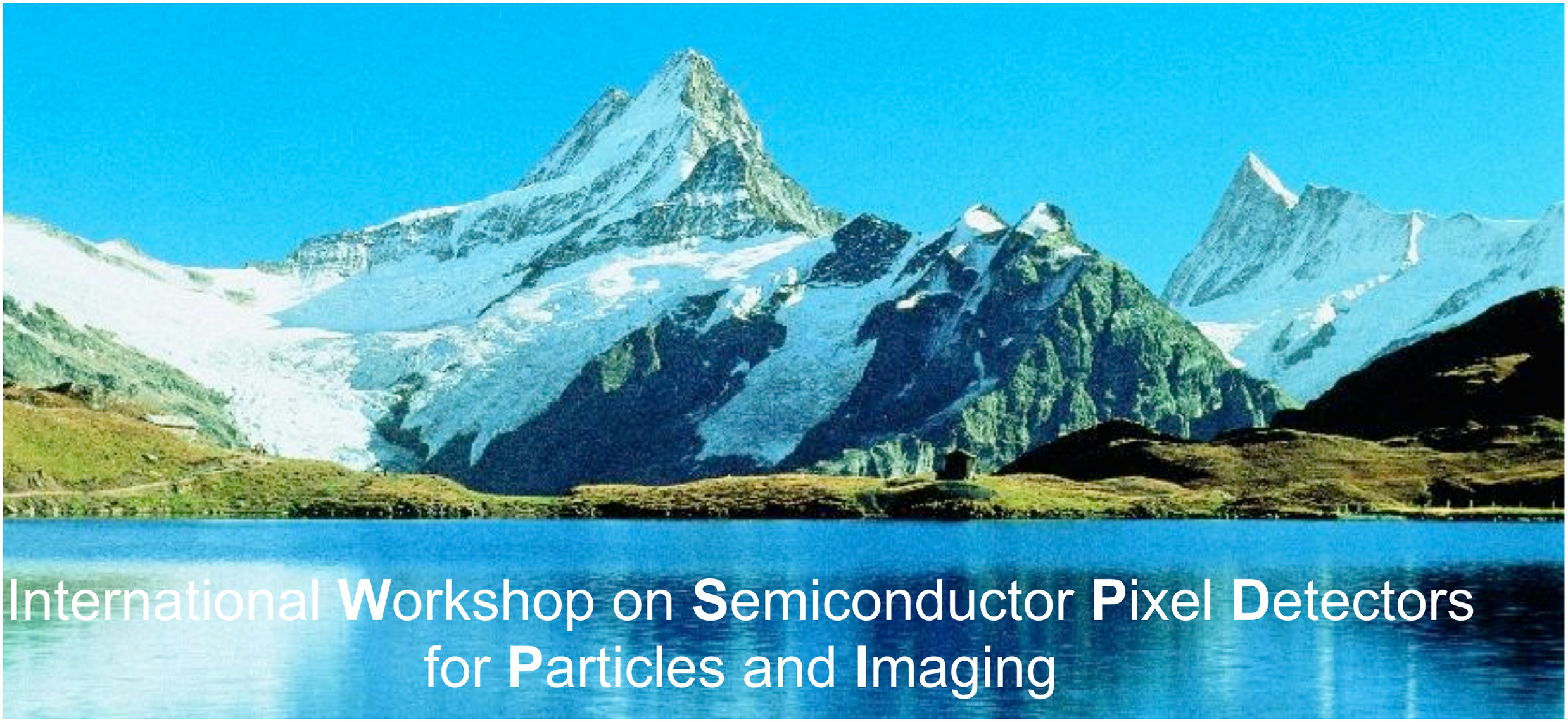
3D silicon sensors from different manufacturers for pixel upgrades at the LHC



Andrea Micelli, Università degli studi di Udine/INFN
on behalf of the ATLAS 3D Pixel R&D Collaboration

Outline

- Introduction
  - ATLAS 3D Pixel R&D Collaboration
  - Motivation
- 3D Sensors Design and Technology
- Test Beam
  - Experimental setup
  - Test Beam Studies
    - Clusters Charge
    - Charge Sharing
    - Tracking Efficiency
    - Active Edge
- Lab Measurements
  - Radiation hardness
- Summary and Outlook

ATLAS 3D Collaboration

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- 18 institutions

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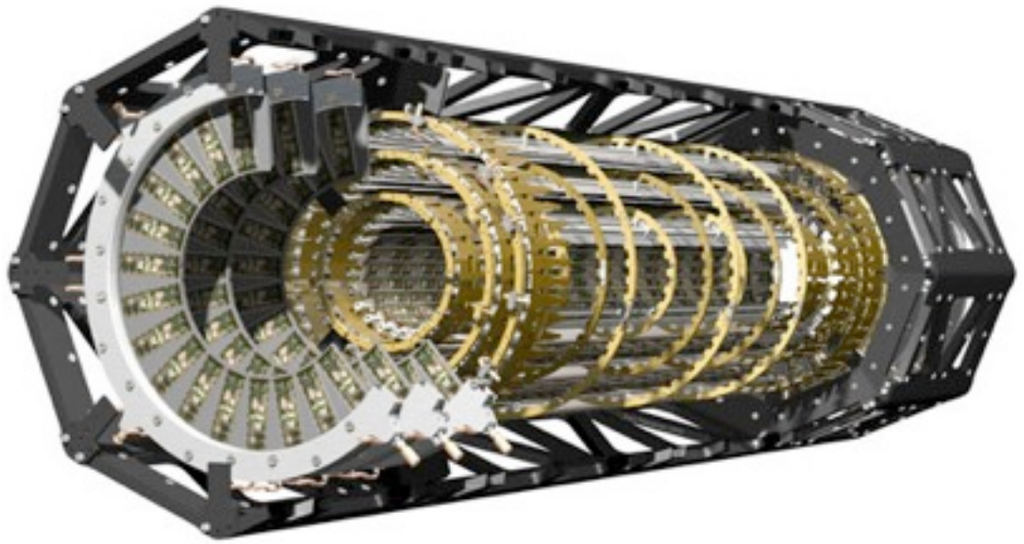
- 4 (+1) processing facilities

CNM (Spain), FBK (Italy), SINTEF (Norway), Stanford (USA) [+VTT (Finland)]

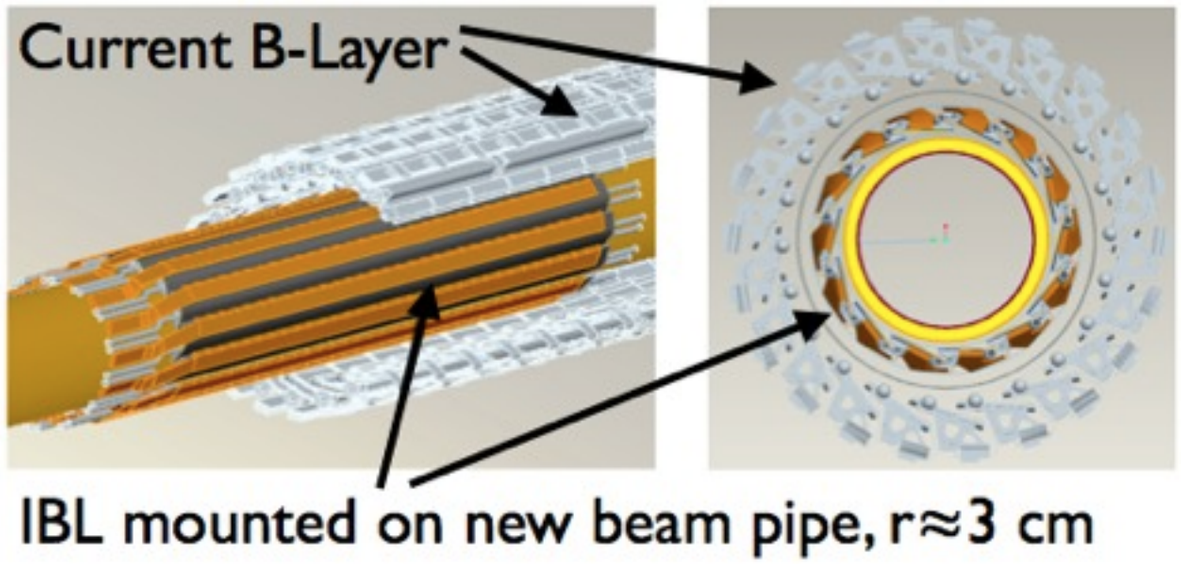
Motivation

- Pixel detectors: technology choice in high-energy physics for innermost tracking and vertexing



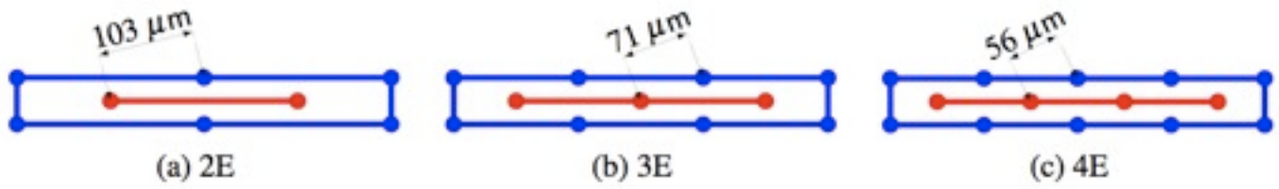
- Atlas pixel detector
  - LHC p-p collisions at 14TeV (L~10^{34} $cm^{-2}s^{-1}$)
  - B-layer at 5 cm from IP (2T magnetic field)
  - designed for fluence of 10^{15} $n_{eq.}cm^{-2}$
  - technology: planar sensor

- Why a new Insertable B-Layer (IBL):
  - B-Layer suffers highest radiation damage
  - performance significantly degraded
  - add new layer:
    - closer to Interaction Point, smaller space, higher radiation...
    - 3 technologies under study: Diamond, new Planar, 3D

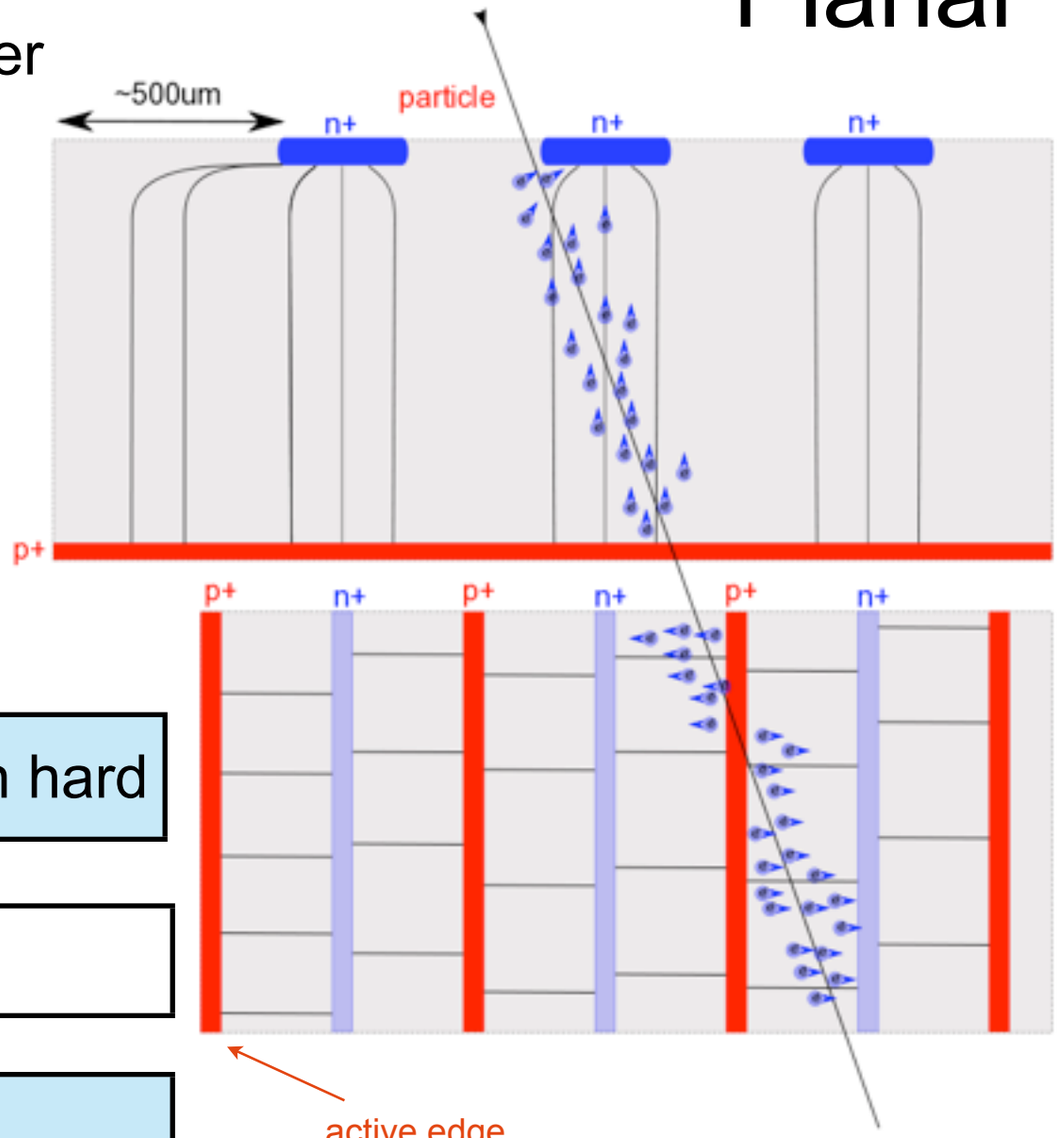


3D Sensors Design and Technology

- Proposed by Sherwood Parker et al.: NIM A 395 (1997) 328
  - Electrodes (both types) processed inside the wafer bulk - perpendicular to surface
  - Different cell configuration: 2E, 3E or 4E



Planar



3D

Advantages:

3D Features:

- high electric field
- short collection path
- sensor edge is an electrode

→ high efficiency / radiation hard

→ lower depletion voltage

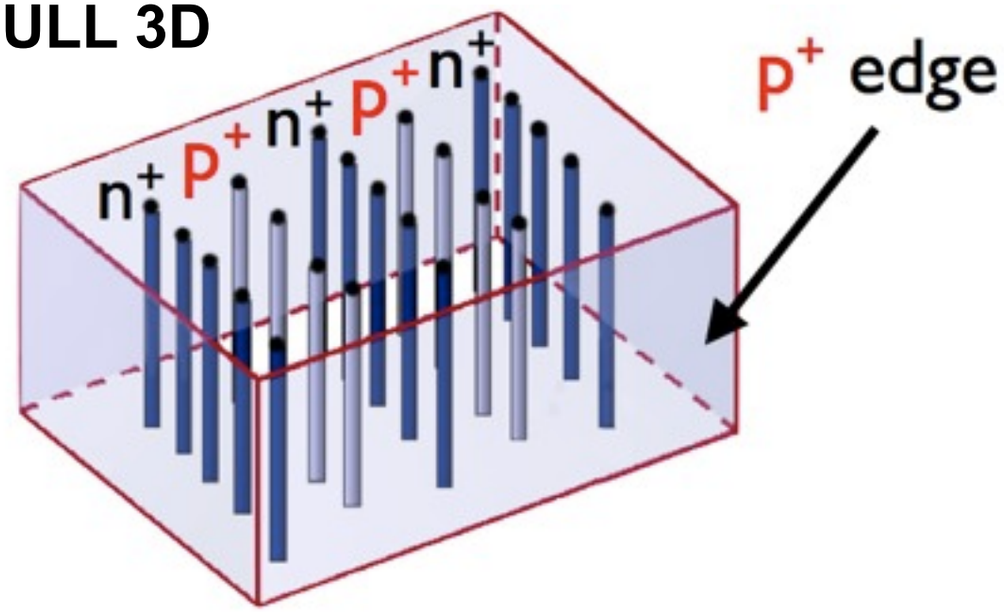
→ faster charge collection

→ active edge ~4μm

3D Sensors Design and Technology

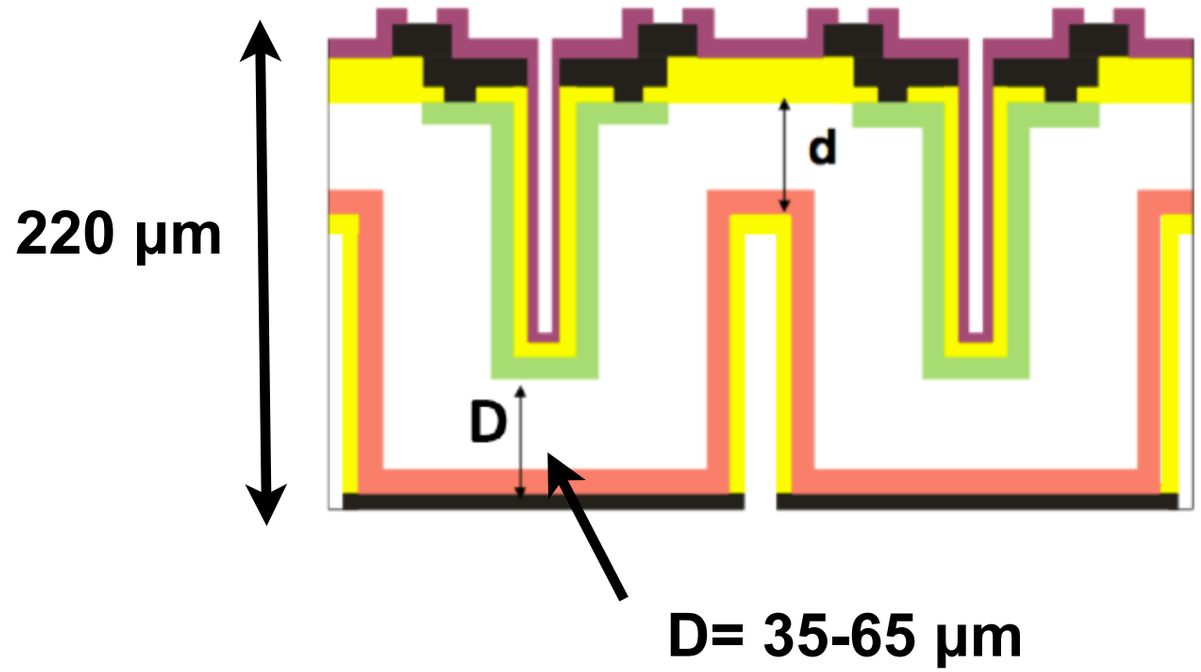
- Two designs under study - similar behavior and performance

FULL 3D



- agreed “baseline” sensor
- produced by Stanford/SINTEF (5th gen.)
- to-be-produced by FBK and CNM
- same dimensions and read-out:
  - 160×18 pixels, each 50×400 μm²
  - bump-bonded to ATLAS FE chip
    - ➡ time-over-threshold (ToT) signal
    - ➡ 60 ToT @ 20 ke⁻, threshold = 3200 e⁻

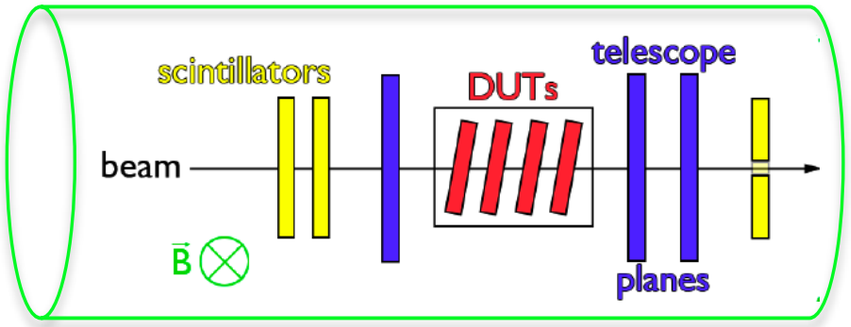
Modified 3D sensors



- partially overlapping electrodes
- simplified wafer handling
- double-sided double-type columns
- produced by FBK and CNM

Test Beam Setups

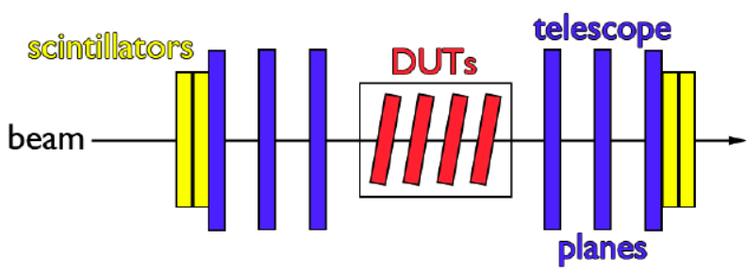
Bonn ATLAS Telescope - Oct '09



- 180 GeV pions from CERN - SPS
- 3 planes: two-sided SI micro-strips (50 µm pitch)
- Trigger: two scintillators (+veto)
- Morpurgo dipole magnet (B~1.57 T)
- DUTs: STA-3E, FBK-3E, Atlas Planar (as reference)

Purpose:
sensors performance in B-field at different tilted angles (-30° to 30°):
➡ tracks efficiency, charge sharing etc.

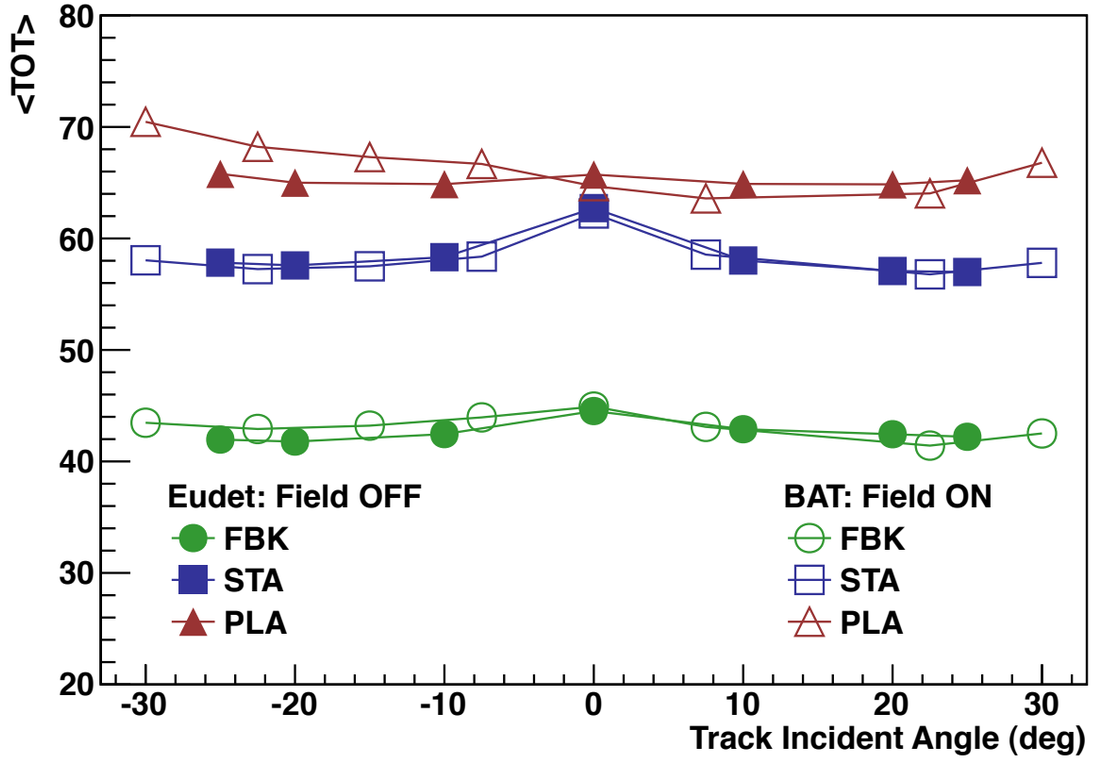
EU Detector Telescope Oct, Nov '09 - June '10

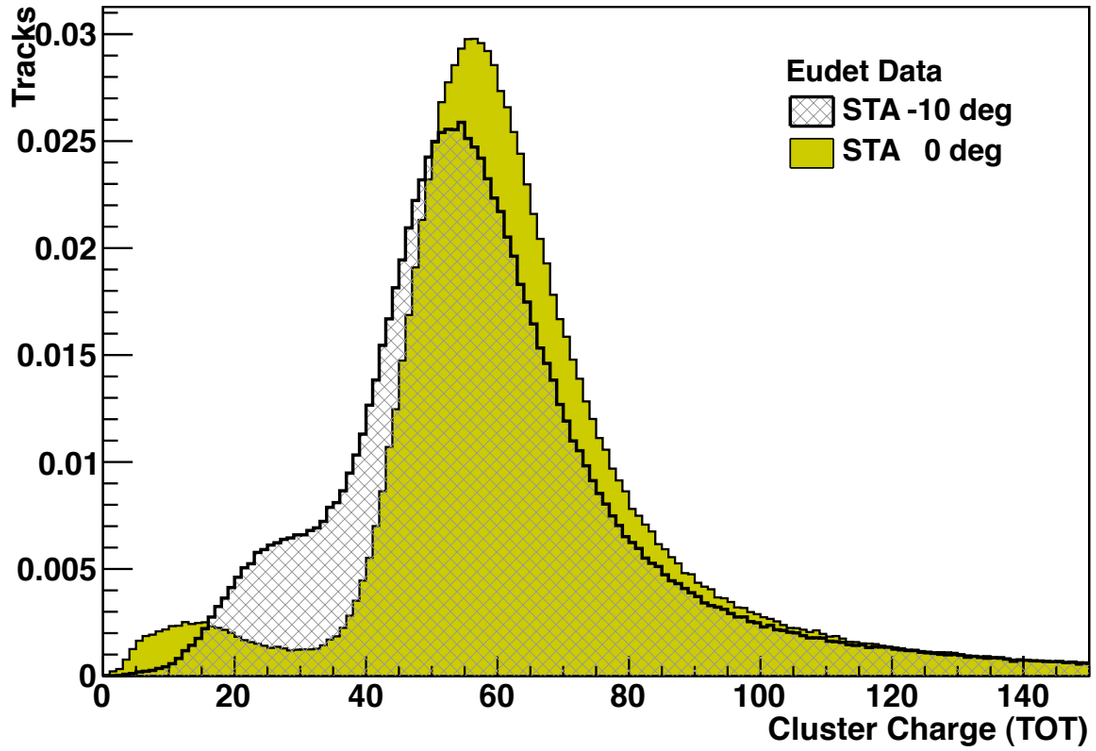


- 120 GeV pions from CERN - SPS
- 6 planes: 660k Si pixels (18.4 µm pitch)
- Trigger: four scintillators
- DUTs: STA-3E, SIN, FBK-3E (also p- and n-irradiated in June), Atlas planar (as reference)

Purpose:
sensors performance after irradiation at different tilted angles (-25° to 25°):
➡ tracks efficiency, charge sharing electrode efficiency etc.

Test Beam Studies: Cluster Charge



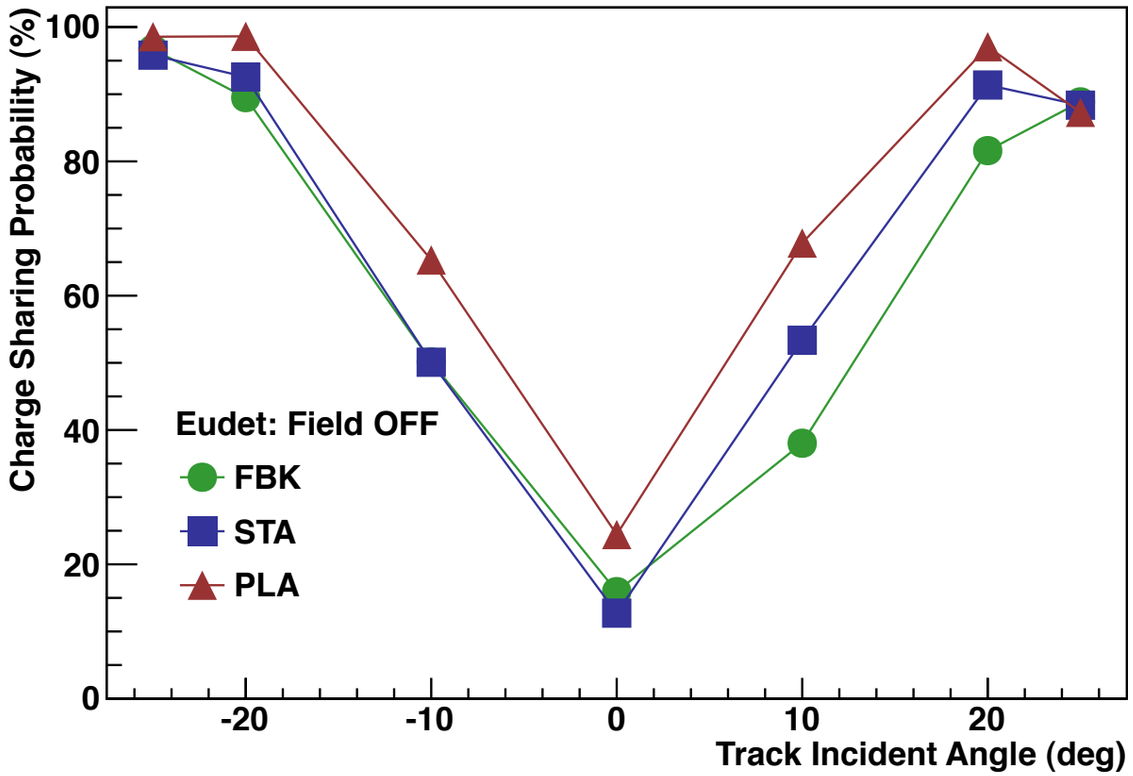


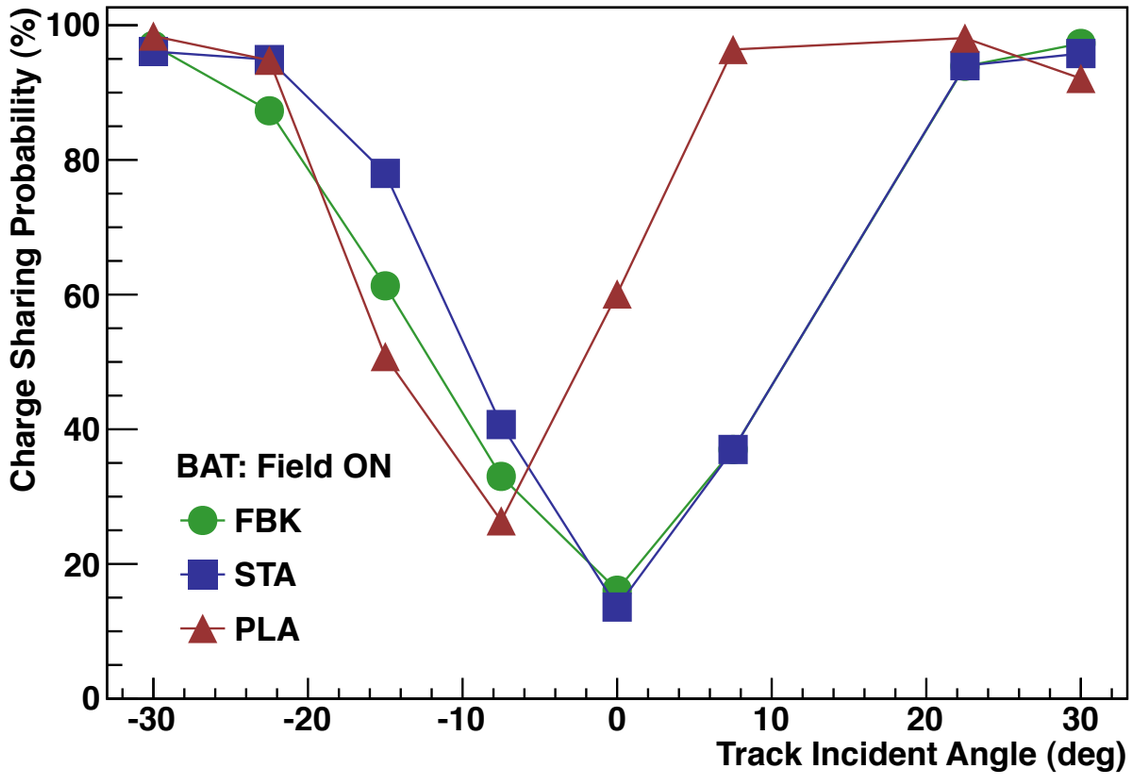
Cluster Charge:

Preliminary results

- ATLAS planar for reference
- charge insensitive to B-field, but it depends on tilt angles
- at 0° cluster charge (TOT) is maximum but charge sharing is minimal (next slide)
- at angles ≠ 0° charge sharing increases, therefore TOT decrease
  - a fraction of charge is lost in neighboring pixel cells (remain below electronic threshold)
- at large angles, more charge is produced from longer path through silicon bulk
  - the charge sharing is compensated
- FBK sensor was not complete depleted
  - lower TOT

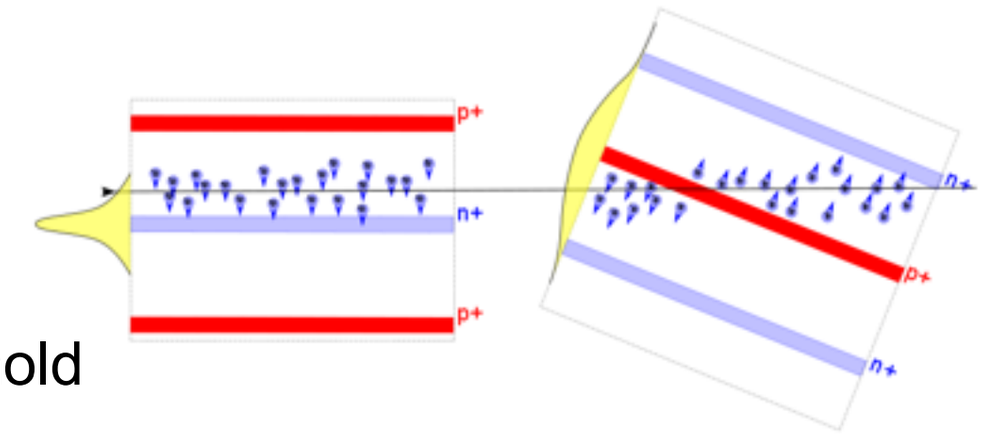
Test Beam Studies: Charge Sharing





Preliminary results

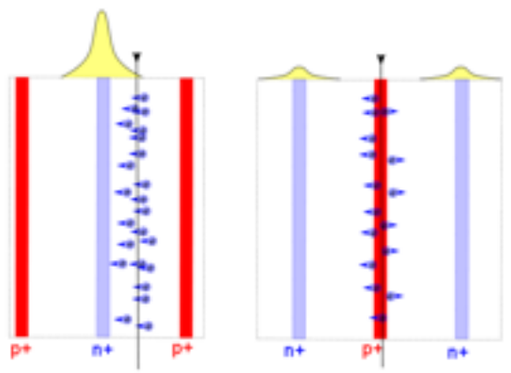
Charge sharing:

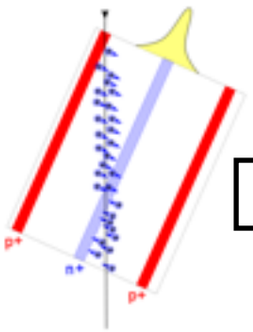


- signal can be shared between two or more cells
  defined as $N_{tracks}(hits>1) / N_{tracks}$ (all)
- 3D sensors almost insensitive to B-field
- less signal, less probability to be above the threshold
- always larger for the planar
- planar: minimum value corresponding to the Lorentz angle -(7.4 ± 0.4)°
  - in agreement with ATLAS measurement -(7.6 ± 0.6)°

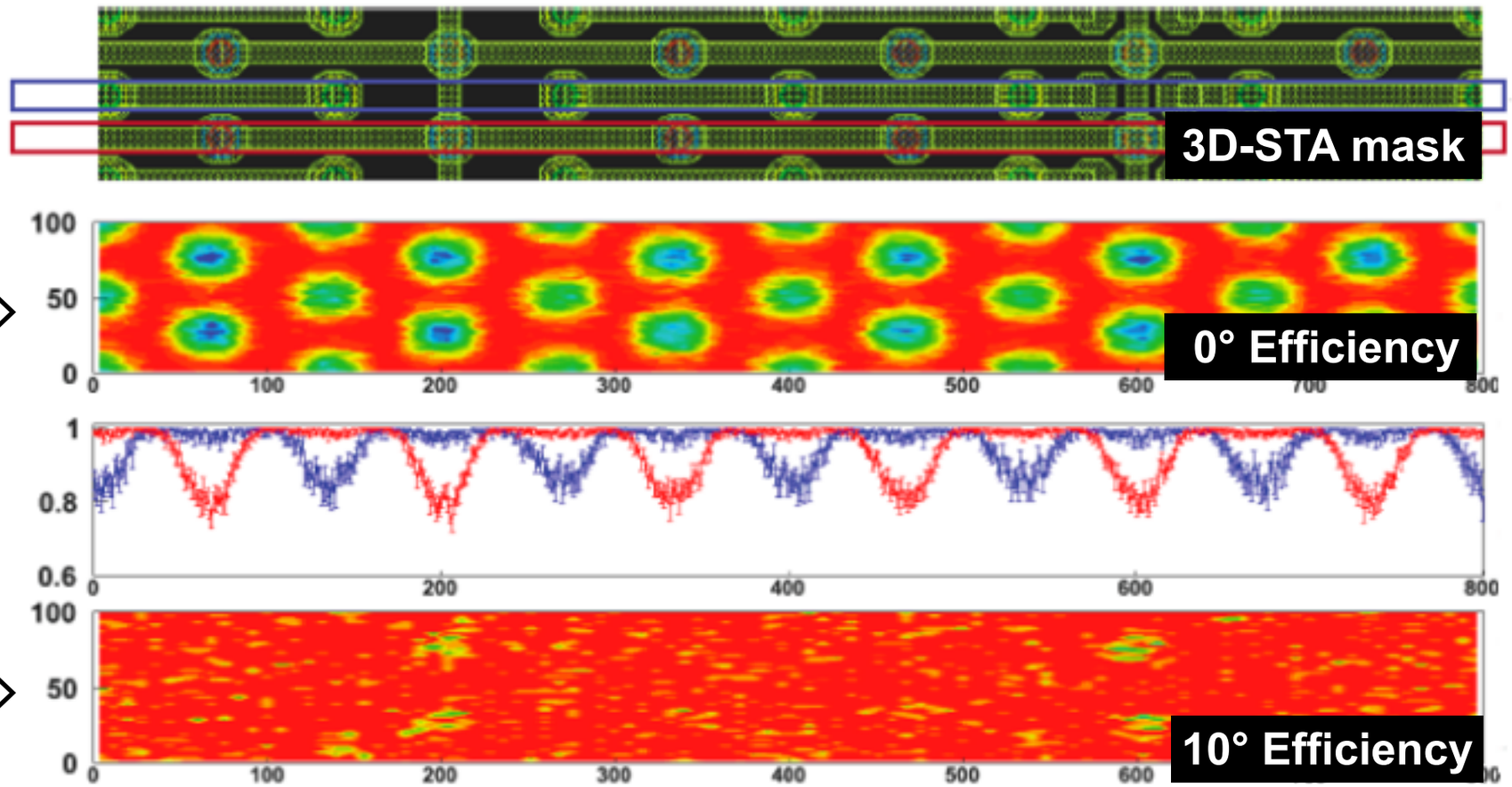
Test Beam Studies: Tracking Efficiency

STA eff.





∠10°



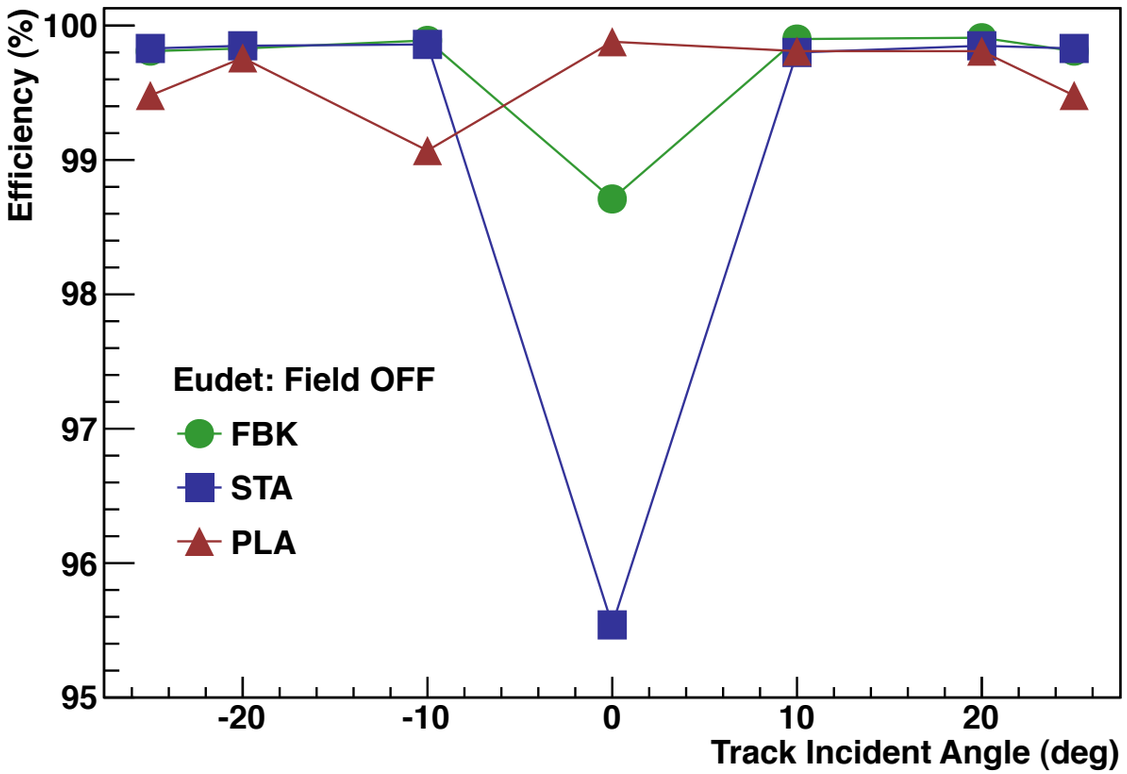
Preliminary results

3D sensors:

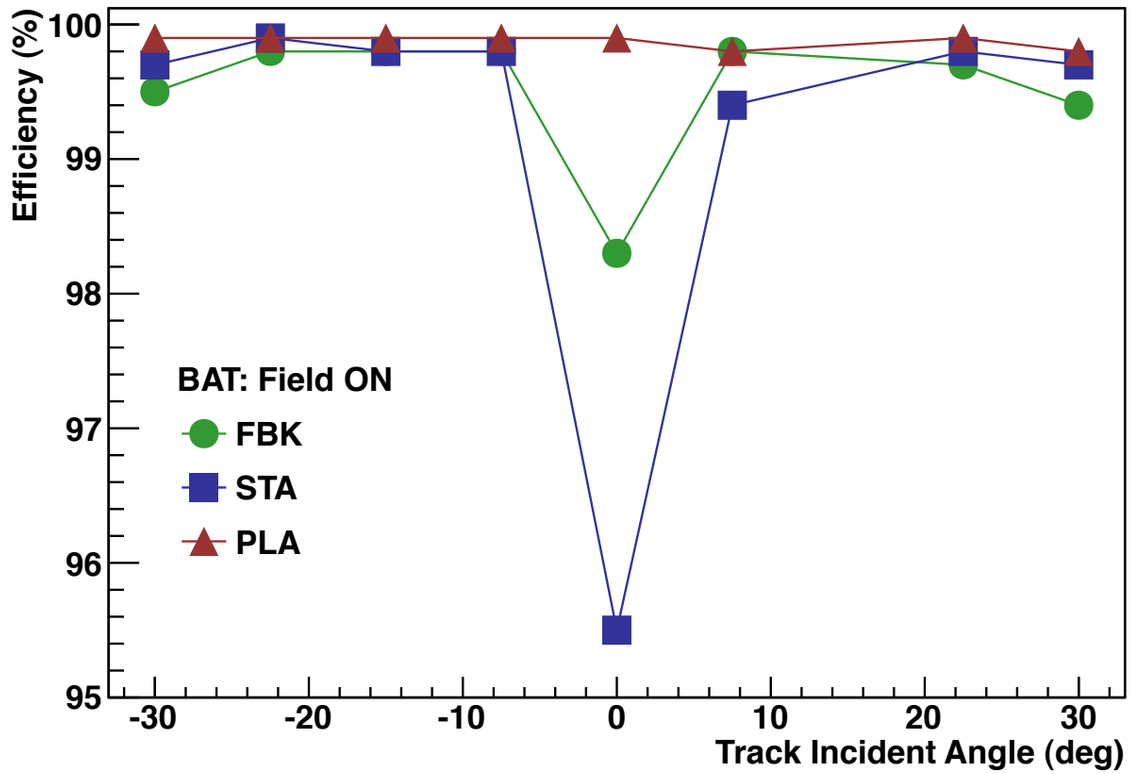
- lower efficiency for 0° (not ‘uniform’ color for the plot)
  - a lot of charge/signal loss for tracks
    - ➡ charge below the threshold
- tilt angle has large impact
  - hit efficiency becomes more uniform when the tracks are inclined
    - ➡ improving of the efficiency (see next slide)

Test Beam Studies: Tracking Efficiency

B-field OFF



B-field ON (~1.6T)

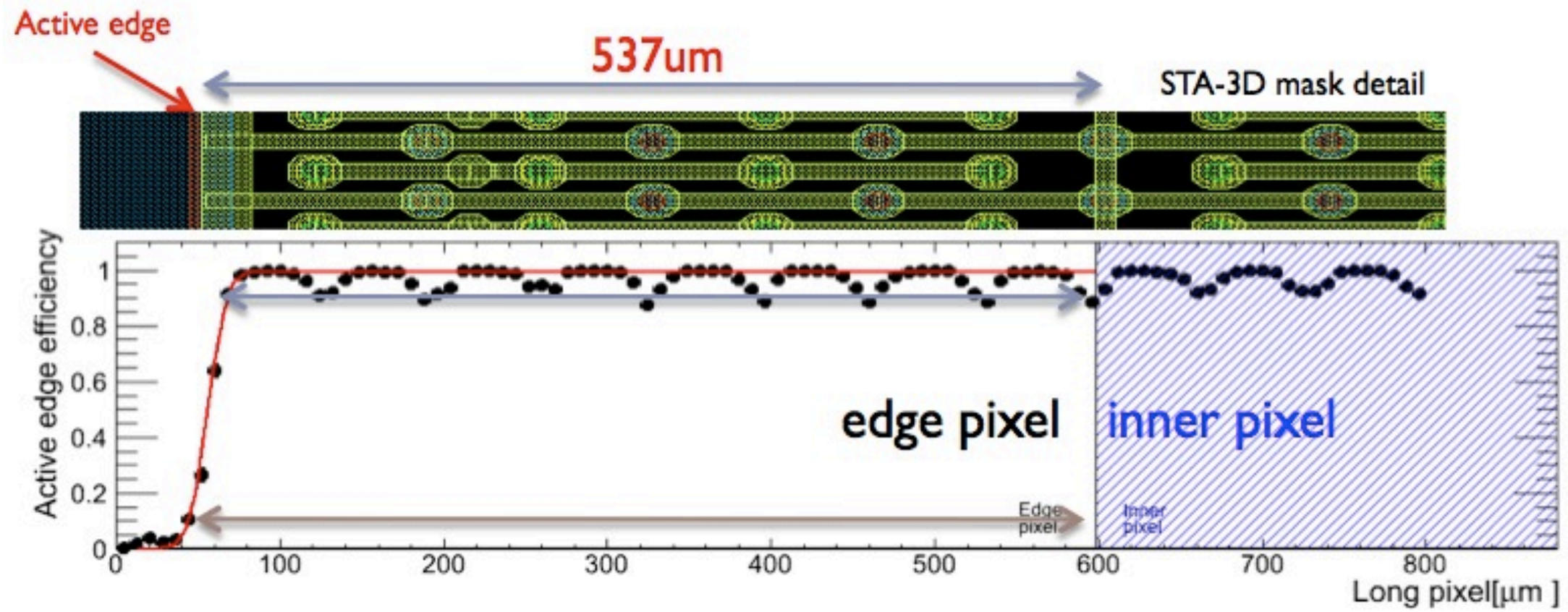


Preliminary results

3D sensors:

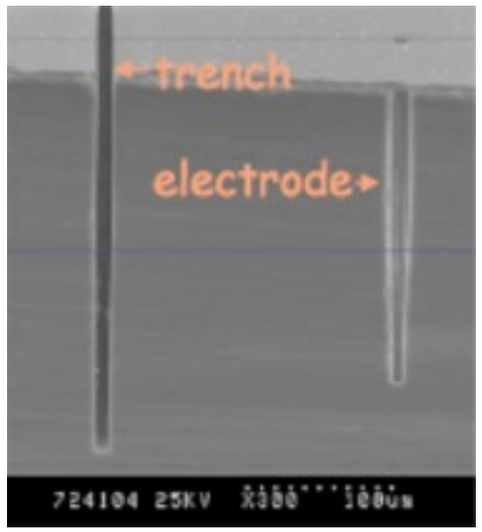
- lower efficiency at 0° but > 99.5% for greater angles (fully recovered with tilt angles >10°)
  - signal loss for tracks passing through the electrodes
- same behavior with or without magnetic field
- at 0° 3D-FBK sensor slightly better efficiency
  - electrodes do not penetrate fully the sensors thickness

Active Edge



P. Hansson, et al., Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.06.321

- Traditional Si sensors have large dead region at edges (~1mm)
- ATLAS IBL has no overlap in z coordinate (along the beam)
- 3D sensors with active edge:
  - etched trench around sensor edge, doped similar to electrodes
  - minimize dead area between modules (IBL)
    - ➡ sensors is still active up to 6 µm from edge



Radiation Hardness

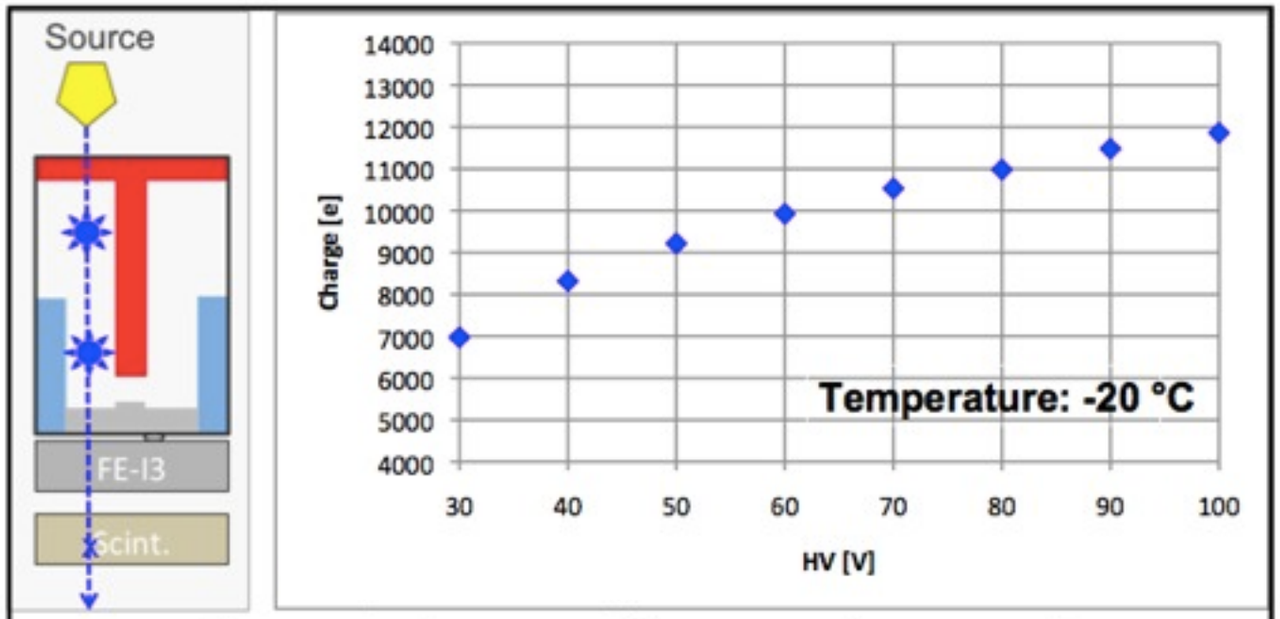
TDAQ software

Lab Measurements:

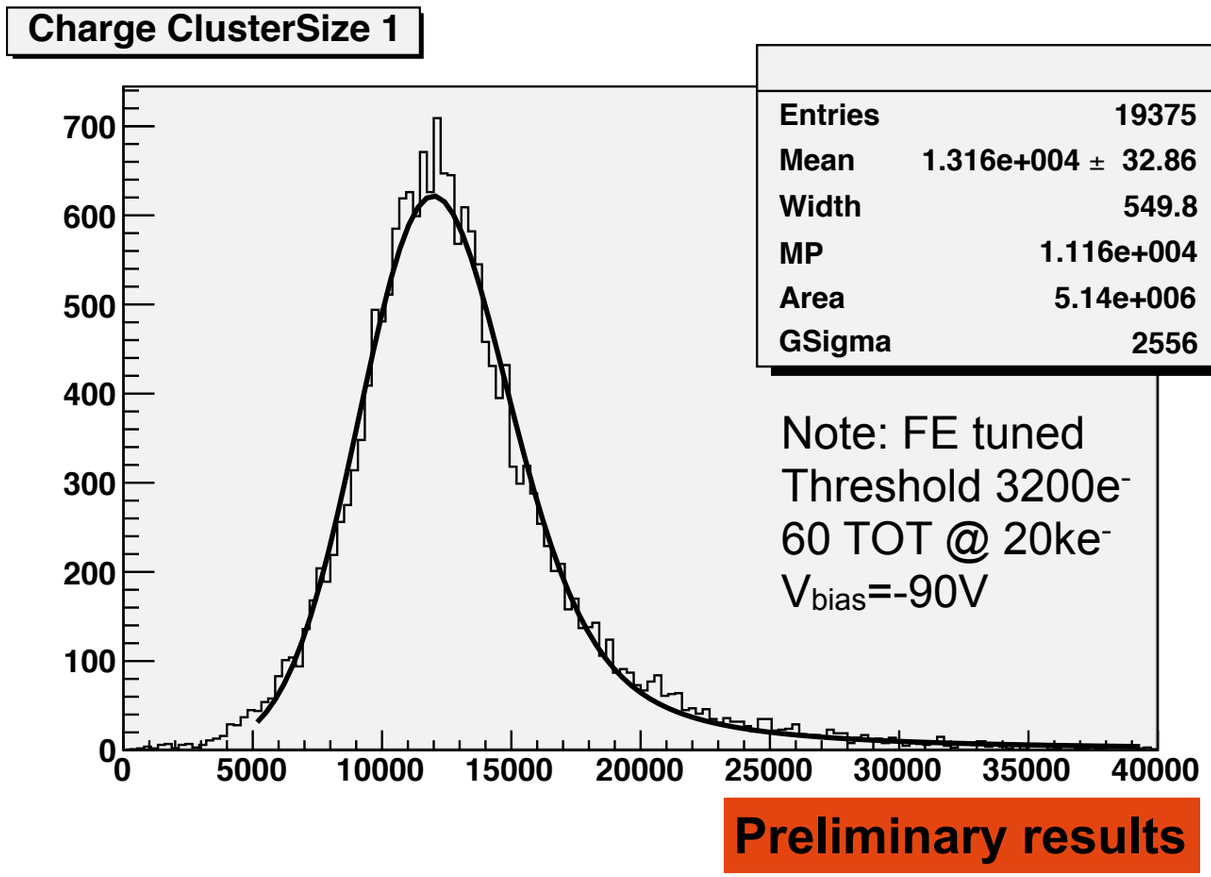
- Electrical and noise tests:
  - IV scan
  - Standard calibration at $V_{nominal}$: Threshold, ToT calib
  - Standard calibration repeated for different voltage settings
  - Noise scan vs HV

- Response to radioactive source (Am^{241} (at Genova/Cern) - Cd^{109} , Sr^{90} (Cern)):
  - The results shown here are still preliminary

Lab Measurements



Bias	-30V	-40V	-60V	-80V	-100V
Charge Lost	49%	40%	30%	21%	15%



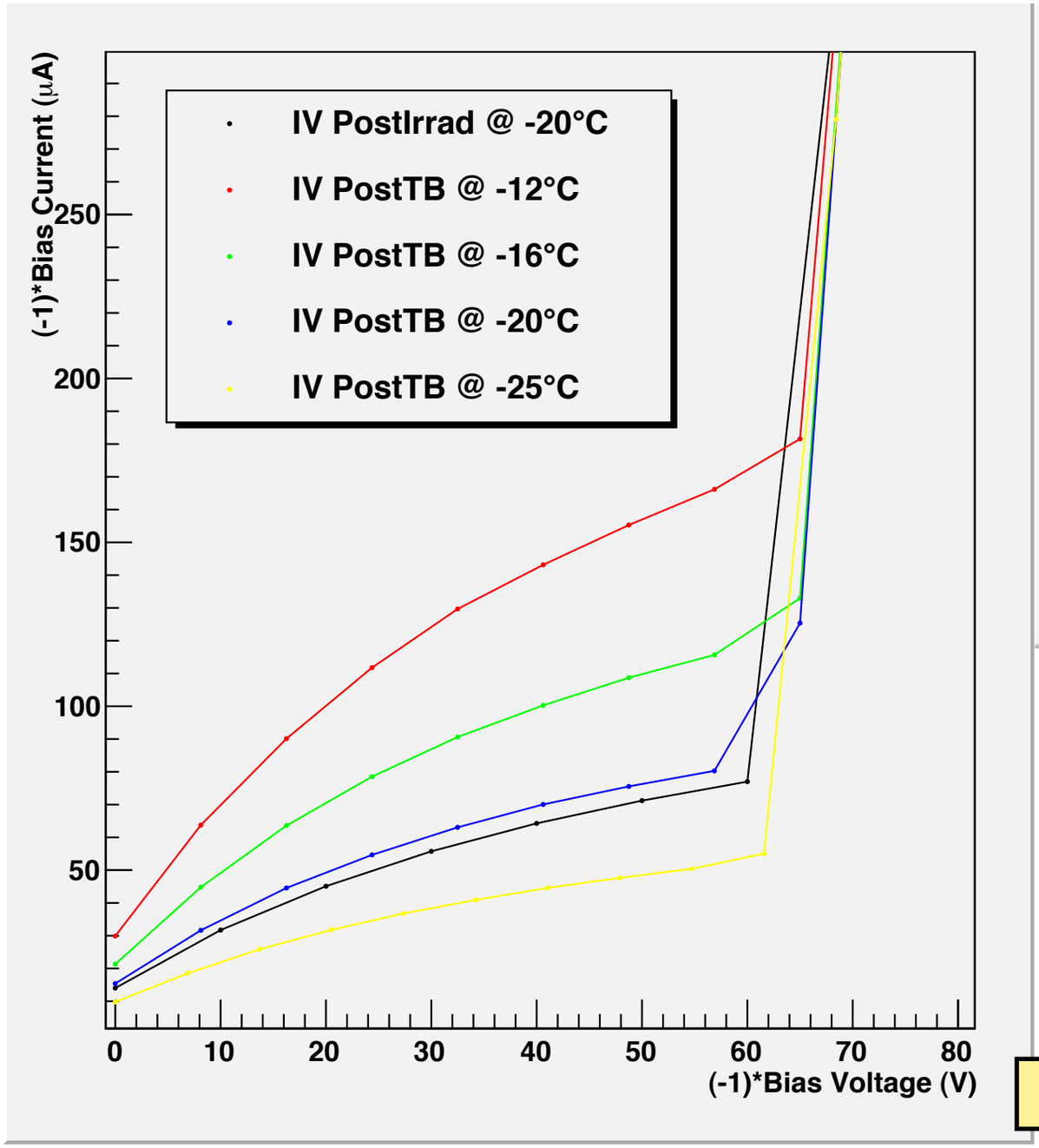
3D-FBK-3E proton-irradiated to 1×10^{15} $n_{eq}cm^{-2}$ (thickness 200μm)

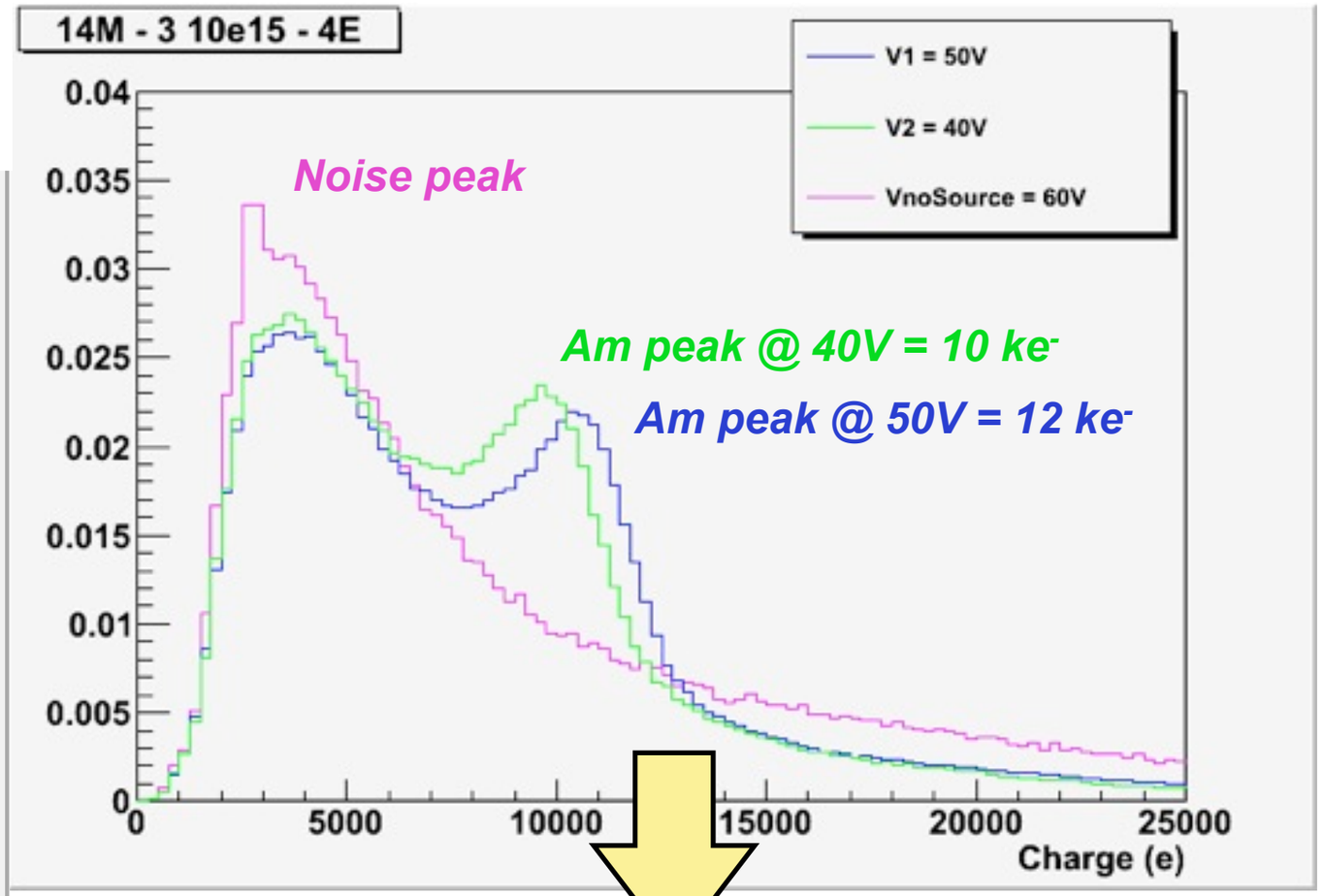
- radiation damage: run with bias voltage -80 V
  - ~ -20% signal loss
    - ➡ in agreement with lab tests made with β source Sr^{90}
  - sensor was not fully depleted
- overall efficiency still high (~99%)

Lab Measurements

Preliminary results

3D-FBK-4E
irradiated to 3×10^{15} n/cm^2





Source scan with γ source (Am^{241}):
to verify TOT tuning
(0.5 Mhits, ~250 entries per pixel)

IV curve at different temperatures
$V_{break\ down}$ ~ -60V

Summary and Outlook

- 3D sensors: good candidate for ATLAS IBL
  - >99.8% efficient with tilted angle tracks
  - insensitive to magnetic field
  - radiation hardness
  - development of passing-through column detector is on going (for FBK sensors first batch expected for the end of the year)

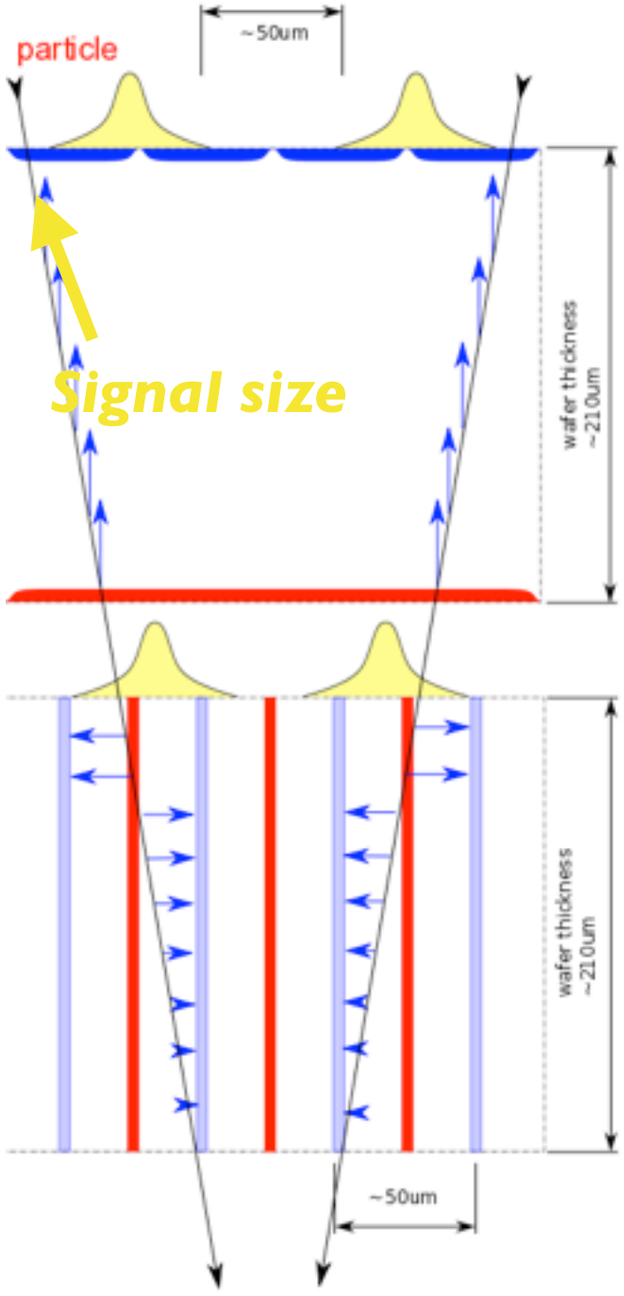
- Test beam plans
  - irradiated sensors in magnetic field (Oct 2010 and 2011)
  - new ATLAS front-end FE-I4 read out chip

- Lab measurements
  - electrical (with also new front end FE-I4)
  - noise tests
  - response to radioactive sources (Am^{241}, Cd^{109}, Sr^{90})

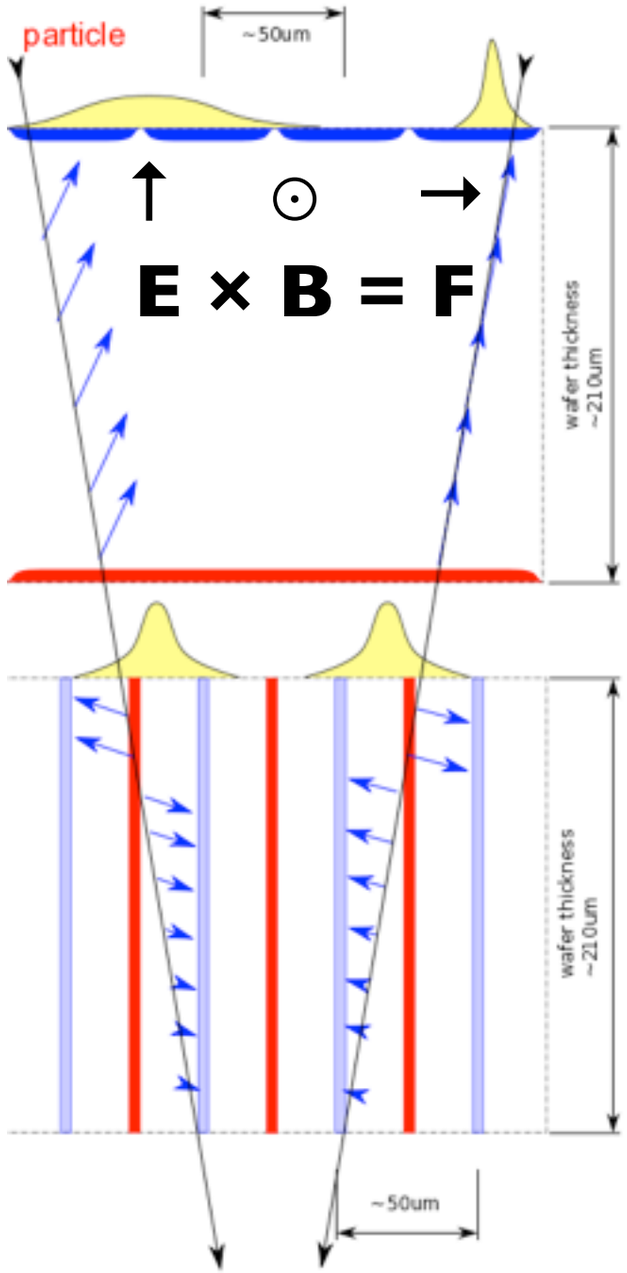
- Post-irradiation validation
  - Electrical measurements, Lab characterization, Test beam measurement

Backup

Sensors in Magnetic Fields



B-field OFF



B-field ON

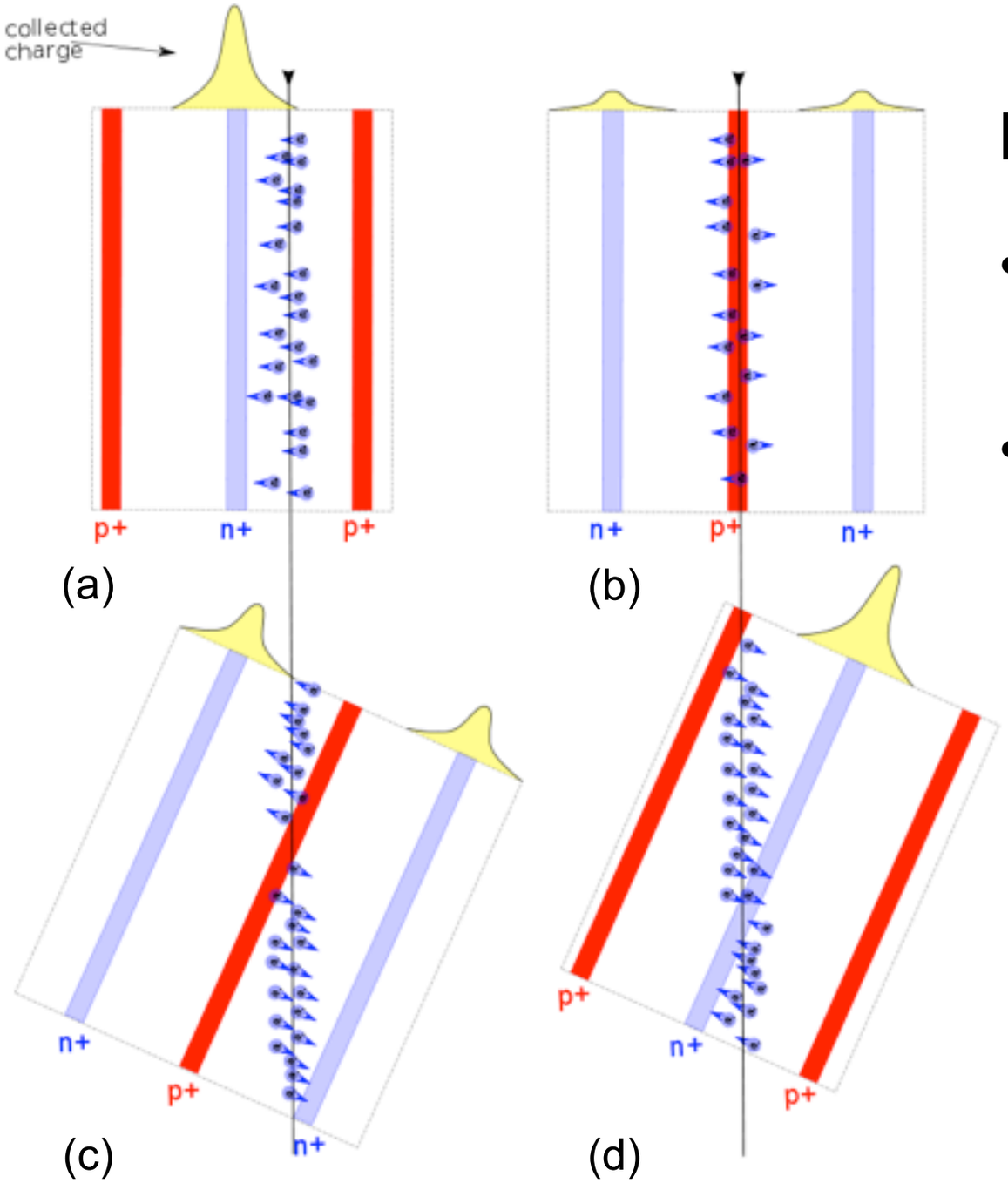
Planar sensors:

- Orthogonal electric & magnetic field
- Focus or de-focus drifting charges
- Minimum cluster size at Lorentz angle

3D sensors:

- Coplanar electric & magnetic field
- Lorentz force depends on hit position
- Expect small effect on observed signal

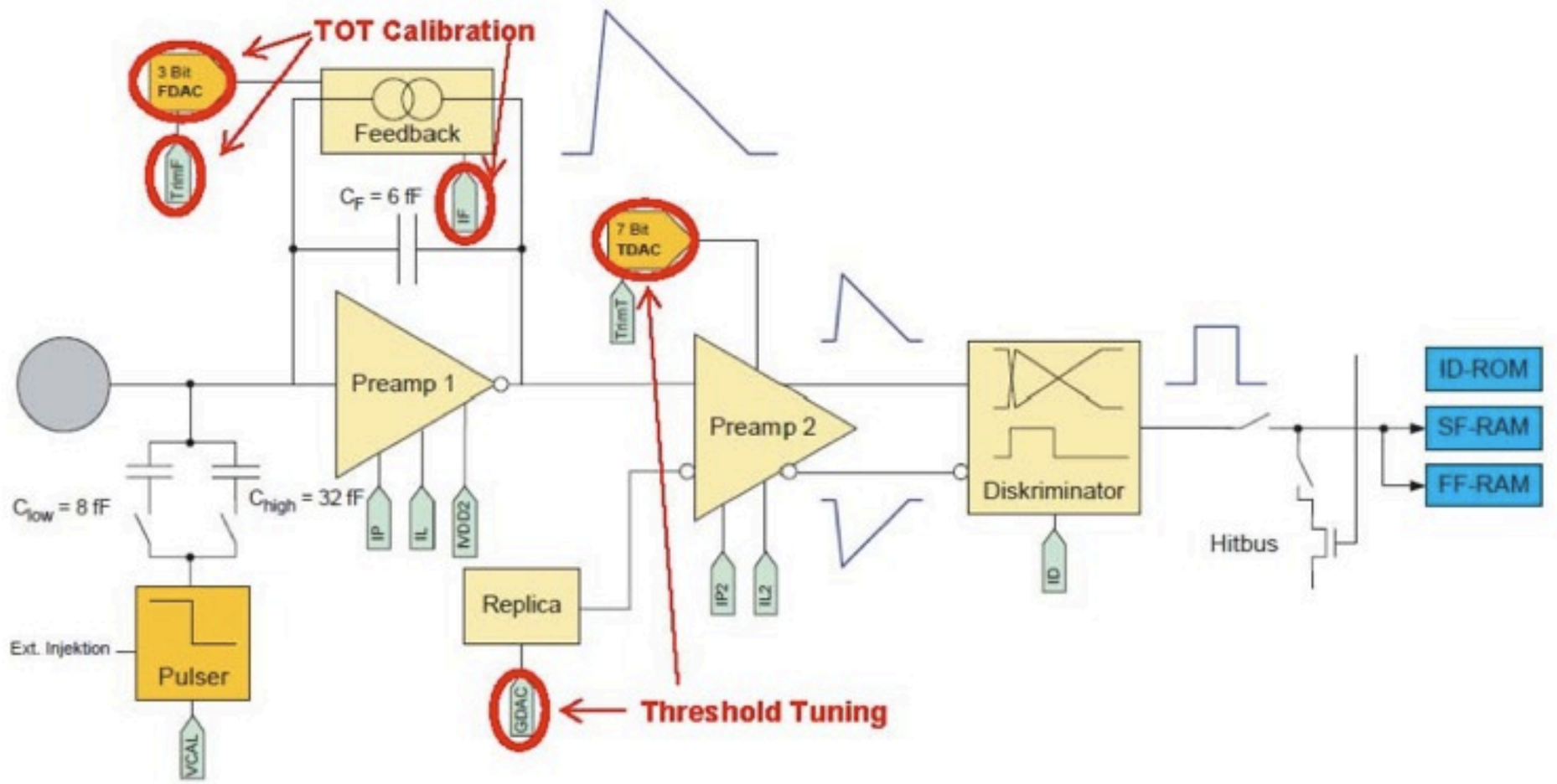
Sensors at Tilted Angle



Due to the small radius of IBL:

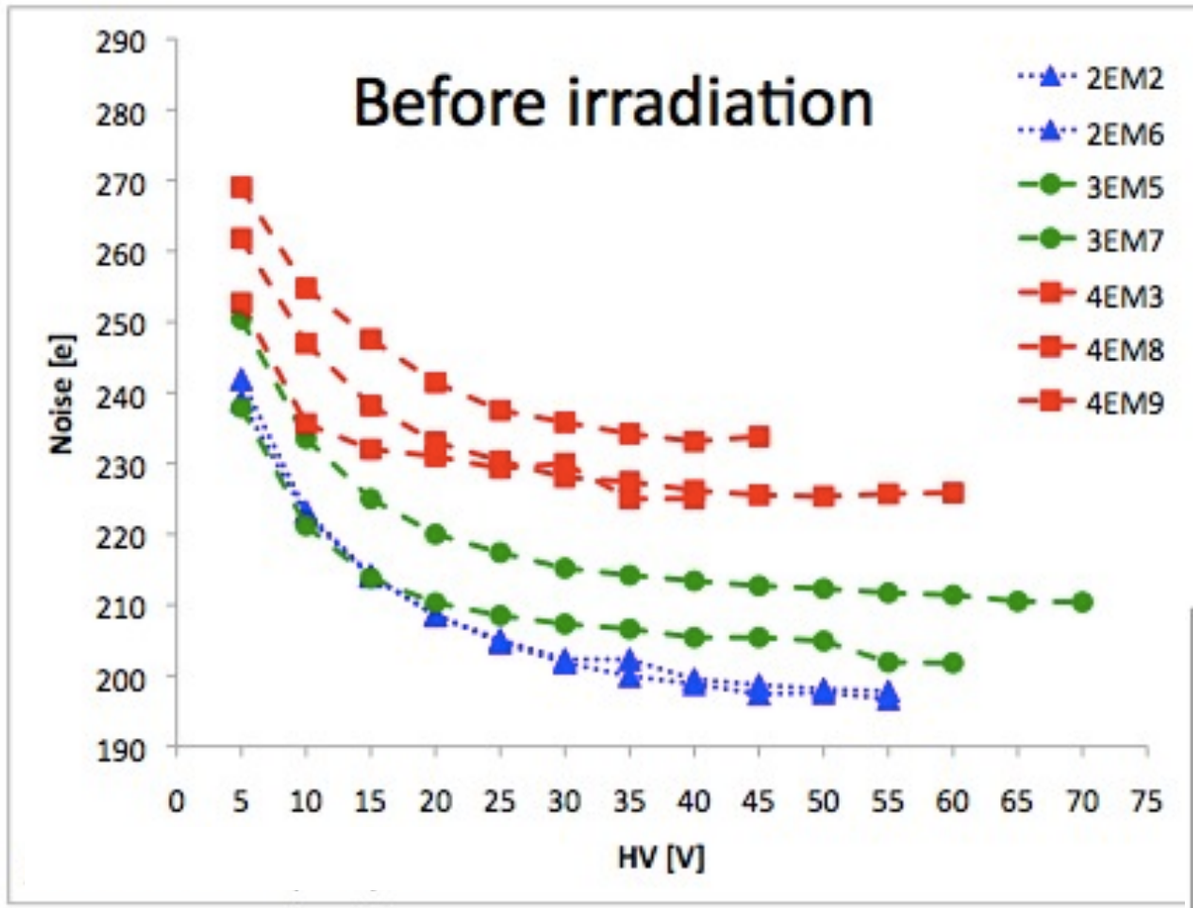
- the angle of the sensor to the radial direction is between 0°- 27° (TDR)
- important to test the sensors with tilt angle:
  - Increases charge sharing between pixels
  - 2-pixel clusters have better tracking resolution than 1-pixel
  - Less path length inside electrodes, but Potential signal loss if charge fraction in a pixel is not above threshold
  - Minimum cluster size at Lorentz angle

FE-I3 Layout: Single Cell

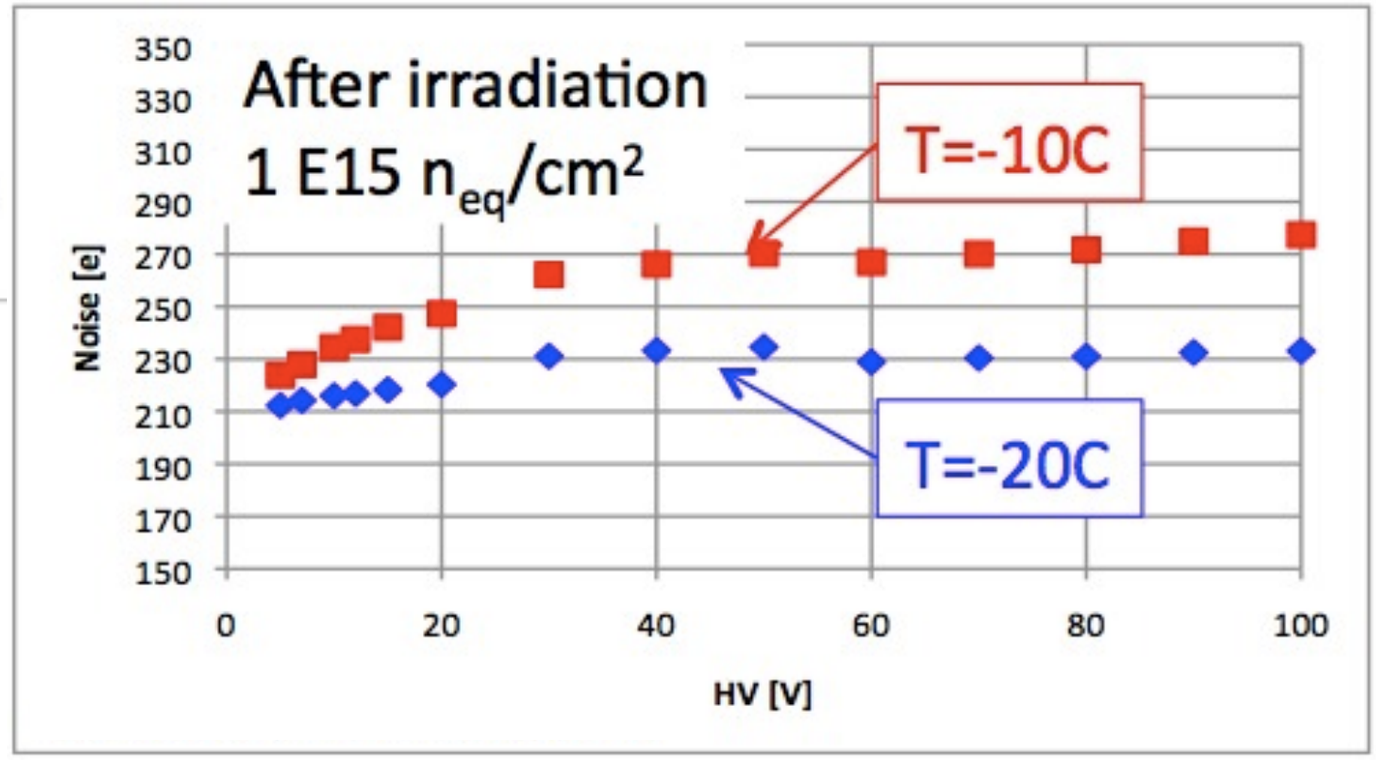


- sensor bump-bonded to the ATLAS Front-End Chip I3 (FE-3)
- 2880 readout cells, 160×18 pixels, each 50×400 μm^2 size
- provides pixel charge measurement through digital-time-over-threshold (TOT)
  - measured in units of LHC bunch crossing rate
- the conversion have been tuned to each individual pixel to respectively:
  - 3200 e^- and 60 ToT for a deposited charge of 20 ke^-
- 3D pixels: threshold tuned and TOT calibrated with “TurboDAQ” software

Radiation Hardness



	Threshold [e]	Noise [e]	T [C]
Before irrad	3292 ± 57	214 ± 8	+ 22
After irrad	3152 ± 145	231 ± 14	- 20



- 3D FBK sensors
- Front End tuned with: 60 ToT at 20ke$^-$ and Threshold = 3.2ke$^-$