WP6: Silicon Detectors R&D for Phase-II
(ALTAS planar pixels)

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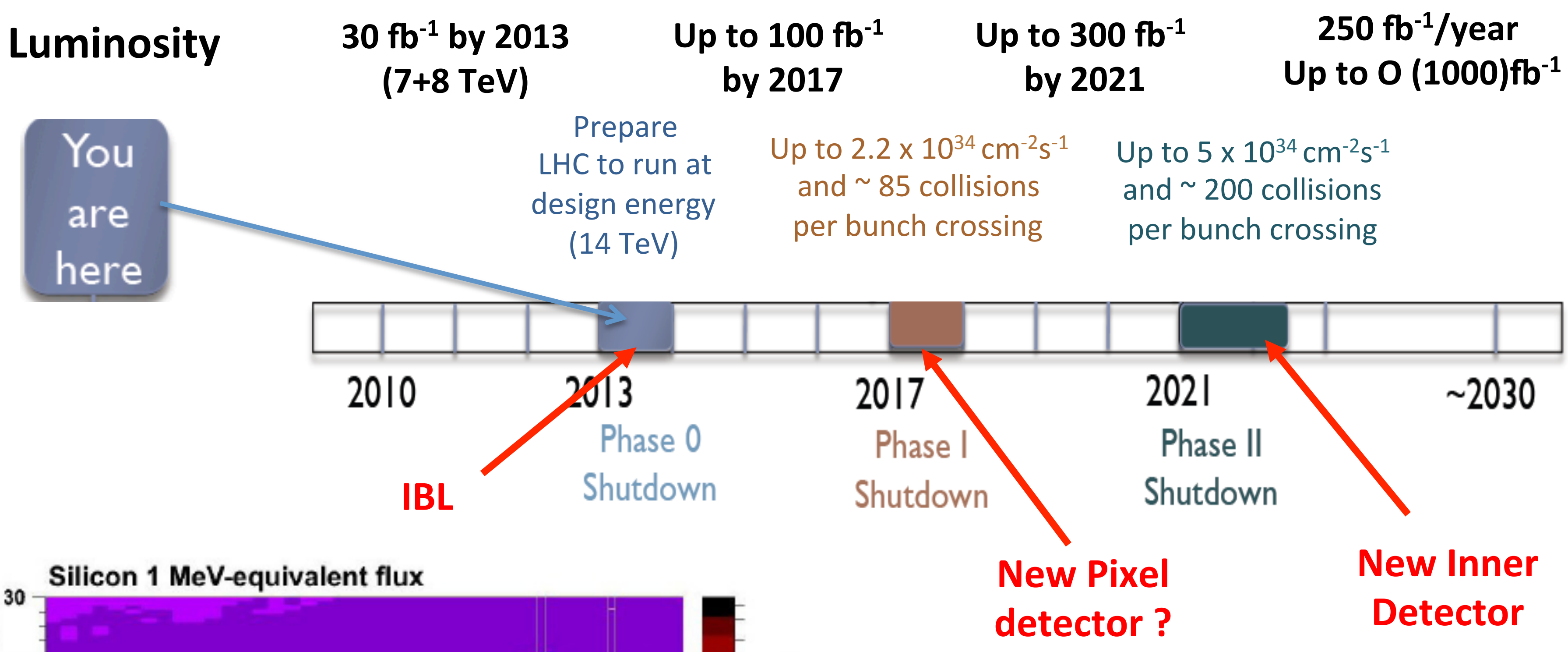
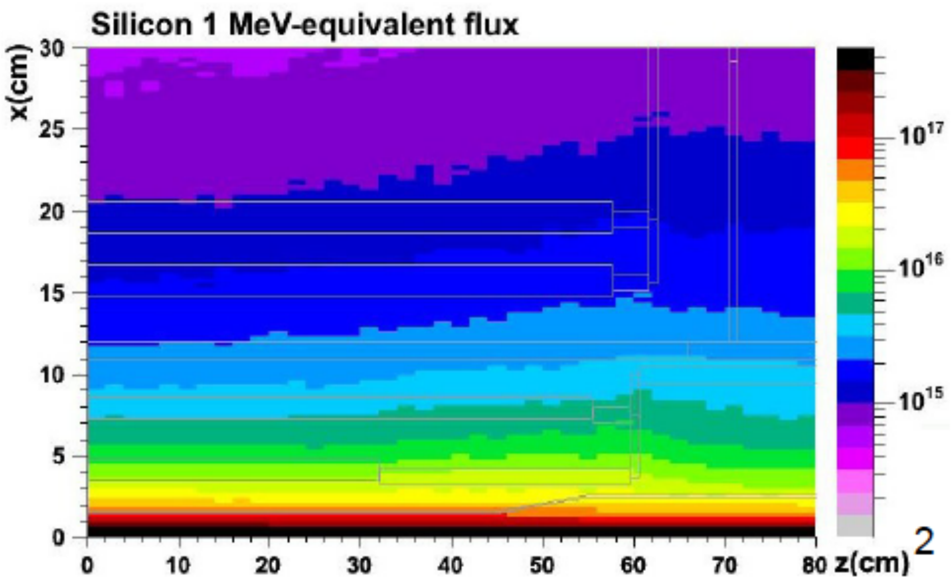
The roadmap for LHC





Fluence: up to 2 x 10^{16} n_{eq}/cm^2

- improved radiation hardness
- thinner bulk

Pileup

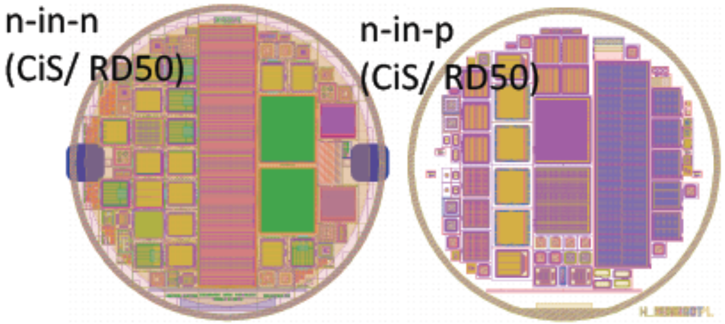
- increased granularity
- faster electronics

Material budget

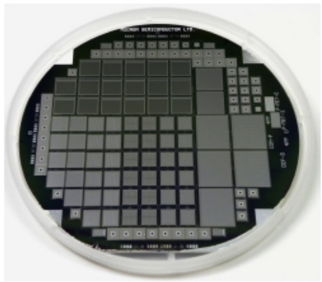
Work on pixels has been done in many directions

A) Planar Pixels:

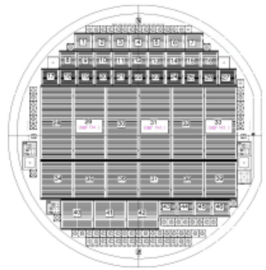
as the one presently used in ATLAS and CMS



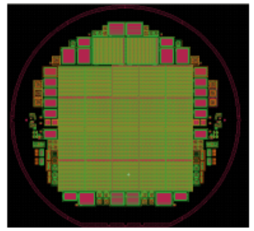
Micron

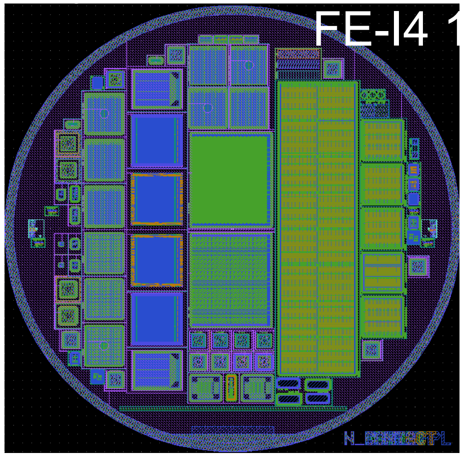


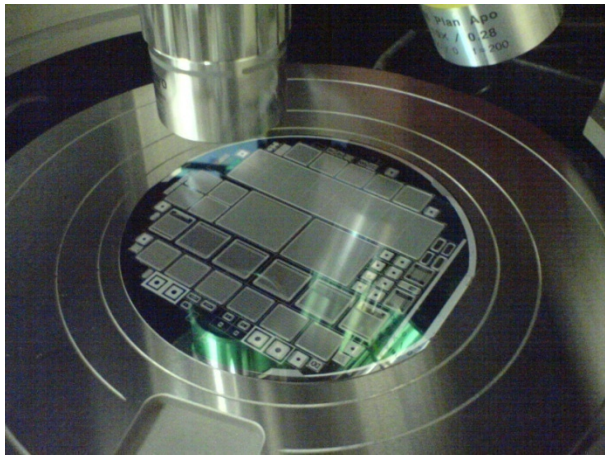
HPK

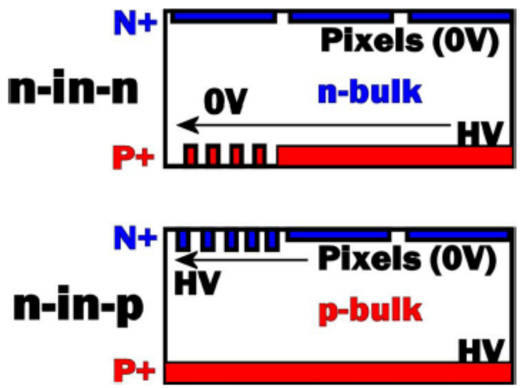


MPI-HLL





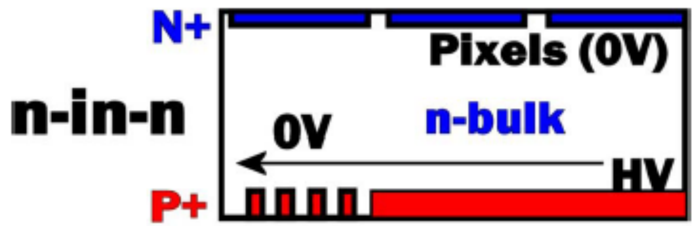




ATLAS productions: both n-in-p and n-in-n

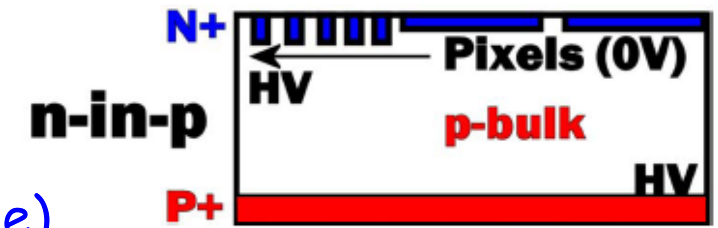
Option n-in-n

- The same technology used in the installed tracker
- Well known and tested
  (to the point that it's the planar candidate for IBL)
- More expensive that n-in-p
  (double side process)



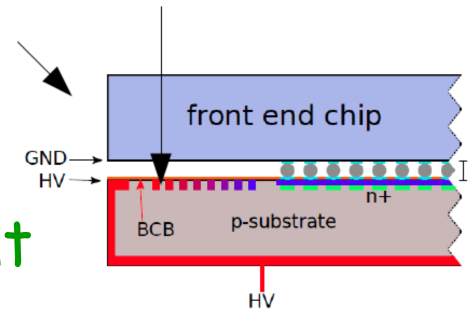
Option n-in-p

- Promising technology
- p-type doesn't invert with dose
- cheaper (pixel and GR on the same side)



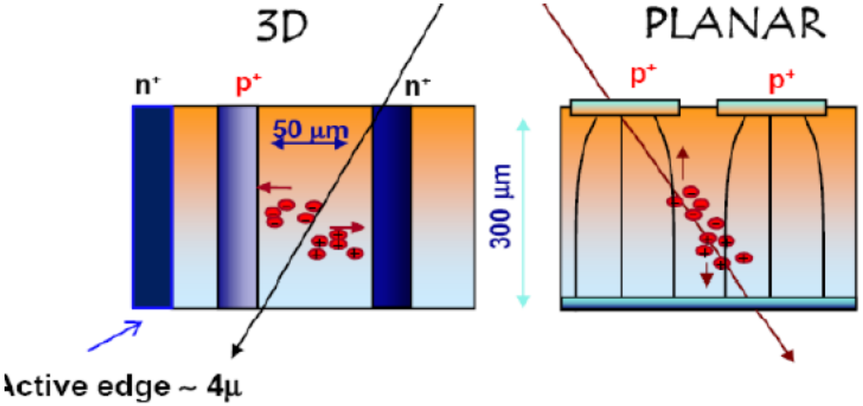
Some unwanted feature
(for example HV reaches the chip side)

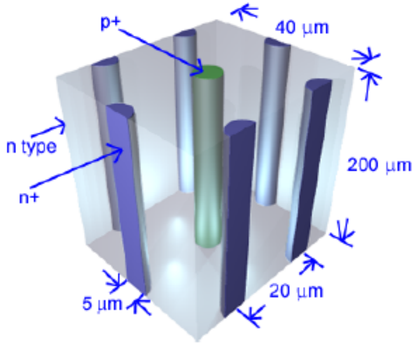
Sensor covered with 3 μm of BCB

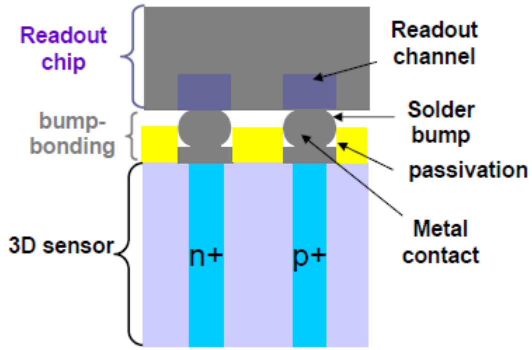


We think n-in-p will become very important in view of tracker replacement

B) 3D Pixels:





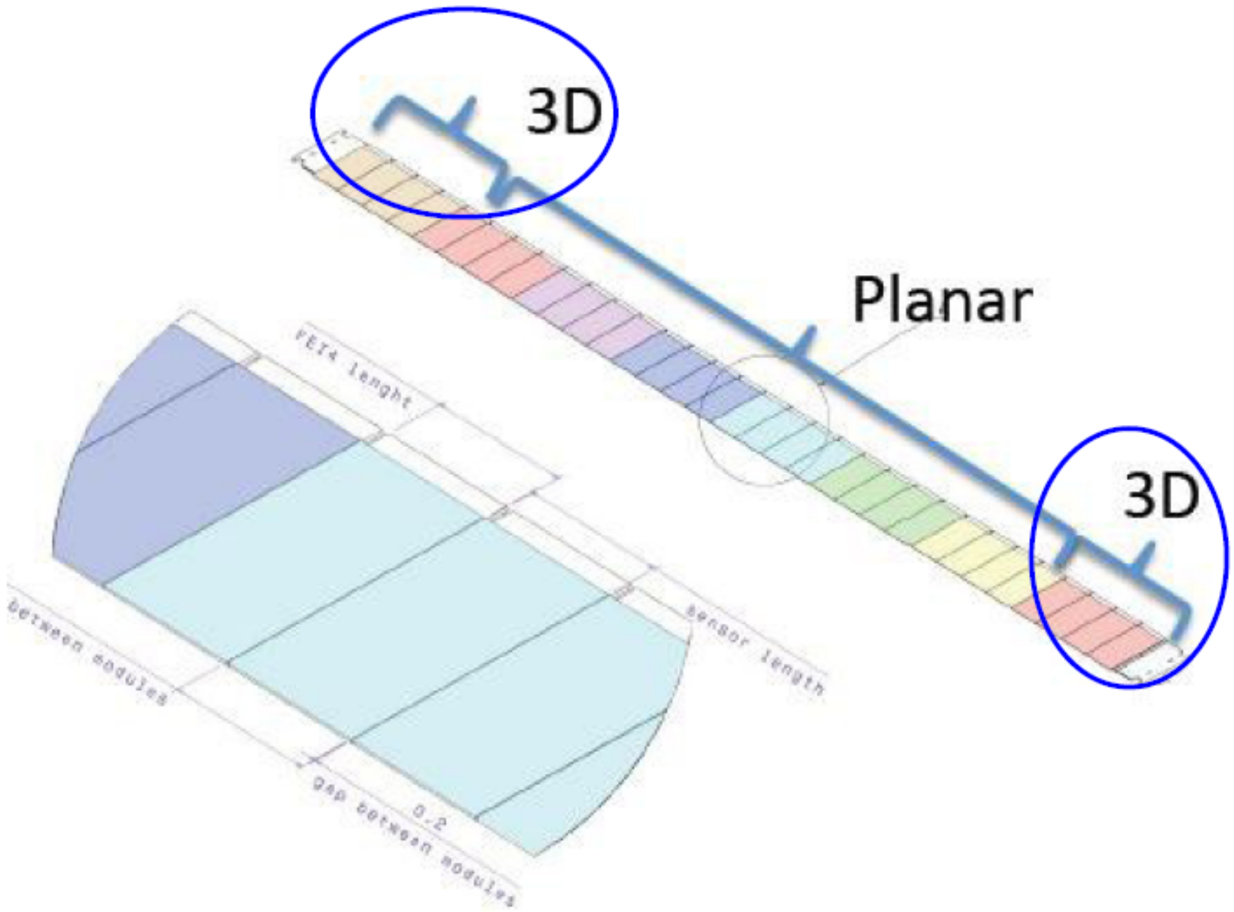


Here the electrodes are columns passing from one face to the other

In this way the electric field is parallel to the face of the sensor and the charge drift evolves in a few tens of um

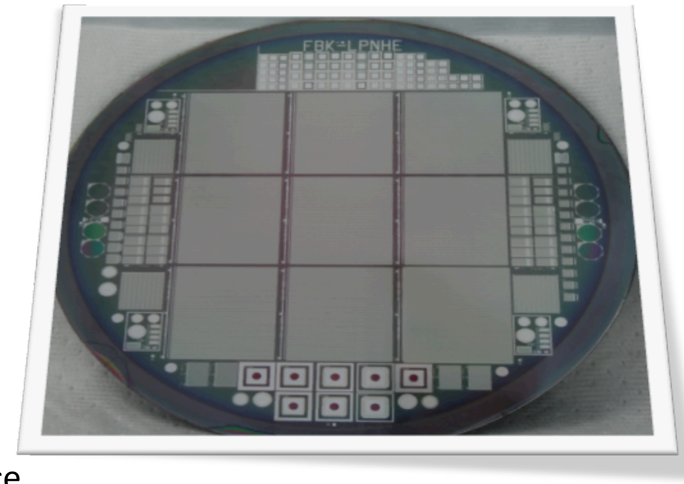
- They are intrinsically more rad-hard wrt to the planars and work at a lower bias voltage.
- Dead regions between the columns!

In the ATLAS IBL, being installed during this LS1

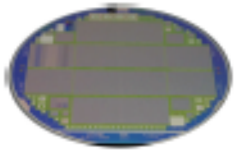
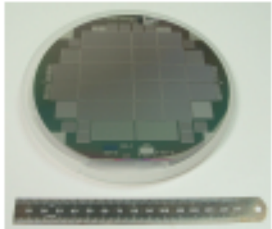
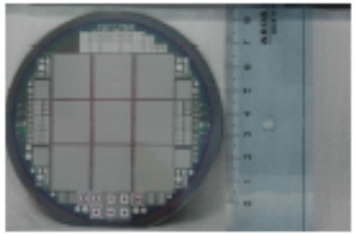


Phase-II: why planar sensors?

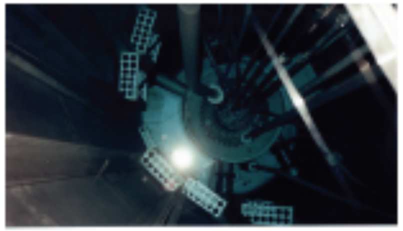
- Planar pixel is a proven technology
  - Modules shown to work after 10^{15} n_{eq}/cm^2
  - Possible replacement for some strip layers
- Low-cost large area production possible
  - n-on-p sensors: single-sided process
- Project research axes
  - Advanced simulation studies
  - Active area optimization (slim/active edges)
  - Radiation damage studies
  - Low cost module production (6", 8", interconnections...)



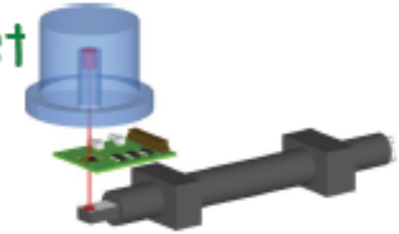
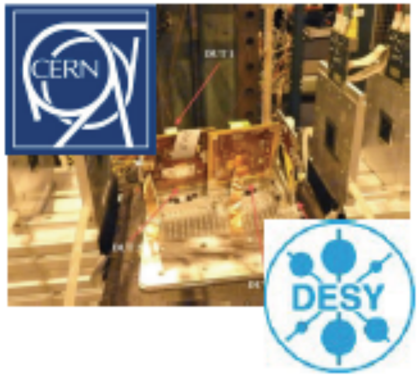
PPS working tools

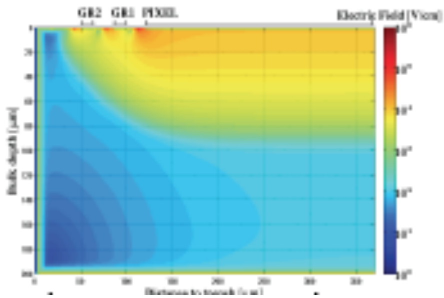




- New productions:
  - CiS, MPI-HLL, MICRON, HPK, VTT, FBK
- Irradiations
  - Reactor neutrons (Ljubljana)
  - 26 MeV protons (Karlsruhe)
  - 24 GeV protons (CERN)
  - 800 MeV protons (Los Alamos)



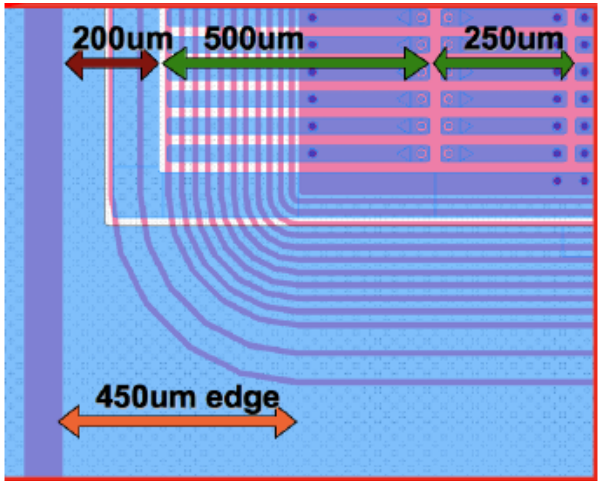

- Lab characterization & beam test
  - Radioactive sources
  - 120 GeV π (CERN)
  - 4 GeV e (DESY)
  - EUdet telescope
- TCAD simulations



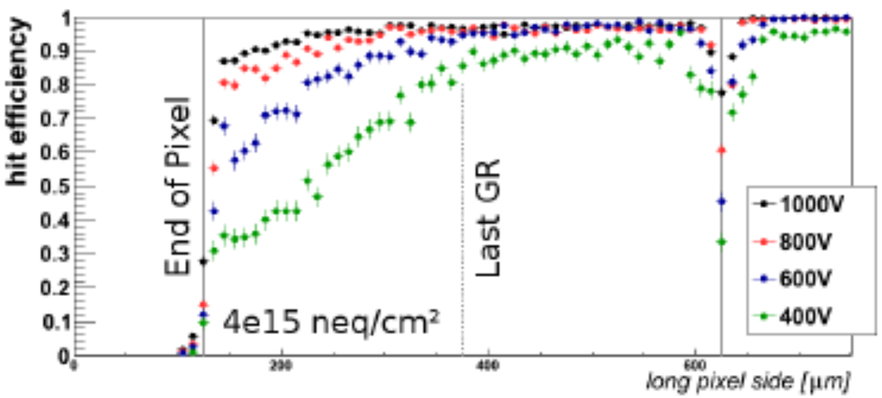
Geometry optimization: slim edges

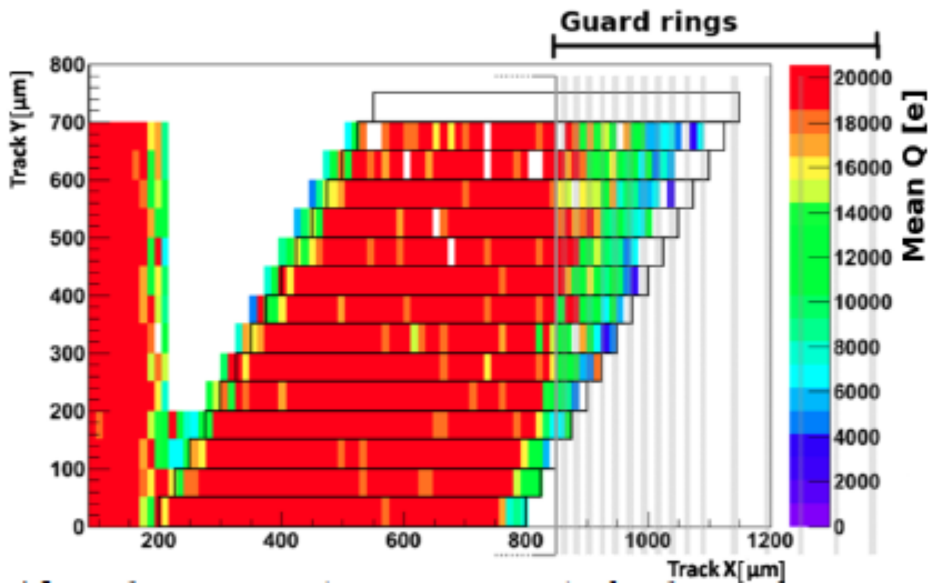
Optimization can be achieved by guard ring design or by active edge functionality



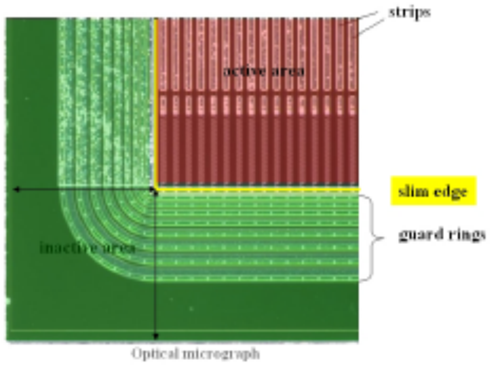
Guard ring optimization already done for present IBL n-in-n sensors

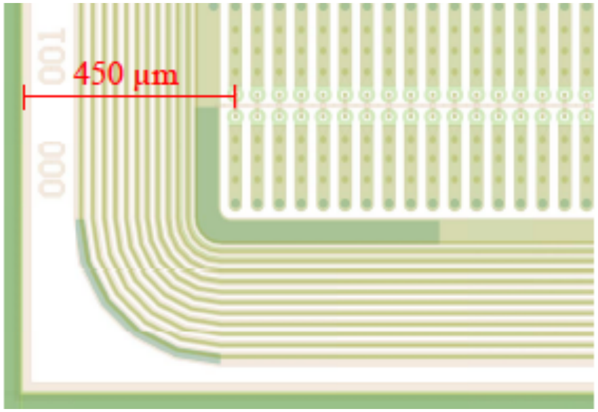
Approach adopted in the IBL
Smallest possible inactive edge ~ 200um





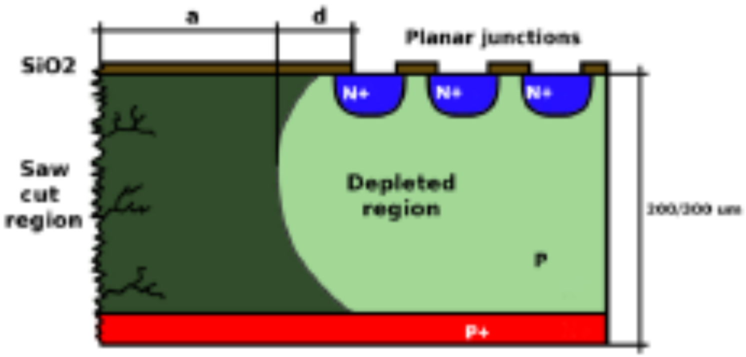
Effective reduction of guard-ring region studied also in n-in-p productions

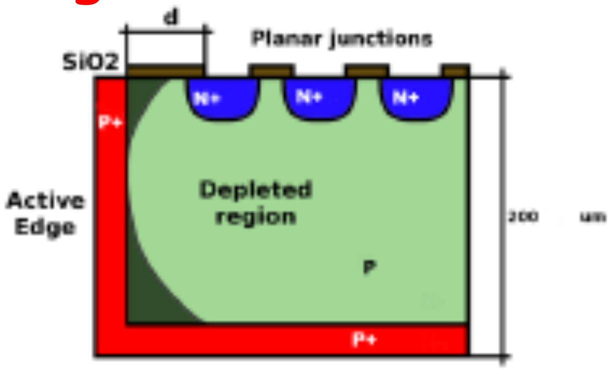




Micron/Liverpool n-in-p prototypes down to $d_{\text{inactive}} = (250 - 300)\ \mu m$

Alternative approach: active edges



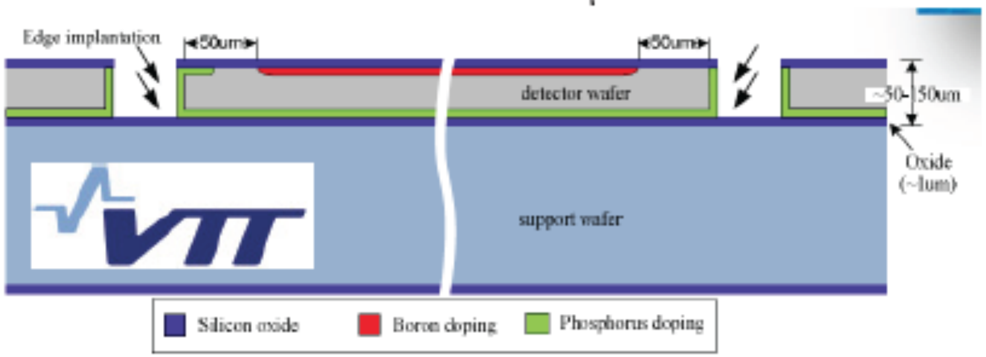


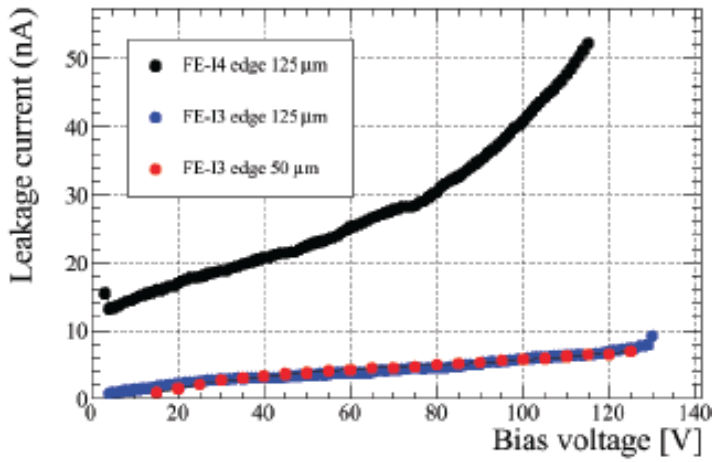
Two technologies investigated within PPS

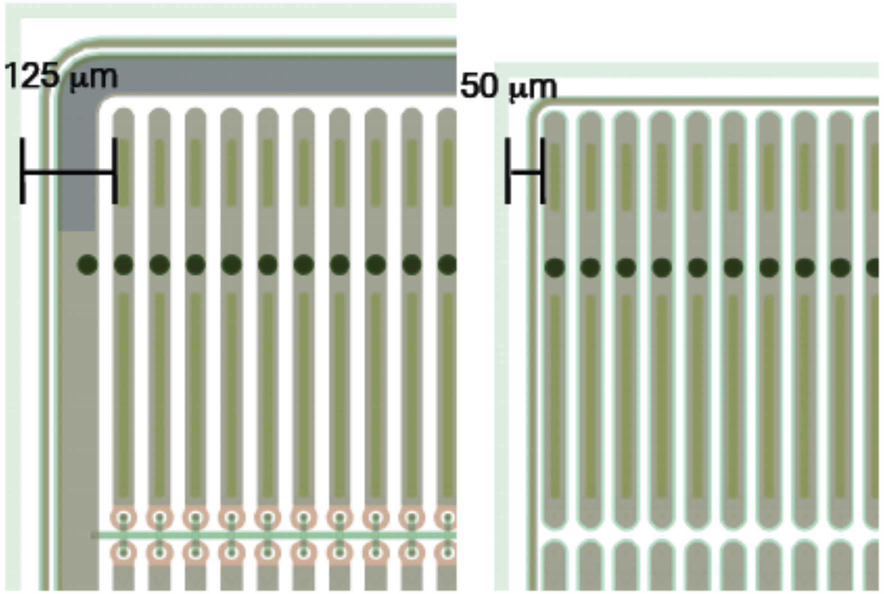
- DRIE: deep reactive ion etching
- SCP: scribe, cleave passivate

VTT/MPP n-in-p active edge pixel sensors

- Trench doped by four-quadrant implantation
- Sensor thickness 100-200 μm

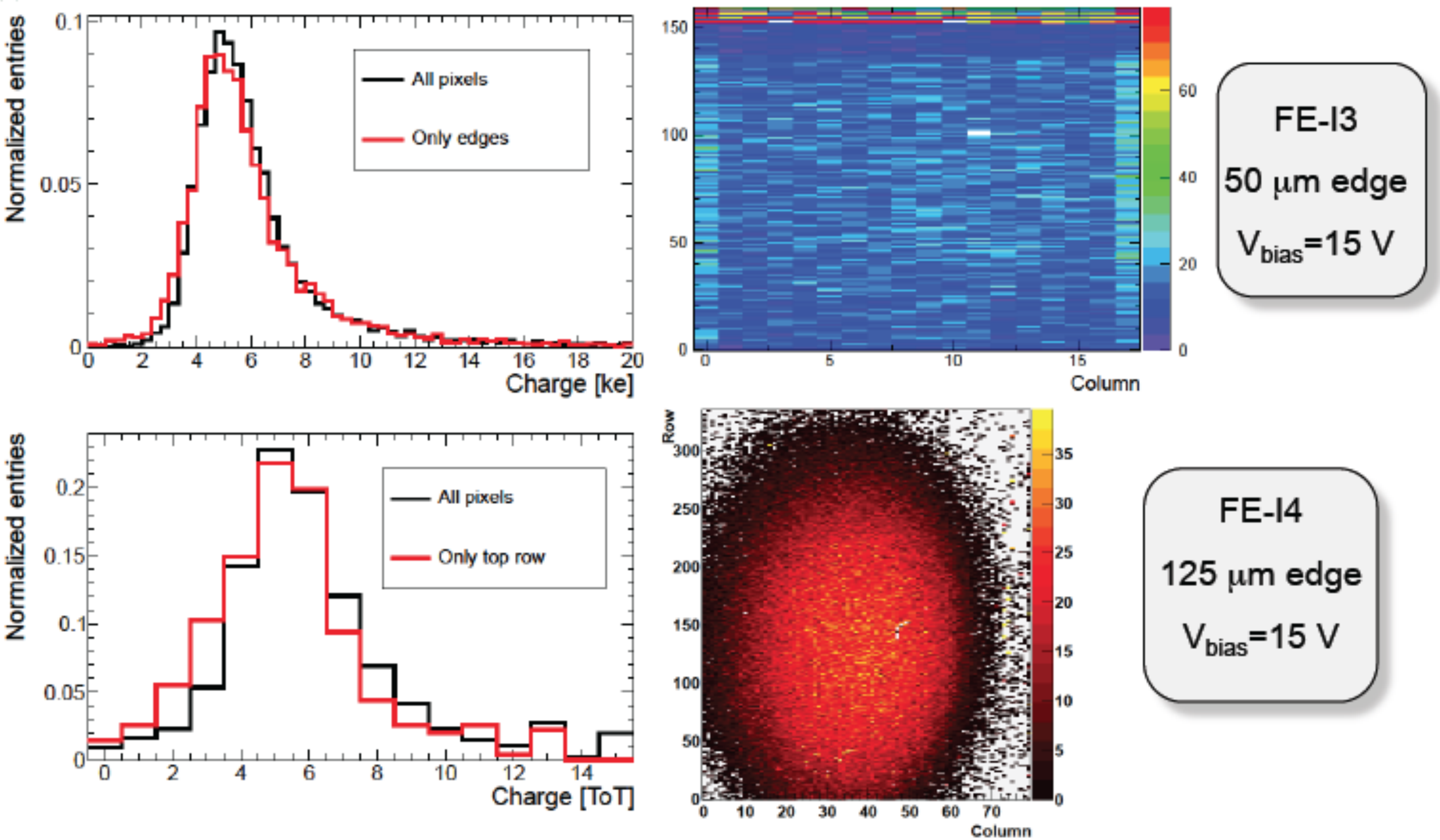






- 125 μm edge implemented In FE-I3 and FE-I4 sensors
- 50 μm implemented only in FE-I3 sensors

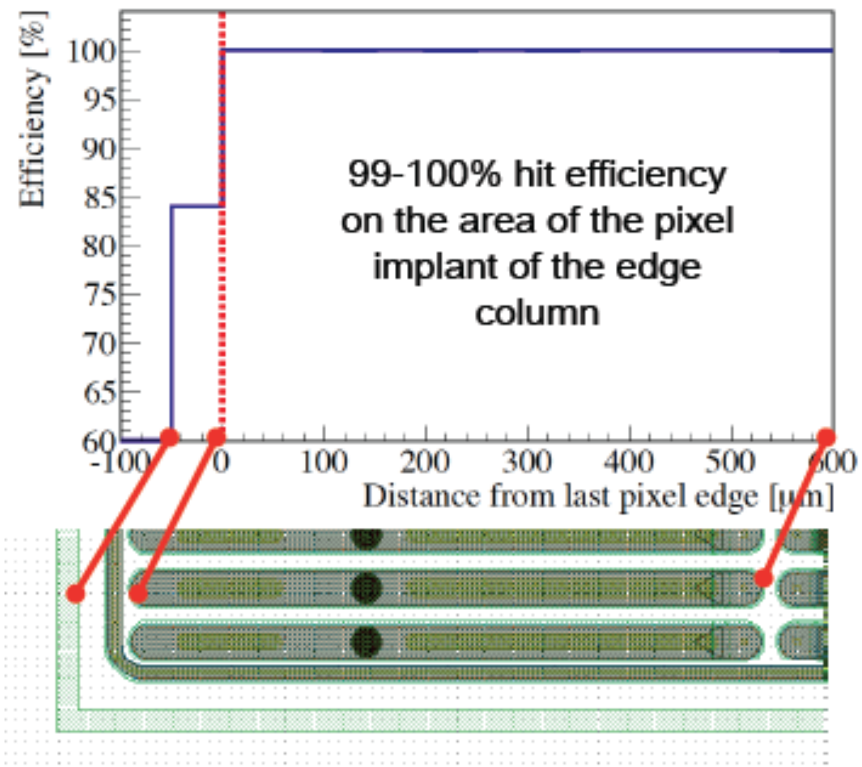
VTT/MPP n-in-p active edge pixel sensors



- Edge pixels show the same charge collection properties as the central ones

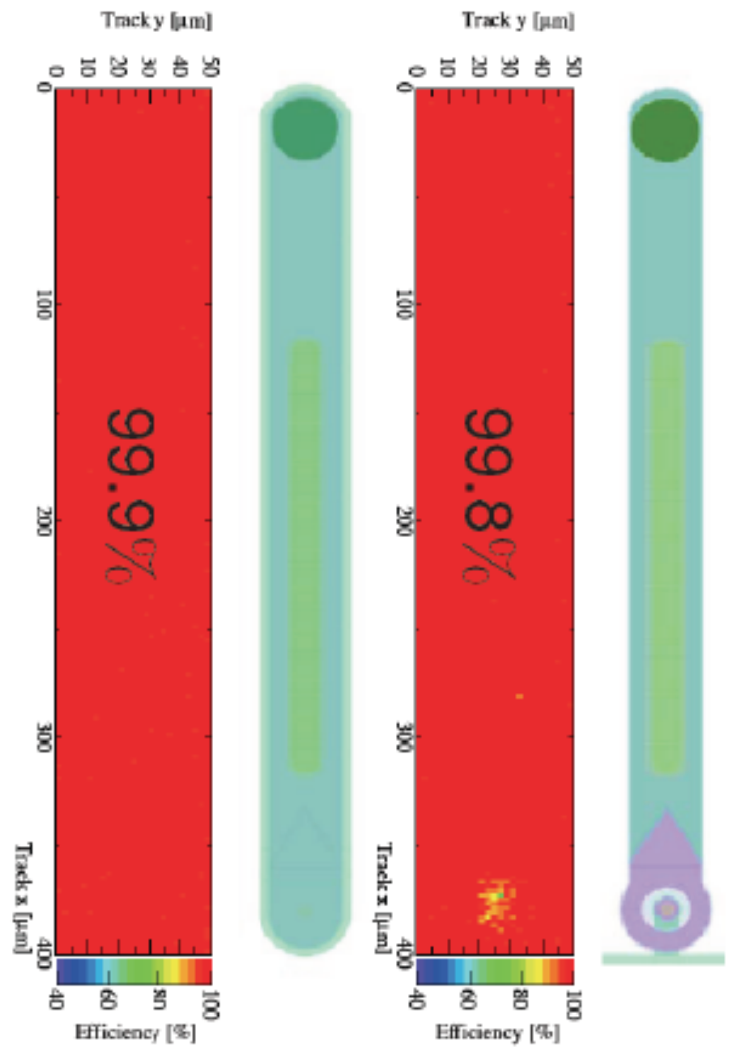
Hit efficiency for edge pixels – FE-I3, 50µm edge

Edge Tracking Efficiency in Beam Tests at SPS



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

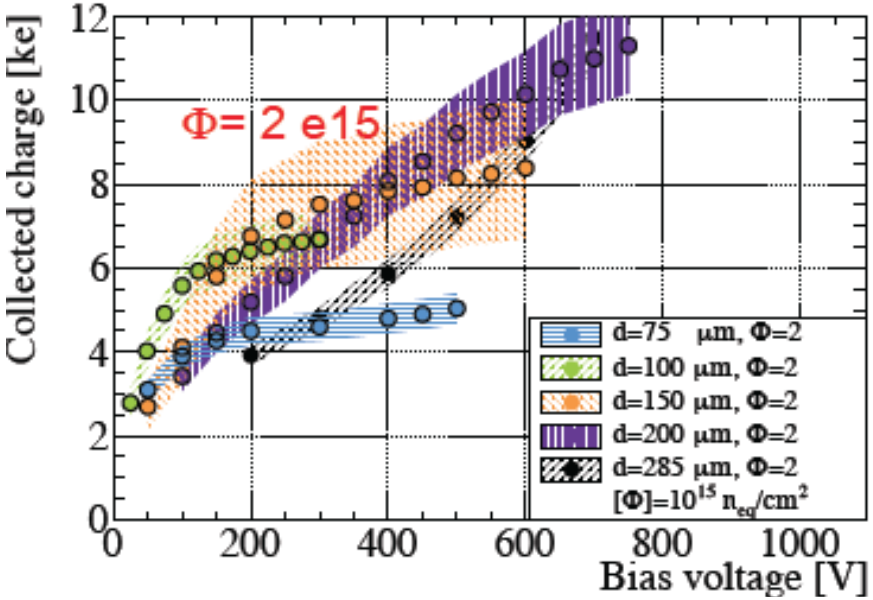
Global Efficiency in beam test

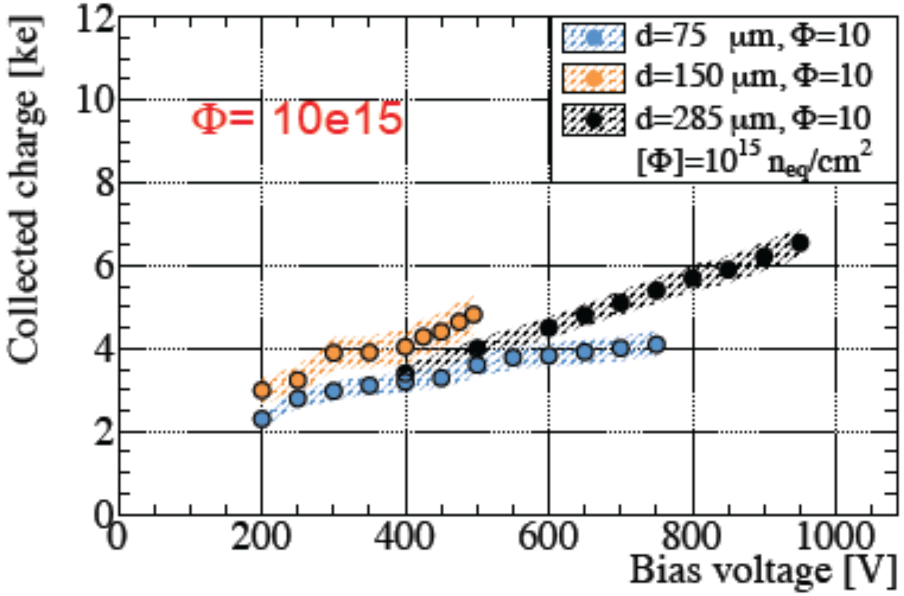


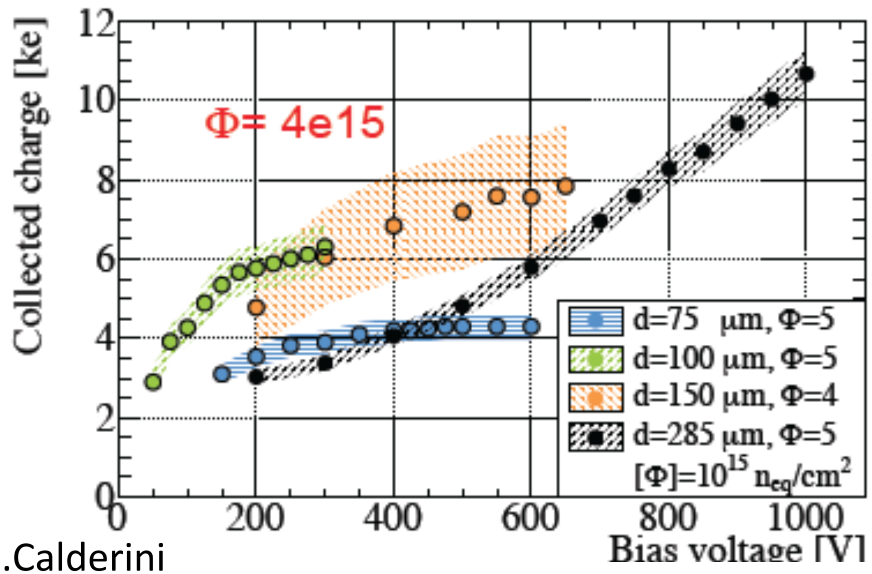
FE-I3, 50 µm edge, Vbias=20V

FE-I3, 125 µm edge, Vbias=20V

By-product: study of CCE after irradiation for different thickness

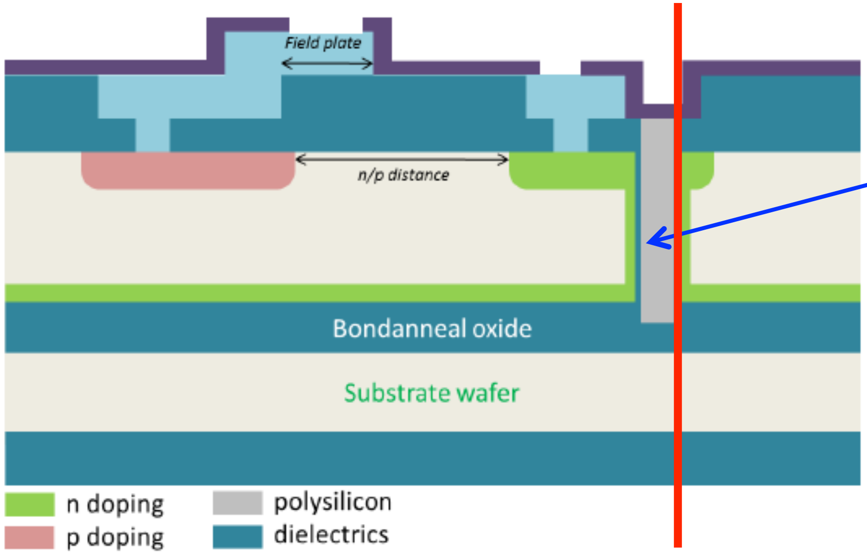






- The 100-150 μm thick sensors show higher charge collection up to a fluence of 4-5x10^{15} n_{eq} / cm^2
- At higher fluences the effect of charge trapping tends to equalize the charge collection efficiency for all thicknesses

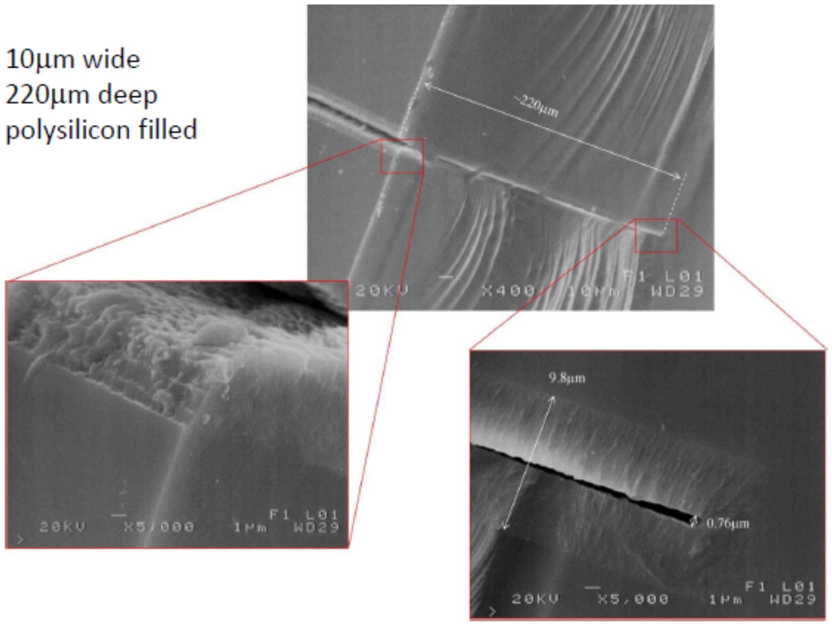
FBK/LPNHE n-in-p active edge pixel sensors

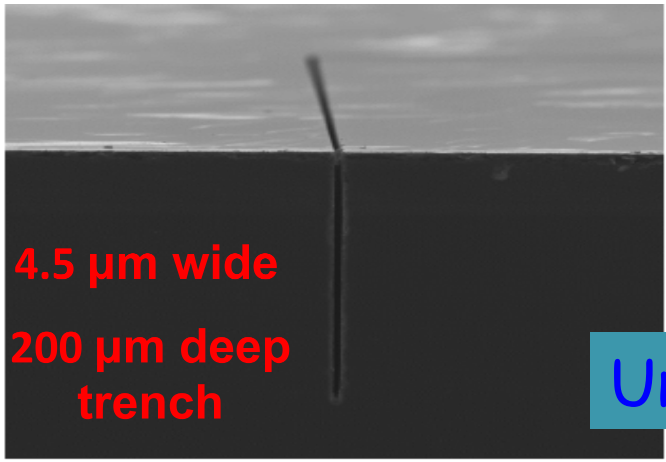


Cut line

Deep trench diffusion (to prevent electrical field on the damaged cut)

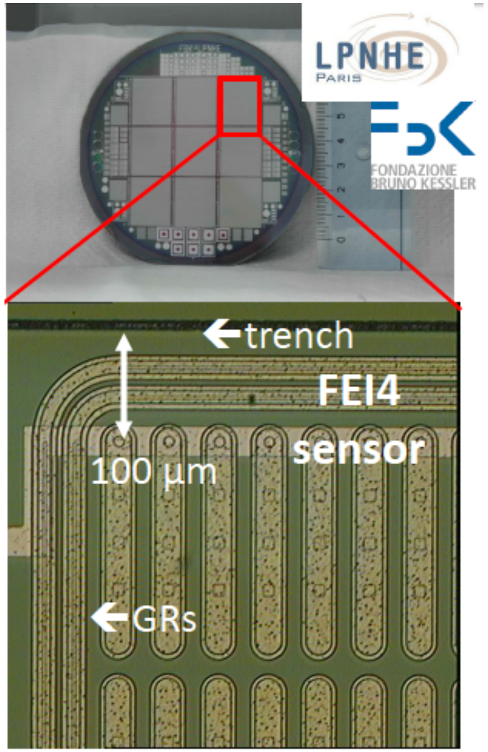
- 10µm wide
- 220µm deep
- polysilicon filled

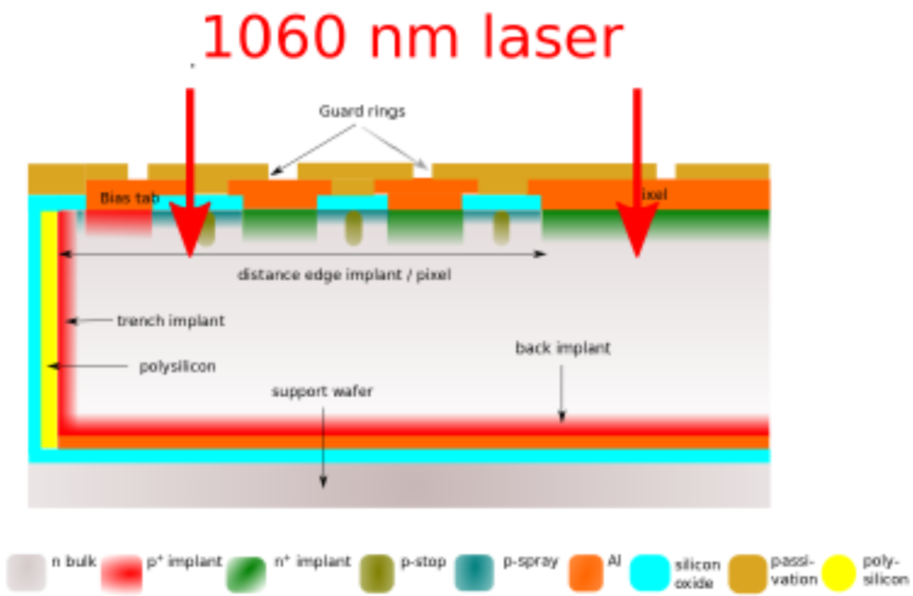


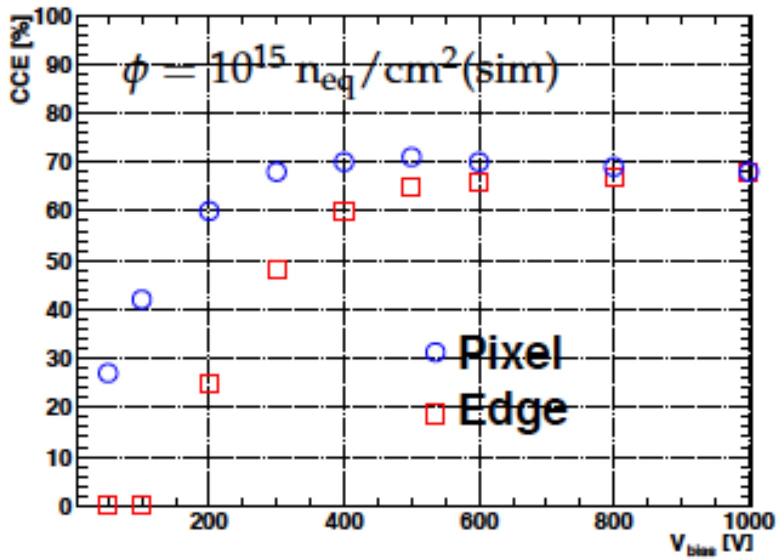


Uniformity of trench filling is critical.

- Trench doping by diffusion
- FE-I3/I4 designs by LPNHE/FBK
- Thickness 200um n-in-p
- Different edge/GR configurations (typically 100-200um)
- Simulations indicate good CCE close to edge after 10^{15} n_{eq}/cm^2
- Modules expected in Autumn

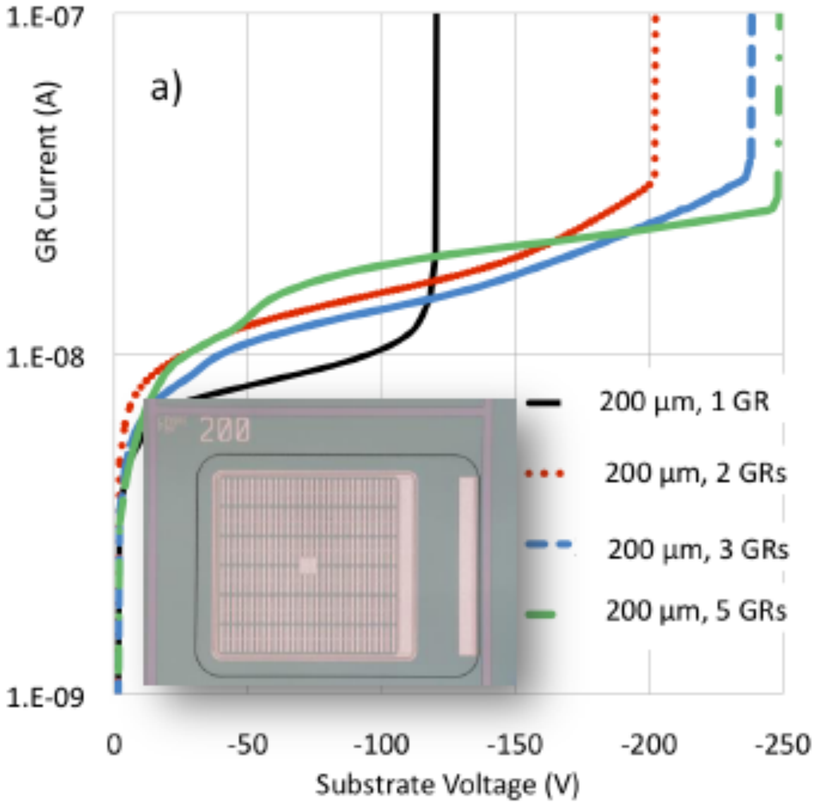




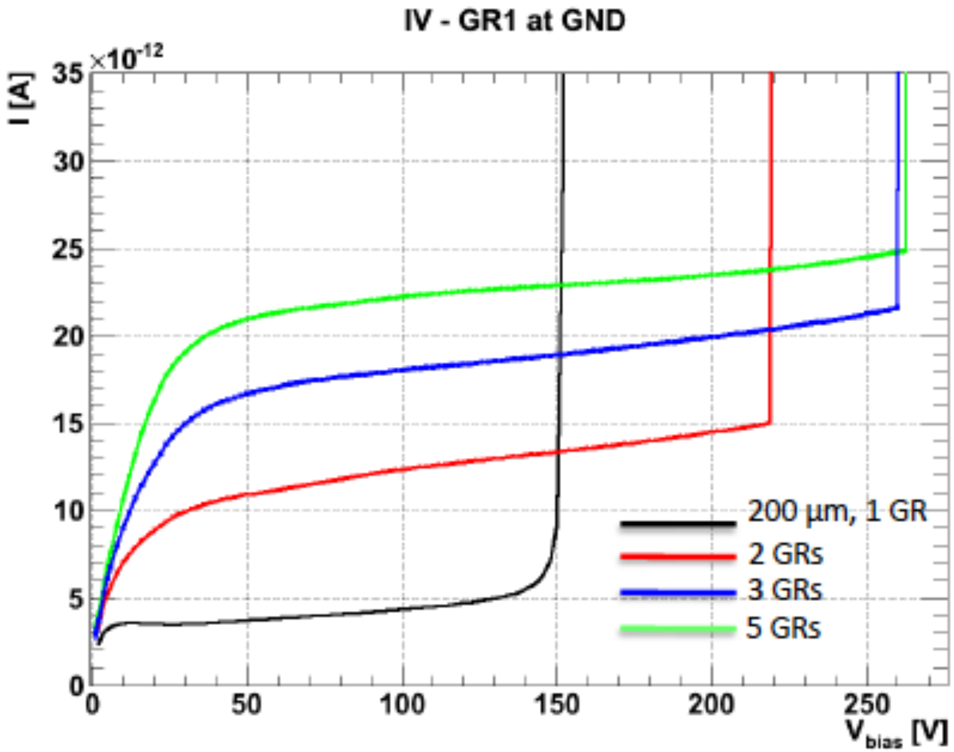


Current in good agreement with simulations

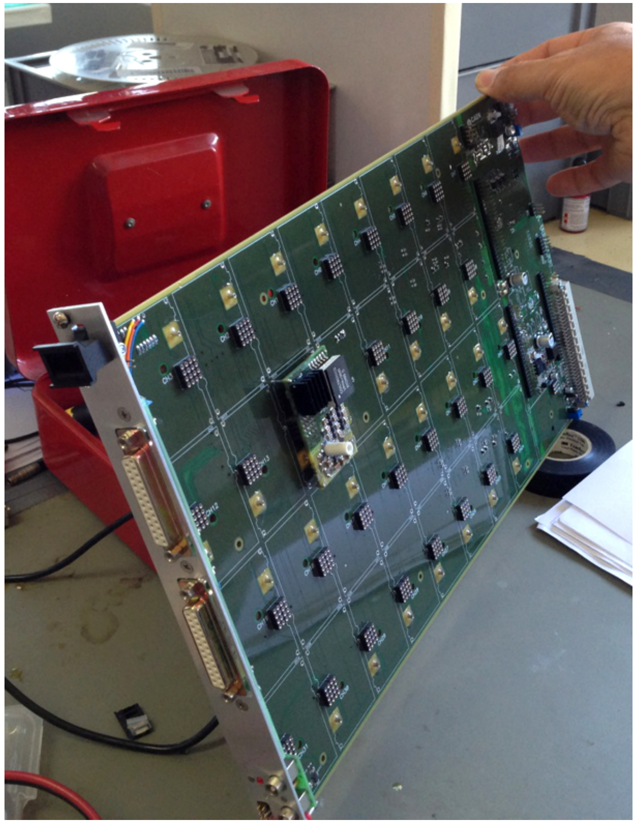
DATA

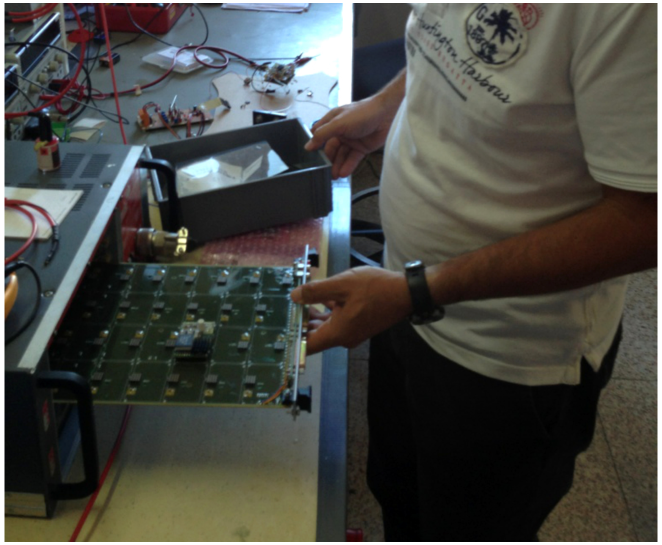


SIMULATIONS



These sensors will be the core of the tests done in the IAPP common ATLAS/CAEN test-bench at Viareggio for the development of new HV power supply boards, in particular the new A1541 future card.

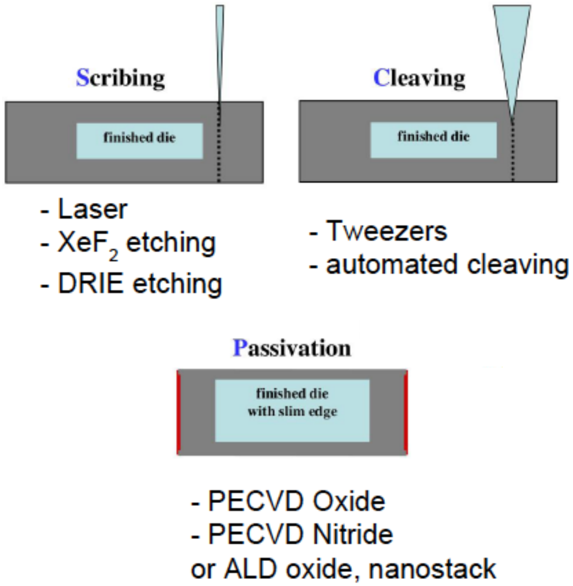


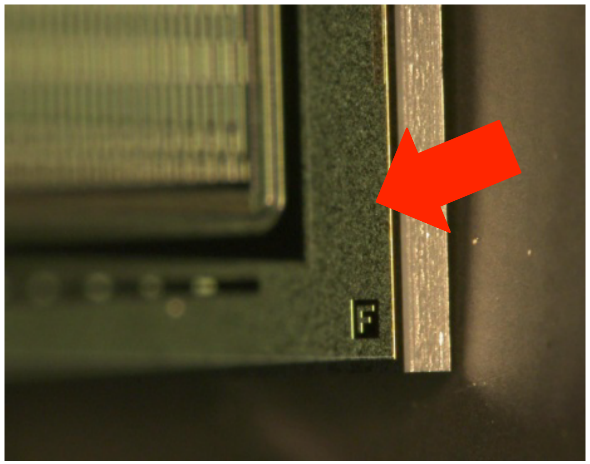


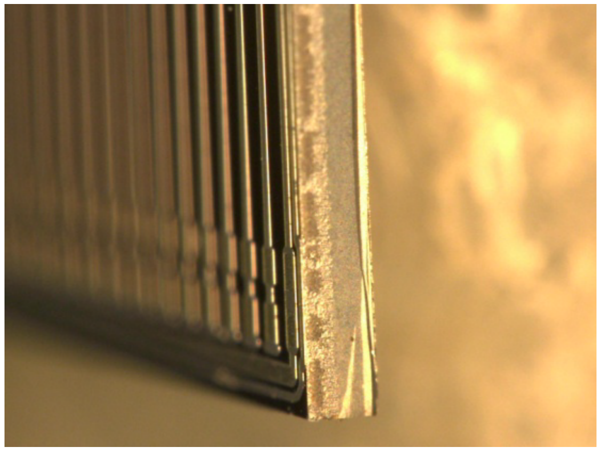
CAEN Tools for Discovery

Scribe-Cleave-Passivate (SCP) for slim edges

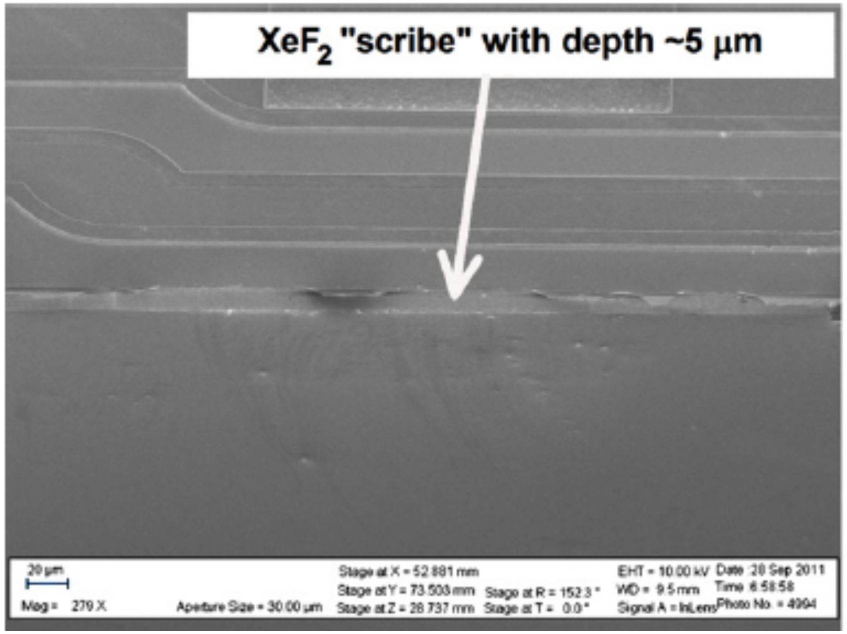
- Project by SCIPP (UCSC) and NRL
- Post-Processing approach
- SCP: Scribe-Cleave-Passivate
- For n-in-p: ALD deposition of alumina
- Relies on:
  - Low damaged sidewall due to cleaving.
  - Controlled potential drop along sidewall due to fixed interface charge from passivation.

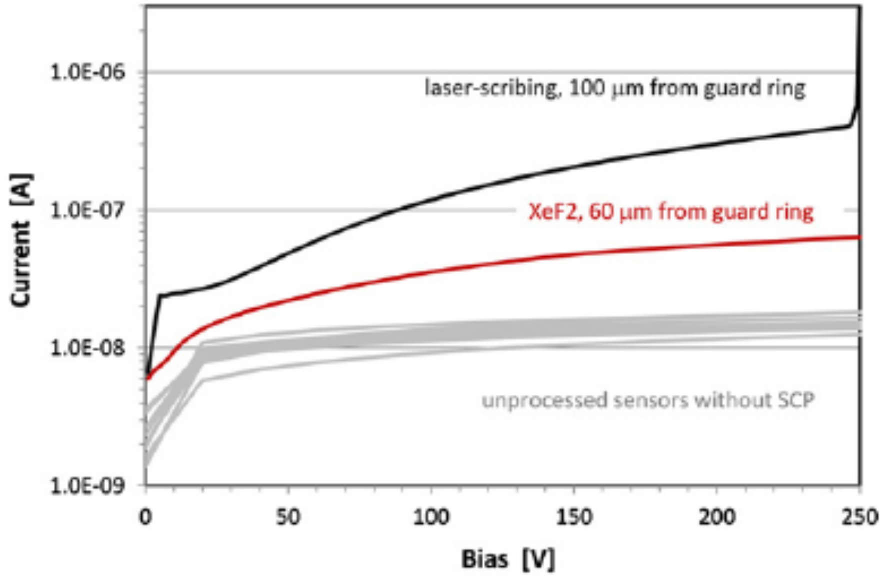






Scribe-Cleave-Passivate (SCP) for slim edges





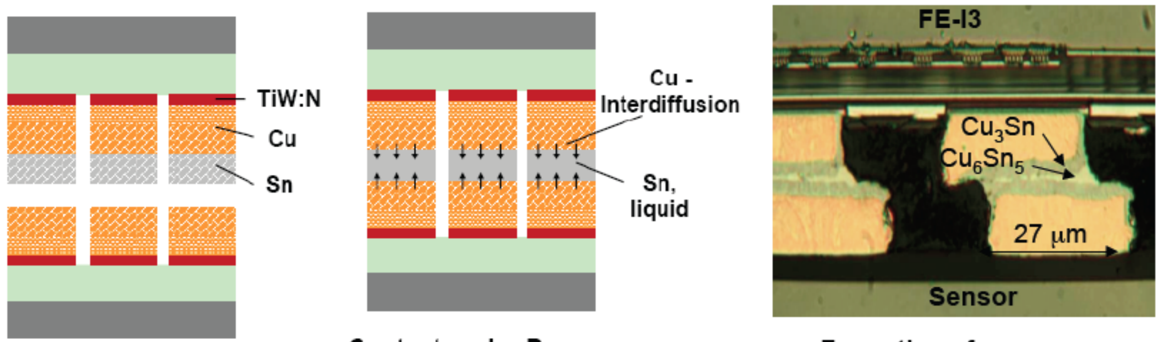
XeF_2 scribe or laser scribe

Reducing the costs

SLID Process

Metallization SLID (Solid Liquid Interdiffusion)

Fraunhofer EMFT



Through Mask Electroplating

Contact under Pressure and Heat
~ 5 bar, 260 – 300 °C (Sn-melt)

Formation of Eutectic Alloy; T_{melt} > 600 °C

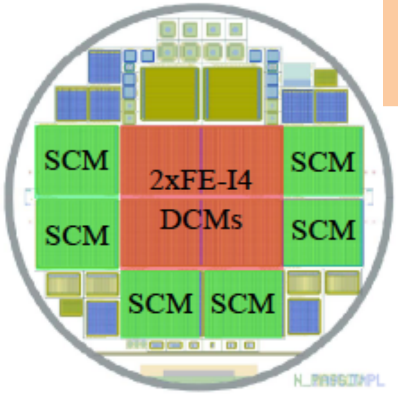
- Alternative to bump bonding (less process steps "lower cost" (EMFT)).
- Small pitch possible (~ 20 μm, depending on pick & place precision).
- Stacking possible (next bonding process does not affect previous bond).
- Wafer to wafer and chip to wafer possible.
- For the analysis of the interconnection efficiency: arXiv:1202.6497

FE-I4 SLID based modules expected at the end of the year

Investigation of 'low cost' bump-bondings (C4NP etc)

New productions: multi-chip modules and cards

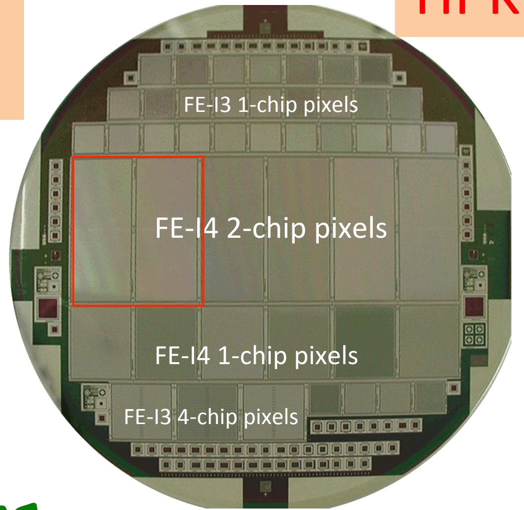
CiS



4" wafers
FZ 200/300

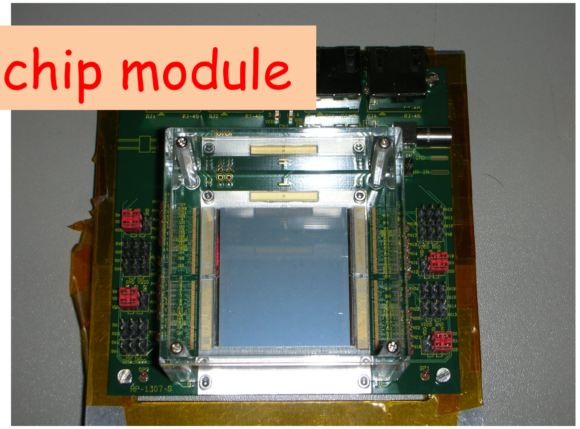
first production at CiS on 6" wafers n-in-p with single and quad-modules

HPK

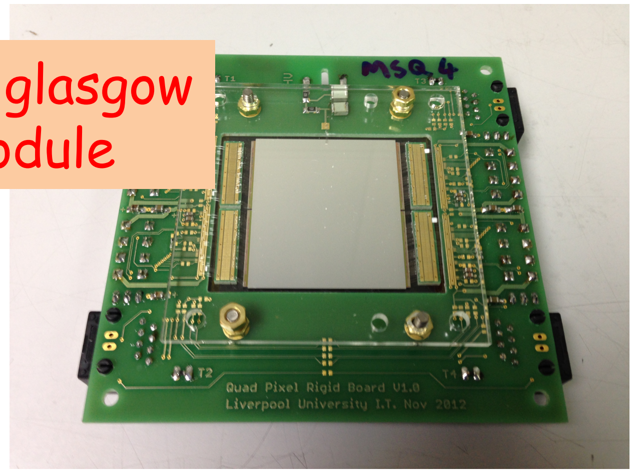


6" wafers

KEK 4-chip module



liverpool / glasgow quad module



- 4chip module on KEK's 4chip card
- 3 KEK 4chip modules in the testbeam in Aug. 2013 at DESY

N-on-n sensors: material studies

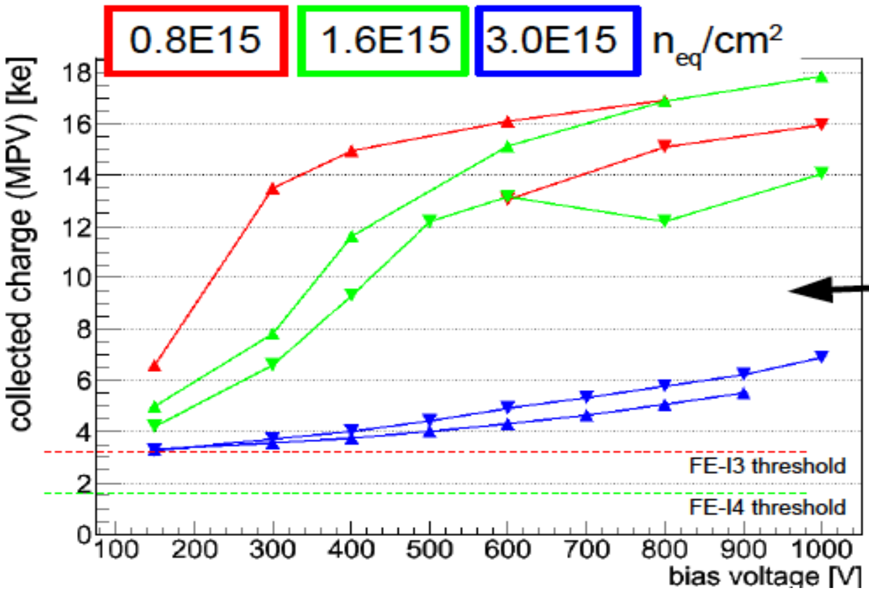
tu Dortmund
Physik E IV

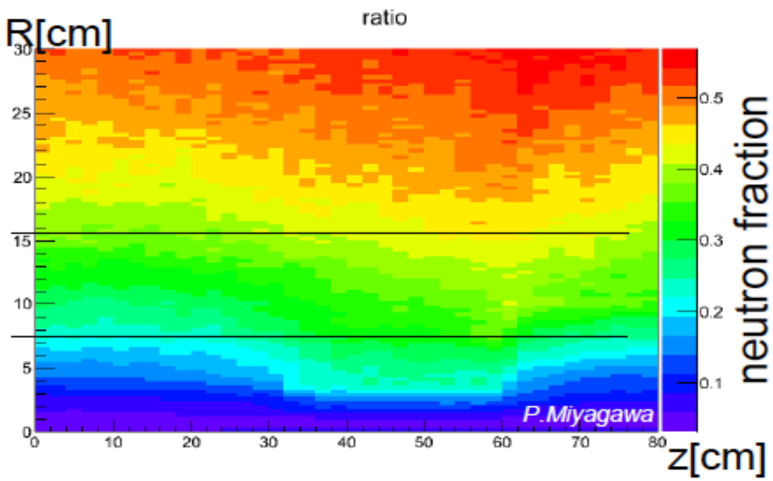
T. Wittig | Radiation hardness & slim edge studies of planar n+-in-n ATLAS pixel sensors | PIXEL 2012

Magnetic Czochralski bulk sensors

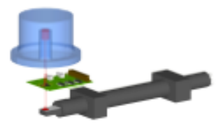
- The medium layers of ATLAS upgrade phase II will be exposed to a mixed radiation of ionising and non-ionising particles
- MCz material is expected to have a better performance for this scenario than standard DOFZ

[G.Kramberger et al. NIMA 609 (2009) p.142–148]





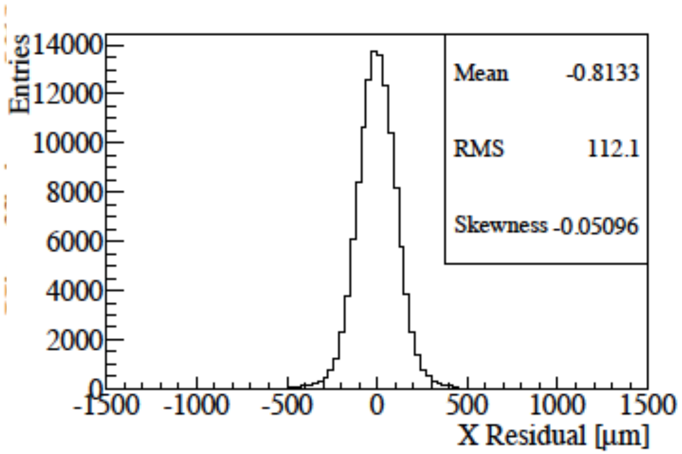
- first (proton) irradiation done at CERN PS
- 3 fluences
- successfully operated in last test beam at CERN
- systematic measurements done in lab with 90SR source
- currently in Ljubljana for neutron irradiation



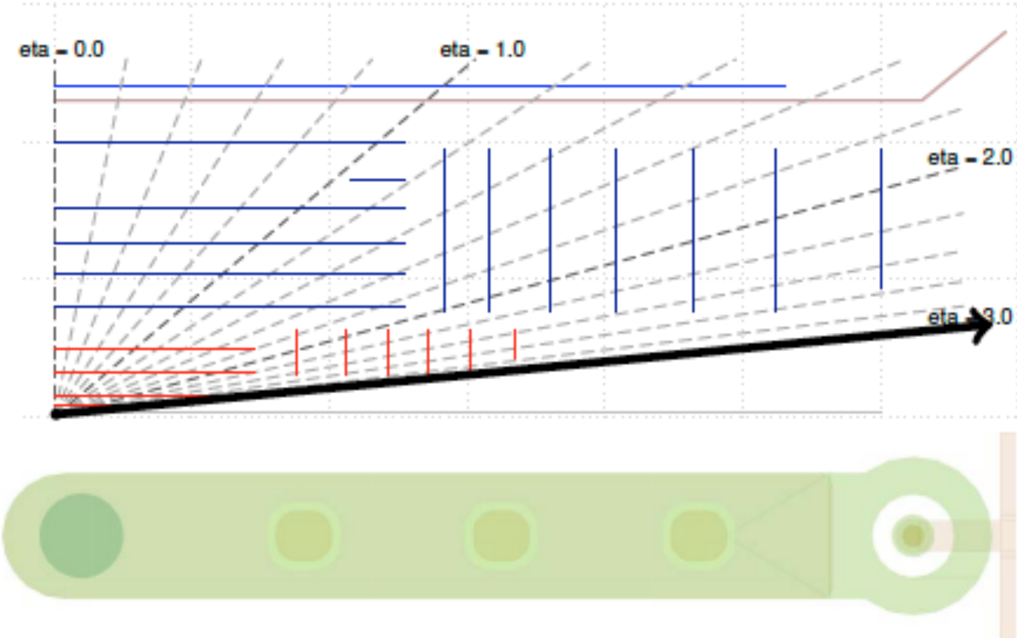
9

One highlight from test-beams: high-η analysis

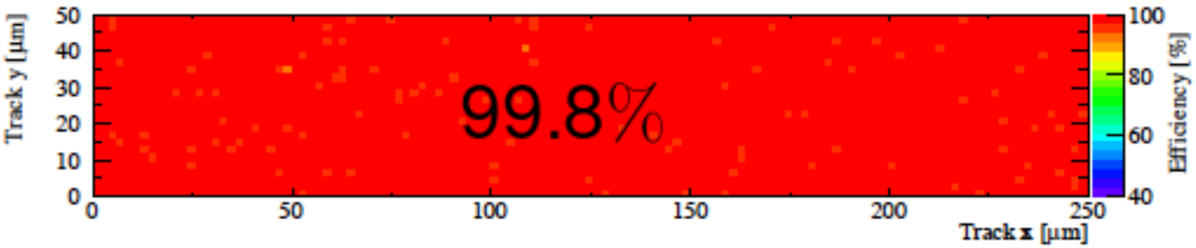
- FE-I4 150 μm thick, irradiated to $4\times10^{15}\mathrm{n_{eq}/cm^2}$ in Los Alamos
- threshold: 1.6 ke (MPV$\sim$7 ke at $\perp$ incidence)



Residual along the tilted direction (pitch: 250 μm)



- 99.8% hit efficiency at ϑ=85° ($\eta\sim$3.1) (500 V)



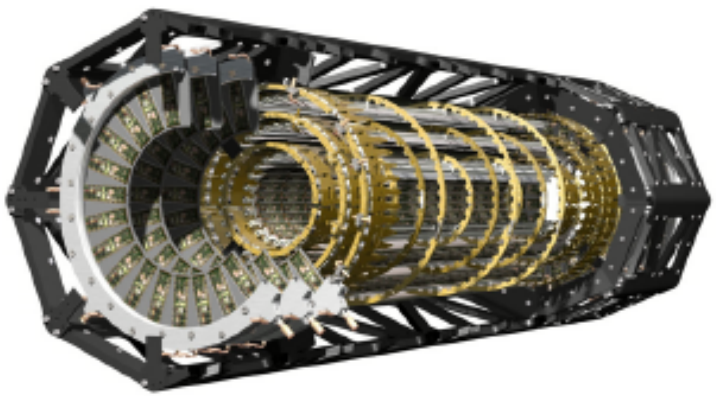
Conclusions

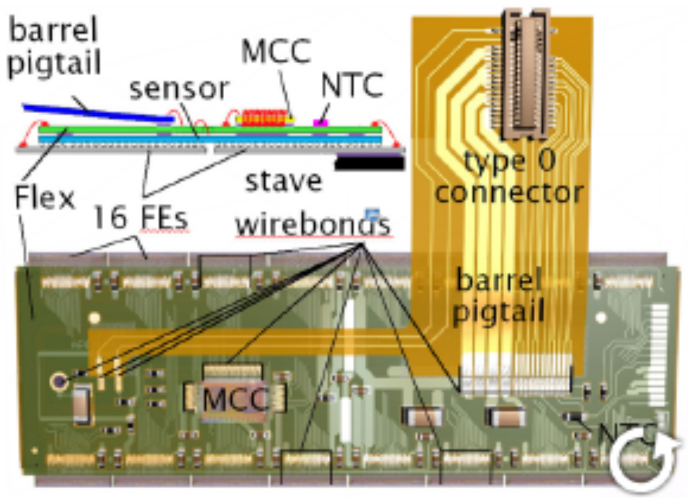
The High Luminosity phase of LHC requires a new ATLAS pixel detector

- New sensors for the inner layers must be radiation hard, thin and with reduced geometrical inefficiency
- The Atlas PPS R&D group is investigating different solutions of n-on-n and n-on-p pixel sensors with reduced inactive edges and thickness
- Radiation hardness proven for n-in-p pixels up to 1×10^{16} n_{eq}/cm^2 and n-in-n pixels up to 2×10^{16} n_{eq}/cm^2
- Cost reduction can be investigated with, among other solutions, the use of cheaper interconnection techniques and multi-sensor modules

Additional material

The original ATLAS Pixel detector





Composition

- 3 barrel layers
- 2×3 endcap discs
- 1744 modules $\sim$ 80 million channels
- Range: $\|\eta\| < 2.5$

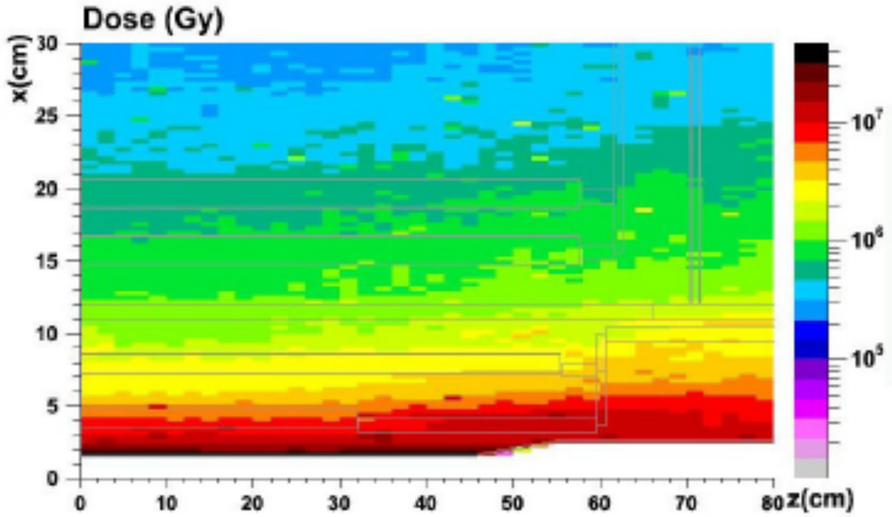
Requirements were met

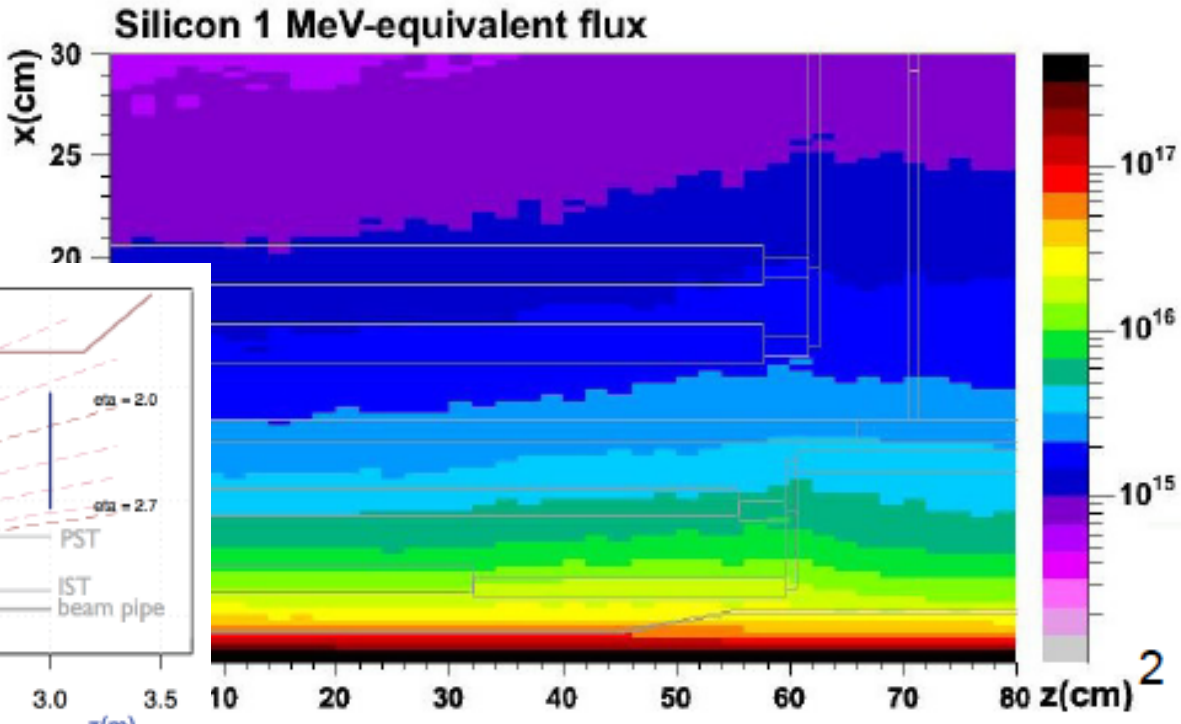
- Transverse impact resolution $< 15\,\mu$m
- Minimal material to reduce multiple scattering and conversions
- High hit efficiency
- Radiation hardness: $500\,\text{kGy} \hat{=} 10^{15}\,\text{n}_{\text{eq}}/\text{cm}^2$

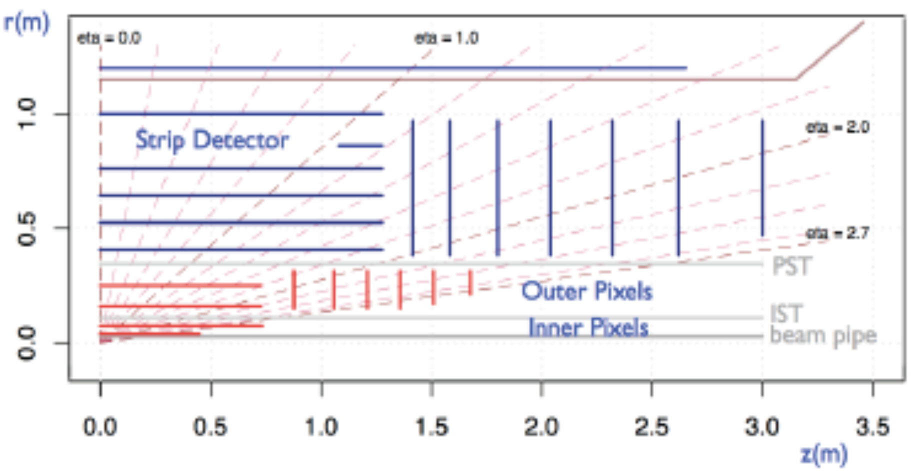
Module Concept

- Planar silicon n^+-in-n sensors
- Read-out chip: FE-I3
- Flex hybrid

- integrated luminosity: 3000 fb^{-1}
- including a safety factor of 2 to account for all uncertainties this yields for ATLAS:
  - at 5 cm radius:
    - ~$2 \cdot 10^{16}$ n_{eq} cm^{-2}
    - ~1500 MRad
  - at 25 cm radius
    - up to 10^{15} n_{eq} cm^{-2}
    - ~100 MRad
    - several m^2 of silicon
  - strip region
    - some 10^{14} n_{eq} cm^{-2}
    - up to ~100 m^2 of silicon







SCP: physics performance

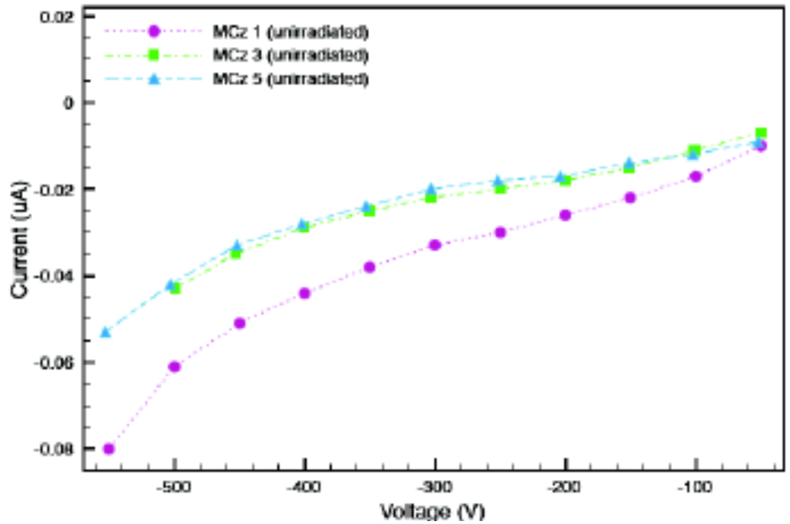
- Two aspects of physics performance are under investigation:
  - Charge collection near the edge. We do not see any problem:

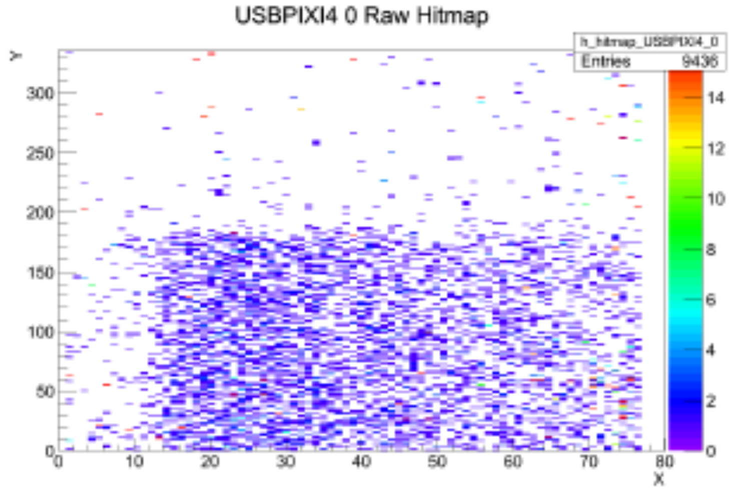
Sensor Type	Origin	Edge-Active area Distance [um]	Signal Read out	Beam	Ref
P-type strips	PPS (CIS)	~200	Binary (PTSM)	^{90}Sr	V. Fadeyev *et al* Pixel 2012, submitted to NIM A
N-type strips	GLAST (HPK	~200	Analog (ALiBaVa)	^{90}Sr	R. Mori *et al*. 2012 JINST 7 P05002
P-type strips	PPS (CIS)	150	Analog (ALiBaVa)	Focused X-ray	R. Bates *et al*., 2013 *JINST* **8** P01018
P-type 3D pixels	IBL (CNM)	50	FE-I3 & FE-I4	CERN Test Beam	S. Grinstein *et al.*, RESMDD12

  - Irradiation hardness:
    - Results with p-type sensors irradiated at Los Alamos were promising at $\geq 10^{15}$ n_{eq}/cm^2. They were ambiguous at $\leq 10^{14}$ n_{eq}/cm^2

Planar n^+-in-n MCz sensors at TU Dortmund

- FE-I3 and FE-I4 single chip sized sensors were produced by CIS together with various test structures (e.g. diodes) on DOFZ (various thicknesses) and MCz bulk material (285 μm thickness) in planar n^+-in-n technology
- 12 FE-I4A based SingleChip-Assemblies (SCA) were made (6 MCz and 6 DOFZ for direct comparison)
- All assemblies lab characterized after flipchipping:
  - IV-curve
  - Tuning (calibration)
  - Charge collection measurement with ^{90}Sr source
- → all unirradiated samples demonstrated excellent behaviour



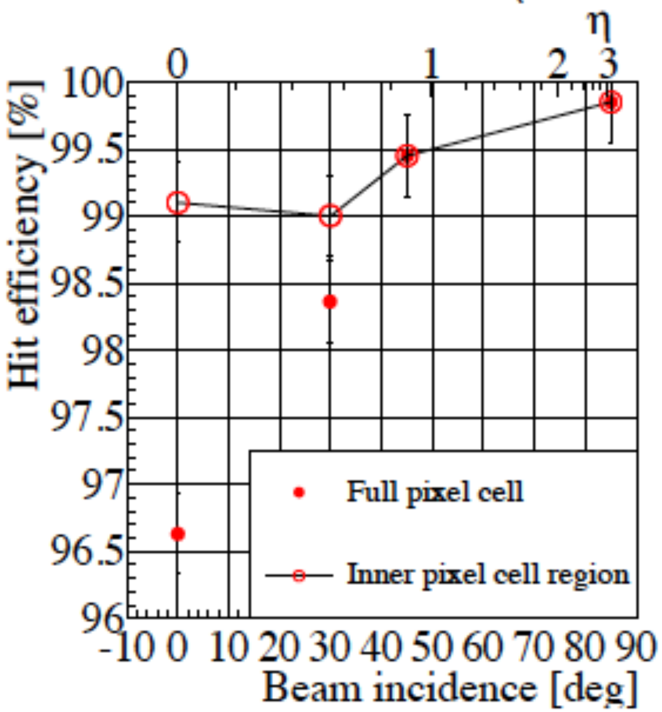


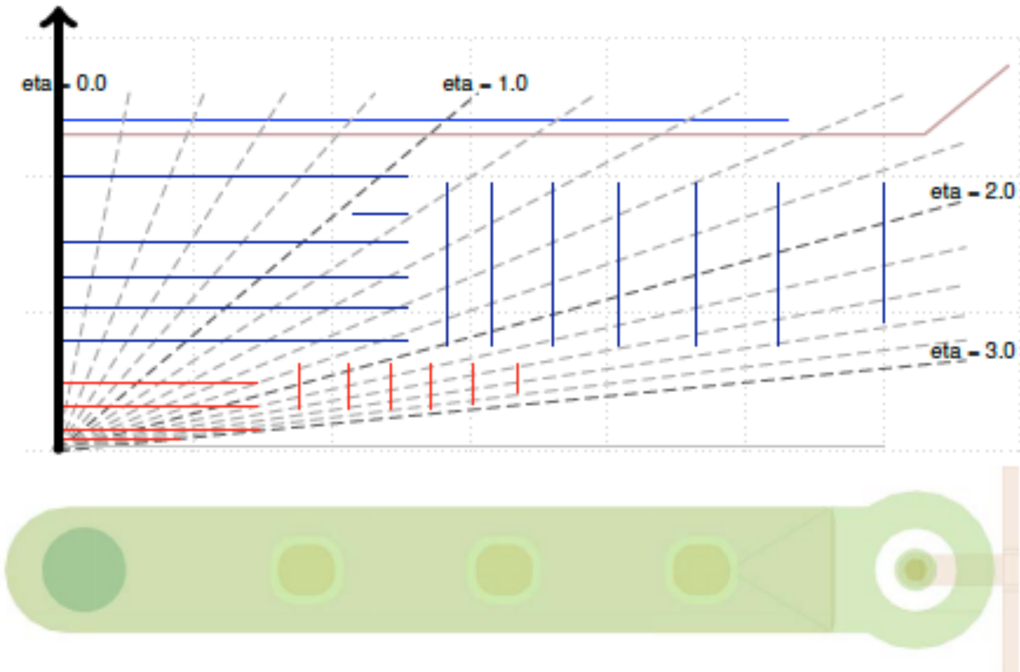
1

USBPIXI4 0 TOT Clusters

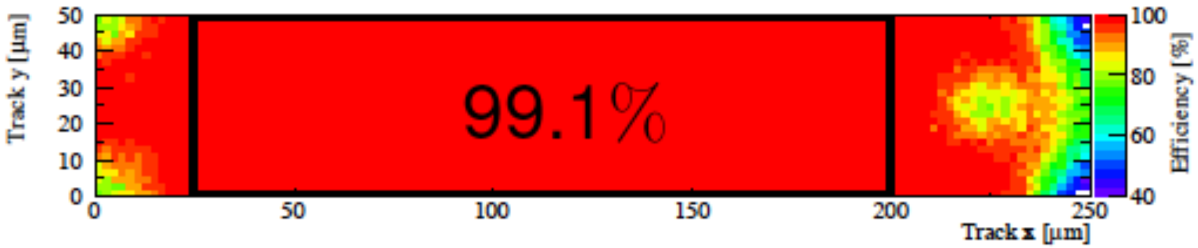
One highlight from test-beams: high-η analysis

- **FE-I4 150 μm thick, irradiated to 4$\times$10^{15}n$_{eq}$/cm^2 in Los Alamos**
- threshold: 1.6 ke (MPV~7 ke at ⊥ incidence)



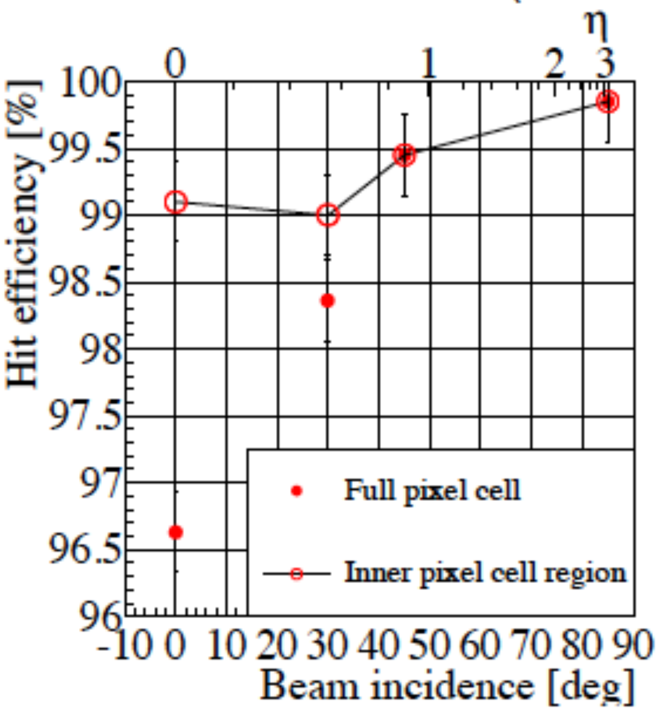


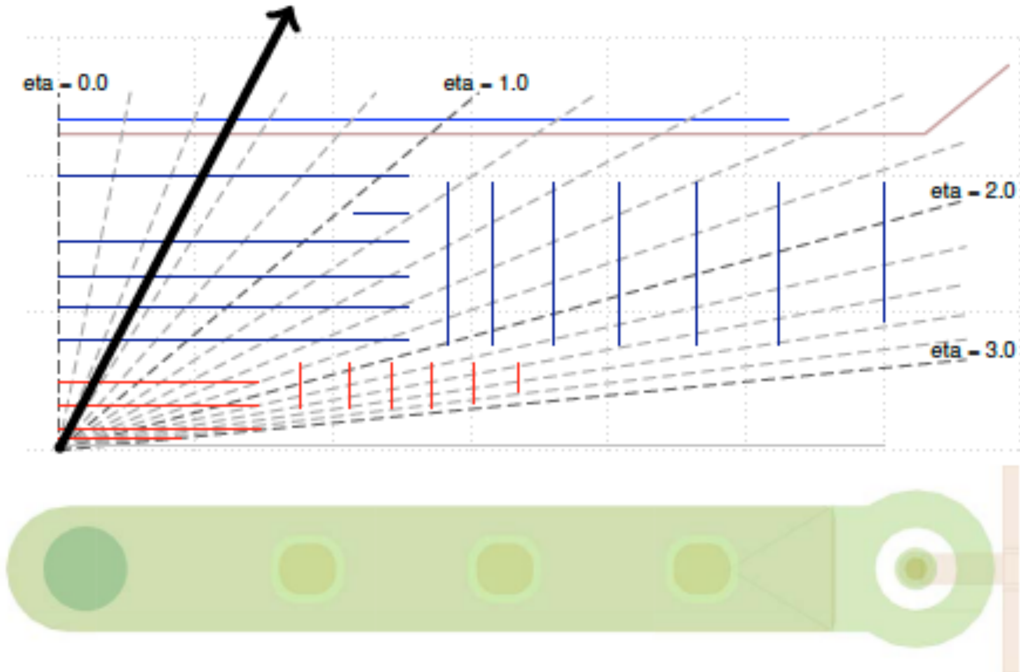
- 96.6% hit efficiency at ⊥ incidence (500 V)



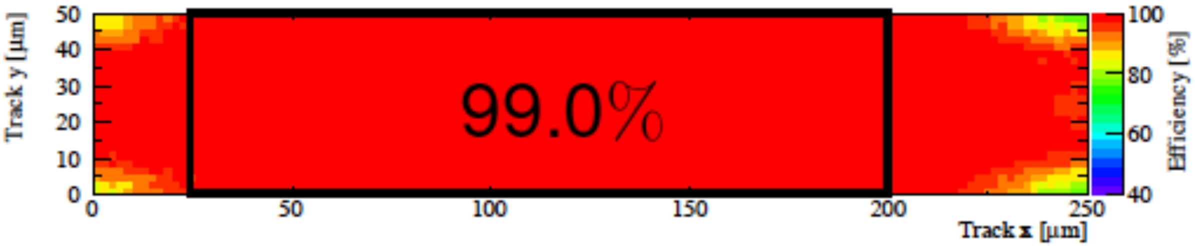
One highlight from test-beams: high-η analysis

- FE-I4 150 μm thick, irradiated to $4\times10^{15}\mathrm{n_{eq}/cm^2}$ in Los Alamos
- threshold: 1.6 ke (MPV~7 ke at ⊥ incidence)



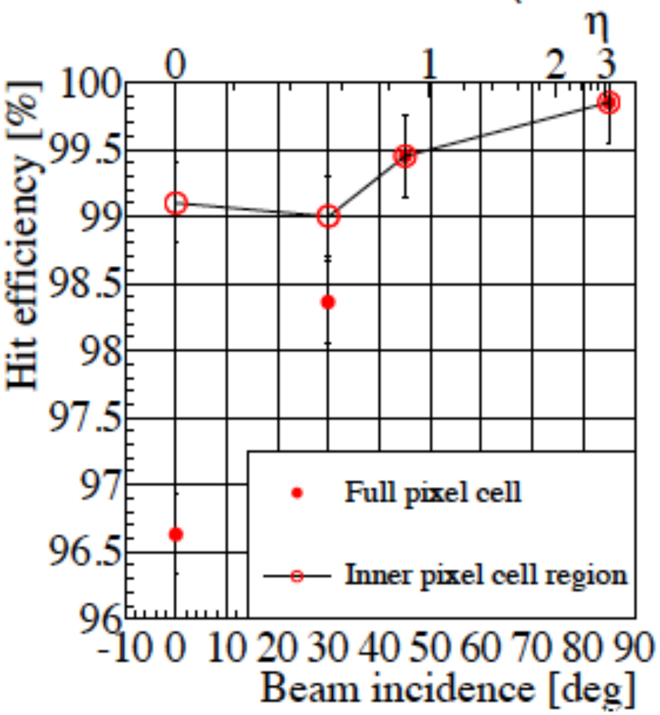


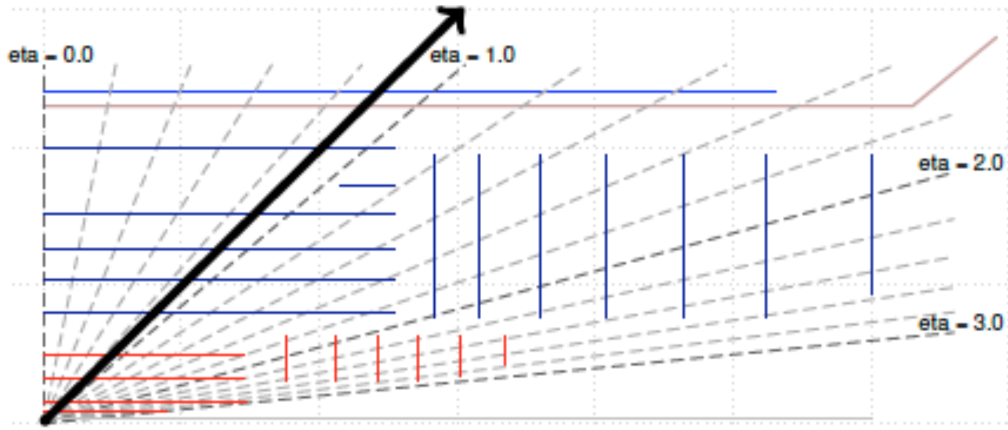
- 98.4% hit efficiency at ϑ=30° (η ~0.55) (500 V)



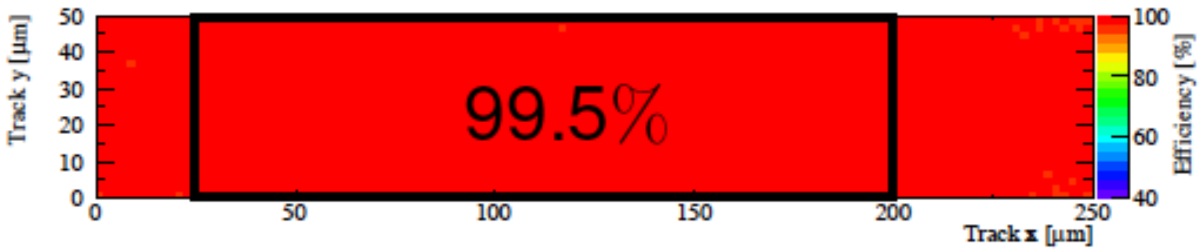
One highlight from test-beams: high-η analysis

- FE-I4 150 μm thick, irradiated to $4\times10^{15}\mathrm{n_{eq}/cm^2}$ in Los Alamos
- threshold: 1.6 ke (MPV~7 ke at ⊥ incidence)

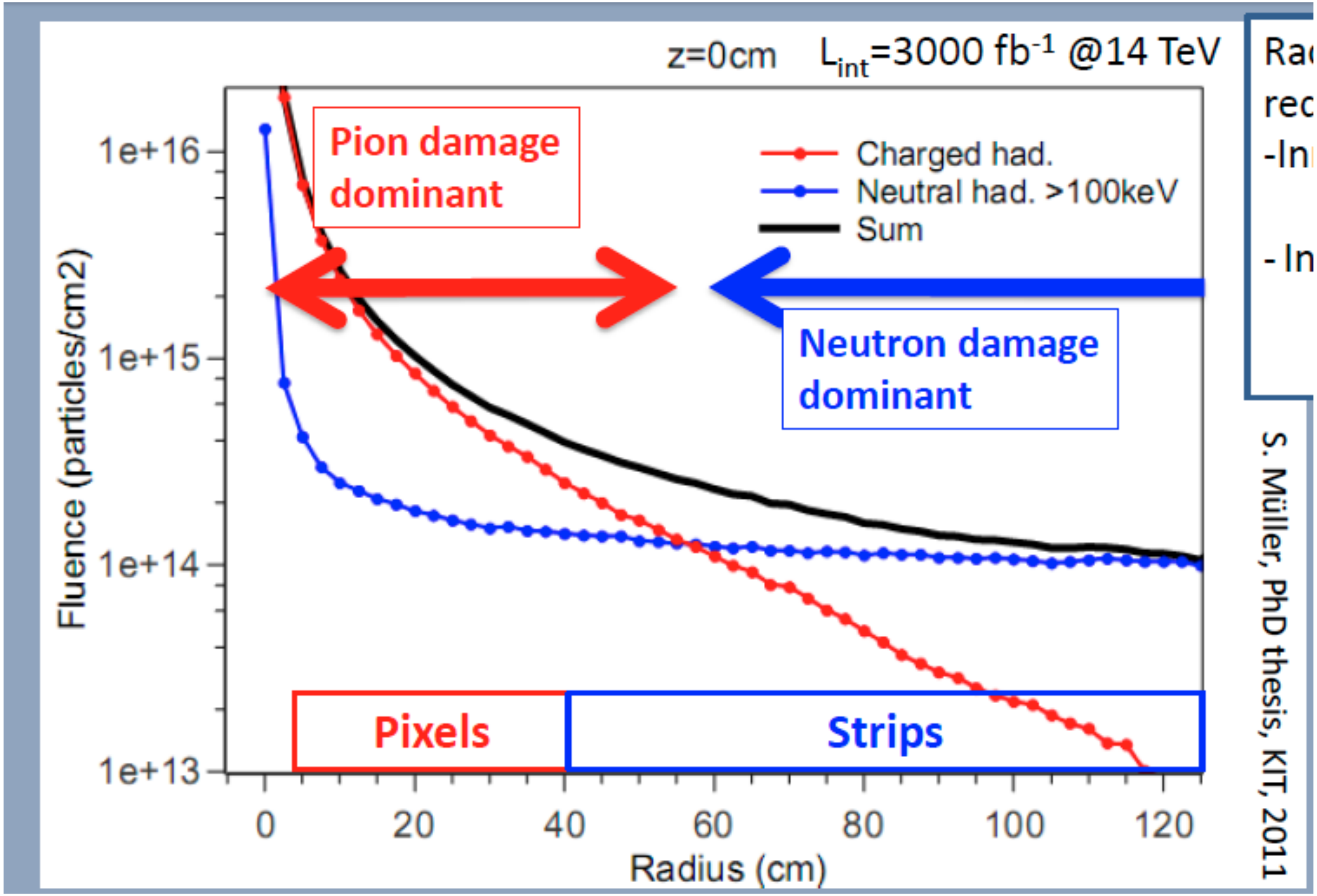




- 99.5% hit efficiency at ϑ=45° (η ~0.88) (500 V)



Radiation composition



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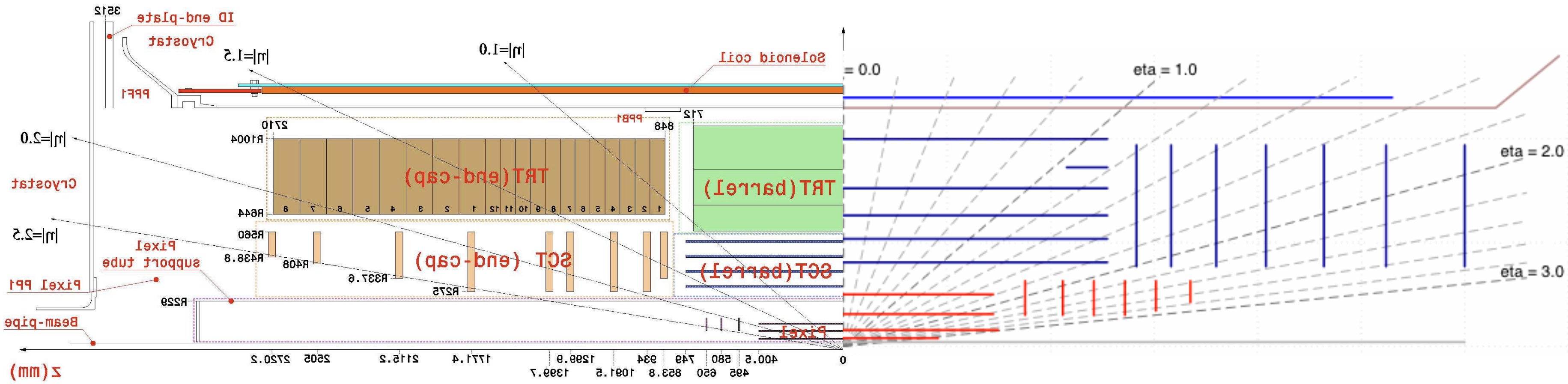
ATLAS Tracker Layouts

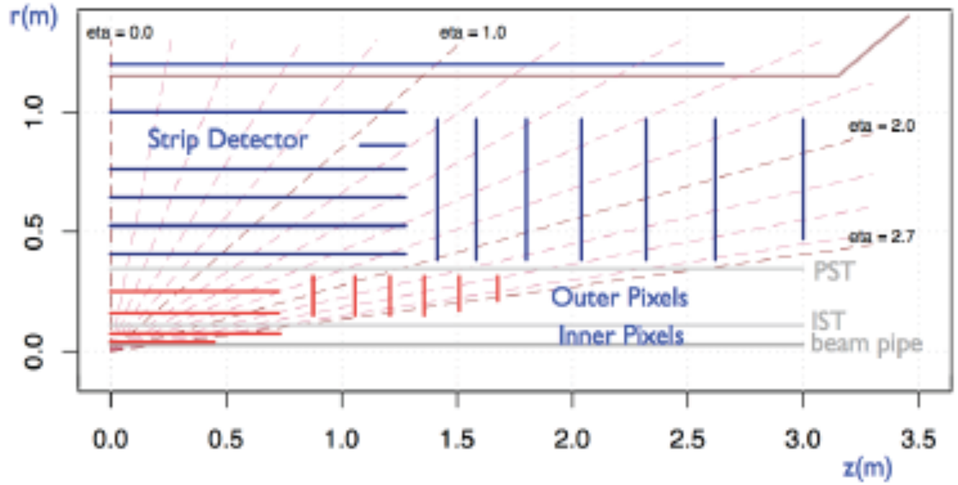


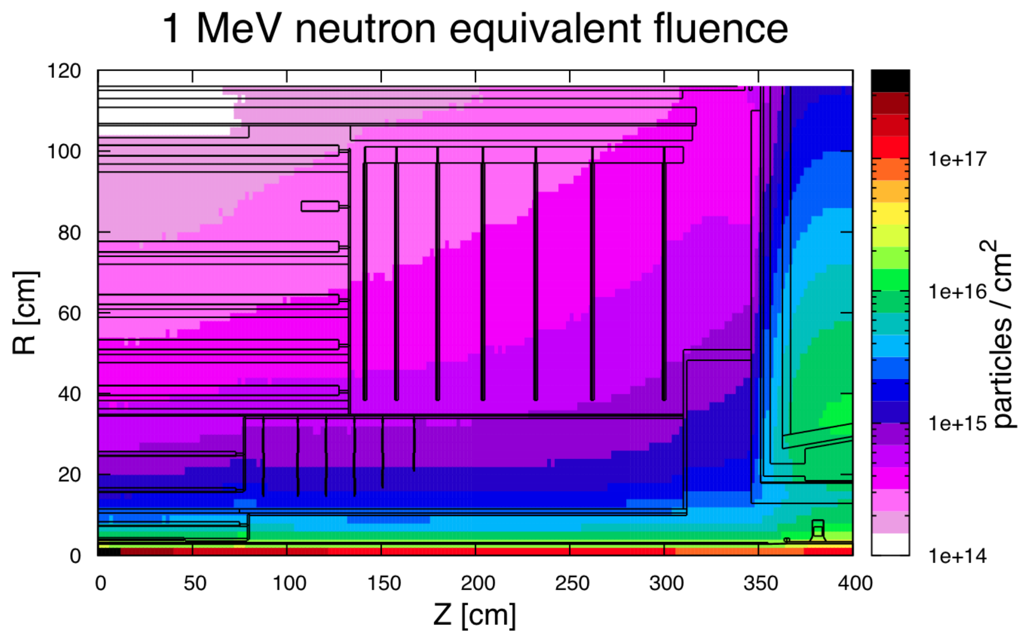
- Current inner tracker
  - Pixels: 5-12 cm
    - Si area: 2.7 m^2
    - IBL(2015): 3.3 cm
  - Strips: 30-51 (B)/28-56 (EC) cm
    - Si area: 62 m^2
  - Transition Radiation Tracker (TRT): 56-107 cm
    - Occupancy is acceptable for <3x10^{34} cm^{-2}s^{-1}
    - Phase-II at HL-LHC: 5x10^{34} cm^{-2}s^{-1}

- Phase-II upgrade (LOI)
  - Pixels: 4-25 cm
    - Si area: 8.2 m^2
  - Strips: 40.-100 (B) cm
    - Si area: 122 (B)+71(EC)=193 m^2
- Major changes from LHC
  - All silicon tracker
  - Large increase of Si area
    - both in Pixels and Strips
    - ~ 3 × LHC ATLAS

The layout proposed in the LoI provides 14 points/track to |η| < 2.7

Pixel: 4 layers + 6 disks, 25 x 150 (in) / 50 x 150 (out) μm^2





Detector:	Silicon area [m^2]	Channels [10^6]
Pixel barrel	5.1	445
Pixel end-cap	3.1	193
Pixel total	**8.2**	**638**
Strip barrel	122	47
Strip end-cap	71	27
Strip total	**193**	**74**

Table 6.6: Inner tracker active area and channel count.

FBK/LPNHE active edge

Doped region	impurity	function	peak value (cm^{-3})	reference value (cm^{-3})	rolloff (μm)
Pixel and GR	D	gaussian	2×10^{19}	10^{16}	1.0
Back	A	gaussian	2×10^{19}	10^{16}	1.0
Trench	A	erf	2×10^{19}	10^{12}	2.0
Bias tab	A	gaussian	2×10^{19}	2×10^{16}	0.5
P-spray	A	gaussian	5×10^{16}	7×10^{15}	0.5
P-stop	A	gaussian	5×10^{17}	7×10^{16}	0.5

Table 3: Implant parameters for simulated detectors; A (D) is for acceptor (donor) impurities.

Type	Energy (eV)	$\sigma_e(cm^2)$	$\sigma_h(cm^2)$	$\eta(cm^{-1})$
A	E_C -0.42	9.5×10^{-15}	9.5×10^{-14}	1.613
A	E_C -0.46	5.0×10^{-15}	5.0×10^{-14}	0.9
D	E_V +0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

Table 4: Relevant parameters for acceptors (A) and donor (D) deep levels in the bandgap, describing the radiation damage.

Multiplicity	Number of GRs	pixel-to-trench distance (μm)
1	0	100
1	1	100
1	2	100
4	3	200
1	5	300
1	10	400

Qox = 10^11 cm2, 3x10^12 cm2