6th “Trento” Workshop
on Advanced Silicon Radiation Detectors
(3D and P-type Technologies)

3D-FBK Pixel sensors: recent beam test results with irradiated devices

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on behalf of the ATLAS 3D Pixel R&D Collaboration

Outline

- Introduction
  - Atlas 3D collaboration
  - Motivation
  - 3D Sensors Design and Technology
  - The ATLAS FE readout chip
- Test Beam setup
  - Test Beam studies
- Summary and Outlook

ATLAS 3D Collaboration

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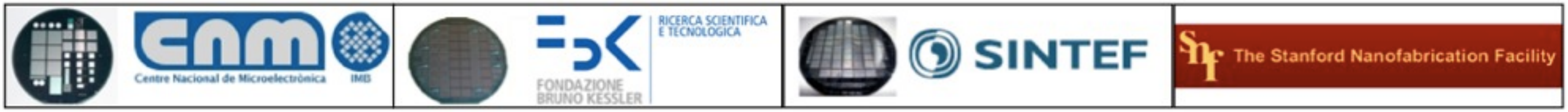
• 18 institutions:

[1]Bergen University, [2]Bonn University, [3]Calabria University, [4]CERN, [5]Czech Technical University, [6]Freiburg University, [7]University and INFN of Genova, [8]Glasgow University, [9]The University of Hawaii, [10]IFAE Barcelona, [11]Lawrence Berkeley National Laboratory, [12]The University of Manchester, [13]The University of New Mexico, [14]Oslo University, [15]SLAC, [16]Stony Brook University, [17]University and INFN of Trento, [18]University of Udine, [19]CNM Barcelona, [20]FBK-Trento, [21]SINTEF Norway, [22]Stanford, [23]VTT, Finland

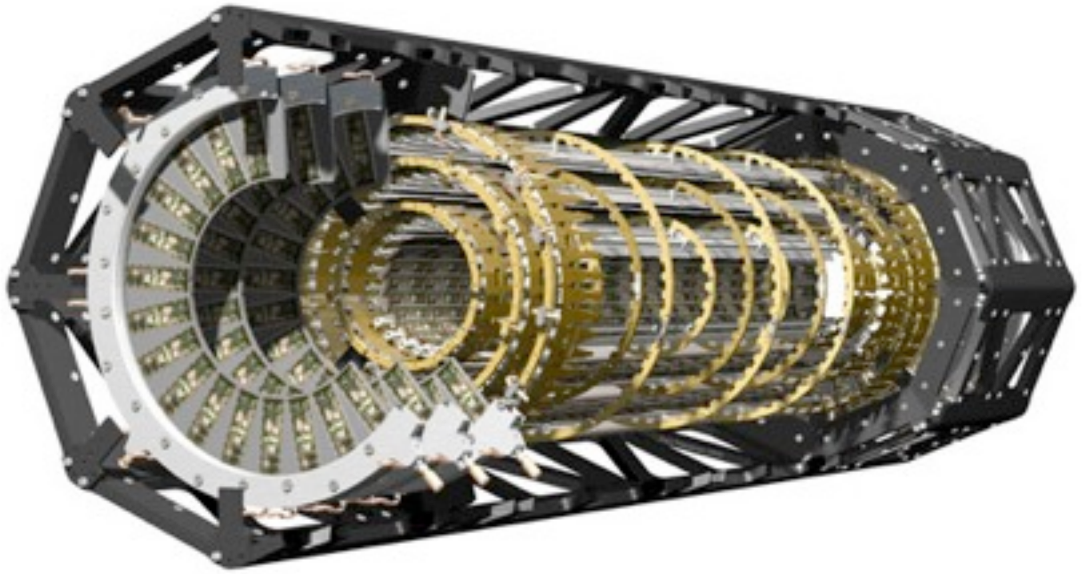
• 4 (+1) processing facilities:

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



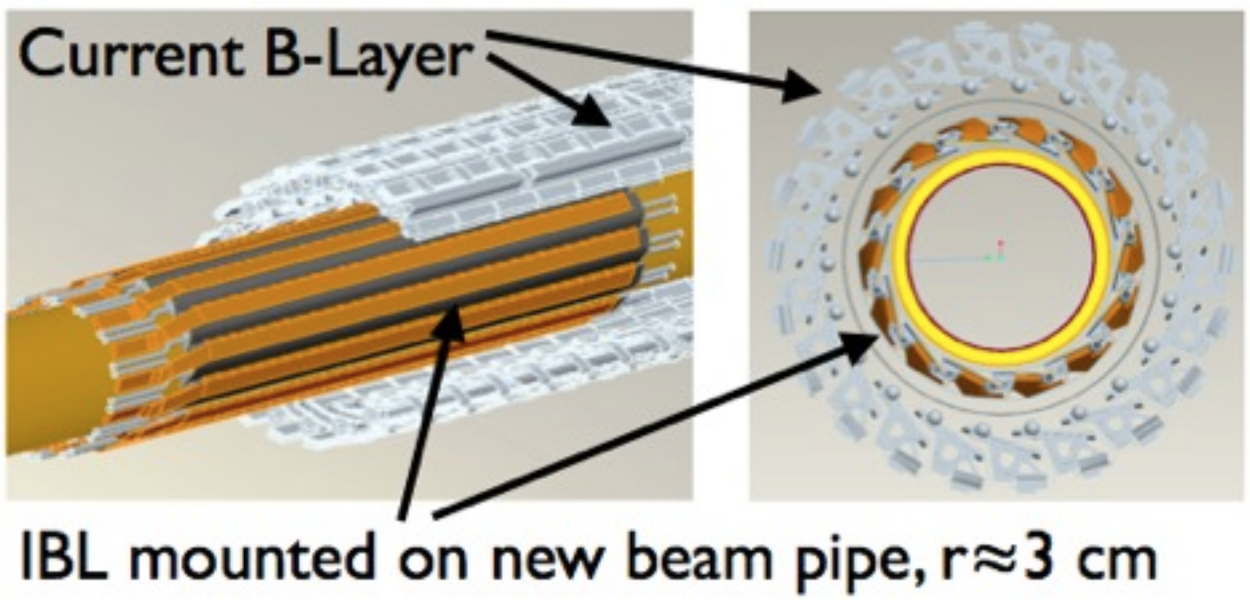
Motivation

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



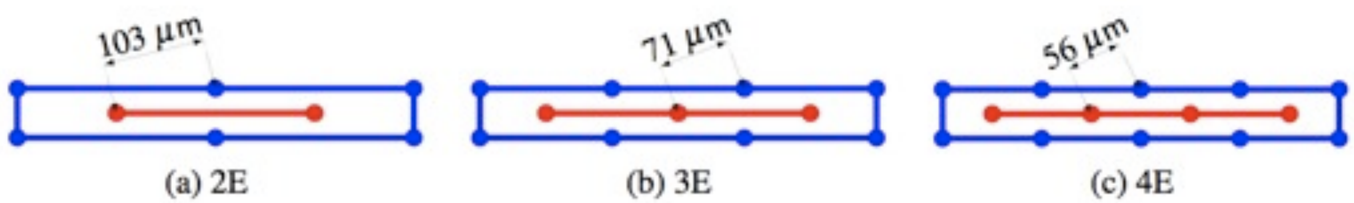
- Atlas pixel detector
  - LHC p-p collisions at 7 TeV ($L \sim 10^{34}\ cm^{-2}s^{-1}$)
  - B-layer at 5 cm from IP (2T magnetic field)
  - designed for fluence of $10^{15}\ n_{eq.}cm^{-2}$
  - technology: planar sensor

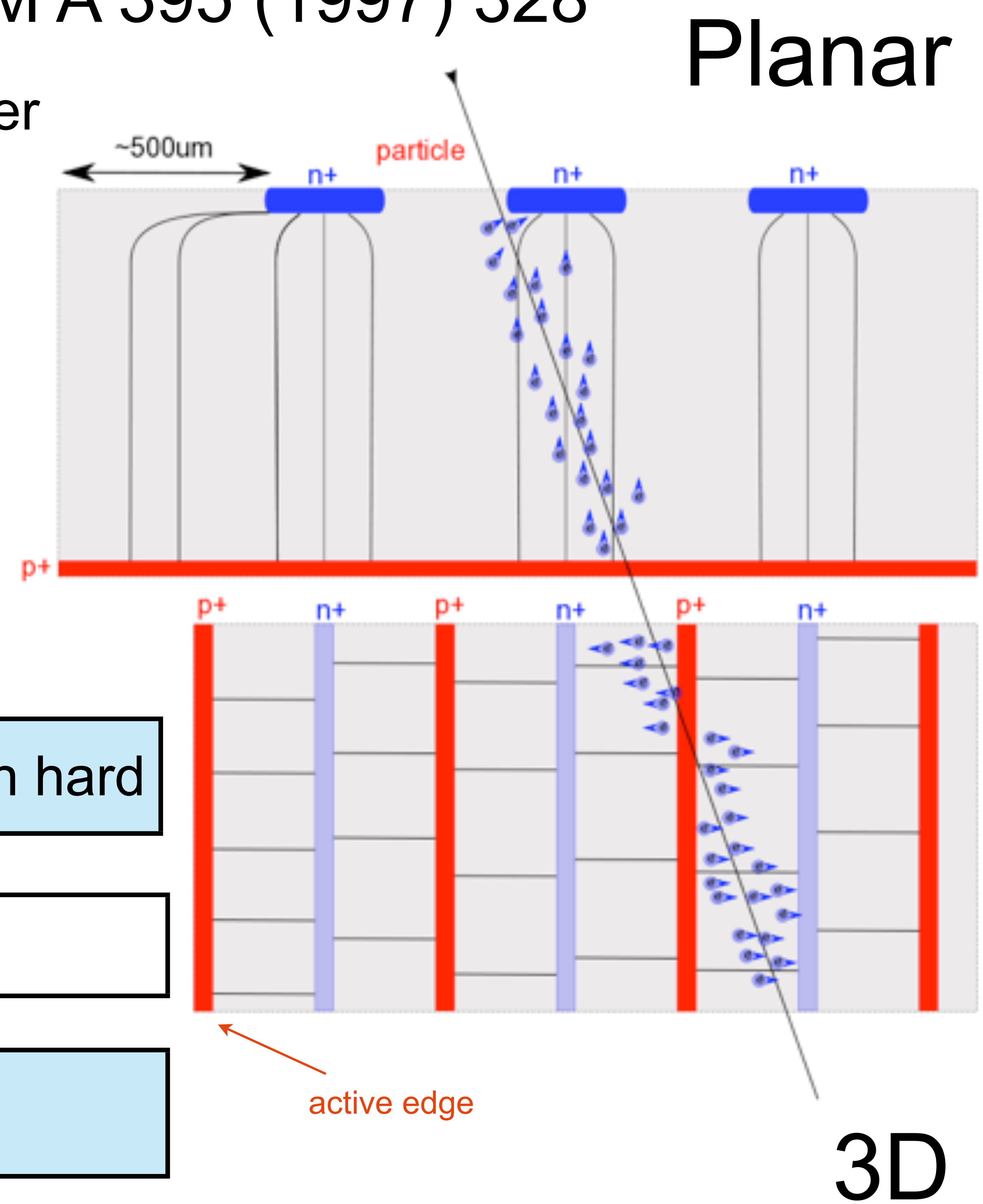
- Why a new Insertable B-Layer (IBL):
  - B-Layer suffers highest radiation damage
  - performance significantly degraded
  - add new layer:
    - closer to Interaction Point, smaller space, higher radiation...
    - 3 technologies under study: Diamond, new Planar, 3D



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





Advantages:

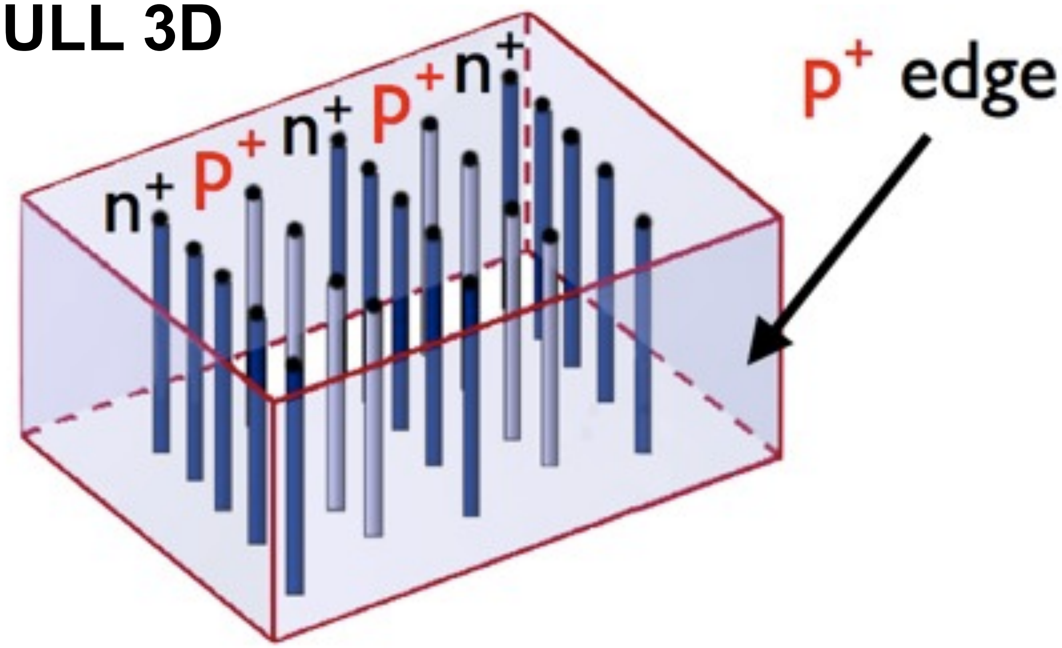
3D Features:
high electric field
short collection path
sensor edge is an electrode

- high electric field → high efficiency / radiation hard
- short collection path → high efficiency / radiation hard; lower depletion voltage; faster charge collection
- sensor edge is an electrode → guard fence 200µm

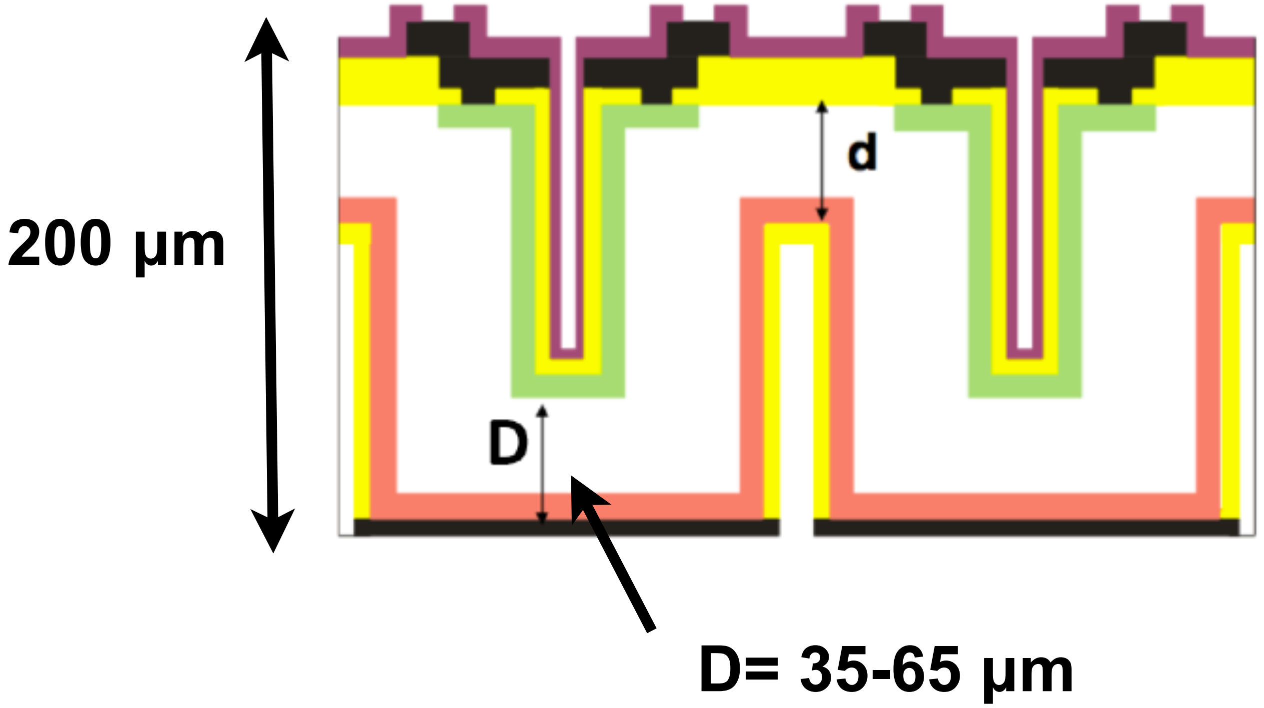
3D Sensors Design and Technology

- Two designs under study - similar behavior and performance

FULL 3D



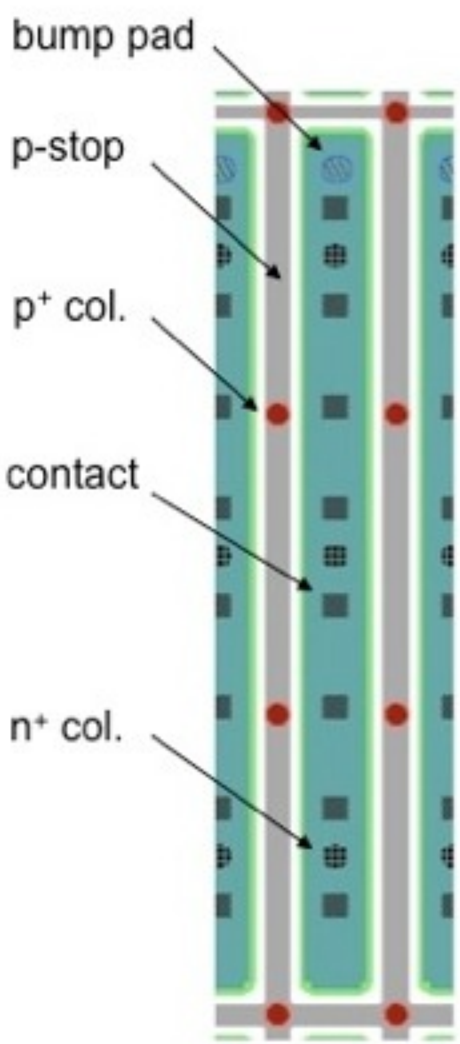
Modified 3D sensors



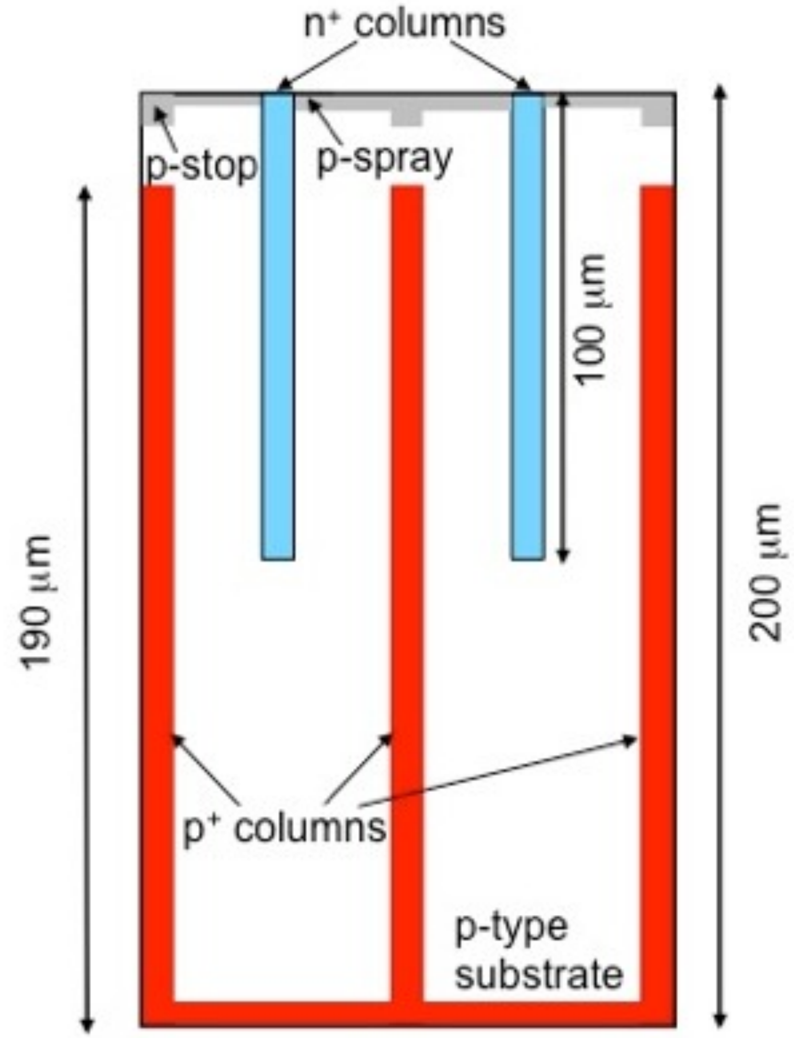
- produced by Stanford/SINTEF (5th gen.) with active edge
- produced by FBK (FE-I3)
- to-be-produced by FBK under bump-bonding (FE-I4)

- partially overlapping electrodes
- simplified wafer handling
- double-sided double-type columns
- produced by FBK and CNM (FE-I3)

Modified 3D sensors (wafer 2008)

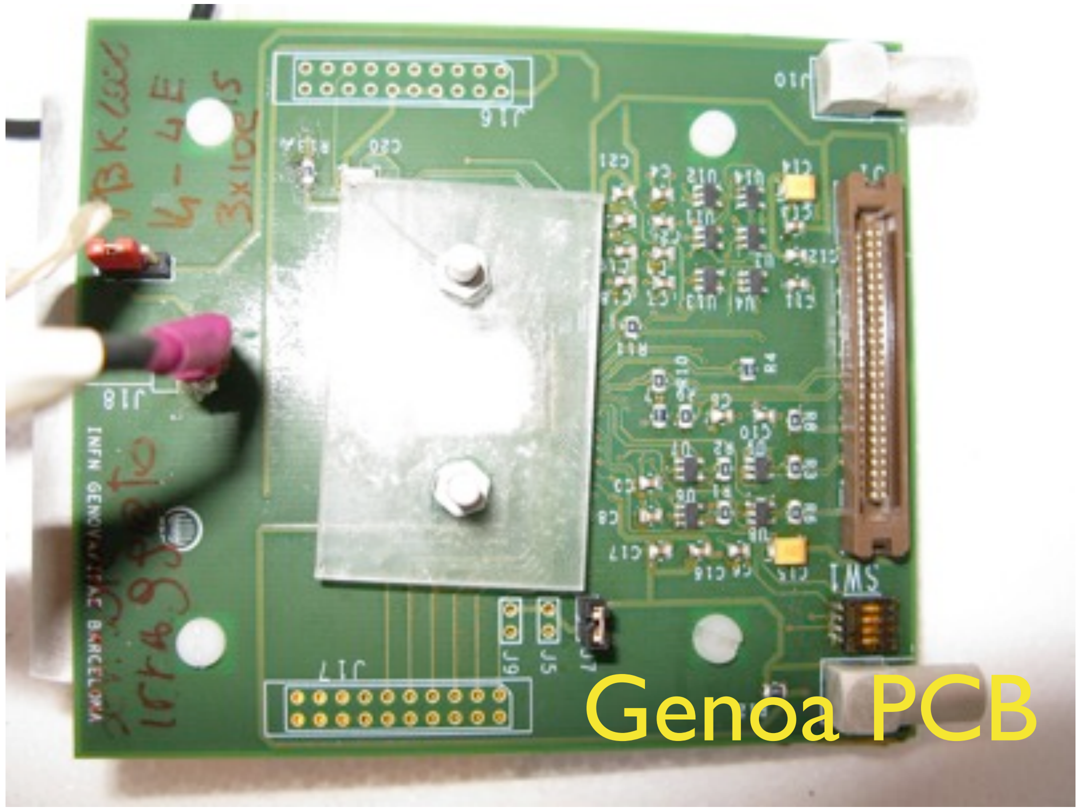


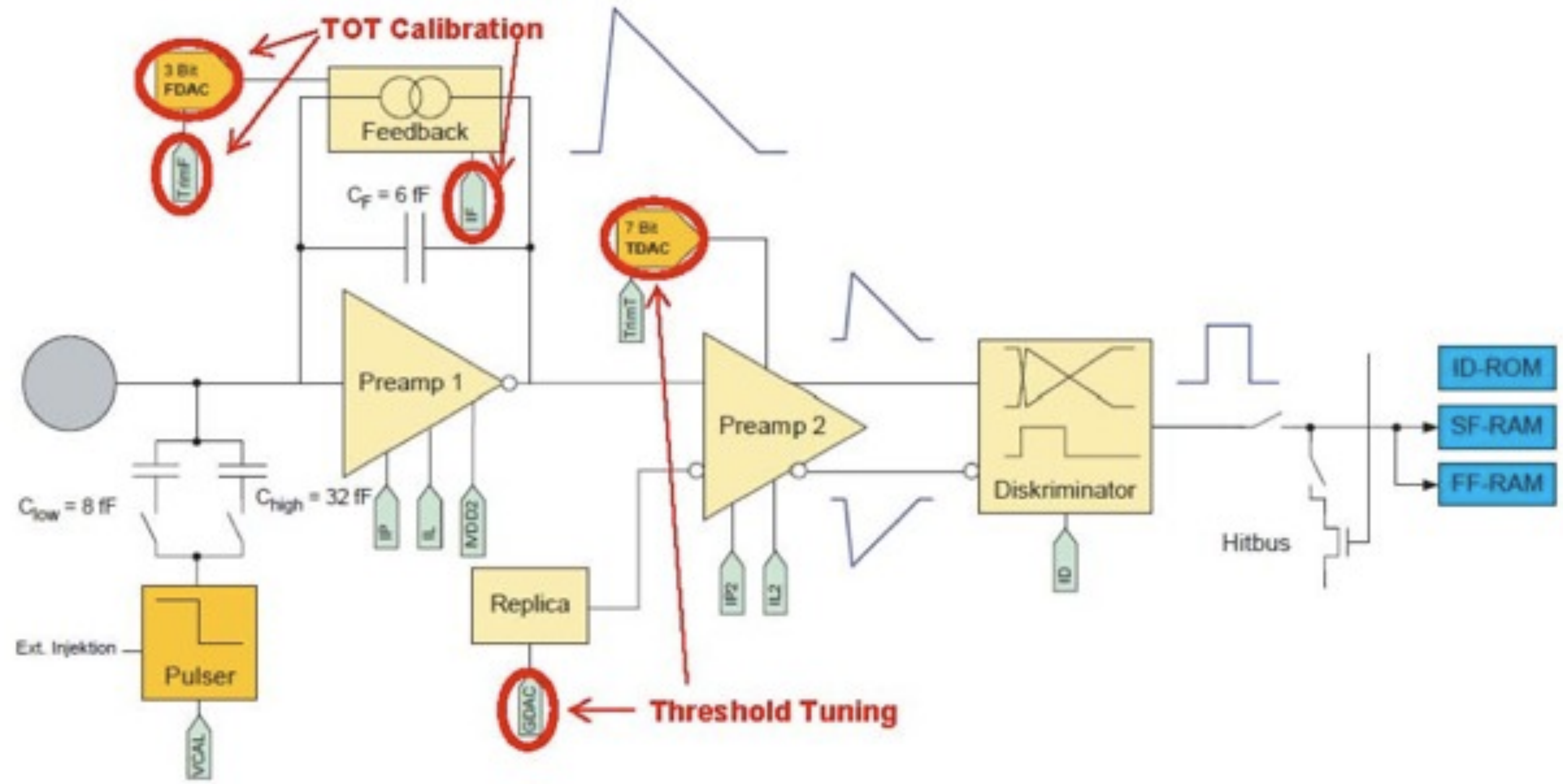
3E cell configuration



Parameter	Unit	Value
		3D-DTC-2
Substrate thickness	µm	200
Junction column thickness	µm	100 -110
Ohmic column thickness	µm	180 -190
Column overlap	µm	90 - 100
Substrate doping concentration	cm^{-3}	1×10^{12}
Lateral depletion voltage	V	3
Full depletion voltage	V	12
Capacitance vs backplane	fF/column	35
Leakage current @ Full depletion	pA/column	< 1
Breakdown voltage	V	> 70

The ATLAS FE Readout Chip



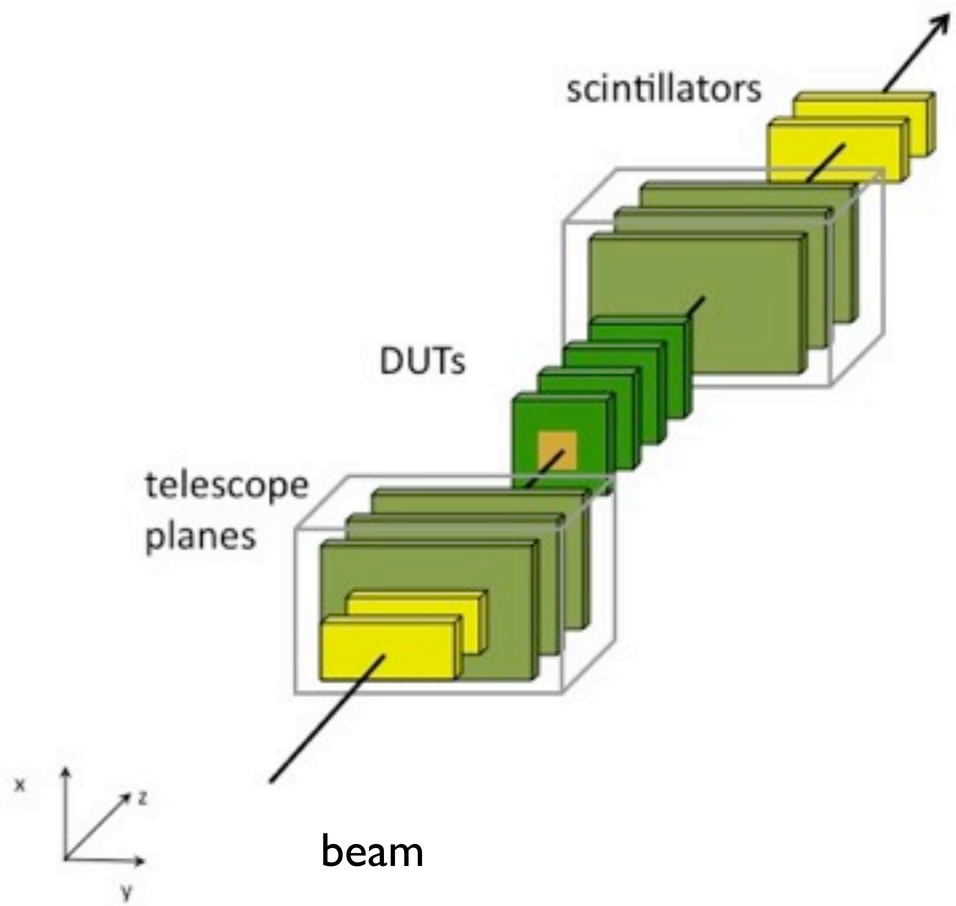


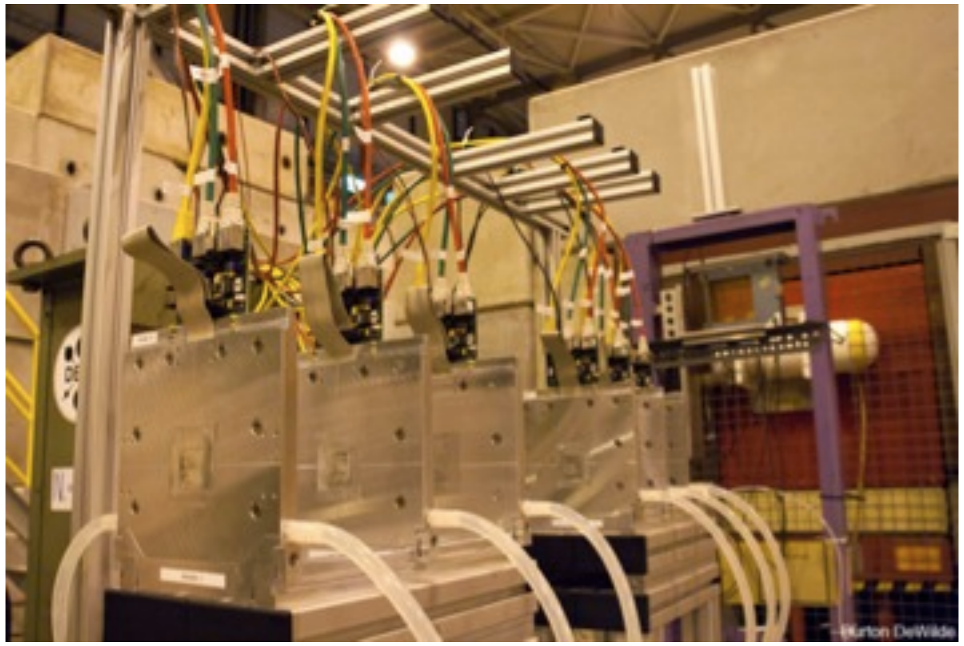
Single Chip Assembly (SCA):

- Sensor bump-bonded to the FE-I3 Chip
- Bump-bonded at Selex (thermo-compression with indium bumps)
- 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 (40 MHz)
- the conversion has been tuned to each individual pixel to respectively:
  - 3200 threshold e^- and 60 ToT for a deposited charge of 20 ke^-
- 3D SCA pixels: threshold tuned and TOT calibrated with “TurboDAQ” software

Test Beam Setups

EU Detector Telescope - June ’10 - Oct, Nov ’10 (IBL)





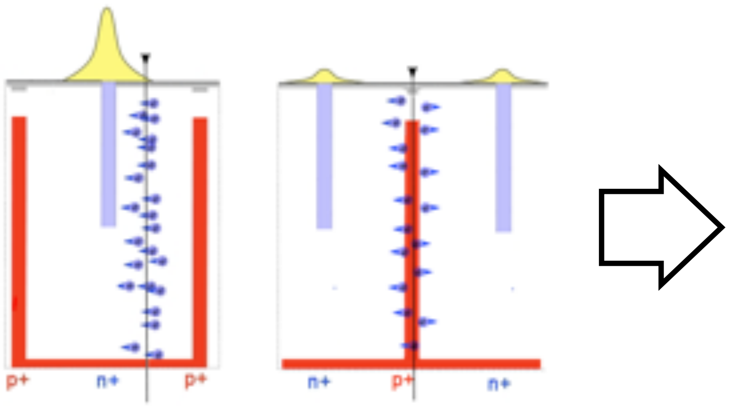
- 120 GeV pions from CERN - SPS
- 6 planes: 660k Si pixels (18.5 μm pitch)
- Trigger: four scintillators
- DUTs (June): FBK-3E p-irrad (*Karlsruhe)*, FBK-3/4E (n-irradiated - *Ljubljana*) both at fluence 10^{15} n_{eq}/cm^2 Atlas planar (as reference)

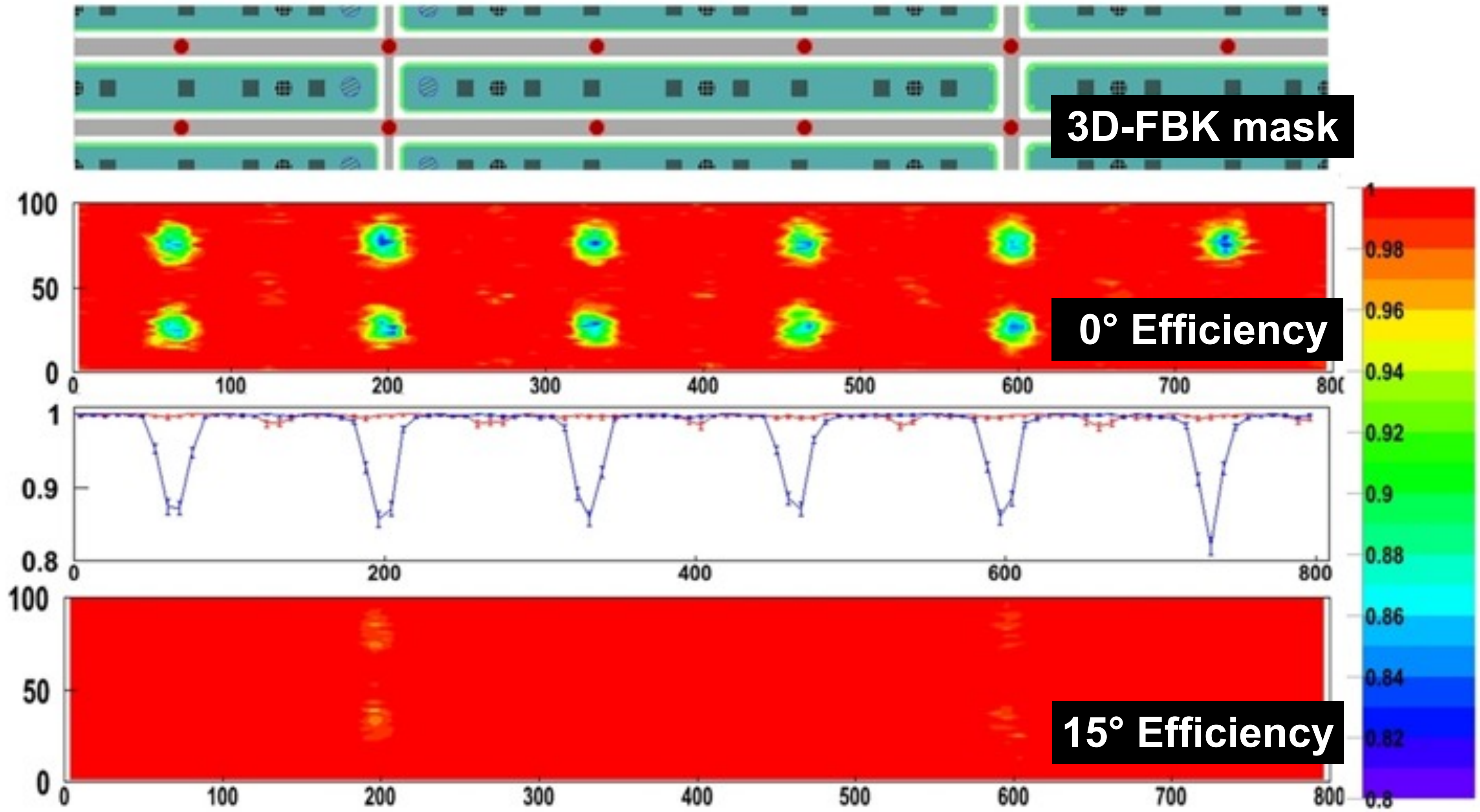
Purpose:

sensors performance after irradiation as a function of beam incidence angle (-25° to 25°):

- tracks efficiency, charge sharing, cluster size etc.

Test Beam Studies: Tracking Efficiency

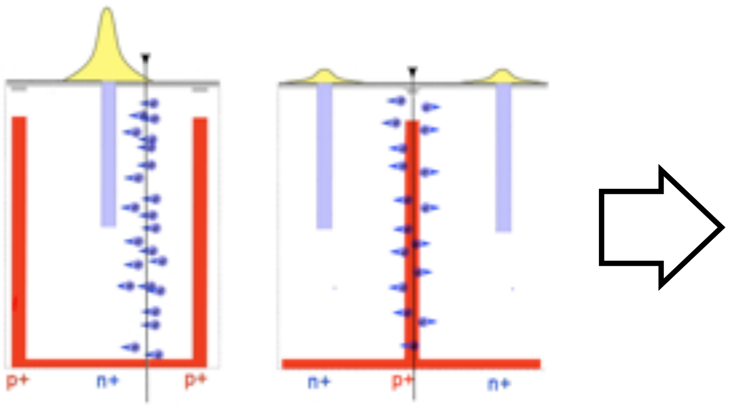


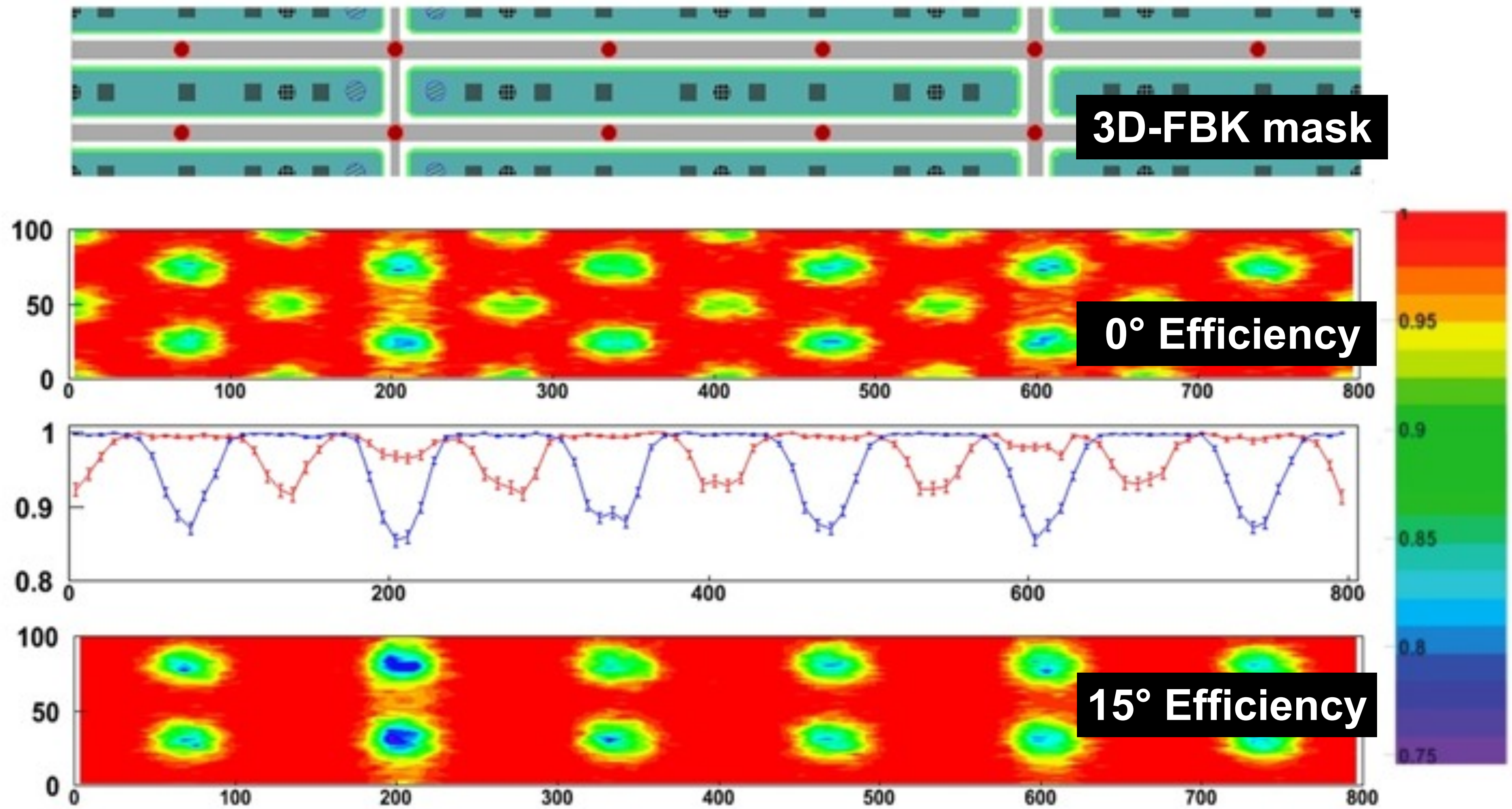


3D FBK-3E proton irradiated:

- lower efficiency for 0°
  - a lot of charge/signal loss for tracks that passed through the electrodes
    - charge below the threshold
- incidence angle has large impact
  - hit efficiency becomes more uniform when the tracks are inclined

Test Beam Studies: Tracking Efficiency

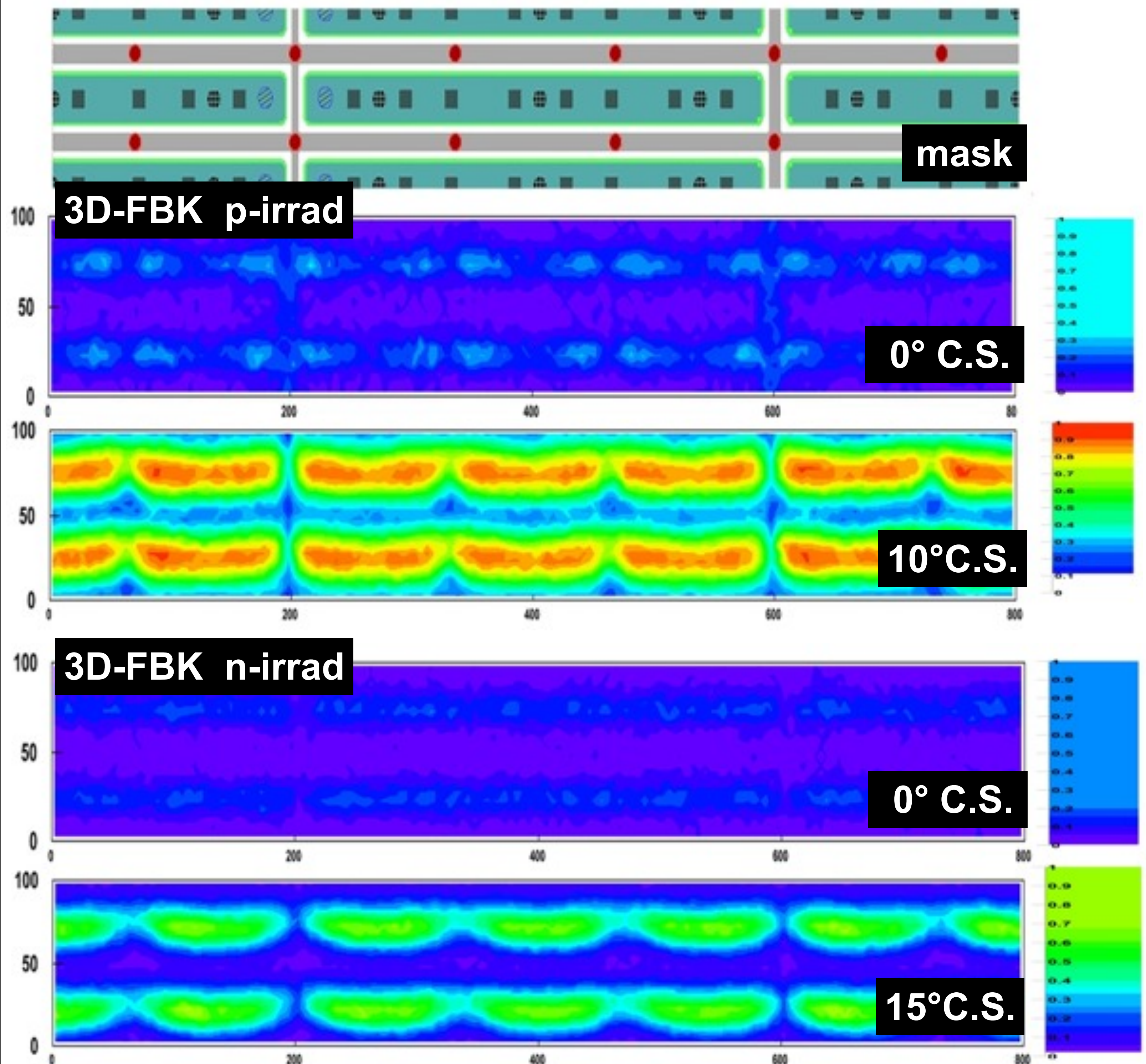




3D FBK-3E neutron irradiated:

- slightly lower efficiency for 0° as the 3D-FBK p-irrad:
  - 97.6% (n-irrad.) vs 99.0% (p-irrad.)
- inclined angle:
  - improving of the efficiency: 98.1% (99.9% p-irrad)
  - efficiency fully recovered for the read-out electrode regions
  - ohmic columns (p-type) still inefficient

Test Beam Studies: Charge Sharing

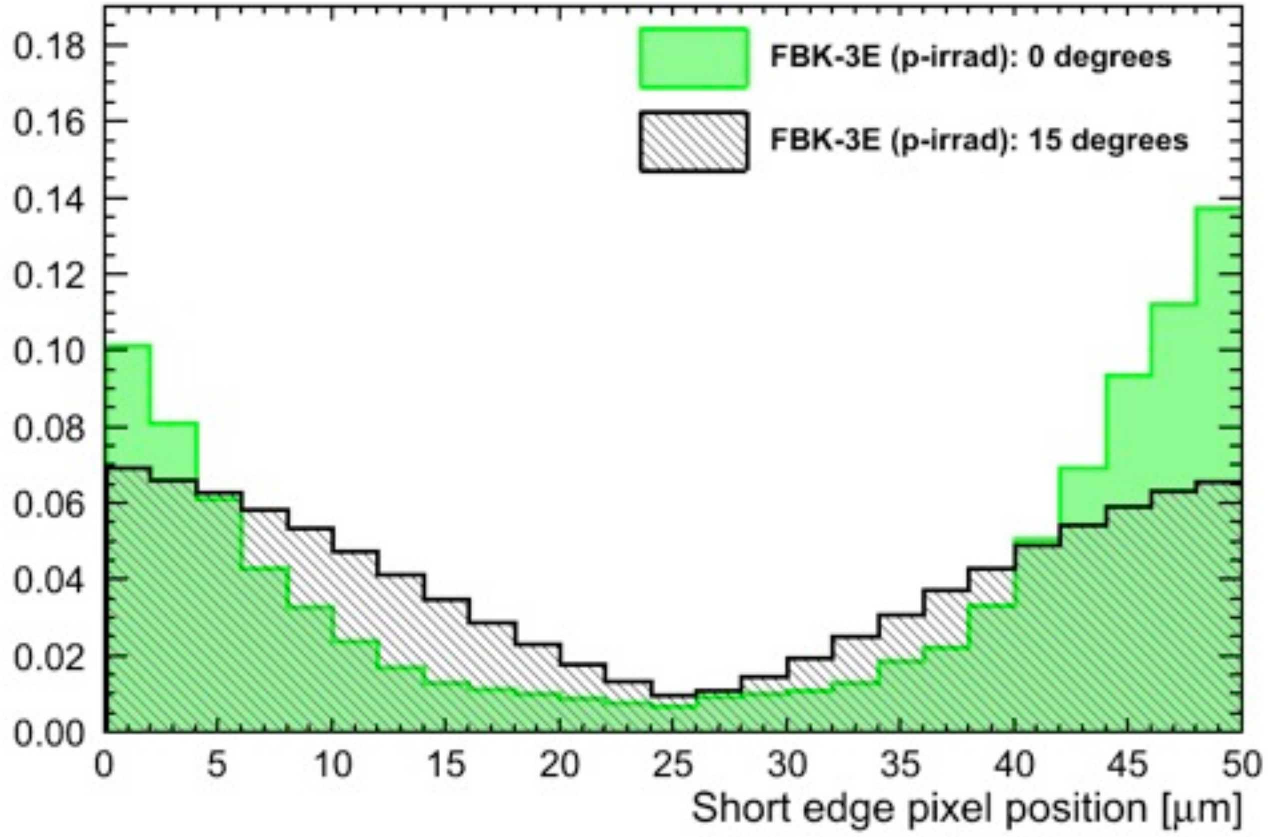


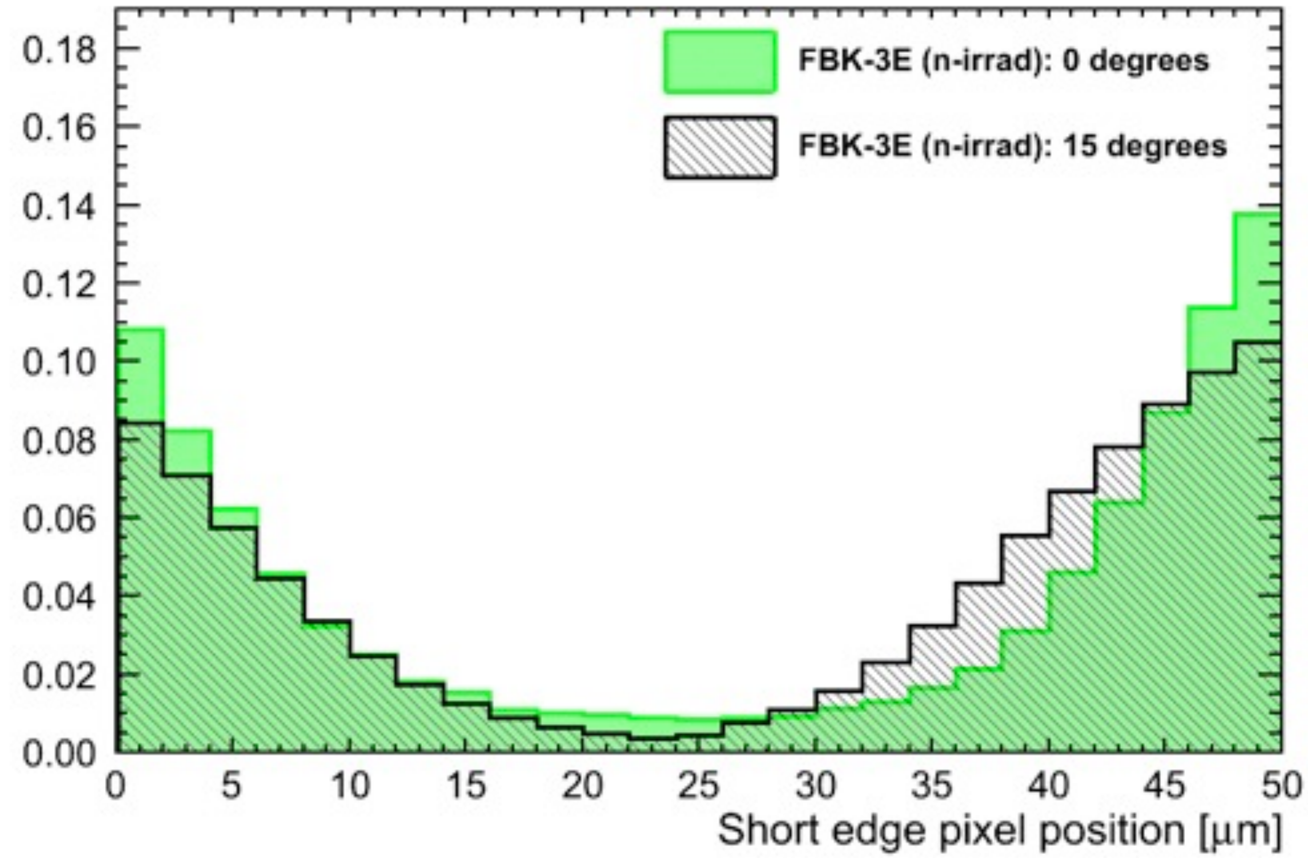
Charge sharing:

- signal can be shared between two or more cells, defined as $N_{tracks}(hits>1) / N_{tracks}(all)$
- good to have more precise determination of track position but collected charge low efficiency around pixel edge
- less signal, less probability to be above the threshold
- at 0° charge sharing pretty small
- as expected, increase in charge sharing at tilted incidence
- p and n irradiated similar behavior (attenuated for n-irrad)

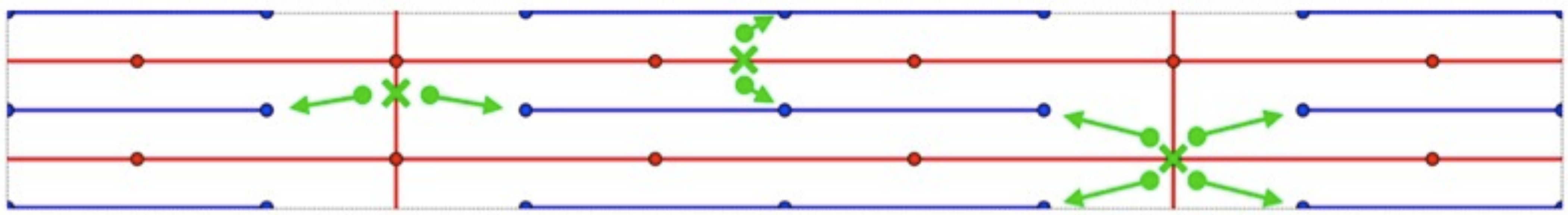
- note the different color coding for p/n

Test Beam Studies: Charge Sharing Probability

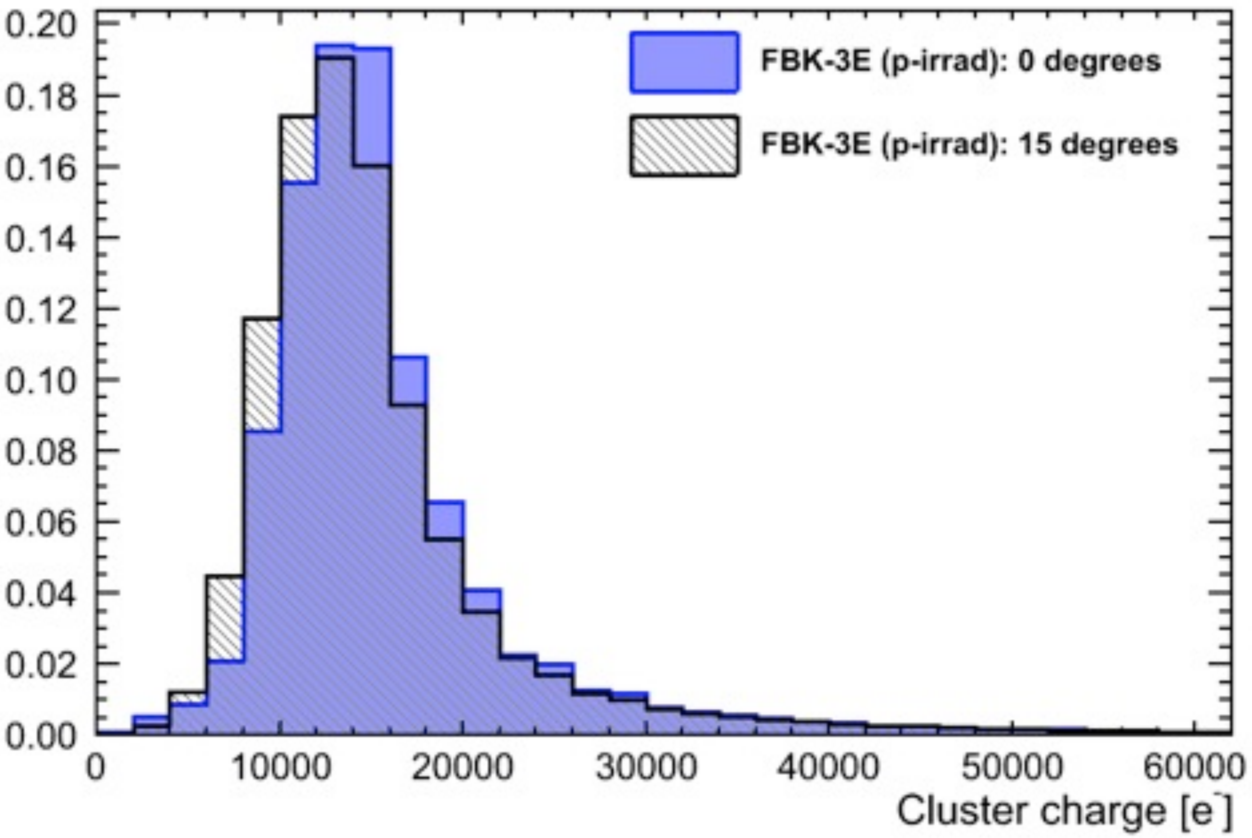


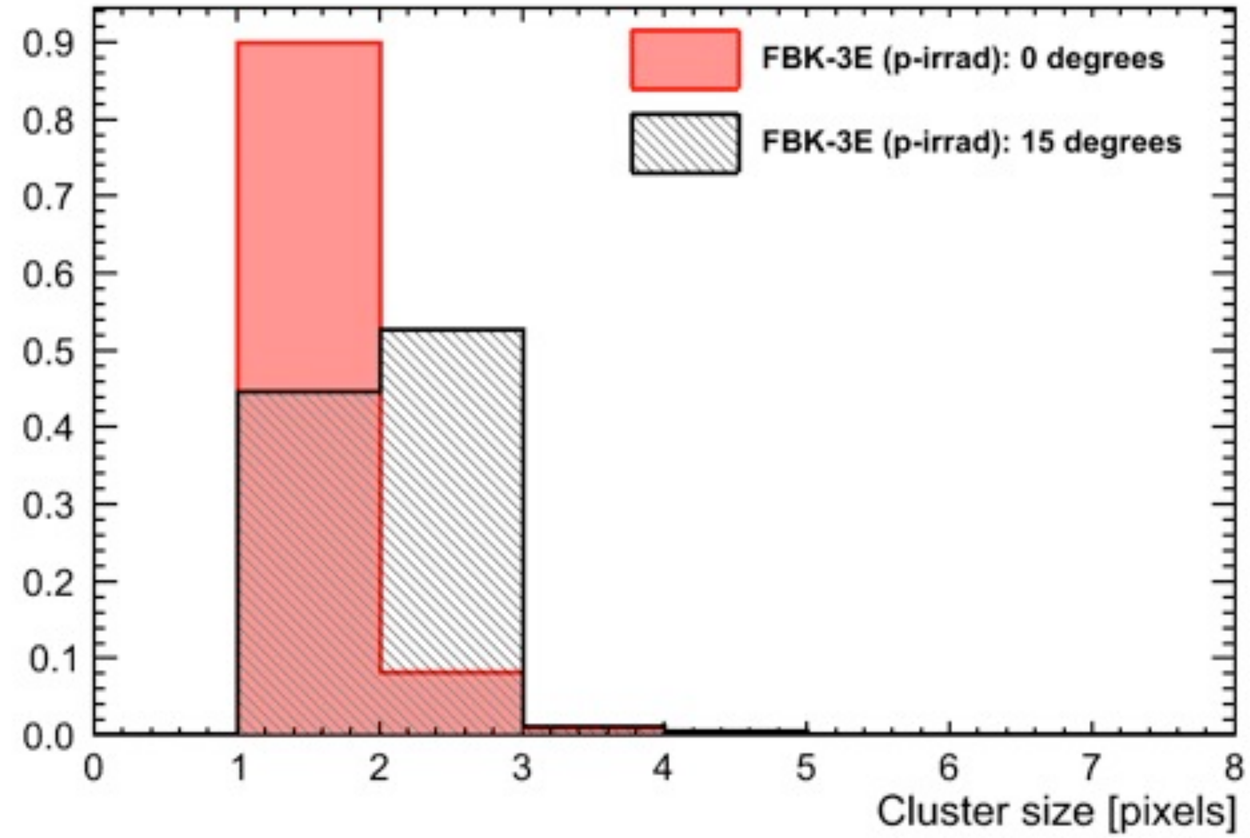


- charge sharing probability in the pixel short direction (50 μm) as a function of track position
- around pixel edge lower charge collected (lower efficiency) higher charge sharing



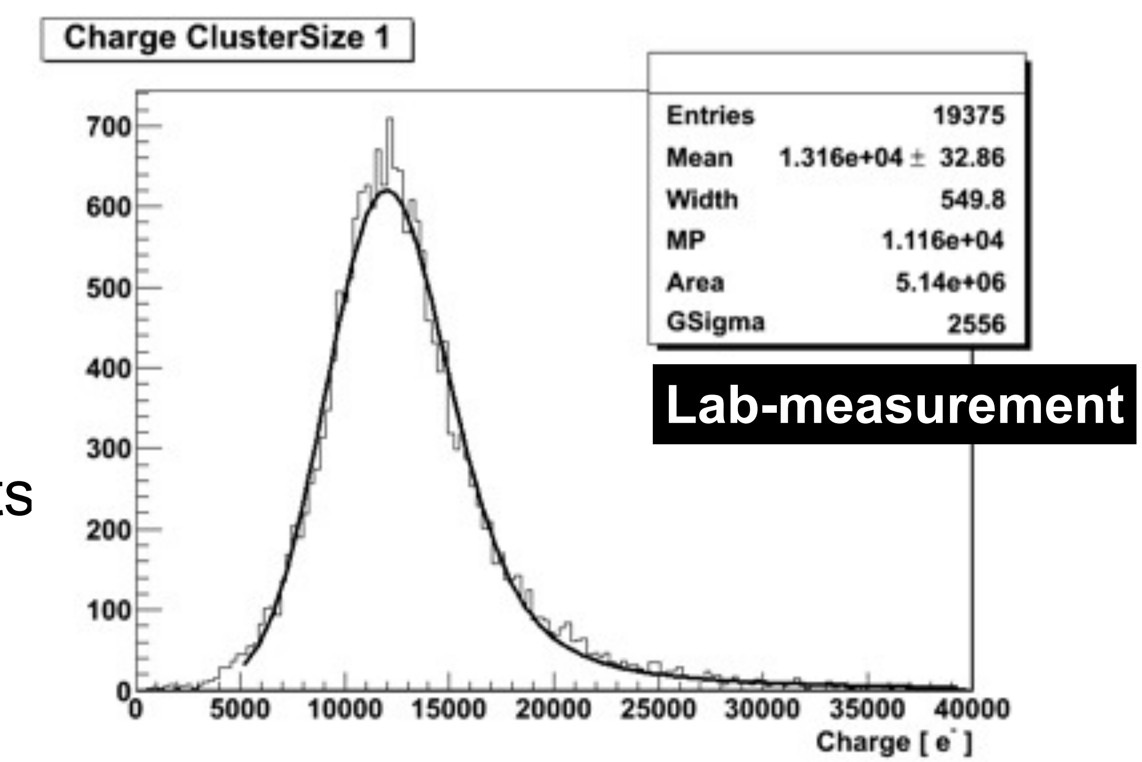
Test Beam Studies: Cluster Charge & Size



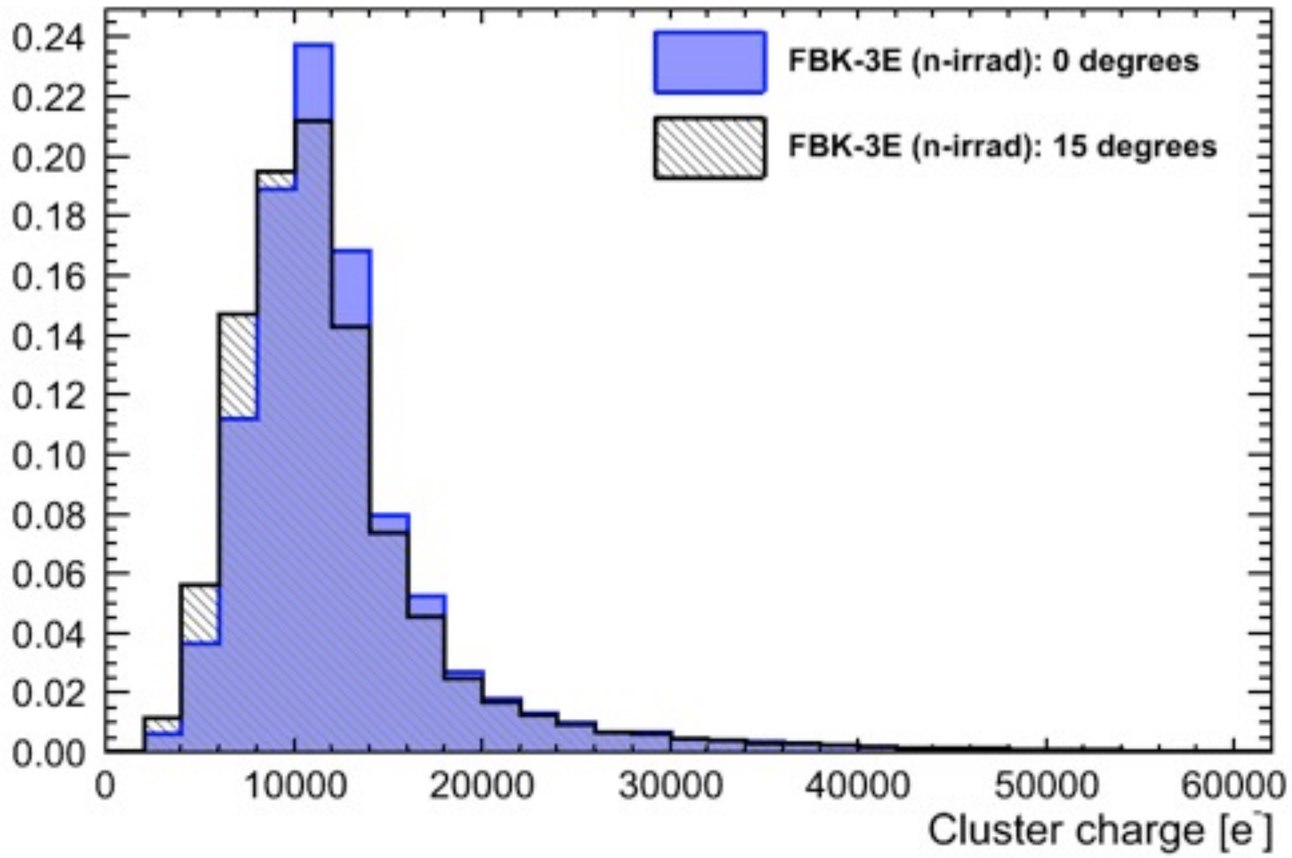


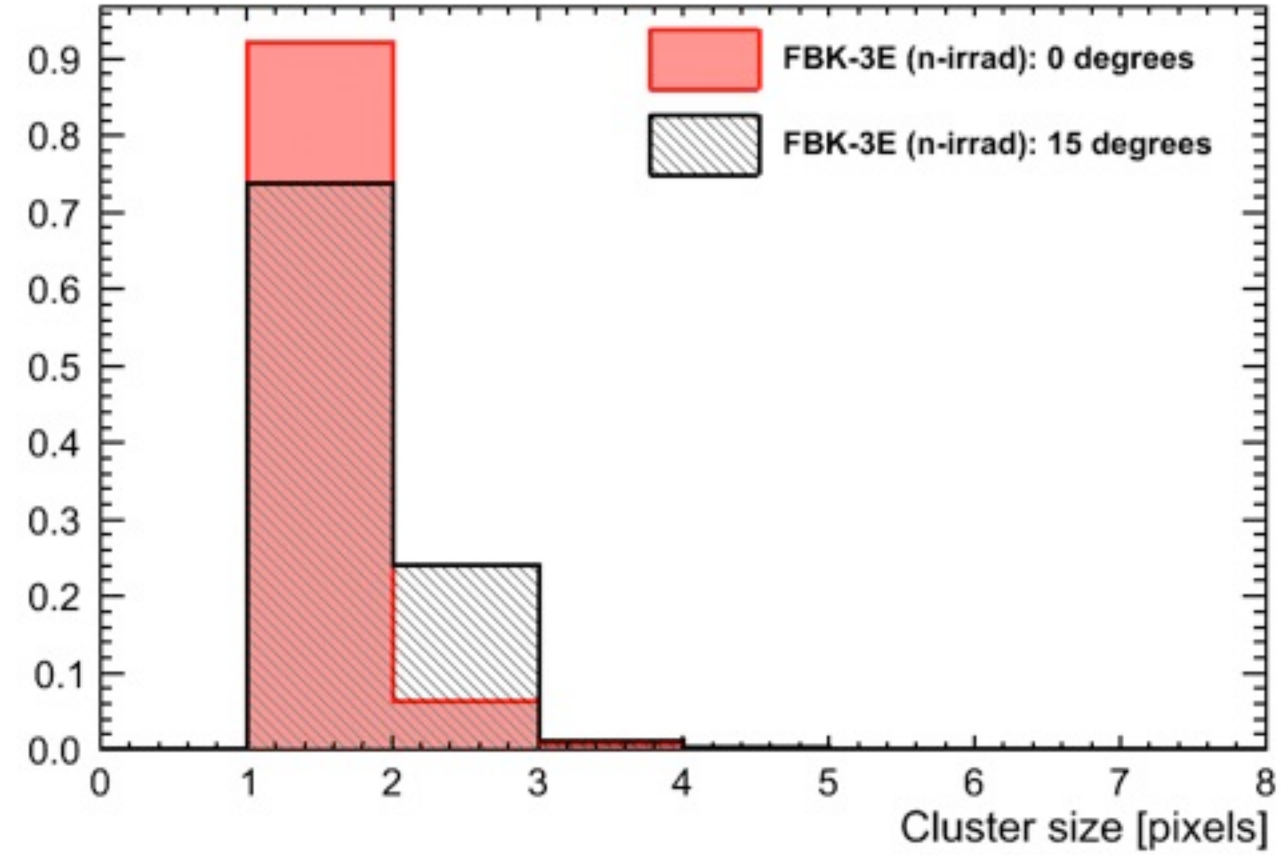
3D FBK-3E proton irradiated:

- mean cluster charge:
  16,210 e^- at 0° and 15,560 e^- at 15°
- mean cluster size:
  1.14 pixels at 0° and 1.60 pixels at 15°
- the results is comparable with the lab measurements with Sr^{90} source



Test Beam Studies: Cluster Charge & Size





3D FBK-3E neutron irradiated:

- charge in neutron irradiated sample is 20% lower than in proton
  - close to threshold
  - consistent with the lower efficiency
- mean cluster charge:
  13,010 e^- at 0° and 12,560 e^- at 15°
- mean cluster size:
  1.11 pixels at 0° and 1.30 pixels at 15°

Test Beam Studies: Summary

	Hit efficiency [%]		Charge Sharing [%]		Mean cluster charge		Mean Cluster size	
FBK	Φ=0°	Φ=15°	Φ=0°	Φ=15°	Φ=0°	Φ=15°	Φ=0°	Φ=15°
n-irrad	97.6	98.1	7.0	25.2	16.210	15.560	1.11	1.30
p-irrad	99.0	99.9	9.2	54.2	13.010	12.560	1.14	1.60
un-irrad	90.2	97.7*	12.2	62.1	16.400	15.980	1.19	1.41

- results here compared with an un-irradiated 3D-FBK (3E type) sample
- hit efficiency at 15°: p-irrad sample a little bit better than n-irrad (98.1% vs 99.9%)
- p-irrad charge sharing probability is almost double than for the n-irrad (15°)
- charge in neutron irradiated sample is 20% lower than in proton
- less collected charge (lower efficiency) and higher charge sharing around edges (at 15°)

* Φ = 14.1° for the un-irradiated FBK sensor

Summary and Outlook

- 3D-DDTC FBK sensors:
  - tested four devices of different fluence
    Here compared n-irradiated with the p-irradiated simple: the behavior looks similar
  - Lab measurements before & after irradiation: electrical, noise tests, response to radioactive sources (Am^{241}, Sr^{90}) has been done to complete the characterization (see talk by Alessandro La Rosa)
  - development of passing-through column detector is on-going
    - more wafers on the way (230 μm of overlap - sensor thickness)
      - should be more efficient: more overlap more collected charge,
      - 8 samples have been sent to be irradiated at fluence of 5×10^{15} n_{eq}/cm^2 (IBL target fluence)
    - behavior of the first 3D-FBK batch full column is currently under studying (test beam at Desy last February-March)
- Results have been already published:
  - A. Micelli *et. al* - “3D-FBK Pixel sensors: recent beam tests results with irradiated devices” (http://cdsweb.cern.ch/record/1304583)
- Future:
  - IBL test beam planned:
    - at Desy (from 4th April to 22nd) - Eudet Telescope
    - at CERN (May-June) with magnetic filed (Morpurgo Magnet)
    - measurements of the irradiated sensors

Thanks for your attention