Thin n-in-p planar pixel sensors and active edge sensors for the ATLAS upgrade at HL-LHC

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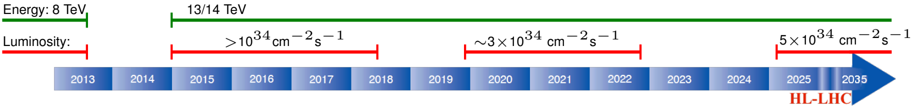
The pixel detector upgrade at HL-LHC



Energy: 8 TeV

13/14 TeV

Luminosity:

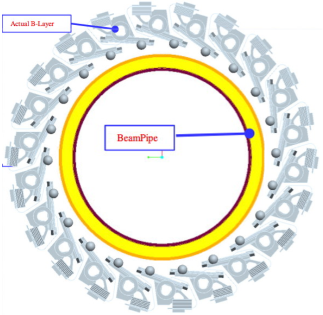
$>10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

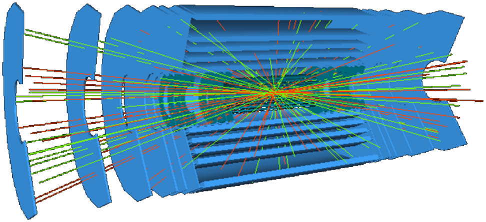
$\sim 3\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

$5\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

HL-LHC





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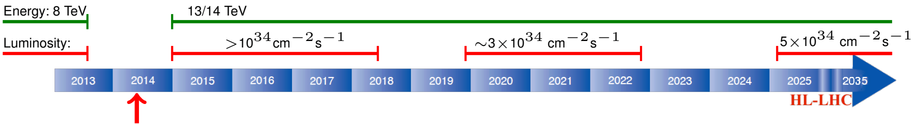

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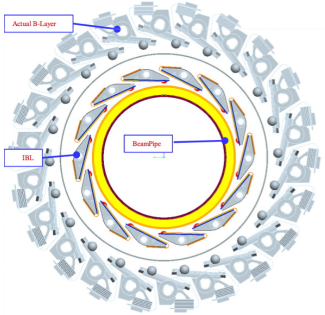
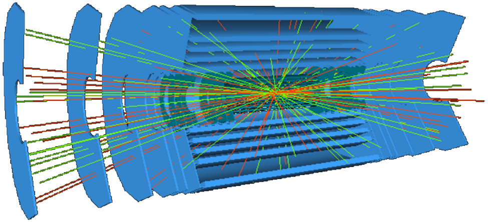
HL-LHC

Insertable B-Layer (IBL): new pixel layer at 3.2 cm from the pp interaction



up to $5\times10^{15}\,\mathrm{n_{eq}}/\mathrm{cm}^2$



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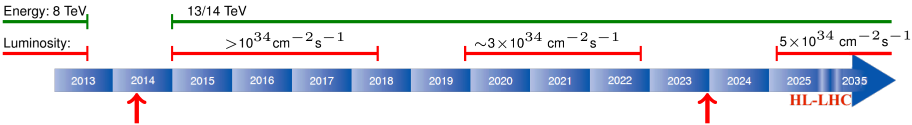

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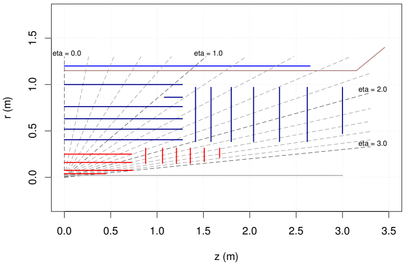
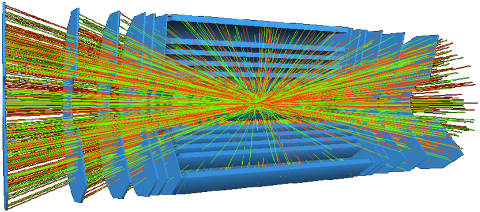
Insertable B-Layer (IBL): new pixel layer at 3.2 cm from the pp interaction

"Phase II": full inner detector replacement (4 layers)

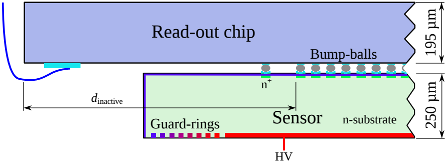


up to $20\times 10^{15}\mathrm{n_{eq}/cm^2}$

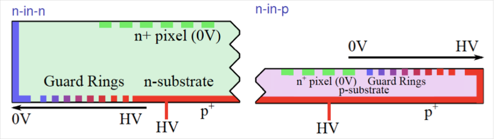


Our module concept

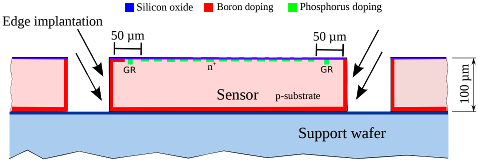
- The present ATLAS module design



- From n-in-n to n-in-p
  - → cost effective to cover large areas of the outer radii
- Thin sensors (100-200 μm)
  - → radiation hardness, material budget, reduced multiple scattering, low occupancy at high eta



- Active edge sensors
  - → attractive candidates for the inner layers of Phase II



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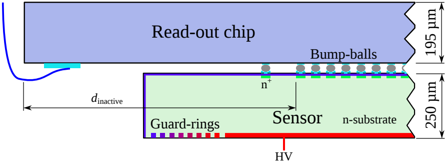

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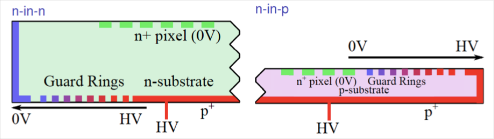
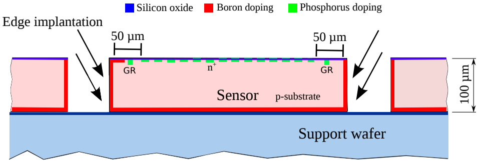
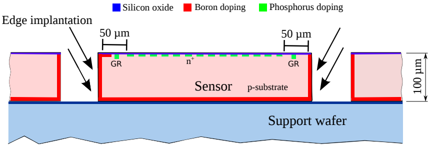


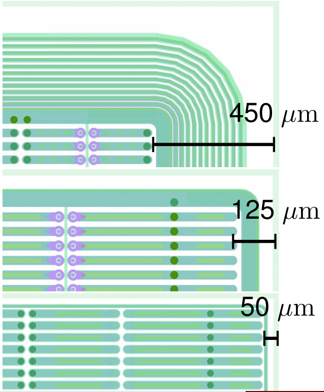


The VTT active/slim edge production

- 100-200 $\mu\mathrm{m}$ n-in-p silicon pixels
  - FZ and MCz material
  - p-spray isolation
- Flip chipping at VTT
  - support wafer removed

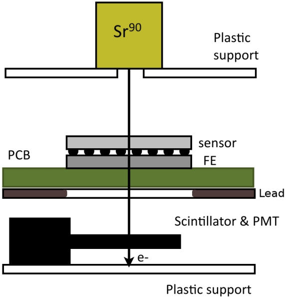


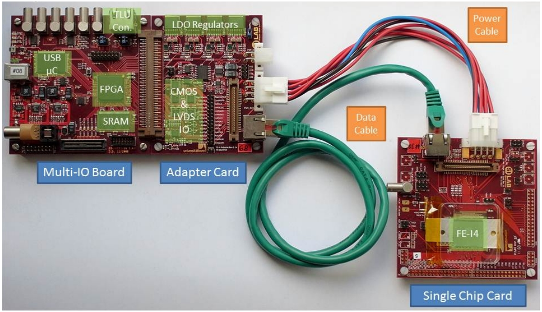
- **Different edge designs:**
  - 450 $\mu\mathrm{m}$ distance between the last pixel implant and the slim edge (Bias Ring (BR) and 11 Guard Rings (GR))
  - 125 $\mu\mathrm{m}$ distance between the last pixel implant and the slim edge (only 1 BR)
  - 50 $\mu\mathrm{m}$ distance between the last pixel implant and the active edge (only 1 floating GR)



Characterization setup in laboratory

- ^{90}Sr beta source (Cd and Am γ source used as reference in the calibration)
- External trigger via scintillator
- From 20°C to -50°C cooling
- ATLAS USBPix read-out system

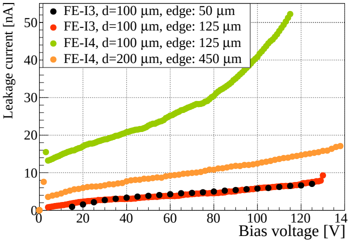




Pixel modules are wire-bonded to detector boards designed by the University of Bonn

Charge collection

IV before irradiation



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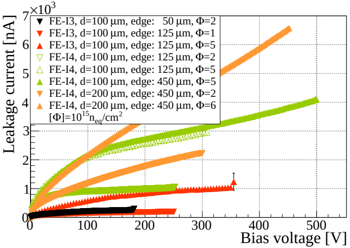

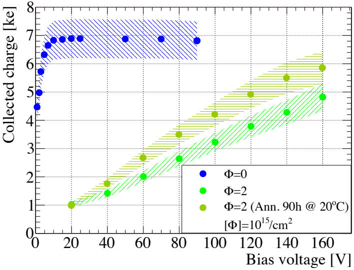

- VTT FE-I3 FZ silicon
  - 100 $\mu\mathrm{m}$ thick
  - **50 $\mu\mathrm{m}$ active edge** (only one floating GR)
  - Threshold: 1.5 ke
  - Same charge collection for the edge pixels after $2\times10^{15}\mathrm{n_{eq}/cm^2}$

Charge collection

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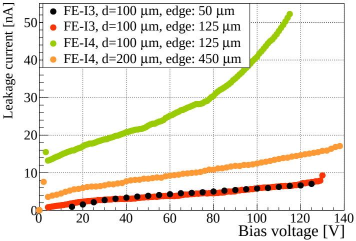

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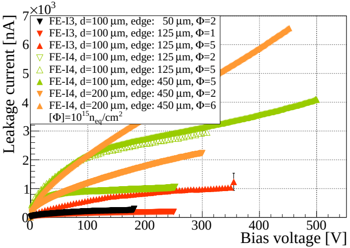

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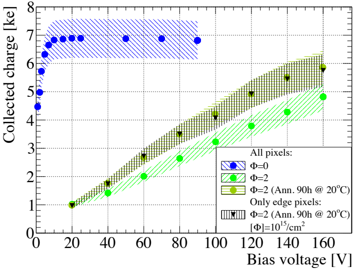
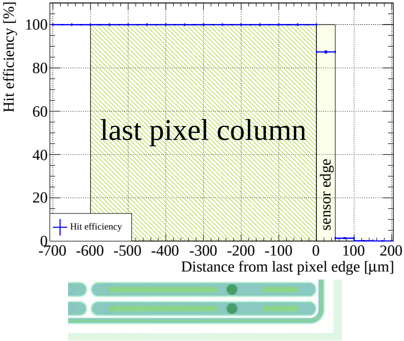


Edge efficiency before irradiation

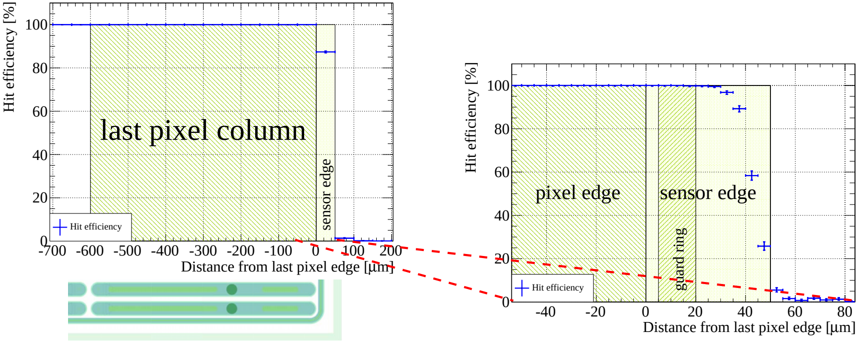
Test beam at DESY (4 GeV electrons) with the EUDET telescope



Efficiency of the last pixel column ∼99.9%

Edge efficiency before irradiation

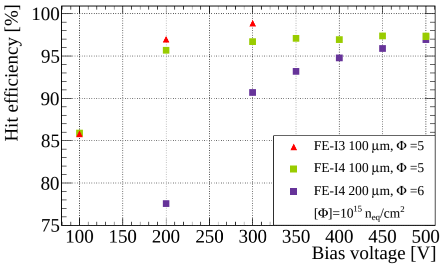
Test beam at DESY (4 GeV electrons) with the EUDET telescope

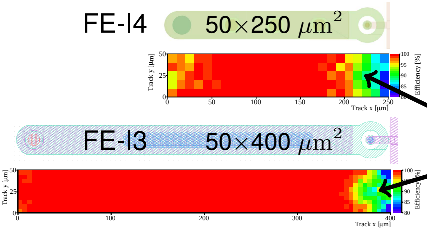


Efficiency of the last pixel column ∼99.9%

(87.4±0.7)% hit efficiency between the last pixel implant and the active edge (50 μm)

Hit efficiency summary after irradiation

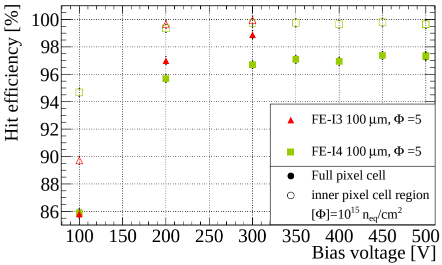


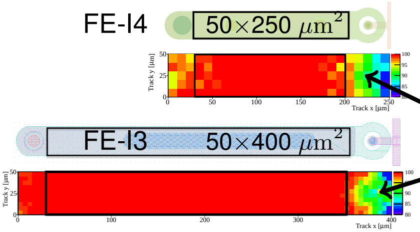


- VTT FE-I3 100 μm (125 μm edge)
  - Φ=5$\times$10^{15}n$_{\rm eq}$/cm^2
  - (99.0$\pm$0.3)% global hit efficiency at V$_{\rm bias}$=300 V
- VTT FE-I4 100 μm
  - Φ=5$\times$10^{15}n$_{\rm eq}$/cm^2
  - (97.0$\pm$0.3)% global hit efficiency at V$_{\rm bias}$=500 V
- VTT FE-I4 200 μm
  - Φ=6$\times$10^{15}n$_{\rm eq}$/cm^2
  - (96.9$\pm$0.3)% global hit efficiency at V$_{\rm bias}$=500 V

The Punch Through is the main inefficiency region after irradiation

Hit efficiency summary after irradiation





- **VTT FE-I3 100 μm (125 μm edge)**
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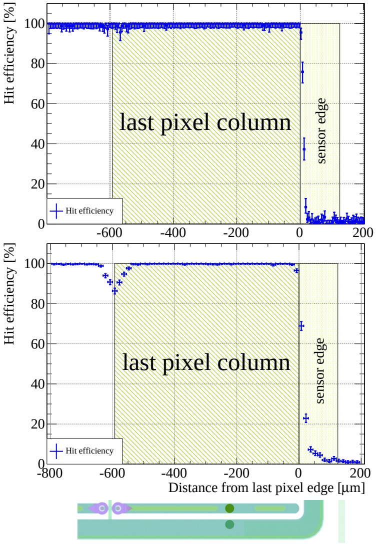
The Punch Through is the main inefficiency region after irradiation

VTT: edge efficiency after irradiation

FE-I3, 125 $\mu\mathrm{m}$ slim edge

- Not irradiated
- Threshold: 1500 e^{-}
- **(69$\pm$3)%** hit efficiency between the last pixel implant and the BR (CERN SpS, 120 GeV pions)

- Φ=5$\times$10^{15}n$_{\mathrm{eq}}$/cm^{2}
- V$_{\mathrm{bias}}$=300 V
- Threshold: 1500 e^{-}
- **(69$\pm$2)%** hit efficiency between the last pixel implant and the BR (DESY, 4 GeV electrons)



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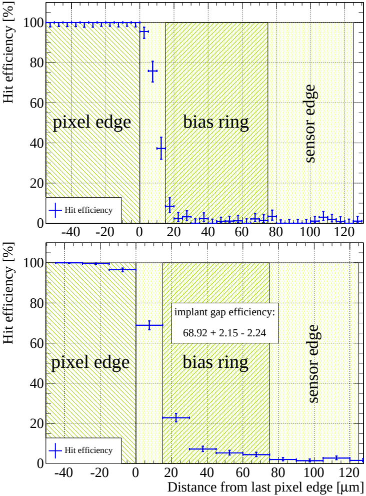
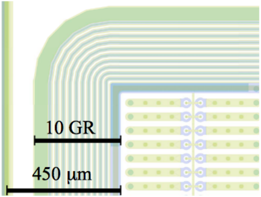
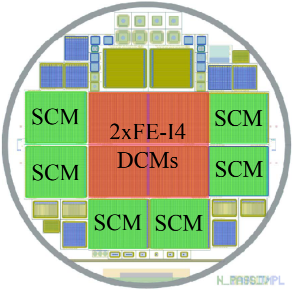


CiS production

- **N-in-p sensors produced at CiS on 4 inch wafers:**
  - FZ silicon sensor 200-300 μm thick
  - spark protection with 3 μm layer of patterned BCB deposited on the sensor surface at IZM
  - GR structure with 450 μm inactive edge
  - On each wafer:
    - 6×FE-I4 Single Chip Module (SCM)
    - 2×FE-I4 Double Chip Module (DCM) interconnected as a Pseudo-quad module
  - Pseudo-quad interconnected to 4×FE-I4 readout chips
  - Collaboration between MPP, Göttingen and Bonn

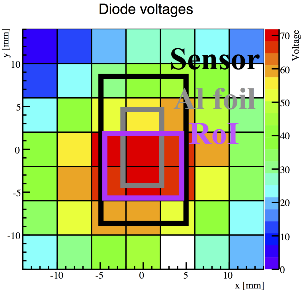


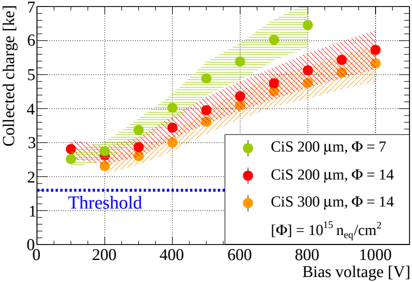


universitätbonn

Charge collection

- ^{90}Sr beta electrons
- Collected charge before irradiation after full depletion:
  - for 200 $\rightarrow \sim$ 14 ke
  - for 300 $\rightarrow \sim$ 24 ke
- Irradiated in Los Alamos (800 MeV protons)
- Only region of central beam spot (RoI)





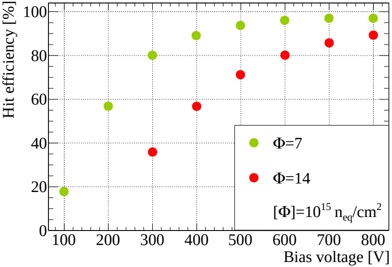
- Uncertainties at high fluence:
  - not uniform irradiation
  - non linearity of the charge calibration at low ToT
  - bias introduced by the threshold at low values of the collected charge

Hit efficiency

FE-I4, 200 μm thick irradiated in Los Alamos

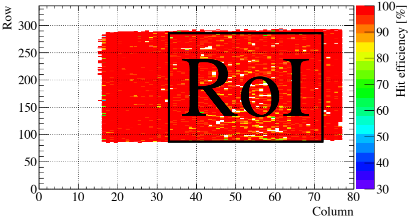
- Test beam at DESY
- Threshold: 1.6 ke

- Hit efficiency calculated in the **RoI** area



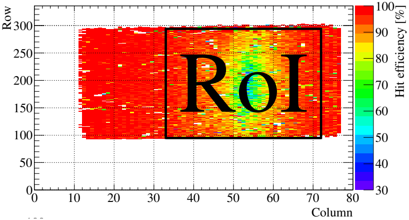
$\Phi=7\times10^{15}\mathrm{n_{eq}/cm^2}$

(97.2±0.3)% @ 800 V



$\Phi=14\times10^{15}\mathrm{n_{eq}/cm^2}$

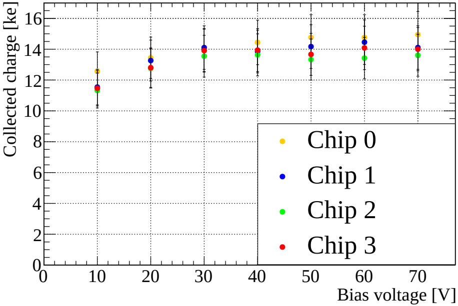
(89.4±0.3)% @ 800 V

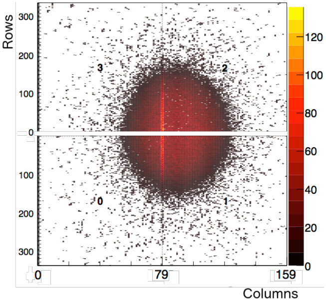


Quad modules for the outer layers

- From the same CiS production:
  - 200 $\mu\mathrm{m}$ thick FZ silicon
  - 4×FE-I4 readout chips interconnected to 2×double chip sensors (Psedo-quad)
  - 150 $\mu\mathrm{m}$ thin chips (IZM technology with glass substrate)
- ^{90}Sr scan with the USBPix readout system


Detector boards designed by Liverpool University





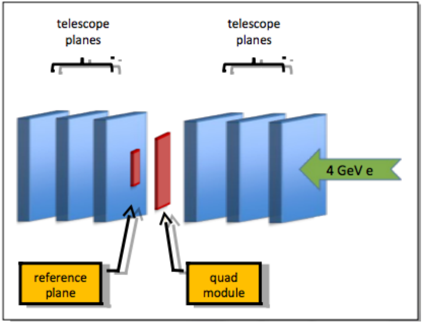
Test beam

Test beam at DESY:

- 4 GeV electrons
- EUDET telescope

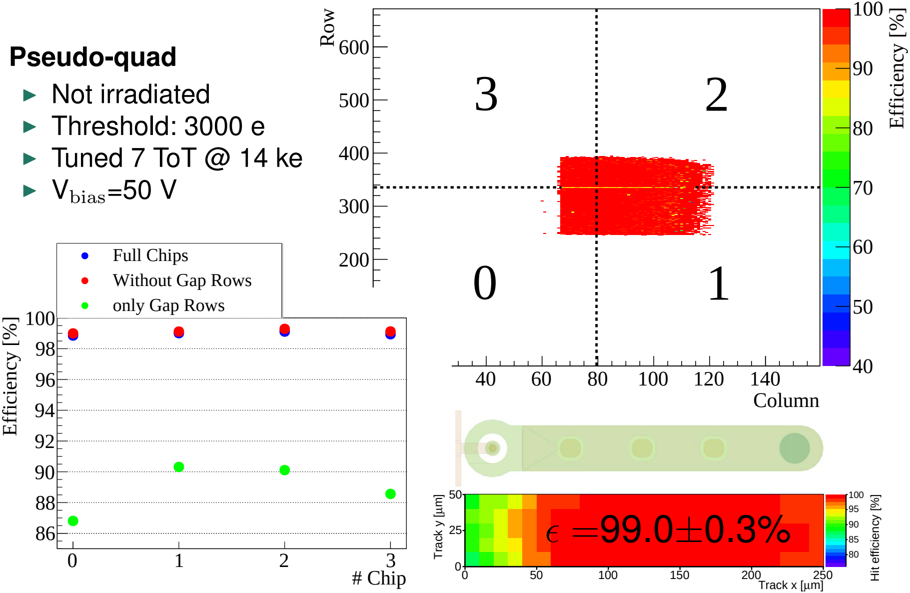
Setup:

- RCE readout system
- 1 Quad (4×FE-I4 chips)
- 1 FE-I4 single chip module as reference plane
- ⊥ beam incidence



Pseudo-quad

- Not irradiated
- Threshold: 3000 e
- Tuned 7 ToT @ 14 ke
- V_{bias}=50 V

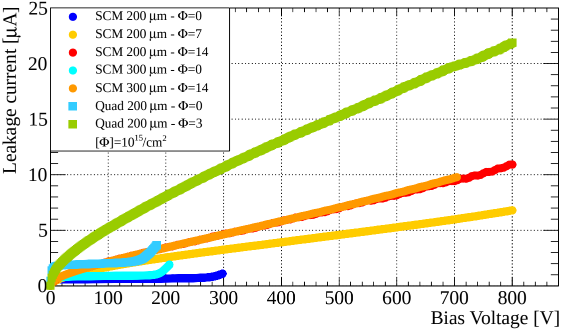


Conclusions and outlook

- Active edge sensors show good performance before and after irradiation up to a fluence of 5×10$^{15}\mathrm{n_{eq}/cm^2}$
- Studies performed with 200 μm thick n-in-p sensors up to a fluence of 14×10$^{15}\mathrm{n_{eq}/cm^2}$
  - modules are still functional after a very inhomogeneous irradiation
- More VTT active edge and CiS modules have been irradiated in Ljubljana and will be characterized soon:
  - VTT FE-I4 100 μm thin MCz silicon → 10×10$^{15}\mathrm{n_{eq}/cm^2}$
  - CiS FE-I4 200 μm thin FZ silicon → 10×10$^{15}\mathrm{n_{eq}/cm^2}$
- More productions at CiS and ADVACAM are foreseen in 2015 on thin substrates (50, 100 and 150μm)

BACKUP SLIDES

CiS production: IV curves

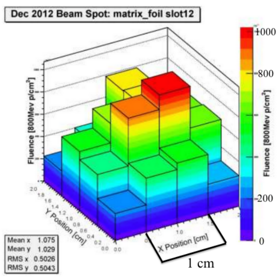


- Quad module irradiated at KIT to $3\times10^{15}\mathrm{n_{eq}/cm^2}$
- SCM irradiated in Los Alamos to 7 and $14\times10^{15}\mathrm{n_{eq}/cm^2}$ (as measured in 1×1 $\mathrm{cm^2}$ Al foil centered on the beam):
  - breakdown before irradiation over 200 V
  - no breakdown after irradiation up to 800 V

Irradiated in Los Alamos at 7 and 14$\times10^{15}\mathrm{n_{eq}/cm^2}$ (as measured in 1$\times$1 cm^2 Al foil centered on the beam)

- Threshold 1.6 ke
- Tuning: 6 ToT to 4 ke
- Beam spot structure observable in many scans during the tuning
- Acceptable tuning after a very inhomogeneous fluence

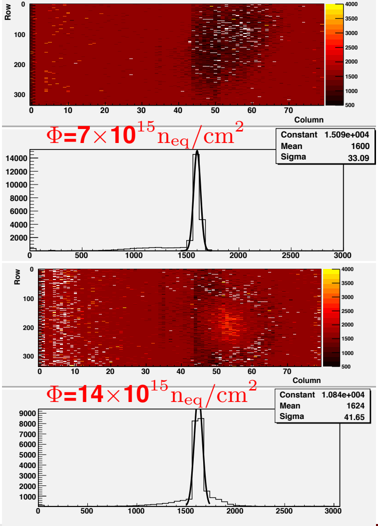
Beam spot structure at Los Alamos



X FWHM
∼1.5 - 2 cm

Y FWHM
∼0.5 - 1 cm

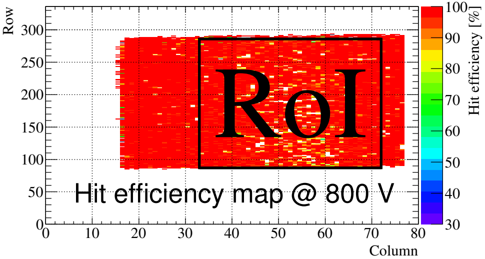
THRESHOLD SCANS

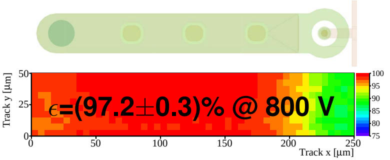


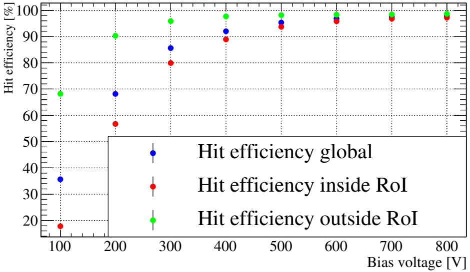
Hit efficiency

FE-I4, 200 μm thick irradiated to Φ=7×$10^{15} \mathrm{n_{eq}/cm^2}$ in Los Alamos

- Threshold: 1.6 ke
- Hit efficiency at 800 V
    - global: (97.8±0.3)%
    - inside RoI: (97.2±0.3)%
    - outside RoI: (98.7±0.3)%



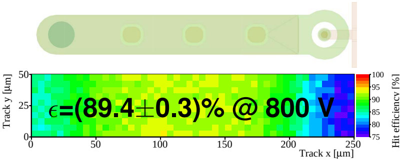


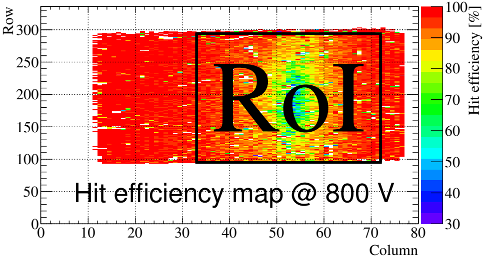


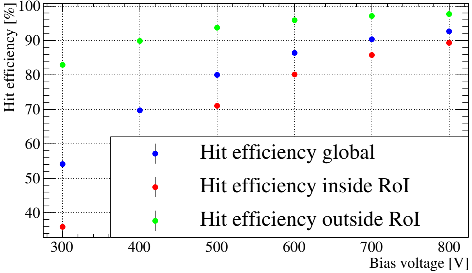
Hit efficiency

FE-I4, 200 μm thick irradiated to Φ=14$\times$10^{15}n$_{eq}$/cm^2 in Los Alamos

- Threshold: 1.6 ke
- Hit efficiency at 800 V
  - global: (92.8±0.3)%
  - inside RoI: (89.4±0.3)%
  - outside RoI: (97.8±0.3)%

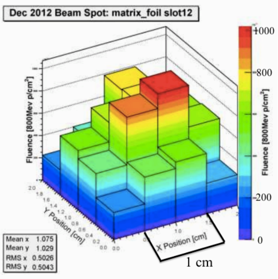






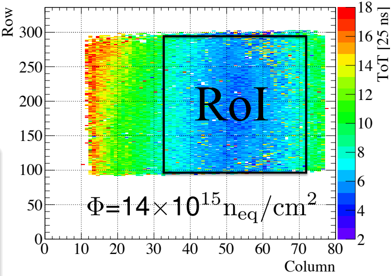
Average ToT from test beam

- The map of the average ToT over the module surface shows clearly the different irradiation levels

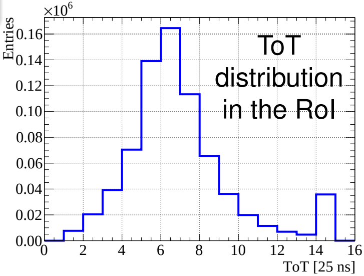


Module still operational even after this highly inhomogeneous irradiation.

- ToT distribution in agreement with laboratory measurements
  - Threshold 1.6 ke
  - 6 ToT to 4 ke
  - V_{bias}=800 V



Φ=14×$10^{15}\,\mathrm{n_{eq}/cm^2}$



ToT distribution in the RoI

Charge Collection: thickness comparison