Recent progress of the ATLAS Upgrade Planar Pixel Sensor R&D Project

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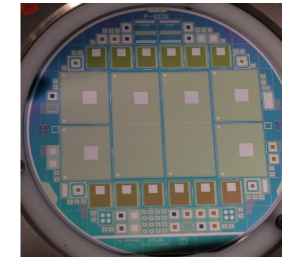
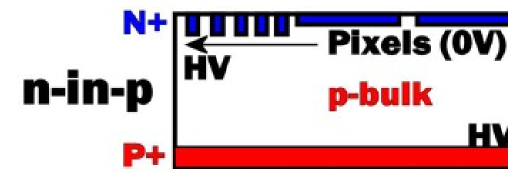
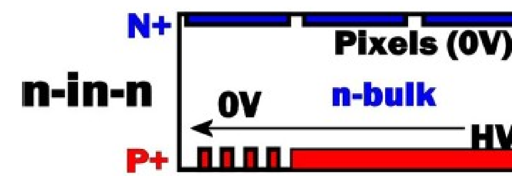
on behalf of the ATLAS PPS collaboration

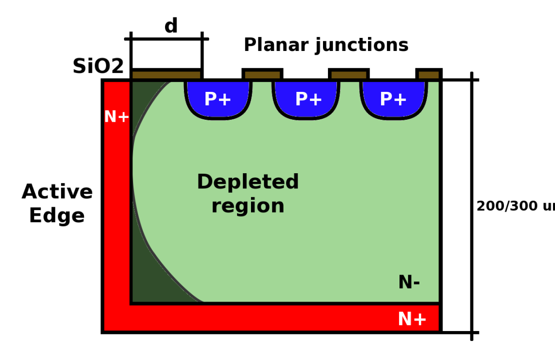
Outline

- The LHC future plans
- A new Atlas Pixel Detector
- The Atlas Upgrade Planar Pixel Sensor R&D Project
- N-in-p: overview
- N-in-n: irradiation & test beams results
- Thin n-bulk production
- Simulation studies
- Slim / Active edge
- Conclusions & outlook



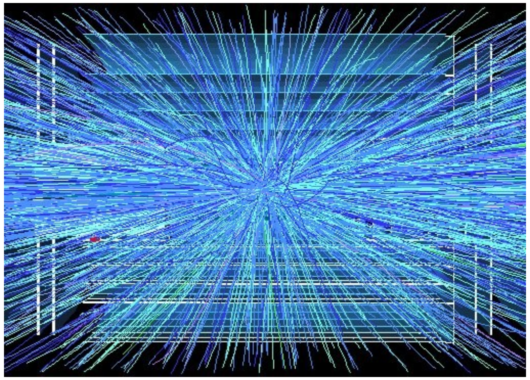


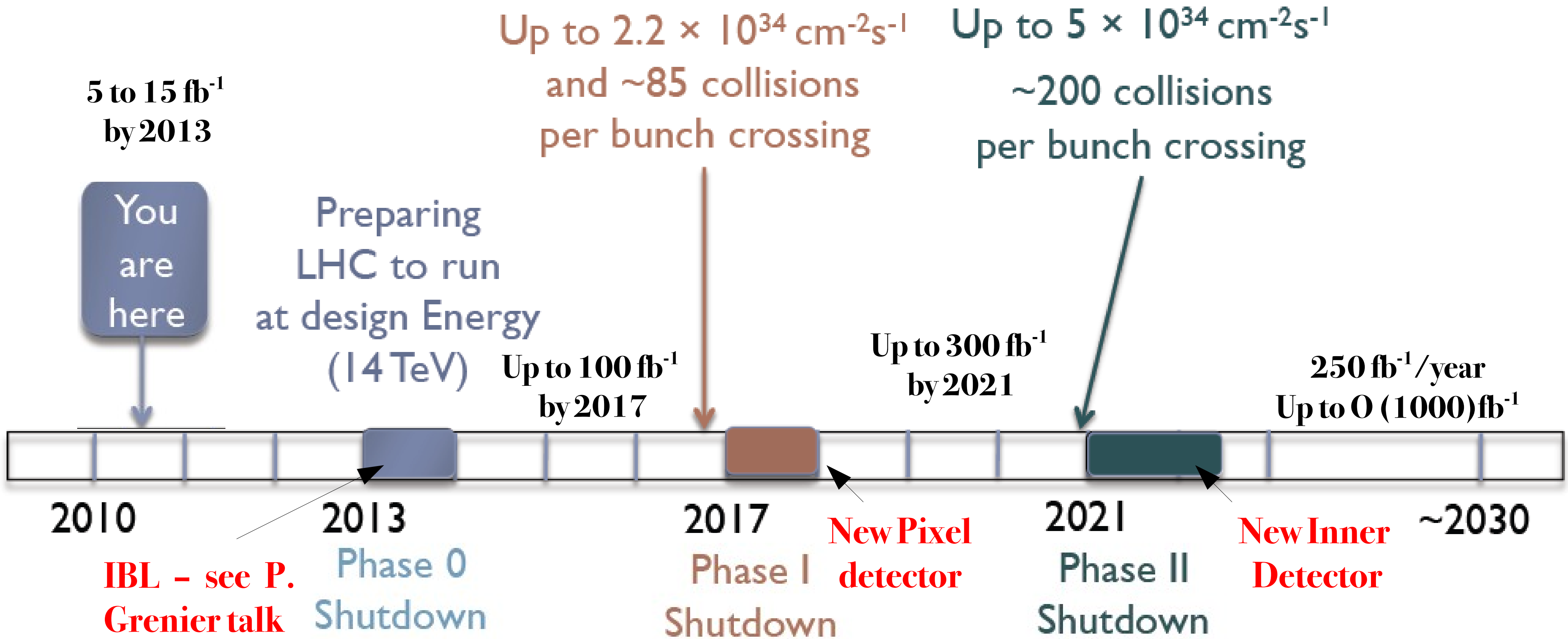




The LHC future plans

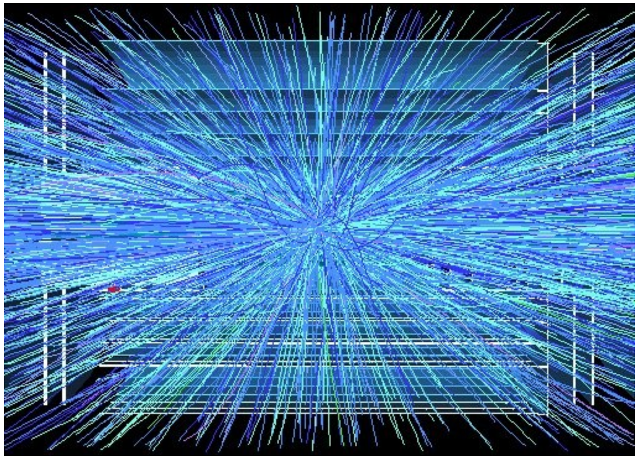
- The discovery potential of the LHC can be enhanced by increasing its luminosity
- **HL-LHC plans**
  - Caveat: this schedule spans decades





HL effects on Pixel Detector

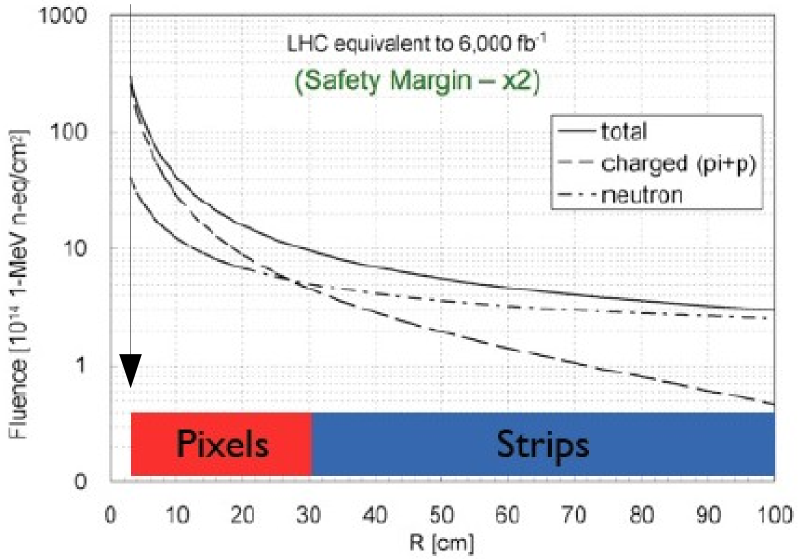
- Higher luminosity means
- ✔ More pile-up & higher rate events
- ➔ Higher granularity



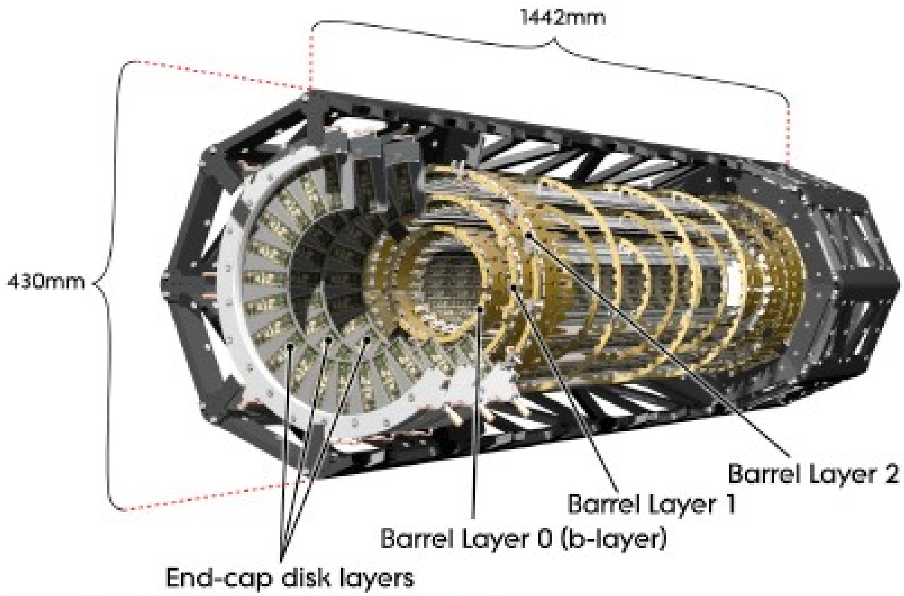
fluences for the innermost pixel layer:

$1\text{-}2 \times 10^{16}\, n_{eq}/cm^2\,(3\, ab^{-1})$

- ✔ Large fluences
  - ✗ Dark current increase
  - ✗ Change of working voltage
  - ✗ Reduced charge collection eff.
- ➔ Radiation hard components

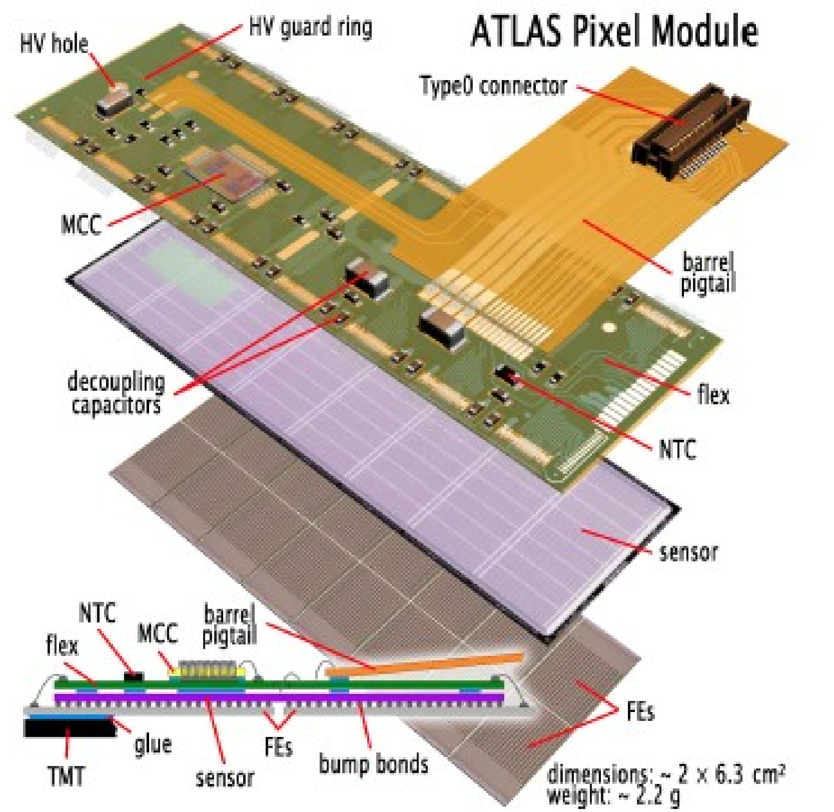


The ATLAS Pixel detector



- ATLAS Pixel Detector
  - 3 barrels + 3 forward/backwarc disks
  - 112 stave and 4 sectors
  - 1744 modules
  - 80 million channels

- **ATLAS Pixel Module**
  - 16 front-end chips (FE-I3) module with a Module Controller Chip (MCC)
  - 46080 R/O channels 50 µm x 400 µm (50 µm x 600 µm for edge pixel columns between neighbour FE-I3 chips)
  - Planar n-in-n DOFZ silicon sensors, 250um tick
  - Designed for 1 x 10^{15} 1MeV fluence and 50 Mrad
  - Optolink R/O: 40÷80 Mb/link



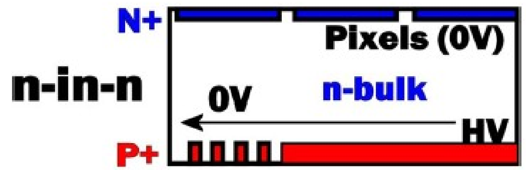
IPRD10, Siena 9.6.2010 - Alessandro La Rosa (CERN)

The PPS R&D project

- Aim: Explore the suitability of planar pixel sensors for highest fluences

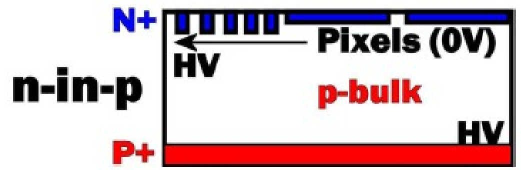
Timeline: new Pixel (2017) + new ID (2021)

  - Approved ATLAS R&D project since 2009: 17 institutes, > 80 scientists

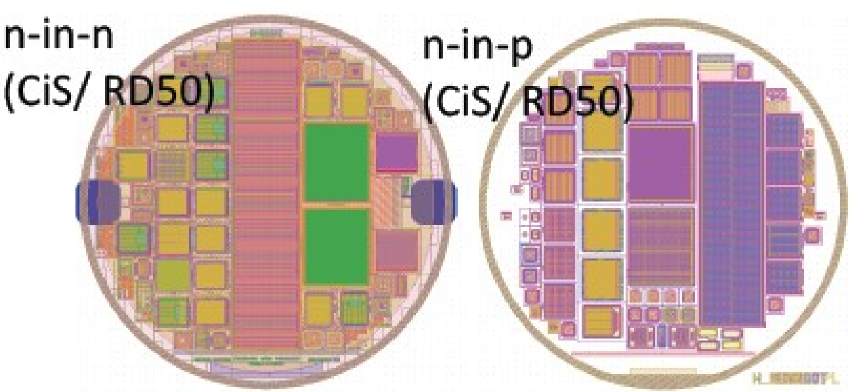


- Planar pixel is a proven technology
  - the current n-in-n pixel detector.
  - present modules already shown to work after $10^{15} n_{eq}/cm^2$
  - If strips not adequate any more, PPS would be the natural option

N-in-p: A. Macchiolo talk (09 June - 3pm)



- Research directions
  - **Radiation damage studies**
  - Active area optimization and geometry redesign
  - Advanced simulation studies



PPS collaborators

Participating Institutes

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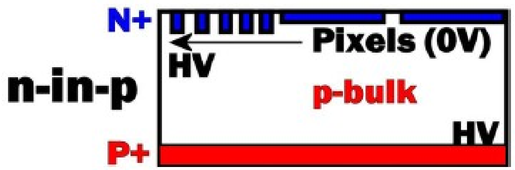
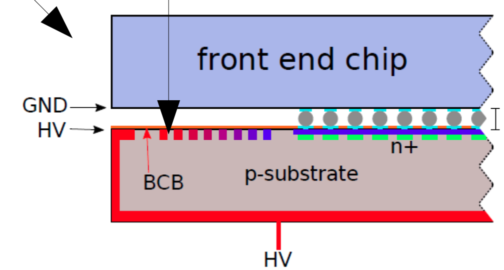
PPS n-in-p overview



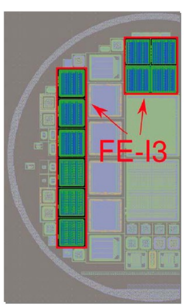
- ✓ Larger **areas** → larger **cost**: **single-side** patterned sensor can **help**! (e.g. An ID with pixels only → 10 m^2)
- ✓ p-type bulk does **not invert** → stable operation
- ✗ Sensor **edge** at **HV**, facing electronics at GND → pixels can suffer from **sparks**
  - ➔ First countermeasures looks promising

Sensor covered with 3 μm of BCB

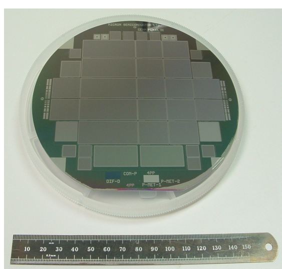


Contributors

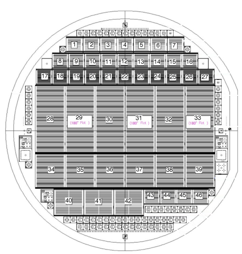
CiS



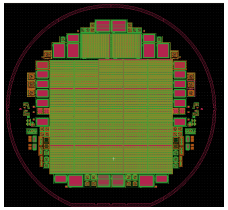
Micron



HPK

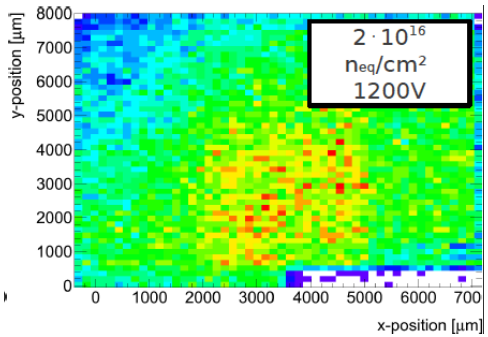


MPI-HLL



	Thickness (μm)	Material	PX Isolation	Tests
CiS (n-in-n too)	285/200/150 (more details later)	FZ	hom./mod. p-spray	See A. Macchiolo talk
Micron (n-in-n too)	300/150 (same)	FZ	p-spray	Irrad., CC, testbeams
HPK	320/150	FZ	p-stop/spray	Irrad., testbeams
MPI-HLL	150/75	FZ	p-stop/spray	Irrad.

N-in-n: radiation hardness

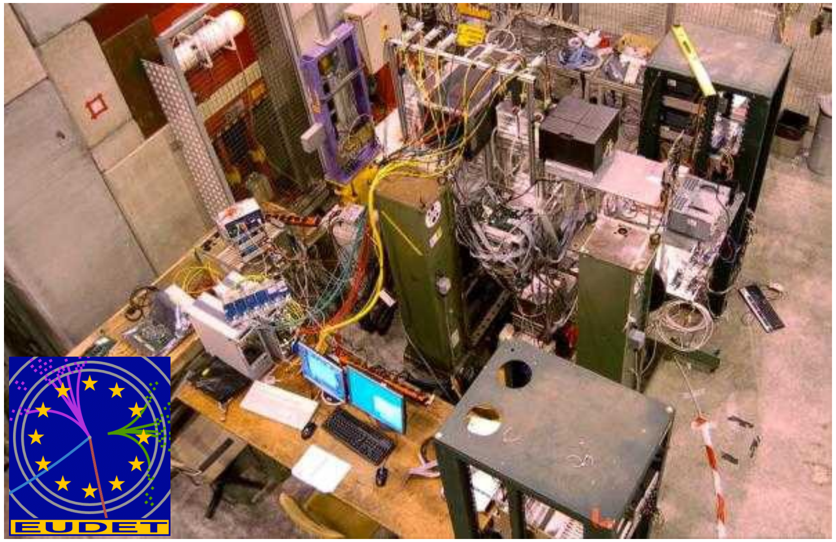


- Current Atlas Pixel modules used
- Fluences up to $2 \times 10^{16}\ n_{eq} / cm^2$
  - Irradations conducted with neutrons at the JSI TRIGA reactor in Ljublijana
- Very cold operation (operation -25/-30 C - test down to -50 C)
- Modules are tested with sources and on beam to measure:

➔ Collected charge

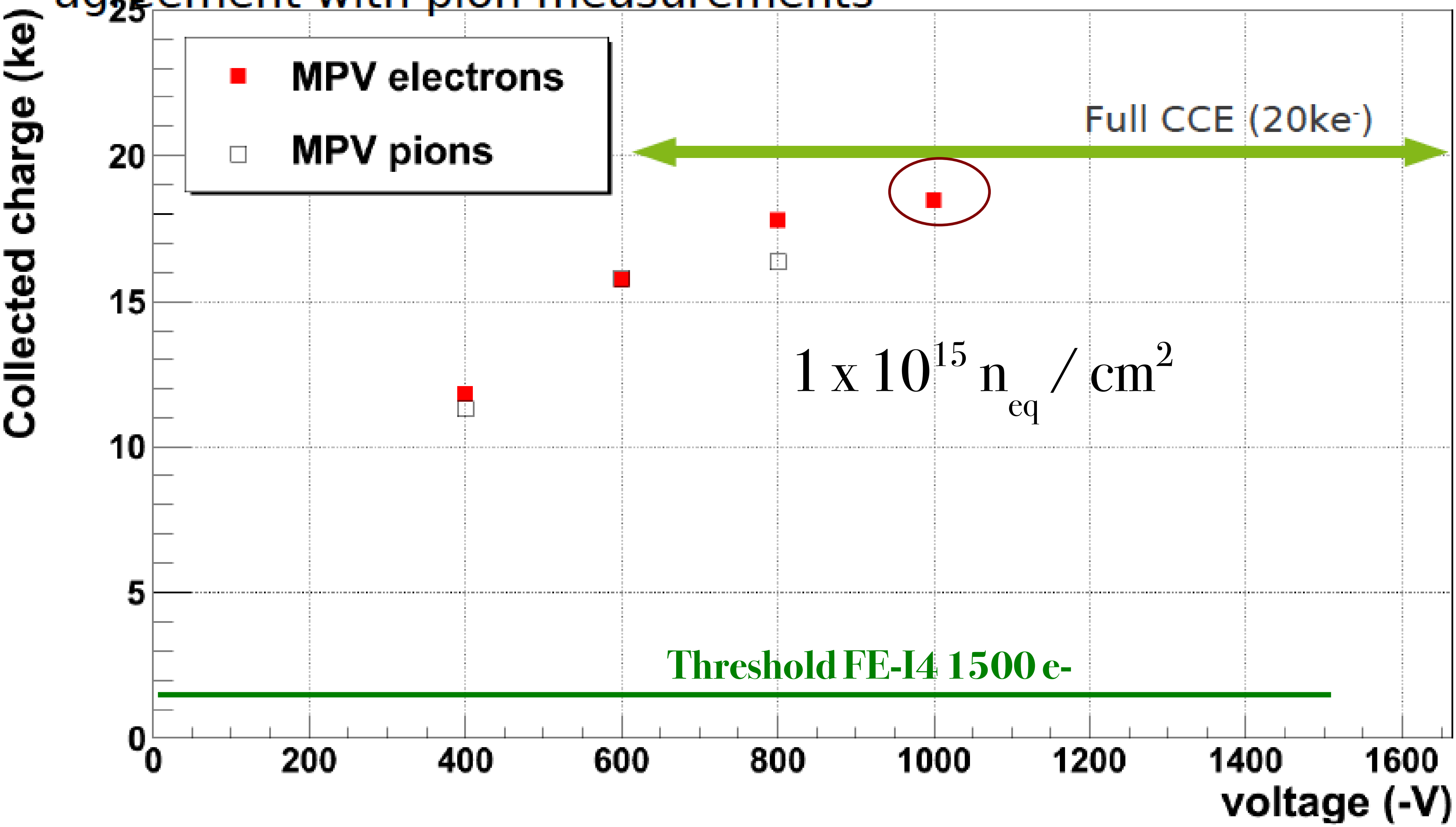
➔ Efficiency

➔ …



Charge collection

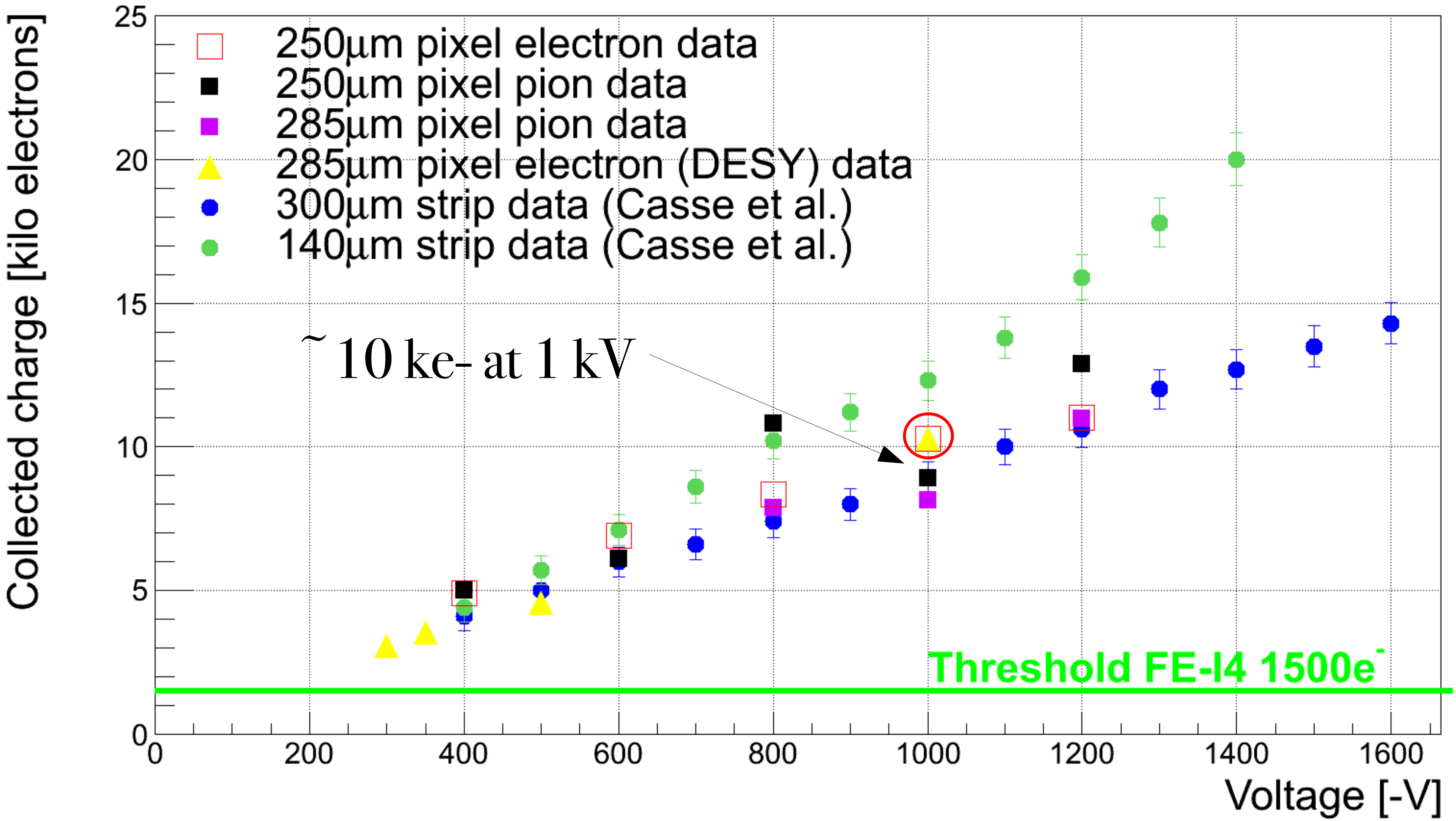
- satisfactory results: 16 ke⁻ at 600V, almost full CCE at 1kV
- agreement with pion measurements



Charge collection

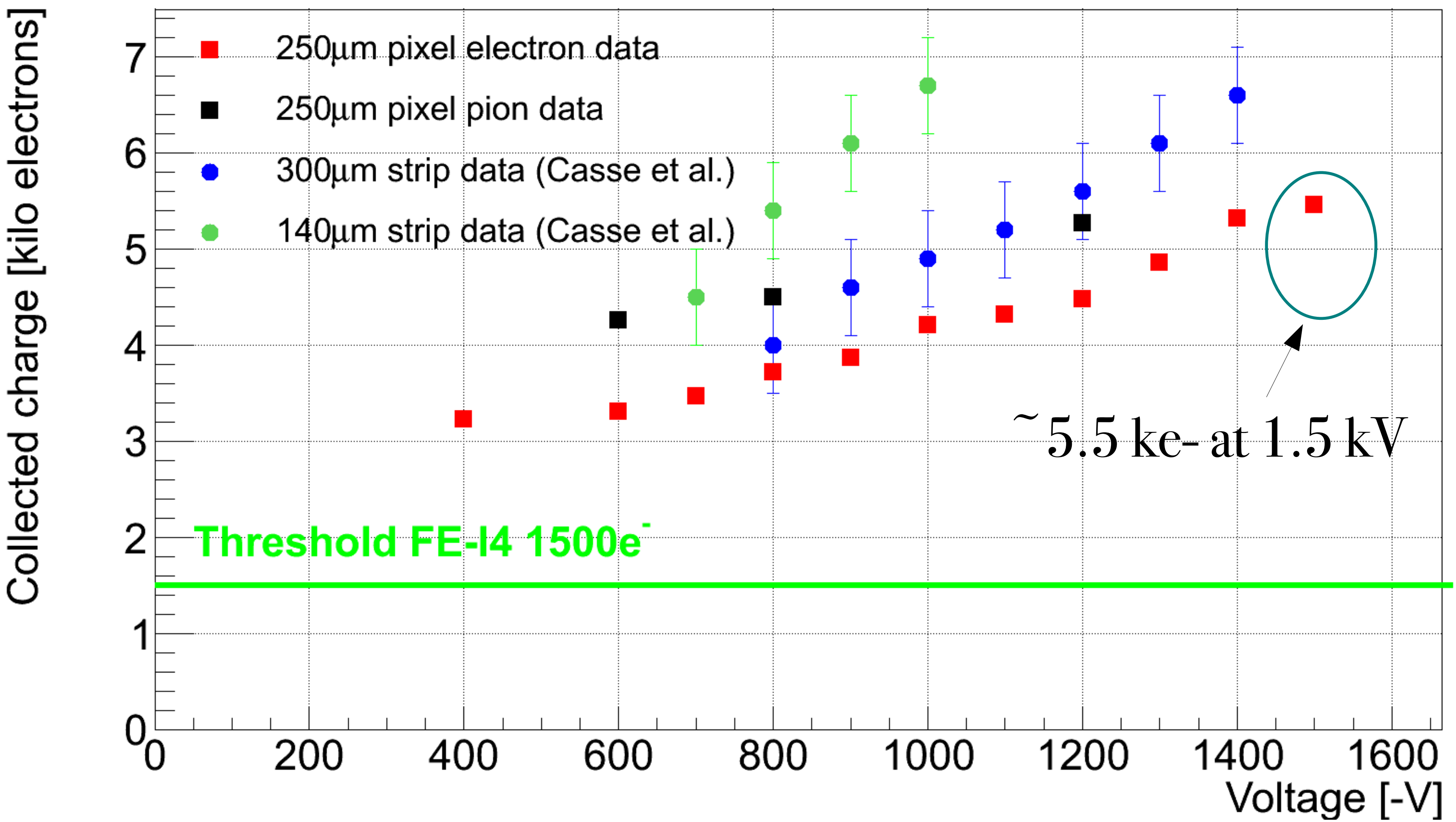
$5 \times 10^{15}\ n_{eq} / cm^2$

- data quite consistent
- MPV



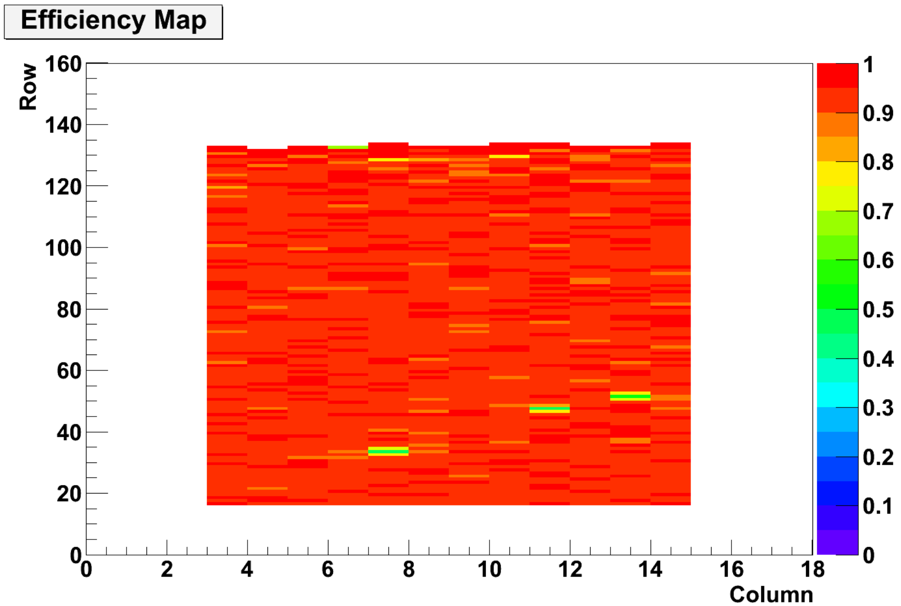
Charge collection

$2 \times 10^{16}\ n_{eq} / cm^2$ - SLHC innermost Layer expected fluence

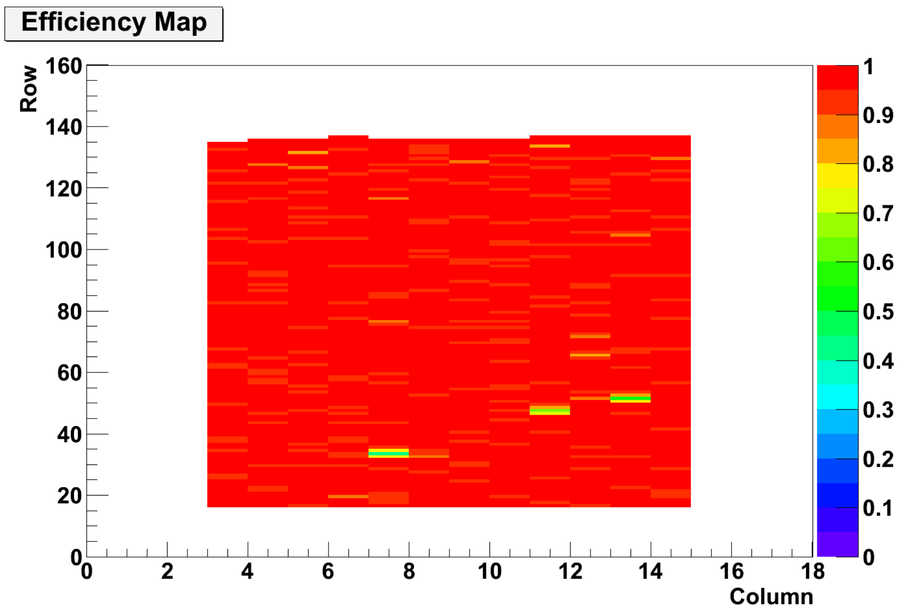


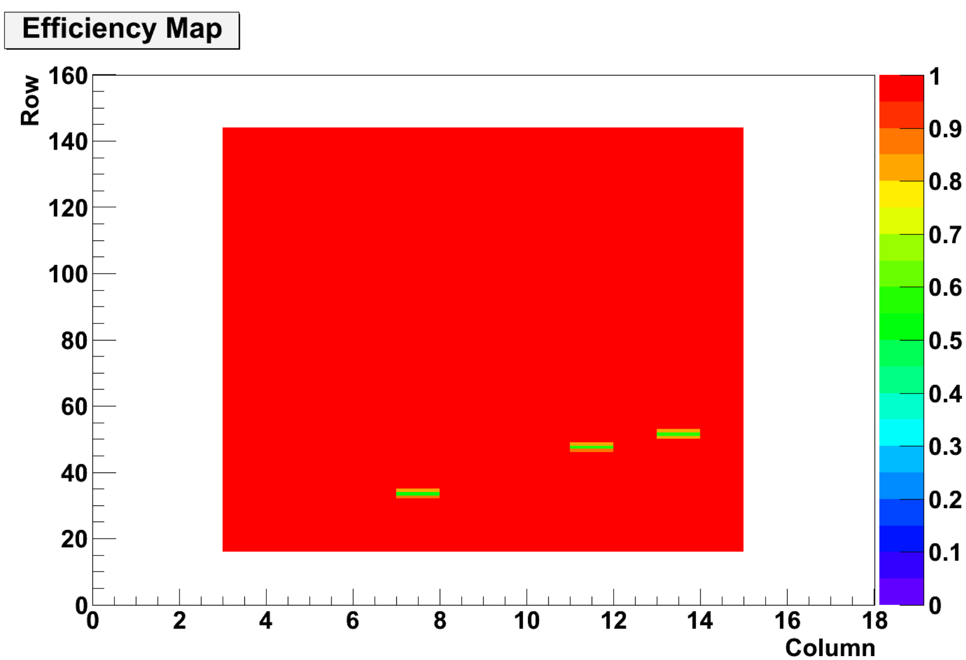
Hit efficiency

$5 \times 10^{15}\ n_{eq} / cm^2$ @ 350 V
$\rightarrow 93.2\ \%$



$5 \times 10^{15}\ n_{eq} / cm^2$ @ 500 V
$\rightarrow 97.3\ \%$

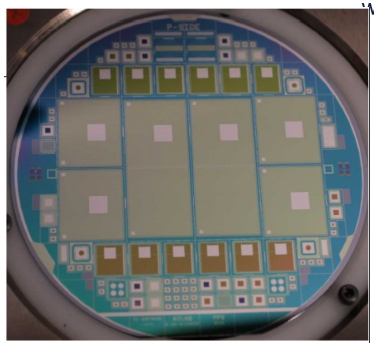




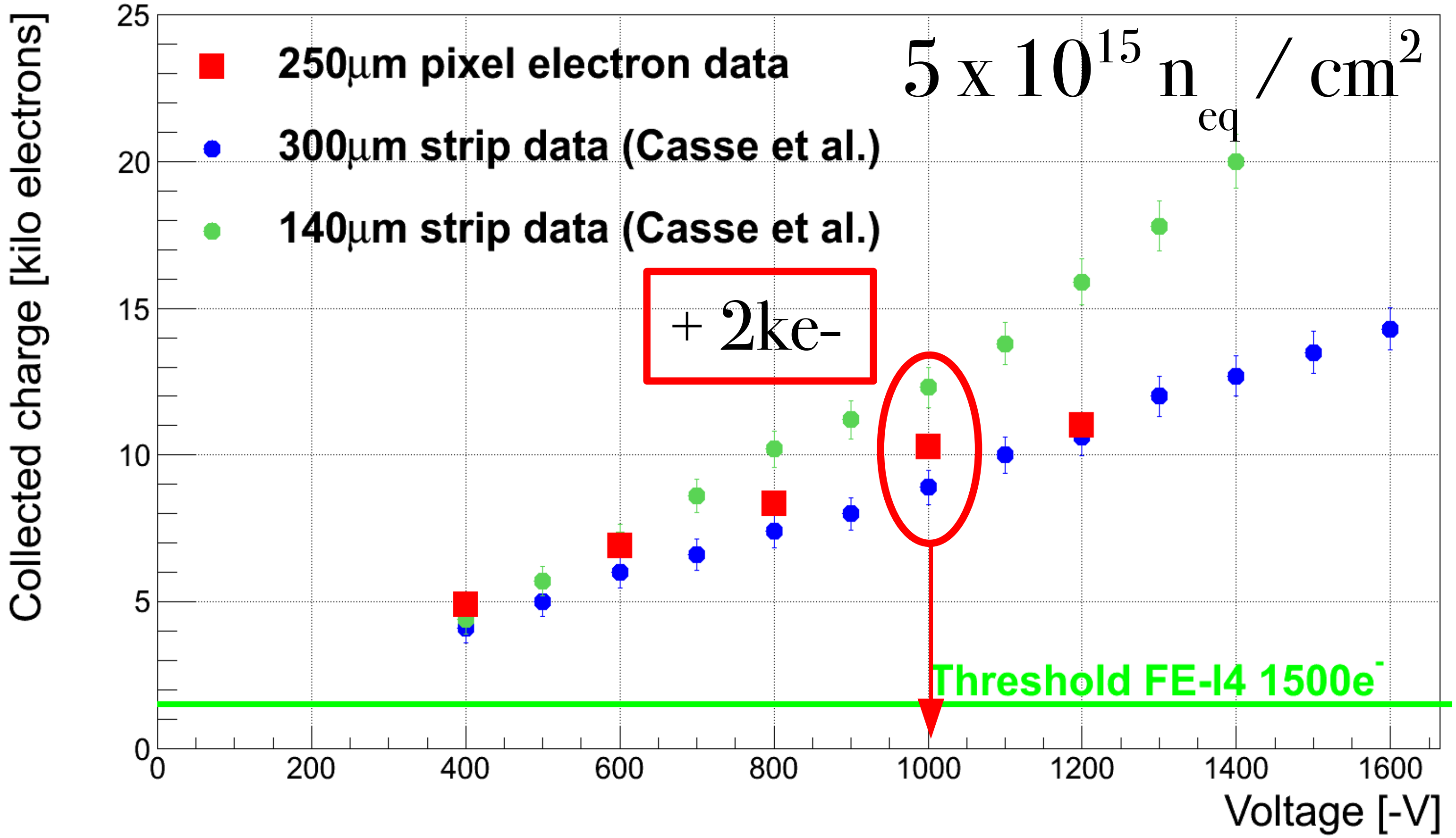
$5 \times 10^{15}\ n_{eq} / cm^2$ @ 1000 V
$\rightarrow 99.6\ \%$ efficient

Thin sensors

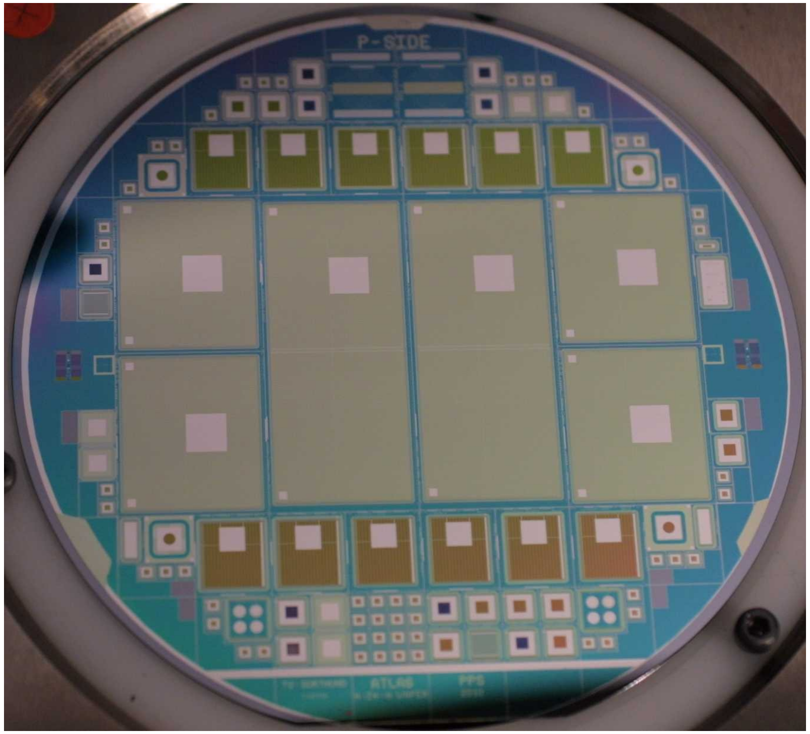
- Thinner sensors
  - With the same voltage → higher E field → More charge amplification
    → Velocity saturation
  - Smaller radiation length



- n-CiS production: down to 150 μm, no support wafer



Thin production



- 5 different thickness
- Detailed studies of

➔ Charge collection

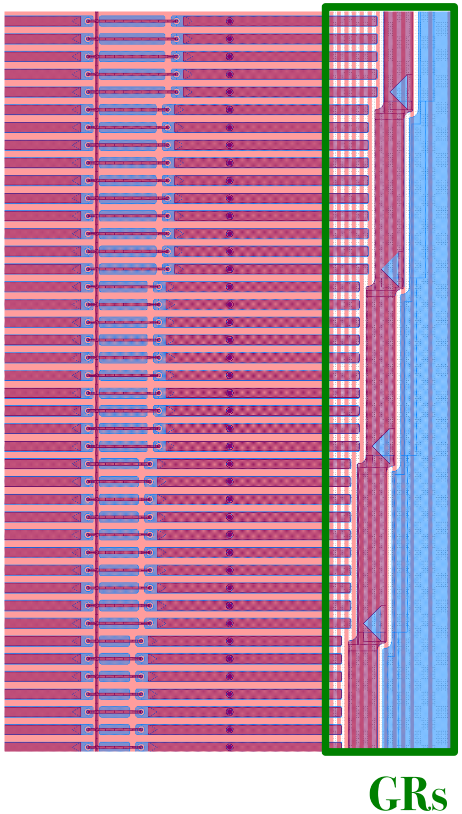
➔ Charge amplification

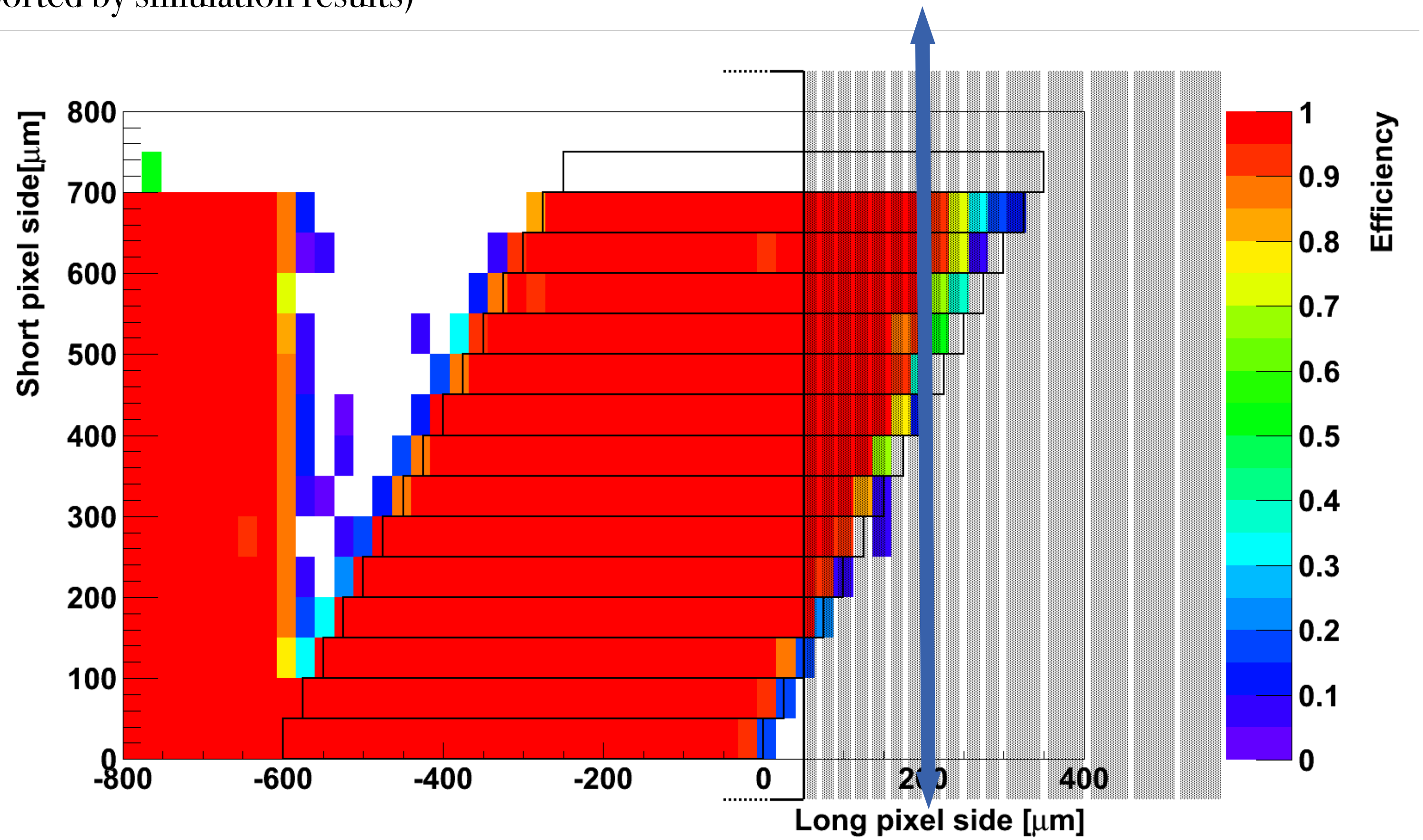
thickness	wafers ordered	wafers received
250um	12	18
225um	6	11
200um	6	10
175um	6	11
150um	6	8

Irradiation studies already started!!! (→ 200um, 150um)

Slim edge

- Inactive area should be kept at minimum
  - *e.g.* Inner layers: no shingling in z
- 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)

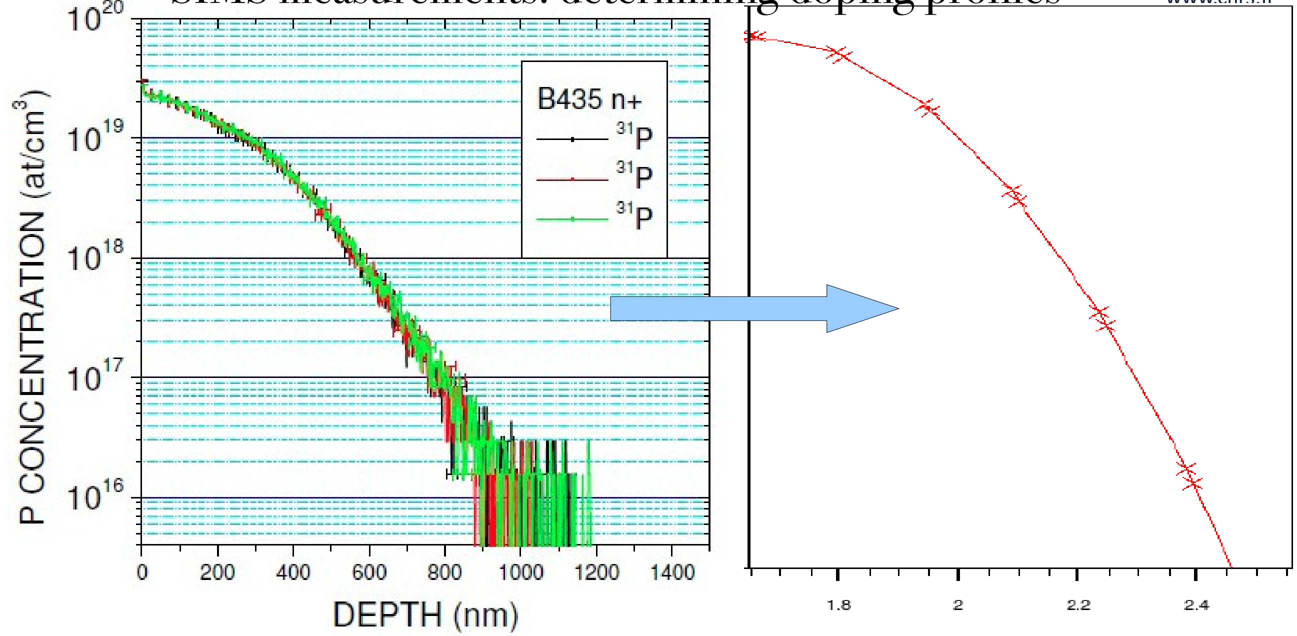




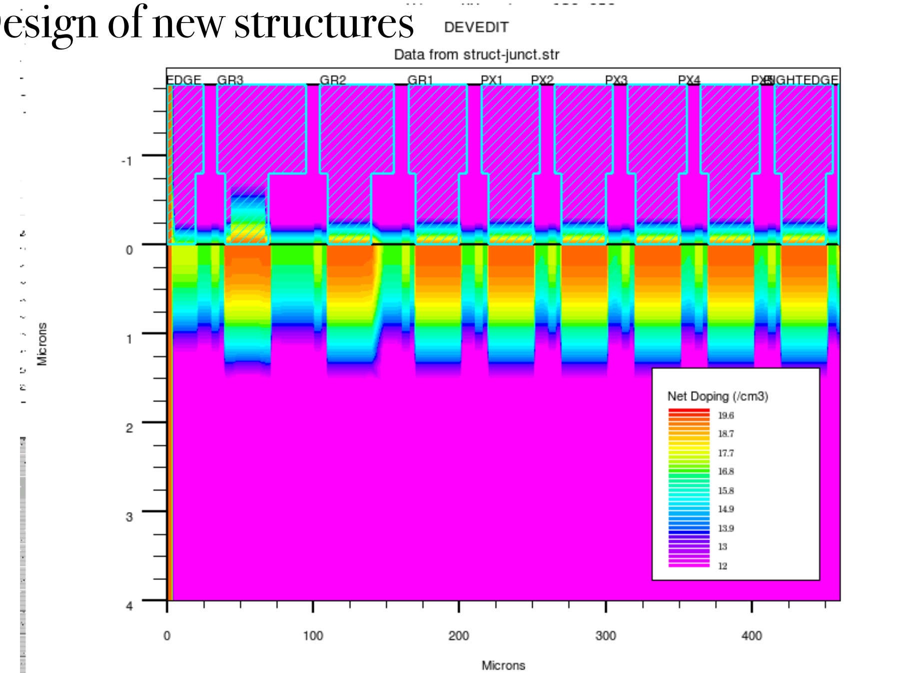
Intermezzo: simulations

- TCAD simulations allows to test in advance several possible sensor designs
- It helps in keeping costs down
- Precise input is needed!!!
- Whole set of "experimental" conditions available
    - Temperature
    - Light
    - Irradiation
    - …

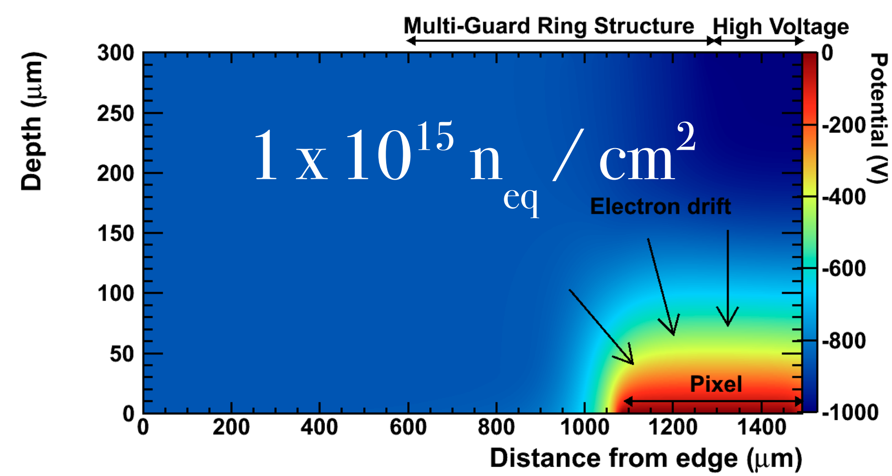
SIMS measurements: determining doping profiles



Design of new structures

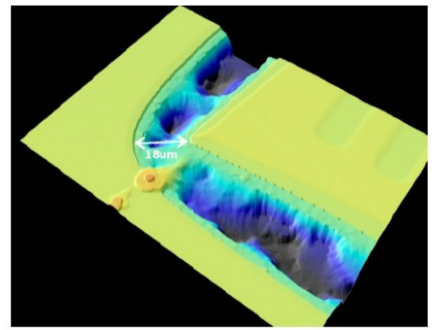


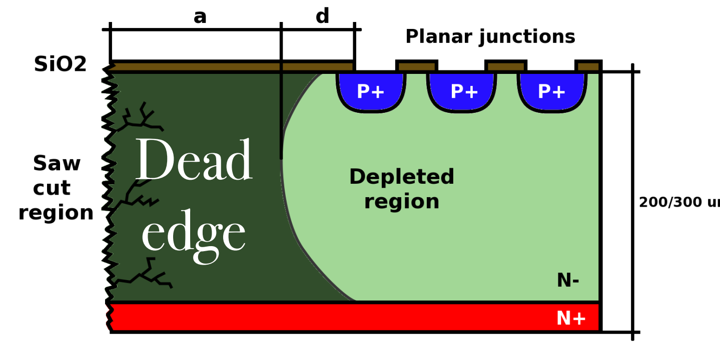
Potential after irradiation for a slim edge structure

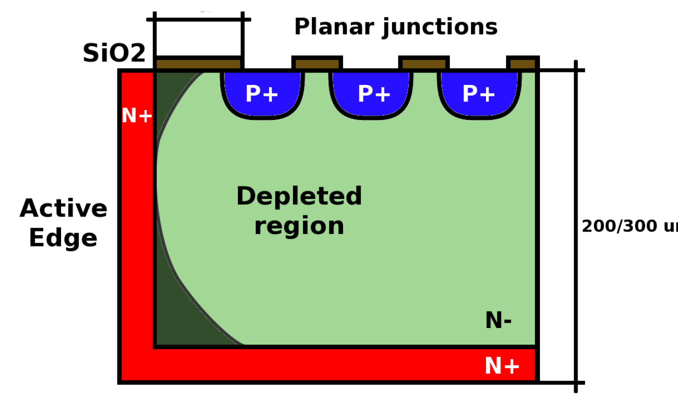


Active edge

- Another approach to reduce dead area
- Several ways to do that





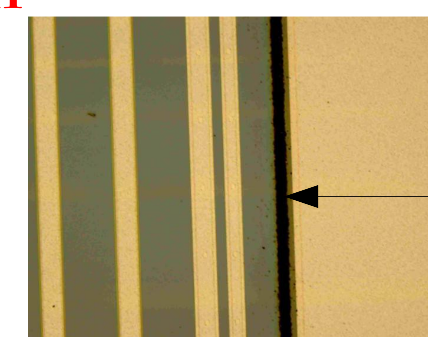


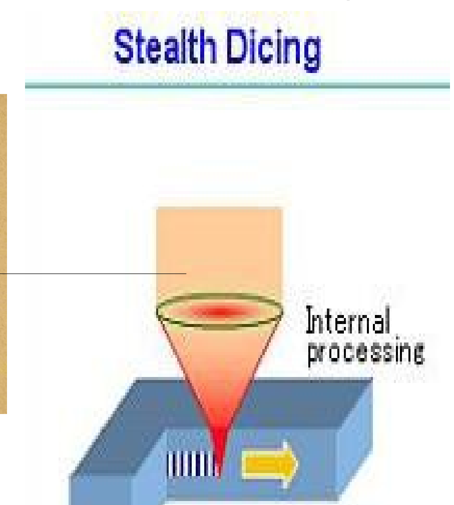
→ Drie-etching approaches

- ✓ CNM/IFAE
- ✓ FBK/LPNHE
- ✓ VTT/Munich

➢ Easy to get thin wafers → inner layers?

→ Scribe + cleave + edge – passivation



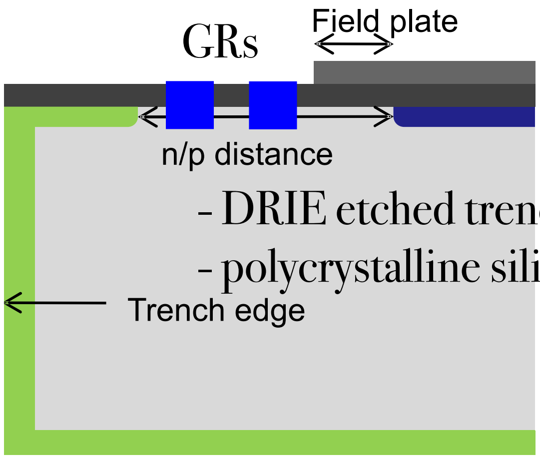


- ✓ UCSC
- ✓ Dortmund

- Post-processing →outer layers?

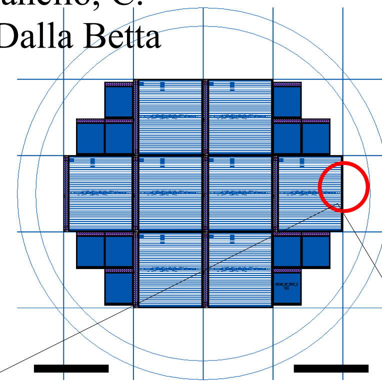
LPNHE – FBK active edge

M. Boscardin, A. Baglioni, G. Giacomini , N. Zorzi, E. Vianello, C. Piemonte, M. Povoli, G.F. Dalla Betta



- DRIE etched trench with p+ doping
- polycrystalline silicon trench filling

Design – work in progress



On 4 inch wafer:
→ 8 FEI4
→ 12 FEI3
→ Test structures (diodes, …)

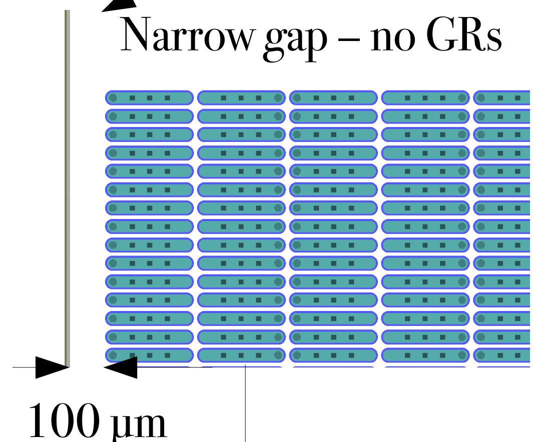
Trench defintion and etching

- Aspect Ratio **1/20**
- Deep etching (200-230 µm)

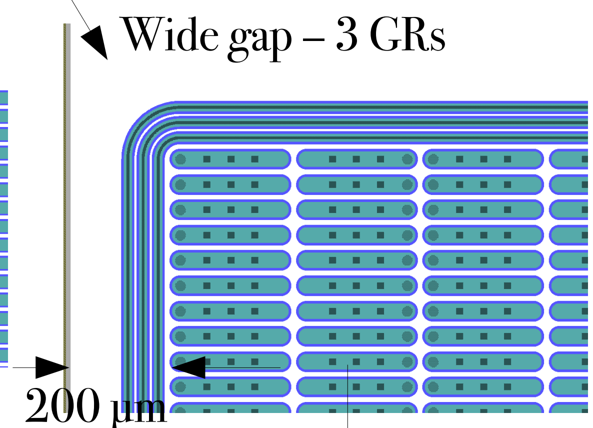
Trench filling

- Trench width 8-12 µm

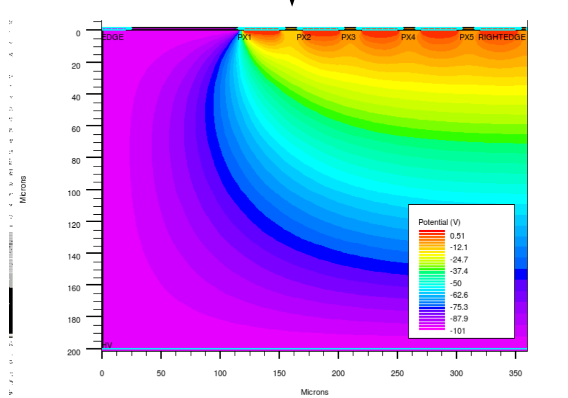
Narrow gap – no GRs

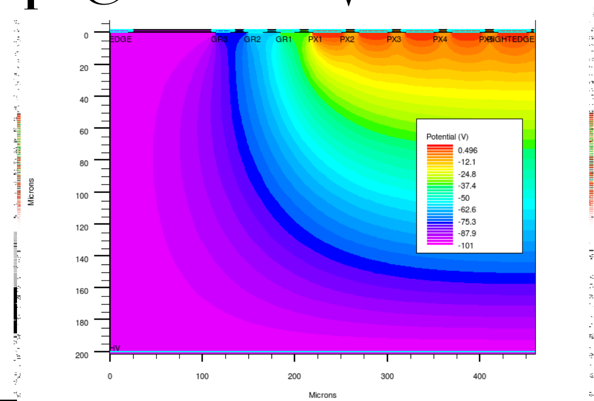


Wide gap – 3 GRs



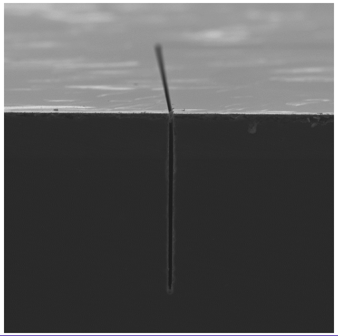
Potential maps @ 100 V





Further trench optimization

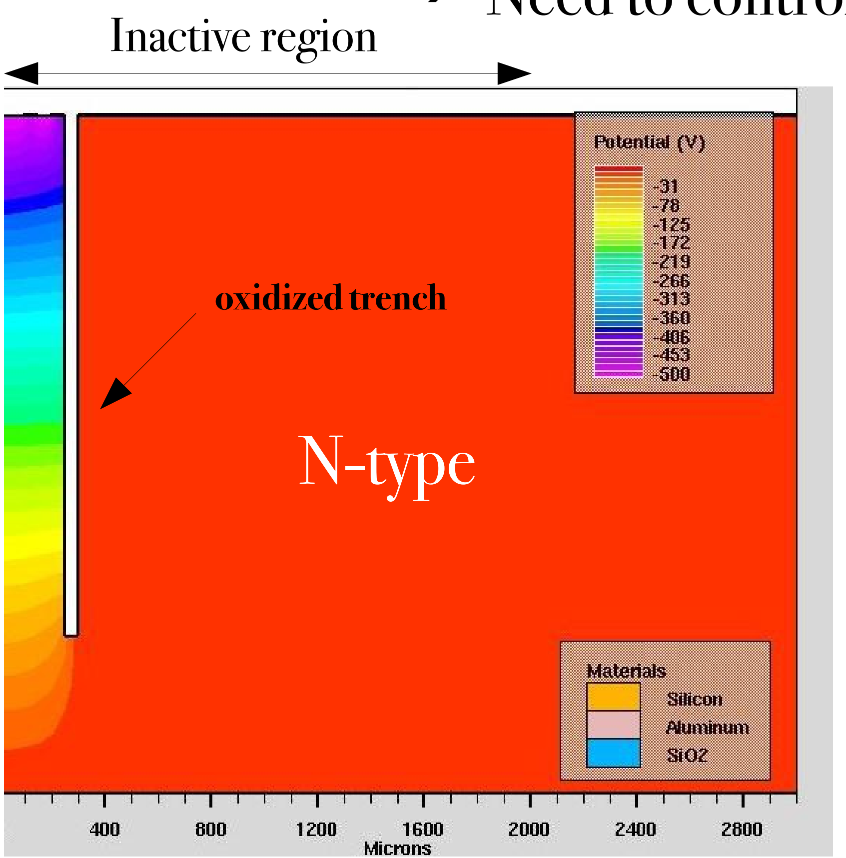
Trying to reduce trench to less than 10 µm
→ Easier to fill the trench

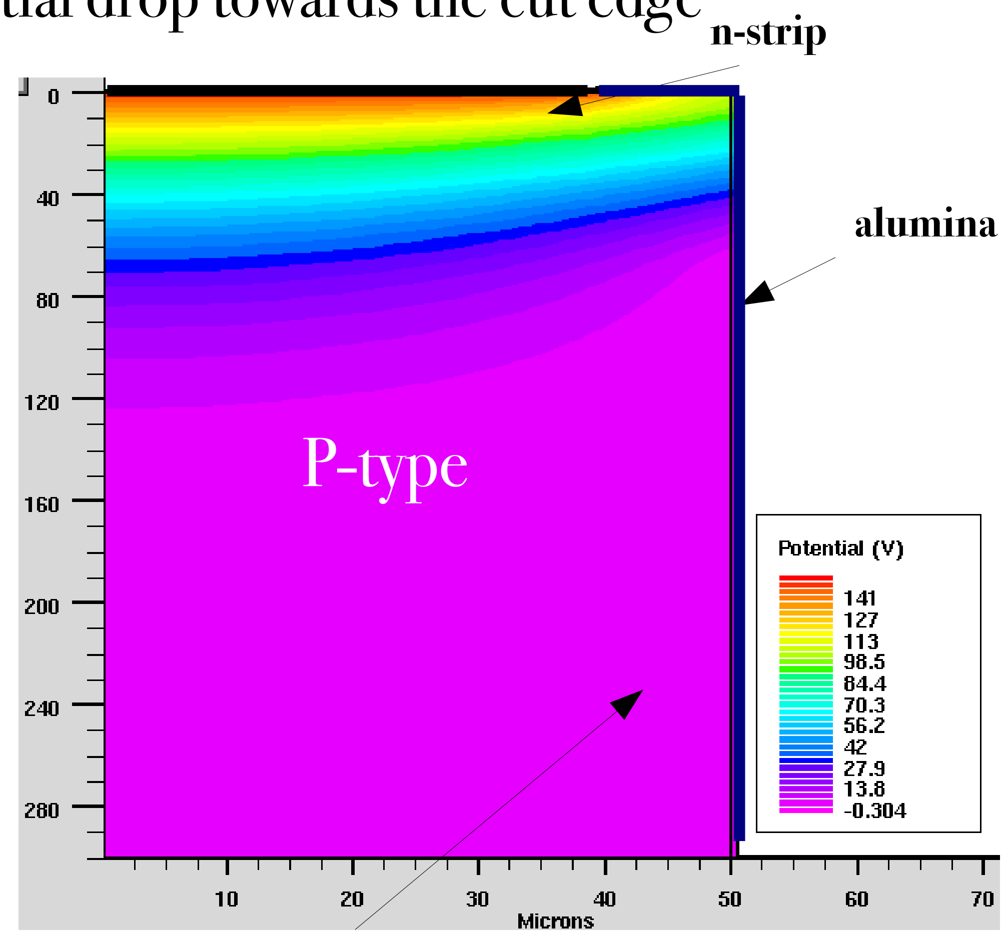


4.5 µm wide
220 µm deep

Passivated trench

➔ Need to control potential drop towards the cut edge





Negative charge (-1E11 cm-2)

A passivated trench with a thermally grown oxide (**positive** charge density 10^{11} cm^{-2}) trench will lead to:

✓ control potential drop toward the cut edge,

✓ protection from saw cut edge.

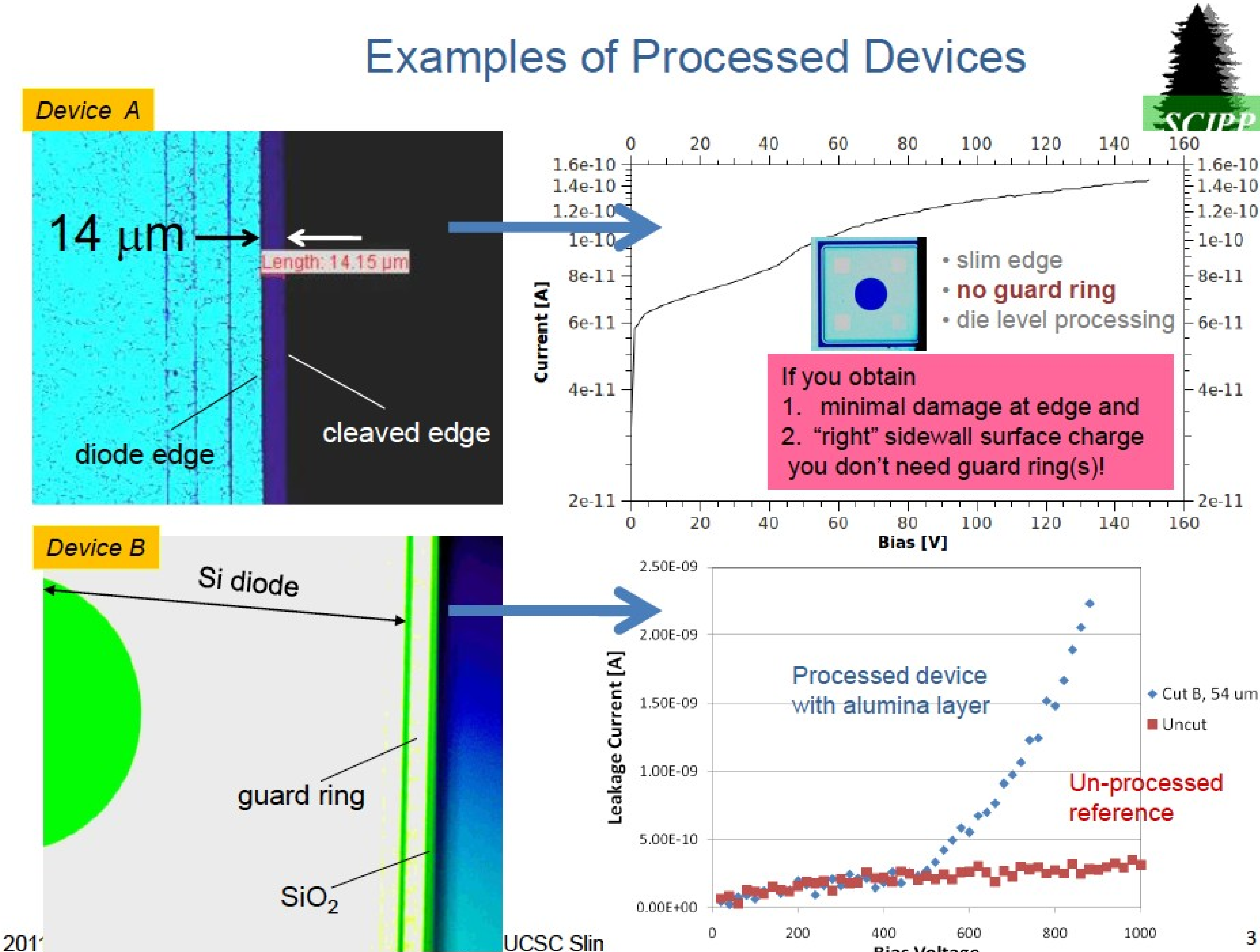
➔ Scribe + nitride/oxide deposit approach too

Alumina deposition by ALD

✓ Partially controlled potential drop towards the cut edge

➔ The more charge, the better

P-type passivated trench



Conclusions & Outlook

- Planar Pixel is a proven technology
- N-in-n modules are fully efficient at 5×10^{15}
  - Hit efficiency at 99.6%
  - … and still collect charge at 2×10^{16}
- Many on-going n-in-p productions (target: post-IBL upgrades)
- Optimization of the geometry is crucial to maximize active area
  - Slim edge: encouraging results from test-beam
  - Active edge: several activities with brand new ideas too
- Next: more test-beams, irradiation campaigns with current & new geometries

Thank you!

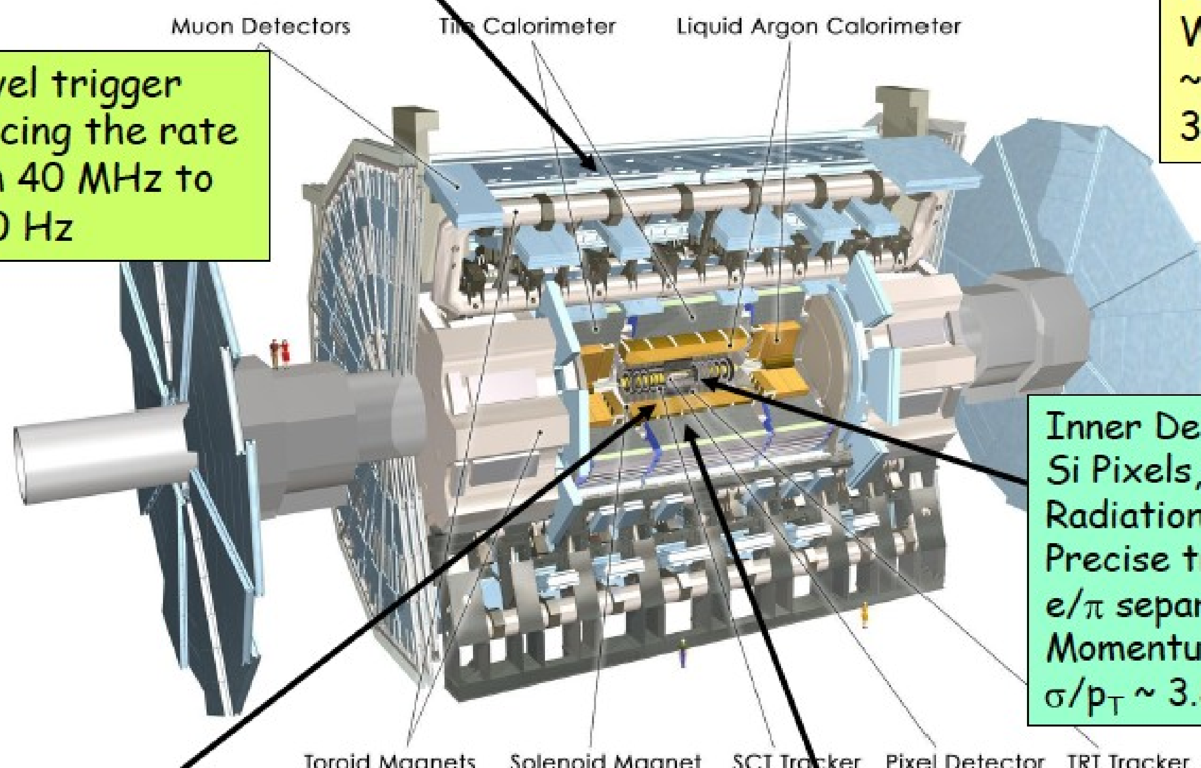
Backup

ATLAS

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



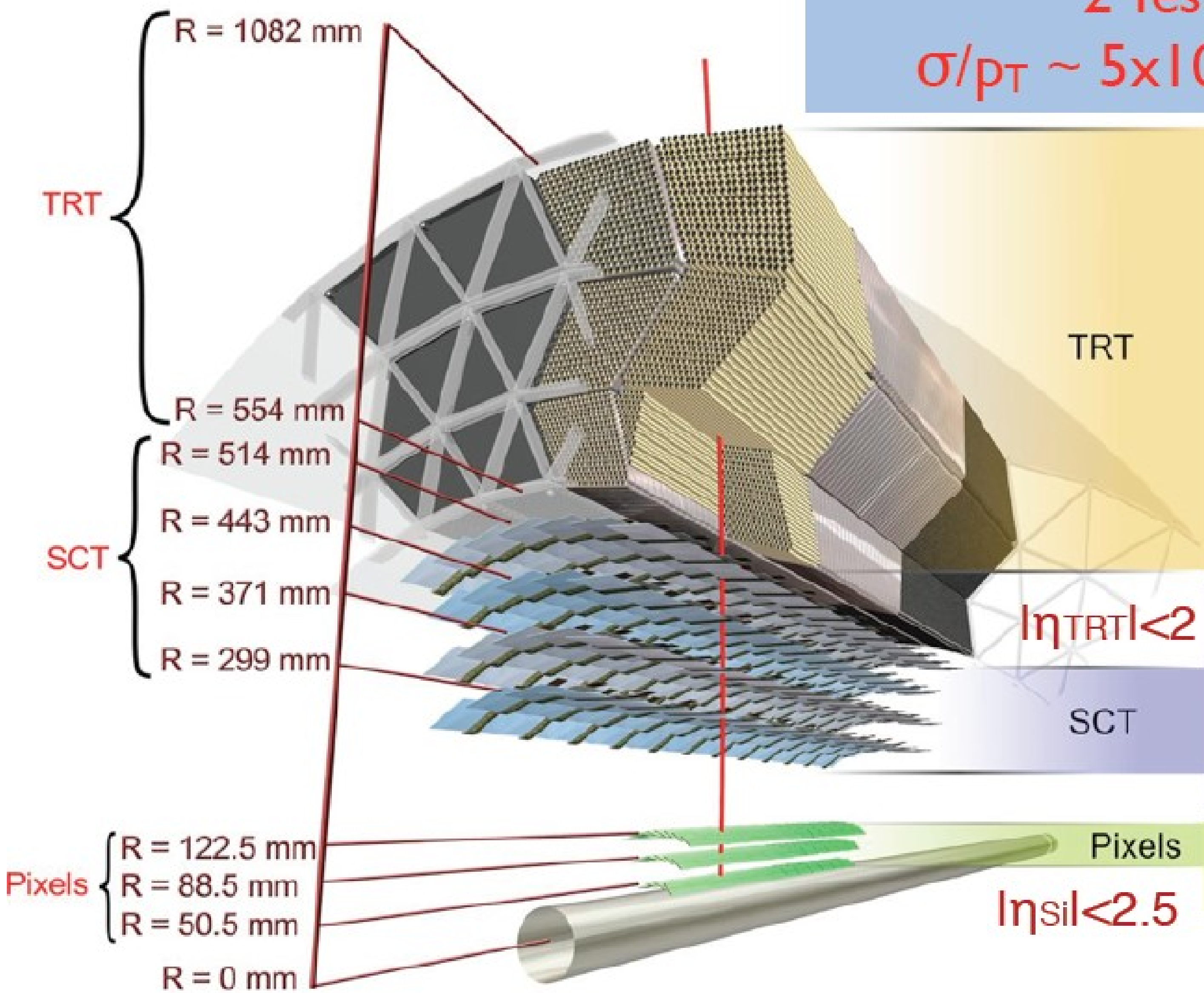
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS status and highlights, ICHEP, 26-7-2010 7

Atlas Inner Detector



2 Tesla Solenoid

$\sigma/p_T \sim 5x10^{-4}\ p_T/GeV \oplus 0.01$

Transition Radiation Tracker (TRT) (350k channels) with e/π separation

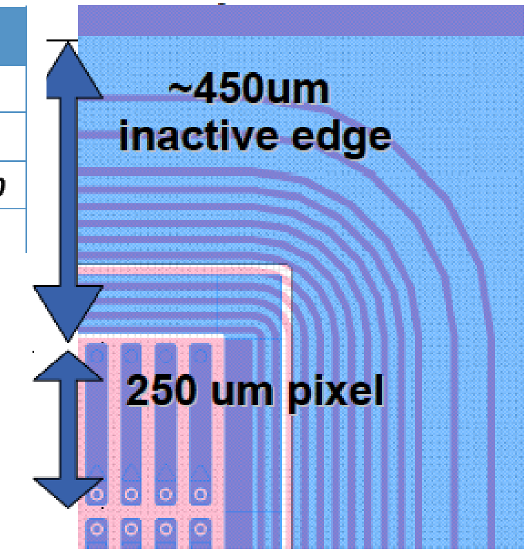
SemiConductor Tracker (SCT) ~6M silicon strips

Pixels: 80M channels

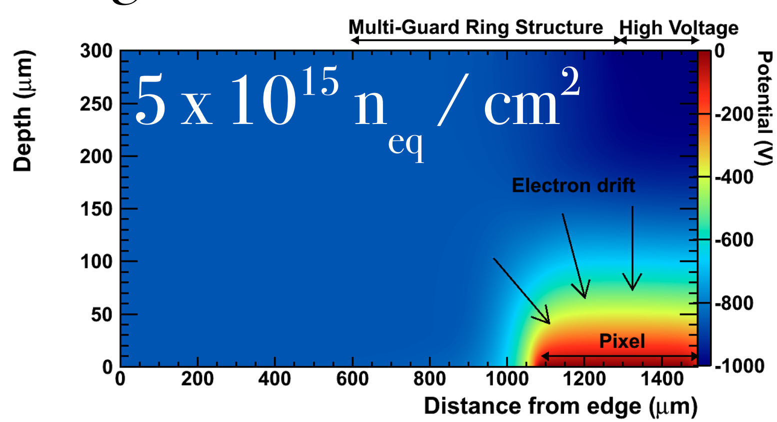
Slim edge

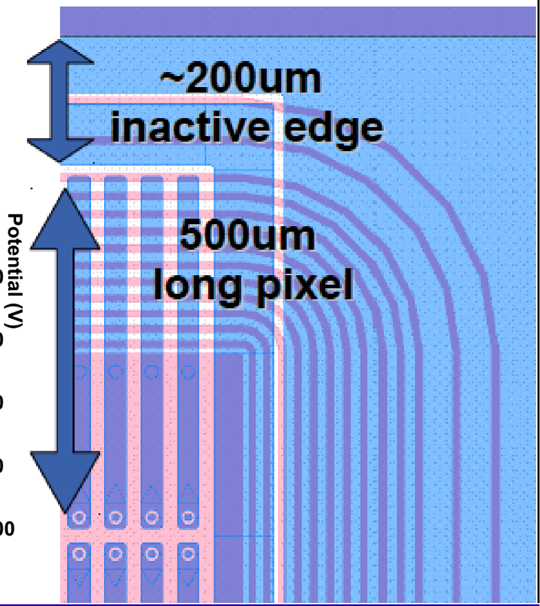
- Inactive area should be kept at minimum
  - *e.g.* Inner layers: no shingling in z

	FE-I3	FE-I4
Pixel size [μm²]	50x400	50x250
Pixel array	18x160	80x336
Chip size [mm²]	7.6x10.8	***20.2x19.0***
Active fraction	74%	89%



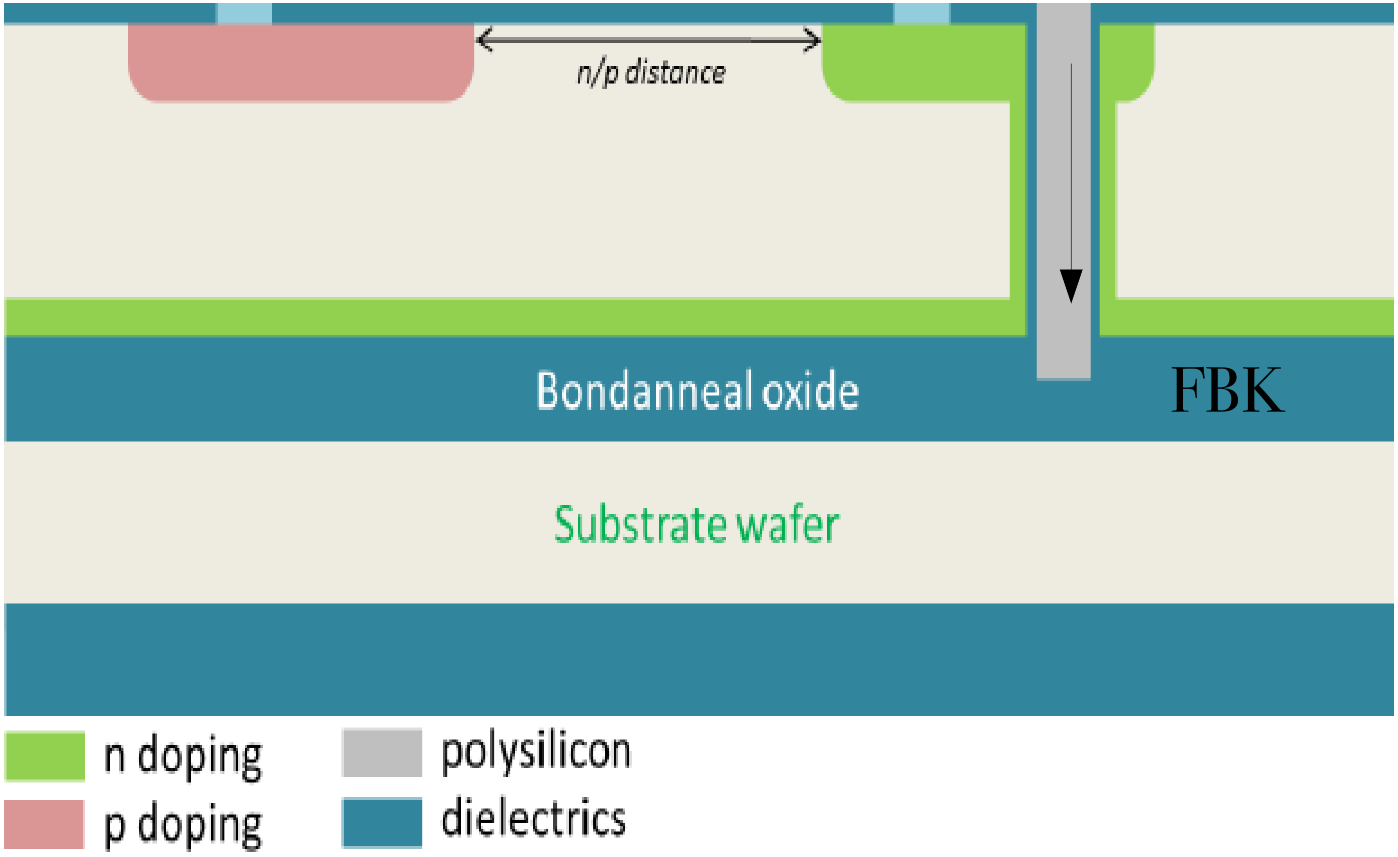
- Two designs for n-bulk sensors
- Conservative design
  - Similar to current ATLAS pixels
  - ~ 450 μm of inactive edge width
  - Electrical field at edges homogeneous
- Slim edge design
  - Guard rings on p-side shifted beneath the outermost pixels → least possible inactive edge
  - Less homogeneous field
  - But ok at large fluences thanks to space charge inversion





Drie etching + trench fill

Trench filled with polysilicon and doped



M. Boscardin

6

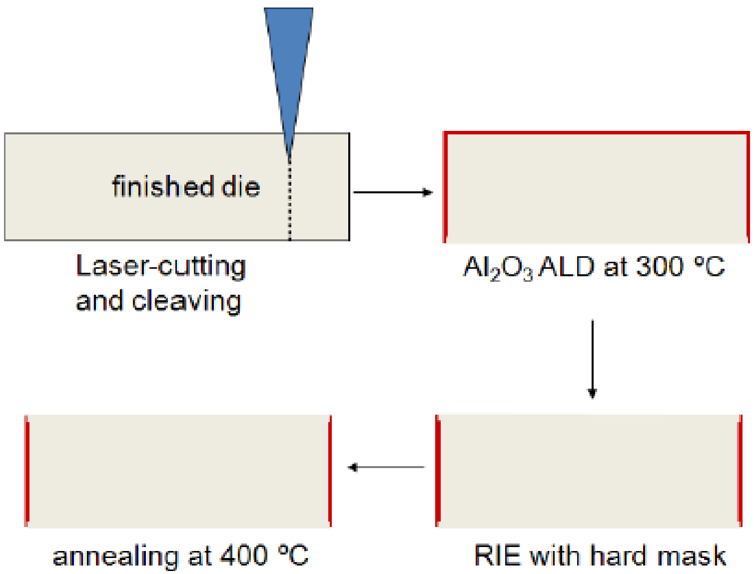
Atomic layer deposition

ALD Processing on p-type Sensors

For p-type sensors the critical step is formation of proper passivation on the surface. The quickly forming Si oxide has a detrimental effect. Alumina deposition by ALD (left) leads to the desirable properties.

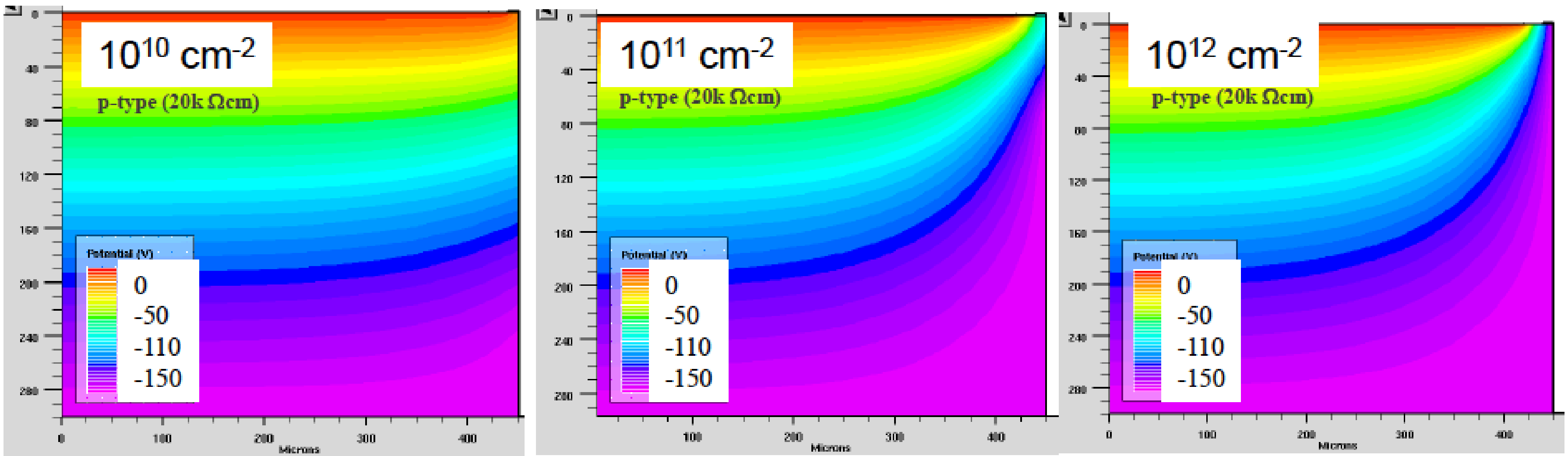
- So far worked with diodes from ATLAS07 batch from HPK (next slide) and strip sensors made by HLL.
- Processed the total of 5 diodes and 2 strip sensors.
- Also need to investigate radiation effects.

Fabrication Sequence



P-type & surface charges

Influence of Surface Charge Concentration: P-Si/Al_2O_3



increasing negative surface charge

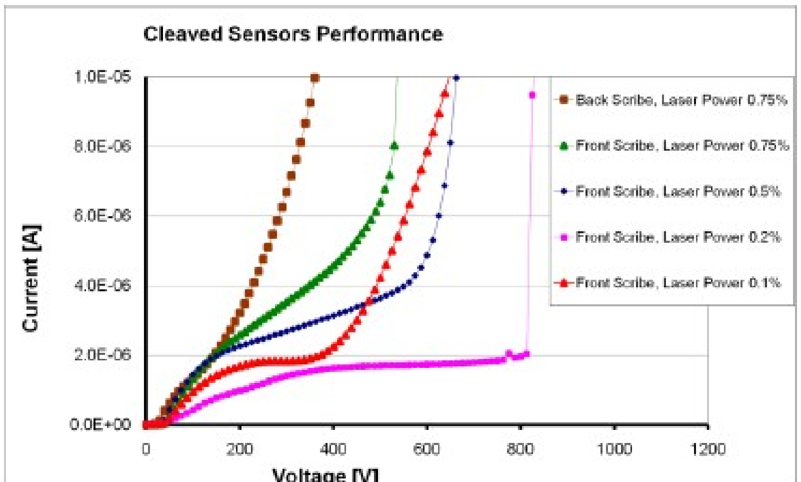
Typical literature values for alumina are ~ $10^{11} – 10^{13}$ cm^{-2} depending on deposition conditions. BUT most research is focused on increasing (*not decreasing)* surface charge.

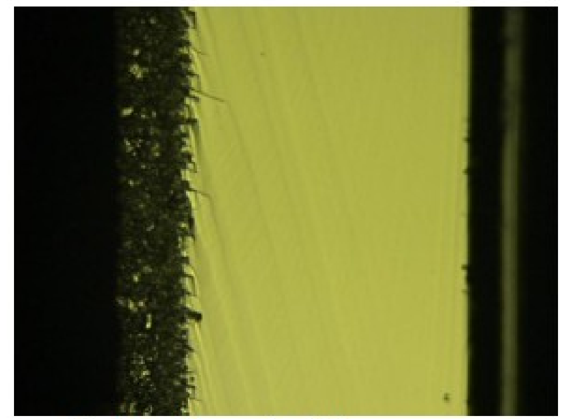
The potential drop at edge depends strongly on surface charge density.

Passivated trench

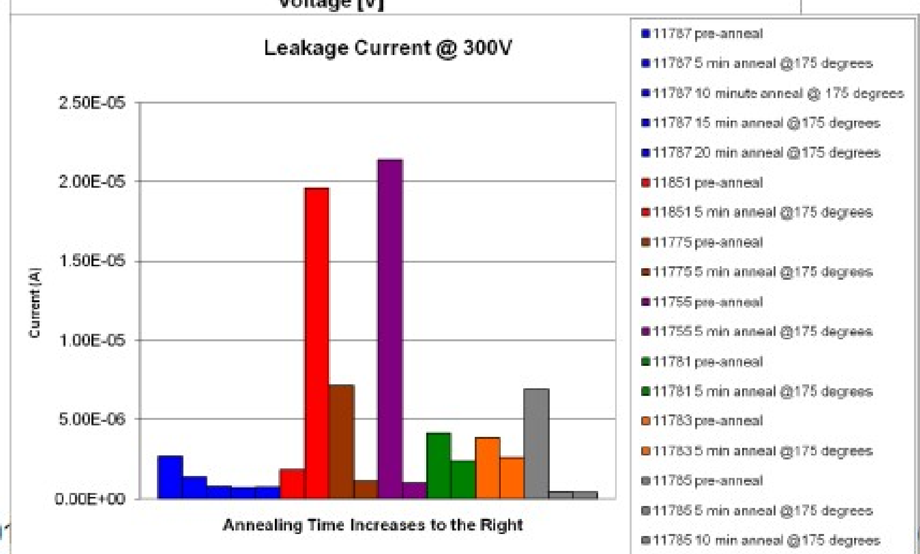
N-bulk sensors

- Processing of n-bulk sensors is easier, since formation of SiO_2 passivates the sidewall. Prototyped with p-on-n HPK sensors from GLAST/Fermi production.





Edge illumination



These sensors were breaking down at relatively high voltages, 100s of volts. Performance improves with high-temperature exposure which facilitates formation of SiO_2 on the sidewall surface.

20 ... y post-processing 6

FE-I4

The FE-I4 front-end

- Reason for a new FE design:
  - Increased rad hard
  - New architecture to reduce inefficiencies (*L*=3xLHC)
- Biggest chip in HEP to date
- Greater fraction of footprint devoted to pixel array
- Lower power: *don't move the hits around unless triggered*
- Able to take higher hit rate: *store the hits locally in each pixel and distribute the trigger*
- No need for extra module control chip: *significant digital logic block on array periphery*
- Present status: *Submission end of June 2010*

Design collaboration (15 IC designers):
Bonn, CPPM, INFN-Genova, LBNL, NIKHEF

Specification & test setup development:
Bonn, CERN, Goettingen, LBNL

- FE-I3 → FE-I4

	FE-I3	FE-I4
Pixel size [µm²]	50x400	50x250
Pixel array	18x160	80x336
Chip size [mm²]	7.6x10.8	***20.2x19.0***
Active fraction	74%	89%
Analog current [µA/pix]	26	***10***
Digital current [µA/pix]	17	***10***
Analog voltage [V]	1.6	***1.5***
Digital voltage [V]	2.0	***1.2***
Pseudo-LVDS out [Mb/s]	40	***160***