FSP 101
ATLAS

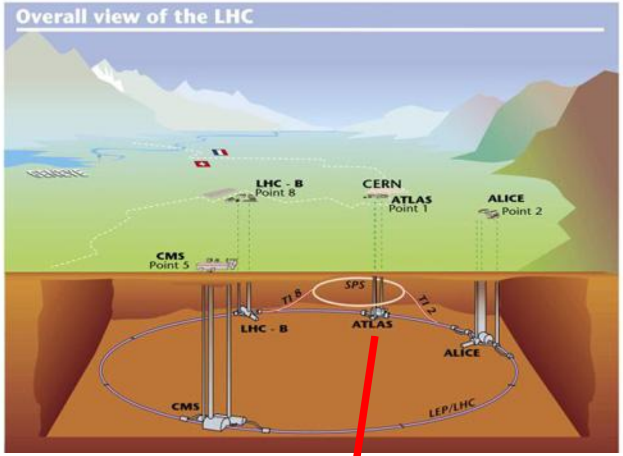
Radiation hardness and slim edge studies of planar n^+-in-n ATLAS pixel sensors for HL-LHC

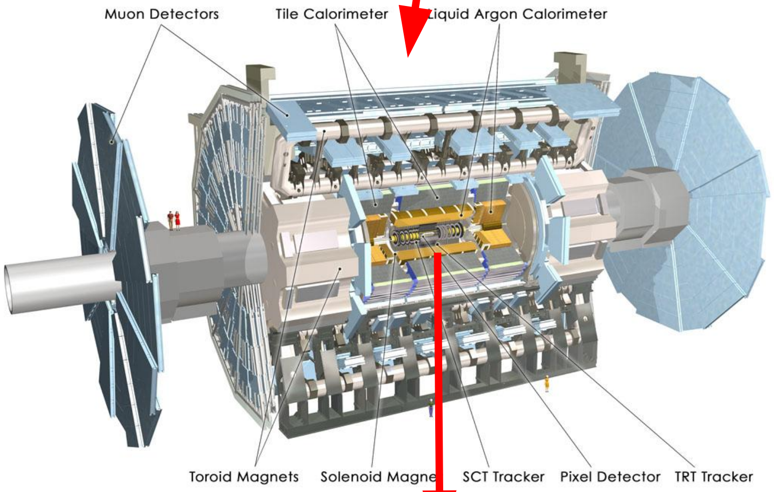
Silke Altenheiner, Karola Dette, Claus Gößling, Jennifer Jentzsch, Reiner Klingenberg,
Till Plümer, Andre Rummler, Tobias Wittig
TU Dortmund

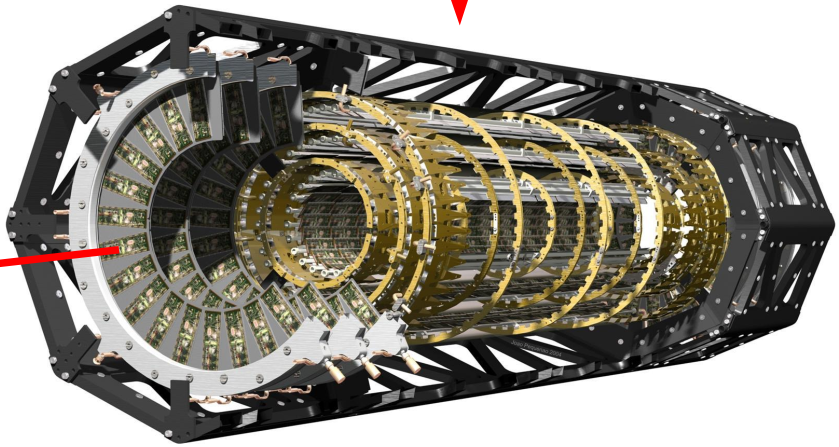
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

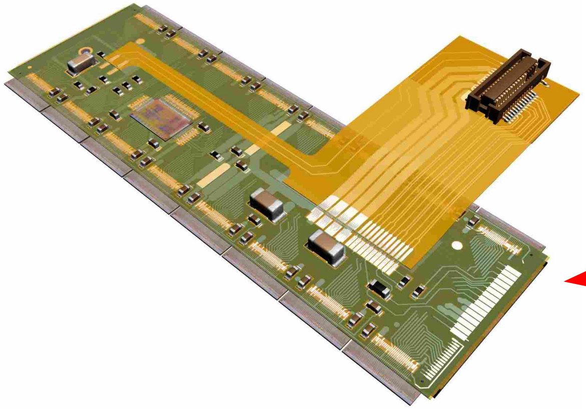
Overview

- the LHC at CERN is the largest particle accelerator
  - length of 27km
  - energy up to 7+7 TeV
- the ATLAS detector is one of the four large experiments
- its pixel detector is the innermost part of the tracking system
  - three layers surrounding the interaction point
  - 3 +3 endcap discs
  - consists of 1744 modules



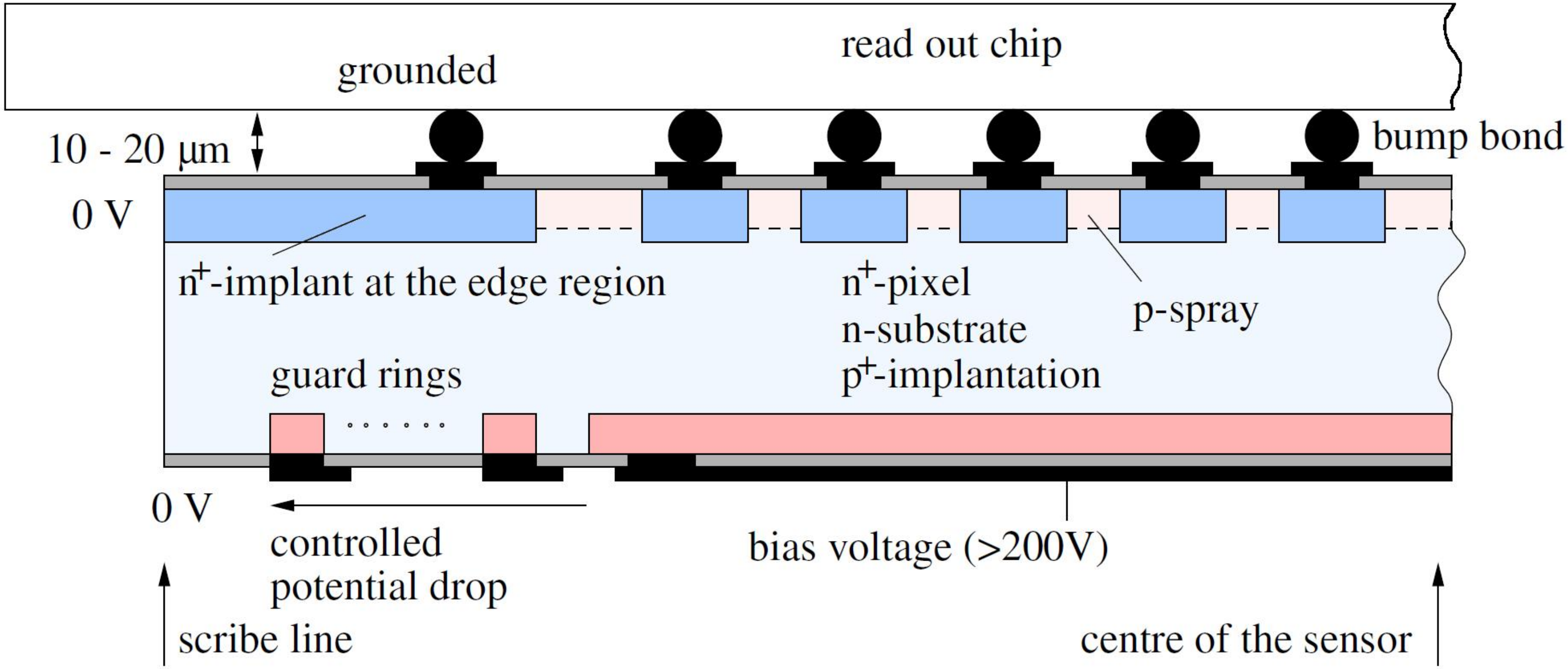




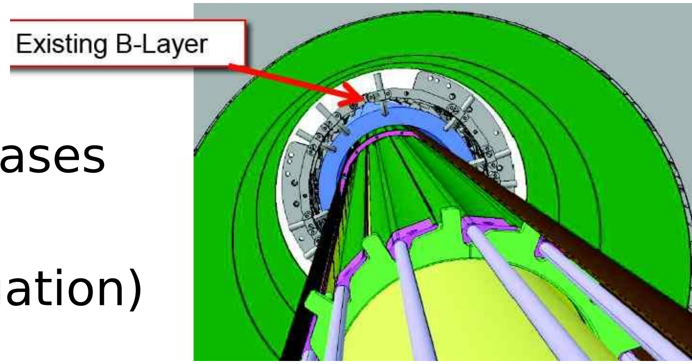


present ATLAS pixel module

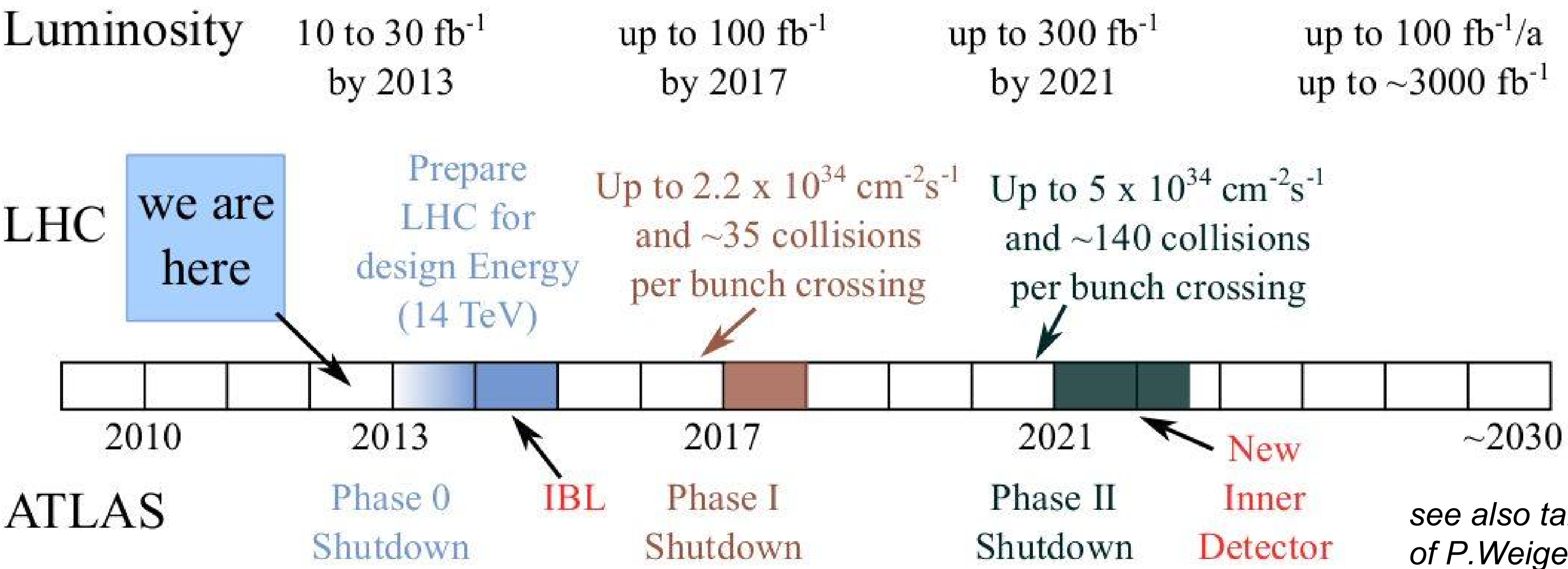
- planar n-in-n silicon sensor
  - n+ pixel
  - n bulk, 250um thick, diffusion oxygenated float zone (DOFZ)
  - p+ implantation
  - guard rings to reduce HV stepwise
  - 46,080 pixel cells, 400um x 50um
- FE-I3 read out chip



time schedule of ATLAS upgrades



- ATLAS upgrades are divided into several phases
  - phase 0: insertable b-layer (IBL)
  - phase I: *new pixel detector* (under evaluation)
  - phase II: new inner detector
- increasing luminosity
- increasing number of bunch crossings per event



Luminosity

10 to 30 fb^{-1} by 2013

up to 100 fb^{-1} by 2017

up to 300 fb^{-1} by 2021

up to 100 fb^{-1}/a up to ~3000 fb^{-1}

LHC

we are here

Prepare LHC for design Energy (14 TeV)

Up to 2.2 x 10^{34} $cm^{-2}s^{-1}$ and ~35 collisions per bunch crossing

Up to 5 x 10^{34} $cm^{-2}s^{-1}$ and ~140 collisions per bunch crossing

2010

2013

2017

2021

~2030

ATLAS

Phase 0 Shutdown

IBL

Phase I Shutdown

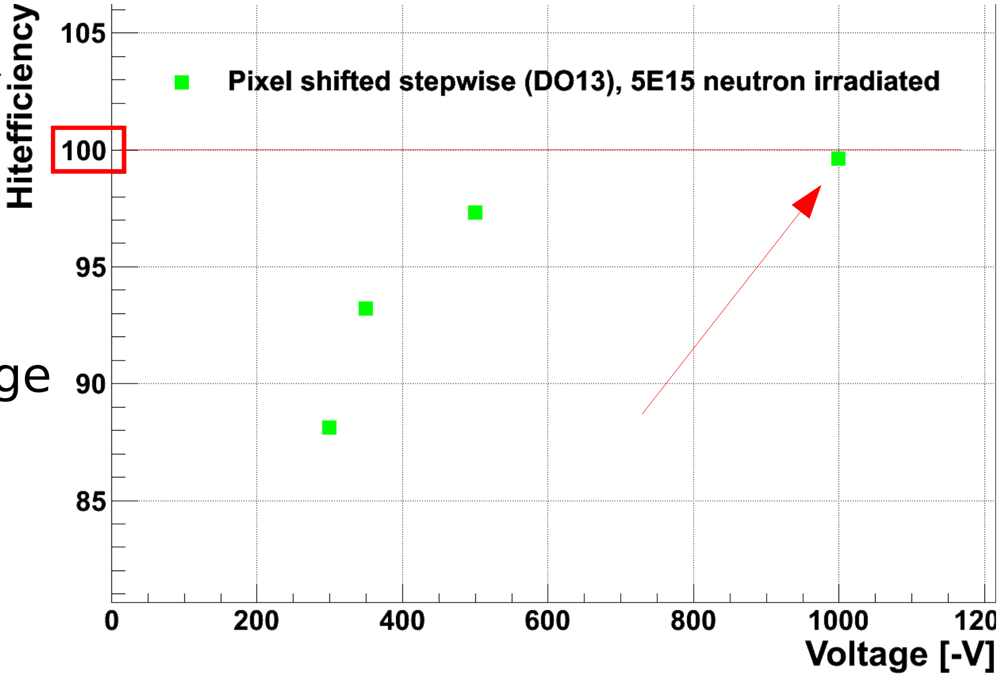
Phase II Shutdown

New Inner Detector

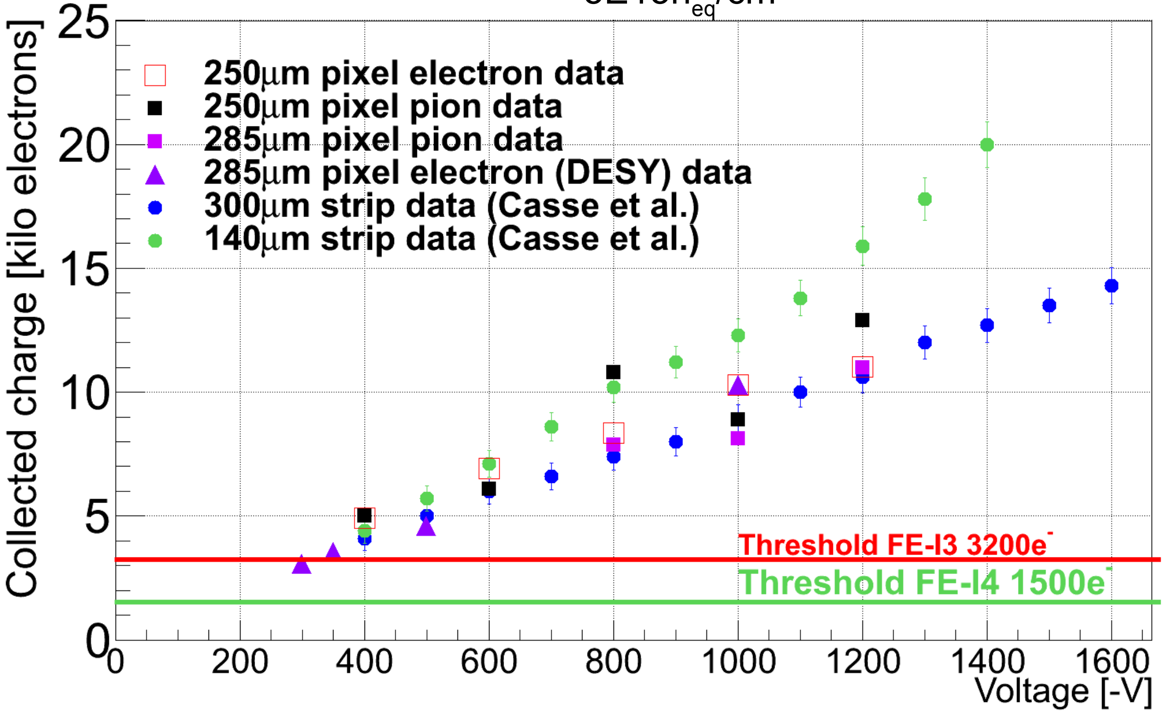
see also talk of P.Weigell

radiation hardness

- required collected charges & hit efficiencies can be obtained by increasing the sensor bias voltage
- IBL fluence (5E15n_{eq}/cm^2)
    - hit efficiency of 99.6% was measured
    - more than 10ke at 1kV are collected



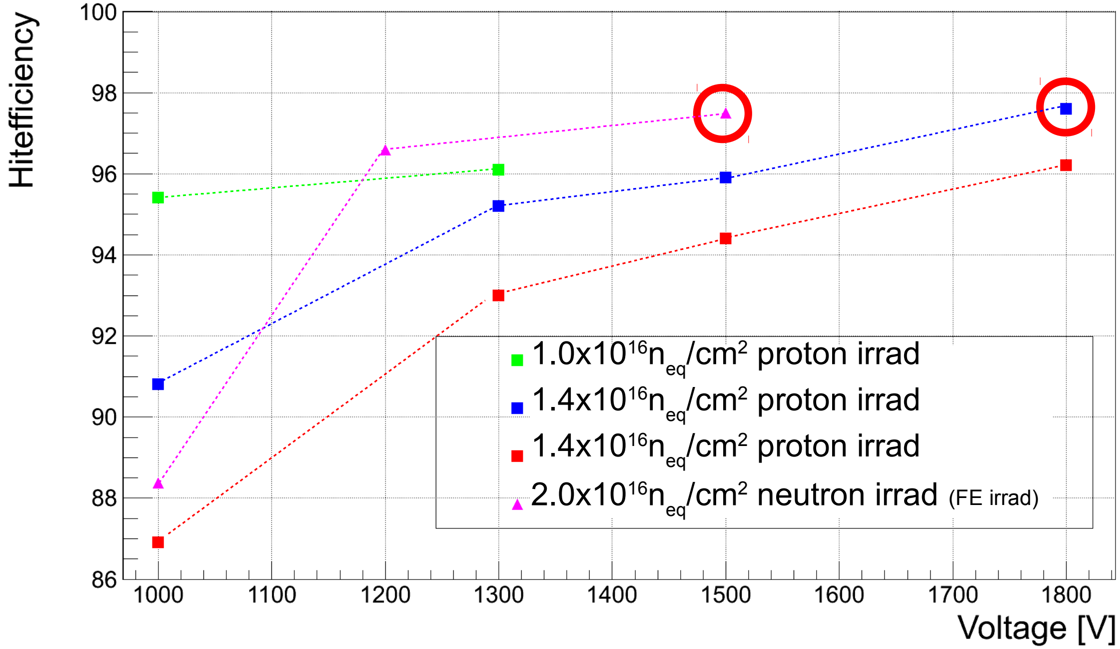
CiS sensors 5E15n_{eq}/cm^2

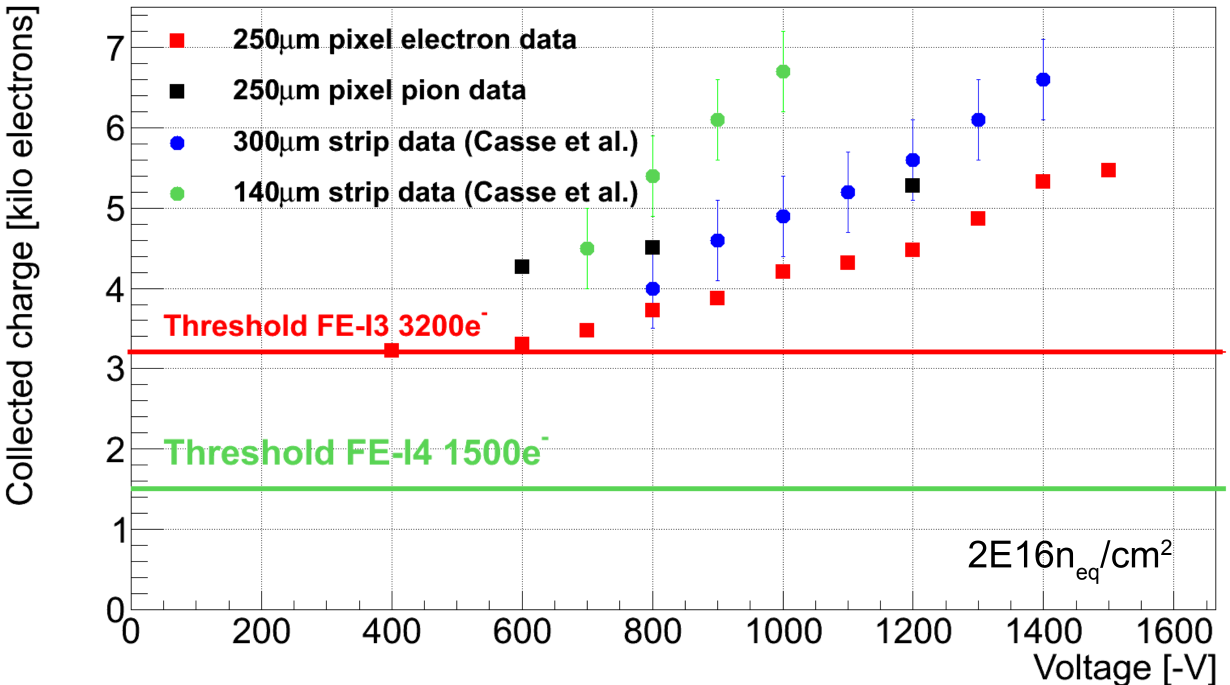


thanks to the PPS and IBL test beam groups

radiation hardness

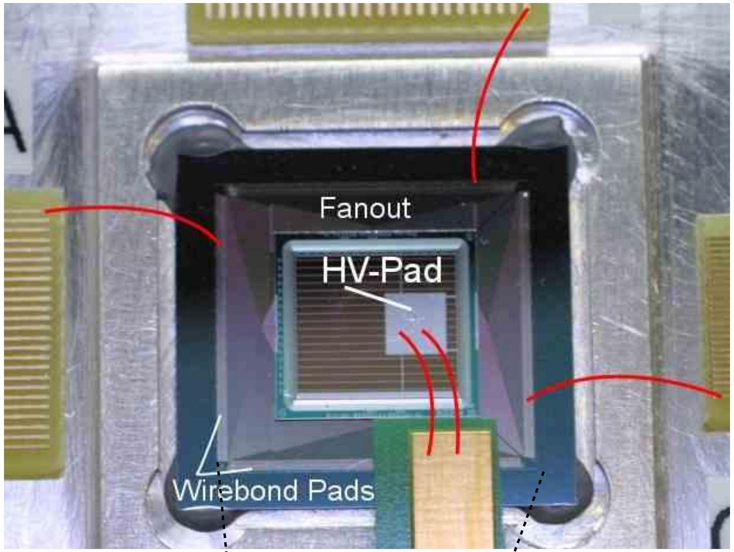
- required collected charges & hit efficiencies can be obtained by increasing the sensor bias voltage
- phase II fluence ($2E16n_{eq}/cm^2$)
  - hit efficiency >97%
  - collected charge well above threshold

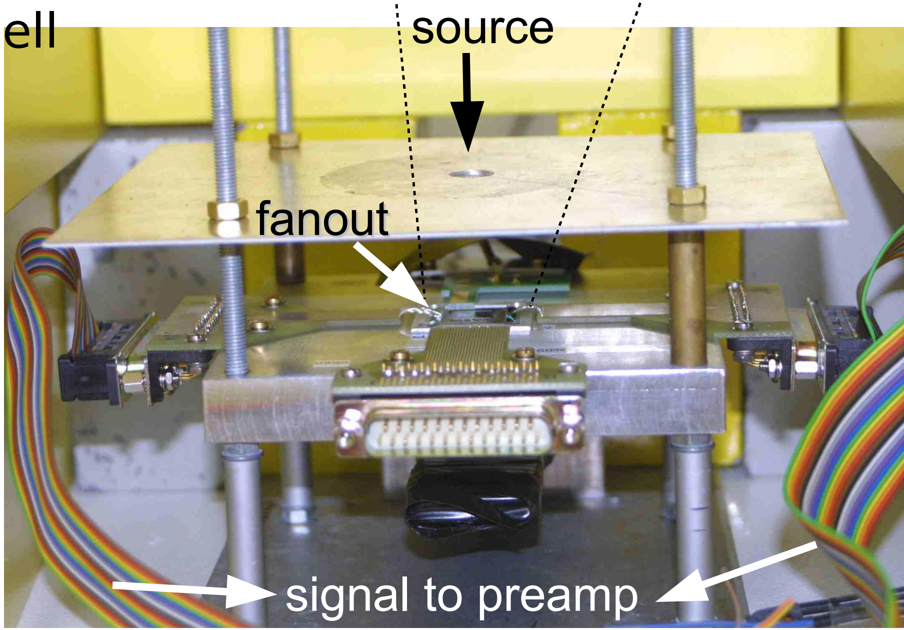


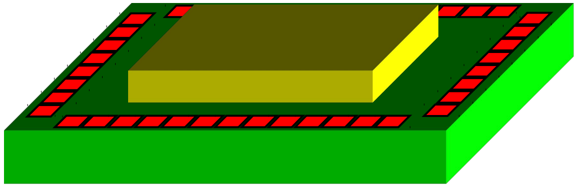


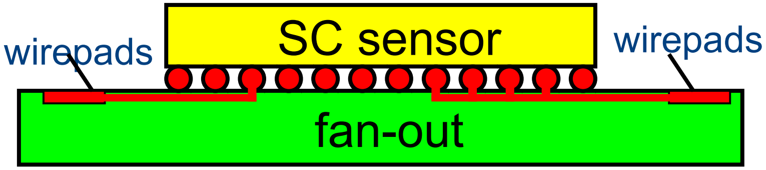
Fanout measurements

- passive fanout is an alternative to contact an FE-I3 sensor in lab
  - to exclude radiation effects of readout chip
  - no option for detector operation but for basic sensor radiation studies
- contacted via wire bond pads
- readout via pre-amplifier
- setup in an EM shielded box
- signal of single pixels possible as well as of a 'pad structure', i.e. several pixels shortened together



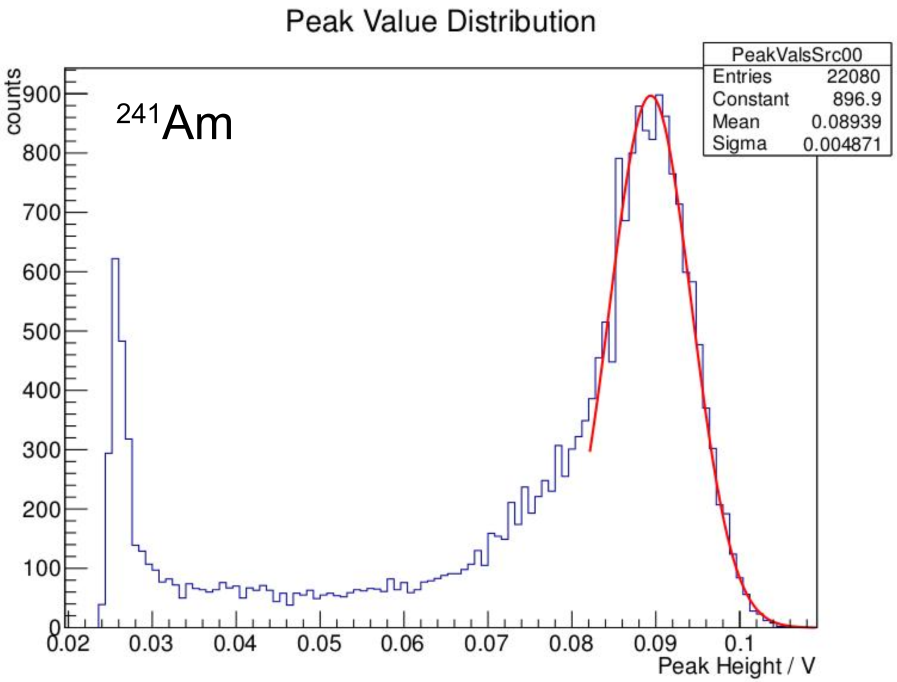


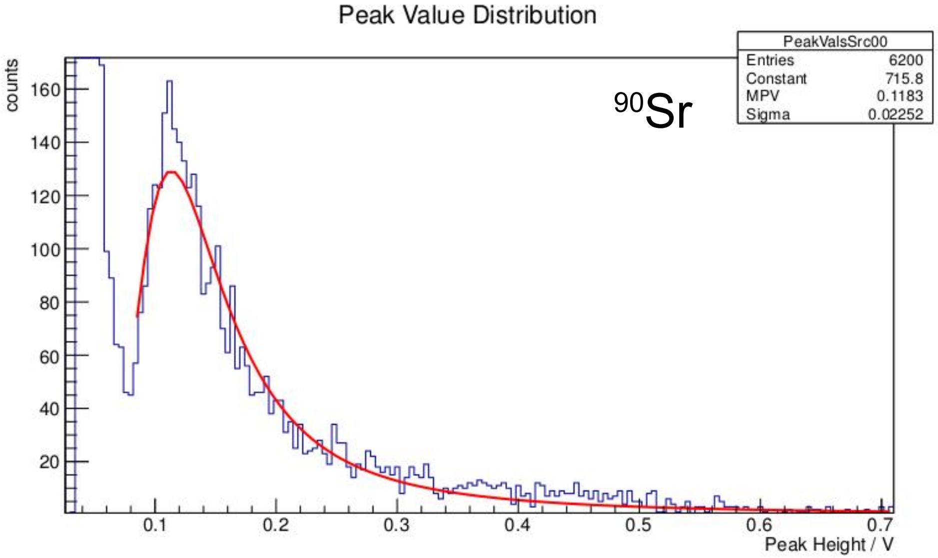




Fanout measurements

- initial source scans done
    - ^{241}Am & ^{90}Sr
    - 60 pixel shortened
    - proof of principle is shown
- signal of single pixel contacting shows too much noise
    - only self trigger mode
    - expect better results with PM trigger, shaper to optimize signal
    - other pad sizes available
- several fanout structures are currently sent to neutron irradiation (Ljubljana)
    - fluences beyond HL-LHC
    - up to 5E16n_{eq}/cm^2

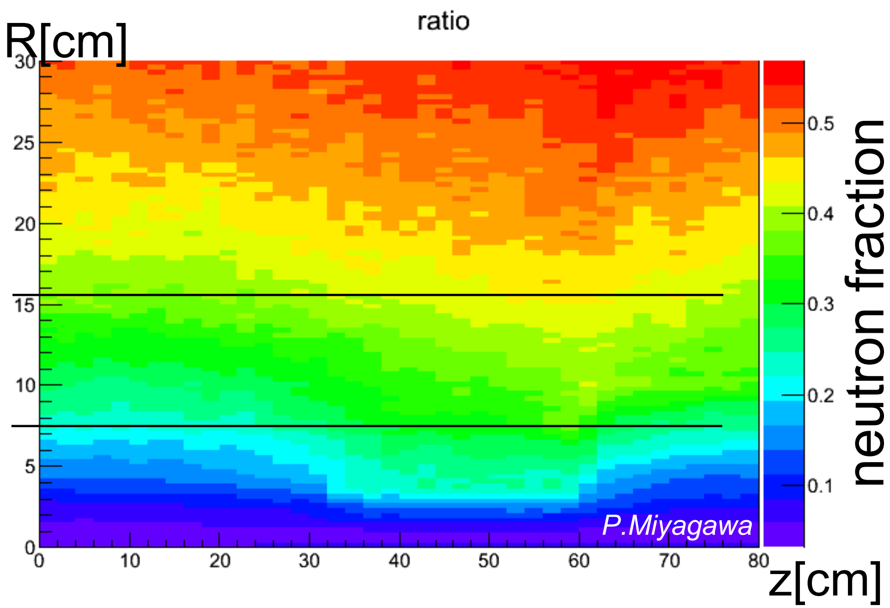


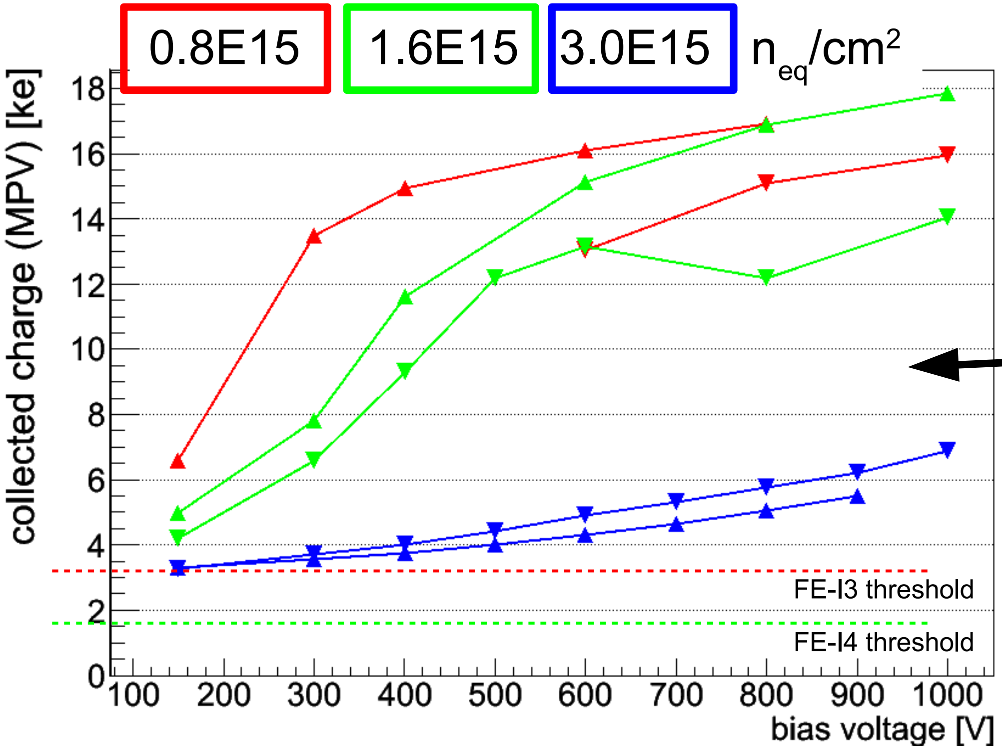


Magnetic Czochralski bulk sensors

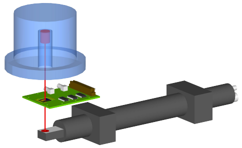
- The medium layers of ATLAS upgrade phase II will be exposed to a mixed radiation of ionising and non-ionising particles
- MCz material is expected to have a better performance for this scenario than standard DOFZ

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

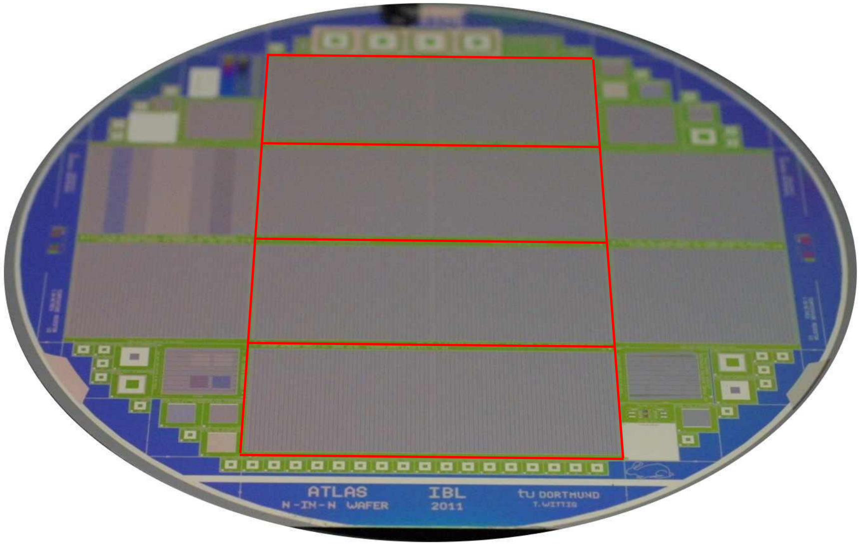




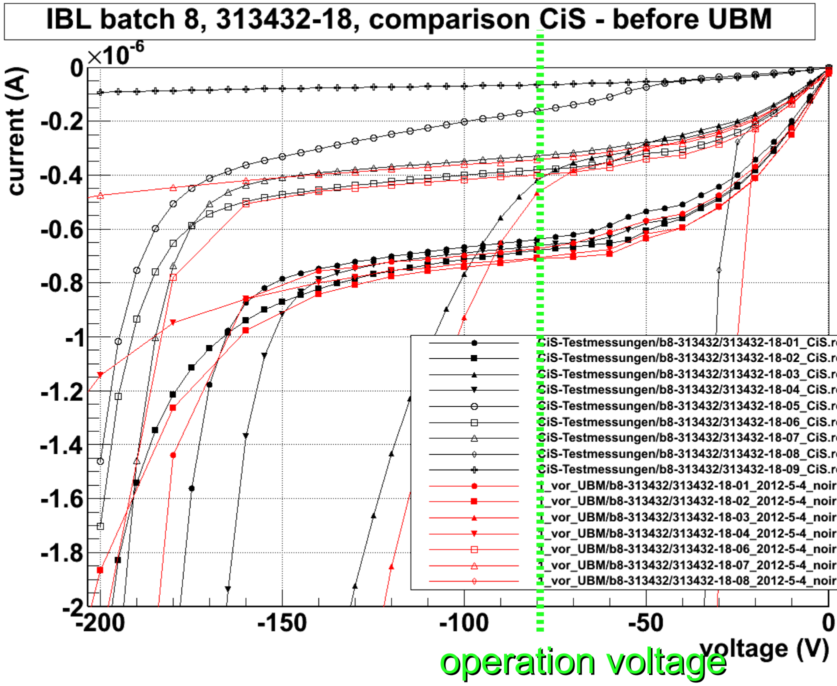
- first (proton) irradiation done at CERN PS
- 3 fluences
- successfully operated in last test beam at CERN
- systematic measurements done in lab with ^{90}SR source
- currently in Ljubljana for neutron irradiation

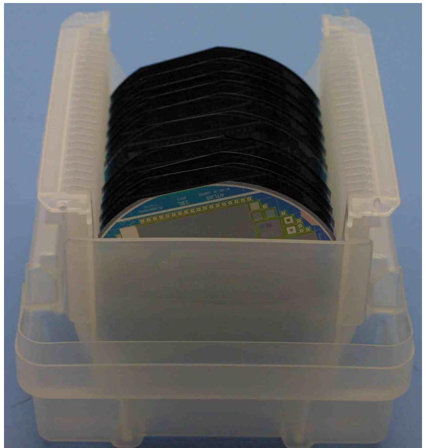


IBL sensor production



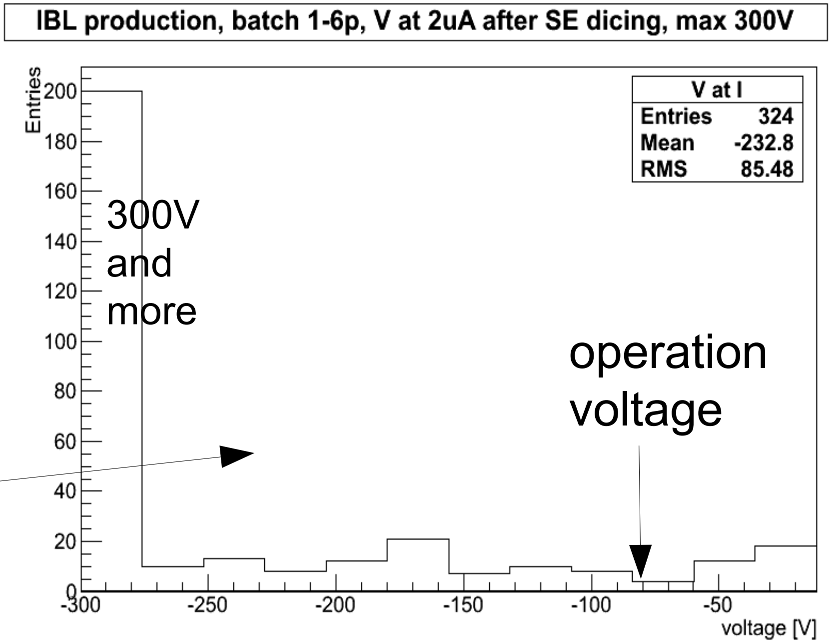
- planar n-in-n sensors are designated sensors for the IBL
  - 2x1 DoubleChipSensor (DCS): one sensor, two FE-I4 chips
  - reduced bulk thickness (200um)
- sensor production is finished
- nine batches with 150 4'' wafers (CiS, Erfurt)
- 4 DCS per wafer
- operation voltage 80V
- 536 of 600 good DCS, 89% yield



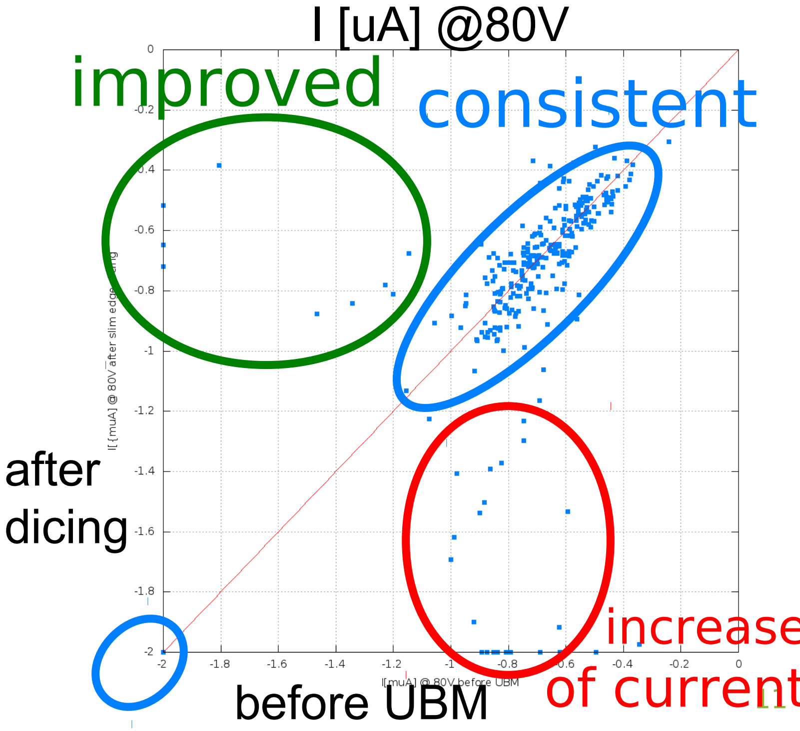


IBL sensor production

- most wafers already got UnderBumpMetal post-processing and were diced (IZM, Berlin)
- 'breakdown voltage': V @ 2uA
    - most sensors have higher voltages than V_{op} after all process steps, O(88%)

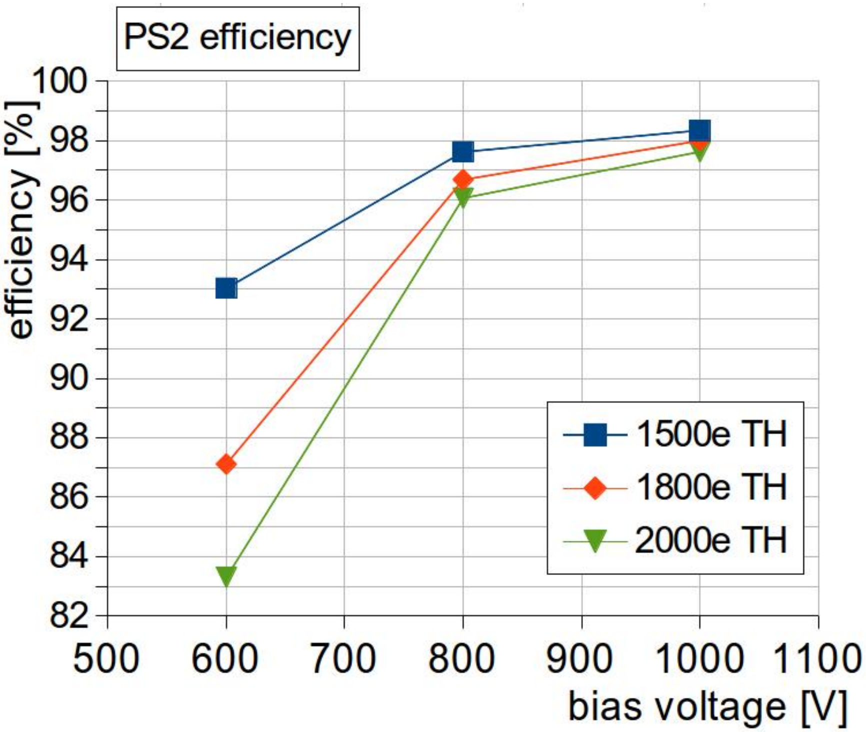


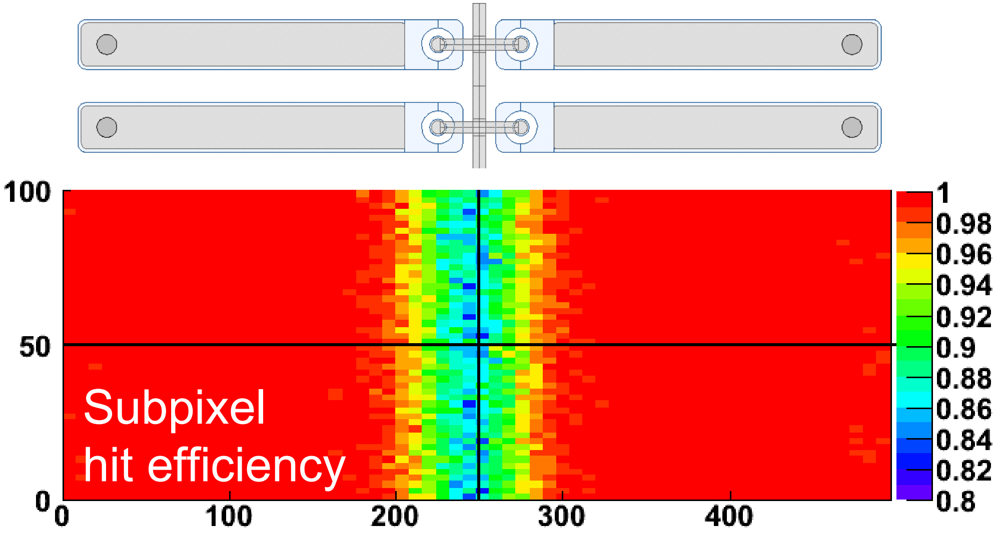
- comparison of cross-check measurements before UBM and after dicing
- most sensors are consistent after dicing
- overall UBM+dicing yield for MultiChipSensors: 95%



n-in-n IBL sensors

- FE-I4 Assemblies were investigated
- before irradiation no problems
- after proton irradiation to IBL fluence ($5E15n_{eq}/cm^2$, CERN-PS)
    - systematic measurements in test beam (DESY) depending on threshold and bias voltage
    - higher hit efficiency
        - with increasing voltage
        - with decreasing threshold
        - up to ~98%
    - main efficiency loss under bias rail



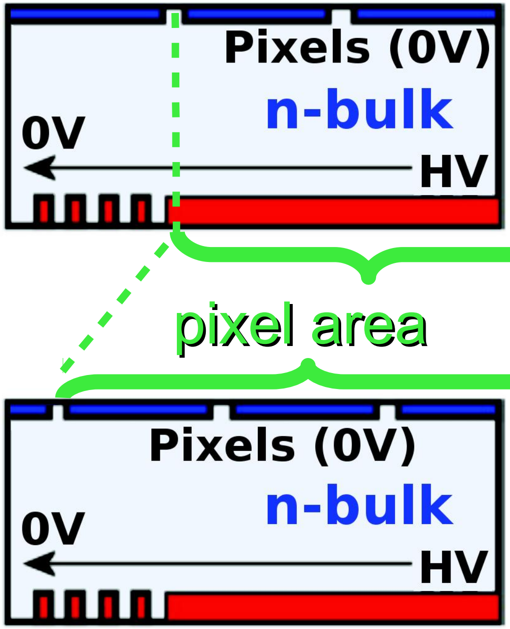


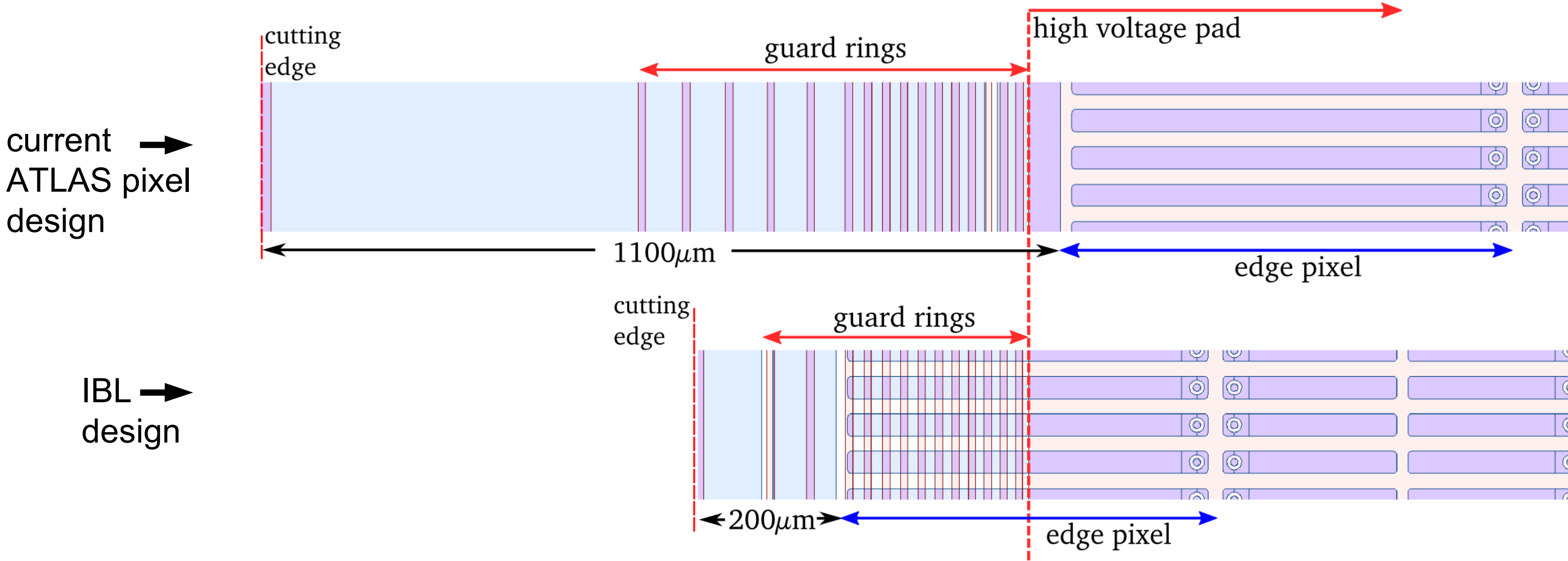
Subpixel hit efficiency

matching criteria:
real hit if distance of track < 1.5 x pixel length/width

IBL sensor edge design

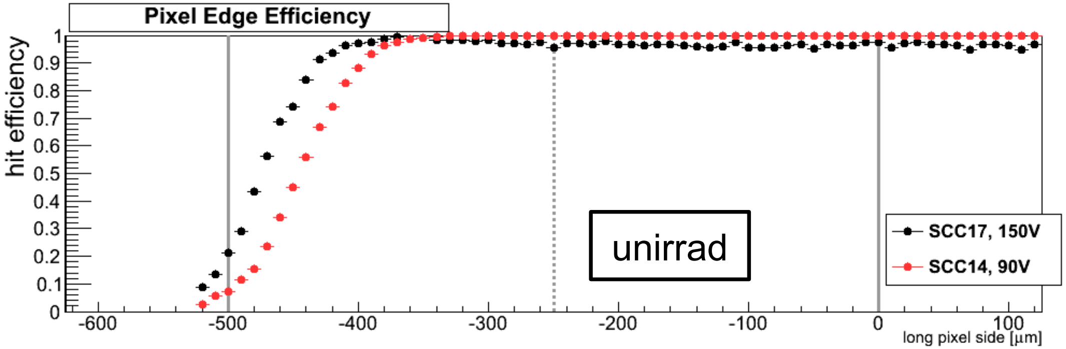
- reduced inactive edge by extended pixel area
  - less guard rings
  - less safety margin
  - pixel opposite guard rings



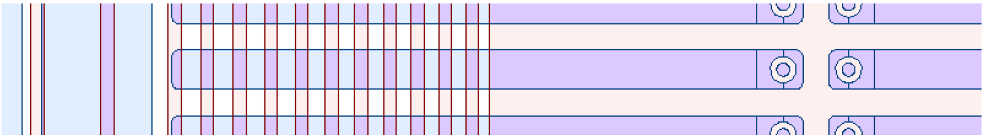


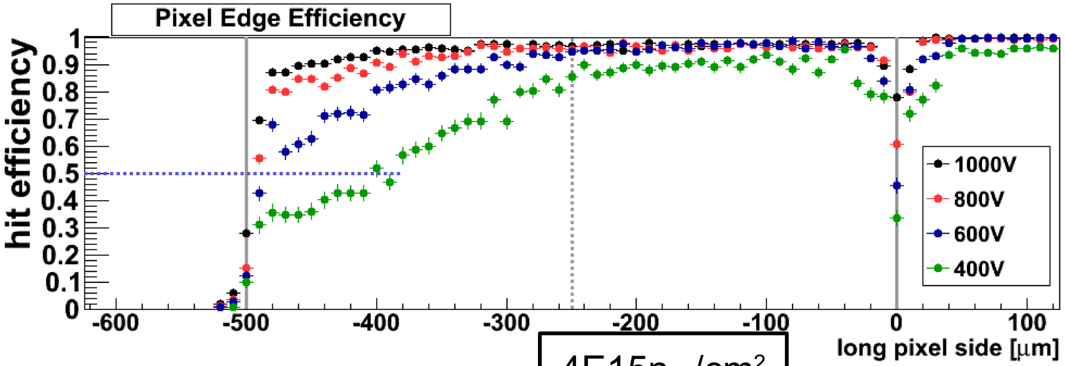
edge efficiency of IBL sensors

- FE-I4 Assemblies were investigated in test beam to study edge efficiency performance
- before and after irradiation (4E15n_{eq}/cm^2) clear dependency on bias voltage visible
- reduction of inactive edge down to ~200um is possible
    - limit is basically reached
    - a different approach has to be investigated to cope with HL-LHC constraints

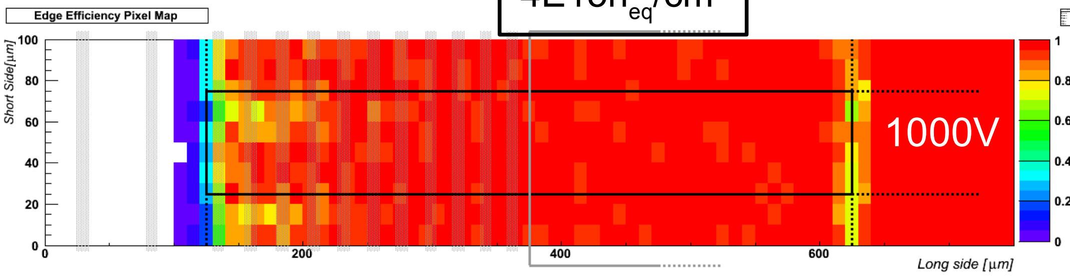


unirrad





4E15n_{eq}/cm^2

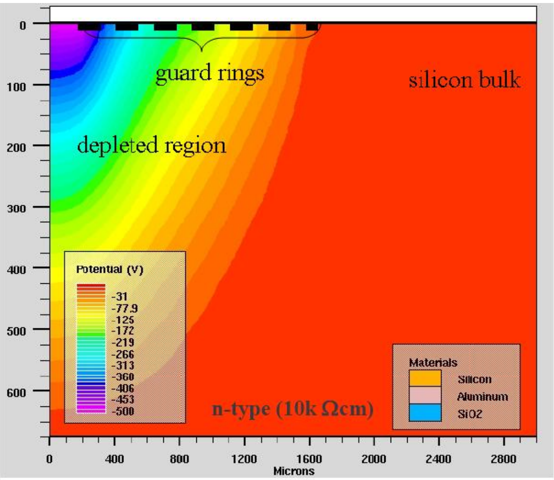


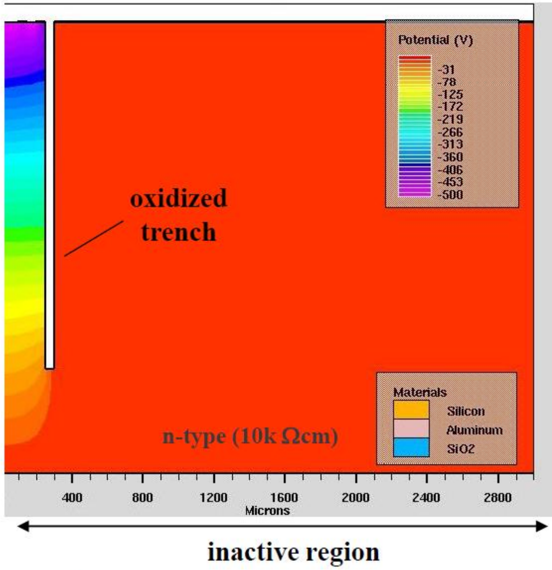
1000V

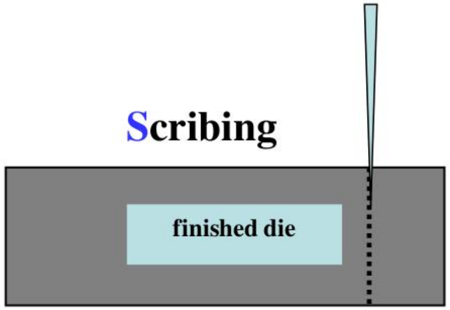
Scott Ely, Vitaliy Fadeyev, Hartmut Sadrozinski
- University of California, Santa Cruz
Marc Christophersen, Bernard F. Philips
- Naval Research Lab

Scribe, Cleave and Passivate (SCP) treatment

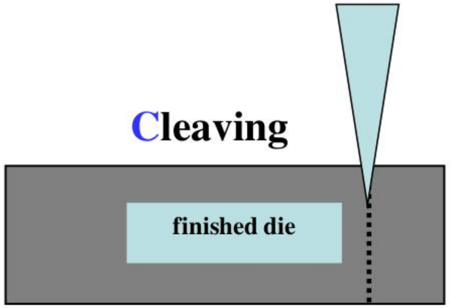
- post processing
  - applicable for all sensor types
  - scribing and cleaving afterwards next to the active area
    - <100> bulk orientation necessary to enable parallel and orthogonal cuts
  - post treatment to passivate the edge







- Laser
- XeF_2 etching
- DRIE etching



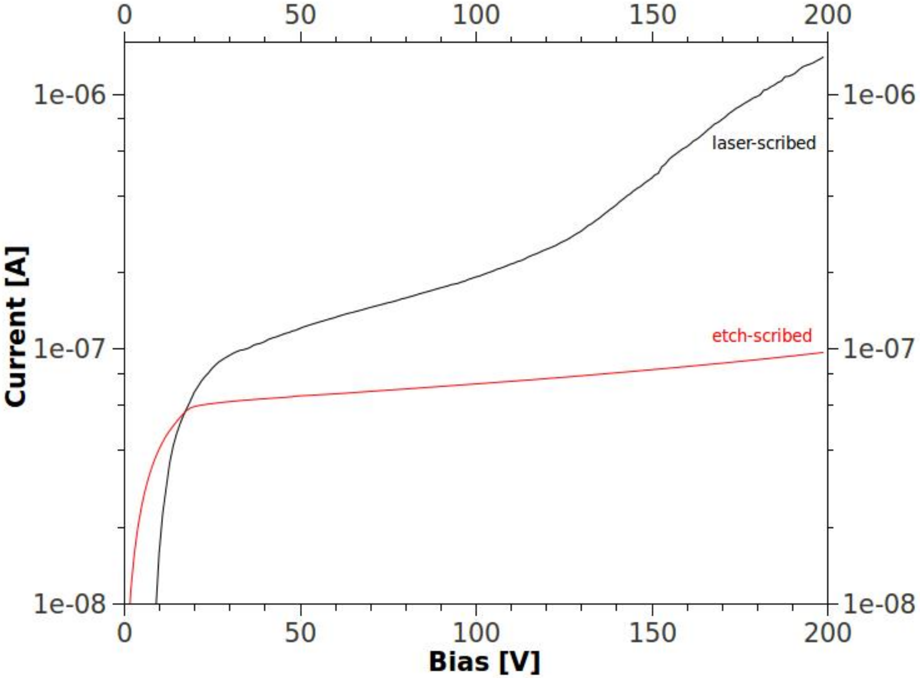
- Tweezers
- automated cleaving

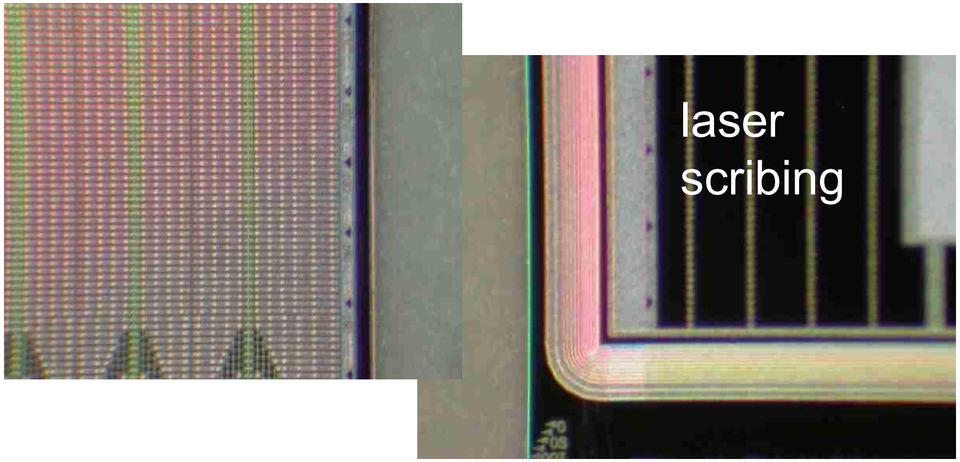
- PECVD Oxide
- PECVD Nitride

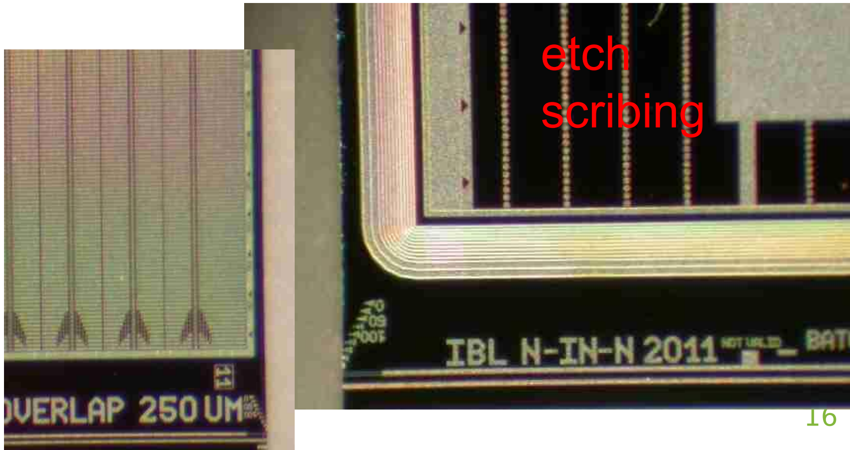
or ALD oxide, nanostack

SCP - scribing outside guard rings comparison of laser & etch scribe

- Laser scribing induces large defect density through silicon recast layer and can thus cause an increase of the leakage current
- repair damage with a XeF_2 sidewall etch afterwards
- better results by replacing laser completely by XeF_2 scribe

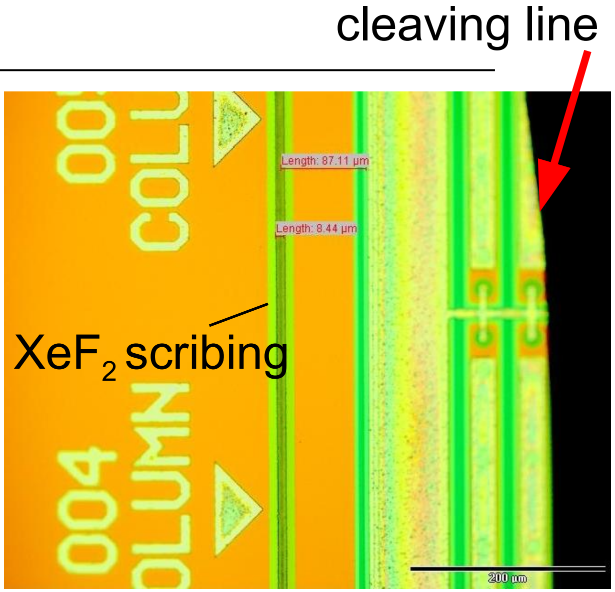


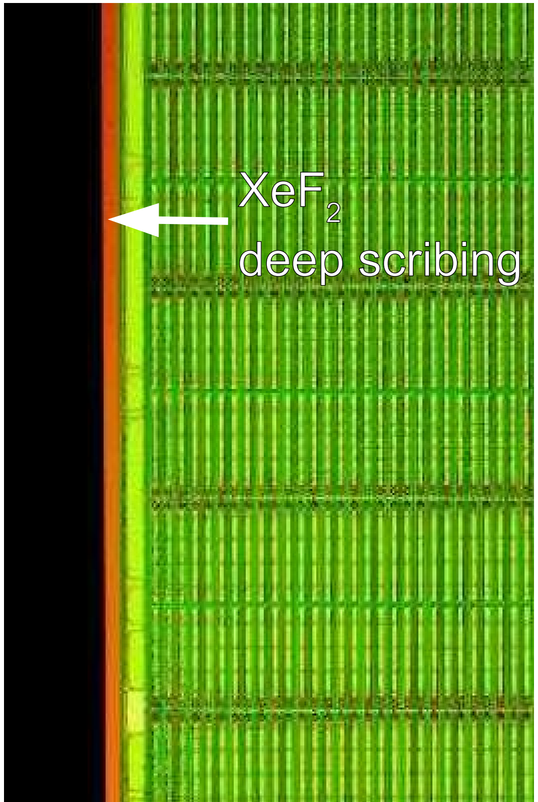




SCP - etch scribing into guard rings

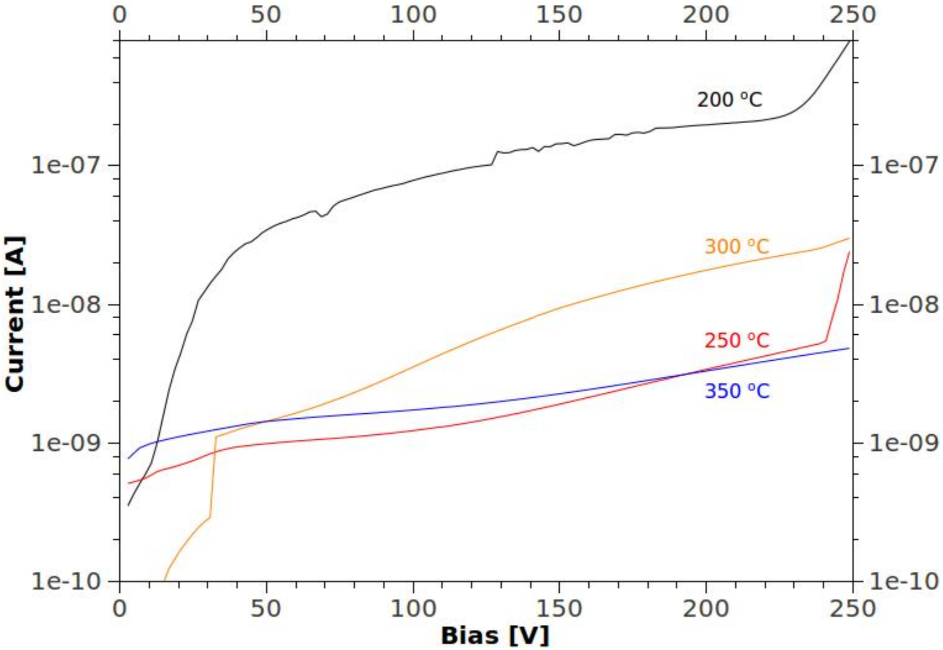
- n-type sensors scribed ~100um close to the HV pad
- challenge because cleaving line didn't follow etch scribing line despite <100> bulk
- have to use deeper etch scribing to ensure that cleaving line follows scribing line
- still working on variations to optimise this method
  - more reliable
  - less device dependent

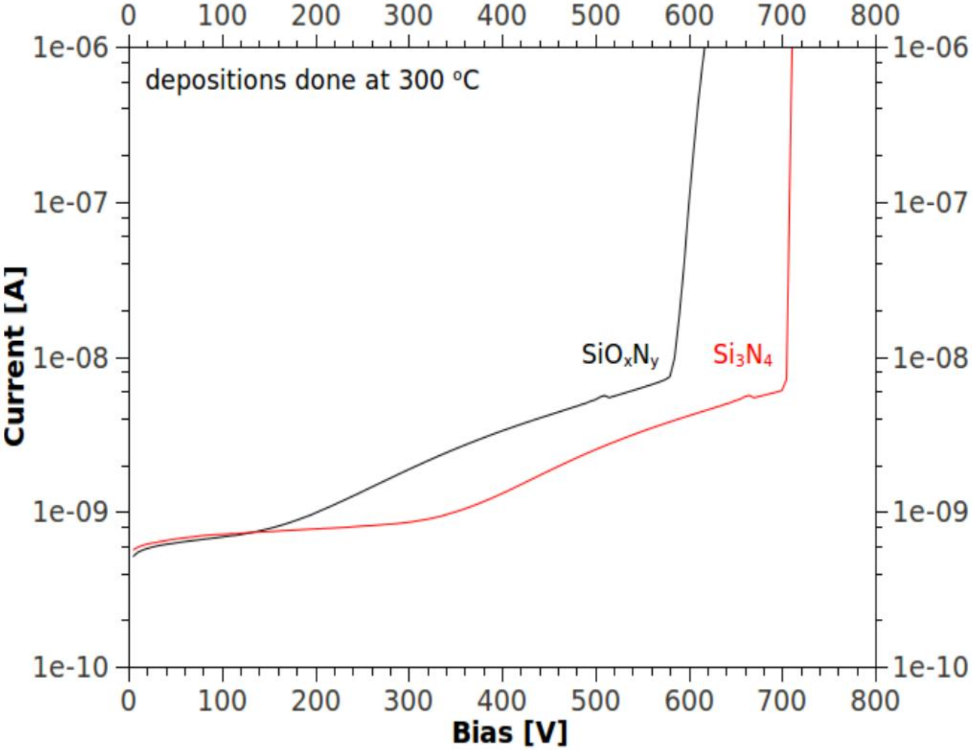




SCP - results of passivation with n-type diodes

- diodes with slim edge of ~50-100um
- Si Oxide PECVD
    - performance dependent on the temperature
    - temperature range still safe for the devices
- Si Nitride PECVD
    - much improved leakage current and break down voltage

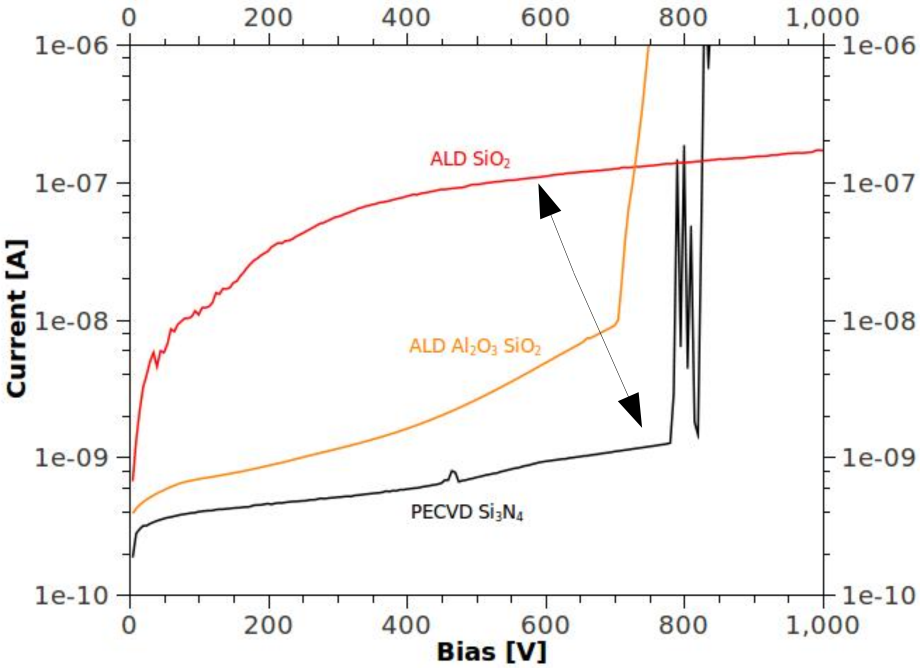


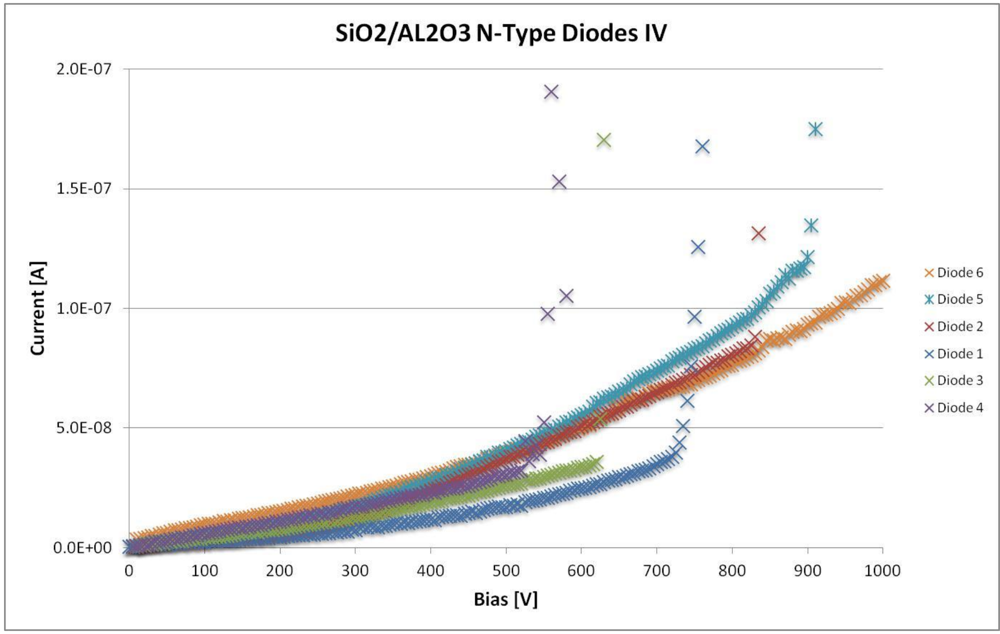


SCP - results of passivation with n-type diodes

- diodes with slim edge of ~50-100um
- PECVD process only possible for small size samples due to limited height in chamber
- for larger samples need alternative: Atomic Layer Deposition (ALD)
- SiO_2 ALD is worse than Si_3N_4 PECVD
- a 'nanostack' of SiO_2 and Al_2O_3 ALD works well

see poster of V. Fadeyev



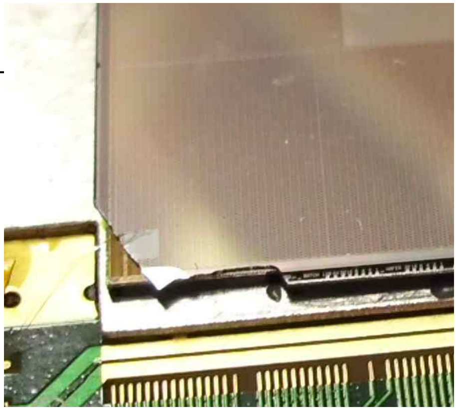


Conclusions & Outlook

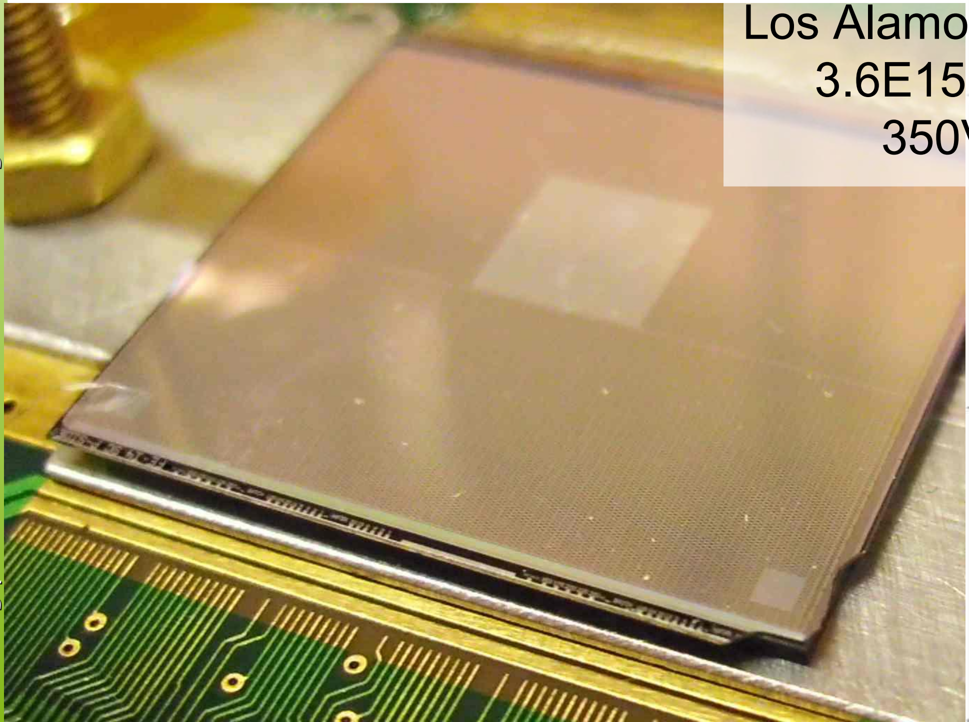
- planar n$^+$-in-n silicon pixel sensors are considered sensors for all upgrade phases of ATLAS
    - have been selected as IBL sensors
    - promising candidates for high-lumi-LHC scenarios
- radiation hardness is demonstrated
    - good signal-threshold ratio up to phase II conditions
- investigations of MCz bulk sensors are currently ongoing
- progress of slim edge investigations
    - IBL sensors show good behaviour
        - quality control
        - edge efficiency in test beam
    - initial SCP tests done, process optimisation ongoing

Backup

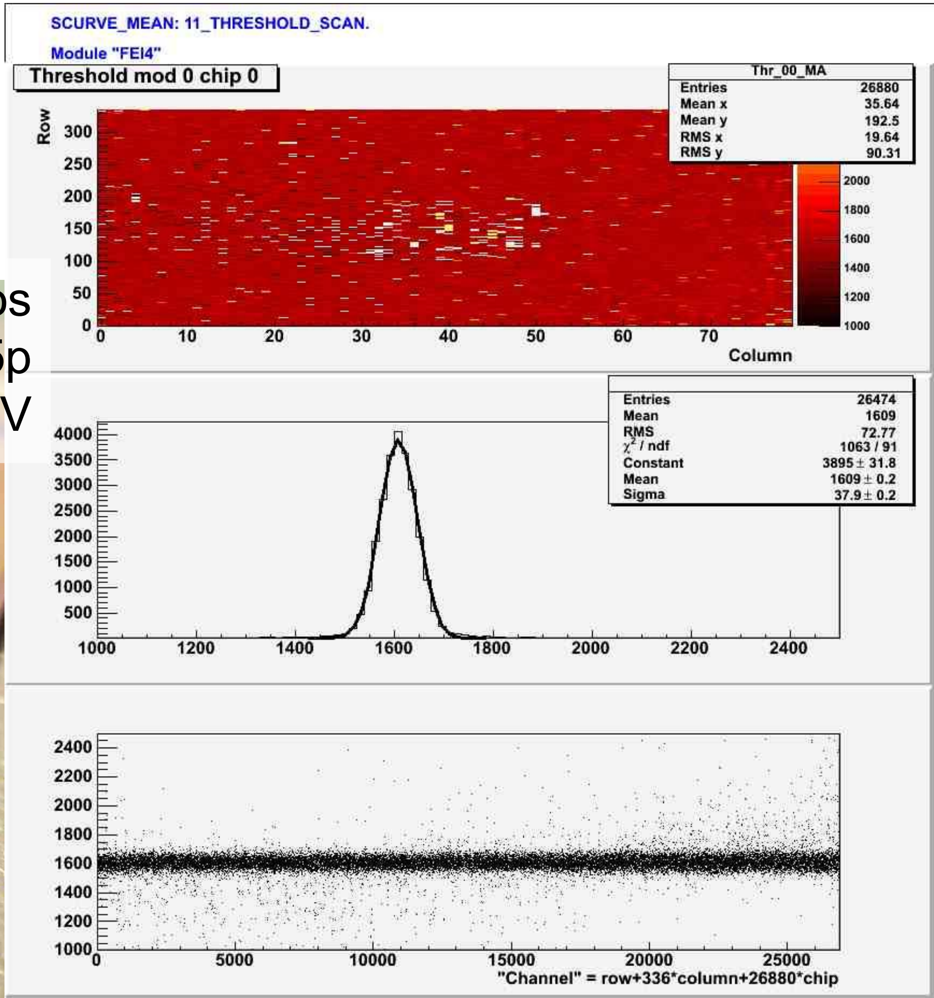
n-in-n IBL sensors



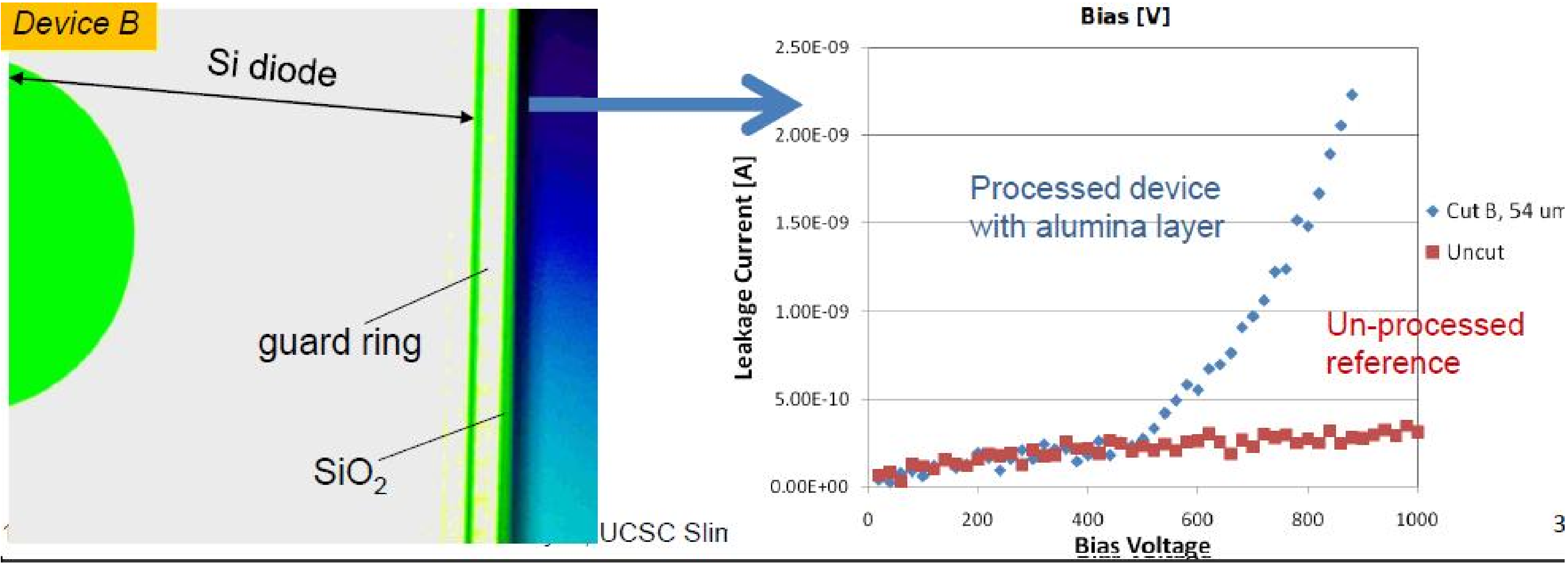
- proton irradiated at Los Alamos
  - 3.6E15 n_{eq}/cm^2
- even despite severe mechanical damages the sensors still can be tuned to standard threshold



Los Alamos
3.6E15p
350V



Slim Edge post processing, second device

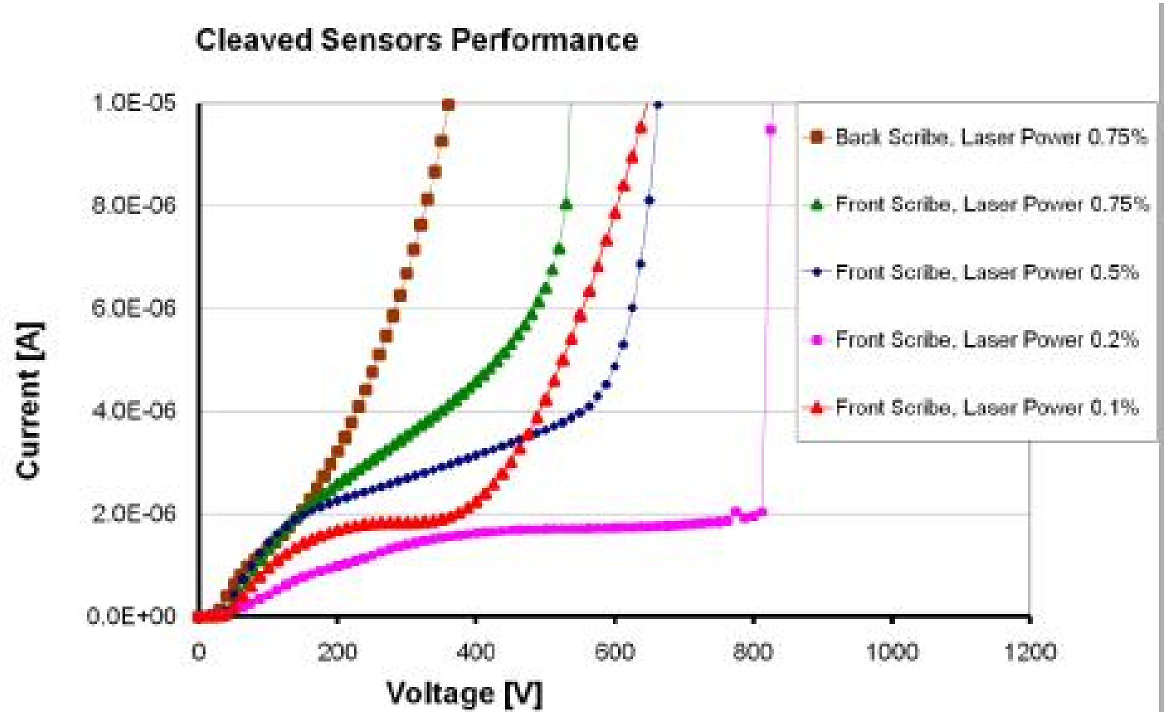


Processed device with alumina layer

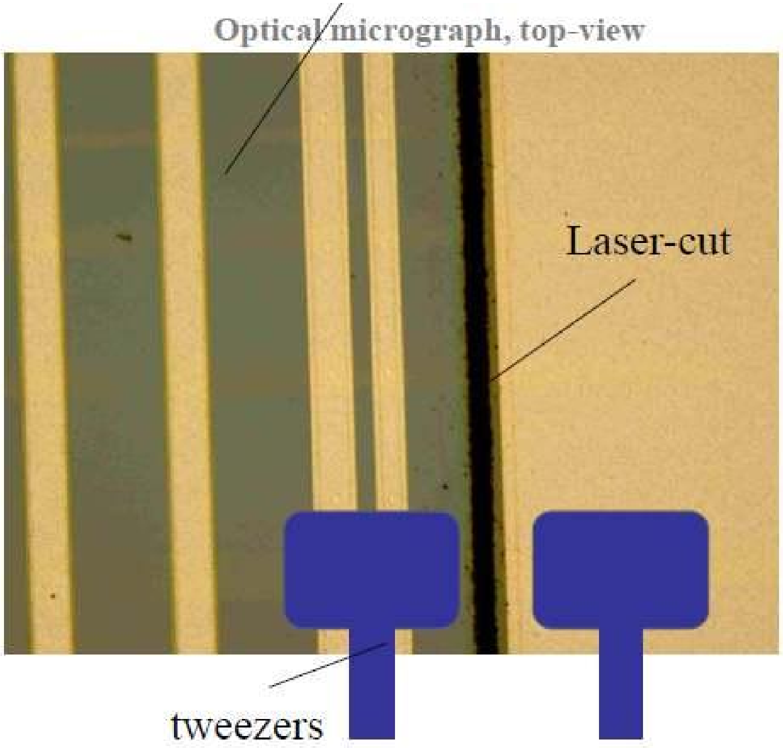
Un-processed reference

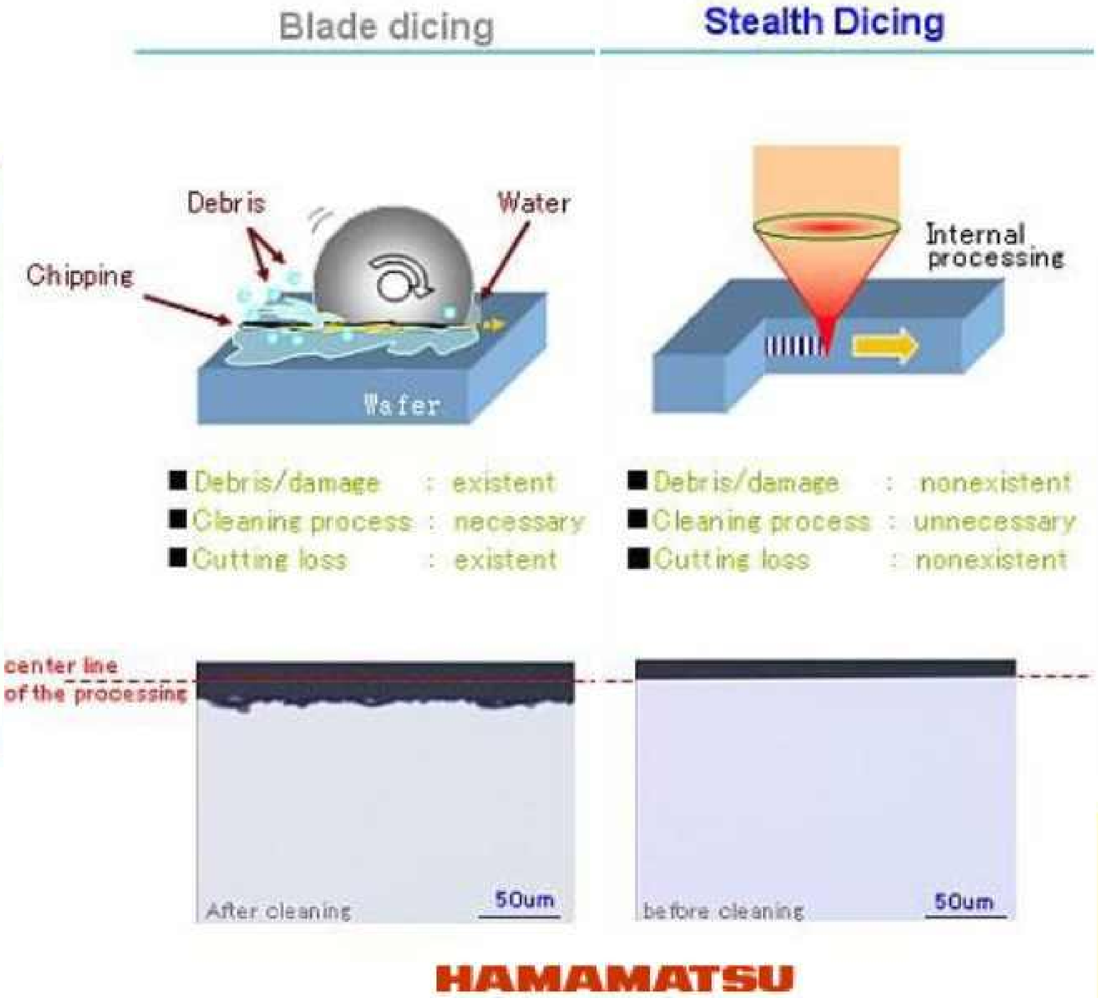
Slim Edge post processing, N-bulk sensors

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



Laser Scribing and Cleaving





Blade dicing		Stealth Dicing	
Debris/damage	existent	Debris/damage	nonexistent
Cleaning process	necessary	Cleaning process	unnecessary
Cutting loss	existent	Cutting loss	nonexistent