Novel Silicon Pixel Detectors

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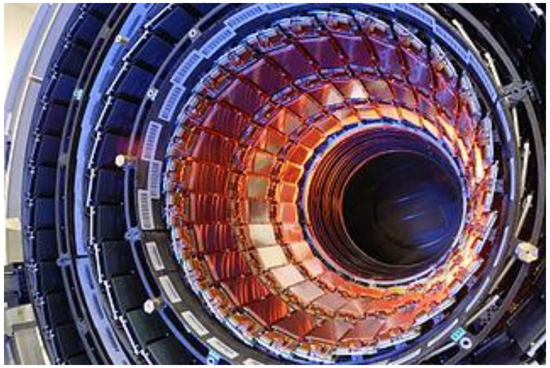
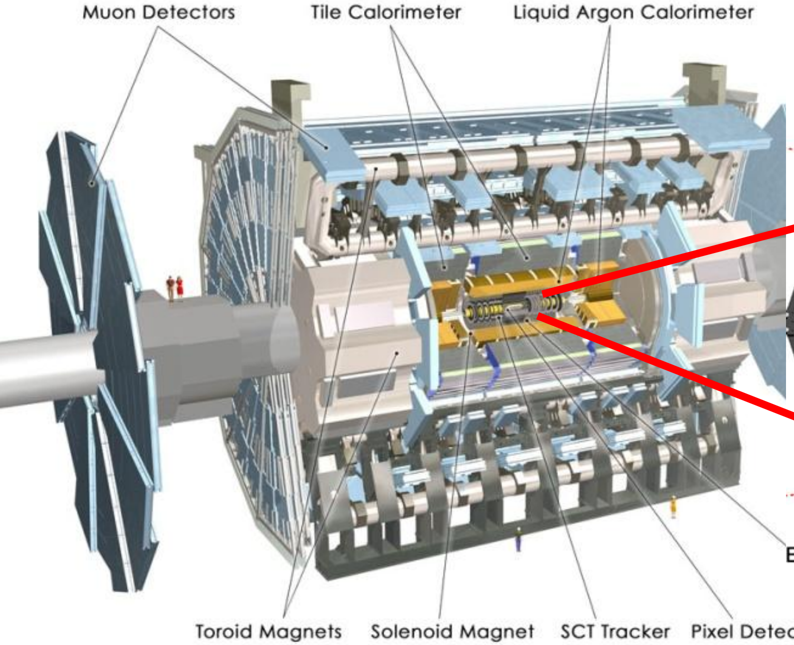
Introduction

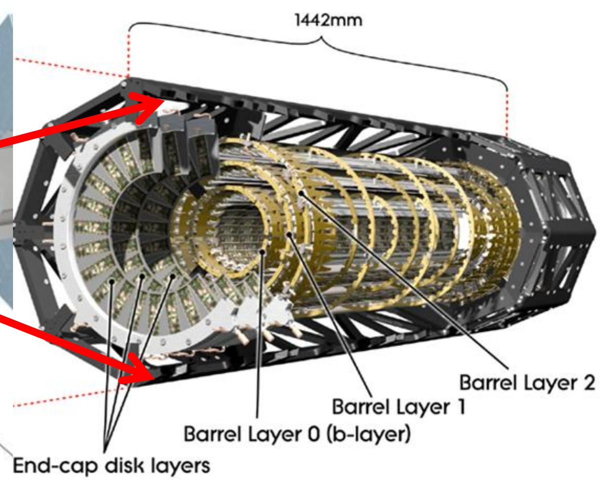
- Silicon tracking detectors are vital for every modern HEP collider experiment (e.g. ATLAS at the LHC) – and beyond
- Huge evolution since 80s from small vertex detectors to complex, large-area, many-channel Si trackers

CMS: All-Si tracker (200 m²)



ATLAS pixel:
80 M readout channels

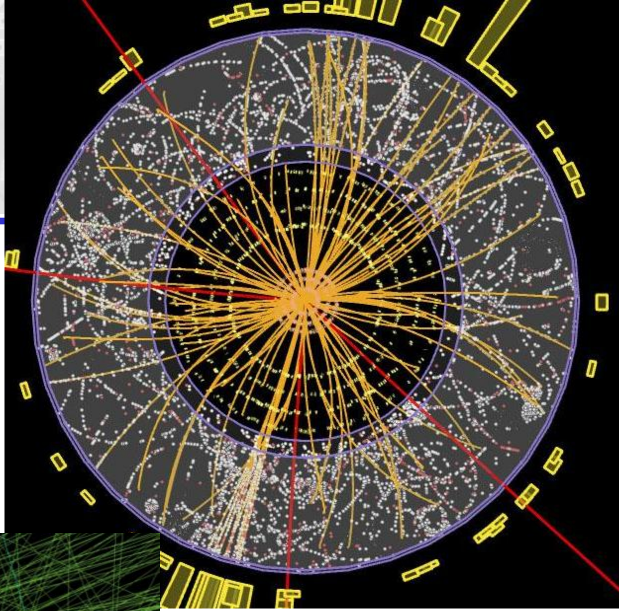




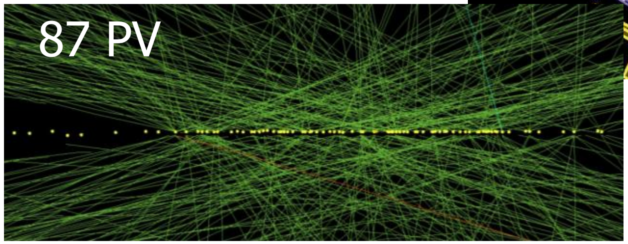
Silicon in space:
AMS, FERMI

Tasks of Si Detectors

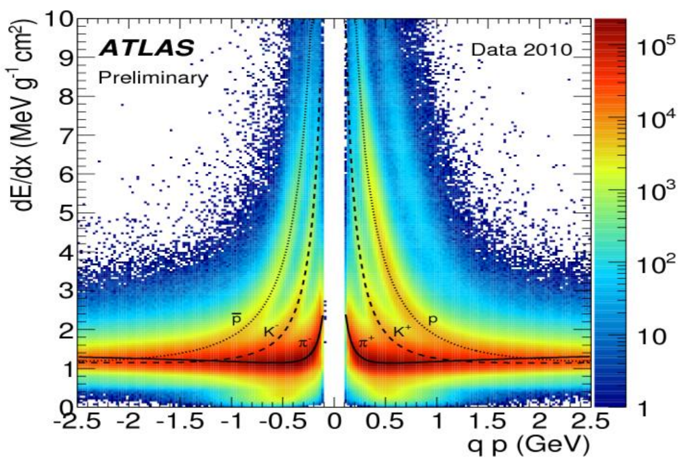
- Direction
- p_T
- Charge ID
  } Bending in B-field

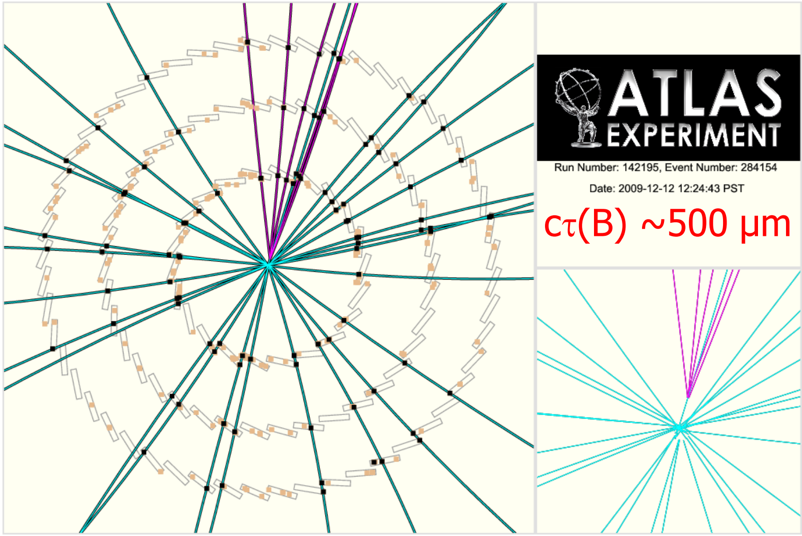


- Vertexing
  - Primary vertex (Pile-Up)
  - Secondary vertex (b-tagging)



- Particle ID

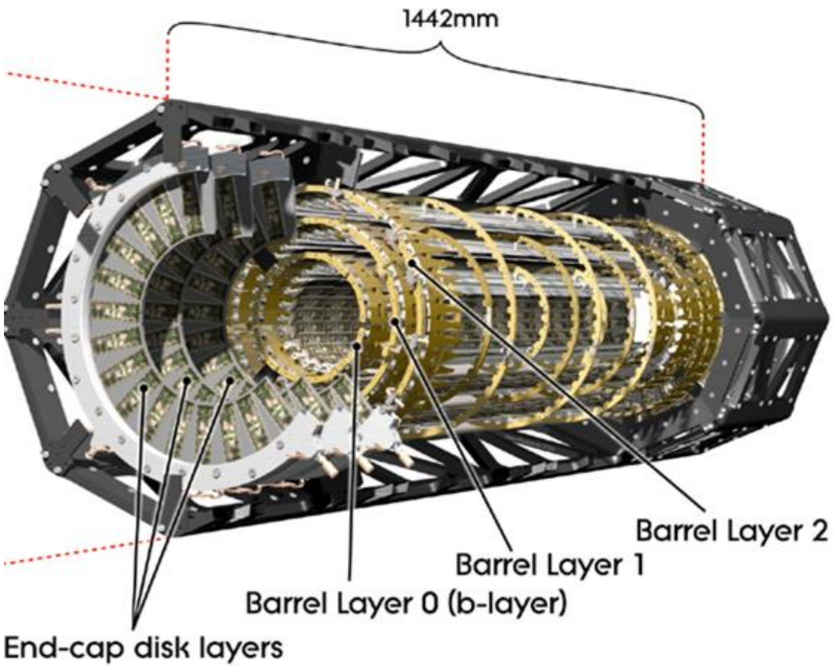


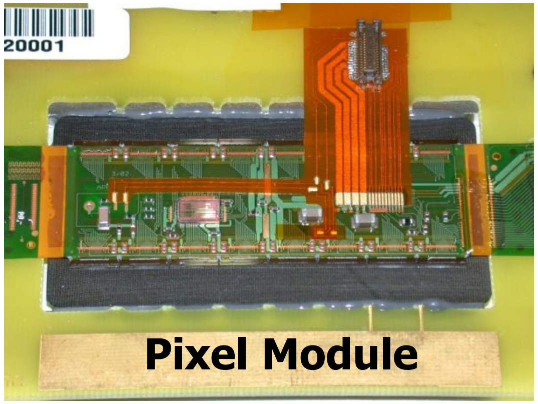


$c\tau(B)$ ~500 μm

Current ATLAS Si Pixel Detector

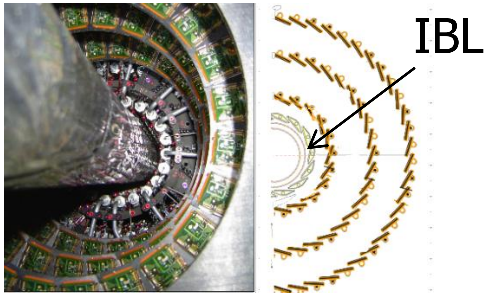
- 3 Barrel layers + end-cap disks
- 80 M readout channels
- Sensor technology:
  n-in-n planar pixel
- Position resolution
  - 50 x 400 μm^2 pixels
  → ~10 µm resolution (short side)
- High rate capability
  - LHC bunch crossing rate 20 – 40 MHz
- Radiation hardness
  - Fluence depends on radial position
  - Most in innermost layer: $2 \times 10^{15}\ n_{eq}/cm^2$



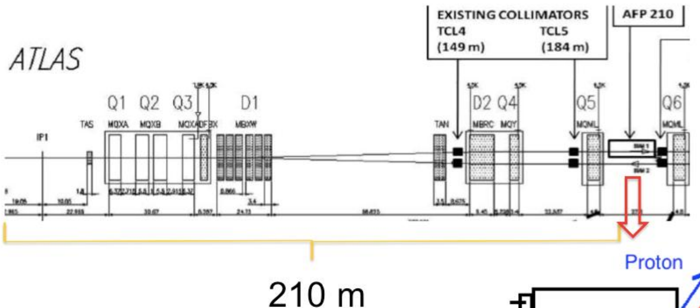


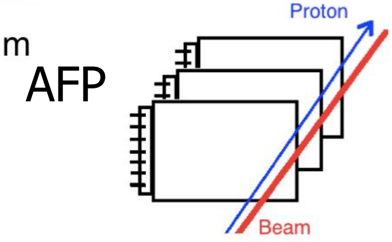
Pixel-Development Projects at IFAE

- ATLAS Insertable B-Layer (IBL), 2014
  - Additional innermost layer at r=3.3 cm
    -> enhanced vertexing/b-tagging, more redundancy
  - Increased radiation requirements: 5×10^{15} n_{eq}/cm^2



- ATLAS Forward Physics (AFP) detector, 2015/2016
  - Diffractive physics: tag intact forward protons
  - 210 m from IP, 2-3 mm from beam
  - Slim edges (only 100-200 μm dead area)
  - Non-uniform radiation: 5×10^{15} n_{eq}/cm^2 (max.)
    to many orders of magnitude lower





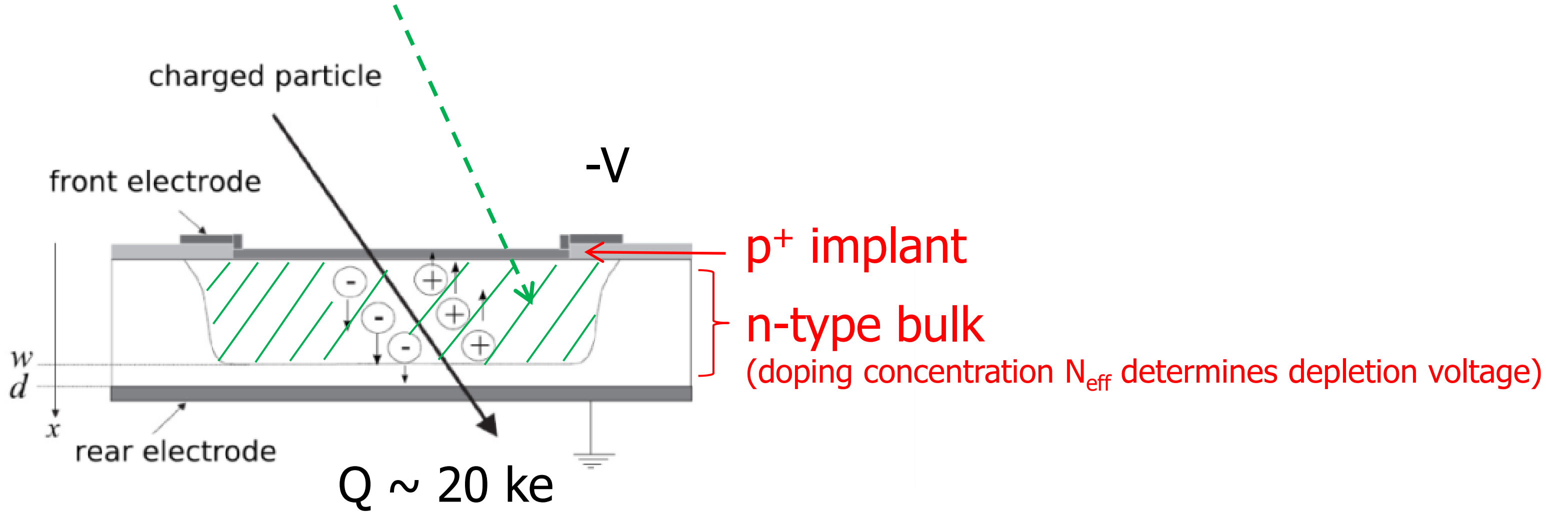
- ATLAS upgrade for high-luminosity LHC (HL-LHC), 2022
  - $L = 5 \times 10^{34}\ cm^{-2}s^{-1}$, 3000 fb^{-1} in total
  - Increased radiation requirements: 2×10^{16} n_{eq}/cm^2

→ Development of pixel detectors with new radiation-hard and slim-edge technologies

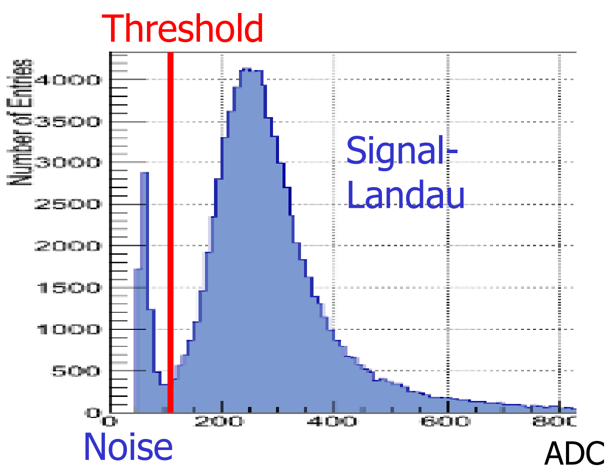
- Close collaboration with semiconductor fabricator CNM-Barcelona (next door)

Basics of Si Detectors

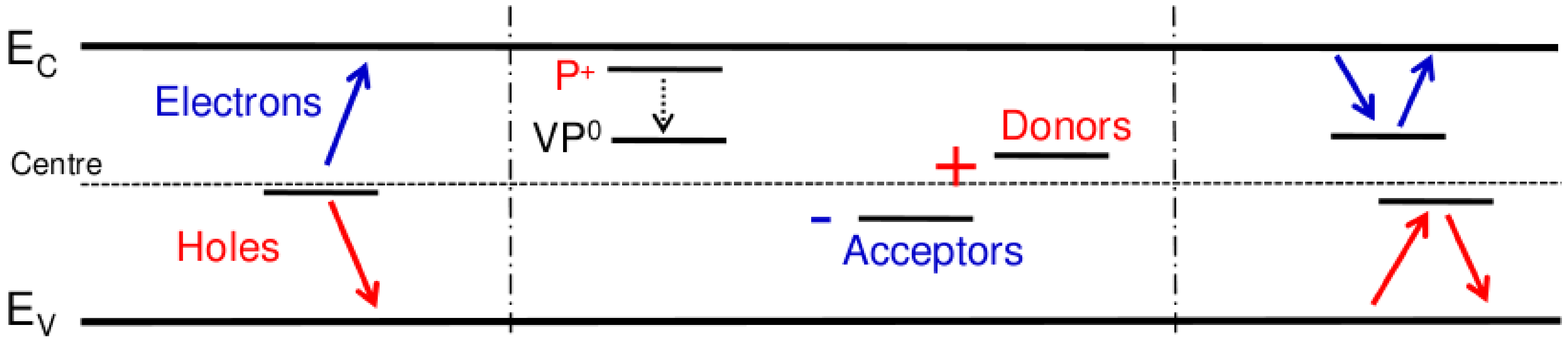
- Reverse-biased diode (e.g. p^+-n)
  depleted space-charge region = sensitive detector volume



- Signal-to-Noise Ratio (SNR): figure of merit
  Determines detection efficiency and noise occupancy
- Noise: $\sigma \sim \sqrt{aI_{leak} + (b + cC_{\det})^2 + \ldots}$



Radiation Damage



Generation	Removal & Creation of Donors and Acceptors	Trapping of e and h
⇒ Higher I_{rev} ⇒ Higher noise	⇒ Change of N_{eff} ⇒ Change of U_{dep} (signal loss for underdepletion)	⇒ Signal loss Most limiting factor at high fluences!

Degradation of signal-to-noise ratio

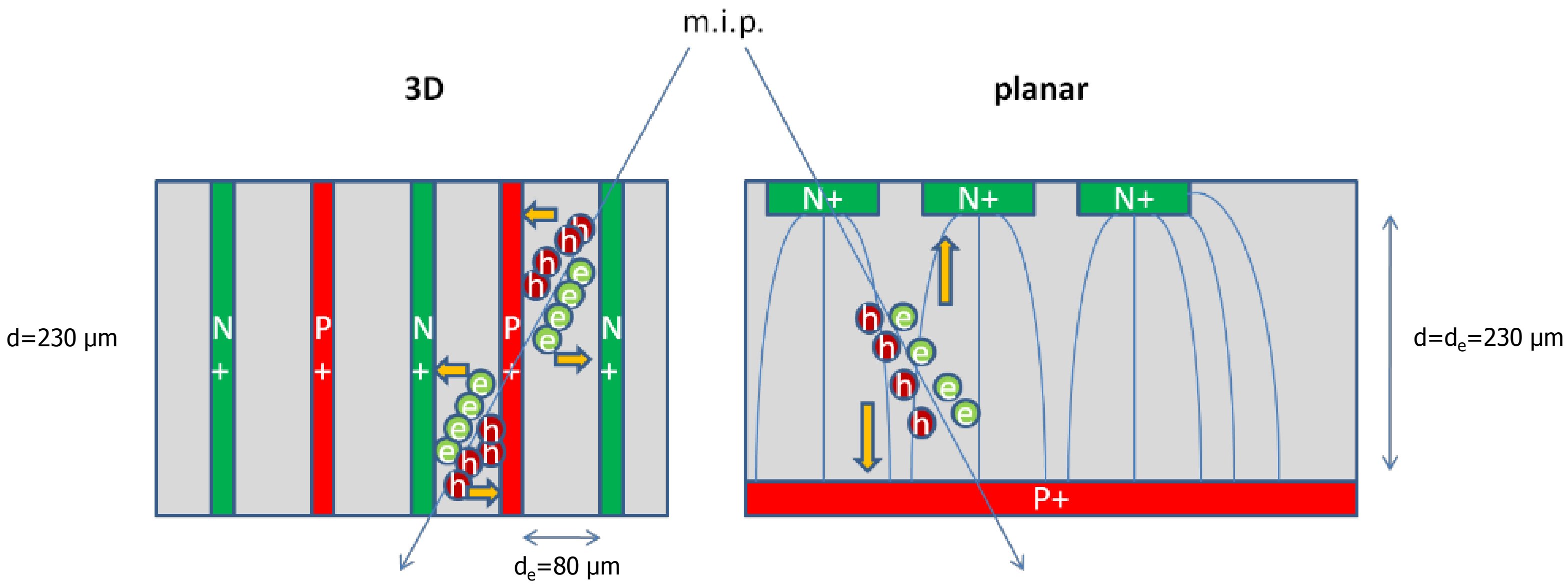
Towards Radiation-Hard Silicon

- Several concepts (CERN-RD-50 collaboration)
- IFAE/CNM: 3D detectors and detectors with charge multiplication

- 3D detectors: columnar electrodes
  - Detector thickness d and electrode distance d_e decoupled
    - Reduce electrode distance (d_e~80 μm) for lower depletion voltage and less trapping
    - Keep thickness (d~230 μm) for large charge deposition by m.i.p.

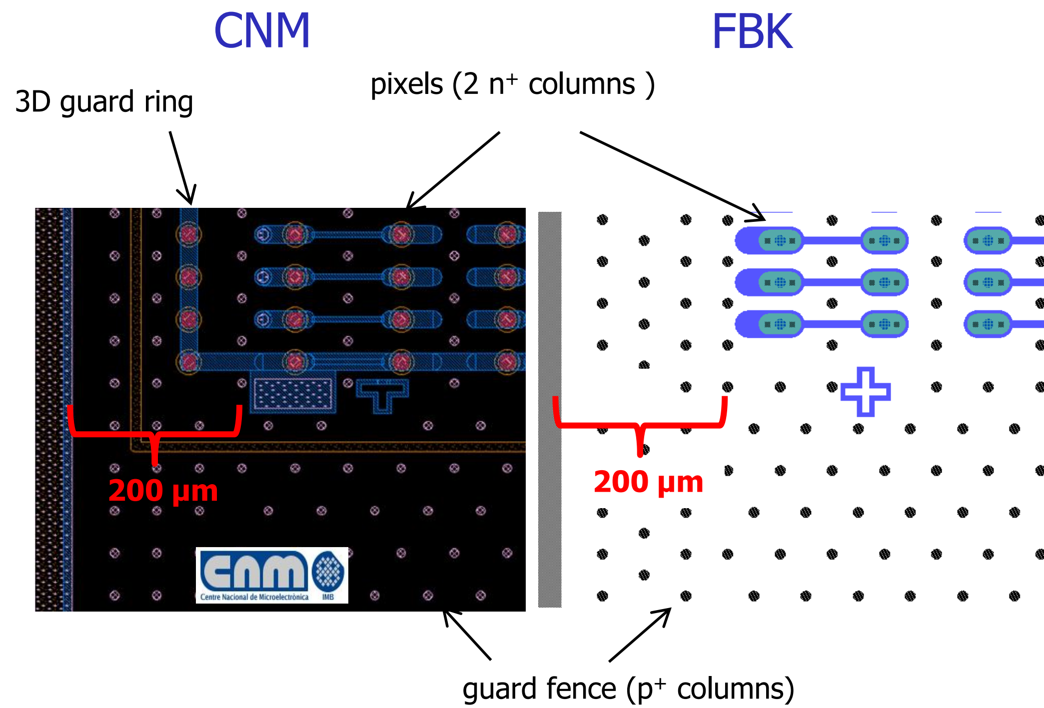
$$U_{dep} \propto N_{eff} d_e^{\,2}$$

$$N(t) = N_o e^{-\frac{t}{\tau_{trap}}}$$



3D Detectors for ATLAS IBL

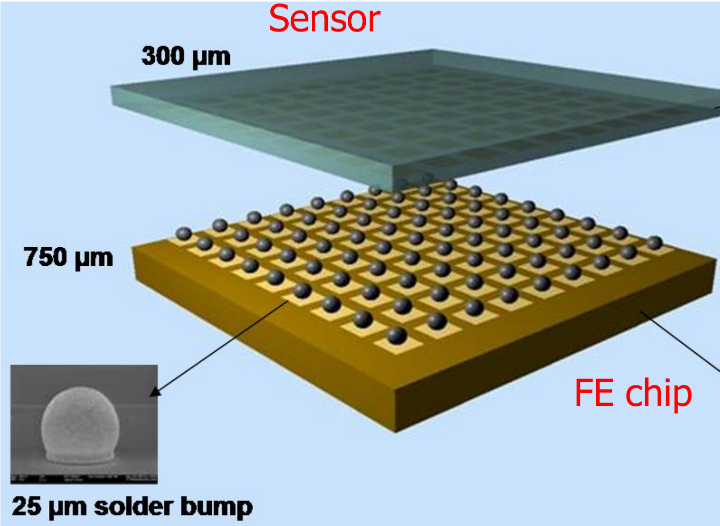
- ATLAS IBL:
  first application of 3D detectors
- Mixed design:
  75% rad.-hard planar sensors
  25% 3D sensors
  (produced by CNM and FBK)
- 336 x 80 pixels of 50 x 250 μm^2
  (new readout chip FE-I4)
- Left/right: 200 µm slim edge

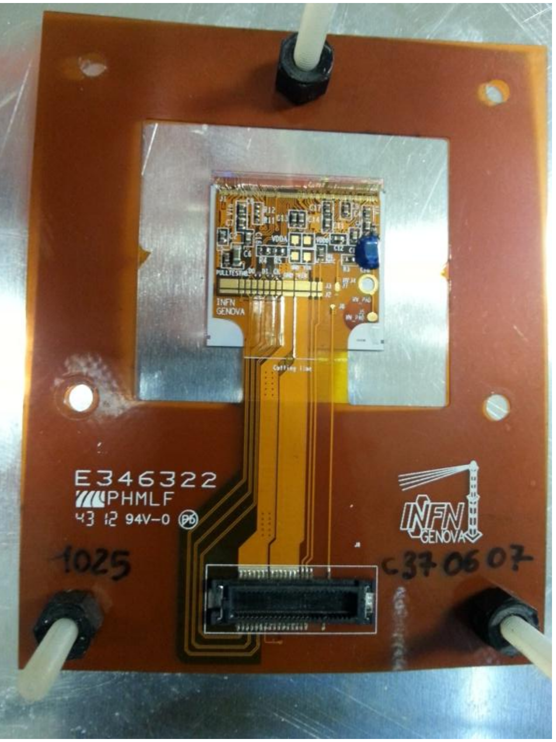


→ New technology needs to be qualified and prove performance

IFAE Pixel Lab – Module Production Facilities

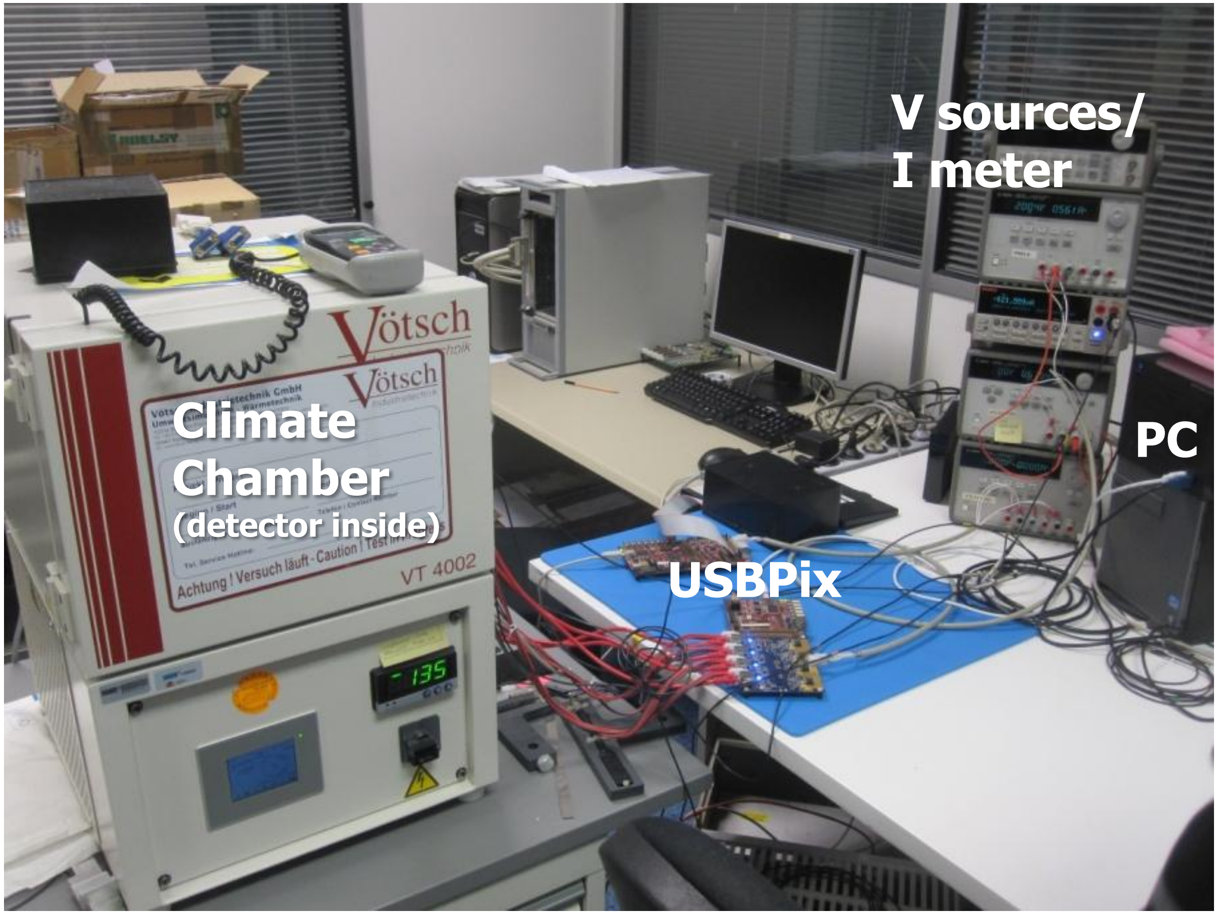
- 50 m^2 clean room
- Bump-bonding machines
  (connect sensor with FE chip)
- Wire-bonding machine
  (connects chip to electronic board/flex)





IFAE Pixel Lab – Operation and DAQ

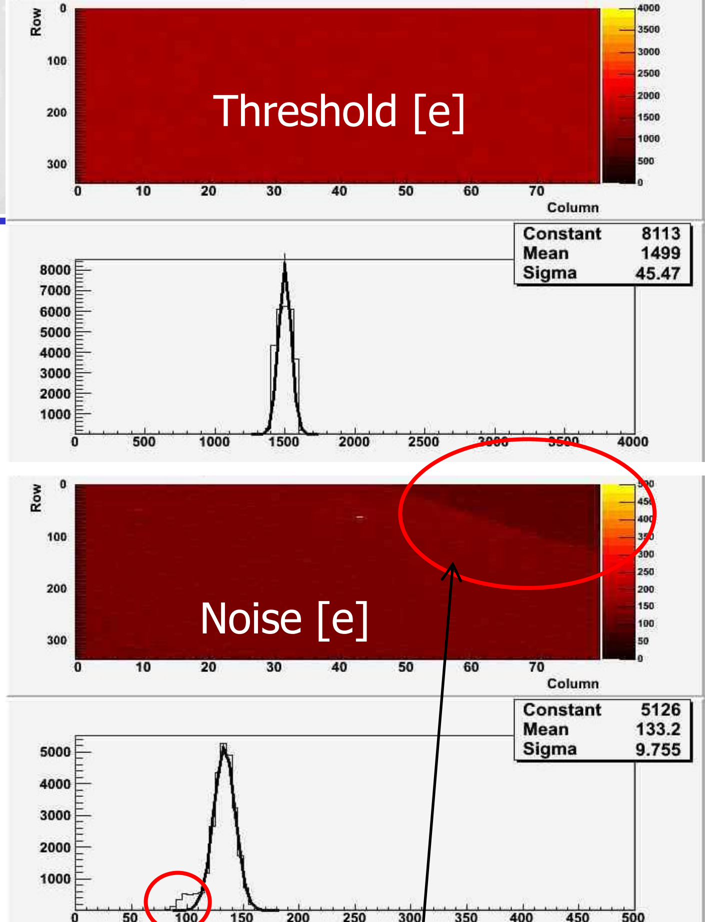
- Full operation and readout system

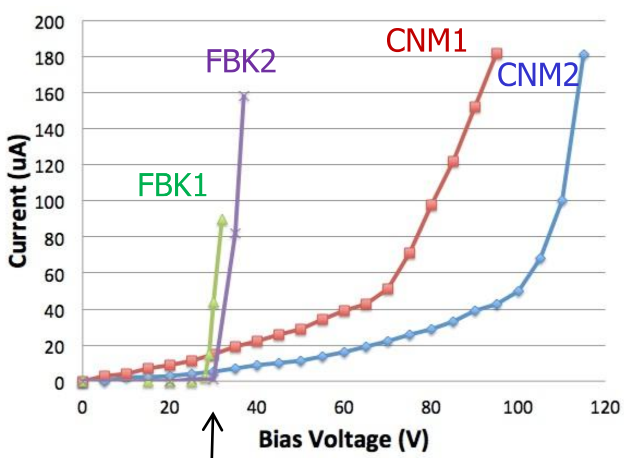


IFAE Pixel Lab – Operation and DAQ

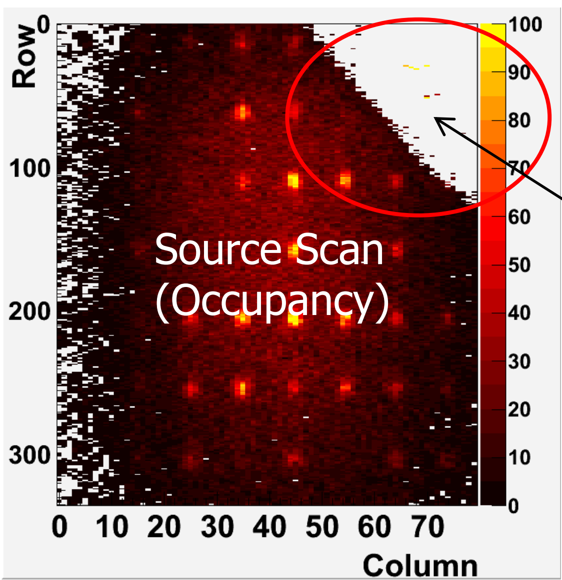
- Full operation and readout system
  - Tuning/calibration of charge and threshold
  - Radioactive source scans (Sr-90) with scintillator triggering
  - Electrical characterisations (current-voltage curves)

  - In general good performance!
  - Here: *BAD* devices for demonstration
    -> rejected for IBL





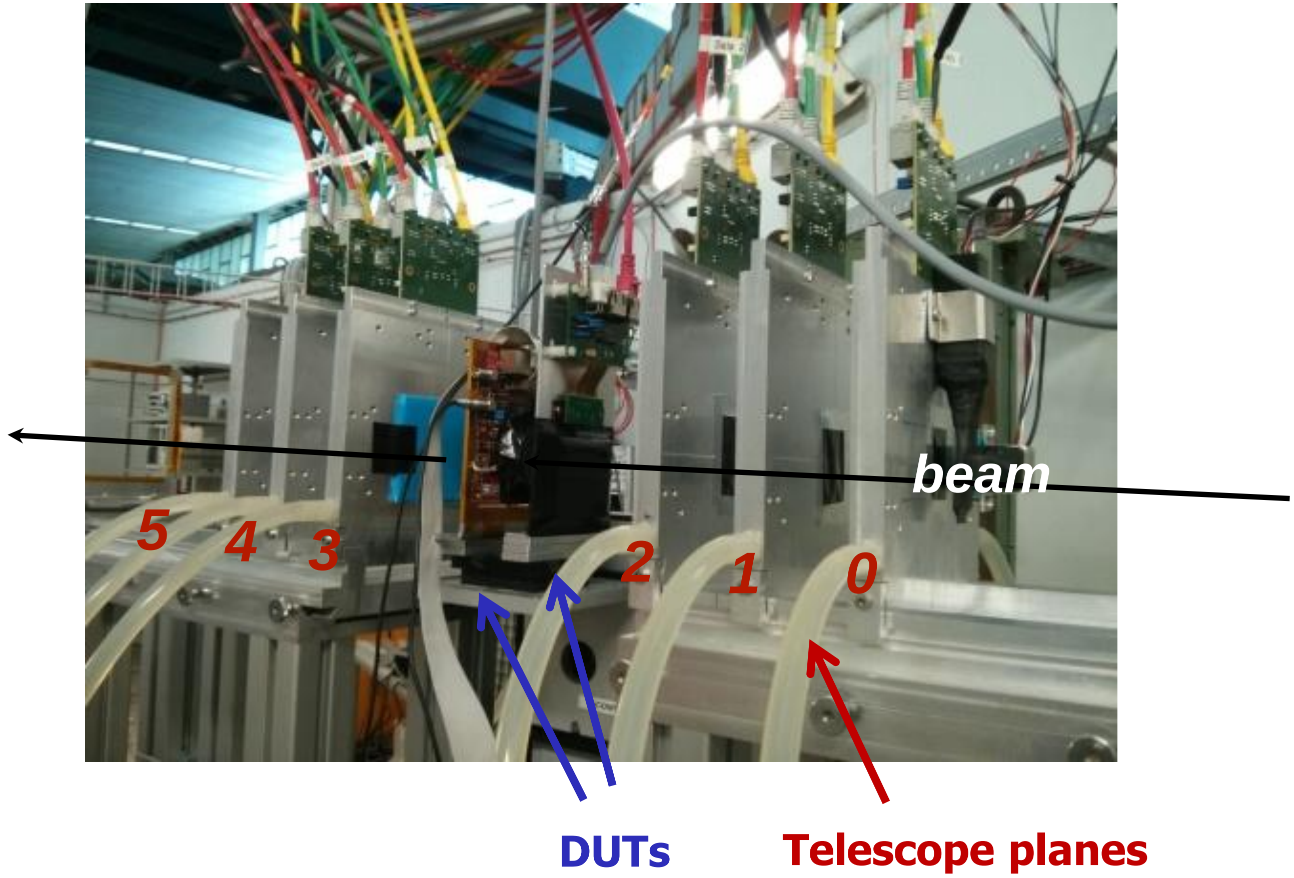
Low breakdown Voltage



Disconnected bumps

Test Beams – Resolution and Hit Efficiency

- Frequent use of test-beam facilities (CERN: Pions, DESY: e, SLAC: e)
- Beam telescope: trajectory precisely measured externally
  → resolution and hit efficiency of DUT determinable

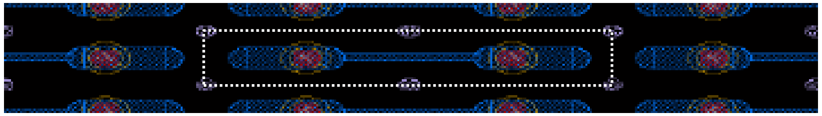


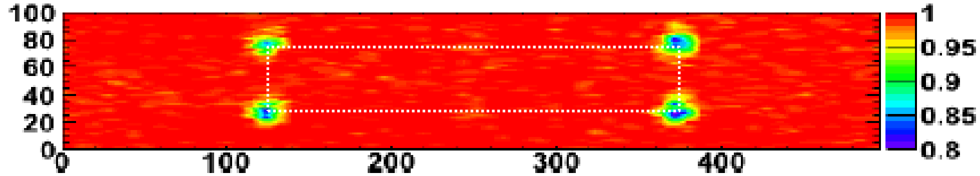
Test Beams – Resolution and Hit Efficiency

- Test of unirradiated and irradiated devices (IBL fluence: 5 x 10^{15} n_{eq}/cm^2)
- Results
  - Efficiency > 97% even after irrad.
  - Resolution ~10 μm in short pixel direction (13 μm after irrad.)

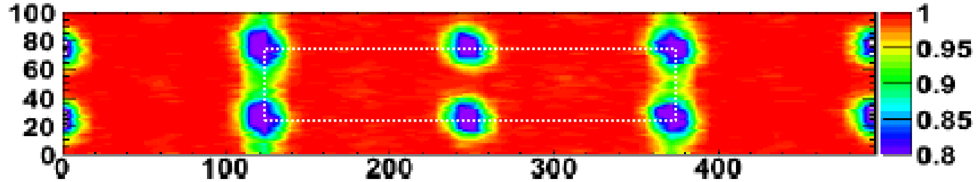
→ IBL requirements fulfilled

2x2-pixel efficiency map:

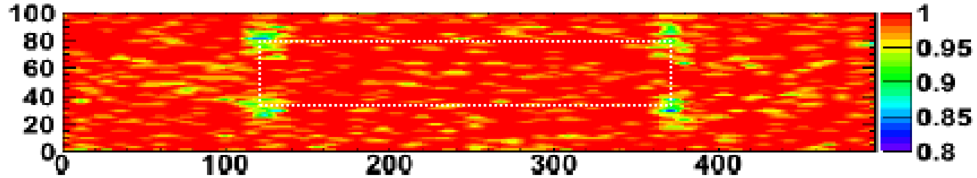




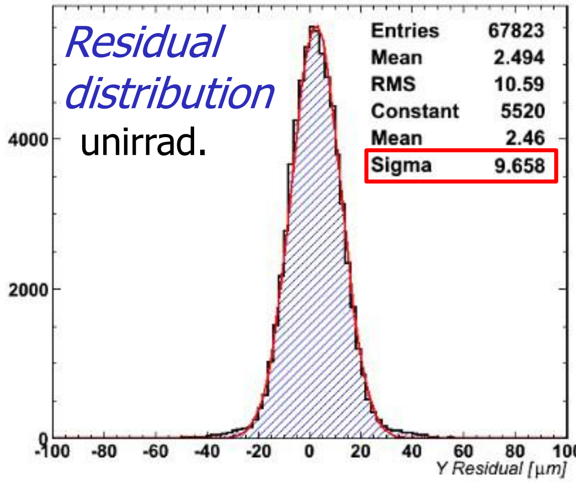
SCC55 **CNM-3D**, un-irrad, HV=20V, **Eff.=99.4%**



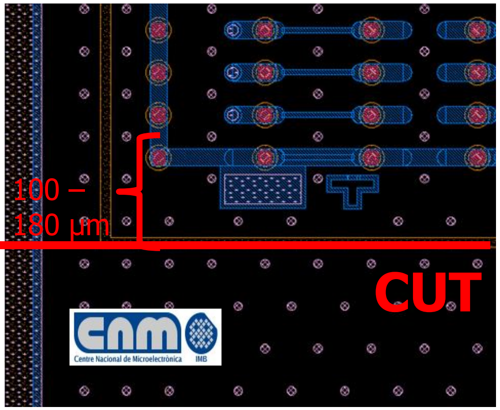
SCC81 **CNM-3D**, n-irrad, HV=160V, **Eff.=97.46%**

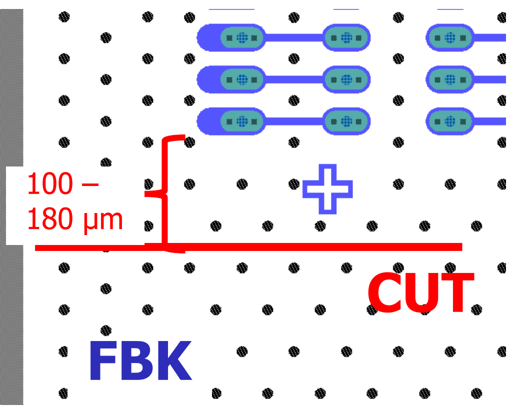


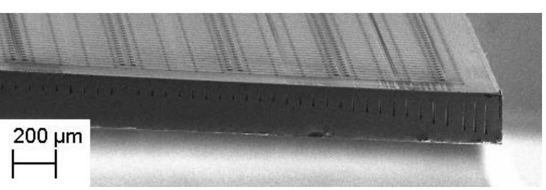
SCC34 **CNM-3D**, p-irrad, HV=160V, **Eff.=98.96%**



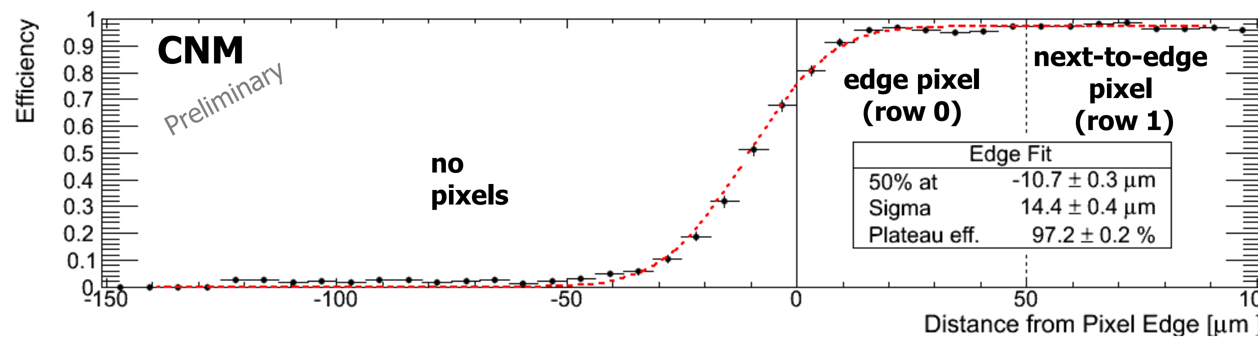
Additional AFP Requirements – Slim Edge and Non-Uniform Irradiation

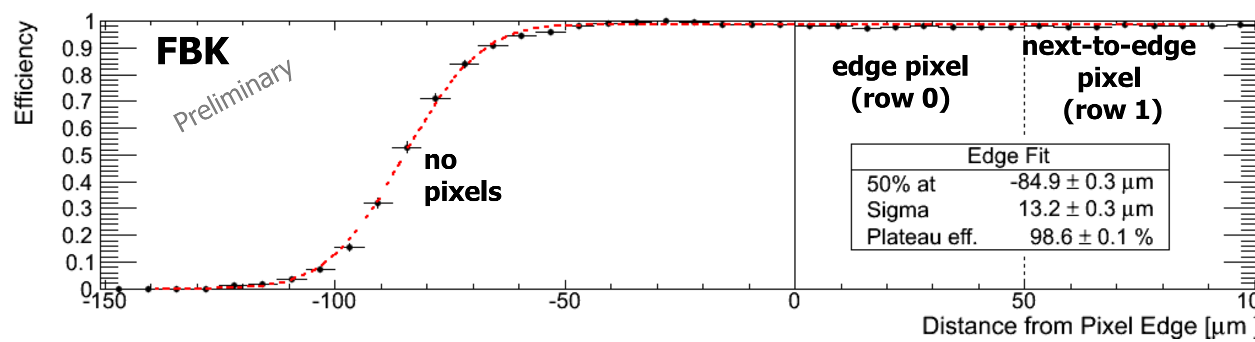






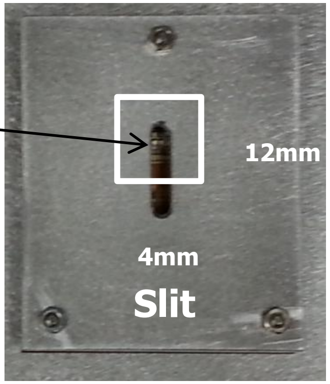
- Slim edge:
  - Cut >1mm dead material away down to 100-180 µm
  - Excellent efficiency up to last pixel
  - Even beyond for FBK:
    efficient edge due to lack of guard ring



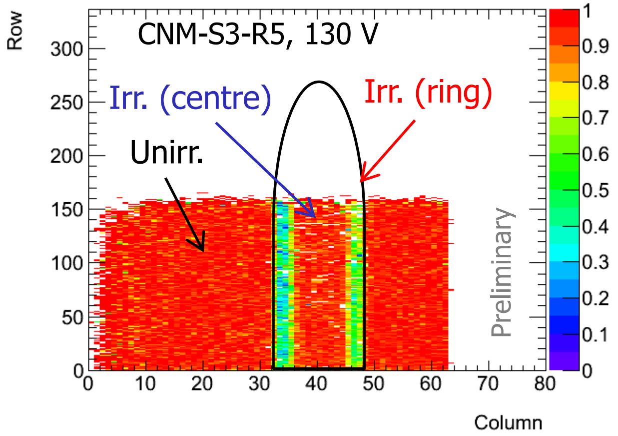


Additional AFP Requirements – Slim Edge and Non-Uniform Irradiation

- Non-uniform irradiation:
  - Through hole (Karlsruhe 23 MeV p)
  - Difficult to tune such a non-uniformly irradiated device
  - Efficiency in centre of irradiated hole within 1% of unirradiated part
    (Ring of lower eff. probably due to higher fluence)



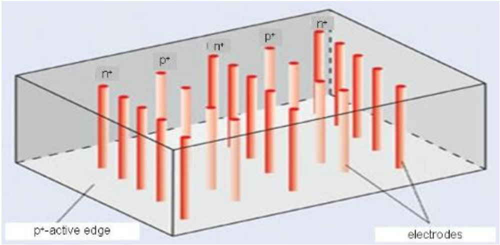
→ AFP requirements fulfilled



- 3D production run at CNM ongoing (end: April)
- Module production and qualification at IFAE

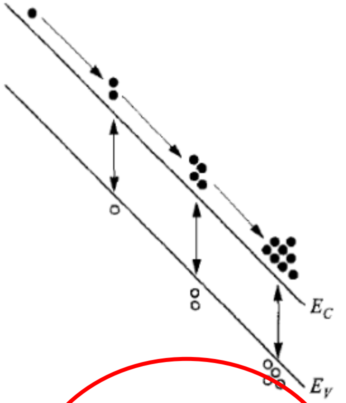
Ultra-Radiation Hardness for High-Luminosity LHC

- HL-LHC radiation: 2 x 10^{16} n_{eq}/cm^2 (compare IBL: 5 x 10^{15} n_{eq}/cm^2)

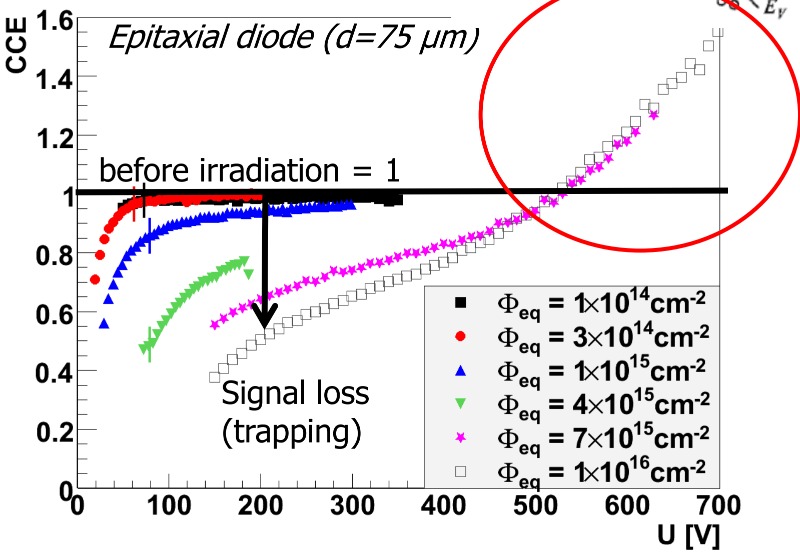


- Strategies:

1) Further development of 3D detectors
   - Only 25 µm pixel size? Possibly also more radiation-hard
   - Challenge: reduce column diameter



2) Silicon detectors with charge multiplication
   - Effect of high electric fields
   - Widely used in gas det. or APD/SiPM
   - Naturally occurring after high irradiation in thin detectors at high voltages
   - New idea: built-in high-electric-field region with high-doping layer
   - Both in planar or 3D sensors
   - Challenges: Gain uniformity, stability, …
   - First test structures produced by CNM investigated

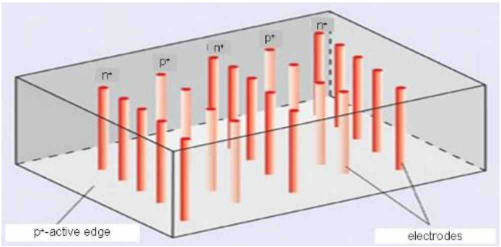


Conclusions

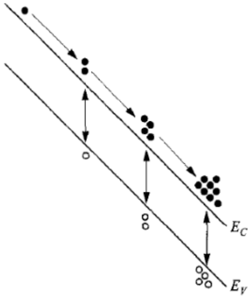
- Silicon pixel detectors are crucial for good performance of collider experiments
- Radiation hardness and slim edges are key requirements for upgrades (IBL 2014, AFP 2015/16, HL-LHC 2022)
- New technologies developed by collaboration incl. CNM and IFAE
  - 3D detectors
    - Electrode distance decoupled from thickness
    - Radiation-hard up to ≥ 5 x 10^{15} n_{eq}/cm^2
    - Slim edges (100-200 µm)

    → Fulfills IBL and AFP requirements

    Further development for HL-LHC ongoing



  - Detectors with charge multiplication
    - Hot topic in radiation-hardness community
    - R&D towards possible application at HL-LHC ongoing



  - Possible involvement of IFAE Pixel group in High-Voltage/Resistivity CMOS
    - (Semi) Monolithic detectors: Readout electronics included in sensor