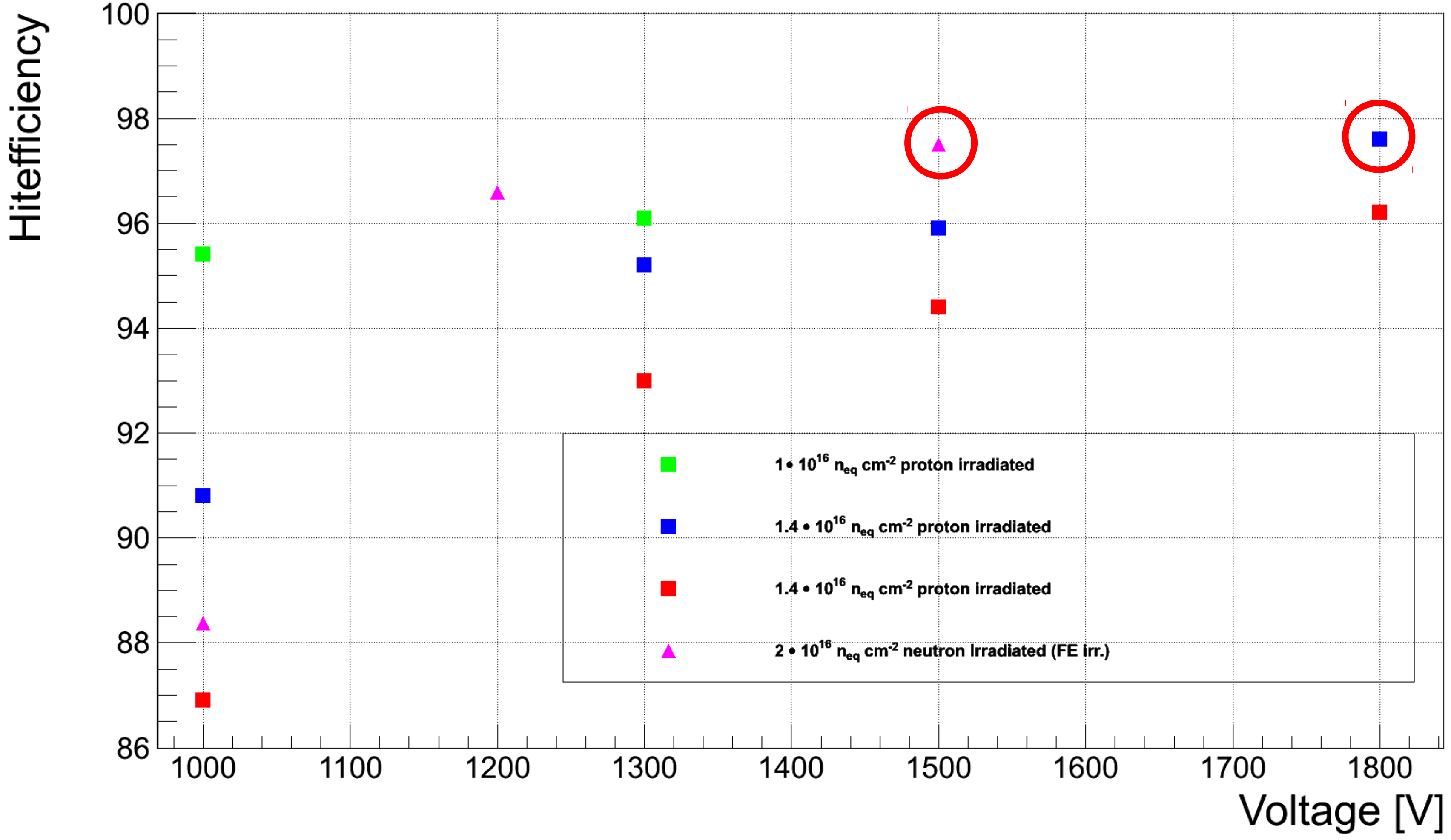
Test beam measurements

- 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)



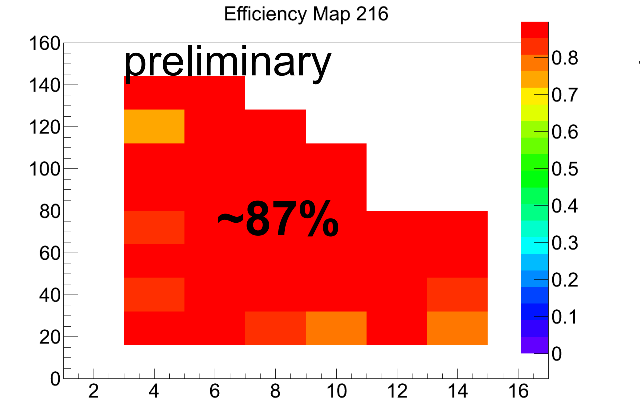
Many thanks to the PPS collaboration and in particular to the PPS Testbeam group and all people involved in the data taking and analysis

Hit efficiency: Indium bumped assemblies

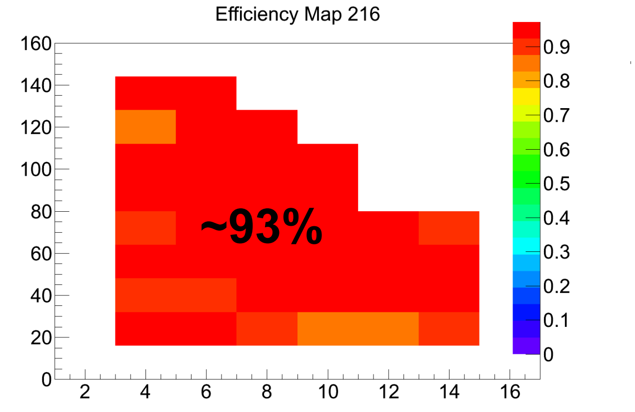


Hit efficiency maps $1.4 \cdot 10^{16}\ n_{eq}\ cm^{-2}$

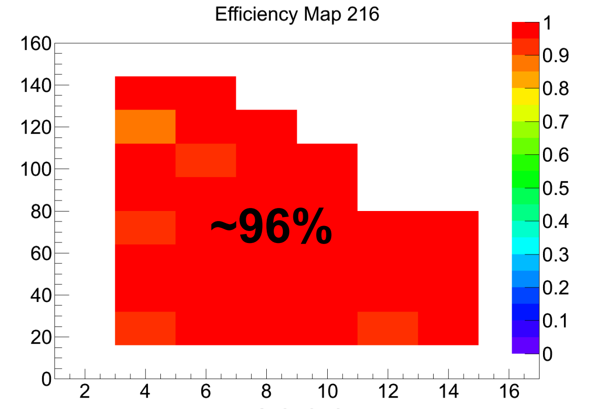
- Some disconnected bumps due to aging



1000V

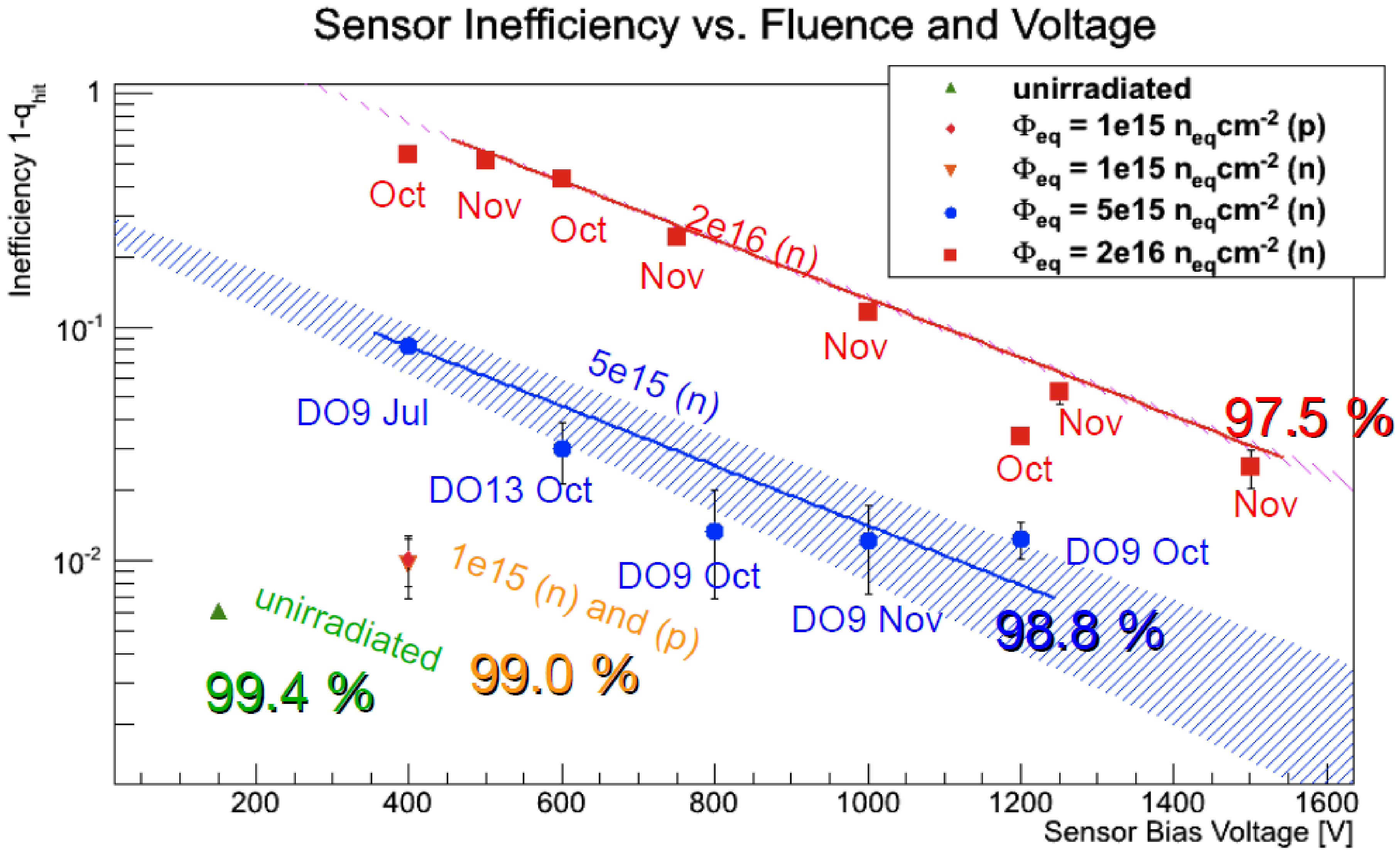


1300V



1800V

Hit efficiency: PbSn bumped assemblies



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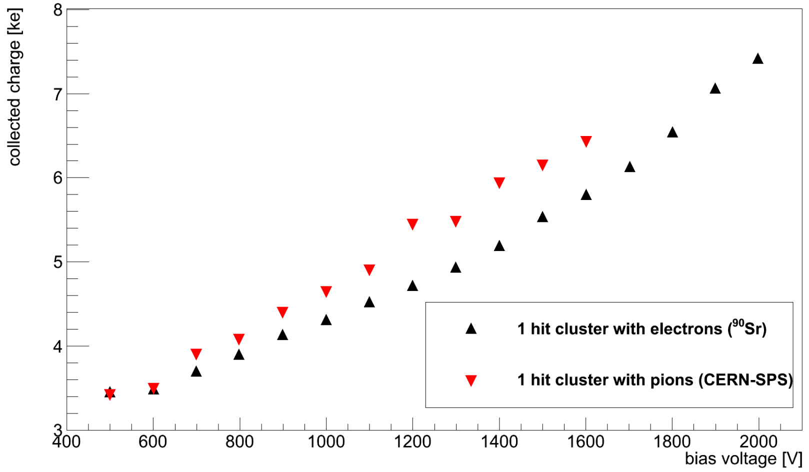
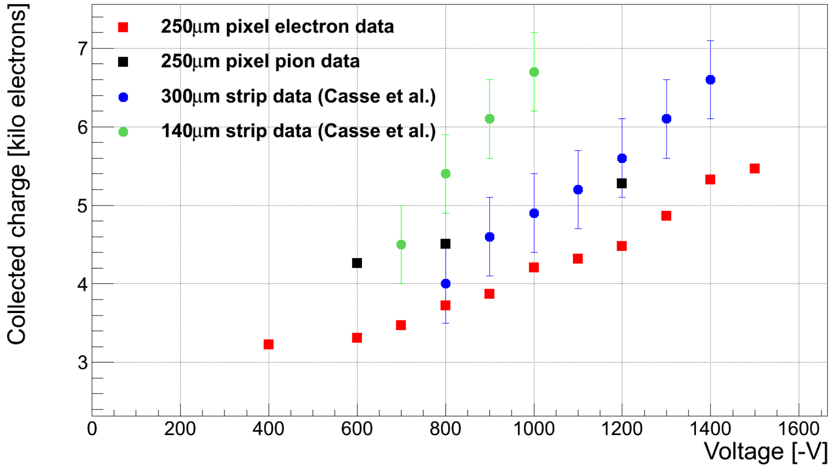
Charge collection

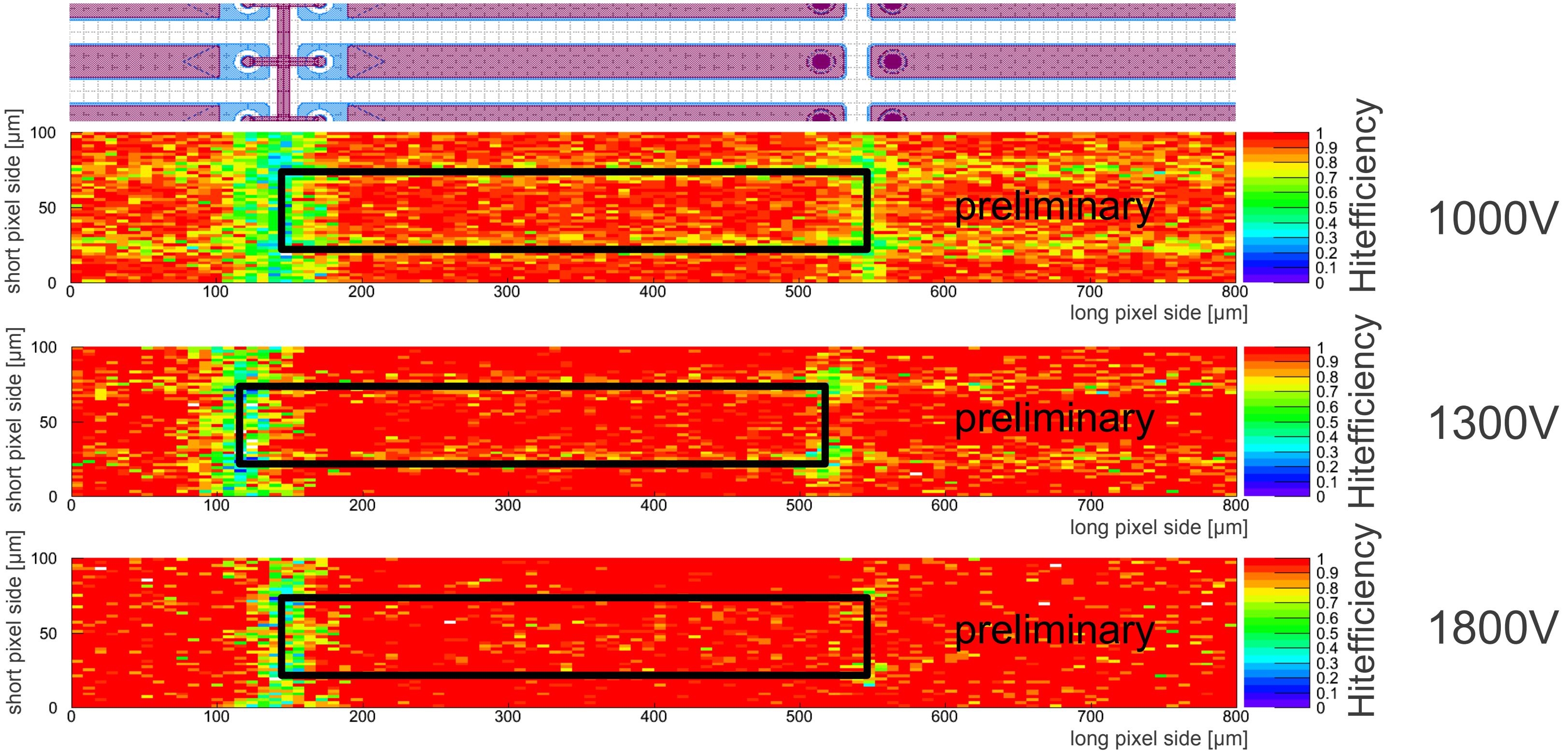
- Charge calibration challenging but comparison with irradiated and unirradiated front end electronics at least comparable at the first glance
- Sensors irradiated to a fluence about $2 \bullet 10^{16}\ n_{eq}\ cm^{-2}$ yield 4-5ke at 1000V and about 7-8ke at 2000V
- More comparisons / evaluation of ToT-Charge conversion upcoming





Charge loss and possible improvements

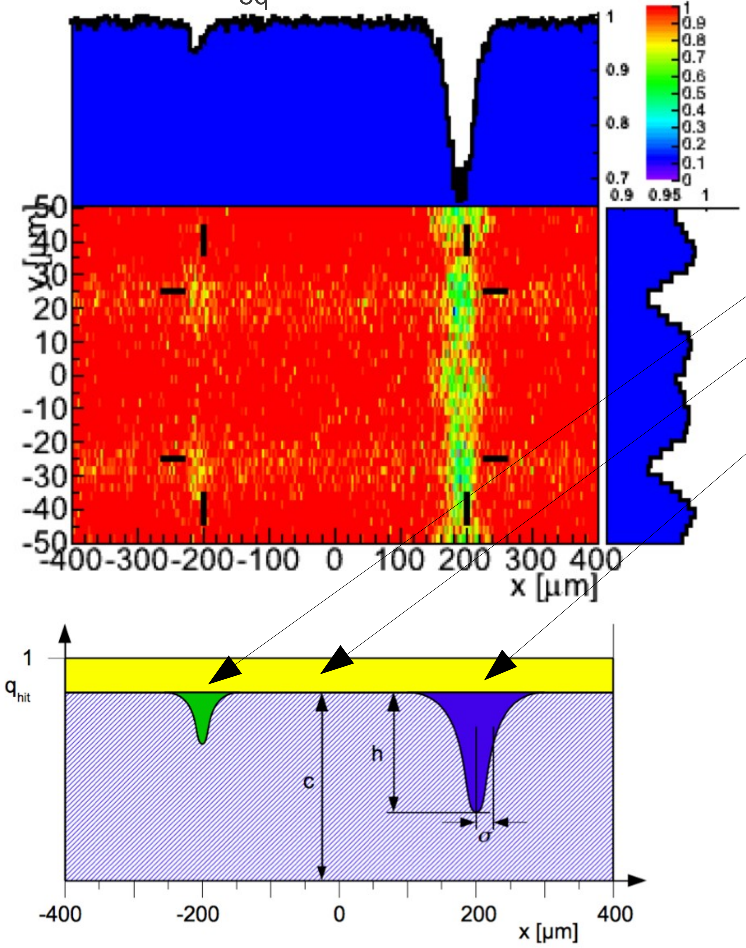
- Most of the pixel has much higher efficiency than 97% – charge loss seems to occur mainly under the bias grid



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

Sub pixel resolved hit efficiency

Hit efficiency of DO10
$2 \cdot 10^{16}\ n_{eq}\ cm^{-2}$ @ 1200V



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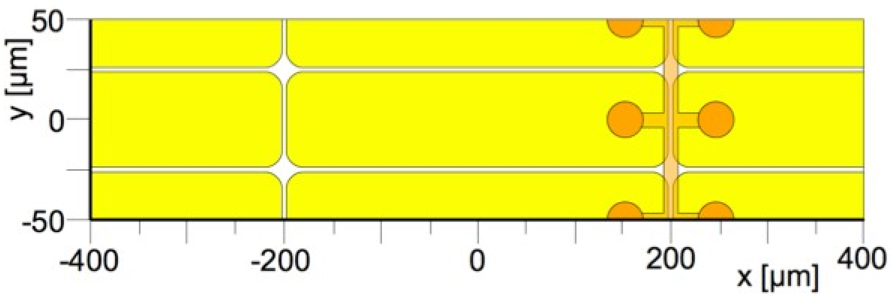
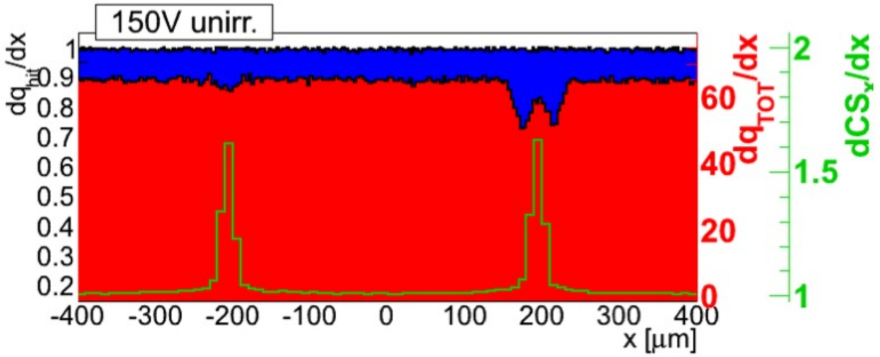
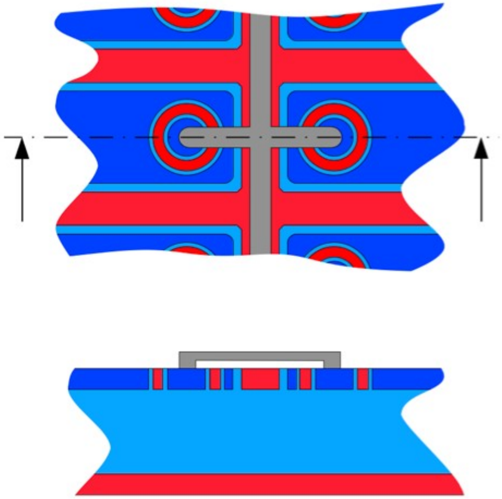
- Bias dot is visibly separated from Bias grid rail
- 3 regions to identified:
  - Pixel edge at bump pad
  - Constant region
  - Pixel edge at bias dot
- The efficiencies of the bump pad region and constant region improve / restore with increased bias voltage
- No impact on bias dot / bias grid region

Bias grid





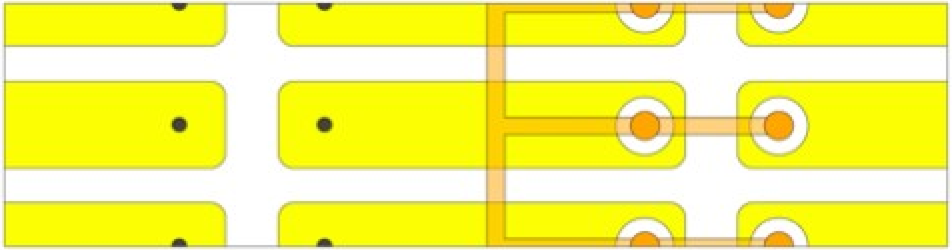
- Bias grid network is an aluminum trace above the inter-pixel area
- The potential is (almost) ground. The trace is AC-coupled to the bulk
- The trace bends the field lines
- Charge loss from this effect and normal charge sharing add up and lead to a localized decreased efficiency



Bias grid variations

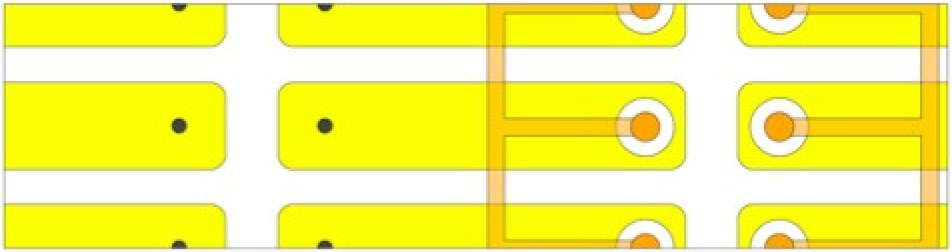
- How to get rid of the inefficiency introduced by the bias grid?
- Omit it completely – has to think about testability (temporary metal?)
- Move it on the n-implants and get more hits above the threshold by differentiating geometrically the charge loss under the bias grid and the charge loss by charge sharing which occurs any case
- In case (a) and (c) the material budget stays the same

(a) Bias grid network on bias dot, single trace



(b) Bias grid network in pixel center, single trace

(c) Bias grid network on bias dot, double trace



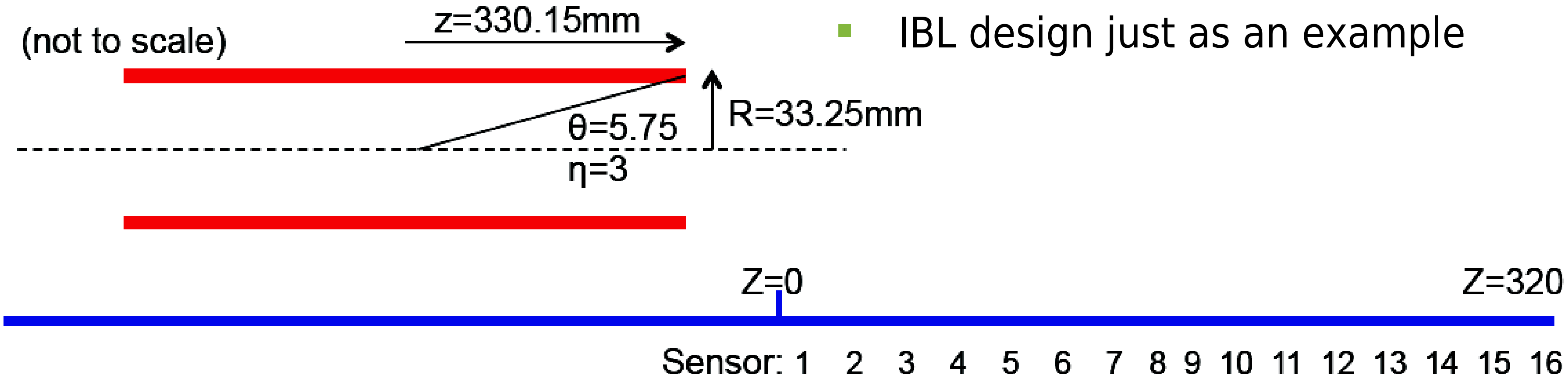
(d) Bias grid network in pixel center, double trace

How critical is it actually?

- Very few modules in a proposed are phase 2 Upgrade are actually at 0°
- It can't be completely disregarded
- IBL design just as an example

IBL Geometry:

(not to scale)



Sensor	Z* (center)	θ	η
1	10	73.26	0.30
2	30	47.9	0.81
3	50	33.6	1.2
4	70	25.4	1.5
5	90	20.3	1.72
6	110	16.8	1.91
7	130	14.3	2.08
8	150	12.5	2.21

Sensor	Z* (center)	θ	η
9	170	11.1	2.33
10	190	9.9	2.45
11	210	9.0	2.54
12	230	8.2	2.64
13	250	7.6	2.71
14	270	7.0	2.79
15	290	6.5	2.87
16	310	6.1	2.93

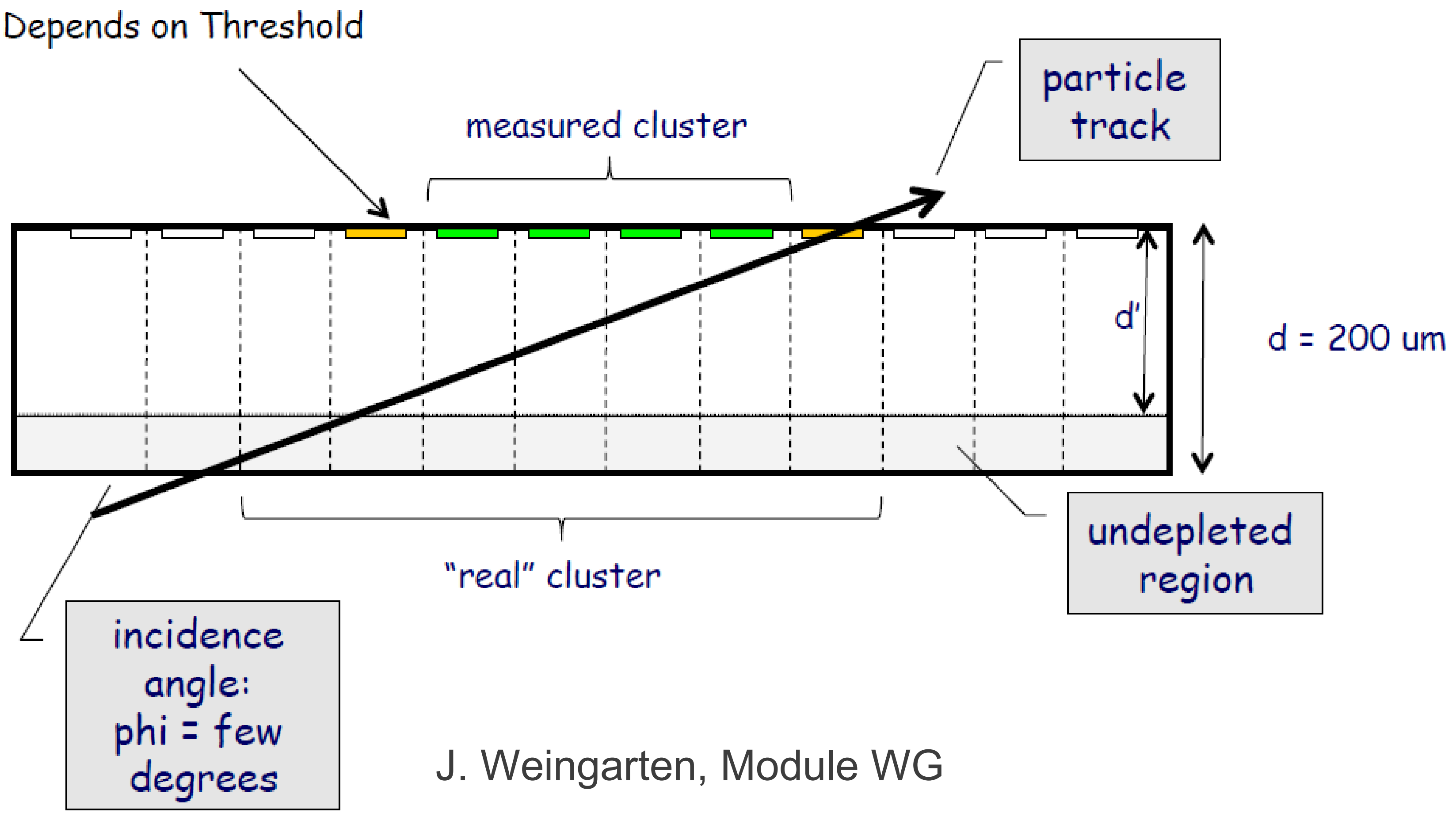
* z(center) rounded, not exact values.

J. Weingarten, Module WG

PPS situation at large eta

- Track segment length longer than bias dot region → charge loss mitigated by smearing out

At theta=6°, in a fully depleted sensor (200µm), tracks hit 7 pixel cells!



Depends on Threshold

measured cluster

particle track

d'

d = 200 um

"real" cluster

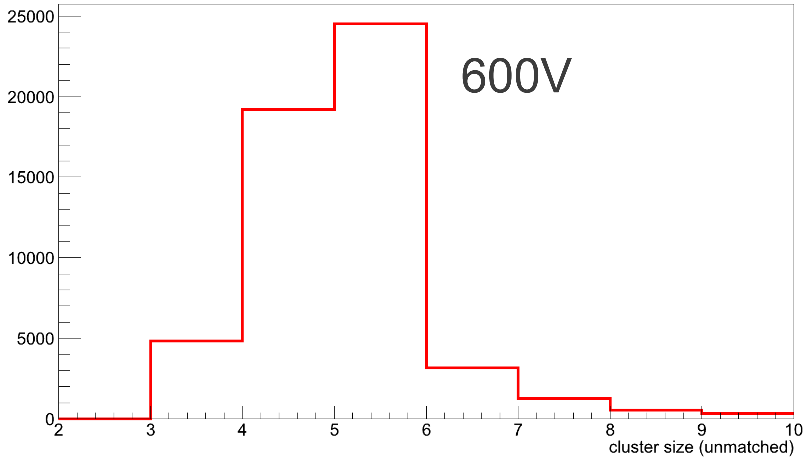
undepleted region

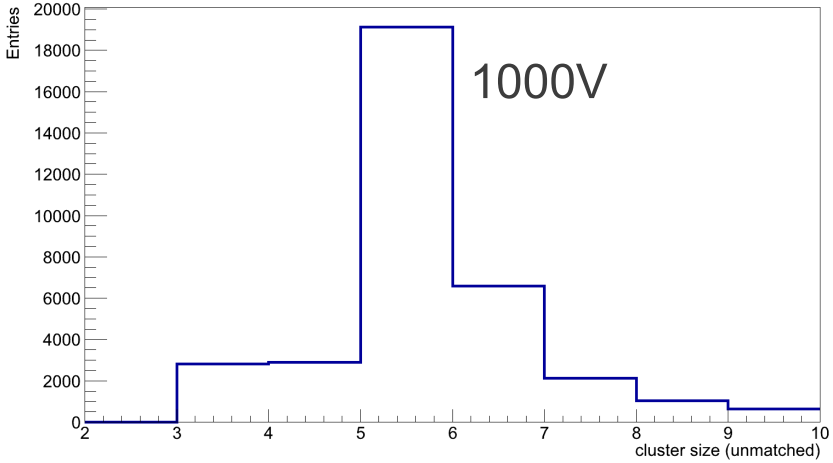
incidence angle: phi = few degrees

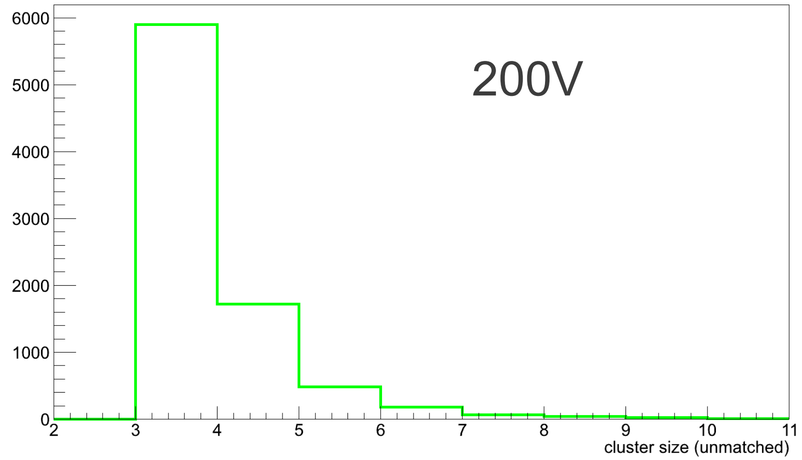
J. Weingarten, Module WG

How to deal with big clusters

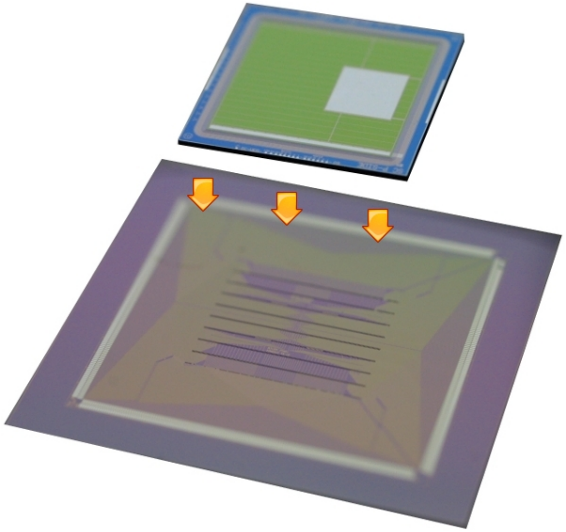
- Impact of smearing out
- Example of the cluster size distribution changes from September 2011 IBL textbeam (not matched)
- It might be advantegeous to be able to reduce the active zone thickness by decreasing the bias voltage → finding the optimum

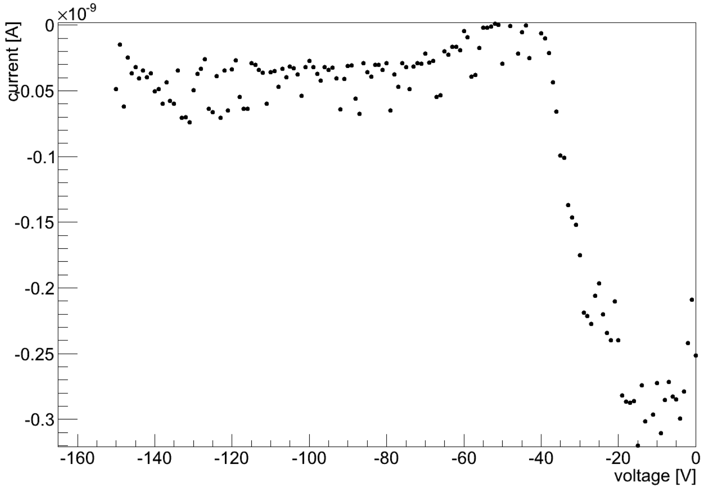


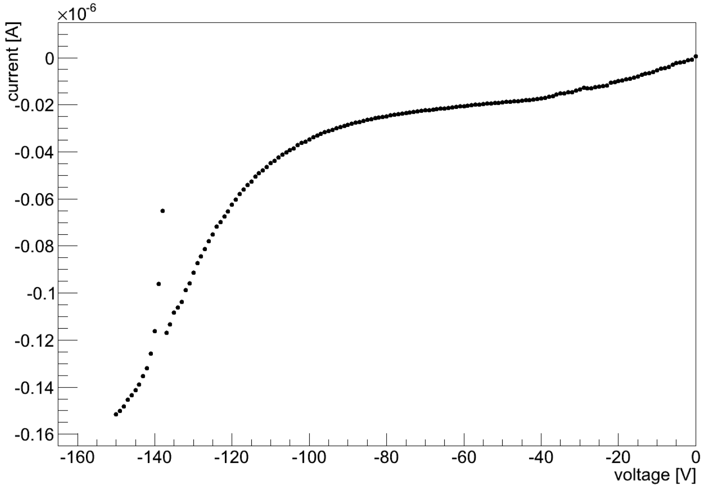




Fanout – A second cross check







- Readout of pixel sensor with unirradiated readout electronics
- Passive aluminium traces on electronics grade silicone wafer material
- Possible comparison by using standard strip readout (ALIBAVA-System)

Conclusions and Outlook

- It has been shown that planar n^+-in-n sensor can be still operated after an irradiation of $2 \cdot 10^{16}$ $n_{eq}cm^{-2}$ (HL-LHC inner most layer end of life fluence)
- Sensors yield a charge at 0° of 5000-7000 electrons and low noise → sufficient for new electronics with thresholds below 1500 electrons
- Beam test measurements show a hitefficiency around 97% at a bias voltage of 1500V and eta=0°
- Cross check with unirradiated readout electronics successful
- The main reason for lost charge is the bias grid → there are ideas how to improve this:
  - New bias grid designs
  - No bias grid / temporary metal
- It has been shown that for slighty more inclined tracks the traversed zone is larger than this area and thus can be disregarded → Only very few tracks will occur at thus low eta
- Tracking resolution at high eta might be improved by lowering the bias voltage an thus decreasing the cluster sizes (cluster size reduction observed in beam test)

Backup