Heavily irradiated thin n-in-p planar pixel sensors & status of the new common RD50 productions

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24th RD50 Workshop, Bucharest 11th-13th June 2014

Tested modules

VTT active/slim edges:

- FE-I3 modules 100 μm thick (125 μm edge, p-type FZ)
- FE-I4 modules 100 μm thick (450 μm edge, p-type FZ)
- FE-I4 modules 200 μm thick (450 μm edge, p-type FZ)

Irradiations:

→ $5\times10^{15}\mathrm{n_{eq}/cm^2}$ at KIT + Ljubljana (reactor neutrons)

→ $5\times10^{15}\mathrm{n_{eq}/cm^2}$ at KIT (25 MeV protons)

→ $6\times10^{15}\mathrm{n_{eq}/cm^2}$ at KIT + Ljubljana (reactor neutrons)

CiS production:

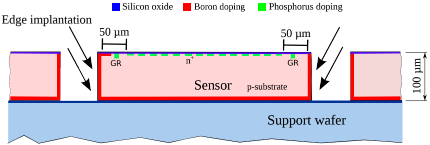
- FE-I4 modules 200 μm thick (450 μm edge, p-type FZ)
- FE-I4 modules 200 μm thick (450 μm edge, p-type FZ)

Irradiations:

→ $7\times10^{15}\mathrm{n_{eq}/cm^2}$ in Los Alamos (800 MeV protons)

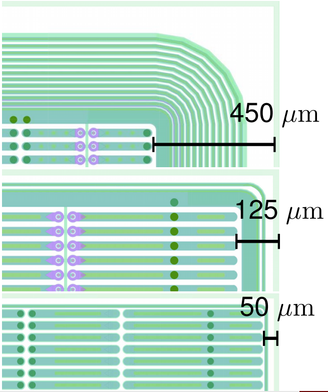
→ $14\times10^{15}\mathrm{n_{eq}/cm^2}$ in Los Alamos (800 MeV protons)

The VTT active/slim edge production



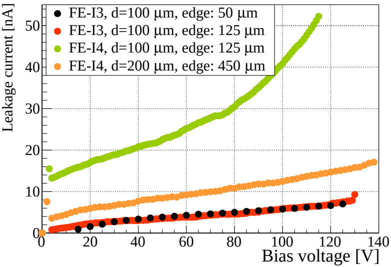
Trenches doped by four-quadrant implantation

- **Different edge designs:**
  - 450 μm distance between the last pixel implant and the slim edge (Bias Ring (BR) and 11 Guard Rings (GR))
  - 125 μm distance between the last pixel implant and the slim edge (only 1 BR and 1 floating GR)
  - 50 μm distance between the last pixel implant and the active edge (only 1 floating GR)

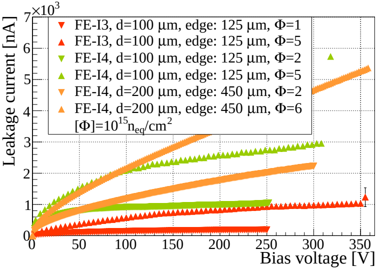


IV curves

- Before irradiation:
  - depletion voltage 10-15 V
  - breakdown 100-140 V

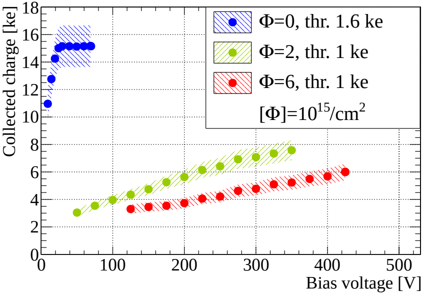


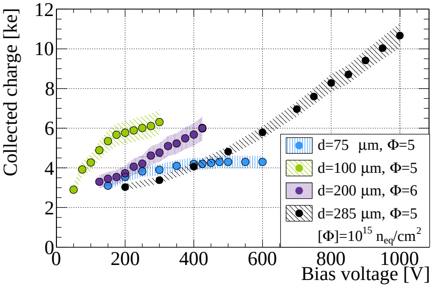
- After irradiation:
  - the breakdown voltage of the active edge modules after $5\times10^{15}\,\mathrm{n_{eq}/cm^2}$ is above the saturation voltage



Charge collection

- ^{90}Sr beta electrons (Cd and Am γ sources used as reference)
- VTT FE-I4 FZ silicon 200 μm thick
- 450 μm slim edge with GRs
- **40% CCE** at 425 V at $6\times10^{15}\mathrm{n_{eq}/cm^2}$



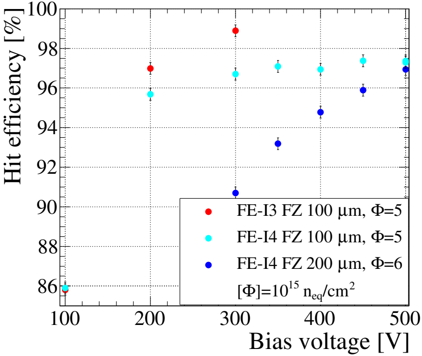


At Φ=5-6$\times10^{15}\mathrm{n_{eq}/cm^2}$ 200 μm thick devices are still under depleted up to 425 V

while the collected charge of 100 μm thick sensors saturates already at 200 V

Hit efficiency summary

Beam test measurements at DESY with the EUDET telescope

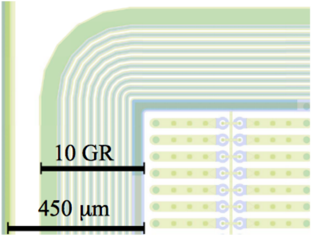


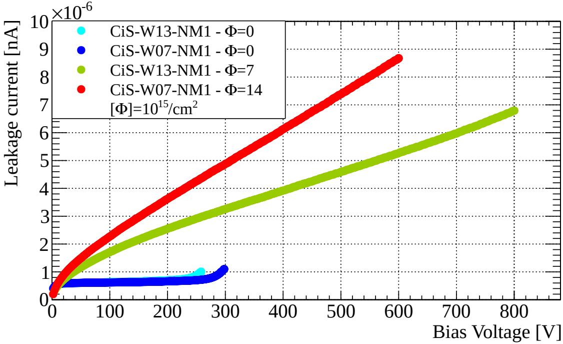
- **VTT FE-I3 100 μm**
  - Φ=5×$10^{15}\mathrm{n_{eq}/cm^2}$
  - (99.0±0.3)% global hit efficiency at V_{bias}=300 V (125 μm edge)
- **VTT FE-I4 100 μm**
  - Φ=5×$10^{15}\mathrm{n_{eq}/cm^2}$
  - (97.0±0.3)% global hit efficiency at V_{bias}=500 V
- **VTT FE-I4 200 μm**
  - Φ=6×$10^{15}\mathrm{n_{eq}/cm^2}$
  - (96.9±0.3)% global hit efficiency at V_{bias}=500 V

200 μm thick sensors need higher V_{bias} for the hit efficiency to saturate with respect to 100 μm thick sensors → consistent with CCE results

CiS production

- 200 μm thick n-in-p pixel sensors produced at CiS on 4 inch FZ silicon wafers
- Bump-bonded on ATLAS FE-I4 chips at IZM
- Spark protection with 3 μm layer of patterned BCB deposited on the sensor surface at IZM
- GR structure with 450 μm inactive edge





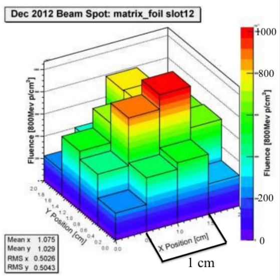
Irradiated in Los Alamos at 7 and 14$\times 10^{15} \mathrm{n_{eq}/cm^2}$ (as measured in 1$\times$1 cm^2 Al foil centered on the beam):

- breakdown before irradiation over 200 V
- no breakdown after irradiation up to 800 V

Irradiated in Los Alamos at 7 and 14$\times 10^{15} \mathrm{n_{eq}/cm^2}$ (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

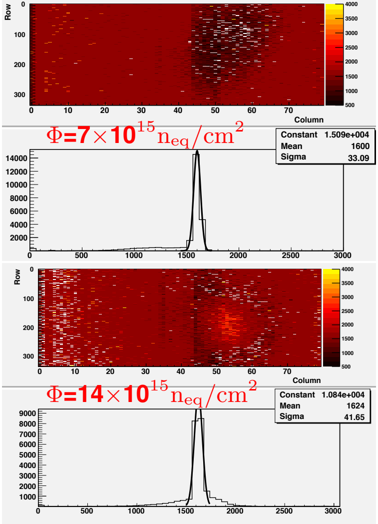
Beam spot structure at Los Alamos



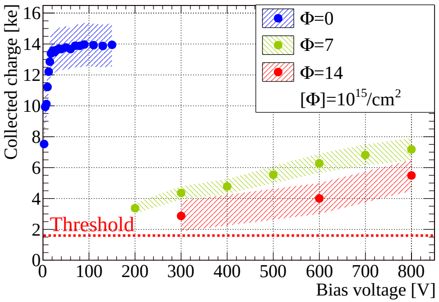
X FWHM
~1.5 - 2 cm

Y FWHM
~0.5 - 1 cm

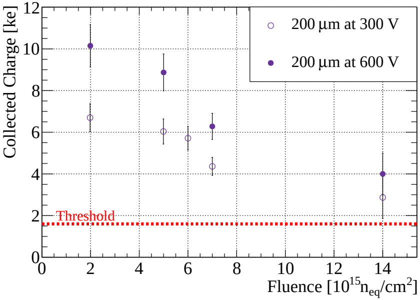
THRESHOLD SCANS



Charge collection



- ^{90}Sr beta electrons (Cd and Am γ sources used as reference)
- Threshold 1.6 ke
- Only region of central beam spot considered in the analysis

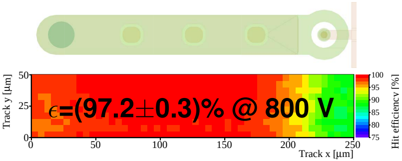


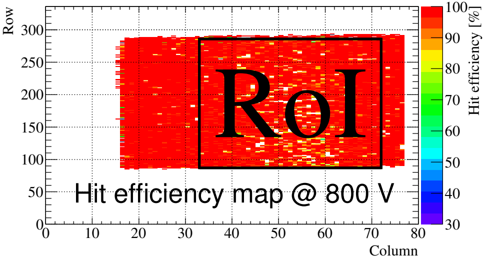
- Larger uncertainties at high fluence:
  - higher uncertainty in the calibration at lower ToT
  - effect of the not uniform irradiation
  - bias introduced by the threshold at low values of the collected charge

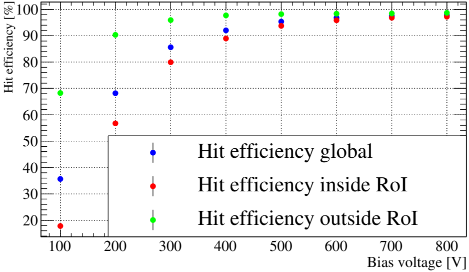
Hit efficiency

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)%



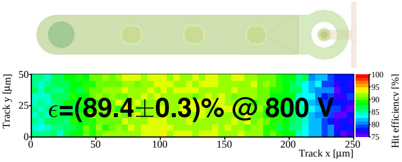


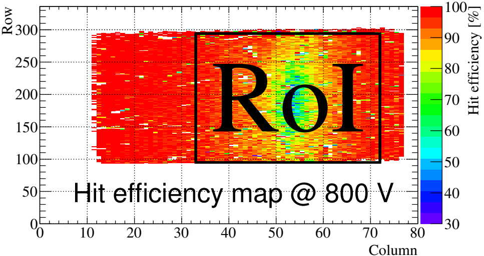


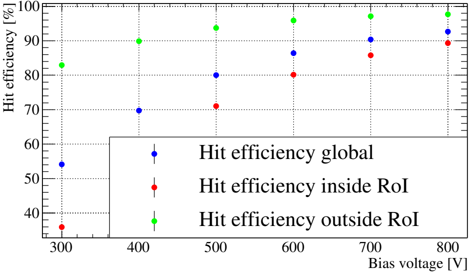
Hit efficiency

FE-I4, 200 μm thick irradiated to Φ=14$\times$10^{15}n$_{\mathrm{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)%

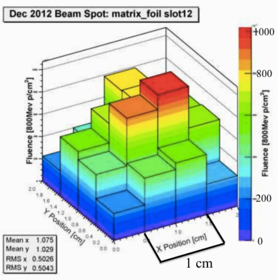

ϵ=(89.4±0.3)% @ 800 V


Hit efficiency map @ 800 V

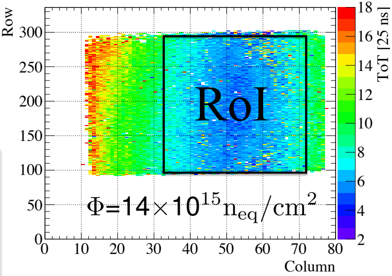


Average ToT from test beam

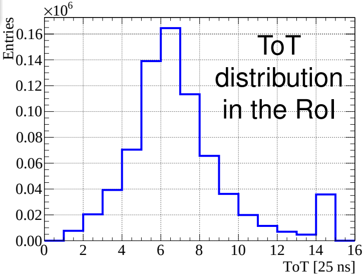
- The map of the average ToT over the module surface shows clearly the different irradiation levels



Module still operational even after this highly inhomogeneous irradiation.



$\Phi = 14 \times 10^{15}\, \mathrm{n_{eq}/cm^2}$



ToT distribution in the RoI

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

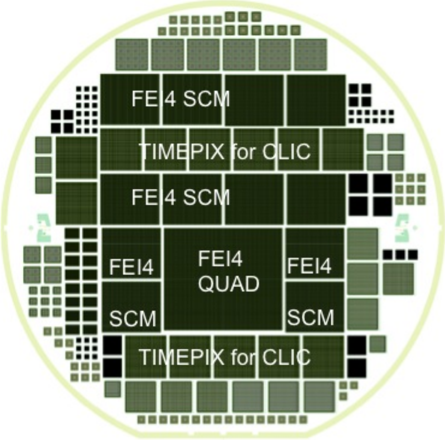
2nd production of active edge pixels at ADVACAM

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

RD50 common project

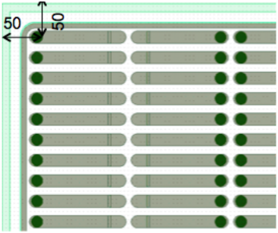
- **50, 100, 150 μm thick sensors (5 FZ p-type wafers for each thickness):**
  - FE-I4 quad sensors
  - FE-I4 single chip sensors with different geometries
  - Omegapix sensors
  - TIMEPIX sensors for CLIC R&D
  - CLICpix sensors for CLIC R&D
  - pixel and strip structures for medical applications

Active edge process for all the structures

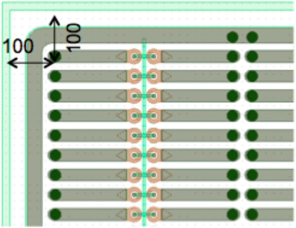


FE-I4 Single Chip Modules

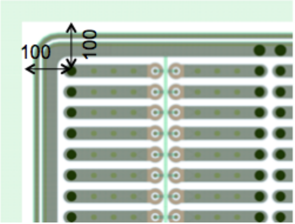
Pixels and diodes with different edges to investigate post-irradiation breakdown properties



FE-I4
50 μm edge
one Guard Ring,
<u>no</u> punch-through
structures



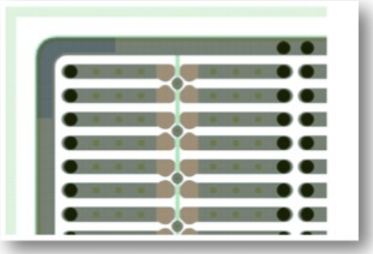
FE-I4
100 μm edge
Bias Ring
punch-through
structures

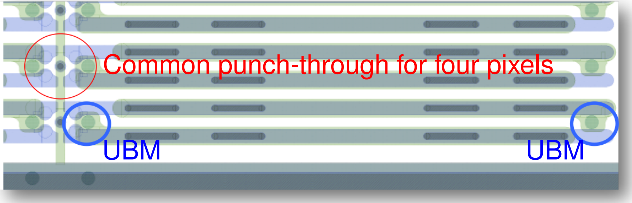


FE-I4
100 μm edge
Bias Ring + Guard Ring
punch-through
structures

Improvement of the punch-through structure design

- Redesign of the FE-I4 sensor with a punch-through structure every four pixels → decrease of the inefficient region
- Reduced space occupied by this biasing scheme allows for its application to $25 \times 500\ \mu\text{m}^2$ pixels
- Interconnected to FE-I4 chips, used to study resolution at the pitch foreseen for inner pixel layers at HL-LHC

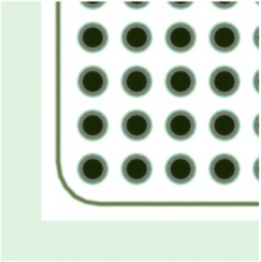




Other sensor designs for the inner layers

Possible example of planar pixel sensor for small pitches

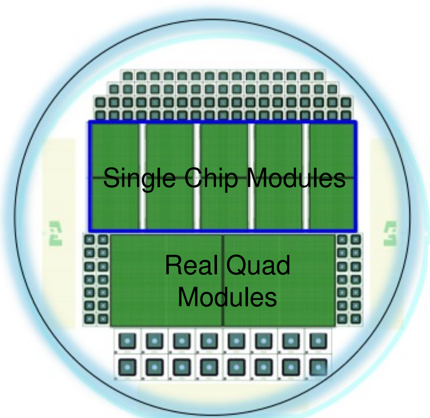
- Timepix sensor designed in n-in-p technology for CLIC R&D $\rightarrow$ possible example of geometry of a sensor to be attached to future chip with $50\times50\ \mu\text{m}^2$
- Sensor of a previous production with this bump-structure already interconnected at ADVACAM



Timepix active edge sensor for CLIC R&D: $55\times55\ \mu\text{m}^2$, edge = $50\ \mu$m

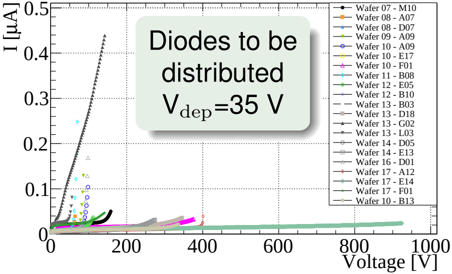
- Implant $30\ \mu$m
- Aluminum $40\ \mu$m
- UBM $25\ \mu$m
- Passivation $20\ \mu$m

N-in-p FE-I4 sensors on 6 inch wafers at CiS



RD50 common production meant to supply diodes for defect characterization

- First 6 inch production at CiS
- 6 inch wafers on p-type FZ material, 16 kΩ cm, 270 μm thick
- 16 wafers delivered, acceptable quality
- BCB and UBM deposition under way at IZM in this moment
- To be interconnected to FE-I4 chips



Diodes to be distributed V_{dep}=35 V

Conclusions and outlook

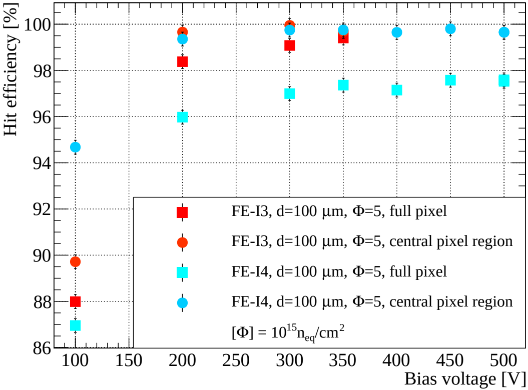
- Excellent performance of thin pixels with active edge sensors demonstrated before and after irradiation up to a fluence of $5\times10^{15}\mathrm{n_{eq}/cm^2}$
- Studies performed with 200 μm thick n-in-p sensors up to a fluence of $14\times10^{15}\mathrm{n_{eq}/cm^2}$
  - modules are still functional after a very inhomogeneous irradiation
- More VTT active edge and CiS modules have been irradiated in Ljubljana and will be characterized soon:
  - VTT FE-I3 100 μm thin FZ silicon with 50 μm active edge (no BR, only 1 floating GR) $\rightarrow 2\times10^{15}\mathrm{n_{eq}/cm^2}$
  - VTT FE-I4 100 μm thin MCz silicon $\rightarrow 10\times10^{15}\mathrm{n_{eq}/cm^2}$
  - CiS FE-I4 200 μm thin FZ silicon $\rightarrow 10\times10^{15}\mathrm{n_{eq}/cm^2}$
- More productions on 6 inch wafers at CiS are foreseen on thin substrates in 2015

BACKUP SLIDES

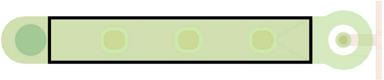
VTT: comparison of FE-I3 and FE-I4 performances

- The Punch Through (PT) is the main inefficiency region after irradiation
- It occupies a bigger fraction of the pixel cell in the FE-I4 than in the FE-I3

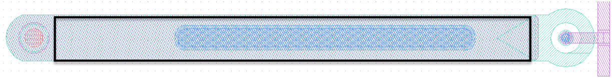
- In the central region, excluding the PT, FE-I3 and FE-I4 pixel modules with 100 μm thick sensors achieve the same hit efficiency.



FE-I4 ($250\times50\ \mu m^2$)

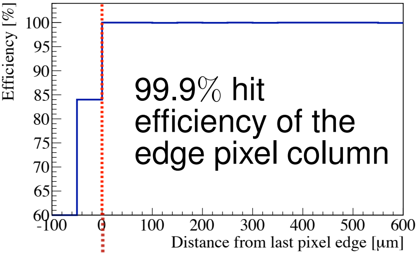


FE-I3 ($400\times50\ \mu m^2$)

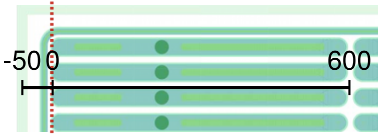


VTT: edge efficiency before irradiation (CERN SpS)

VTT FE-I3, 50 μm active edge

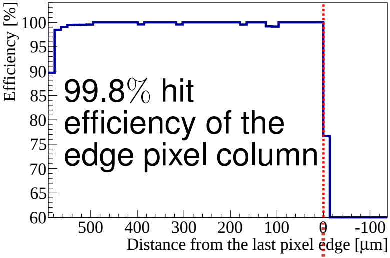


99.9% hit efficiency of the edge pixel column

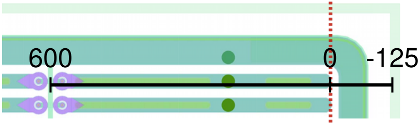


$84^{+9}_{-14}\%$ hit efficiency between the last pixel implant and the active edge

VTT FE-I3, 125 μm slim edge



99.8% hit efficiency of the edge pixel column

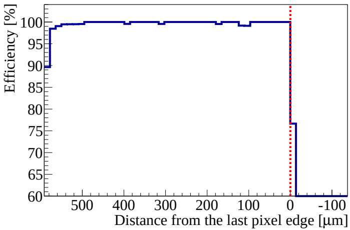


77$\pm 1\%$ hit efficiency between the last pixel implant and the Bias Ring

VTT: edge efficiency after irradiation

FE-I3, 125 μm slim edge

- not irradiated
- threshold: 1500 e$^-$
- **(77$\pm$1)%** hit efficiency between the last pixel implant and the BR (CERN SpS, 120 GeV pions)



- Φ=5$\times$10^{15}n$_{\rm eq}$/cm^2
- V$_{\rm bias}$=300 V
- threshold: 1500 e$^-$
- **(59$\pm$2)%** hit efficiency between the last pixel implant and the BR (DESY, 4 GeV electrons)