Recent Progress on 3D Silicon Detectors

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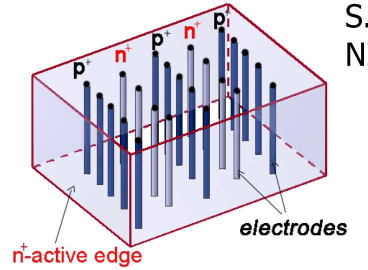
IFAE Barcelona

26th RD50 Workshop, Santander, 22-24 June 2015

With material from the ATLAS 3D group,
CNM, FBK, SLAC and SINTEF

3D Detectors – a Success Story

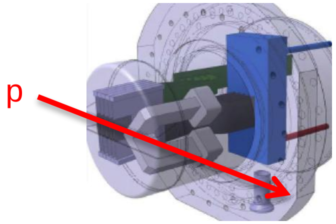
- 1997: First idea and devices



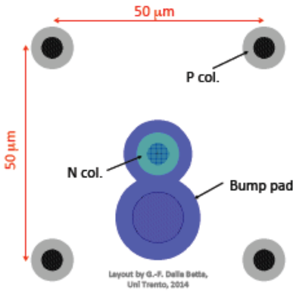
S. Parker, C. Kenney, J. Segal
NIM A 395 (1997), 328

- Huge R&D effort
  - Manufacturers, ATLAS+CMS, RD50, …

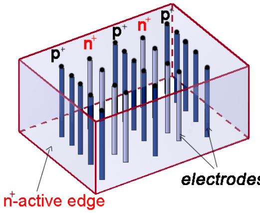
- ATLAS IBL
  - First installation of 3D detectors in a HEP experiment
- Forward Detectors: 2nd use of 3D detectors within 1/2 year
  - ATLAS Forward Proton (AFP)

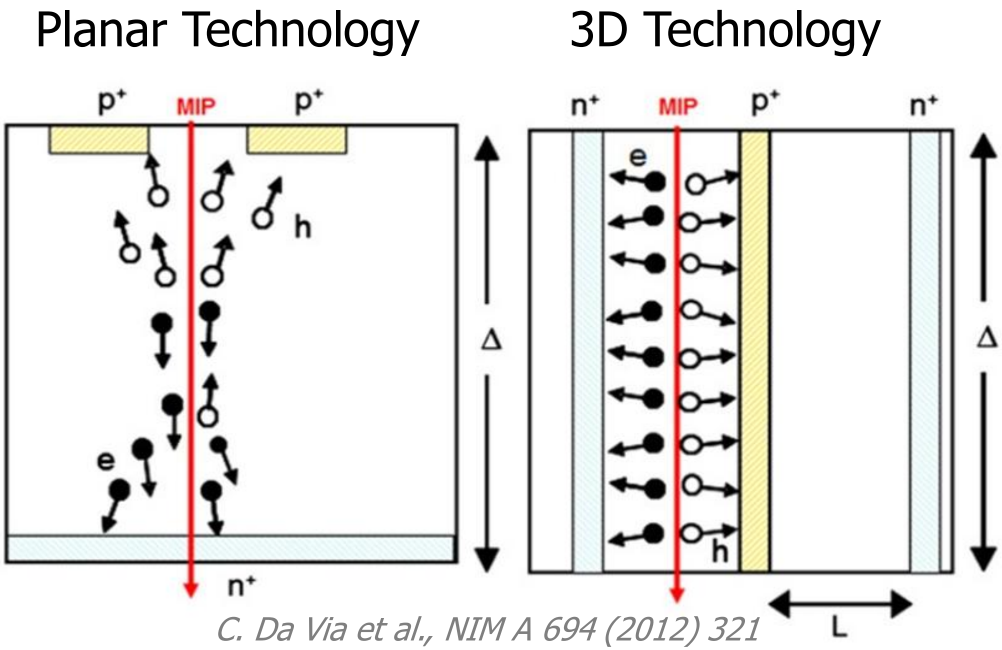


- HL-LHC Phase-2 Upgrades ~2024
  - New generation of 3D detectors



3D Detector Principle





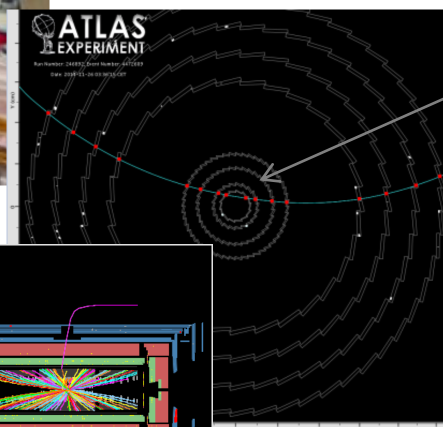
C. Da Via et al., NIM A 694 (2012) 321

Radiation-hard and active/slim-edge technology

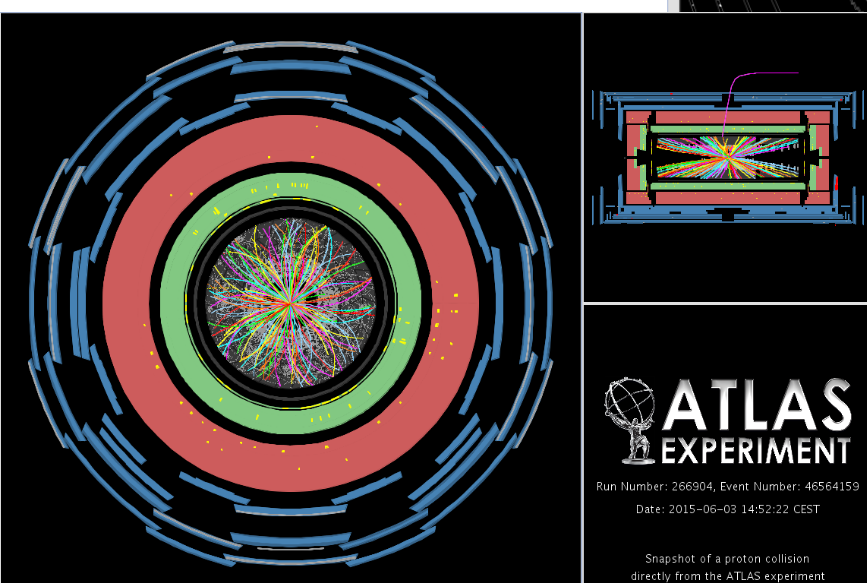
- **Advantages**
  - Electrode distance decoupled from sensitive detector thickness
    → lower $V_{depletion}$
        → less power dissipation, cooling
    → smaller drift distance
        → faster charge collection
        → less trapping
  - Active or slim edges are natural feature of 3D technology
- **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°

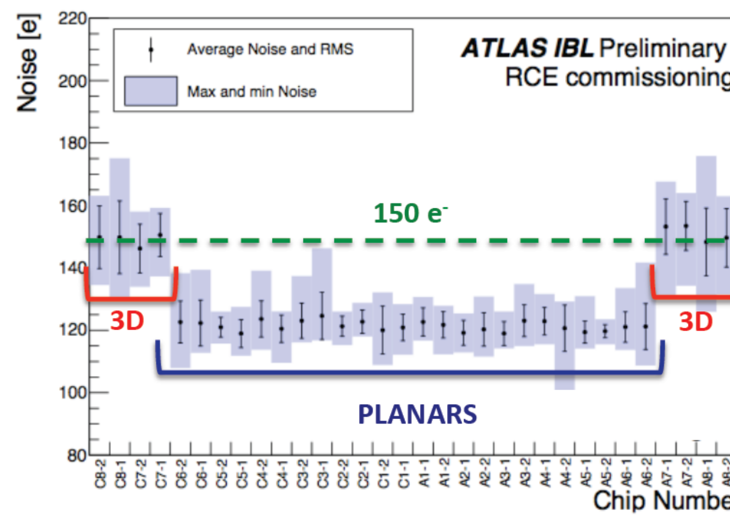
IBL Installation and Commissioning

- IBL installed in May 2014: 25% 3D detectors
- First 13 TeV collisions this month!
- Overwhelming fraction of sensors works according to specifications

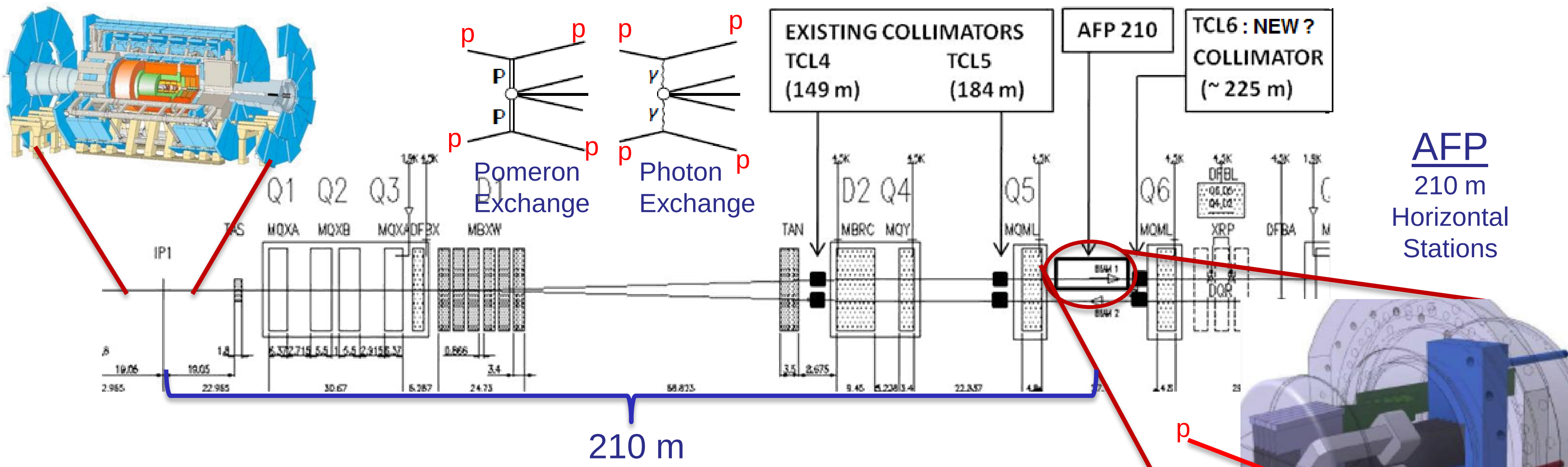


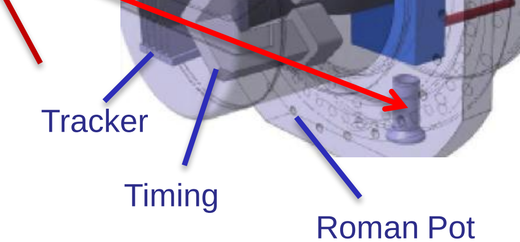
3D is in and working!!!





3D Sensors for Forward Detectors



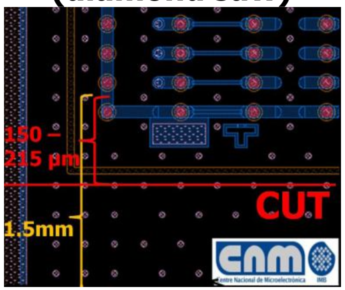


- ATLAS Forward Proton (AFP) detector intends to study forward protons scattered under very small angle
- Finally completely approved (final CB vote last Friday)
- Tracking and timing detectors very close to the beam (2-3 mm)
- Tracker requirements
  - Good position resolution (full tracker): 10 µm (x), 30 µm (y)
  - Slim edge of side facing beam: 100-200 µm
  - Highly non-uniform irradiation (up to 3×10^{15} n_{eq}/cm^2)

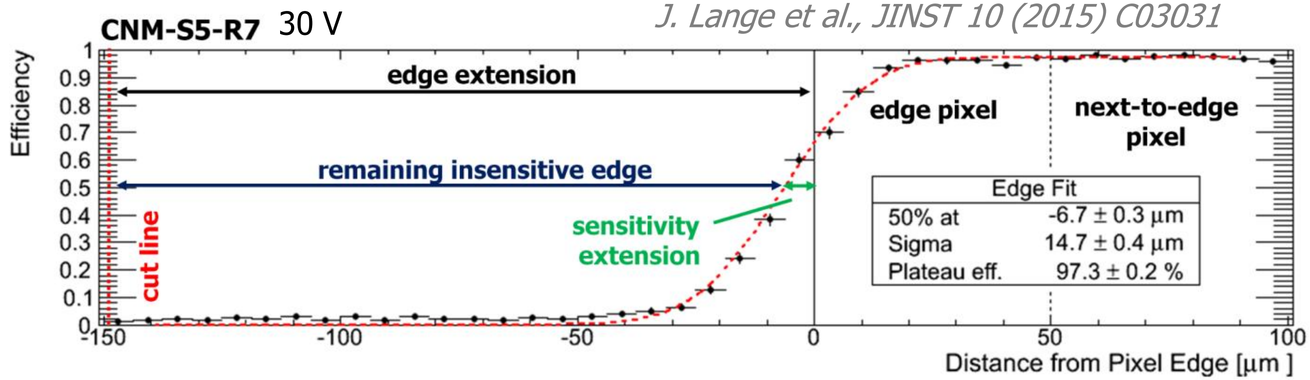
AFP TDR , LHCC-2015-009, ATLAS-TDR-024

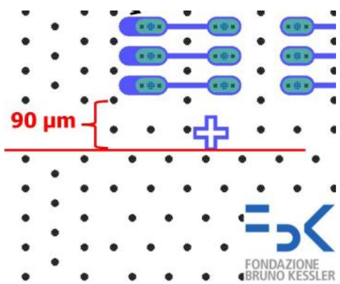
AFP: Slim-Edge Efficiency

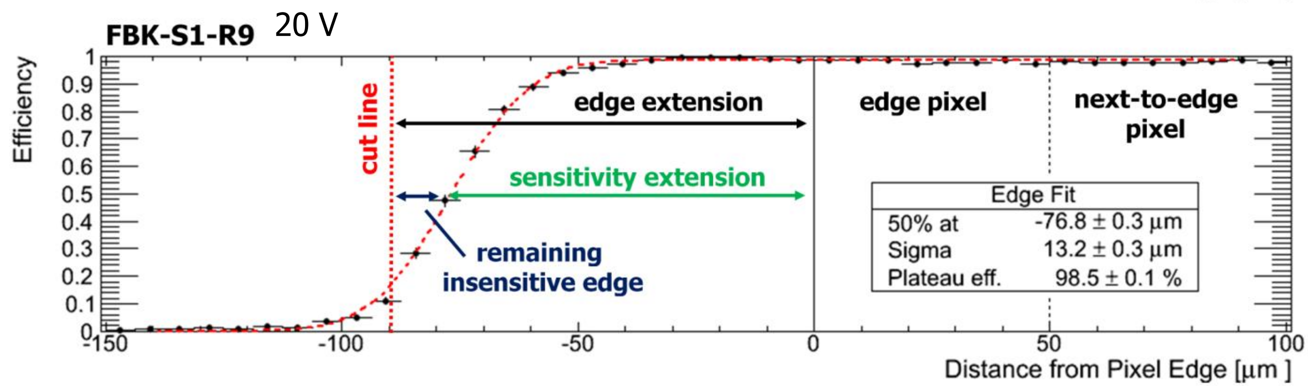
Slim-edged 3D FE-I4 (diamond saw)



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

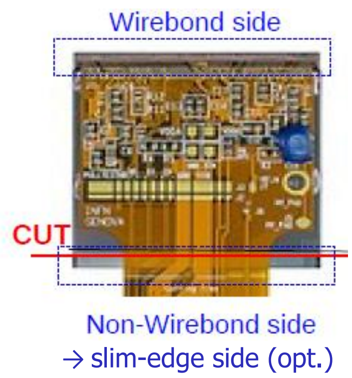
→ AFP slim-edge requirements fulfilled

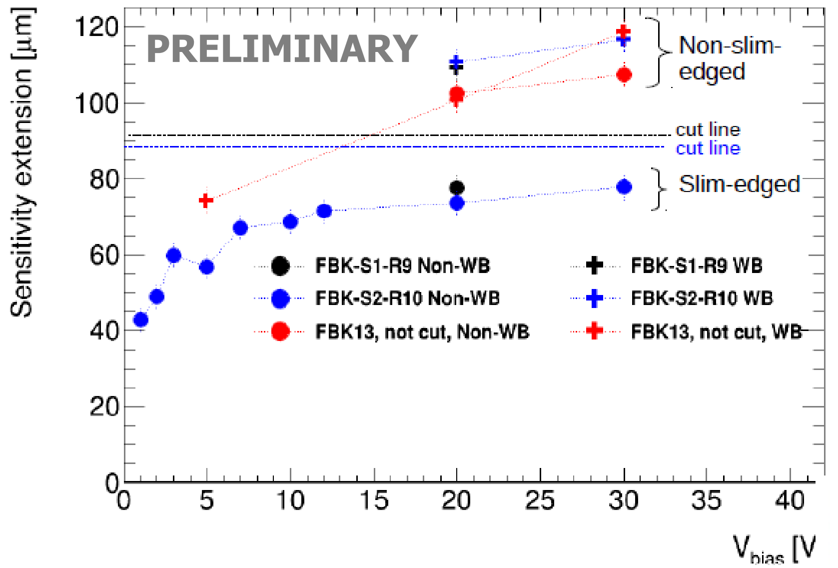
AFP: FBK Slim-Edge Efficiency –
Dependence on V, Side and Fluence

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

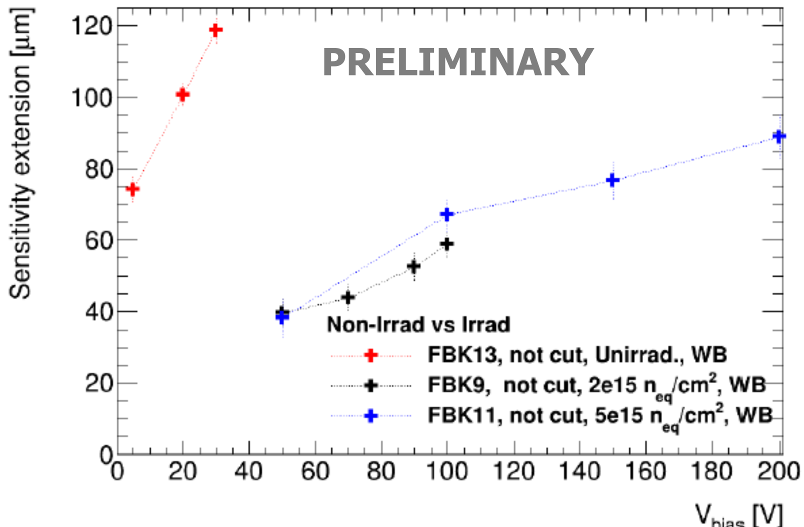
    → probably cut (defects) influence depletion growth and increased recombination near cut edge

    → to be followed up in simulations (FBK)





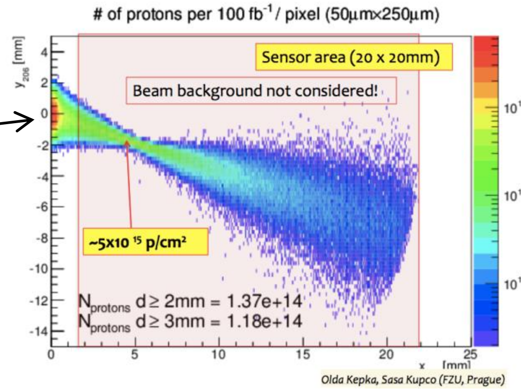
- Dependence on irradiation
  - Here: non-cut devices
  - Sensitivity extension still present after irradiation, but reduced (increasing with V)



I. Lopez et al., ANIMMA 2015, Lisbon

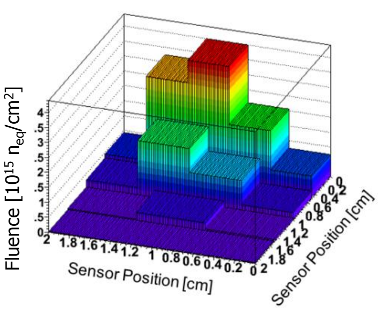
AFP: Irradiation Studies

- Radiation hardness for uniform radiation to 5×10^{15} n_{eq}/cm^2 known from IBL
- AFP: Highly non-uniform fluence from diffractive p
  - 3×10^{15} n_{eq}/cm^2 in max. (~7 TeV p), orders of magnitudes less nearby
- 2 irradiation campaigns with different non-uniformity scenarios

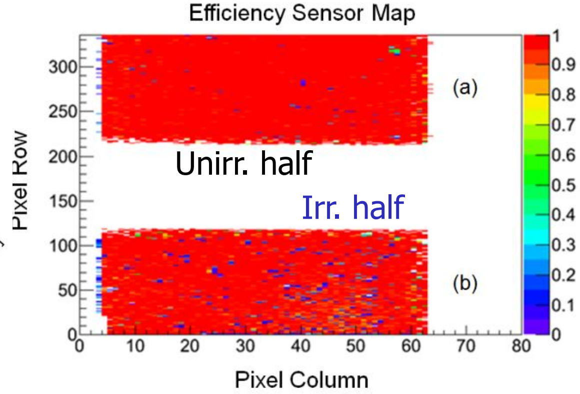


1) Focussed 23 GeV p irradiation (CERN-PS)
   → fluence spread large

max. 4×10^{15} n_{eq}/cm^2

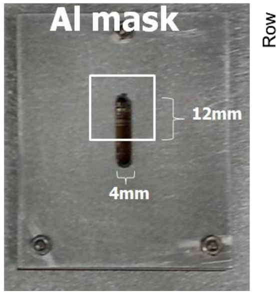


CNM-57, 130 V

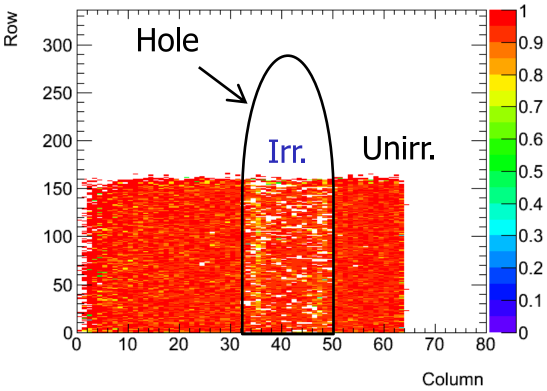


2) 23 MeV p (KIT) through hole in 5mm Al plate
   → very localised fluence with abrupt transition

3.6×10^{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

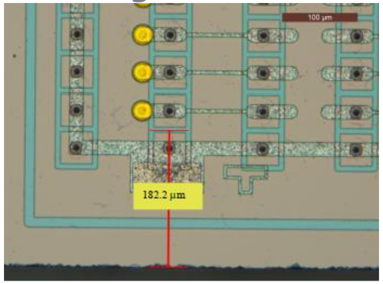
Efficiency 96-99% in all regions
→ AFP radiation-hardness requirements fulfilled

AFP Production

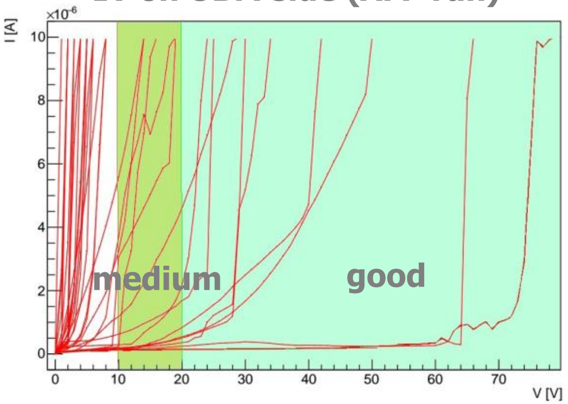
- 3D detectors qualified for AFP
- Production run at CNM finished
  in July 2014
- 8 lost wafers due to machine malfunctions,
  5 wafers successfully finished (40 sensors)
- Slim-edged to 180 µm
- 9 good + 5 medium quality sensors
  → Low yield due to etching problems with DRIE
  → Identified and solved 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!)

Slim-edged AFP sensor



IV on UBM side (AFP run)



M. Baselga, CNM

IFAE Bump-Bonding

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)

- 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

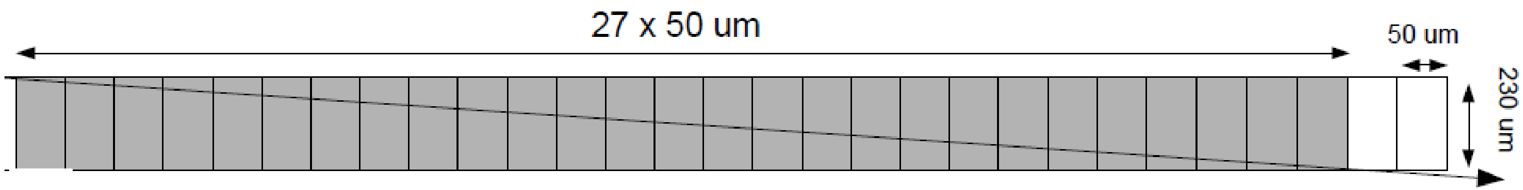
- Strategy for 3D HL-LHC R&D
  - New generation of 3D productions under way
    - But takes time (~1 year)
  - Explore the limits of existing 3D technology and devices from previous productions

HL-LHC Studies: High Eta

- 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 + 1500 e threshold
  - Cluster size 24-27
  - >99% efficiency per pixel before irradiation

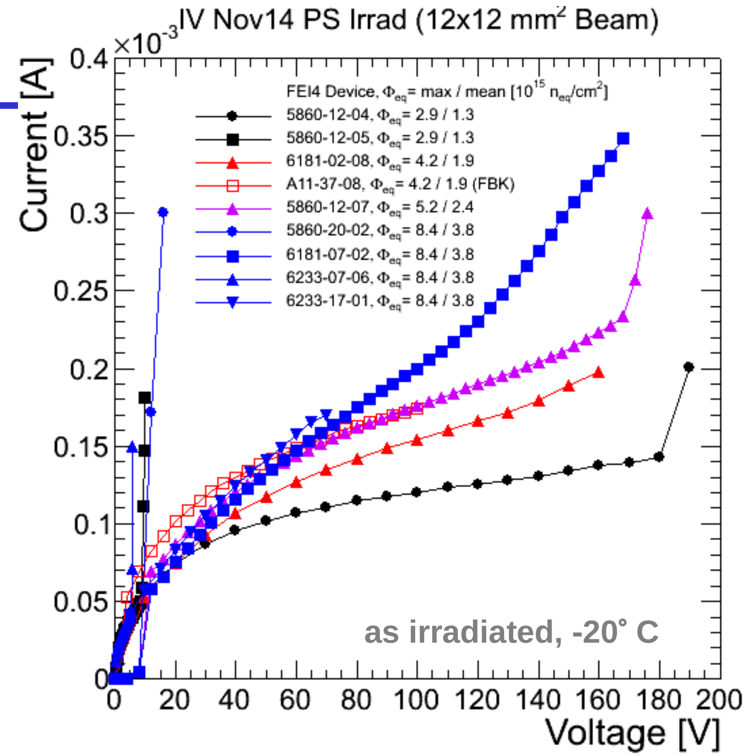
See talk by Ivan Lopez

80° (η=2.4) → Q=3300 e/pixel (50 μm)

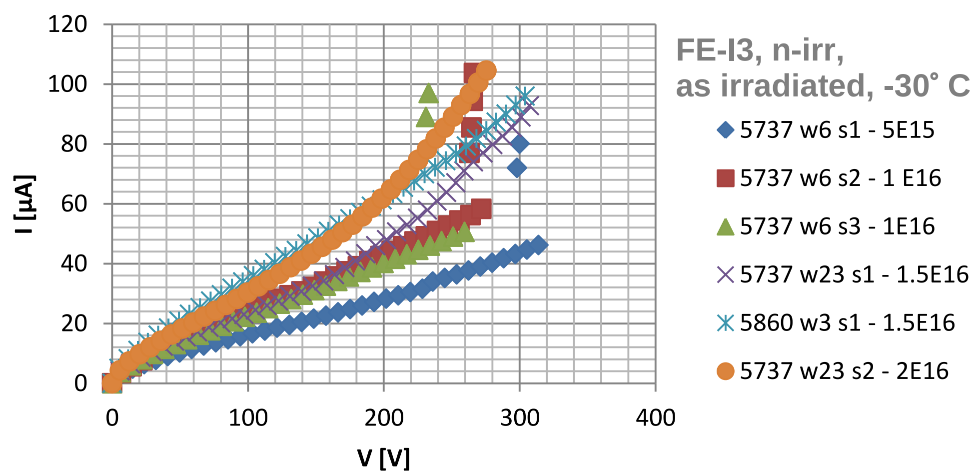


HL-LHC Studies: Irradiation Campaigns

- PS 23 GeV p (Nov 2014)
  → thanks to Federico Ravotti for irradiation!
  - 8 CNM, 1 FBK FEI4 bare assemblies; 3D strips
  - Non-uniform (12 mm FWHM beam)
  - Did not reach desired ITk fluence, but more than IBL fluence in peak (and 23 GeV instead of 23 MeV p used for previous IBL studies)
  - Shipped two good pixel devices to IFAE
    - Max fluence 5.2 and 8.4e15 n_{eq}/cm^2
    - Assembled on SCC PCBs
  - The rest stayed at CERN to be irradiated further (June/August 2015)
    - 1 device non-uniformly to 2e16 n_{eq}/cm^2 (max)
    - 3 devices more uniformly (scanning or wider beam) to 1.1 and 1.3e16 n_{eq}/cm^2 (mean)

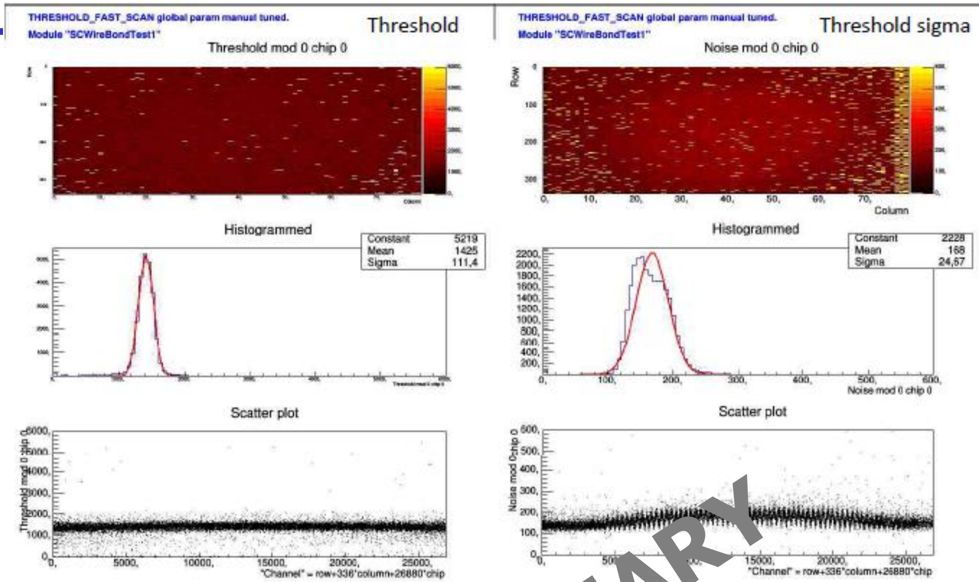


- JSI Ljubljana n (May 2015)
  → thanks to Igor Mandic, Vladimir Cindro for irradiation and AIDA2020 support!
  - FEI3 bare assemblies from CNM IBL wafers (to avoid Ta activation, also have great V_{BD})
  - 5e15, 1e16 (2x), 1.5e16 (2x), 2e16 n_{eq}/cm^2
  - Assembled at IFAE recently



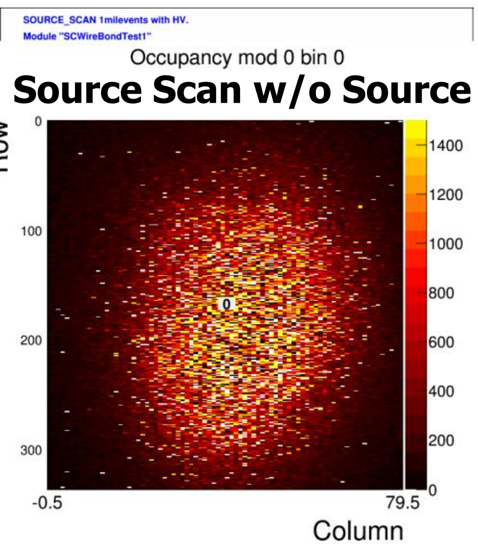
PS p Irradiated FE-I4 Devices

- First measurements   Here: 8.4e15 n_{eq}/cm^2
- Chip alive with no bad digital/analog if Amp2Vbpf=200 used
- Tuned to 1.5 & 3 ke, 6 ToT @ 6ke
    - Non-uniformity visible in tuning parameters, but seems to be under control
    - 1376 (7) noisy pixels at 1.5 (3) ke threshold
- Major problem with source scans!
    - Sample very active
      → trigger rate ~75 Hz w/o source!!!
      → can only use sample itself as a source
      → beam profile visible in occupancy map
    - Cosmic scan works → ready for testbeam next week

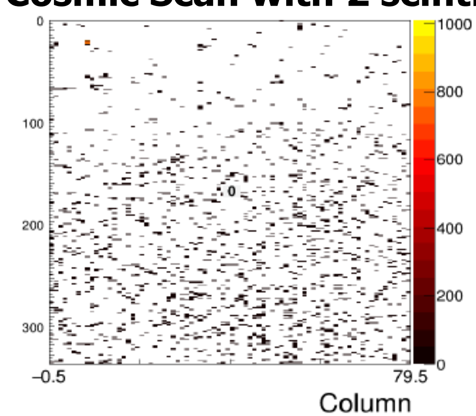


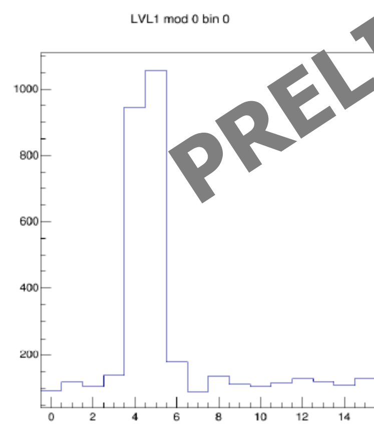
PRELIMINARY

Source Scan w/o Source



Cosmic Scan with 2 scint.



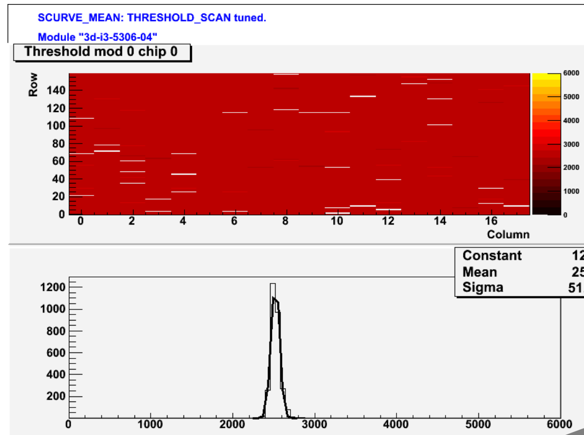


JSI n Irradiated FE-I3 Devices

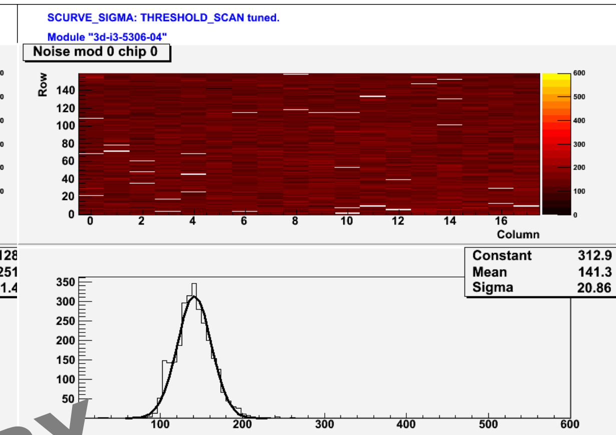
- First measurements (arrived 2 weeks ago)
- Mostly alive
- Tuned to 2.5 ke, 30 ToT @ 10ke
- Successful source scan for first devices
- Ready for testbeam next week

Here: 1e16 n_{eq}/cm^2

Threshold

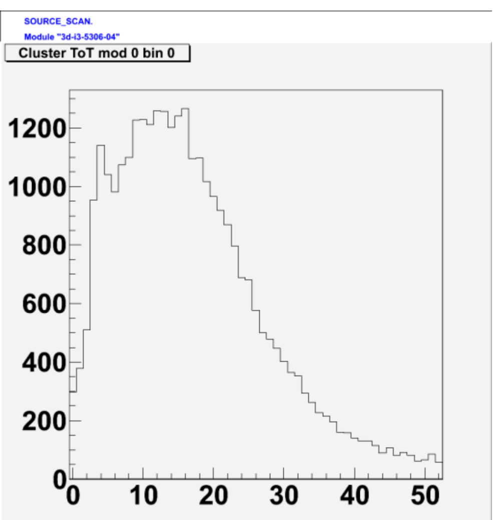


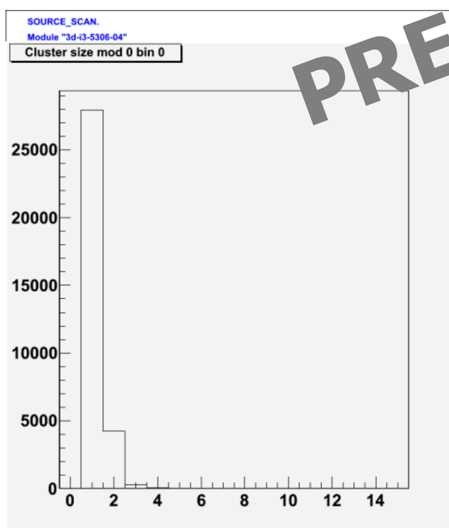
Noise



PRELIMINARY

Source Scan



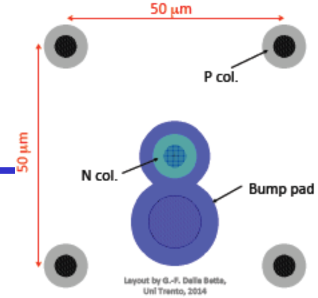


Mostly 1-hit clusters (unusual for source scan)
-> probably only seed above threshold
-> measured MPV~5.5 ke biased to low values

New 3D Productions

at CNM, FBK, Stanford, SINTEF

50x50 1E



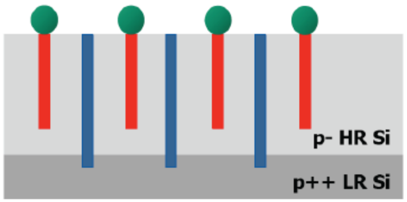
G.F. Dalla-Betta, FBK

- 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

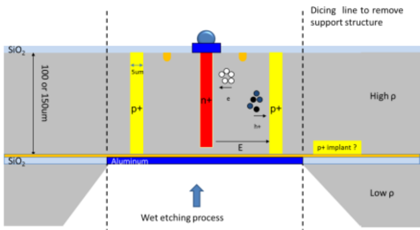
cf. FE-I4: L=67 µm

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



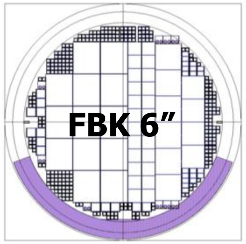
Si-Si bonding

G.F. Dalla-Betta, FBK

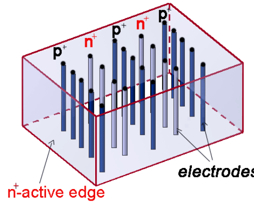


SOI

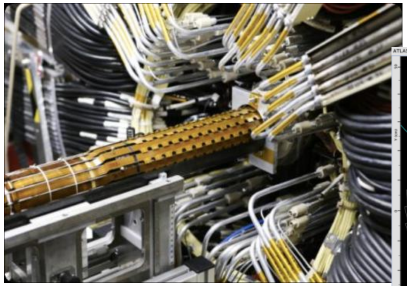
G. Pellegrini, CNM

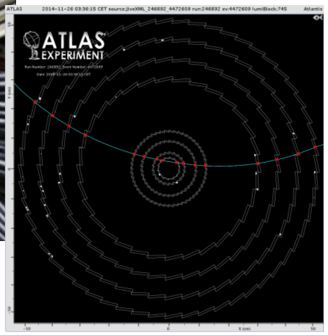


Conclusions

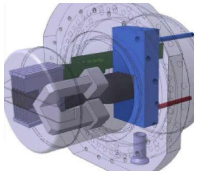


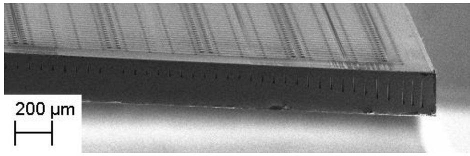
- 3D silicon detectors mature for HEP applications
- First-time use in HEP experiment in ATLAS IBL
  - Successful qualification, production, installation, commissioning and first collision data



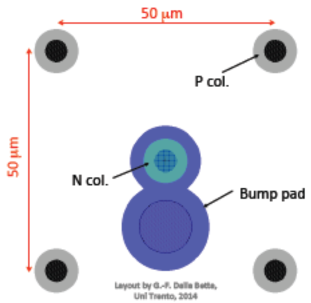


- Second use in AFP imminent
  - Successful qualifications (slim edge and non-uniform irradiation)
  - Productions on-going





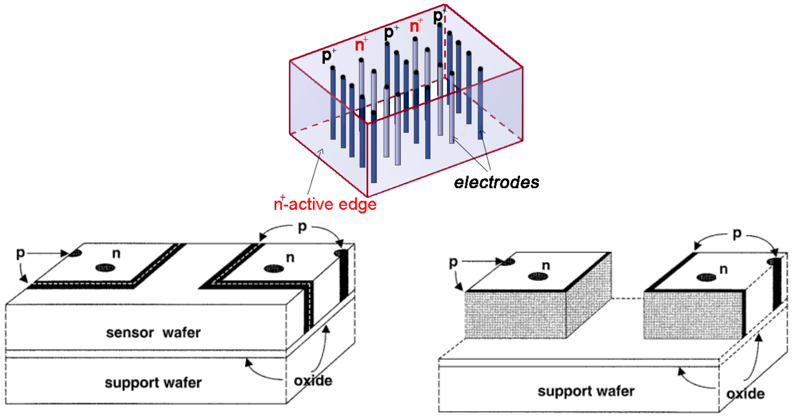
- R&D for HL-LHC pixel detectors on-going
  - New 3D production runs at CNM, FBK, Stanford, SINTEF
  - Smaller cell size, thinner, smaller columns, partly 6”
  - R&D with existing devices on-going



BACKUP

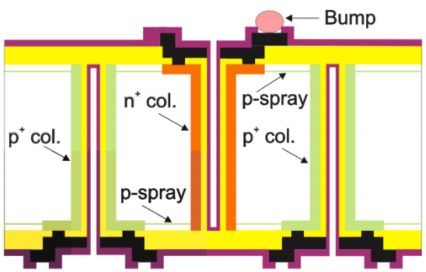
Different 3D Technologies

SNF (Stanford) / SINTEF (Oslo)



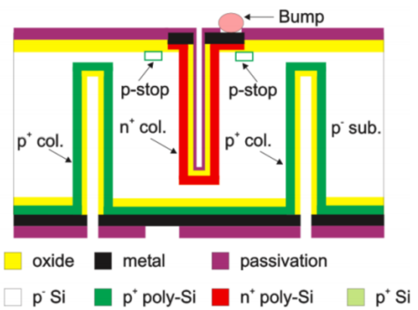
C. Kenney et al., IEEE TNS 48 (2001) 2405

FBK (Trento)



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

CNM (Barcelona)



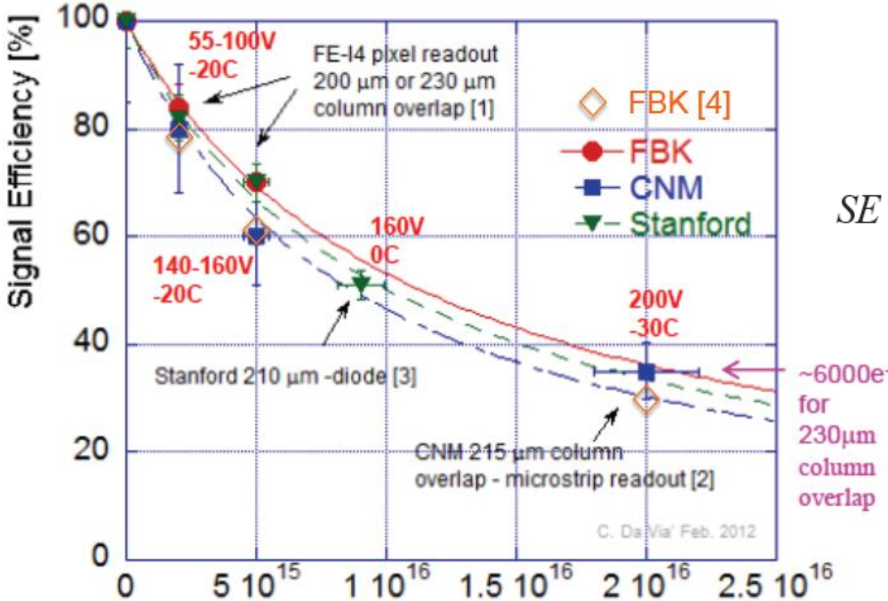
G. Pellegrini et al. NIMA 592(2008) 38
G. Pellegrini et al. NIMA 699(2013), 27

- **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

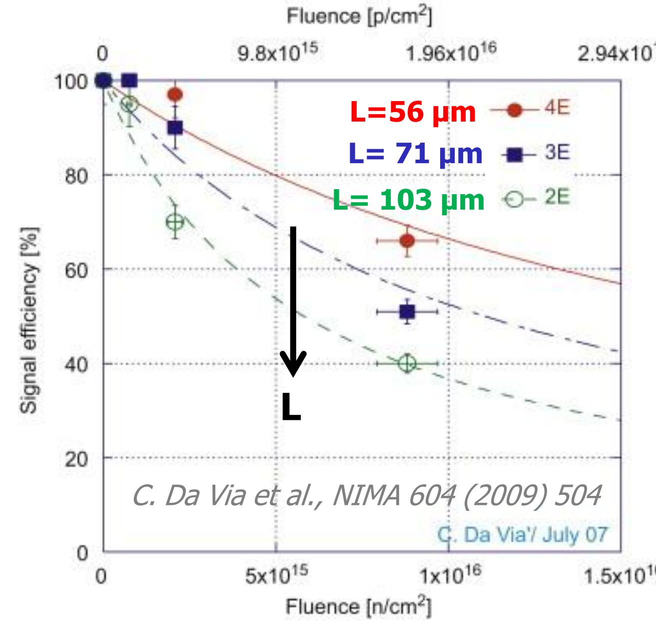
- **Double-sided process**
  - n columns etched from front, p from back
    - FBK: passing-through columns, p-spray
    - CNM: non-passing-through columns, p-stop
    - No support wafer needed
    - Bias applied at back side → no bias tab needed

    → 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



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



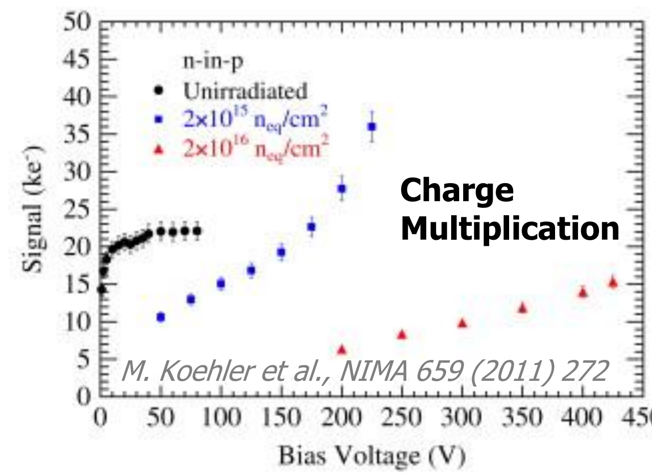
[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010

[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



- 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