Recent Progress on 3D Silicon Detectors

Jörn Lange

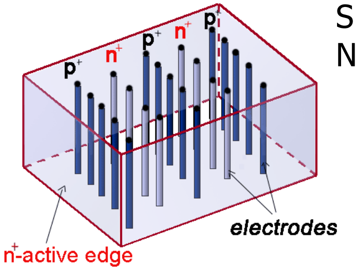
IFAE Barcelona

24th International Workshop on Vertex Detectors, Santa Fe, 3 June 2015

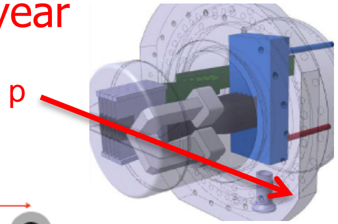
With material from the ATLAS and CMS 3D groups, RD50,
CNM, FBK, SLAC and SINTEF

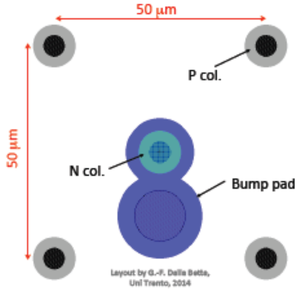
3D Detectors – a Success Story

- 1997: First idea and devices
- Huge R&D effort
  - Manufacturers, ATLAS+CMS, RD50, …
- ATLAS IBL
  - First installation of 3D detectors in a HEP experiment
- Forward Detectors: 2nd use of 3D detectors within 1 year
  - ATLAS Forward Proton (AFP)
  - CMS-TOTEM PPS
- HL-LHC Phase-2 Upgrades ~2024
  - New generation of 3D detectors



S. Parker, C. Kenney, J. Segal
NIM A 395 (1997), 328





Outline

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- ATLAS IBL
  - First installation of 3D detectors in a HEP experiment
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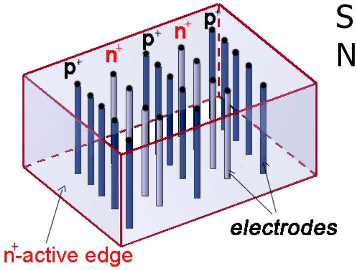
- Conclusions



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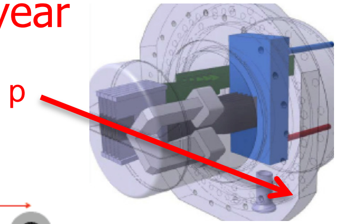
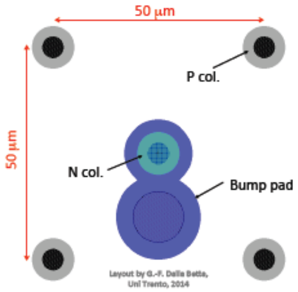
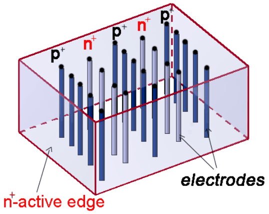
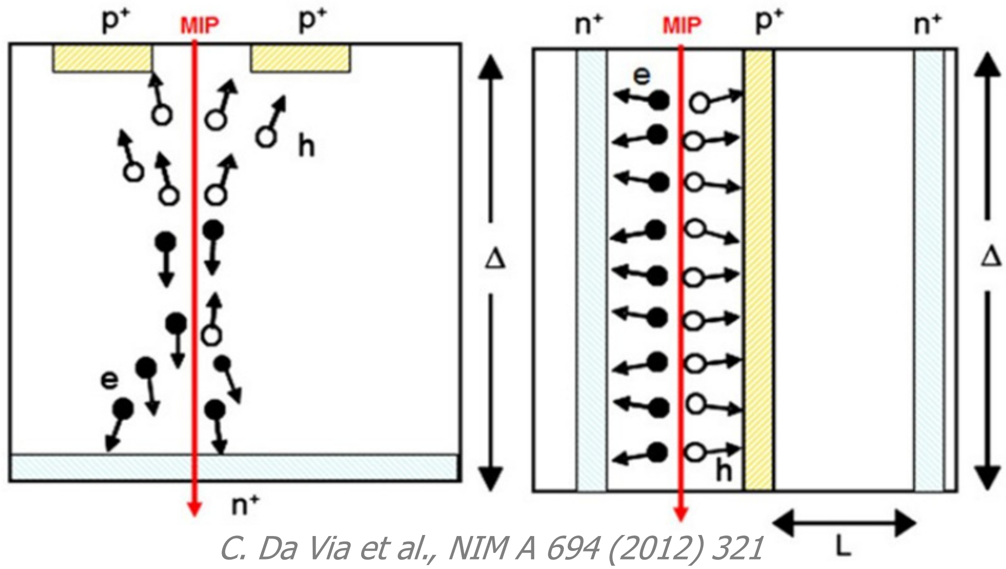




3D Detector Principle



Planar Technology 3D Technology



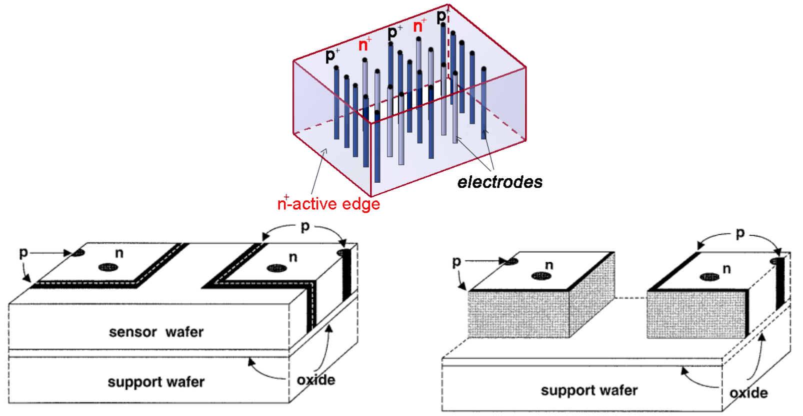
C. Da Via et al., NIM A 694 (2012) 321

Radiation-hard and active/slim-edge technology

- **Advantages**
  - Electrode distance decoupled from sensitive detector thickness
    → lower $V_{depletion}$
      → less power dissipation, cooling
    → smaller drift distance
      → faster charge collection
      → less trapping
  - Active or slim edges are natural feature of 3D technology
- **Challenges**
  - Complex production process
    → long production time
    → lower yields
    → higher costs
  - Higher capacitance
    → higher noise
  - Non-uniform response from 3D columns and low-field regions
    → small efficiency loss at 0°

Different 3D Technologies

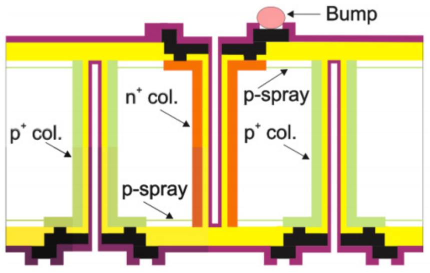
SNF (Stanford) / SINTEF (Oslo)



C. Kenney et al., IEEE TNS 48 (2001) 2405

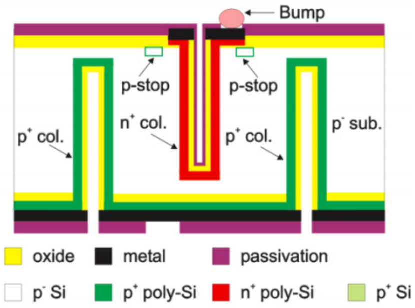
- **Single-sided process (“Full 3D”)**
  - Both column types (n, p) edged from front
    - Needs support wafer
→ removal needed
    - Bias to be applied at front side
→ overhanging bias tab or other front-side biasing
  - Allows active edges
    - Only few μm dead material

FBK (Trento)



A. Zoboli et al., IEEE TNS 55(5) (2008) 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

CNM (Barcelona)

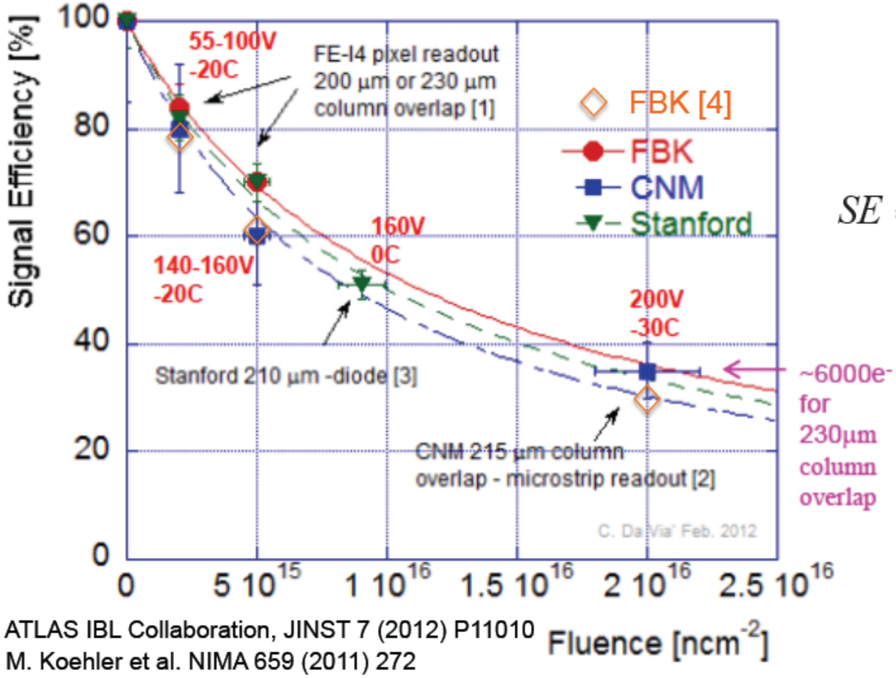


G. Pellegrini et al. NIMA 592(2008) 38
G. Pellegrini et al. NIMA 699(2013), 27

- **Double-sided process**
  - n columns etched from front, p from back
    - FBK: passing-through columns, p-spray
    - CNM: non-passing-through columns, p-stop
    - No support wafer needed
    - Bias applied at back side → no bias tab needed

    → reduced process and assembly complexity
  - Allows slim edges
    - FBK: p^+ guard fence → ~10 μm
    - CNM: p^+ guard fence + 3D guard ring → ~150 μm

R&D Performance Summary



[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010

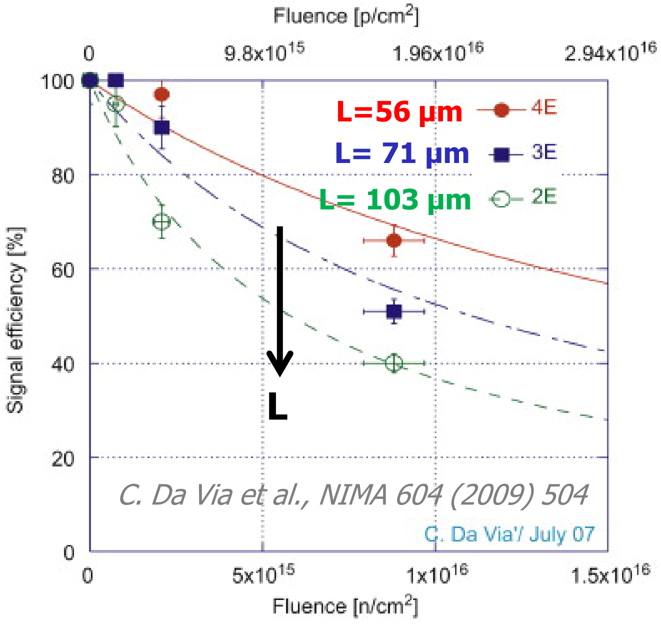
[2] M. Koehler et al. NIMA 659 (2011) 272

[3] C. Da Via, et al., NIMA 604 (2009) 505

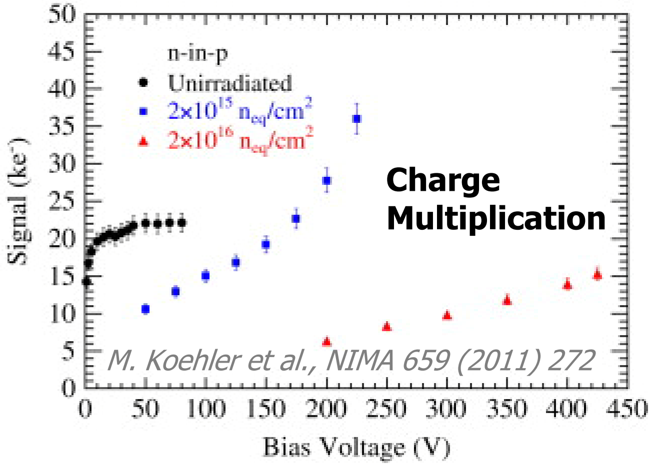
[4] G.-F. Dalla Betta, et al., HSTD9 (2013)

Compilation by C. Da Via, modified by G.F. Dalla Betta

$$SE = \frac{1}{1 + 0.6L \dfrac{K_\tau}{v_D} \Phi}$$



C. Da Via et al., NIMA 604 (2009) 504

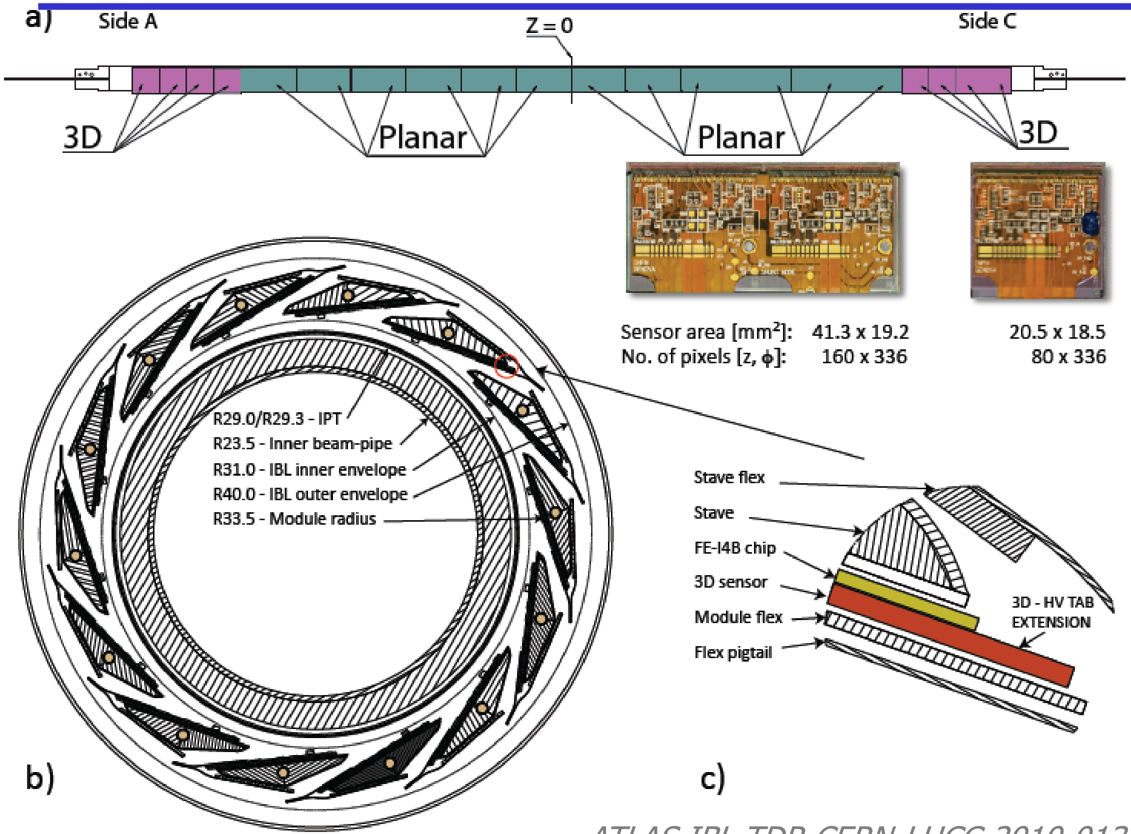


Charge Multiplication

M. Koehler et al., NIMA 659 (2011) 272

- Signal efficiency (SE) of 60-70% at 5×10^{15} n_{eq}/cm^2 and 30% at 2×10^{16} n_{eq}/cm^2 achieved for moderate V < 200 V
- Signal efficiency (SE) improves with decreasing electrode distance L
- Charge multiplication at high fluences and V can further boost collected charge

ATLAS IBL: First Use of 3D Detectors

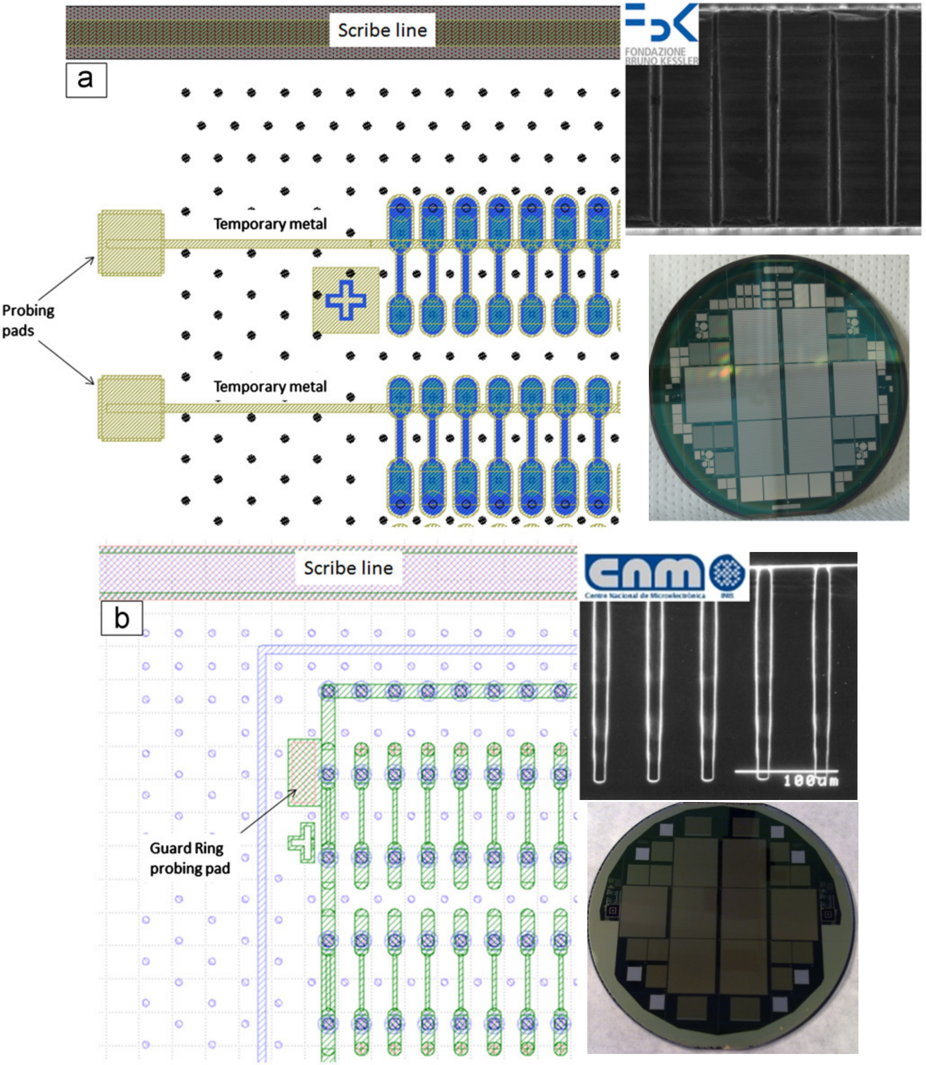


ATLAS IBL TDR CERN-LHCC-2010-013
G. Darbo, JINST 10 (2015) C05001

See talk by D. Dobos

- First upgrade of ATLAS pixel in long shutdown 1 (2013-2015): new innermost layer at 3.3 cm
- FE-I4: largest pixel front-end chip
- Radiation levels up to $5\mathrm{x}10^{15}$ n_{eq}/cm^2, 250 Mrad
- 2011 sensor technology decision:
  - 75% n-in-in planar 200 µm (CIS)
  - **25% double-sided 230 µm 3D** (CNM+FBK)

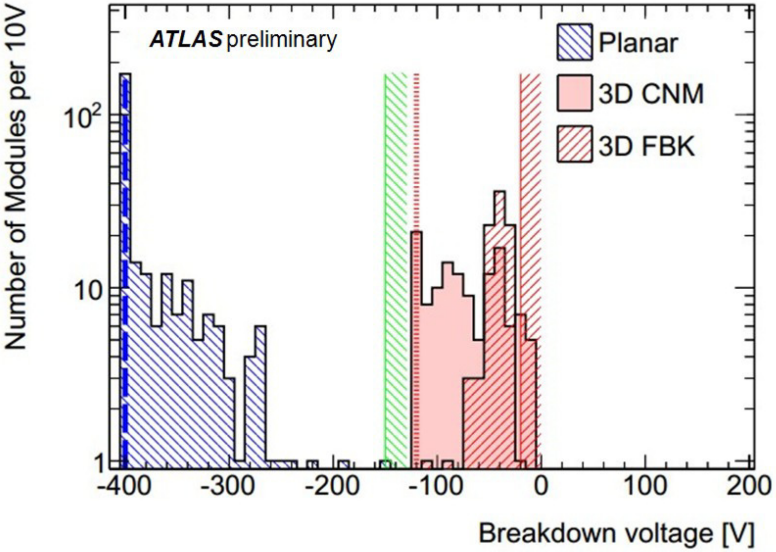
IBL 3D Production



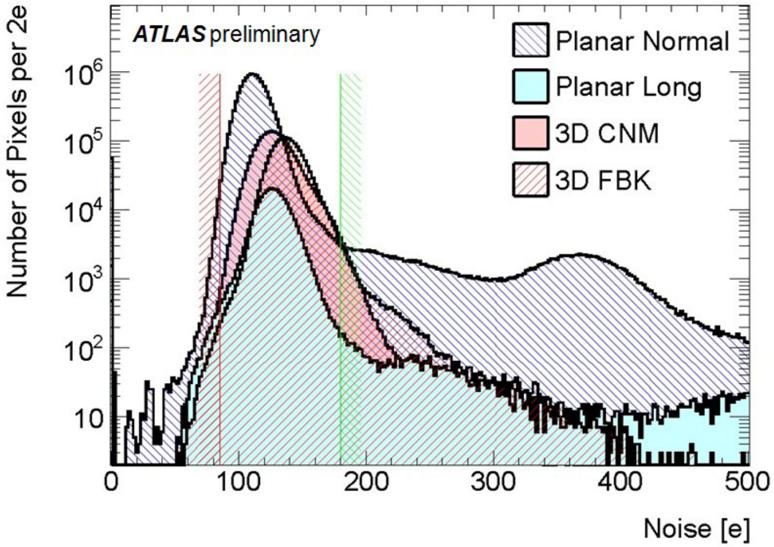
C. Da Via et al., NIM A 694 (2012) 321

- Sensors
  - FE-I4 geometry: 80x336 pixels of 250x50 μm²
  - 2 n⁺ junction columns per pixel (2E) surrounded by 6 p⁺ ohmic columns in 230 μm p substrate → L=67 μm
  - Slim edge of 200 μm along columns
- Technology details
  - FBK:
    - Passing-through columns
    - p⁺ guard fence
    - Sensor selection from IV on temporary metal
  - CNM:
    - Columns ~20 μm shorter than thickness
    - 3D guard ring+p⁺ guard fence
    - Sensor selection from IV on guard ring (GR) (not ideal)

IBL 3D Performance – Breakdown and Noise



- Breakdown voltage
  - Lower for 3D than planar, but much less bias voltage needed
  - Lower for FBK than CNM due to through-passing junction columns
- Noise
  - Larger for 3D than planar due to larger capacitance (170 vs. 110 fF)
  - Larger for FBK than CNM due to larger column overlap



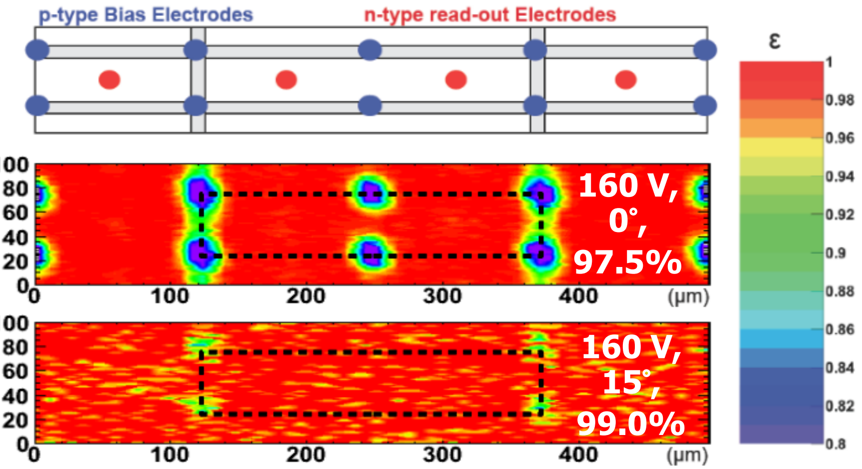
Pixel type	Noise [e]
Planar Norm.	114
Planar Long	134
3D FBK	140
3D CNM	131

Measurement in lab during QA
- Calibration: 10ToT@16ke
- Threshold: 3000e
- Temperature: -15 ˚C

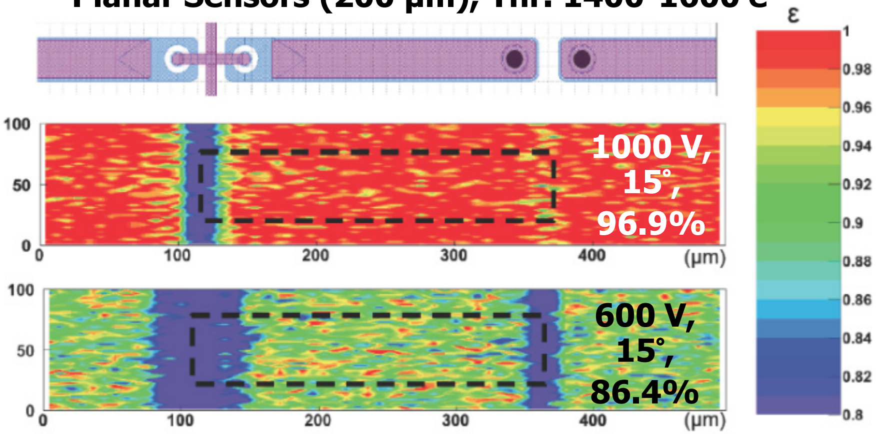
IBL 3D Performance – Radiation Hardness

Sub-Pixel Efficiency at $5 \times 10^{15}\ n_{eq}/cm^2$

CNM 3D Sensors (230 µm), Thr. 1500 e



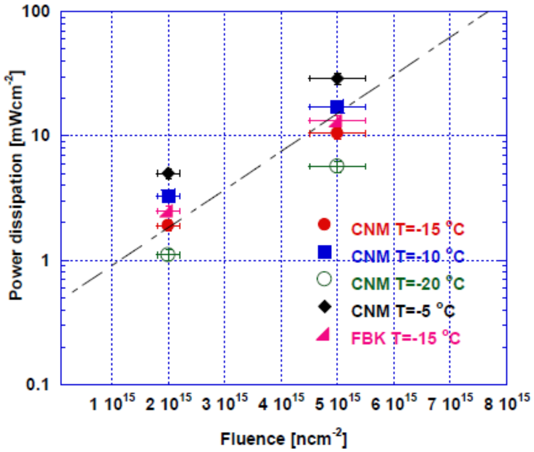
Planar Sensors (200 µm), Thr. 1400-1600 e



ATLAS IBL Coll., JINST 7 (2012) P11010

- Radiation hardness tested up to $5 \times 10^{15}\ n_{eq}/cm^2$
- 3D sensors
  - **Fully efficient at 160 V** and 15° angle
  - Mean efficiency 1-2% lower at normal incidence due to columns
  - Power dissipation <15 mW/cm^2 at T=-15° C
- Planar sensors
  - Need 1000 V for similar efficiency
  - Power dissipation ~90 mW/cm^2 at T=-15° C

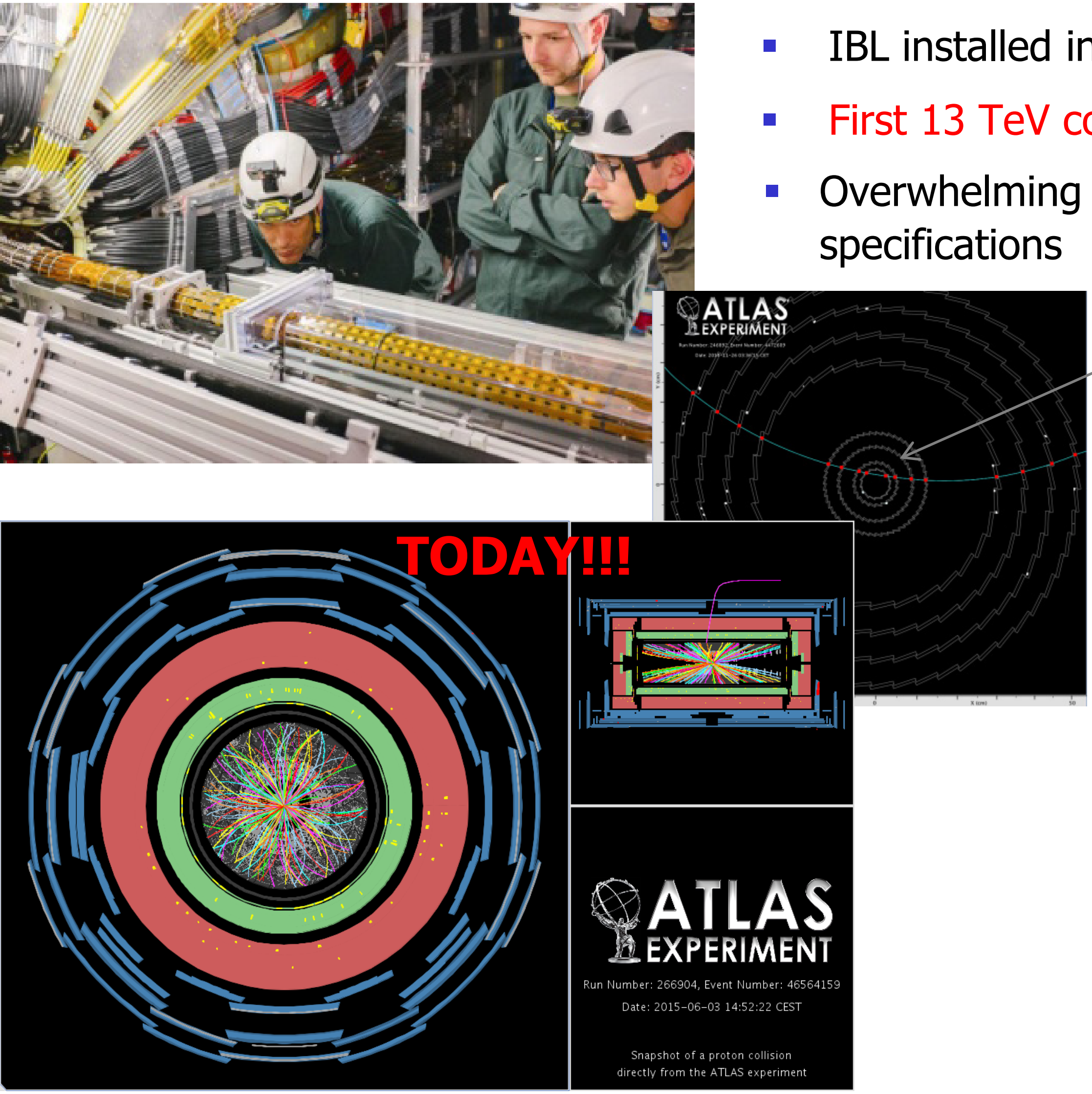
→ operational advantage for 3D sensors



IBL Installation and Commissioning

See talk by D. Dobos

- IBL installed in May 2014
- First 13 TeV collisions!
- Overwhelming fraction of sensors works according to specifications



TODAY!!!

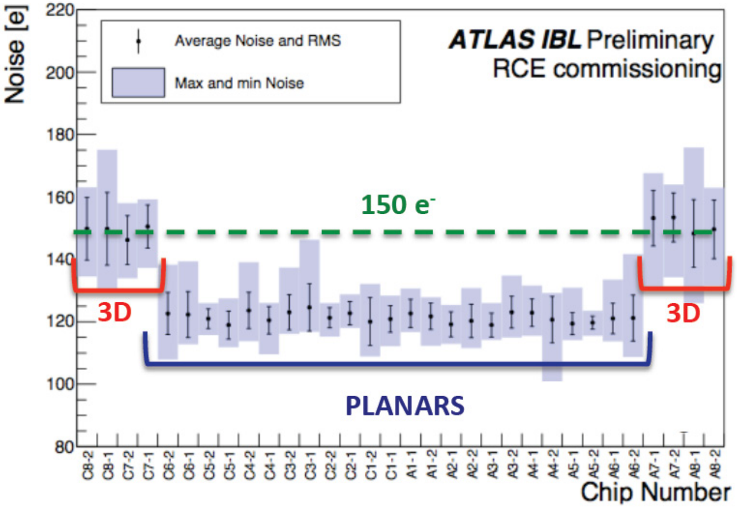
ATLAS EXPERIMENT

Run Number: 266904, Event Number: 46564159

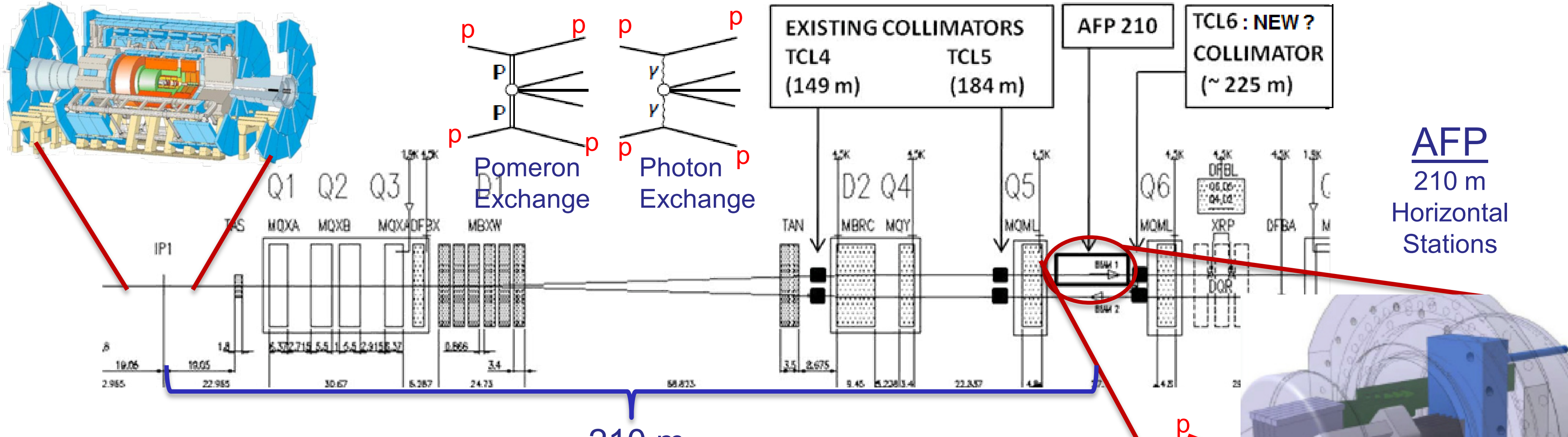
Date: 2015-06-03 14:52:22 CEST

Snapshot of a proton collision directly from the ATLAS experiment

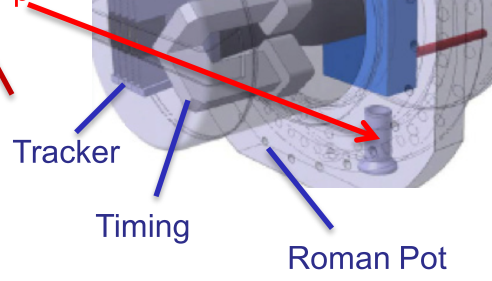
3D is in and working!!!



3D Sensors for Forward Detectors



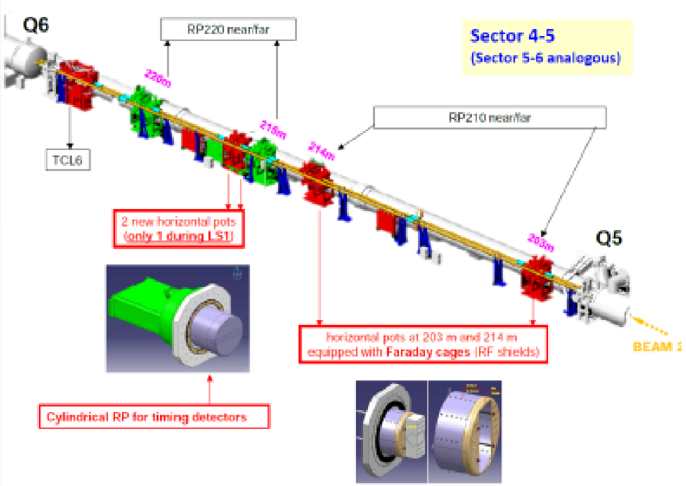
210 m



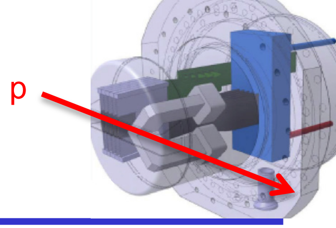
- ATLAS Forward Proton (AFP) and CMS-TOTEM Precision Proton Spectrometer (PPS) intend to study forward protons scattered under very small angle
- Tracking and timing detectors very close to the beam (2-3 mm)

AFP TDR submitted to LHCC , LHCC-2015-009
CMS-TOTEM PPS TDR, LHCC-2014-021

PPS

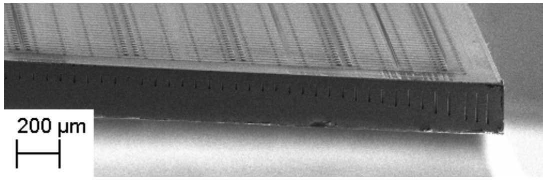


AFP and PPS 3D Trackers

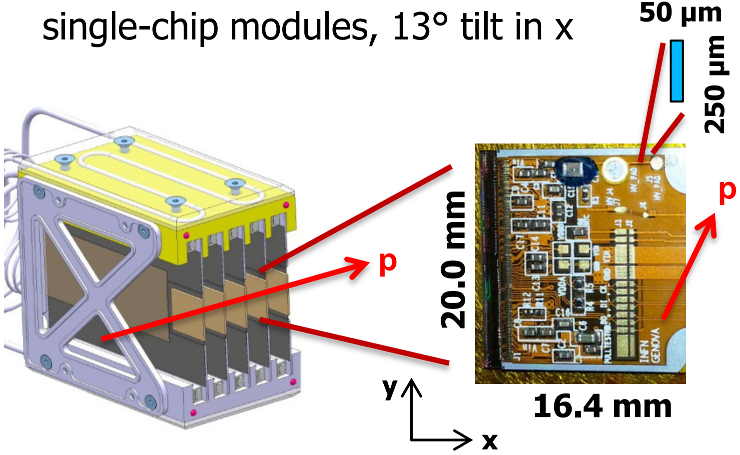


- Requirements
  - Good position resolution (full tracker): 10 µm (x), 30 µm (y)
  - Slim edge of side facing beam: 100-200 µm
  - Highly non-uniform irradiation (up to $3\text{x}10^{15}$ n_{eq}/cm^2)
- Solution
  - Several layers of slim-edged 3D pixel detectors (telescope configuration)

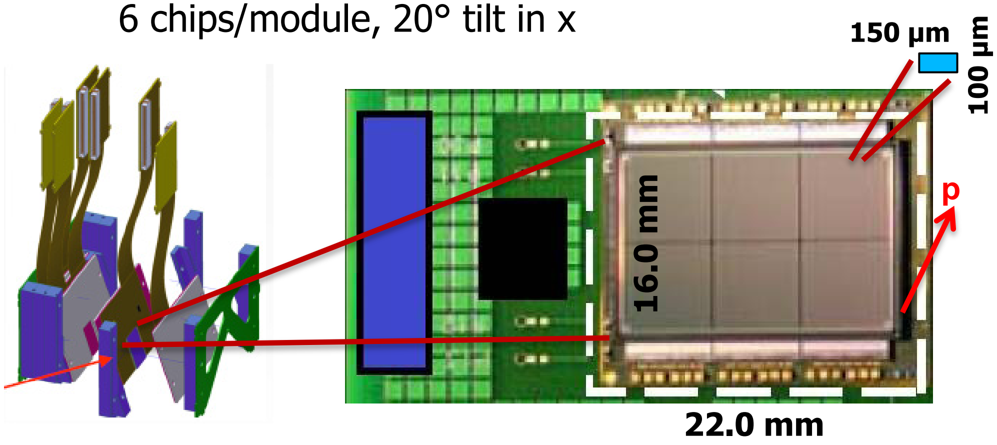
Simple diamond-saw cut



- AFP:
  4 slim-edged IBL 3D FE-I4 single-chip modules, 13° tilt in x



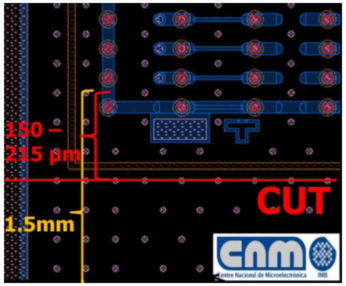
- PPS:
  6 3D modules with PSI46dig, 6 chips/module, 20° tilt in x

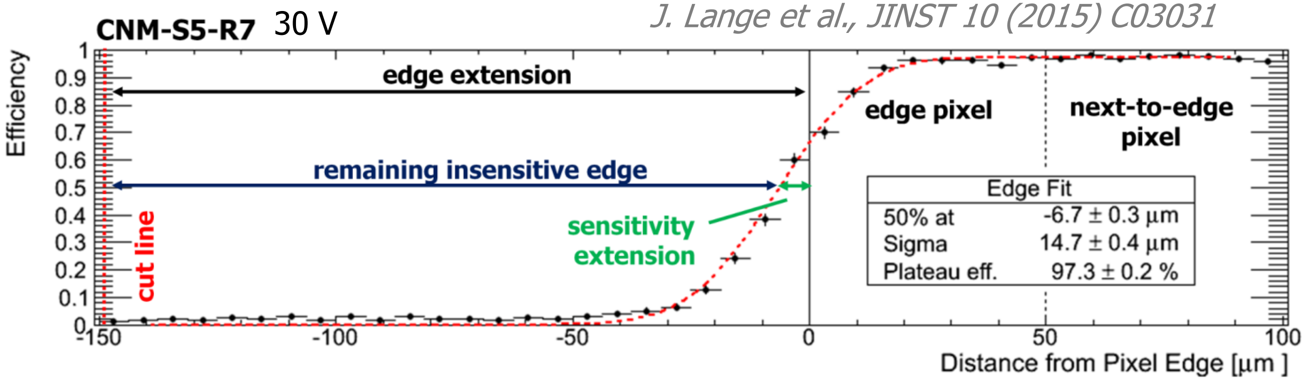


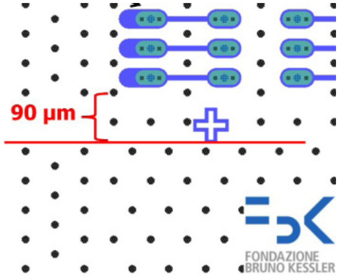
AFP: Slim-Edge Efficiency

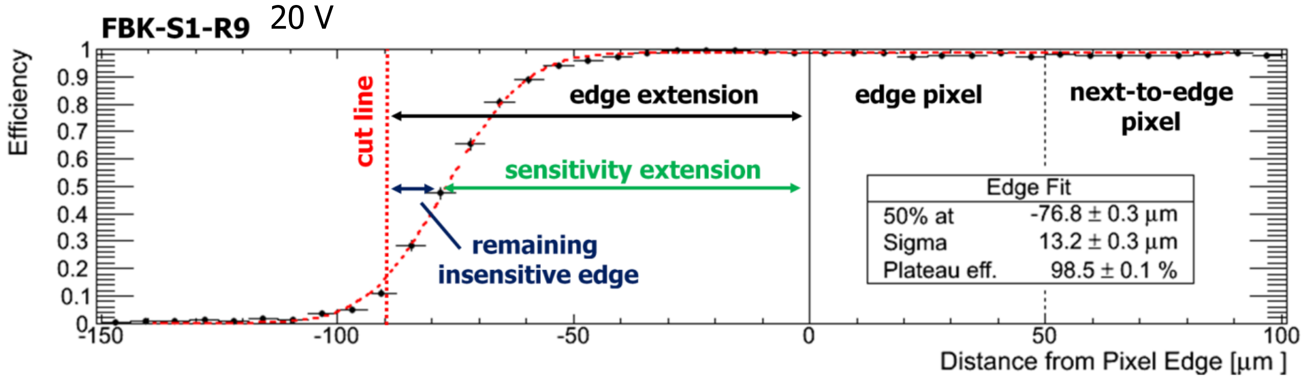
Slim-edged 3D FE-I4

J. Lange et al., JINST 10 (2015) C03031









- **CNM:** Fully sensitive up to last pixel (3D guard ring design)
- **FBK:** Sensitivity extends ~75 µm beyond last pixel (no guard ring)
  → <15 µm insensitive edge: slimmest edge apart from fully active edge
- For both CNM and FBK: <150 µm insensitive edge possible

→ AFP slim-edge requirements fulfilled

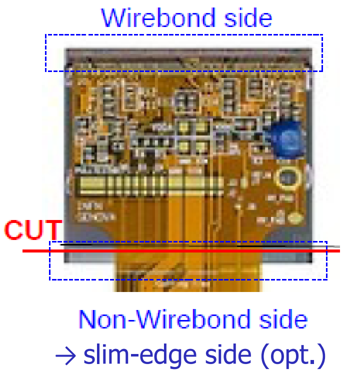
AFP: FBK Slim-Edge Efficiency –

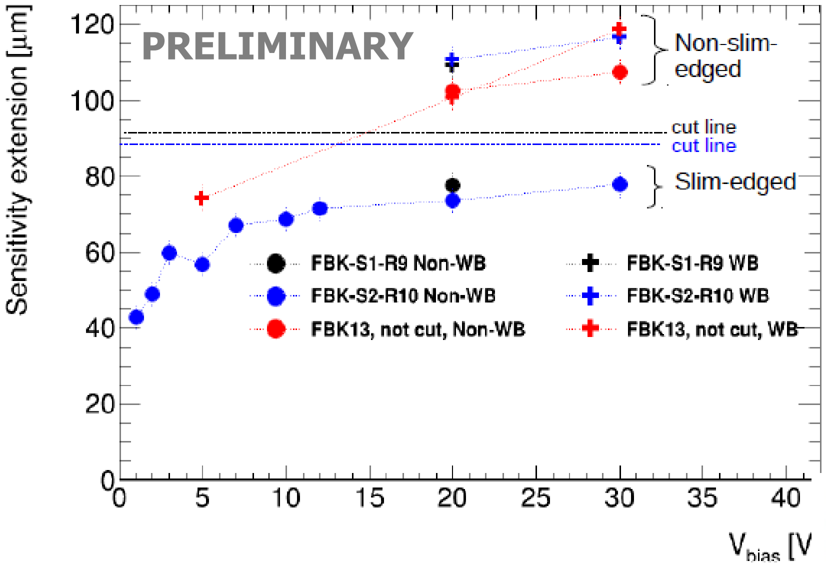
Dependence on V, Side and Fluence

- Dependence on the side
  - Edges that are cut to obtain slim-edges have ~75 µm sensitivity extension, non-cut edges ~110 µm

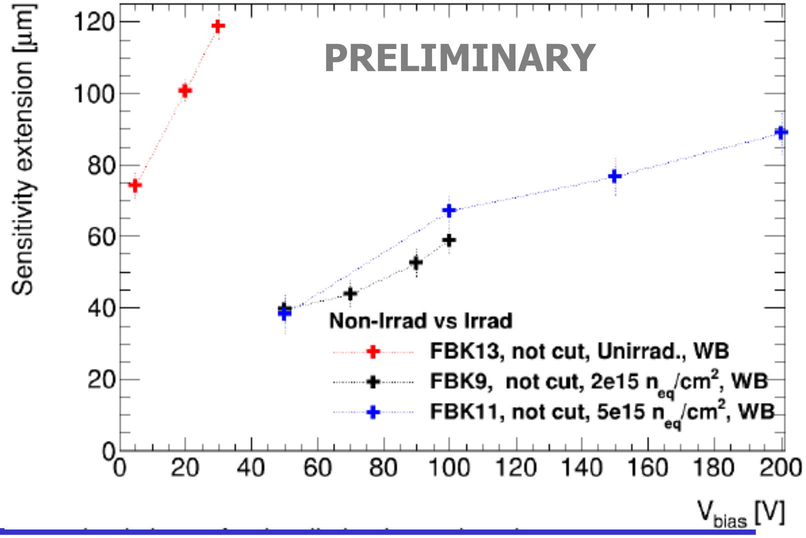
    → probably cut defects influence depletion growth and increased recombination near cut edge

    → to be followed up in simulations





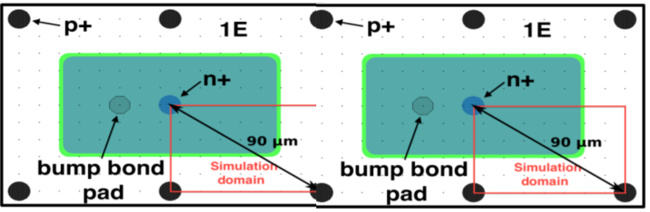
- Dependence on irradiation
  - Here: non-cut devices
  - Sensitivity extension still present after irradiation, but reduced (increasing with V)

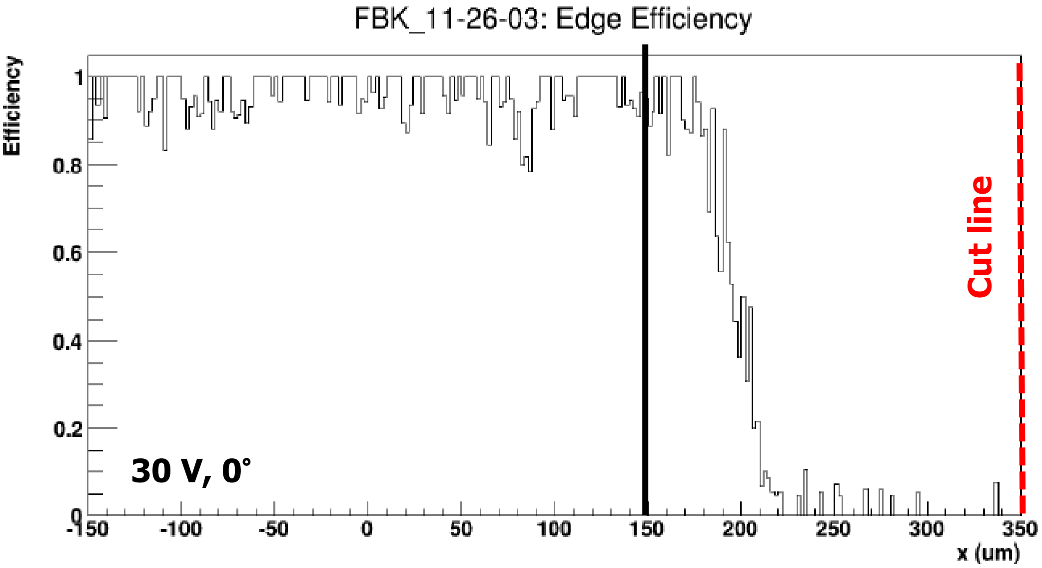


I. Lopez et al., ANIMMA 2015, Lisbon

PPS: Slim-Edge Efficiency

Edge Pixel: 300x100 µm²





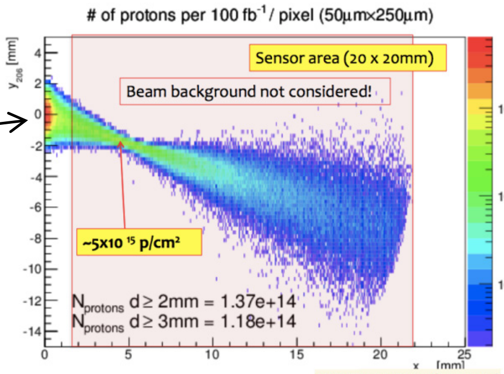
- Typical CMS pixel 150x100 µm²
  - Here: edge pixel double size in long direction (300 µm) for this prototype (not for PPS)
- Edge-efficiency studies with 1E FBK sensors
  - 50 µm sensitivity extension at 0°, 70 µm at 20°
  - 130-150 µm remaining insensitive edge

CMS-TOTEM PPS TDR, LHCC-2014-021
F. Ravera et al., 10th Trento Workshop 2015, Trento

→ PPS slim-edge requirements fulfilled

AFP: Irradiation Studies

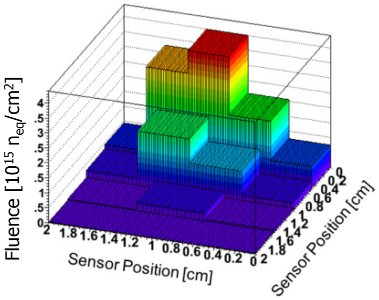
- Radiation hardness for uniform radiation to $5\times10^{15}\ n_{eq}/cm^2$ known from IBL
- AFP: Highly non-uniform fluence from diffractive p
  - $3\times10^{15}\ n_{eq}/cm^2$ in max. (~7 TeV p), orders of magnitudes less nearby
- 2 irradiation campaigns with different non-uniformity scenarios



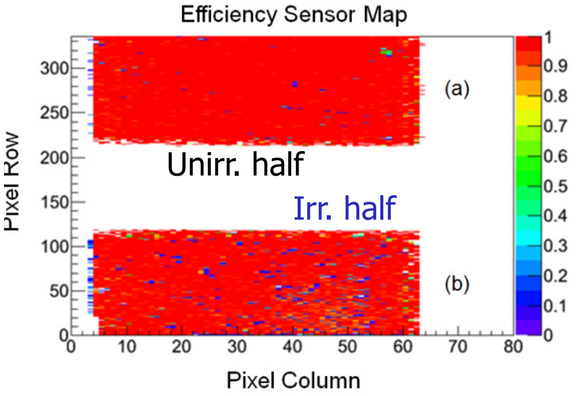
Olda Kepka, Sasa Kupco (FZU, Prague)

1) Focussed 23 GeV p irradiation (CERN-PS)
→ fluence spread large

max. $4\times10^{15}\ n_{eq}/cm^2$

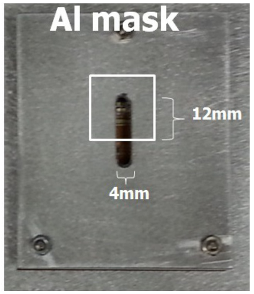


CNM-57, 130 V

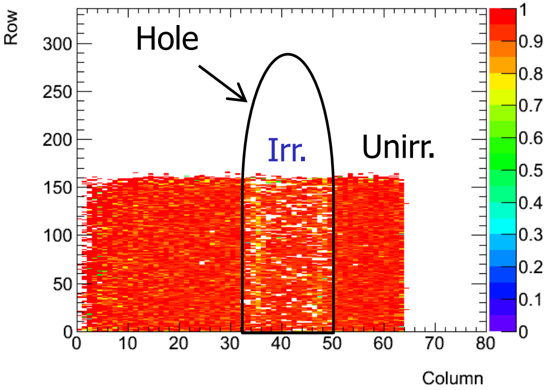


2) 23 MeV p (KIT) through hole in 5mm Al plate
→ very localised fluence with abrupt transition

$3.6\times10^{15}\ n_{eq}/cm^2$



CNM-S5-R7, 100 V



S. Grinstein et al., NIM A730 (2013) 28
J. Lange et al., JINST 10 (2015) C03031

Efficiency 96-99% in all regions

→ AFP radiation-hardness requirements fulfilled

PPS: Irradiation Studies

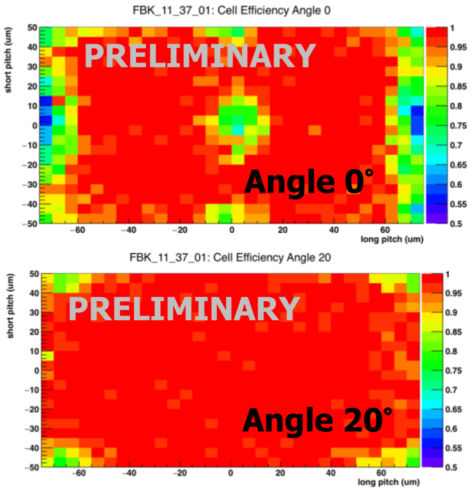
- Study of uniform irradiation
- Builds on experience of previous CMS 3D radiation hardness studies
  - Problems in past: chip PSI46 (analog) not radiation hard enough

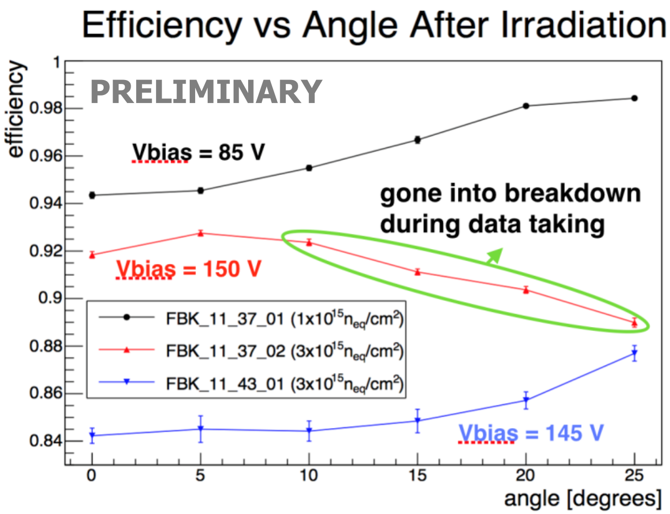
F. Muñoz, PhD thesis (2014)
A. Krzywda et al., NIM A763 (2014) 404

- New studies with new PSI46dig: more radiation hard, lower threshold
  - Efficiency of 98% after 1x10^{15} n_{eq}/cm^2 and 93% after 3x10^{15} n_{eq}/cm^2 (only 1E available in first studies, 3 ke threshold)
  - Some remaining non-uniform inefficiencies, expected to improve with 2E configuration

See talk by L. Caminada for chip details

1x10^{15} n_{eq}/cm^2
85 V





F. Ravera et al., 10th Trento Workshop 2015, Trento

AFP and PPS Production

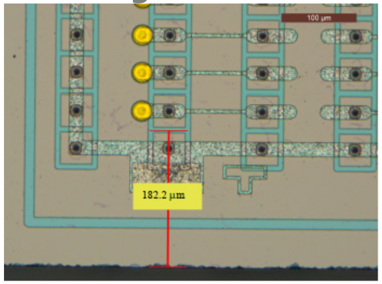
- AFP
  - Production run at CNM finished in July 2014
  - 8 lost wafers due to machine malfunctions, 5 wafers successfully finished (40 sensors)
  - Slim-edged to 180 µm
  - 9 good + 5 medium quality sensors after slim-edging
    → Low yield due to etching problems with DRIE
    → Identified and solved for next runs
  - New IBL-like run started at CNM in February 2015
  - Module assembly incl. bump- and wirebonding and QA to be done at IFAE Barcelona (on AFP flex from Oslo)

→ Installation of first two AFP stations with 2 x 4 3D FE-I4 pixel modules planned for winter shutdown 2015/16 (tight!)

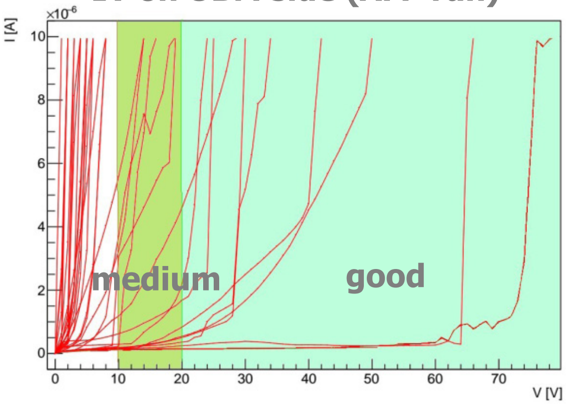
- PPS
  - First FBK 6" 3D commissioning run had low yield on large sensors due to local defects
  - CNM production run for PPS on-going
    - 2E default (also 1E); up to 6-chip sensors; no guard ring

→ Installation of PPS 3D pixel modules planned for 2016

Slim-edged AFP sensor

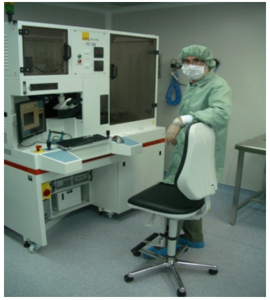


IV on UBM side (AFP run)

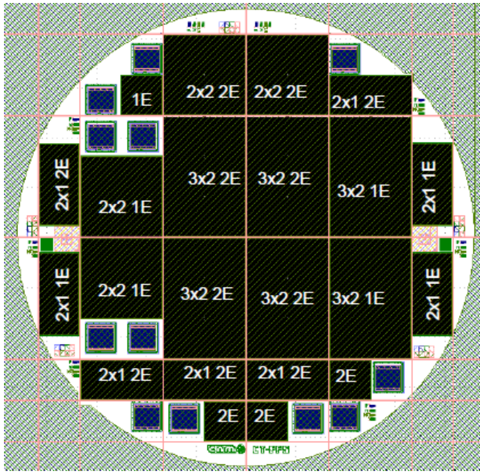


M. Baselga, CNM

IFAE Bump-Bonding



CNM PPS run



New Developments for HL-LHC

- High-Luminosity LHC (HL-LHC) upgrade 2024
  → increased occupancy
  → unprecedented radiation levels (1-2x10^{16} n_{eq}/cm^2 innermost pixels)

See talks by R. Bates &
R. Stringer (sensors),
M. Garcia-Sciveres (chip)

- Development of new pixel sensors and front-end (RD53)
  - Reduced cell size: 50x50 μm^2 or 25x100 μm^2
  - Reduced threshold ~1000e (in-time), C_{det}<100 fF/pixel, I_{leak}<10nA/pixel

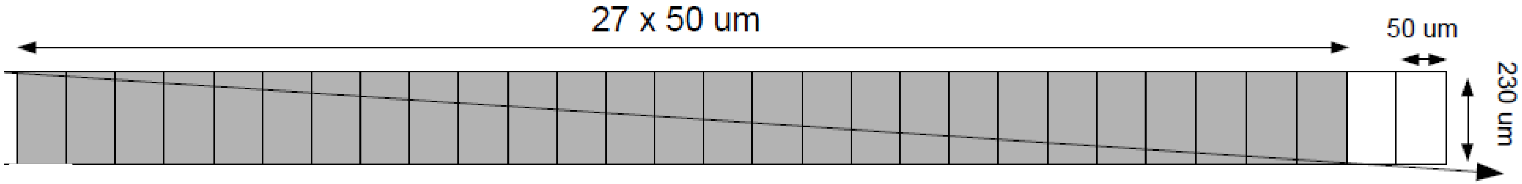
- Strategy for 3D HL-LHC R&D
  - New generation of 3D productions under way
  - Explore the limits of existing 3D technology and devices from previous productions

HL-LHC Studies with Existing Technology

- Radiation-hardness studies on-going
  - With strips, PSI46dig, FE-I3, FE-I4: irradiations at PS, KIT, Ljubljana
- High-eta studies
  - Large clusters → large total charge → efficiency for whole cluster not a problem
  - But for 50 µm pitch very small charge deposition per pixel (almost parallel tracks): 3300 e
  - Testbeam campaign to measure CNM+FBK IBL FE-I4 devices with 80° angle in short pitch direction (50 µm)
    - 1000 e threshold
    - Cluster size 24-27
    - >99% efficiency per pixel before irradiation
    - Analysis on-going for irradiated devices

IFAE (I. Lopez et al.)

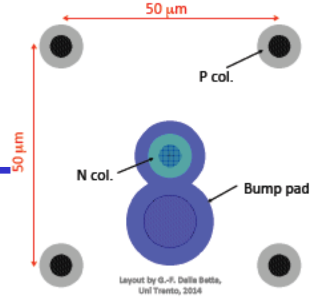
80° ($\eta=2.4$) → Q=3300 e/pixel (50 µm)



New 3D Productions

at CNM, FBK, Stanford, SINTEF

50x50 1E



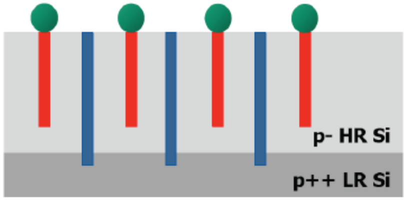
G.F. Dalla-Betta, FBK

- Smaller cell sizes folded into existing FE geometries, also FE-RD53 prototypes
  - Cross-experiment runs: CMS PSI46dig, ATLAS FE-I3/4, LHCb Timepix/Velopix
- Reduced cell size means reduced electrode distance L
  - Advantageous for radiation hardness
  - Need to reduce 3D column diameter to ~5 µm to keep dead material low
    - Go to thinner detectors with fixed aspect ratio (column length/diam.) 20:1 → all vendors
    - Increase aspect ratio to 40:1 with cryogenic technique → CNM

Layout	50x50 1E	25x100 1E	25x100 2E
El. Dist. L	35 µm	52 µm	28 µm

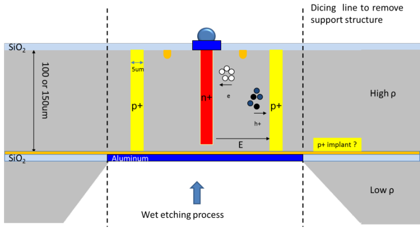
cf. FE-I4: L=67 µm

- Thinner sensors
  - To reduce 3D column diameter, C_{det} and cluster size at high eta
  - Double-sided: CNM 200 µm
  - Single-sided
    - Si-Si wafer-bonding (FBK 100-130 µm, Stanford 75-150 µm)
    - SOI (SINTEF 50+100 µm, CNM 100+150 µm)



Si-Si bonding

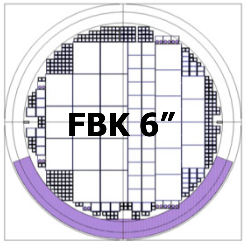
G.F. Dalla-Betta, FBK



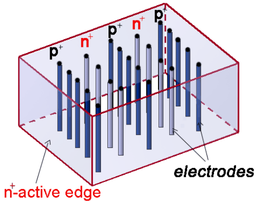
SOI

G. Pellegrini, CNM

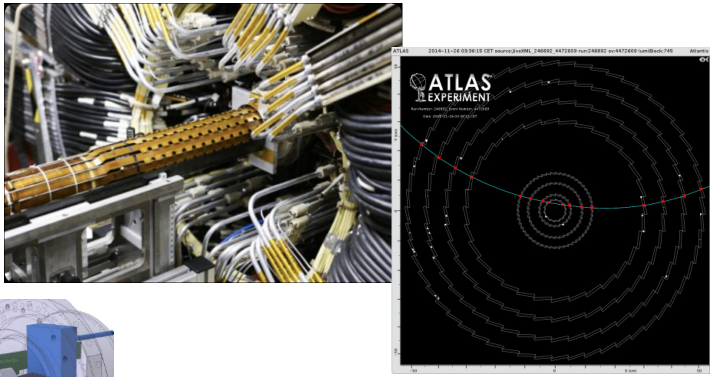
- 6” wafer production (FBK, SINTEF)
- Improved on-wafer sensor selection (CNM: poly-Si)
- Improved breakdown (FBK: non-passing through junction column)
- Varying depth of junction columns to sense full 3D hit information (Stanford)
- Active (Stanford, SINTEF) or slim (CNM, FBK) edges



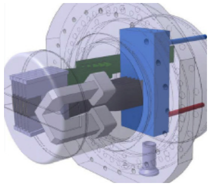
Conclusions

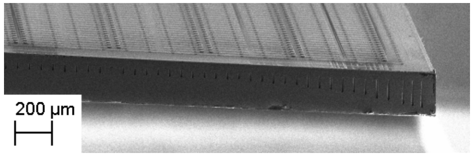


- 3D silicon detectors are an intrinsic radiation-hard and active/slim-edge technology
  - Now mature
- First-time use in HEP experiment in ATLAS IBL
  - Successful qualification, production, installation, commissioning and first collision data
  - Operational advantages compared to planar

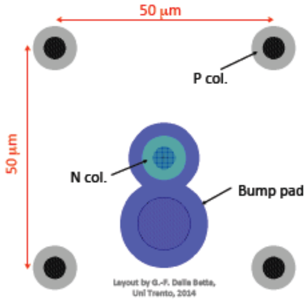


- Second use in forward detectors imminent
  - ATLAS Forward Physics (AFP)
  - CMS-TOTEM PPS
  - Successful qualifications (slim edge and non-uniform irradiation)
  - Productions on-going



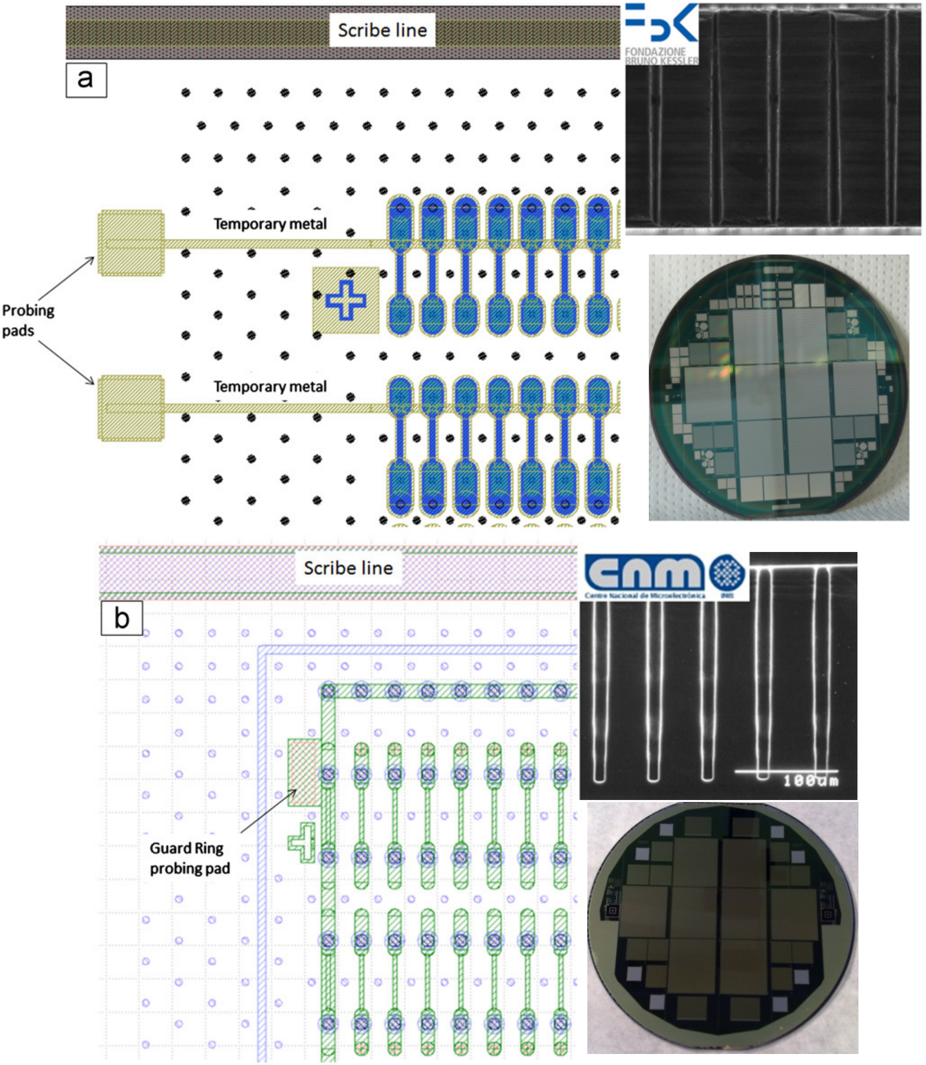


- R&D for HL-LHC pixel detectors on-going
  - New 3D production runs at CNM, FBK, Stanford, SINTEF
  - Smaller cell size, thinner, smaller columns, partly 6”
  - R&D with existing devices on-going



BACKUP

IBL 3D Production

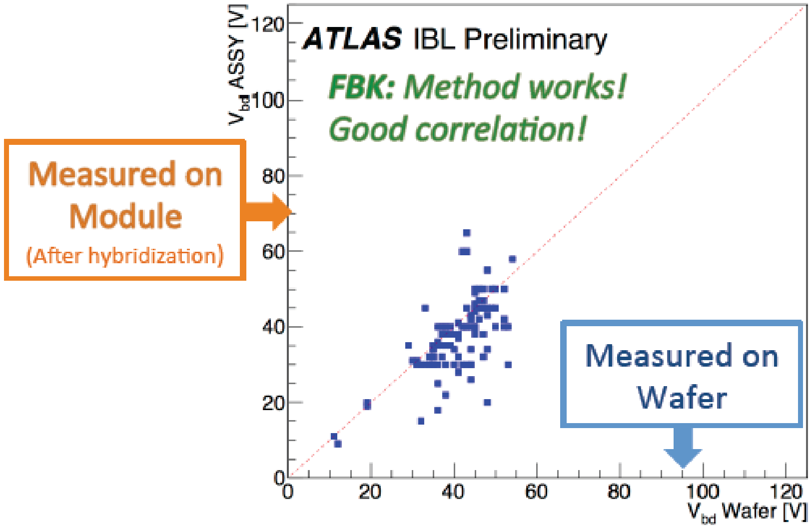


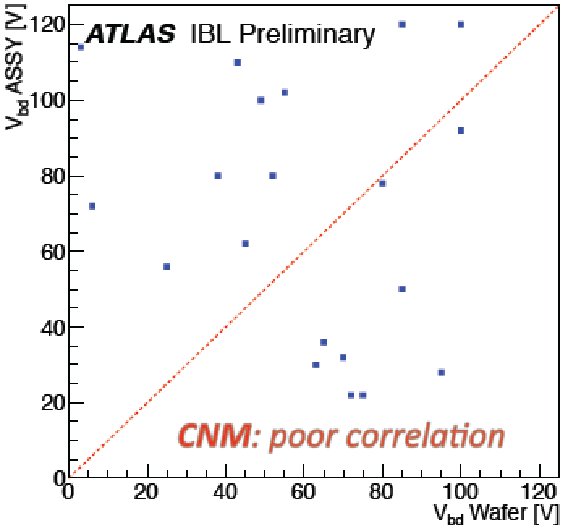
C. Da Via et al., NIM A 694 (2012) 321

- Sensors
  - FE-I4 geometry: 80x336 pixels of 250x50 μm^2
  - 2 n$^+$ junction columns per pixel (2E) surrounded by 6 p$^+$ ohmic columns in 230 μm p substrate → L=67 μm
  - Slim edge of 200 μm along columns
- Technology details
  - FBK:
    - Passing-through columns
    - p$^+$ guard fence
    - Sensor selection from IV on temporary metal → 57% wafer production yield
    - Assembly yield 56% (bump-bonding issues)
  - CNM:
    - Columns ~20 μm shorter than thickness
    - 3D guard ring+p$^+$ guard fence
    - Sensor selection from IV on guard ring (GR) → 72% wafer production yield
    - Assembly yield 50% (GR IV bad indicator)

IBL 3D Assembly Yield

V_{BD} COMPARISON AFTER HYBRIDIZATION





CNM 3D-Guard Ring evaluation method not good enough!

CNM V_{BD} plot is done with a small subset of produced modules, because in the QA too low bias current (≤ 10 μA) limit has been used.

CNM implementing poly-silicon bias structure for new production

A. Gaudiello - 10th "Trento" Workshop on Advanced Silicon Radiation Detectors **8**