Development of hybrid pixel modules for HL-LHC

A. Macchiolo
Max-Planck-Institut für Physik, Munich

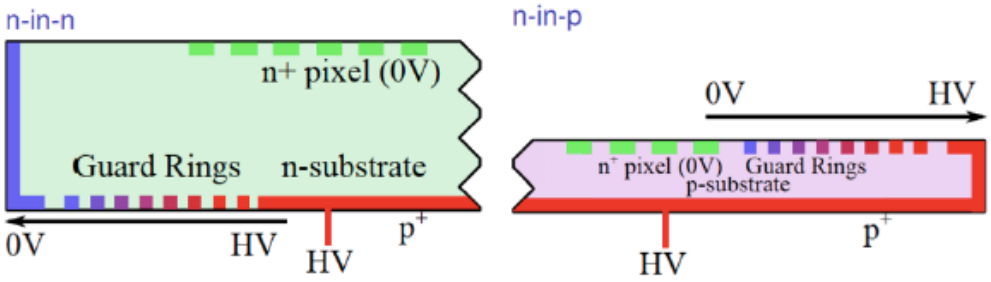
8th Terascale Detector Workshop, Berlin, 6 March 2015

Introduction

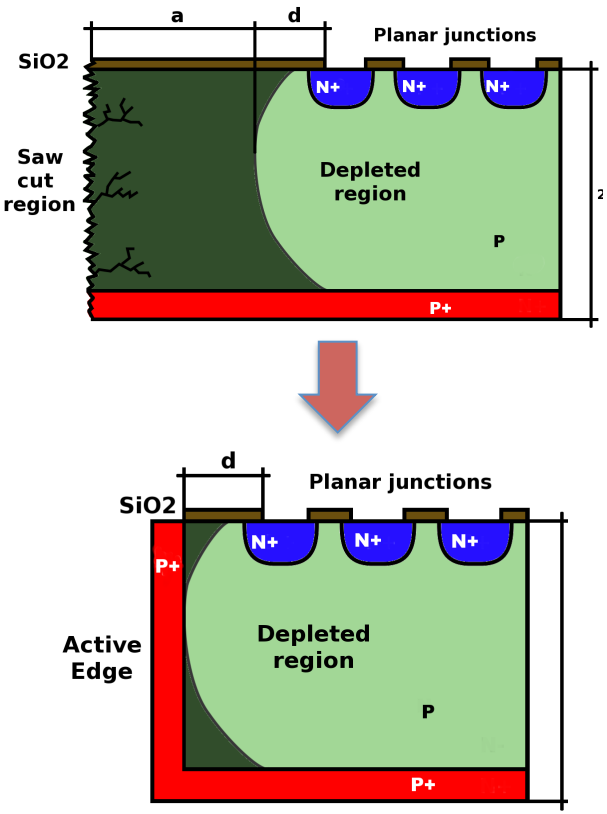
- Thinning technologies for pixel sensors
- Comparison of Charge Collection results at different thicknesses after irradiation
- Effect of thickness on tracking at high eta
- Performance of active / slim edge 3D and planar sensors
- Module design for hybrid pixel modules at HL-LHC

Thin pixel sensors for HL-LHC

Thin active thickness very attractive:



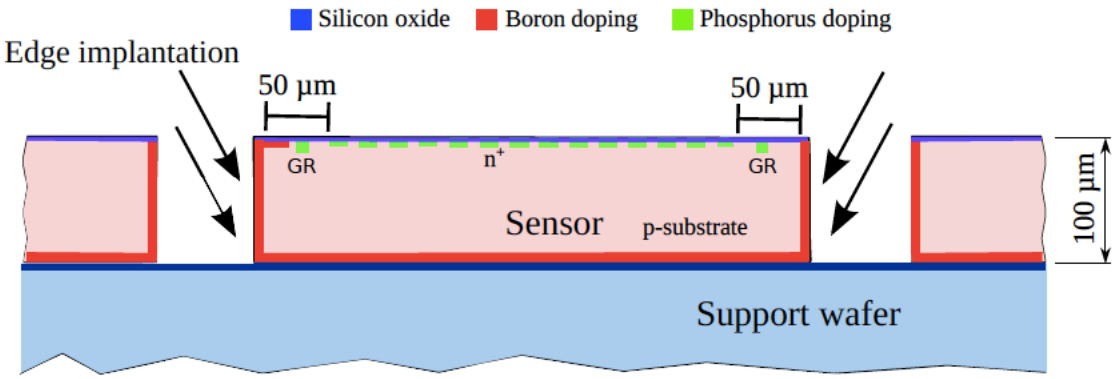
- After irradiation charge collection length reduced, so thickness no advantage
- Higher electric field, faster collection times
- Lower operation bias voltages → lower power
- Lower occupancy at high eta
- Possibility to reduce material (multiple scattering)



Reduce dead regions at edge of sensors

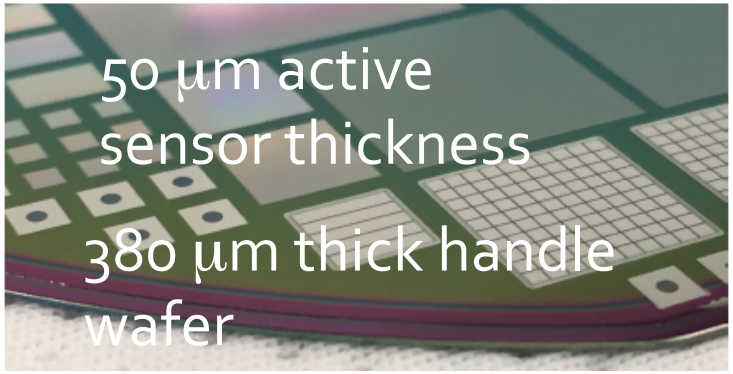
- Allows the innermost layers to remain closer to the IP by avoiding the need for tiling → several methods investigated

Thin planar pixels on SOI material + active edges



- First production: n-in-p pixels on FZ and MCZ SOI material
- 100 µm and 200 µm thickness
- Flip-chipping performed at VTT after removal of support wafer (etching down to SiO_2 interface, acting as a natural etching stop)

- Second production: 50, 100 , 150 µm active thickness, Single chip FE-I4 sensors



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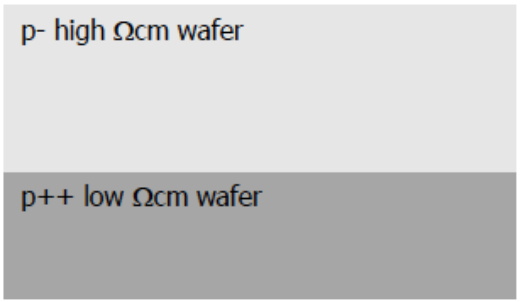
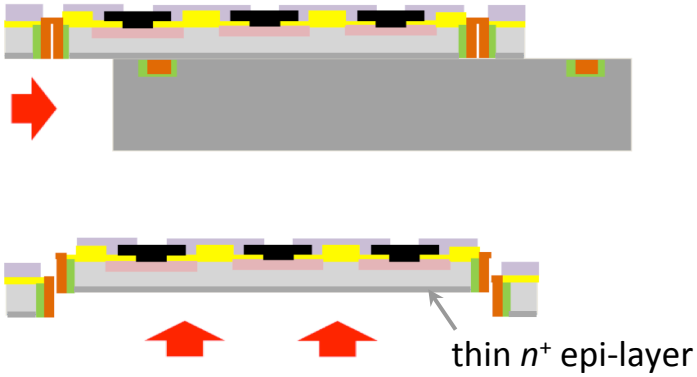
Thin Silicon Substrates



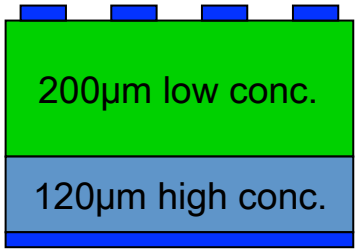


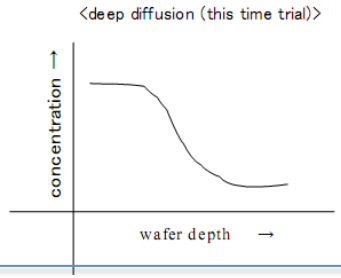
S. Ronchin, New Technology for next generation of 3D sensors, Trento Workshop 2015

Device separation along the trenches

- Use wafer stacks with a low resistivity substrate than can be used as a contact on the backside
  - Epi material with MCz substrate
  - Si-Si direct bonding: for our applications high resistivity FZ to low resistivity MCz

- CMS HPK Campaign
  - Deep Diffused Silicon, effective thin active layer created on thicker substrate
  - Smoother Neff transition than in composite substrates

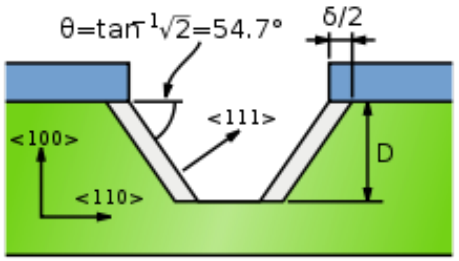




L. Spiegel, CMS beam test for the CMS Upgrade program, 22nd RD50 workshop

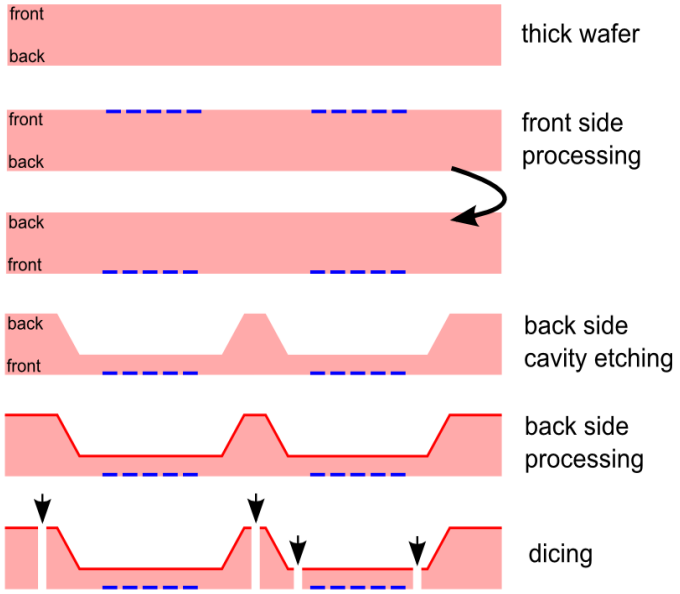
Alternative thinning method without support wafers (I)

- relatively simple technology without using support / handling wafers
  - anisotropic wet etching (KOH) on <100> wafers
  - Experience with this technology at CIS for MEMS/ pressure sensors production



- First R&D production on 4" p-type FZ wafers; process contributed by CIS; **target thickness 100 and 150 µm**

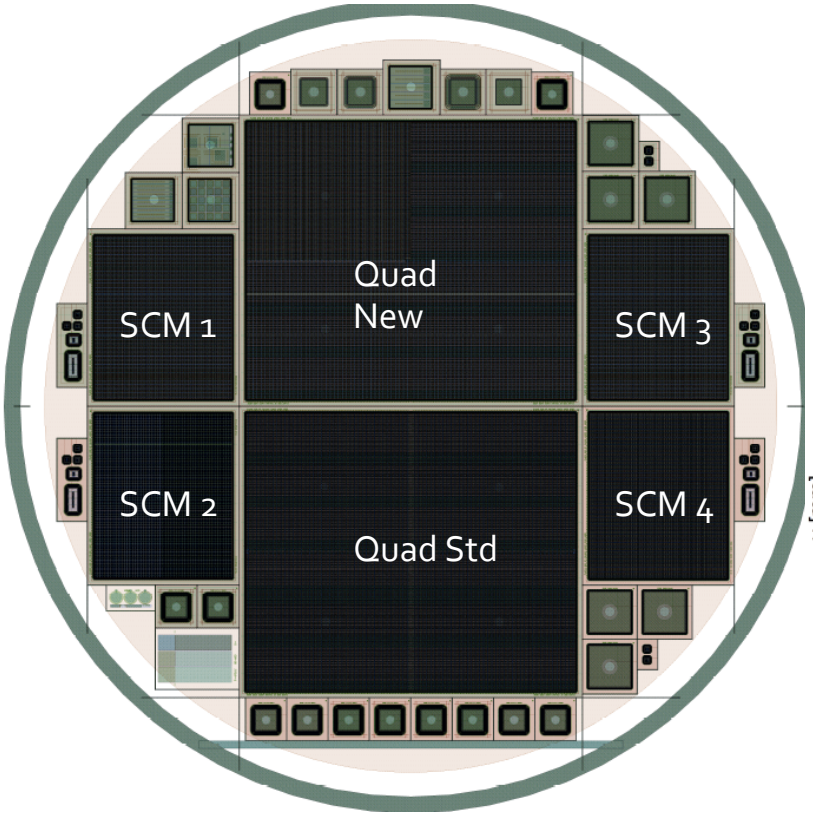
- Starting thickness 525 µm
- Front-side processing up to nitride deposition
- Back-side p+ implantation, top-side p-spray → common annealing step
- Metallization on the front and back side
- UBM (electroless Nickel at CiS or standard one at IZM)
- dicing



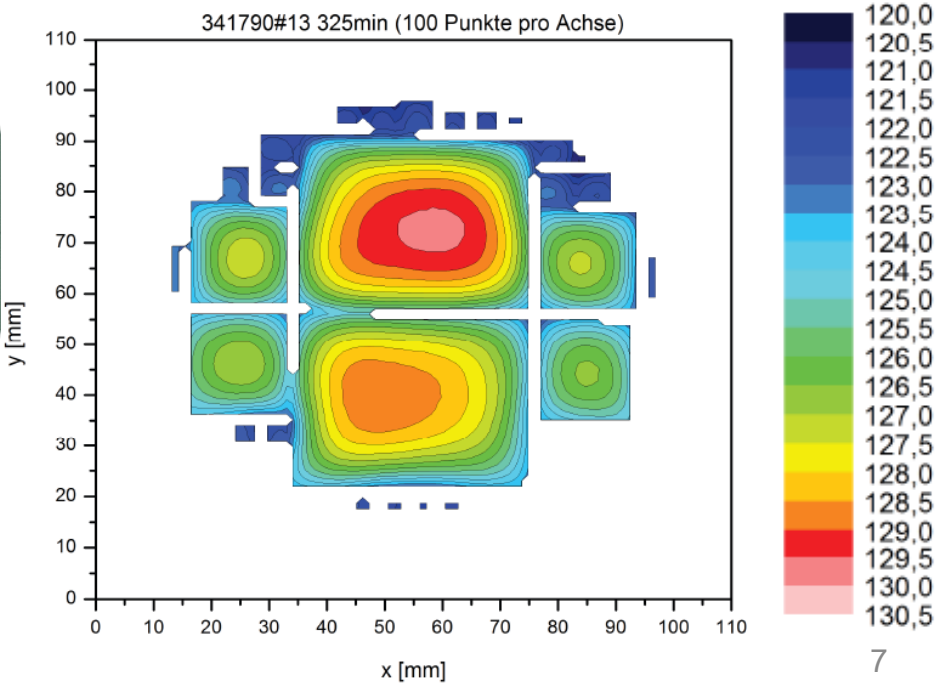
Alternative thinning method without support wafers (II)

- Two sets of dicing lines:
  - On the 420 μm wide frame between the structures
  - Dicing along the sensor perimeter on the thinned substrate
  - Guard ring structure within the thinned area

Design in collaboration between MPP and CIS

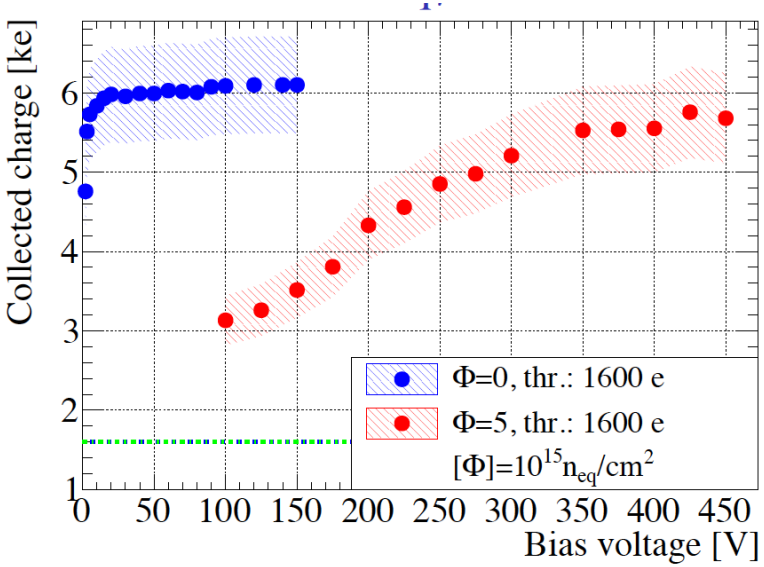


- First etching trials on test wafers :
- 325 minutes etching time
- Maximum thickness variation inside the quad sensors ~ 10 μm

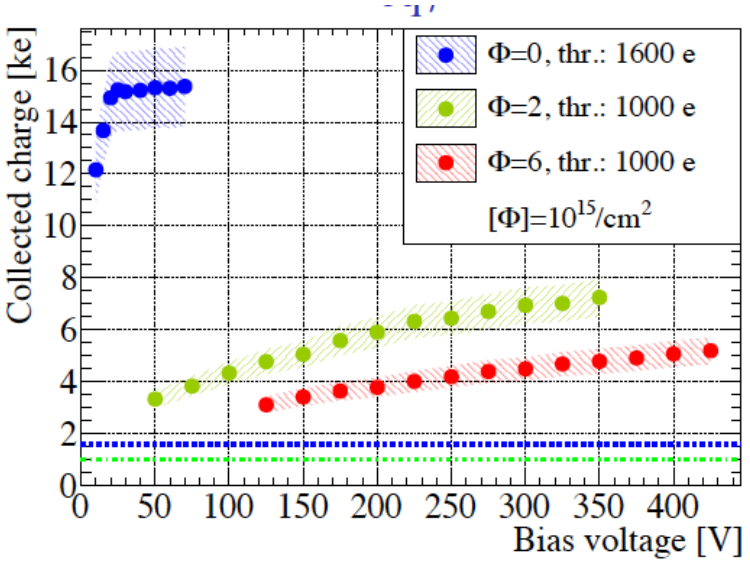


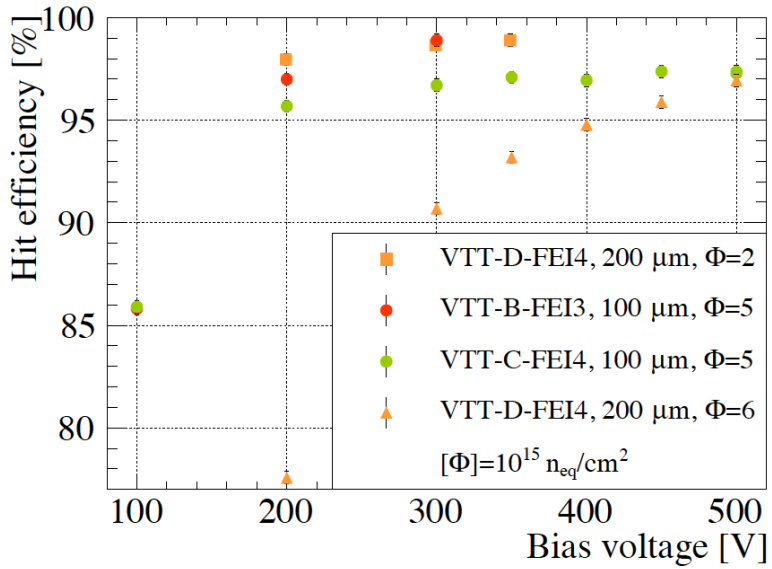
Comparison between 100 and 200 μm thick sensors

FE-I4, 100 μm thick, 5x10¹⁵ n_{eq}/cm²



FE-I4, 200 μm thick, 5x10¹⁵ n_{eq}/cm²





VTT FE-I3 100 μm, Φ=5x10¹⁵ n_{eq}/cm²

(99.0±0.3)% global hit efficiency at Vbias= 300 V (125 μm edge)

VTT FE-I4 100 μm, Φ=5x10¹⁵ neq/cm²

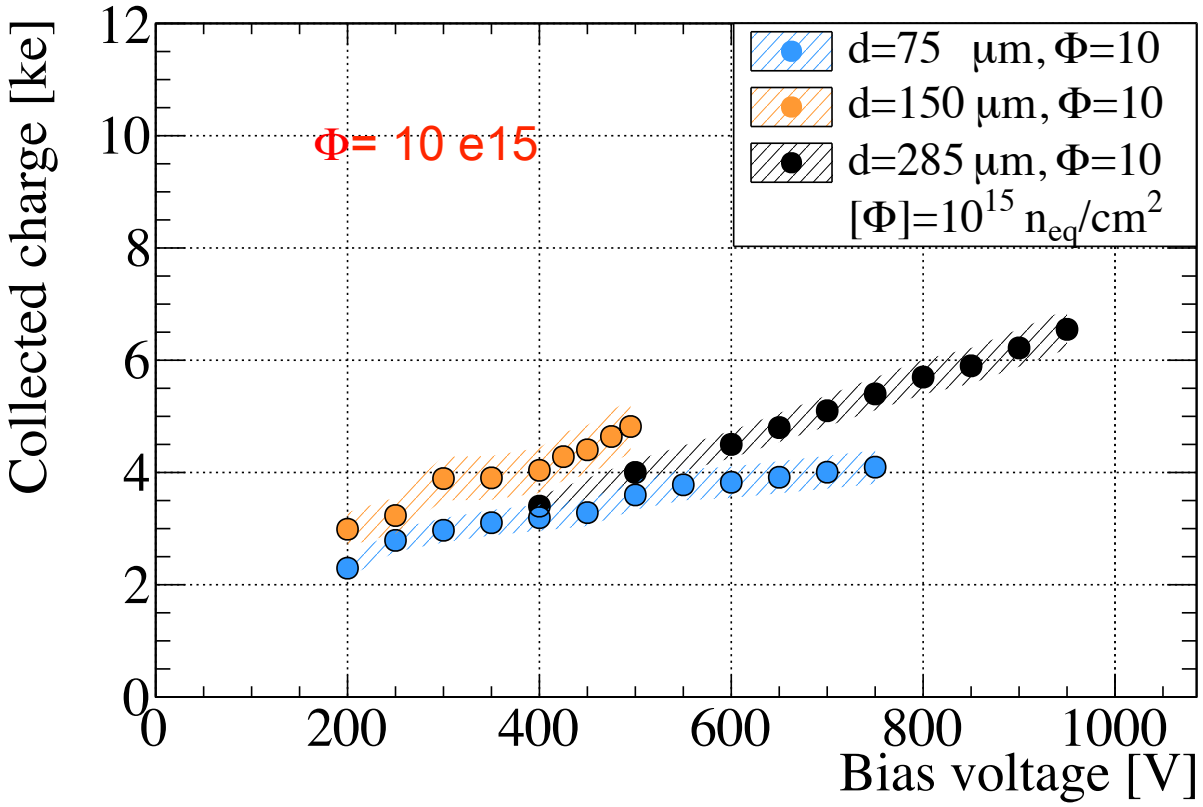
(97.0±0.3)% global hit efficiency at Vbias ≥ 350 V

VTT FE-I4 200 μm, Φ=6x10¹⁵ neq/cm²

(96.9±0.3)% global hit efficiency at Vbias= 500 V

Charge collection for pixels of different thickness (I)

At higher fluences the effect of charge trapping tends to equalize the charge collection efficiency for all thicknesses



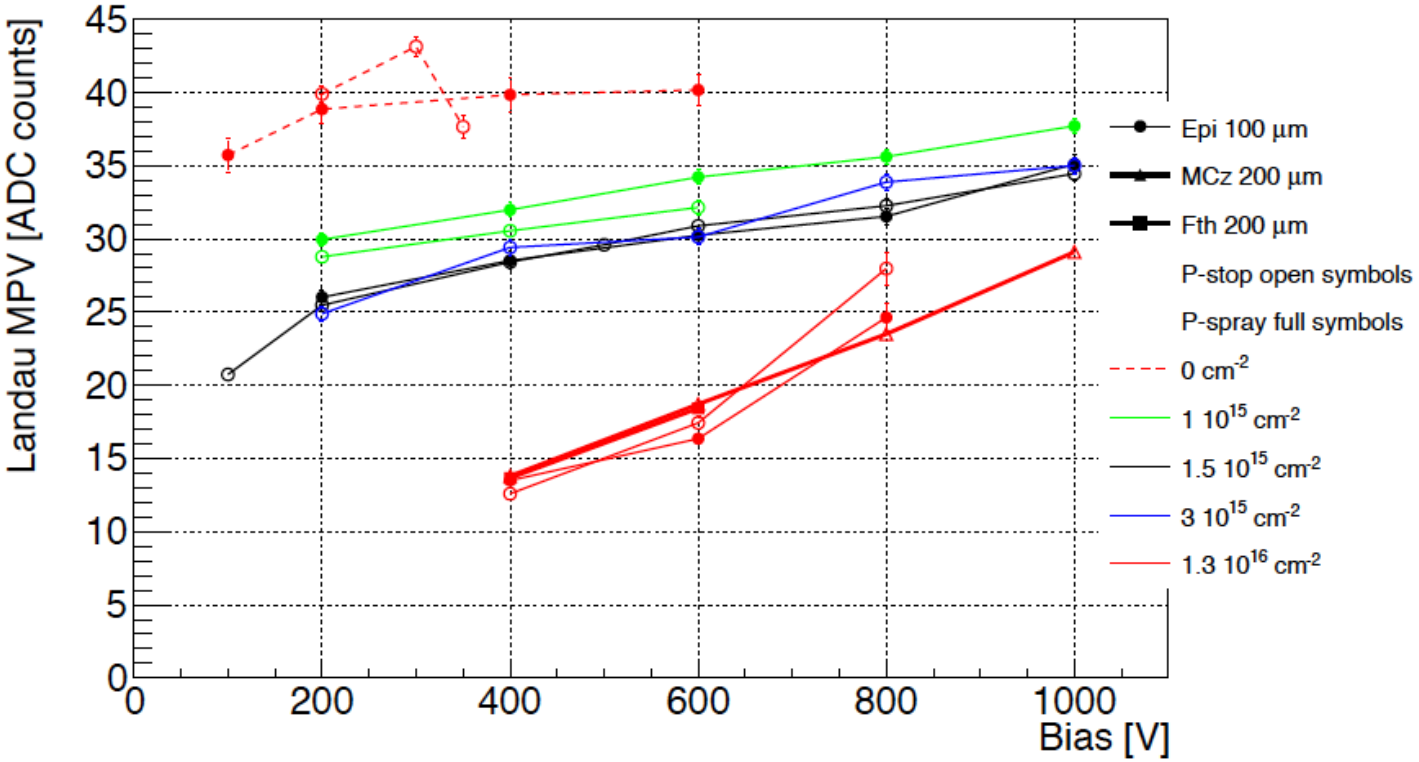
Charge collection for pixels of different thickness (II)

- Epitaxial strip silicon sensors of n and p-type - baby sensors from HPK campaign
- 100 µm active thickness + 200 µm thickness for 1.3 x 10^{16} neq cm^{-2}
- MCZ with 200 µm physical thickness, only @ 1.3 x 10^{16} neq cm^{-2}

  → 100 µm → faster signal recovery

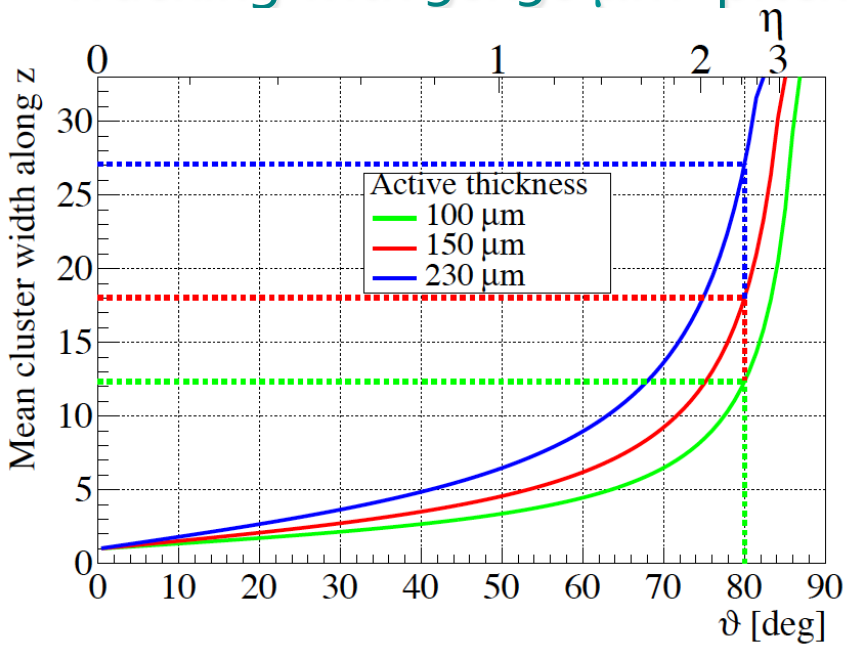
  → 200 µm → higher breakdown voltage

  → Similar signal height for both thicknesses at highest bias



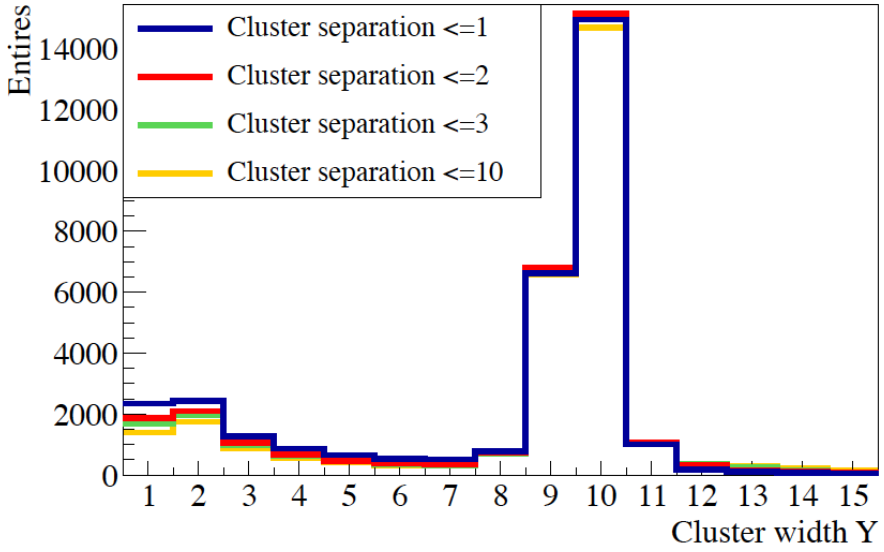
Effect of thickness on tracking at high eta

Tracking with 50x50 μm² pitch pixels: Cluster Multiplicity

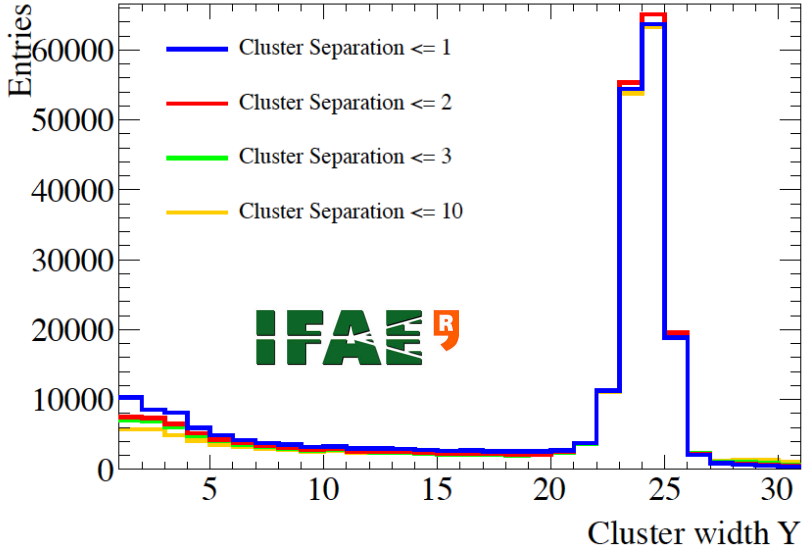


- Module Tuning:
  - Threshold 1 ke (planar, 3D), 1.5 ke (3D)
  - Charge calibration 6 ToT at 4 ke
- Measured cluster width in Y (along 50 μm pitch direction) 2-3 units less than pure geometrical expectations
- Difference is due to ~ 1 degree misalignment and threshold effects in the entrance and exit pixels

Planar Sensor (100 μm thick), eta=2.5



3D Sensor (230 μm thick), eta=2.5

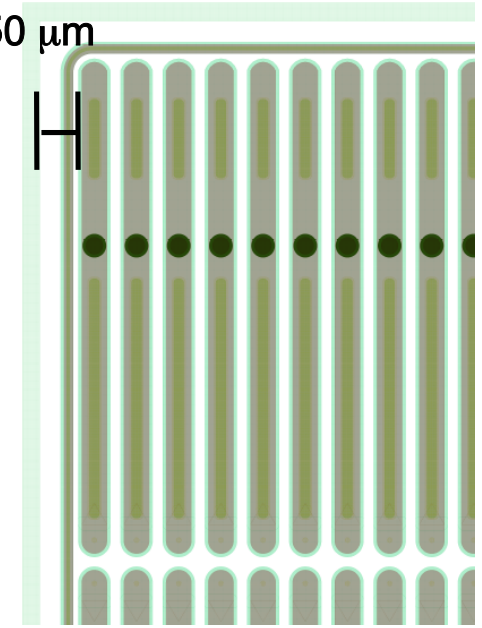


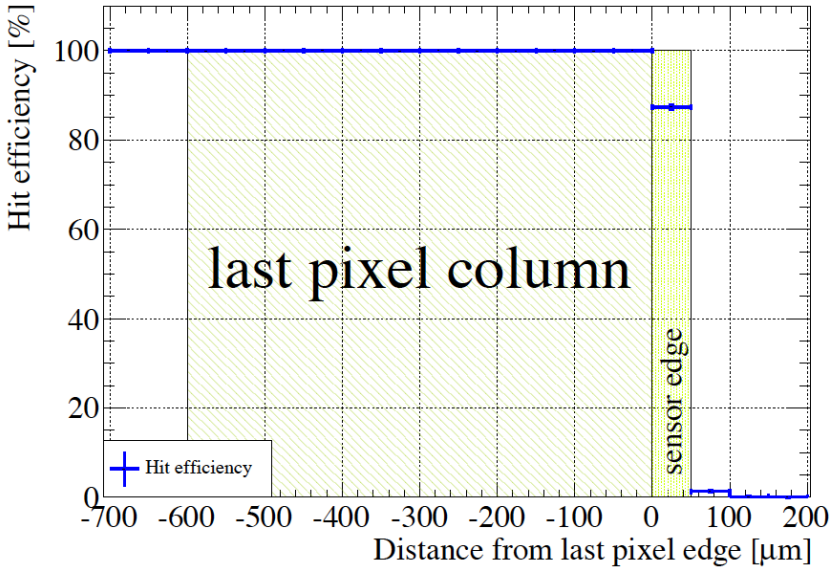
Slim / active edges

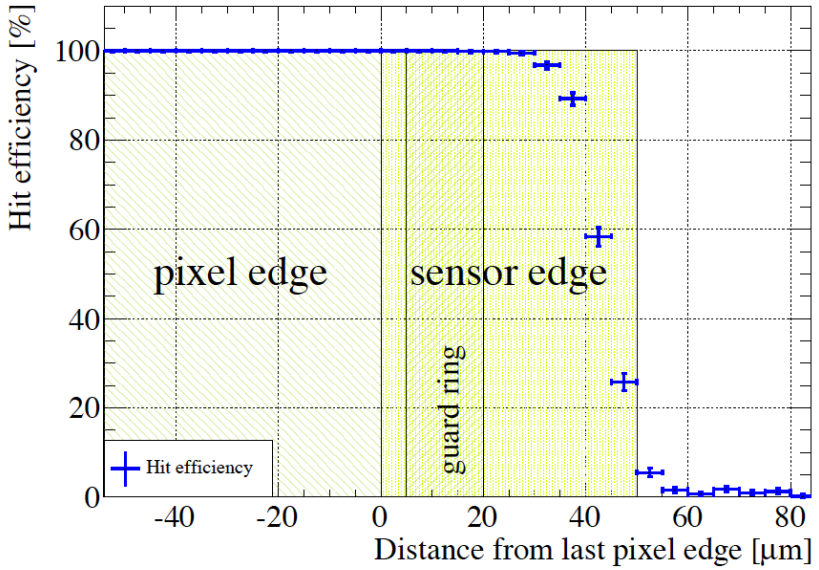
Hit efficiency for active edge planar pixel modules

- FE-I3: 50 μm active edge with floating GR
- 4 GeV electrons, EUDET telescope
- 99 % hit efficiency on the last pixel column
- (87.4 ±0.7) % hit efficiency between pixel implant and sensor edge (50 μm)

→ Completely efficient up to last 20 μm from the edge



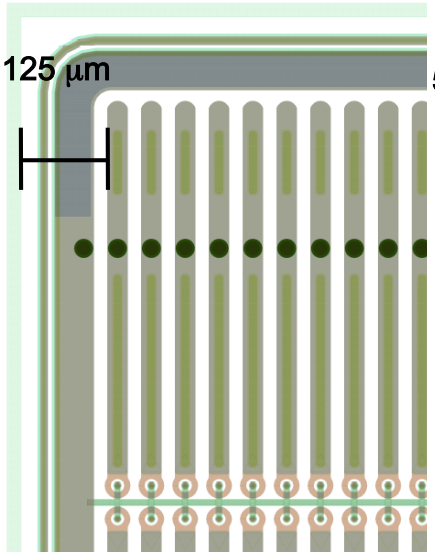




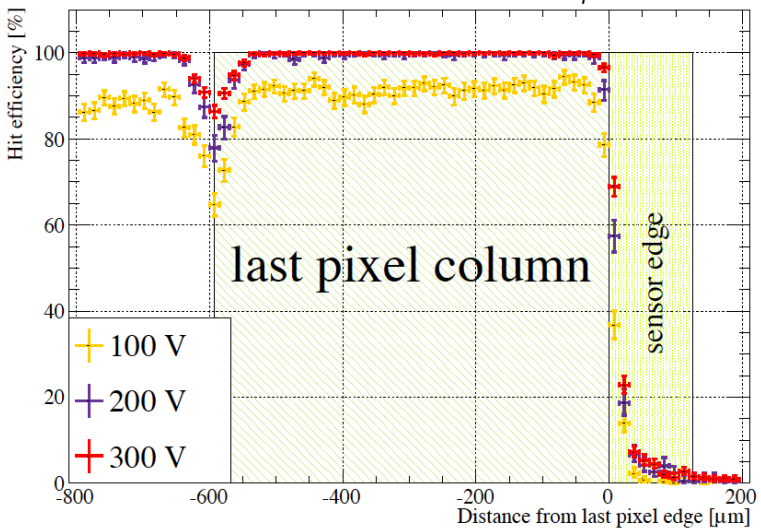
Slim edge pixel modules after irradiation

- FE-I3: 125 μm edge with grounded BR
  - irradiated at $\Phi=5x10^{15}$ n_{eq}/cm^2
  - threshold: 1500 e−
  - **(69±3=2)%** hit efficiency between the last pixel implant and the BR (DESY, 4 GeV electrons)

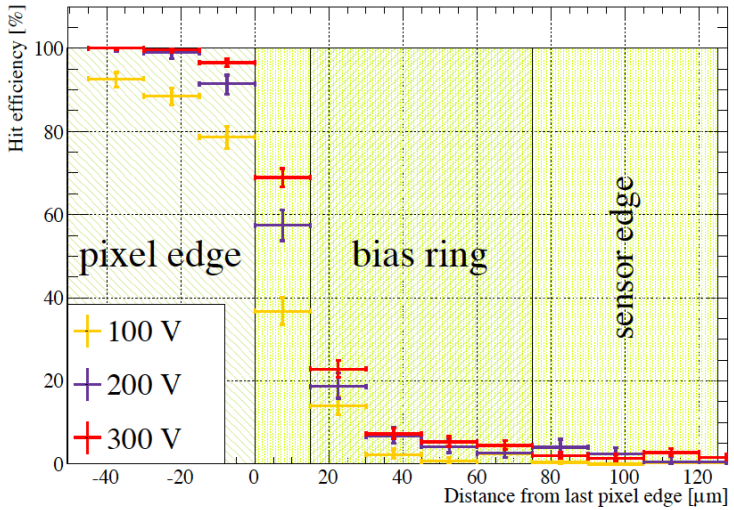
→ 100 μm effective inactive edge



FE-I3, 100 μm thick, 5x10¹⁵ n_{eq}/cm^2



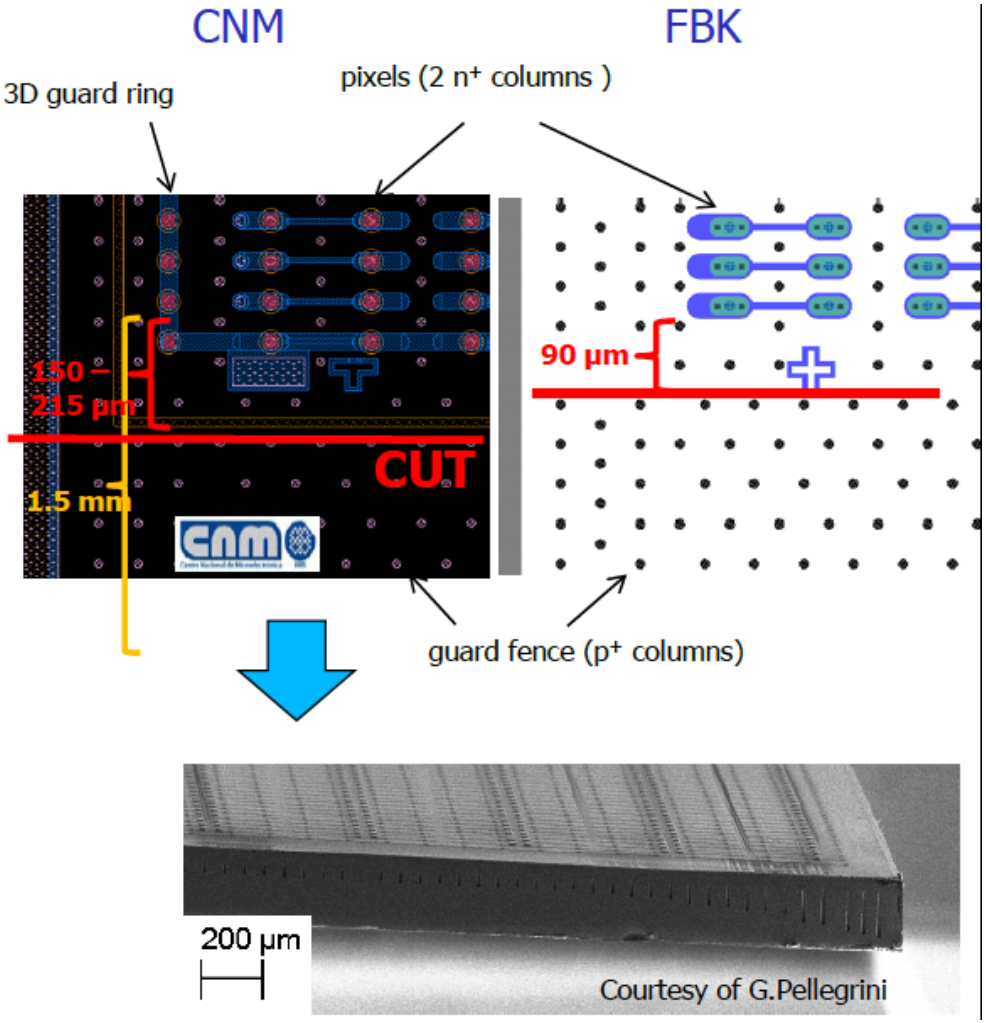
FE-I3, 100 μm thick, 5x10¹⁵ n_{eq}/cm^2, zoomed in the edge



Active / slim edge 3D sensors

- Studies to achieve very slim edges with 3D sensors for ATLAS Forward Physics Experiment (AFP)

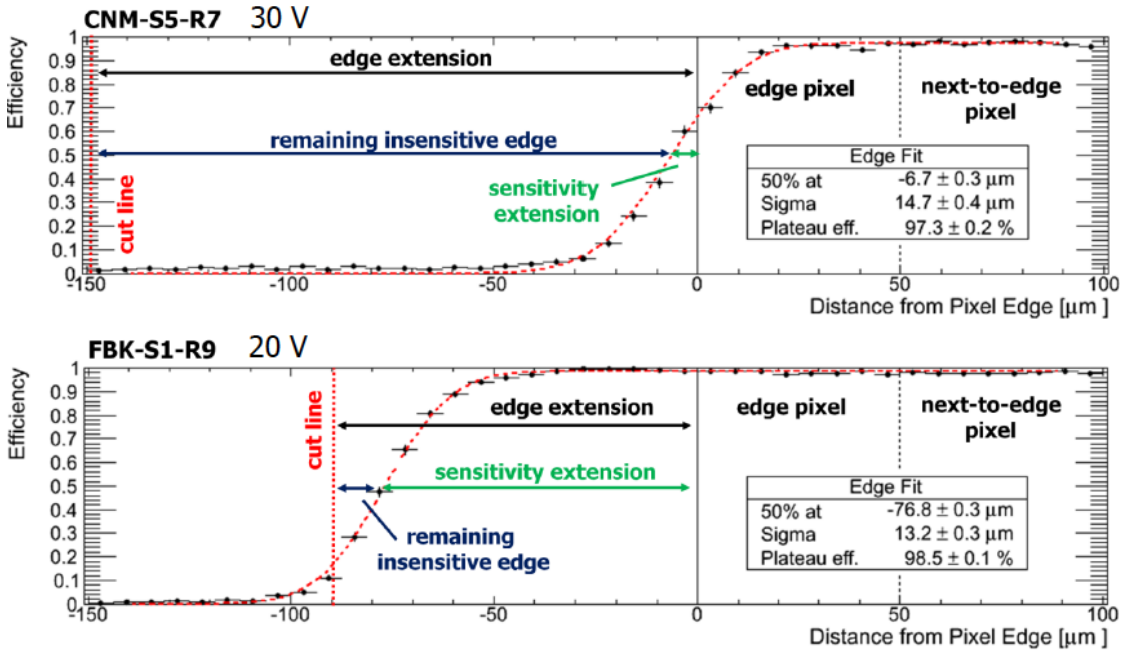
- Edge termination: CNM: 3D guard ring of n^+ columns + p^+ ohmic-column fence
- FBK: p^+ ohmic-column fence
- Left/right edge: already 200 µm slim edge for IBL
- Bottom (should be slim for AFP): 1.5 mm bias tab in IBL production (not needed!)



E. Cavallaro, Status of the 3D silicon detectors for the ATLAS AFP, Trento Workshop 2015

Test beam results of active / slim edge 3D sensors

E. Cavallaro, Status of the 3D silicon detectors for the ATLAS AFP, Trento Workshop 2015

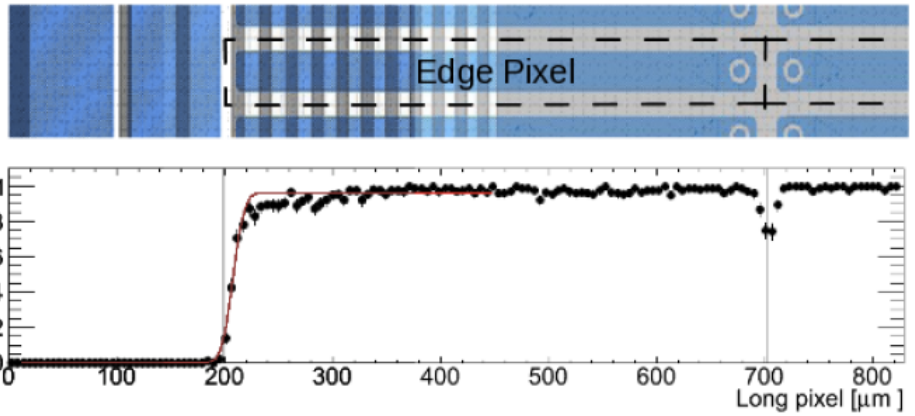


- DESY testbeam (4-5 GeV e-) with EUDET-type telescope
- Efficiency stable up to last pixel (smeared by telescope resolution)
- For FBK even ~75 um beyond pixel edge → Efficient edge due to absence of guard ring
- For both CNM and FBK <150 µm insensitive edge! → Slimmest edge apart from fully active edge technology

Slim edge in the ATLAS IBL n-in-n sensors

technische universität dortmund

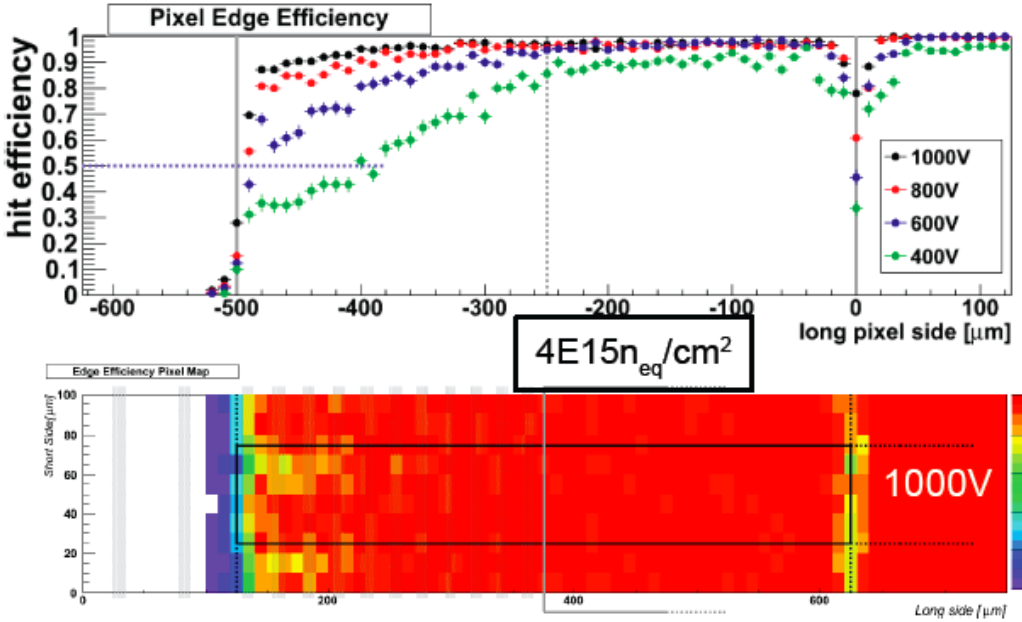
CIS production of IBL sensors



other 100 μm to the edge

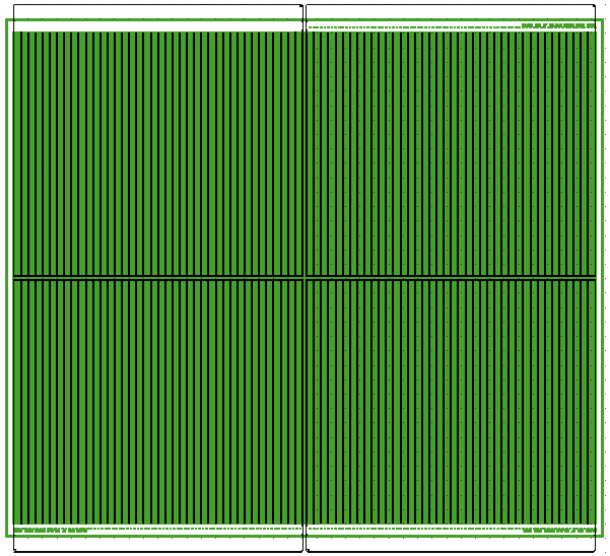
- Study of edge efficiency in beam tests for for FE-I4 n-in-n modules (IBL type)
- Before and after irradiation a clear dependence on the bias voltage is visible
- reduction of the inactive edge to ~200 μm demonstrated

T. Wittig, Pixel 2012

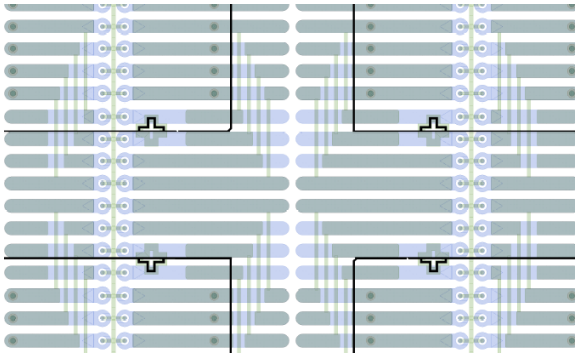


Pixel module design for HL-LHC

Multi chip module assemblies for HL-LHC

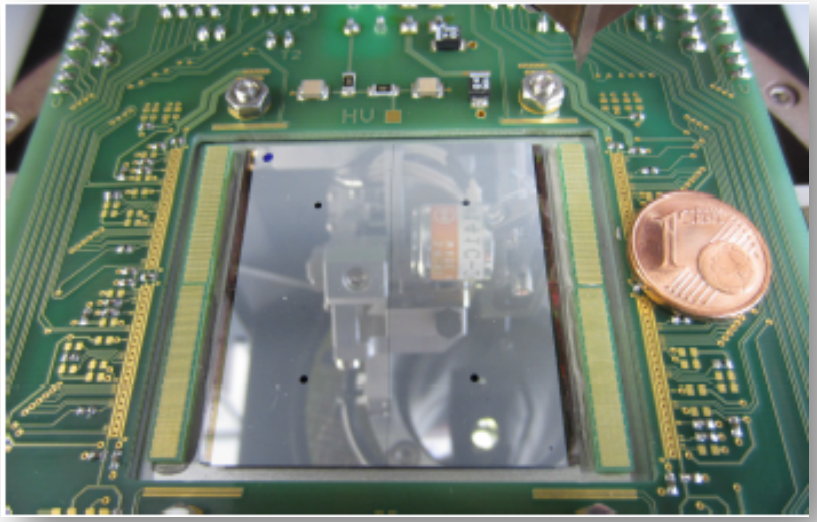


- Outer pixel layers will be instrumented with multi chip modules: quad sensors cover 4 FE-I4 chips, using long and ganged pixels between FE-I4 to increase active area

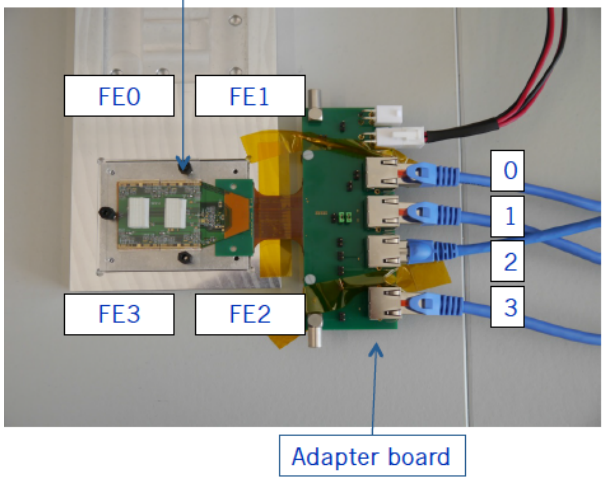


- Quad modules are being developed by German, Japan, UK ATLAS groups

Liverpool Quad PCB

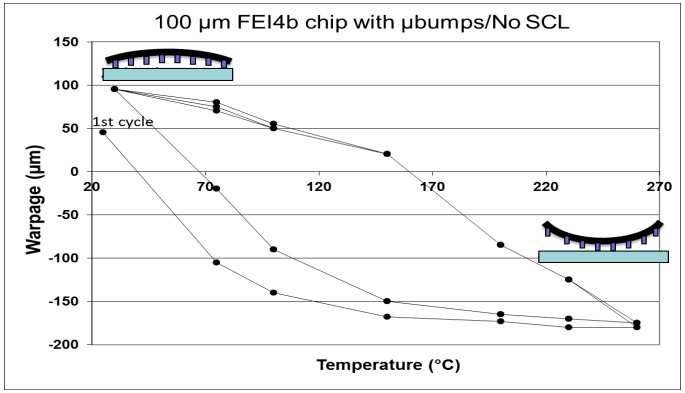


Bonn Quad Flex



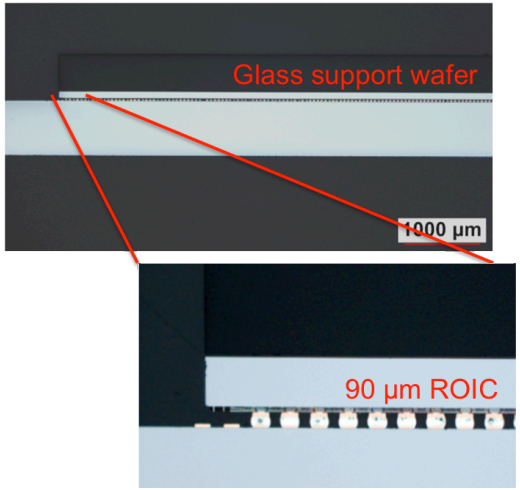
Thinning the read-out chip

- Good yield for full thickness modules with solder bump bonding and different vendors
- Modules with chips thickness ≤ 150 μm shows disconnected areas at the edges → Bowing due to CTE mismatch between metal stack and silicon substrate



- ATLAS: Investigate remove or reduce bowing with **stress compensation layer** on back of chip
- Effort underway at a number of vendors (HPK, LETI)
- Measurement of bow and material properties suggest using: 0.5μm SiN/Ti/4μm Al-Si SCL

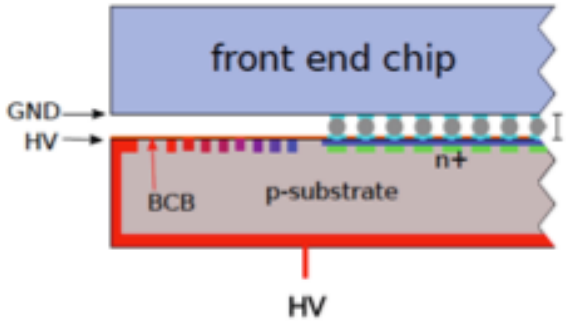
Large area pixel modules for HL-. -LHC pixel upgrades, C.Buttar, Pixel 2014



- IZM developed a glass carrier substrate, glued with polyimide glue, that can be dissolved by laser exposure
- Used for the ATLAS IBL with chip 150 μm thick, now under study for quad modules and chips 100 μm thick

Spark protection

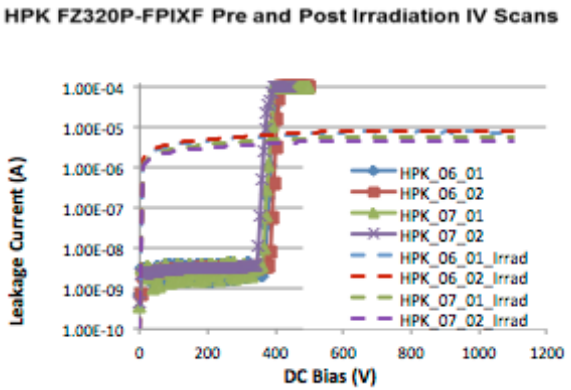
- Consequence of p-type choice: HV is close to ASIC and sparking can occur
- As voltages of up to 1000V may be required, protection is necessary



- Parylene-N coating: KIT irradiated module → no HV breakdown up to 1000 V

Development of HPK/KEK pixel sensors, Y. Unno, Pixel 2014

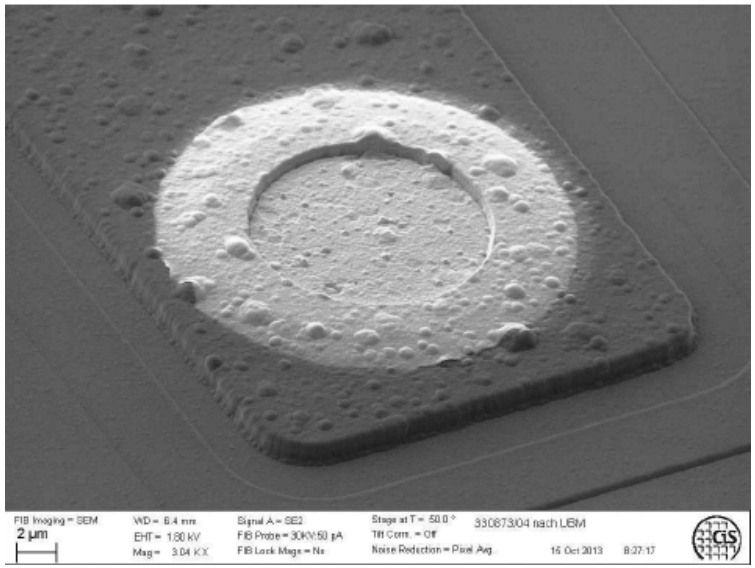
- Very good radiation hardness shown with sensors of the CMS HPK campaign



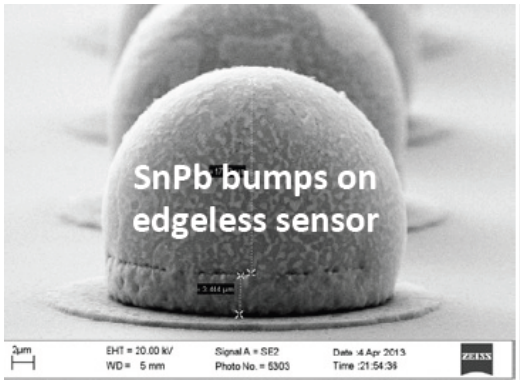
- 3 μm thick BCB coating (ATLAS) with lithography on sensor surface to open the bump contact → also tested up to 1000V
- The vertical walls of the sensors are still unprotected → BCB coating also on the cantilever side of the chip could help

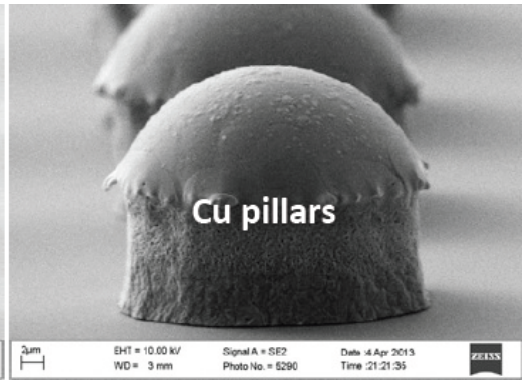
Alternative interconnection methods

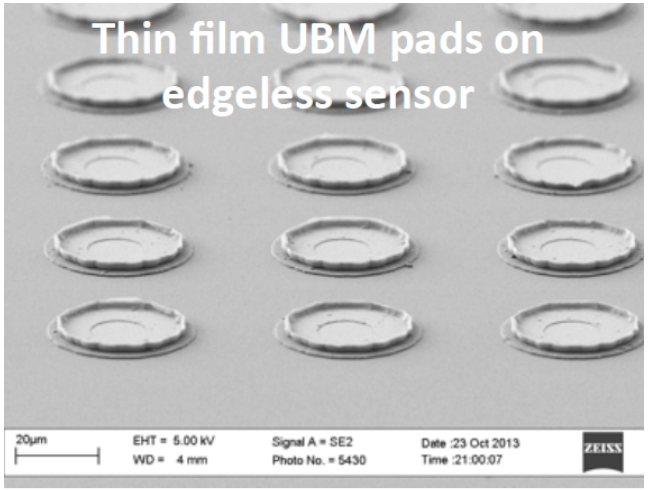
- A cheaper alternative sensor post-processing under development at CIS is electroless Nickel UBM (w/ or w/o mask), in combination with IZM solder bumps
  → also in this case UBM pad= 20 μm



- At ADVACAM thin film UBM pads on sensor side compatible with SnPb solder bumps processed in house or Cu pillars in collaboration with CEA-LETI





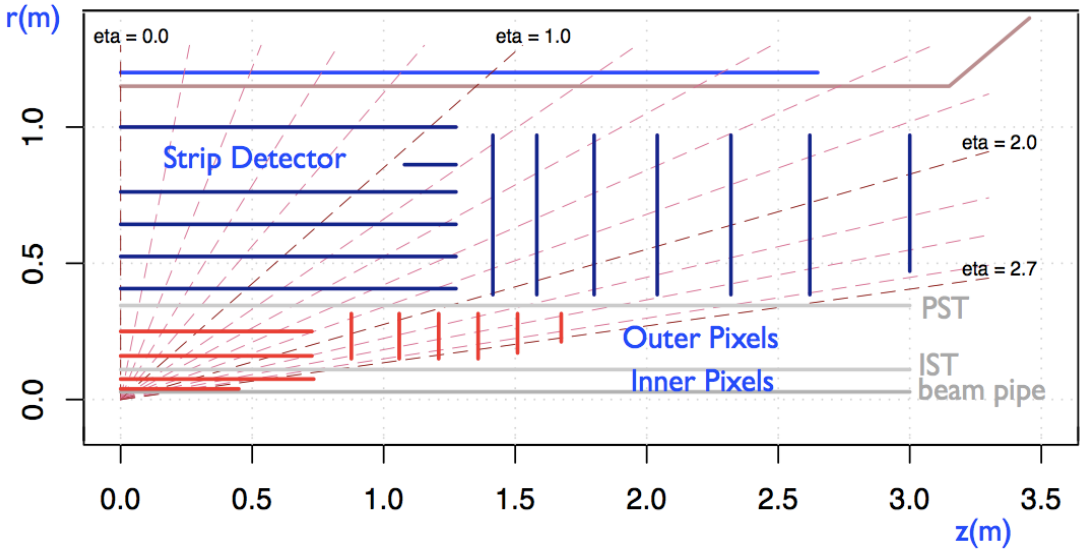


Summary

- Different technologies are being investigated for the production of thin hybrid pixel modules for the ATLAS/CMS trackers at HL-LHC
  - Charge collection measurements and beam tests prove the possibility of operating thinner detectors at reduced bias voltages with respect to thicker devices
- Slim/ active edges can be employed to avoid module superimposition in the inner layers → compromise between reduction of inactive area and achievable V_{break}
- Many engineering solutions explored for the production of full hybrid pixel modules for HL-LHC. Prototyping effort needed to address:
  - Spark protection
  - Flip-chipping of thin read-out chips
  - Low cost bump-bonding

Additional material

Phase II Pixel System Layout and Requirements



The layout proposed in the LoI provides 14 points/track to $|\eta| < 2.7$

Pixel: 4 layers + 6 disks

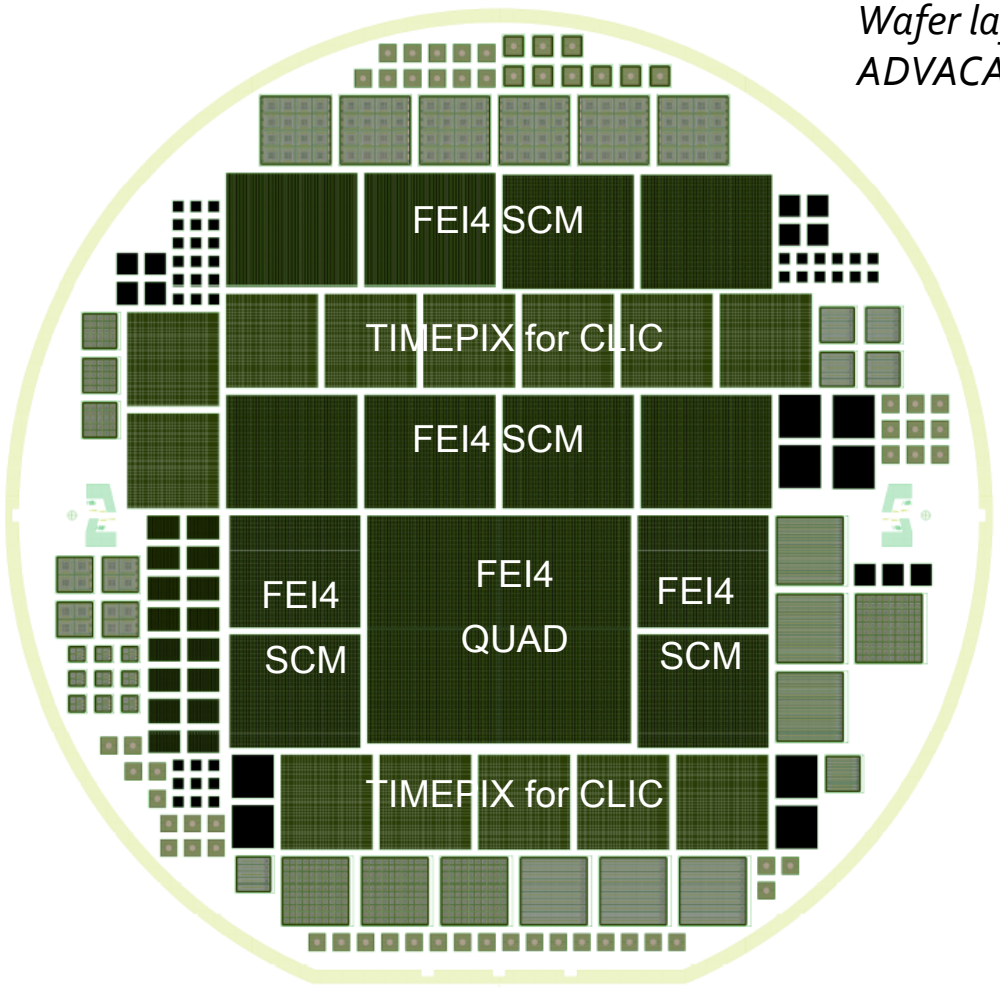
2 Outer Barrel Layers / Disks

- Planar n-in-p sensors baseline option
- Sensor thickness 150 μm
- 2x2 (Quad) chip modules

2 Inner Barrel Layers

- Sensors: different materials and technologies possible
- Radiation hardness up to 2×10^{16} n_{eq}/cm^2
- Thickness: 150 μm or lower
- Pixel pitch of 25x100 μm^2 or 50x50 μm^2 → FE-chip in 65 nm CMOS technology

Second production of active edge pixels at ADVACAM



Wafer layout of the new production at ADVACAM (spin-off VTT)

- In collaboration with Glasgow, Göttingen, LAL, CLIC CERN-LCD,
- Geneva University for medical applications

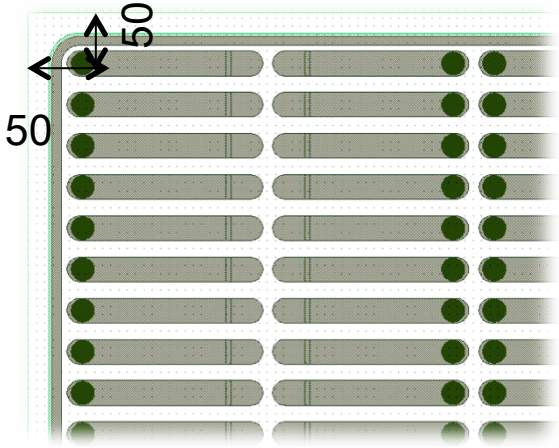
50, 100, 150 μm sensor thickness: 5 FZ p-type wafers for each thickness

- FE-I4 quad sensor
- FE-I4 single chip sensors different geometries
- Omegapix sensors
- TIMEPIX sensors for CLIC R&D
- CLICpix sensors for CLIC R&D
- Pixel and strip structures for medical applications

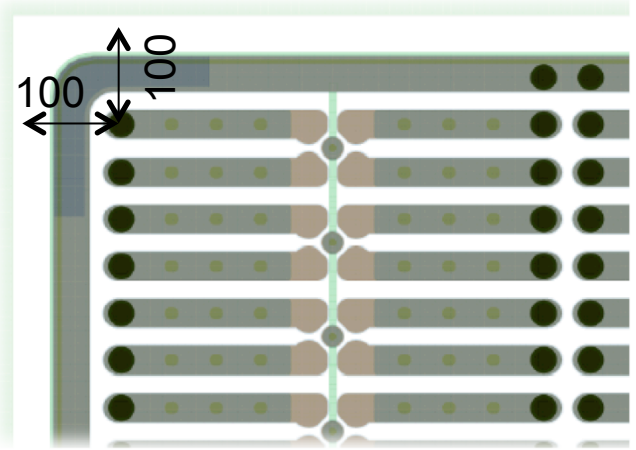
Active edge process for all the structures

FE-I4 Single Chip Modules

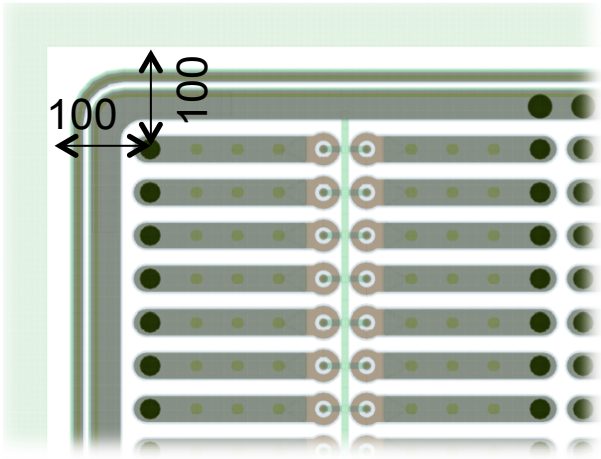
FE-I4 with 50 μm edge, one GR, no punch-through structure



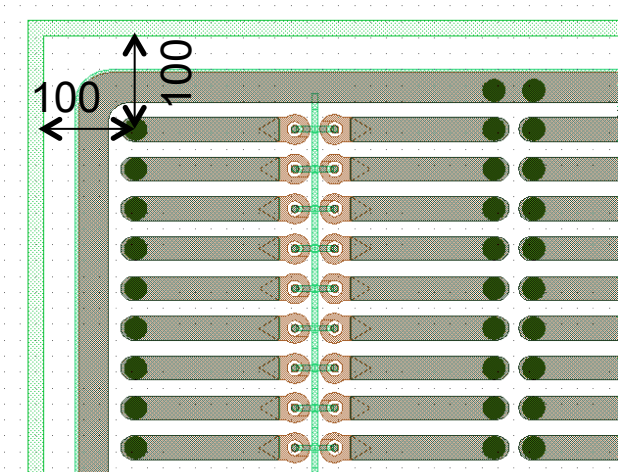
FE-I4 with 100 μm edge, Bias Ring, new external punch-through structure



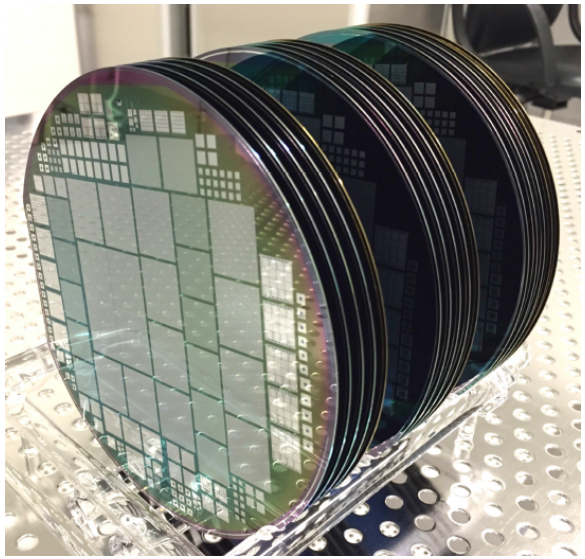
FE-I4 with 100 μm edge, Bias Ring + Guard Ring, std punch-through structure

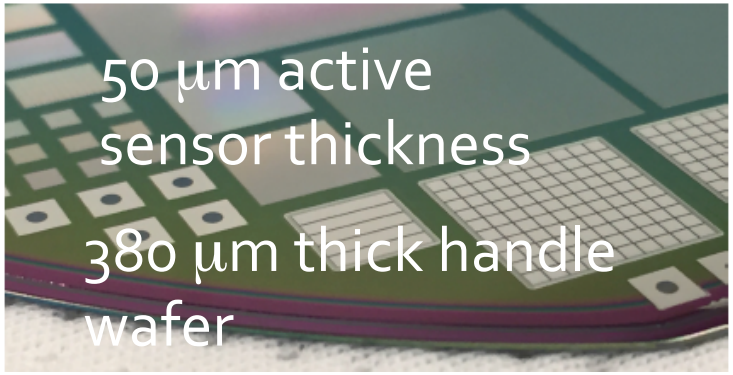


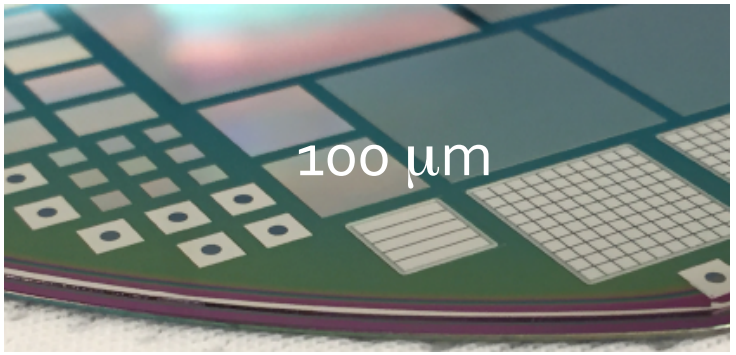
FE-I4 with 100 μm edge, Bias Ring, std punch-through structure



Status of the production



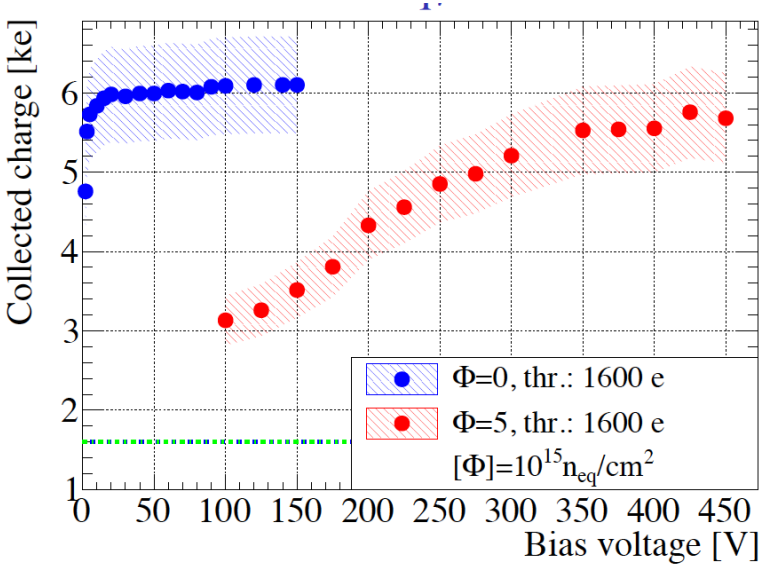




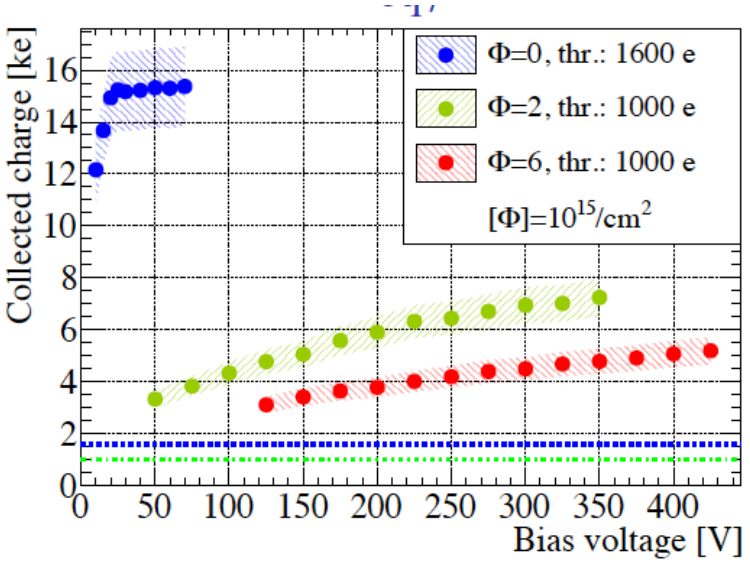
- Production of the sensor wafers completed
- Next steps:
  - Electroless UBM
  - Removal of the handle wafer
  - Flip-chipping of the first FE-I4 and TIMEPix modules

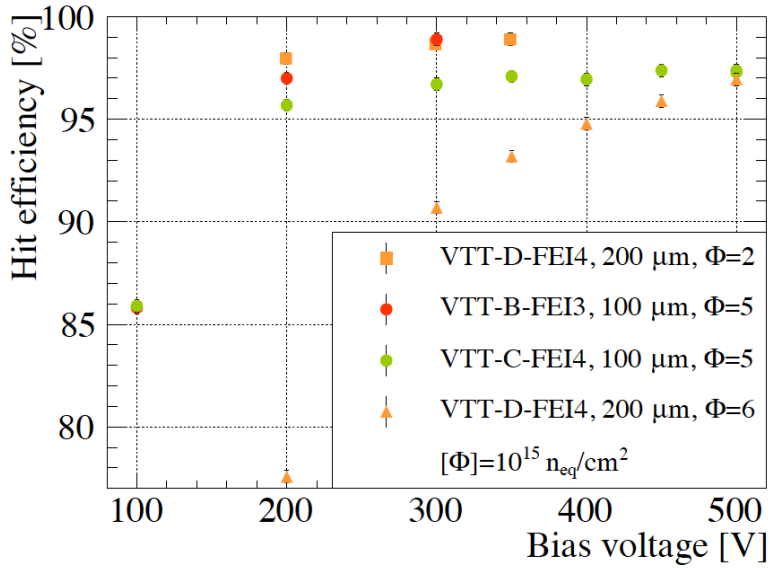
Comparison between 100 and 200 μm thick sensors

FE-I4, 100 μm thick, 5x10¹⁵ n_{eq}/cm²



FE-I4, 200 μm thick, 5x10¹⁵ n_{eq}/cm²





VTT FE-I3 100 μm, Φ=5x10¹⁵ n_{eq}/cm²

(99.0±0.3)% global hit efficiency at Vbias= 300 V (125 μm edge)

VTT FE-I4 100 μm, Φ=5x10¹⁵ neq/cm²

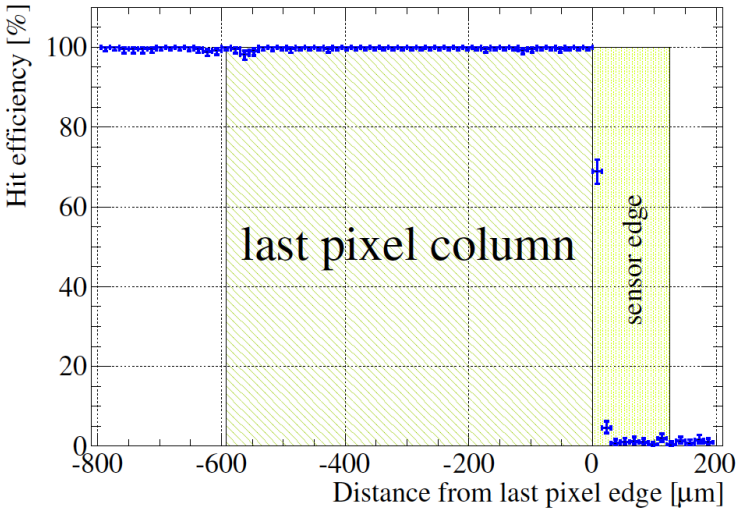
(97.0±0.3)% global hit efficiency at Vbias ≥ 350 V

VTT FE-I4 200 μm, Φ=6x10¹⁵ neq/cm²

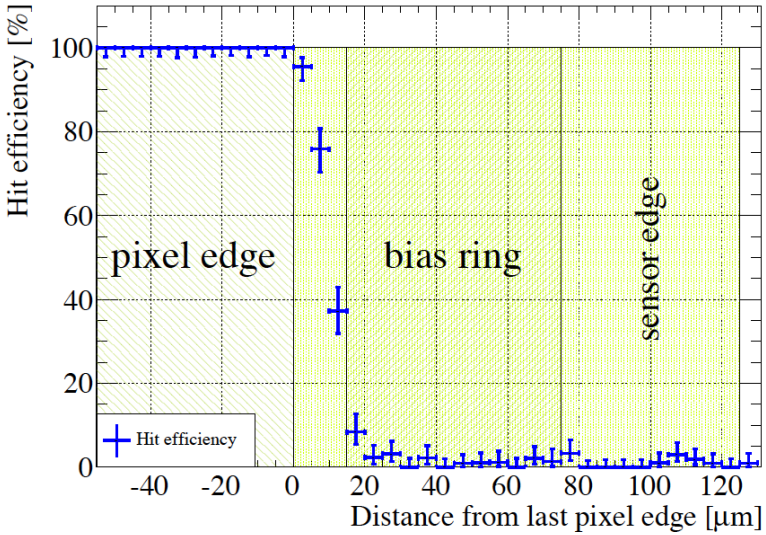
(96.9±0.3)% global hit efficiency at Vbias= 500 V

Hit efficiency for slim edge pixel modules

- 125 μm slim edge (only one Bias Ring)

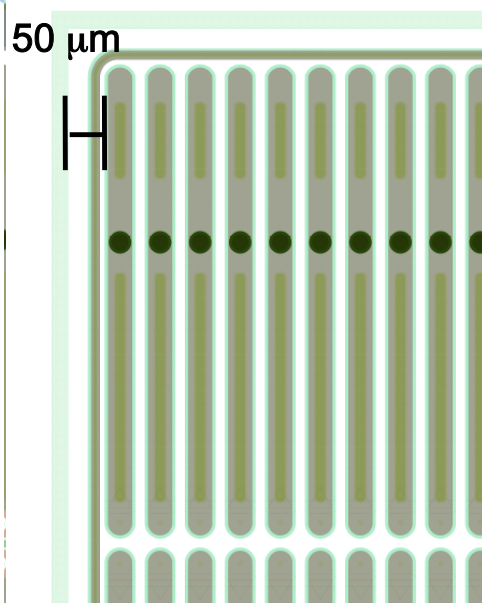


FE-I3, 100 μm thick, not irradiated

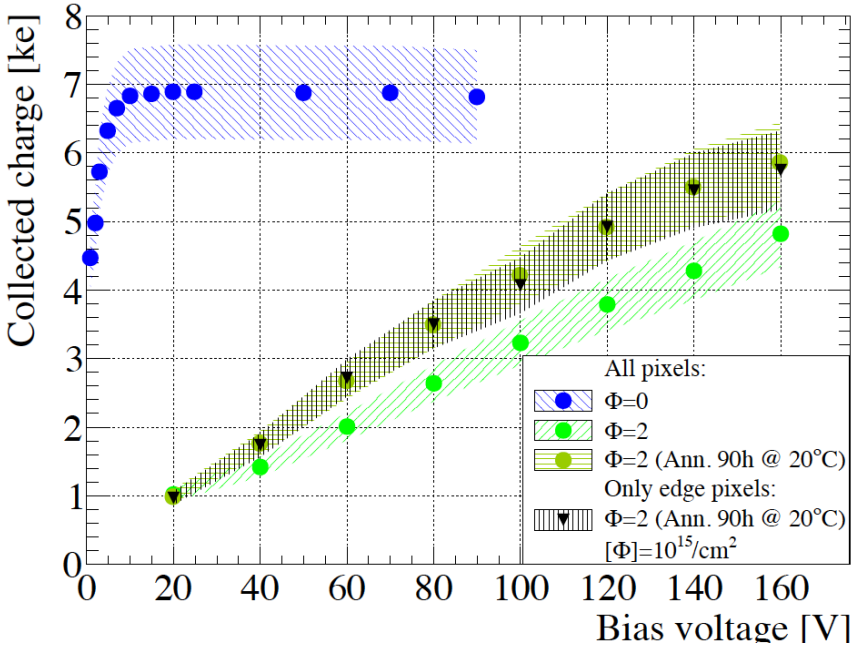


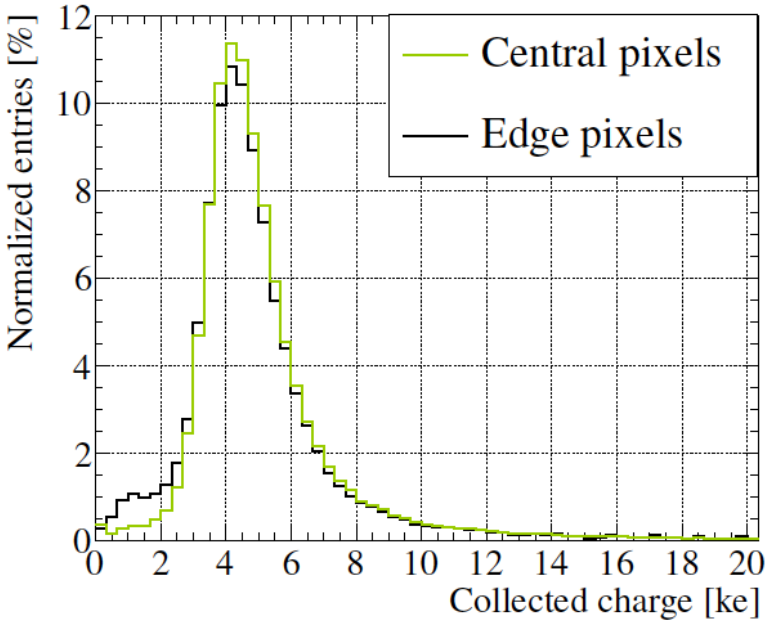
- FE-I3: 125 μm edge with BR
  - not irradiated
  - V_{bias}= 20V
  - threshold: 1500 e–
  - **(69±3)%** hit efficiency between the last pixel implant and the BR (CERN SpS, 120 GeV pions)

VTT active edge sensors

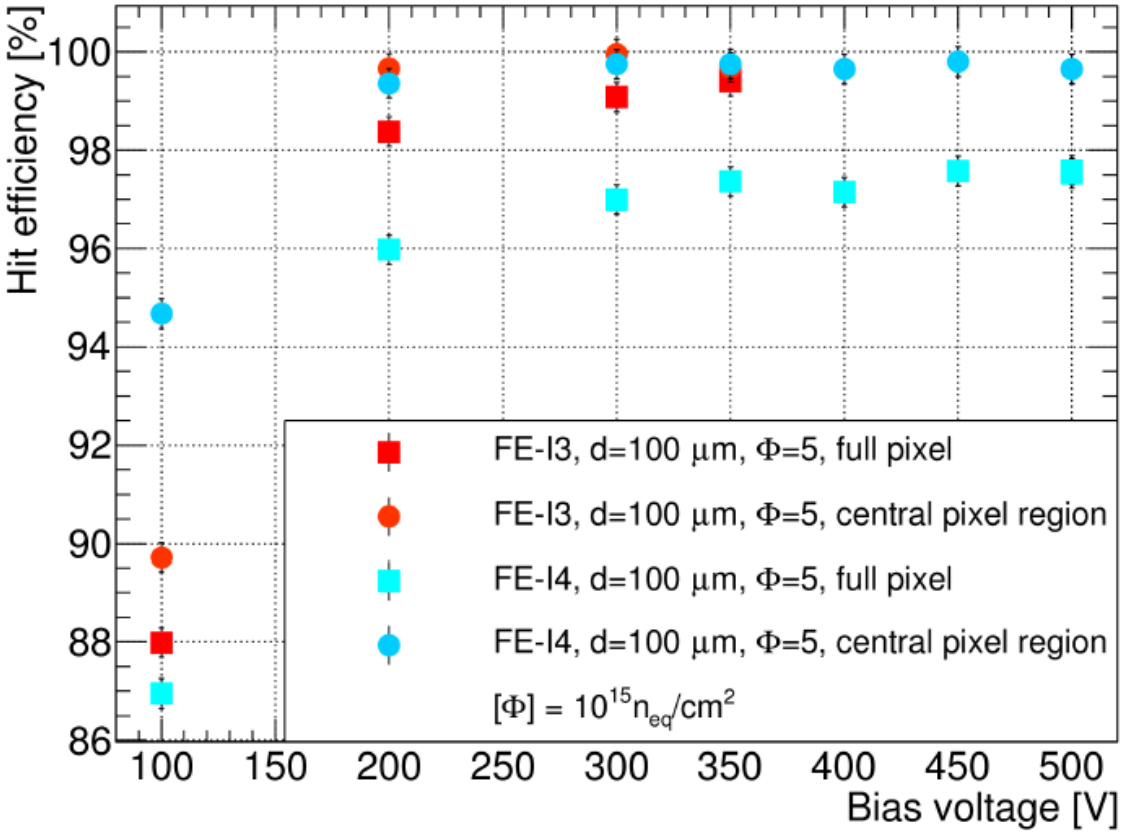


- Irradiation of active edge FE-I3 module with reactor neutrons in Ljubljana at $\Phi=2\times10^{15}$ n_{eq}/cm^2
- 100 μm thickness
- Charge collection measurements after irradiation with a ^{90}Sr source and the USBPix system
  - CC comparison between central and edge columns

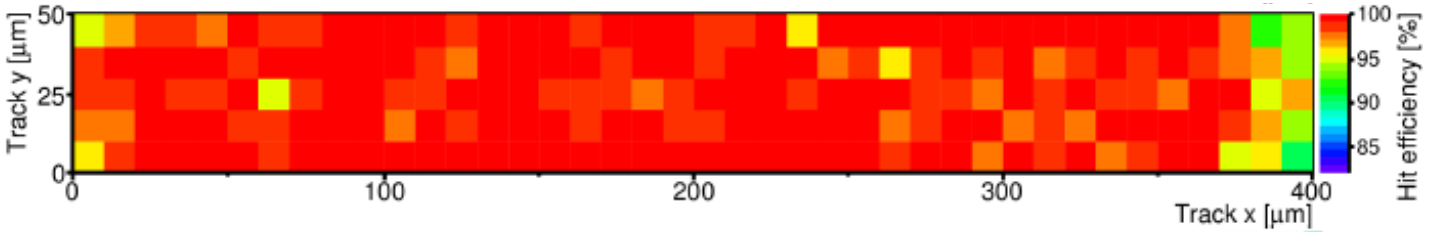




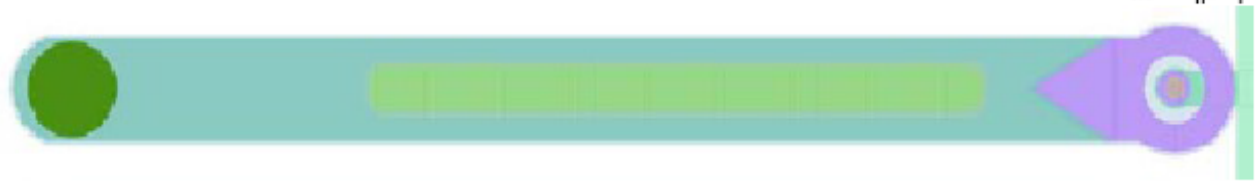
Comparison of FE-I3 and FE-I4 performance



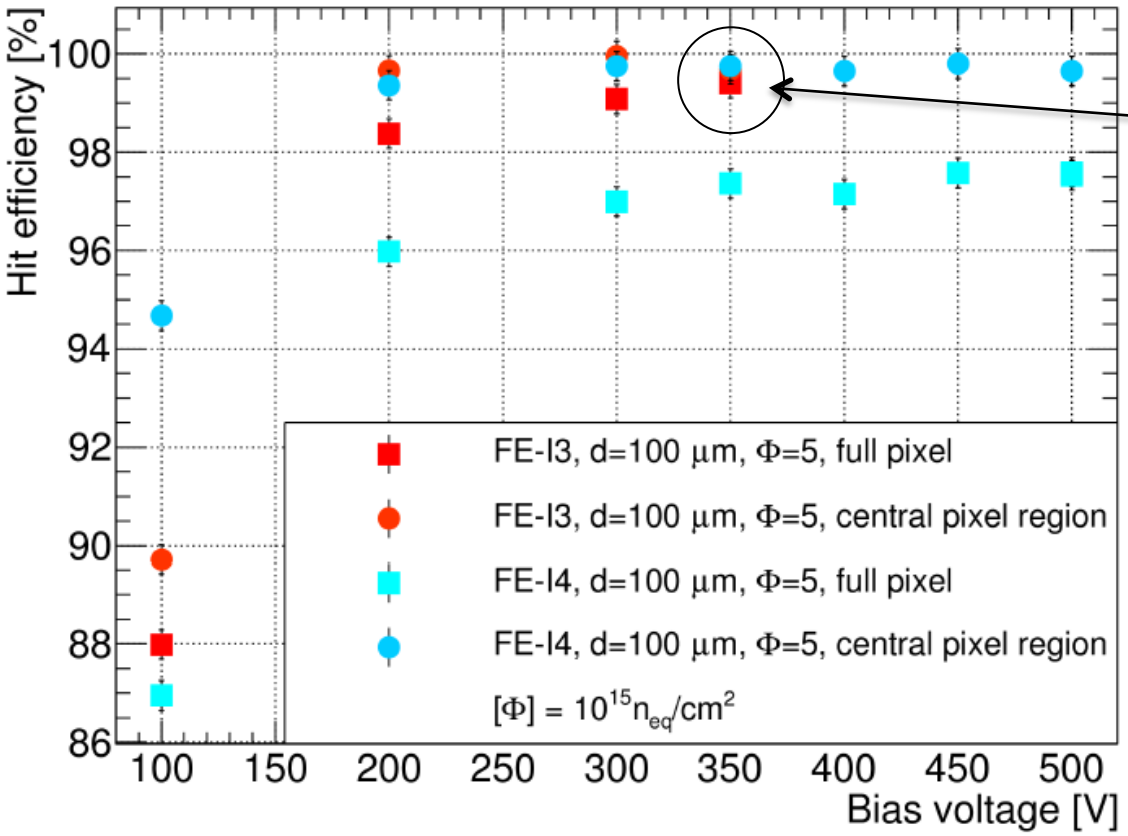
- 100 μm thickness: FE-I3 modules show a hit efficiency higher than FE-I4 modules at equal fluence and voltage



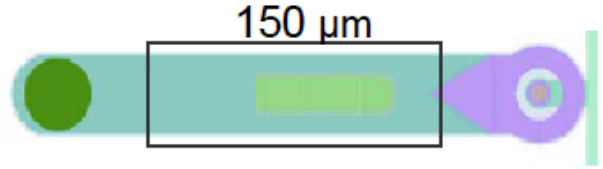
FE-I3 module
V_{bias}=350 V



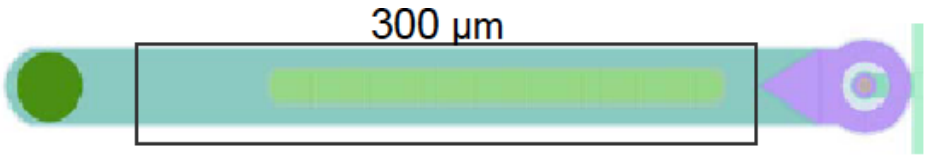
Comparison of FE-I3 and FE-I4 performance



In the central region, excluding the bias dot, FE-I3 and FE-I4 pixel modules with 100 μm thick sensors achieve the same hit efficiency



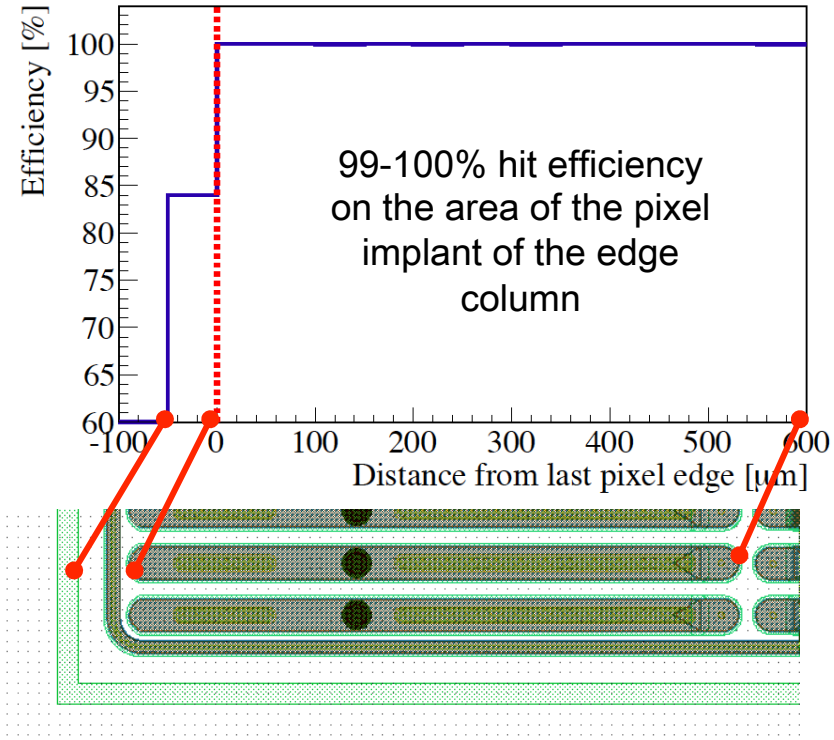
FE-I4 50x250 μm²



FE-I3 50x400 μm²

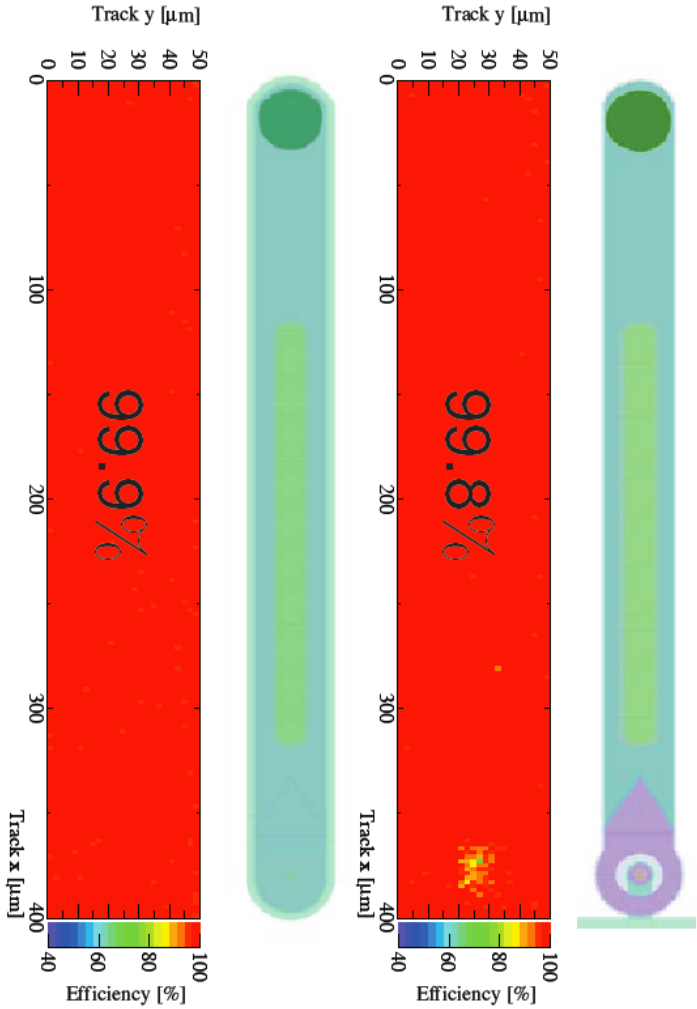
Active edges with planar n-in-p sensors - 100 μm thick

Edge Tracking Efficiency in Beam Tests



- 84^{+9}_{-14} % efficiency in the last 50 μm of the sensor edge, beyond last pixel implant

Global Efficiency in beam test

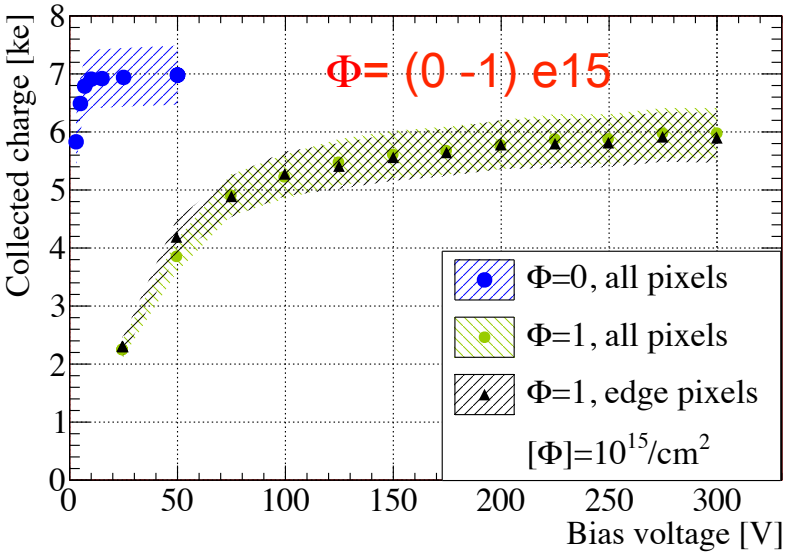


FE-I3, 50 μm edge, Vbias=20V

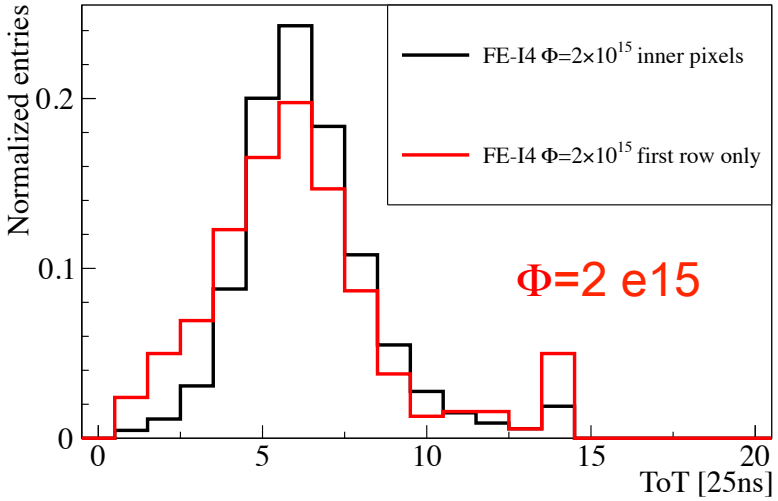
FE-I3, 125 μm edge, Vbias=20V

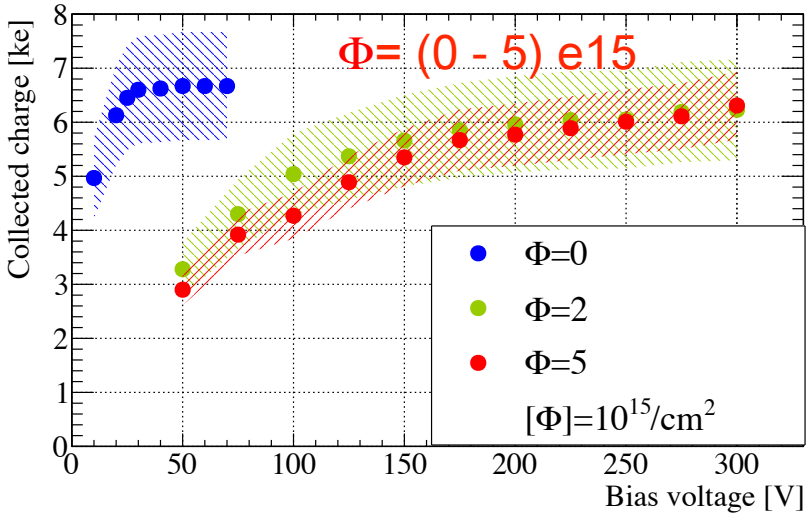
Charge collection efficiency after irradiation

- FE-I3 100 μm thick sensor with 125 μm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT ($1x10^{15}$ n_{eq}/cm^2)



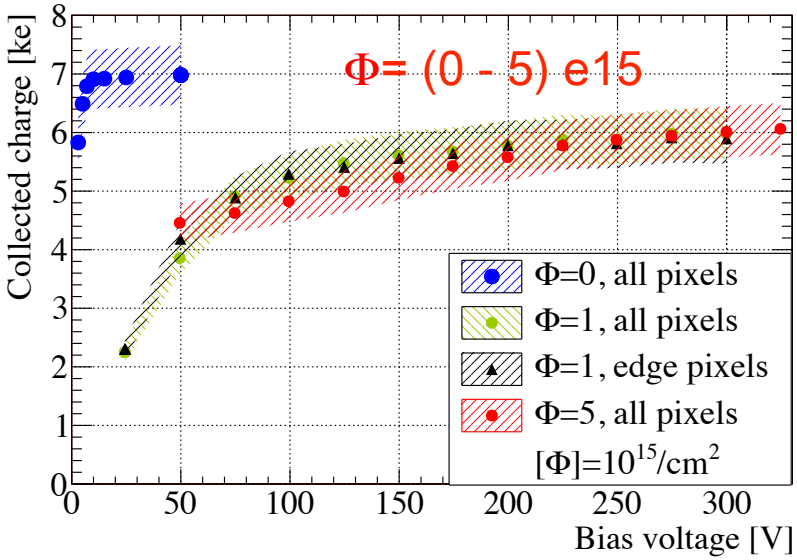
- p-type MCZ FE-I4, 100 μm thick sensor, with 125 μm slim edge, threshold 1100 e- → compatible charge collection properties between edge and internal pixels



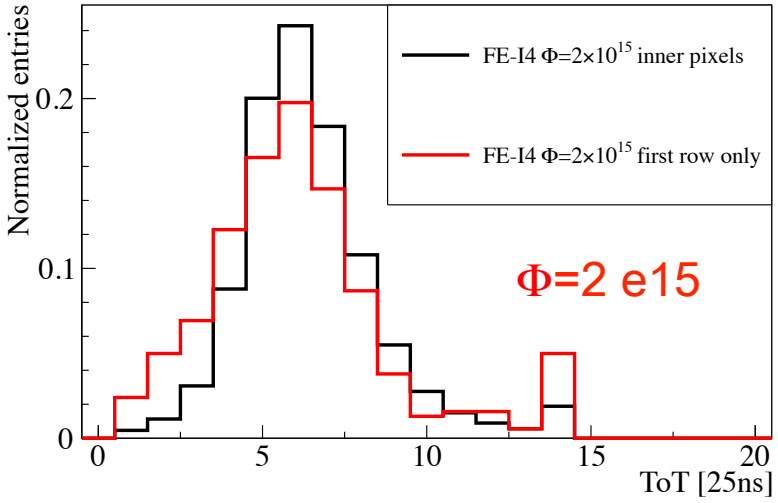


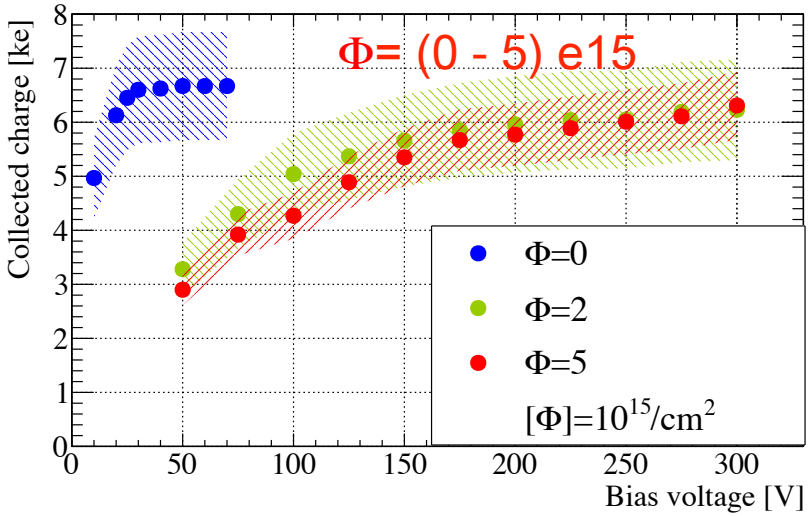
Charge collection efficiency after irradiation

- FE-I3 100 μm thick sensor with 125 μm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT ($1x10^{15}$ n_{eq}/cm^2) and in Ljubljana ($5x10^{15}$ n_{eq}/cm^2)

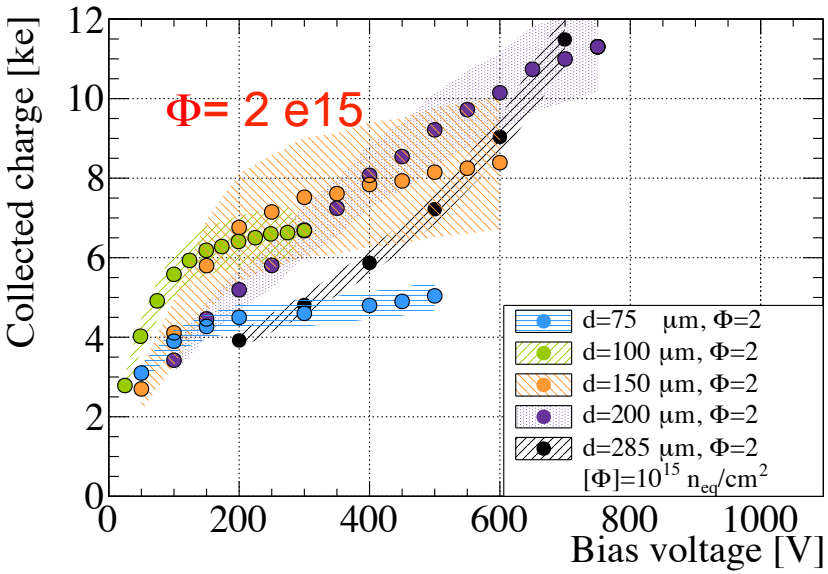


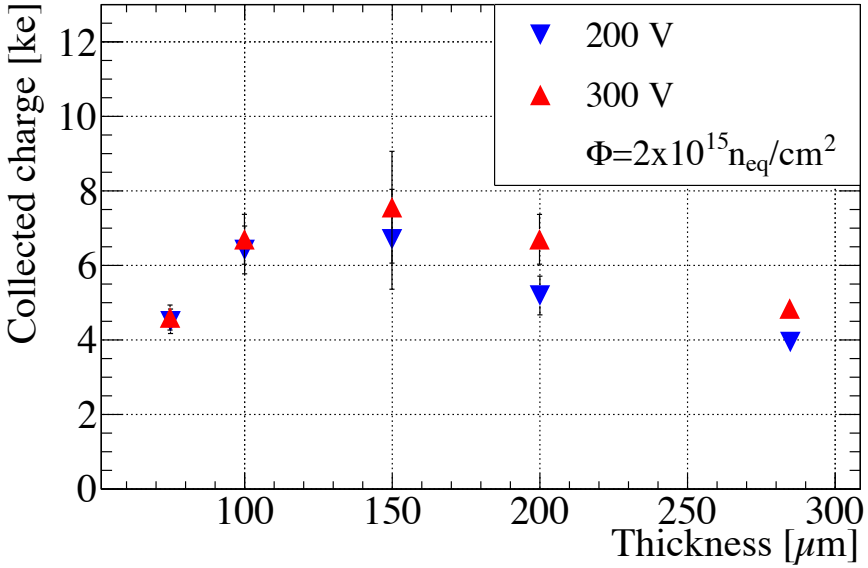
- p-type MCZ FE-I4, 100 μm thick sensor, with 125 μm slim edge, threshold 1100 e- → compatible charge collection properties between edge and internal pixels

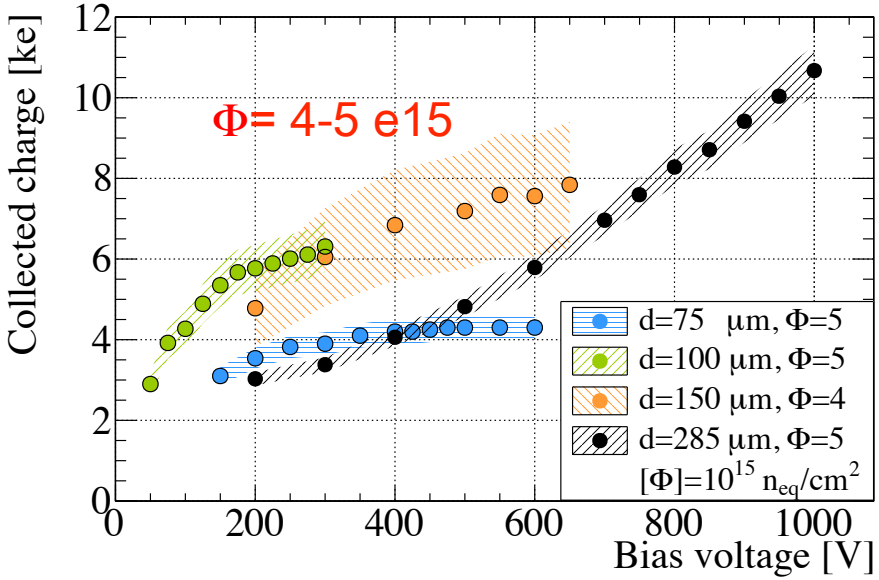


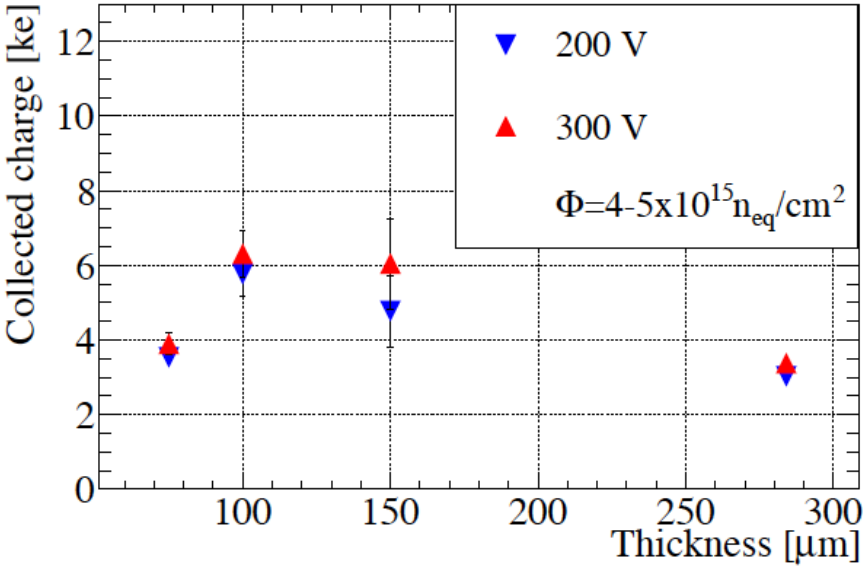


Charge collection for pixels of different thickness

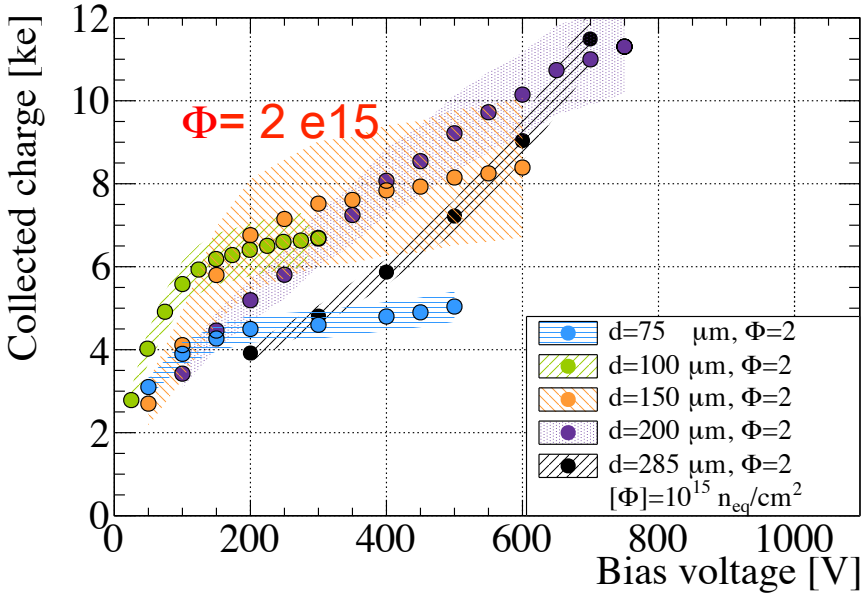




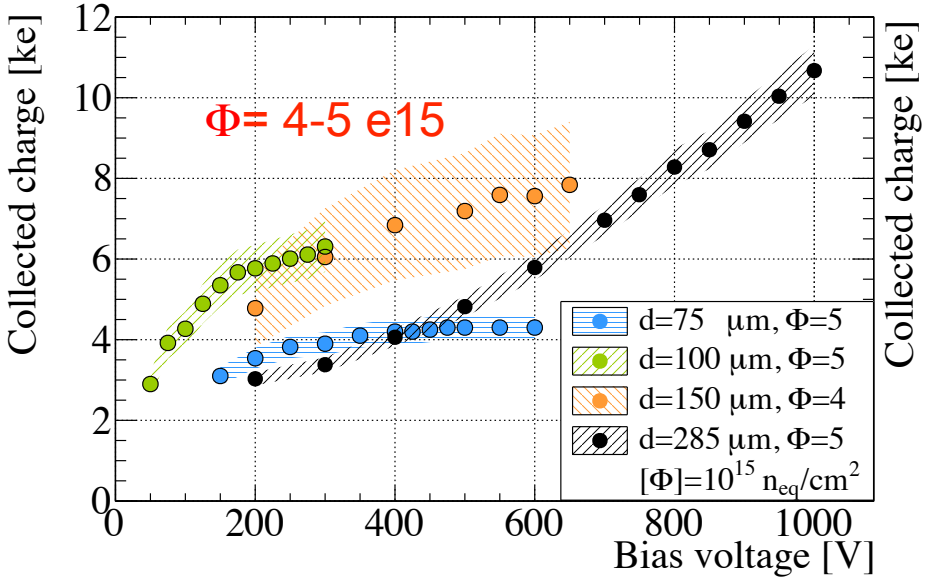


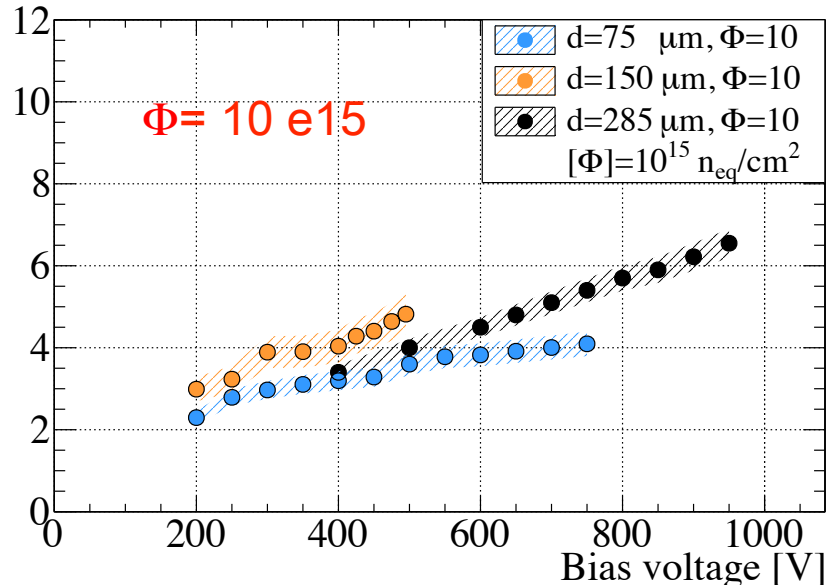


Charge collection for pixels of different thickness



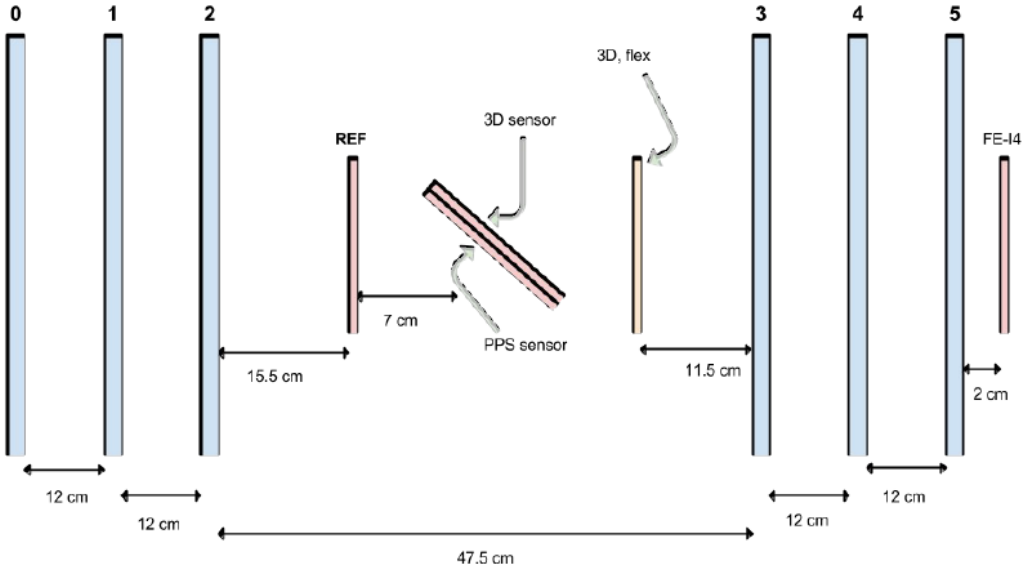
- The 100-150 μm thick sensors show higher charge collection up to a fluence of 4-5x10^{15} n_{eq} / cm^2
- At higher fluences the effect of charge trapping tends to equalize the charge collection efficiency for all thicknesses

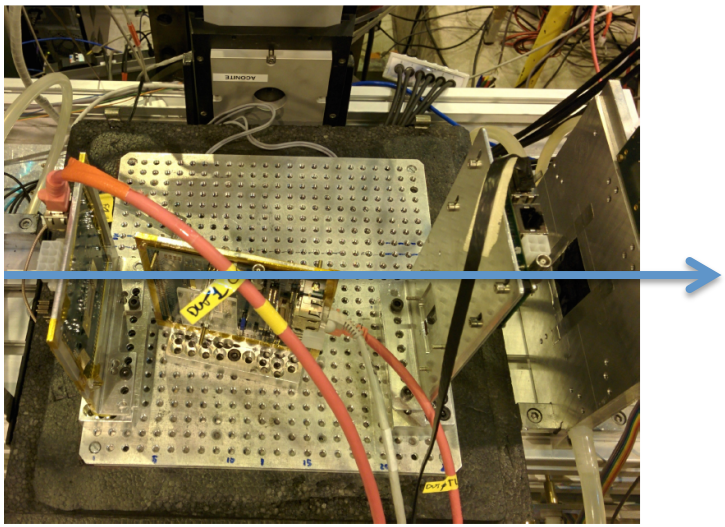




Tracking with 50 μm pitch pixels at high eta

- Aim: study the performance of 50x50 μm^2 pitch at high η
- Solution: use FE-I4 modules at high ϕ (80^0 → η=2.5) almost parallel to the beam but rotated by 90^0 with respect to their normal pixel orientation in the detector
- Samples: 100 μm thick planar sensor (VTT) + 230 μm thick 3D sensor (CNM) , back to back in the beam
- ITK/ RD50 test-beam at CERN SPS, October 2014

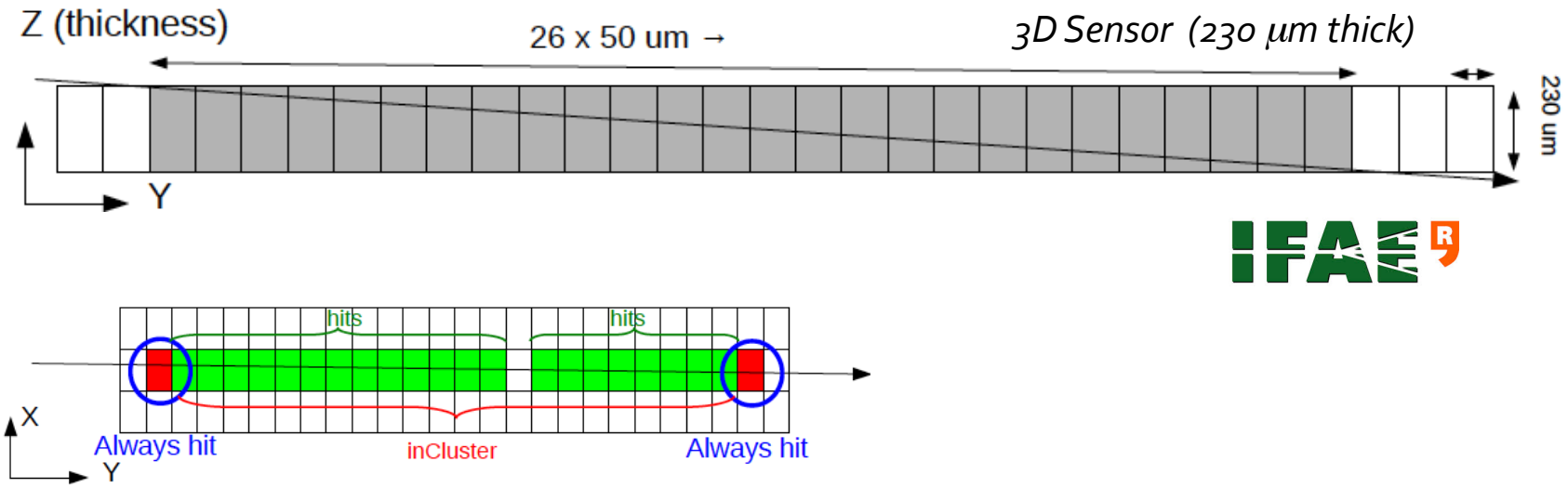




3D sensor results by I.Lopez

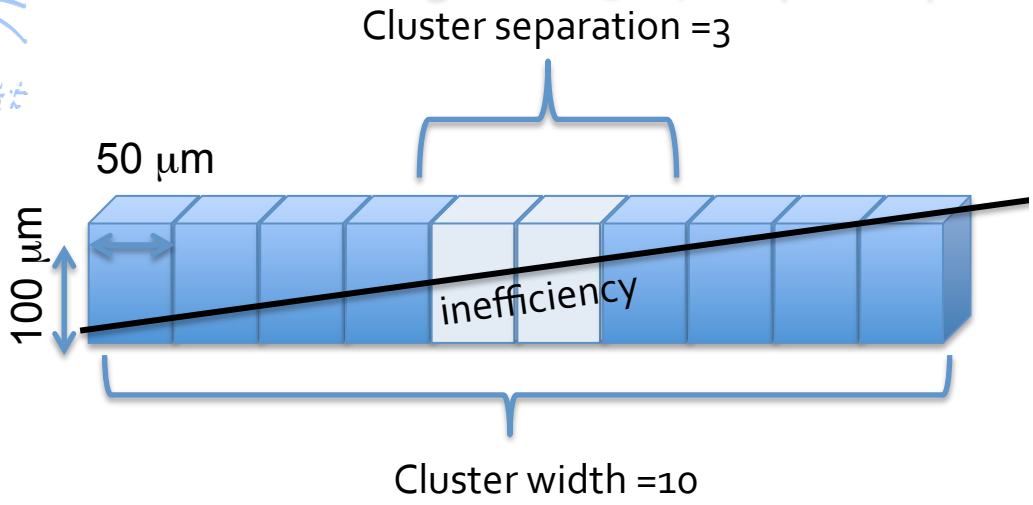
E. Cavallaro, S. Grinstein, J. Lange

Tracking with 50 μm pitch pixels at high eta (II)

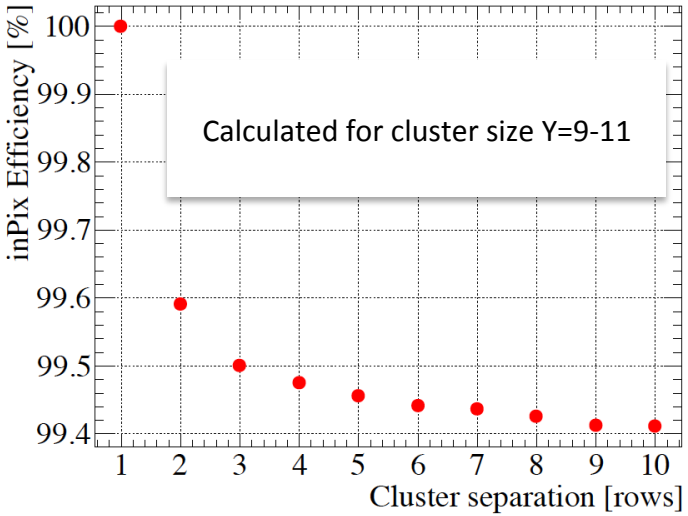


- No tracking information from EUDET telescope used (problems encountered in reconstruction)
- Very long cluster expected along z for high $\phi = 80^{o}$ (η=2.5) , use them as "tracks"
  - ~100 % cluster efficiency, more interesting to look at cluster splitting
  - Per pixel hit efficiency determined looking at the pixel w or w/o hits inside the cluster, excluding entrance and exit pixels.

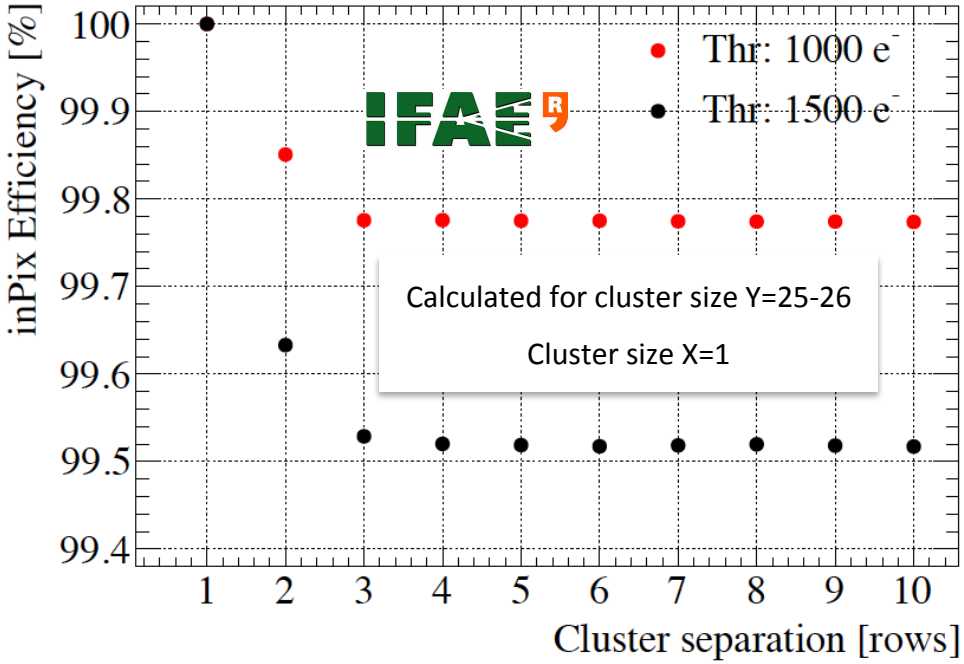
Tracking with 50 μm pitch pixels: Hit Efficiency



Planar Sensor (100 μm thick)



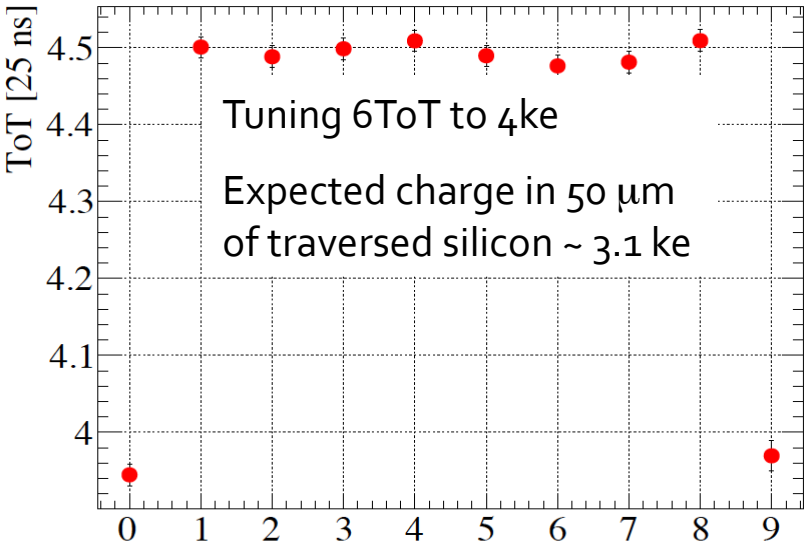
3D Sensor (230 μm thick)



Good hit efficiency with both type of sensors at 50 μm pitch at high eta !

Tracking with 50 μm pitch pixels: Charge Collection

Planar Sensor (100 μm thick)



- Before irradiation: flat charge distribution, except for the edge pixels that are only partially traversed
- After irradiation (250 μm pitch): overflow peak due to the calibration (10ToT @ 10 ke) at the edge of the ToT range (1-14) for a particle crossing 250 μm (~20 ke)
- ToT distribution inside clusters of width X=7 along the wide pixel side

Planar Sensor (150 μm thick), $\Phi=4\times10^{15}$ n_{eq}/cm^2,