3D Pixel Detectors at ATLAS

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On behalf of the **ATLAS Collaboration**

23rd International Workshop on Vertex Detectors – **Vertex 2014**
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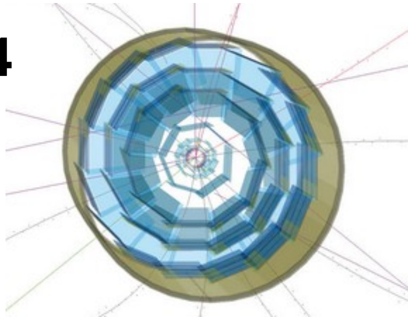
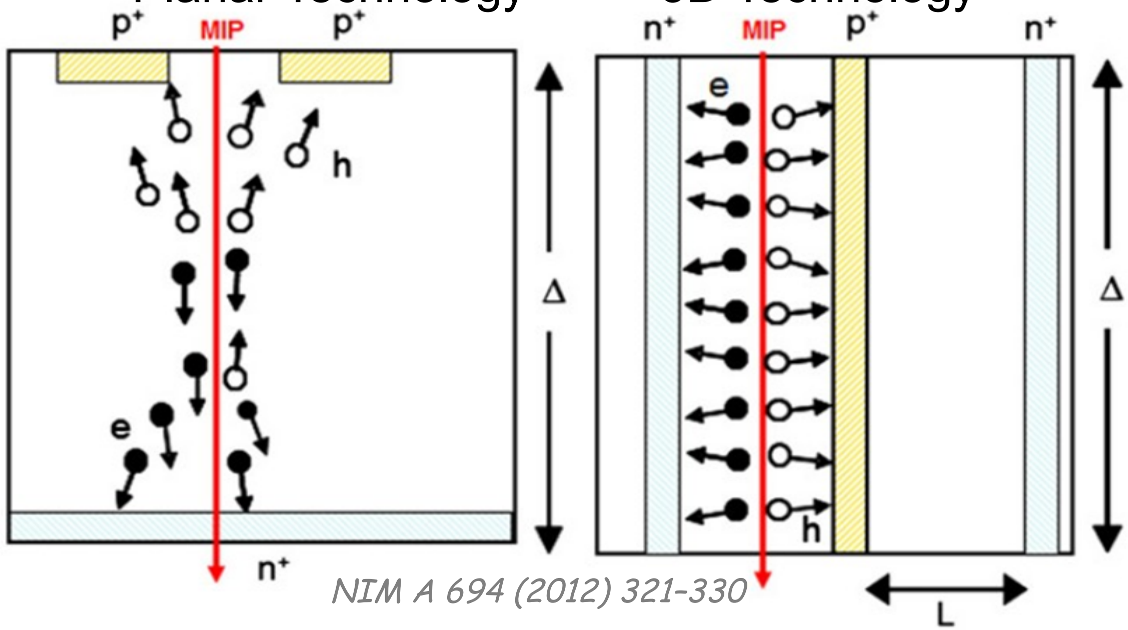


3D Pixels at ATLAS

- Introduction
- 3D pixels in IBL
  - Qualification
  - Production, sensor selection and yield
- 3D pixels in AFP
  - AFP introduction
  - Qualification of 3D sensors
- 3D Plans
- Summary

3D Pixel Detectors

• Proposed by S. Parker, C. Kenney and J. Segal (NIM A 395 (1997) 328)



NIM A 694 (2012) 321-330

Advantages of 3D

- Carriers drift parallel to wafer surface: shorter collection distance (less trapping)
- Lower depletion voltage
- Requires less cooling
- Active edges possible*

Disadvantages of 3D

- Complex fabrication (lower yield)
- Higher capacitance (more noise)
- Columns can reduce collected charge

Nucl. Instr. And Meth, 603 (2009) 319-324

* Also possible in planar technology (*NIM A 2006 Sep 1;565(1):272*)

3D Pixels at ATLAS: History

- In 2005 the FP420 collaboration (ATLAS+CMS) included 3D sensors for the forward tracker (CERN-LHCC-2005-025)
- In 2008 AFP (ATLAS Forward Protons) collaboration formed
  - Passed physics/technical reviews in 3.2014 (more on second part of talk)

- 3D R&D proposal (ATL-P-MN-0022,14/3/2007) approved by ATLAS Executive Board, creation of the ATLAS 3D Collaboration (18 institutions, 4 fabrication sites*), aim: 3D sensors for extreme radiation hardness
  - Big R&D effort on 3D sensors (see for e.g.: NIM A 604 (2009) 505)

- In 2009 ATLAS to install a new pixel layer: the IBL project
  - Evaluate possible sensor technologies for IBL: Planar, 3D and Diamond
- IBL TDR approved with installation date 2016 (LS2)
  - 1.2011 schedule changed, IBL to be installed in 2014 (LS1): *fast-track IBL*
  - 7.2011 IBL Sensor Review: install 75% planar and 25% 3D sensors
- Now the IBL is being commissioned!

* SNF (SLAC, US), Sintef (Norway), FBK (Italy) and CNM (Spain)

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2nd part

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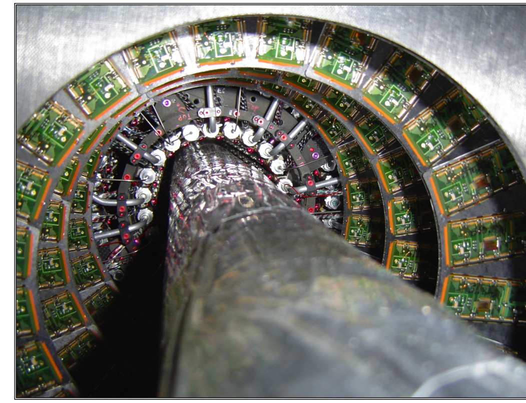
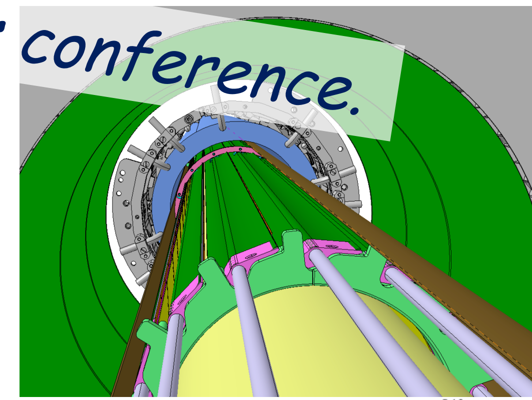
1st part

Insertable B-Layer (IBL)

Fourth ATLAS pixel layer, motivation:
improve physics, backup current inner layer

See Alessandro La Rosa's talk at this conference.

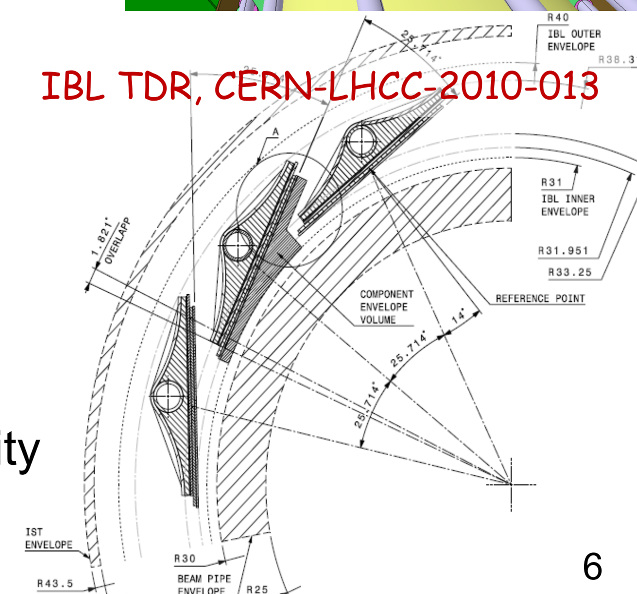




- Layout:
  - 14 Staves, each with 32 front-end chips
  - Mean radius 33cm, tilt angle: 14 deg
  - No overlap on Z due to space restriction
- Front-end/Sensor Design:
  - NIEL dose = 5×10^{15} n_{eq} cm^{-2} (w/ safety factor)
  - TID 250 Mrads
  - Small dead area (slim/active edge)
  - Max sensor power < 200 mW/cm^2 @ -15 C
  - Max bias voltage: 1000V
  - Hit efficiency after irradiation >97%

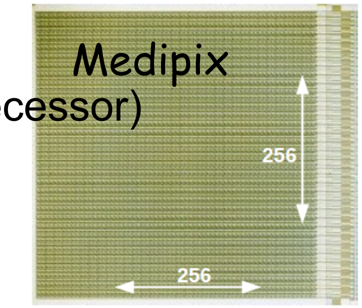
➢ Planar, 3D and diamond sensors considered for IBL
- Planar (n-on-n) used in first ATLAS pixel detector
- 3D and diamond had to demonstrate manufacturability
  - ➢ *Evaluate sensor prototypes for IBL qualification*

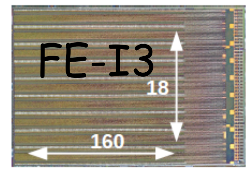
IBL TDR, CERN-LHCC-2010-013

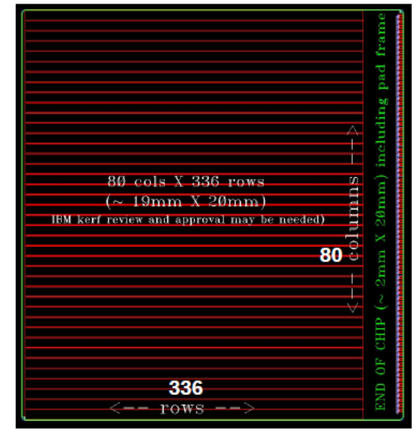


IBL: Font End Chip: FE-I4

- Biggest chip in HEP to date
- Higher active fraction (x6) (than ATLAS predecessor)
- Higher data rate, lower power
- More radiation hard (130nm technology)
  - *250 Mrads*

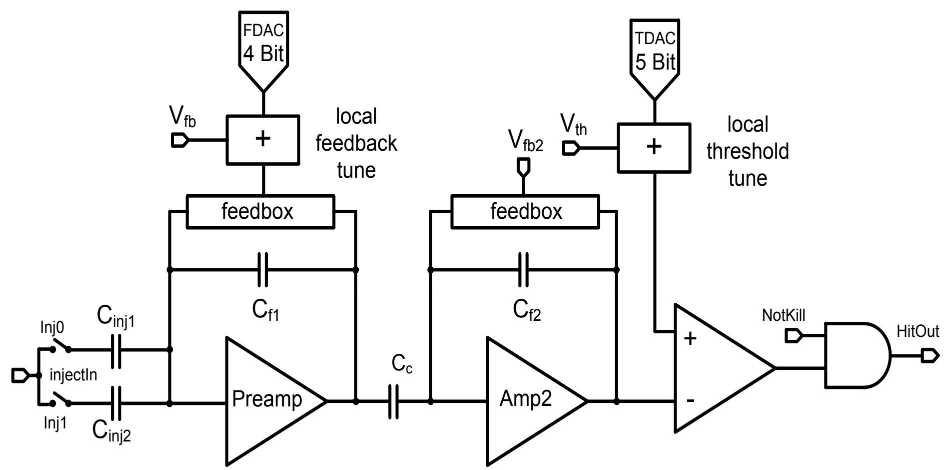


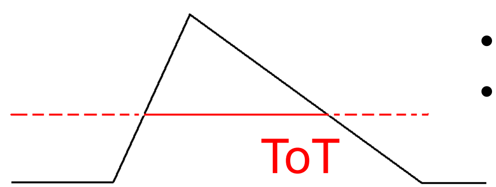




FE-I4

Pixel size (um2)	50x250
Pixel array	80x336
Chip size (mm2)	20.2x19.0
Active fraction (%)	89
Analog/Digital current (uA/pix)	12/6
Analog/Digital voltage (V)	1.5/1.2
LVDS output (Mb/s)	160
ToT Resolution	4-bit
Thickness	150 um



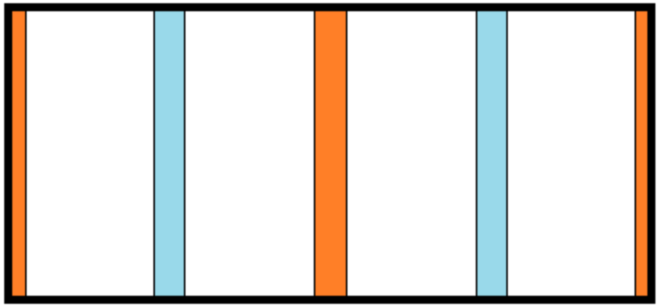


- Pixel above threshold
- Time over threshold (~collected charge)

- FEI4-A: *NIM A 636, 1, Pages S155, 2011*
- FEI4-B: *2012 JINST 7 C02050*

3D Pixel Detectors

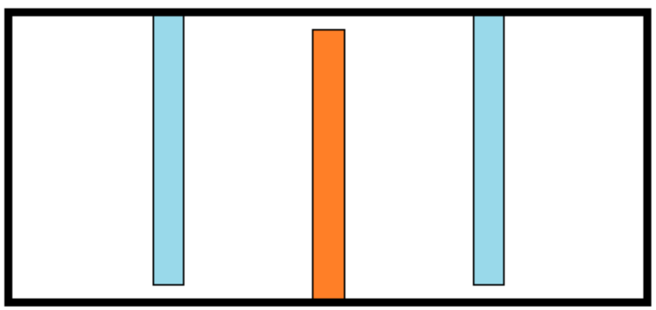
Full 3D technology:



SNF (SLAC) and Sintef

- Initial design
- Provides active edges
  - Charge collection within few μms of sensor edge *(NIM A 628 (2011) 216)*
- Difficult processing steps (requires support wafer)

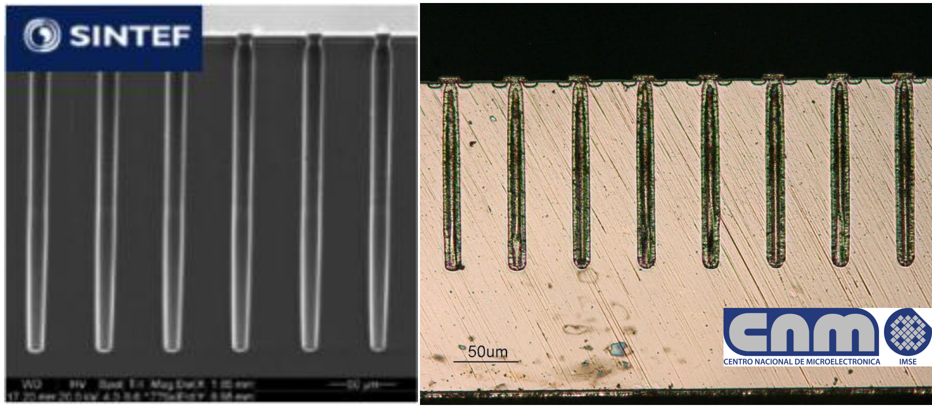
Double-sided 3D technology:



CNM and FBK

- Columns etched from both sides
- Simpler production process
- Larger dead region close to edges

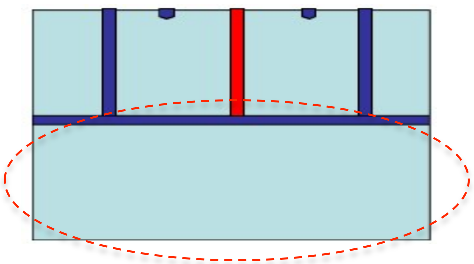
➢ 3D R&D Collaboration decided on a common design mask to evaluate technology options



Critical for 3D: DRIE - column etching

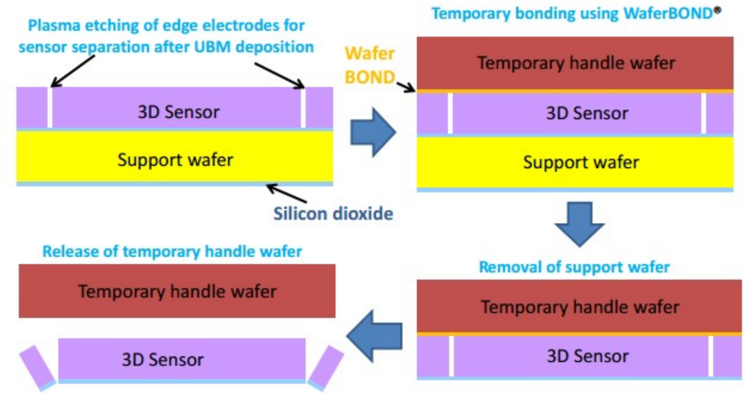
3D Pixel Detectors for IBL

- Full 3D: active ohmic trenches at edge, but needs **support wafer** and "**HV bias tap**"

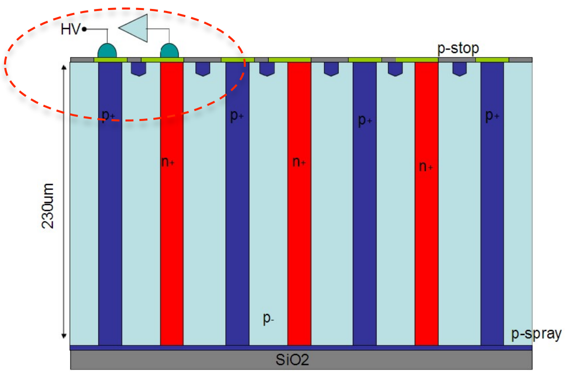


Support wafer has to be removed
SINTEF: deep reactive ion etching and temporary handle wafer

arXiv:1402.6384v2



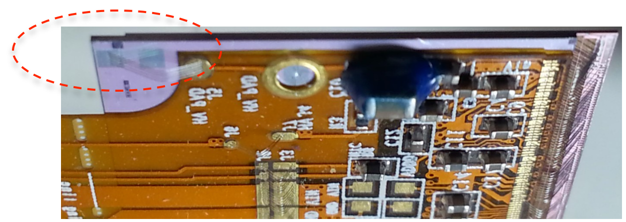
More complex process

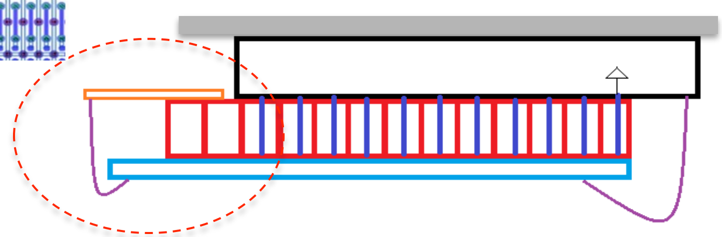


NIM A 694 (2012) 321-330

1.5mm for bias tab

Biasing solution not fully engineered

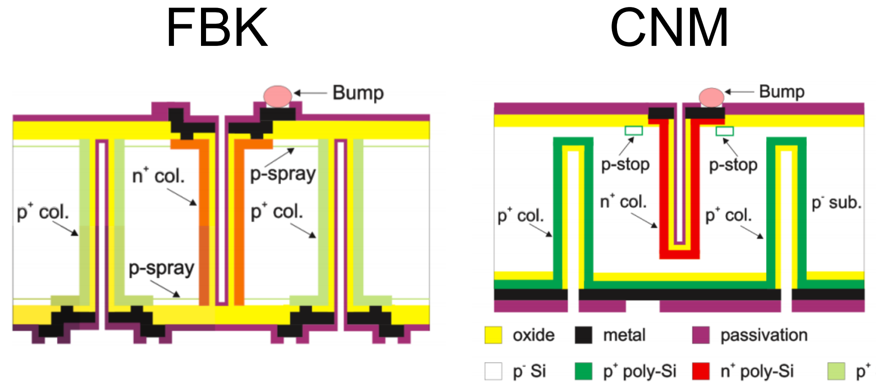


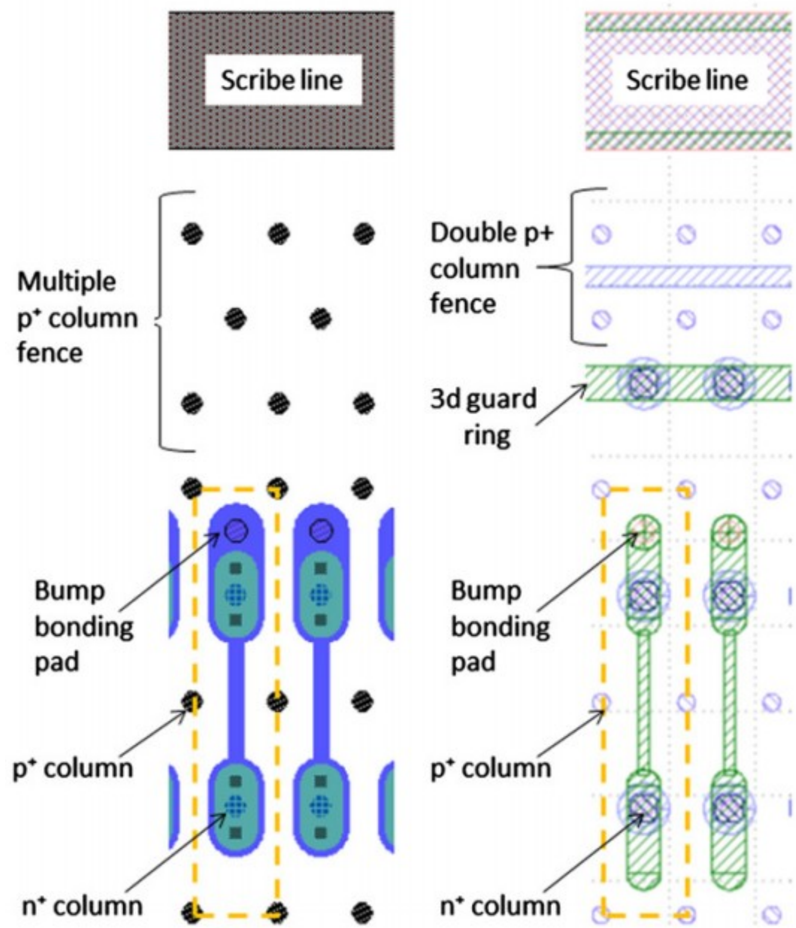


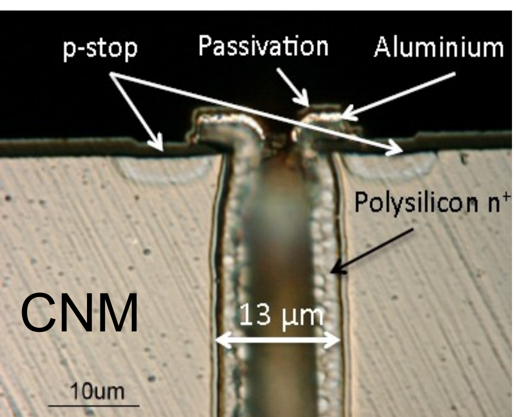
IBL installation anticipated by 1 year:
selected 3D double sided for IBL since it was a better established process

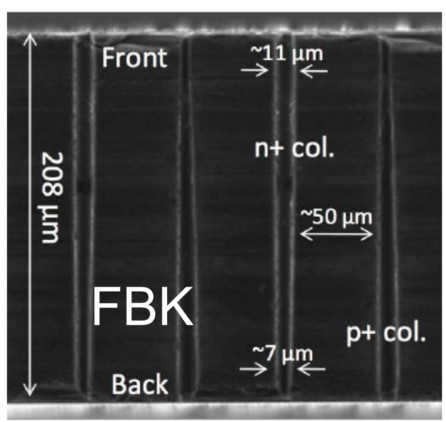
IBL 3D Pixel Sensors

- Standard 4” FZ p-type high resistivity wafers
  - 230 μm thick, ρ = 20 kΩ•cm
- Pixel geometry (50 x 250 μm^2): 2E
  - 6 p+; 2 n+ readout electrodes
- Double sided process:
  - CNM: 210 μm columns
  - FBK: full-through
- Pixel isolation:
  - CNM: p-stop
  - FBK: p-spray
- Slim-edges: 200 μm
  - CNM: 3D GR + fences
  - FBK: fences









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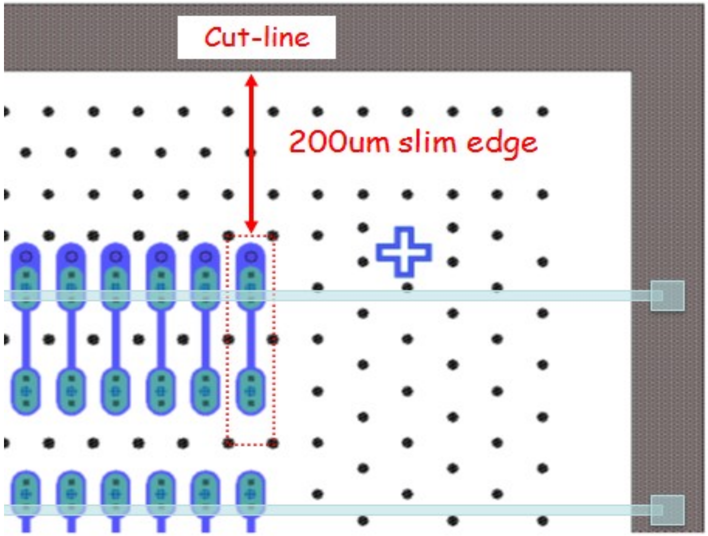
IBL 3D Pixel Sensors

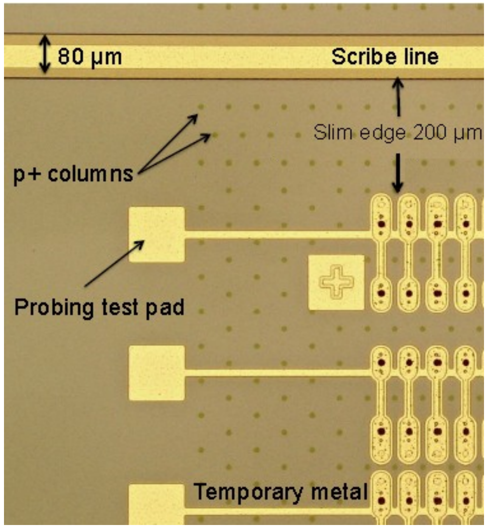
Evaluation of sensor at wafer level:
- ➢ Bump-bond only “good” sensors



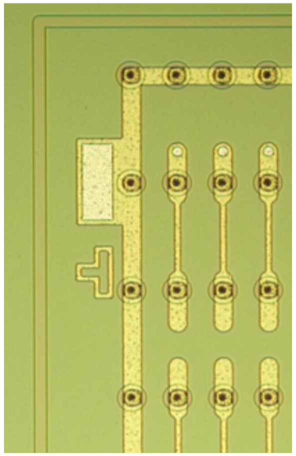
Provided by:
G-F Dalla Betta
G. Pellegrini

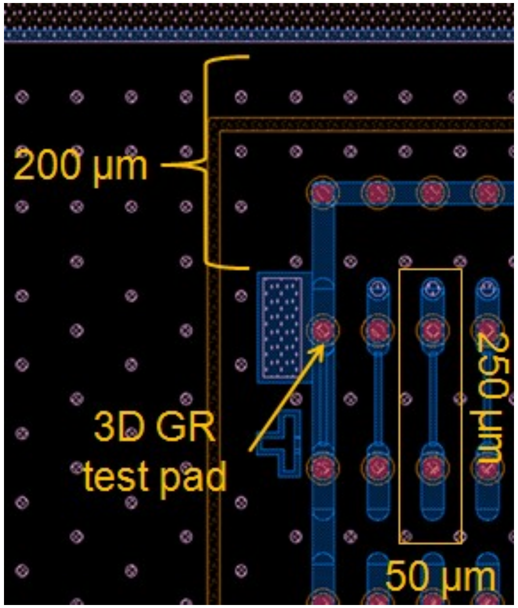
FBK: temporary metal
- Short all pixel in a column
- Measure IV of 80 strips
- Needs extra steps to deposit/remove metal

IEEE TNS 60(3) 2357-2366



CNM: 3D Guard-ring
- Measure IV only along the 3D guard-ring
- Does not test full sensor area!

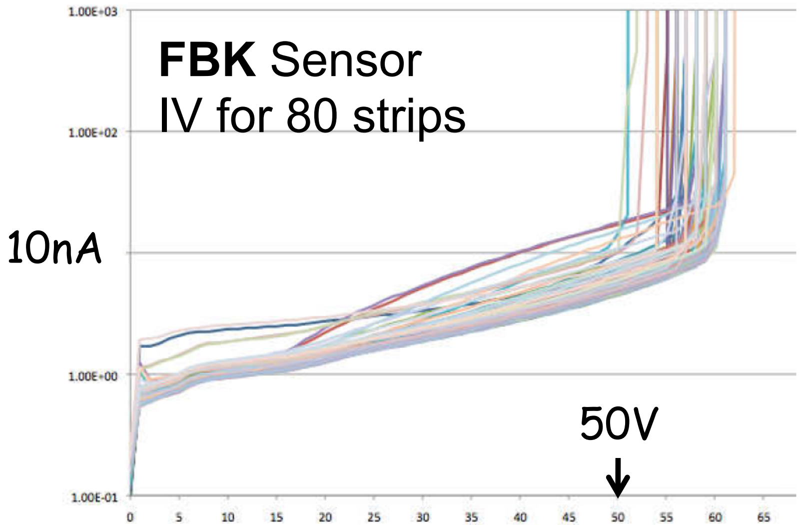


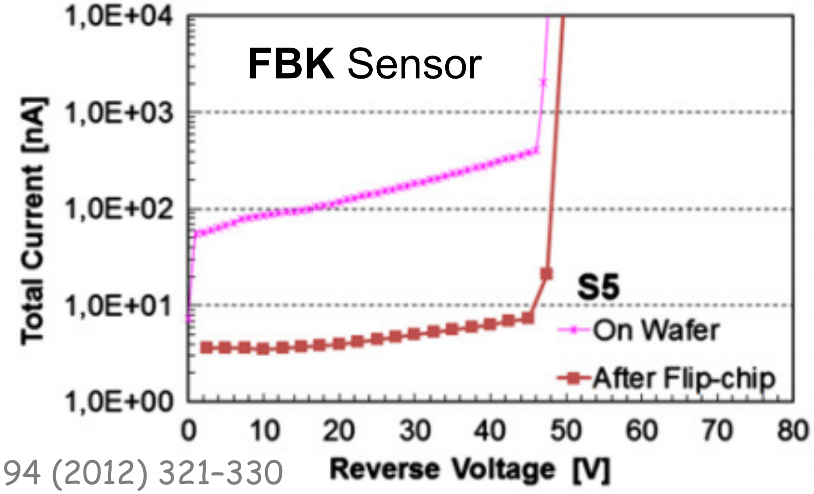


IBL 3D Pixel Sensors: pre-production

Sensors had to meet wafer quality (bow, thickness tolerance, etc) and electrical specifications (leakage current, Vbd,…)

S. Grinstein (IFAE) – Vertex 2014





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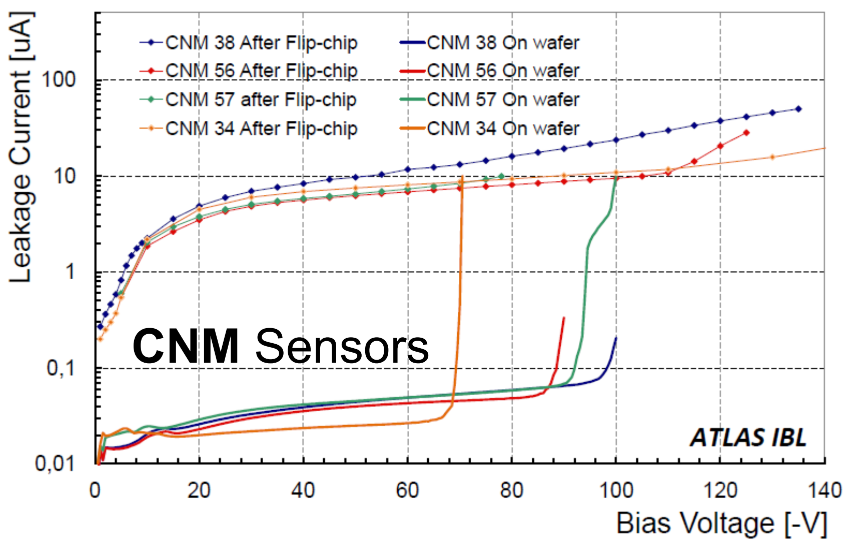
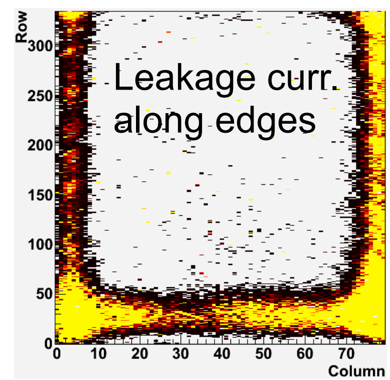
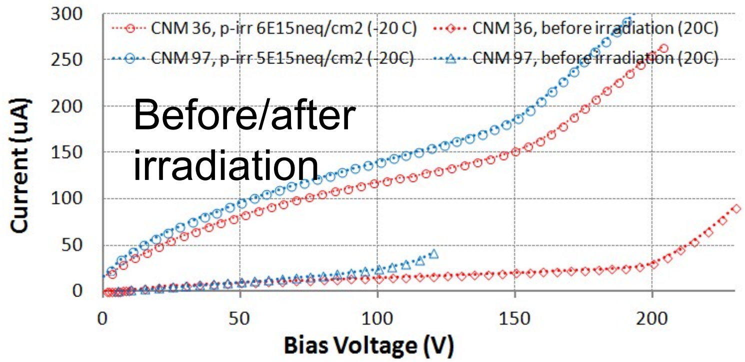




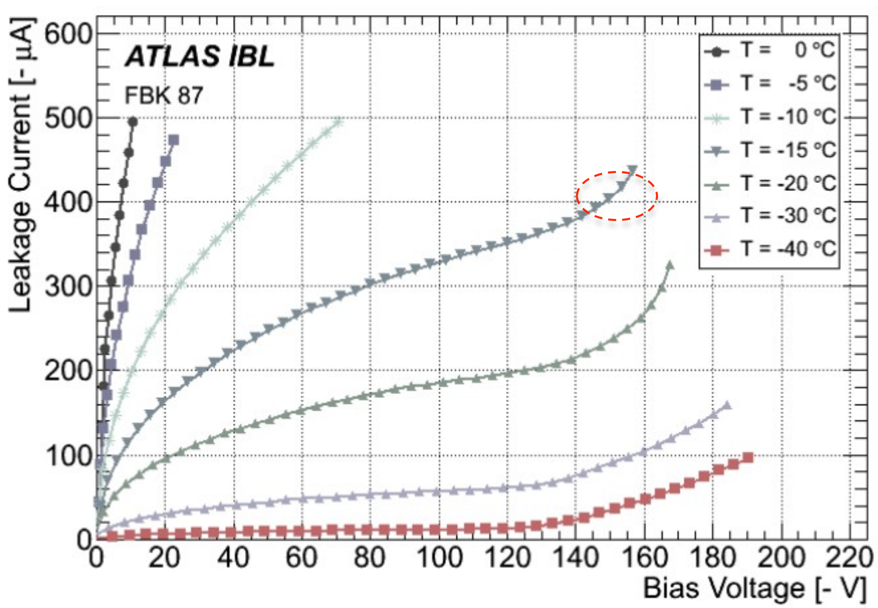
- Good yield of pre-productions (~60% on selected wafers)
- Only ~20 assemblies bump-bonded…

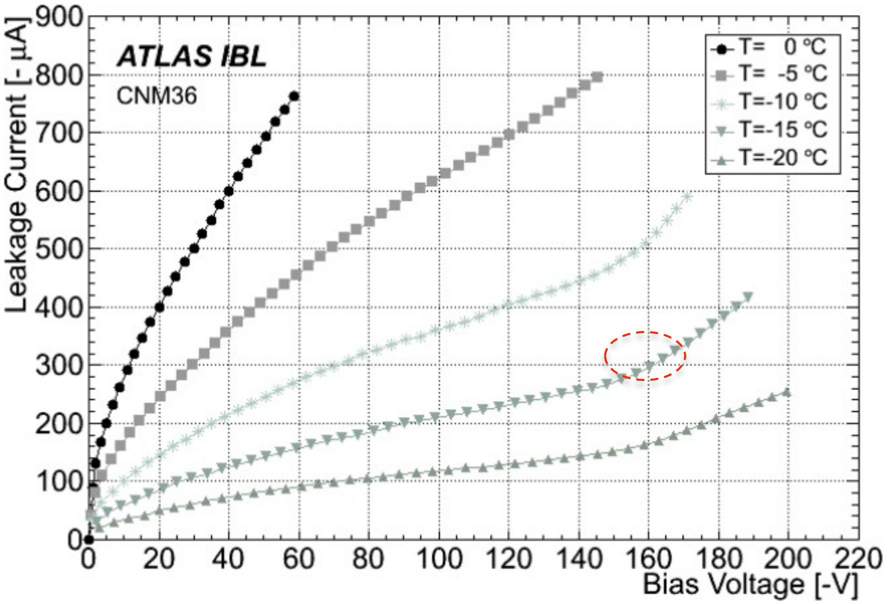
Irradiation of IBL 3D Prototypes

- 3D IBL devices irradiated to IBL fluencies:
  - Karlsruhe (http://www.fzk.de/) : 25MeV protons
  - Ljubljana (http://www.ijs.si/): reactor neutrons
  - Also LANL and CERN



5E15 neq/cm2



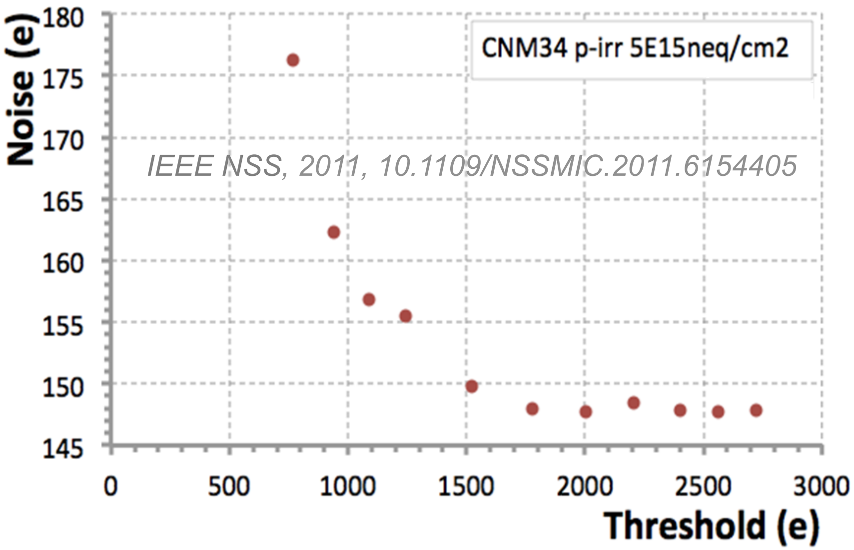


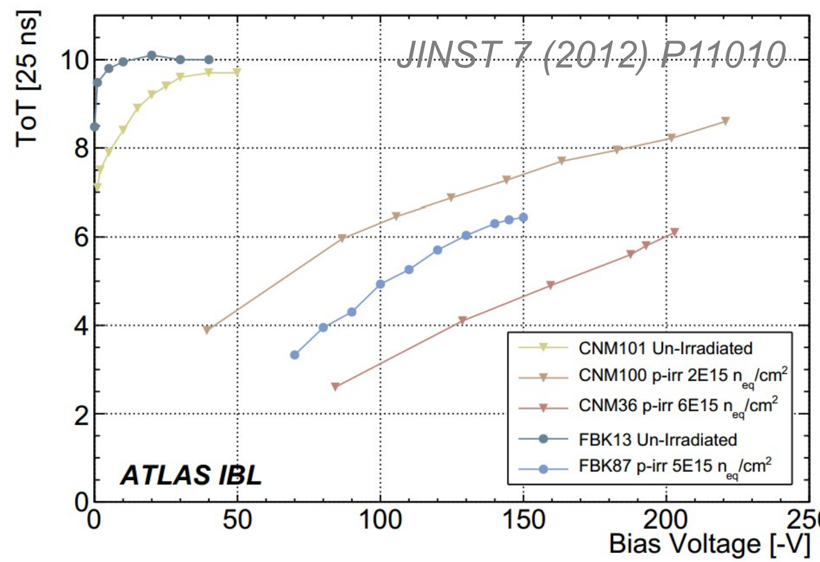
JINST 7 (2012) P11010

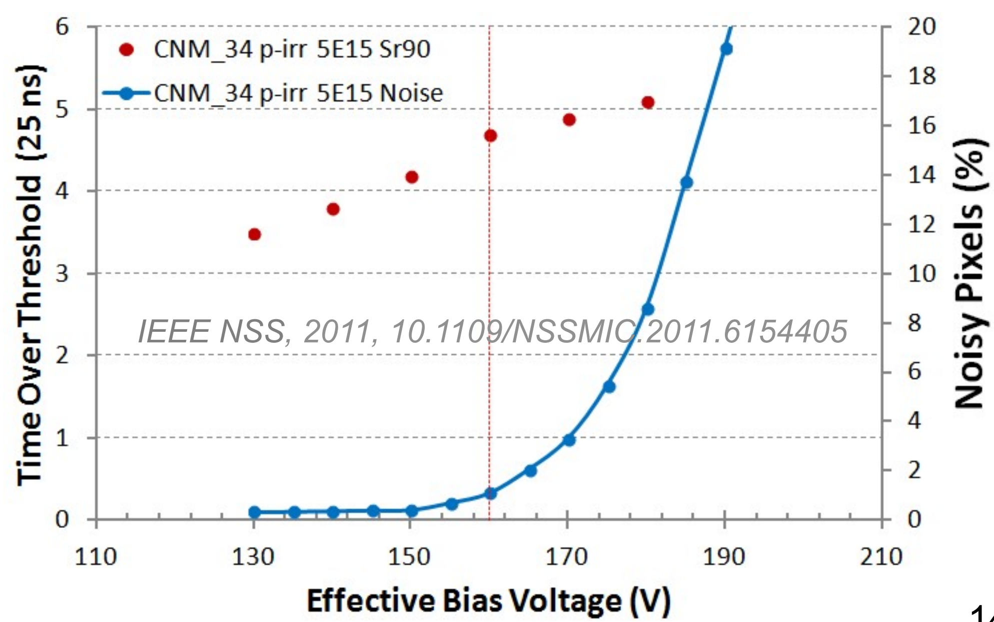
For 3D devices irradiated to IBL fluencies power dissipation is no constraint:

- At -15C and Vop (see next slide): 20mW/cm2 (planar ~90mW/cm2)

Device Performance (laboratory)



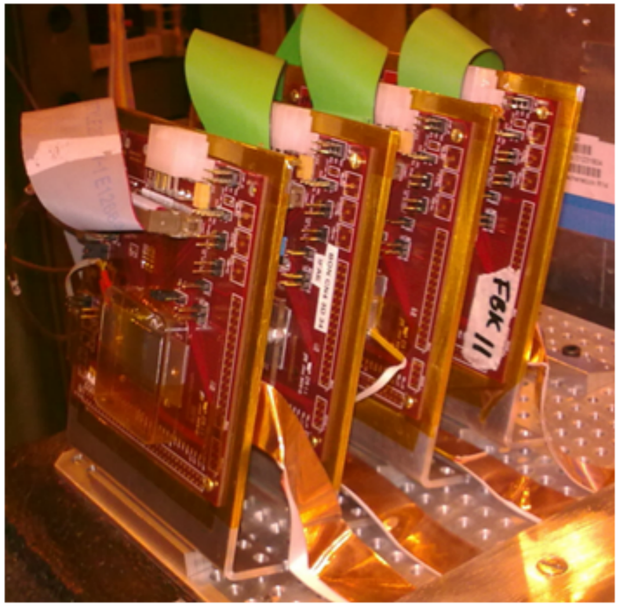


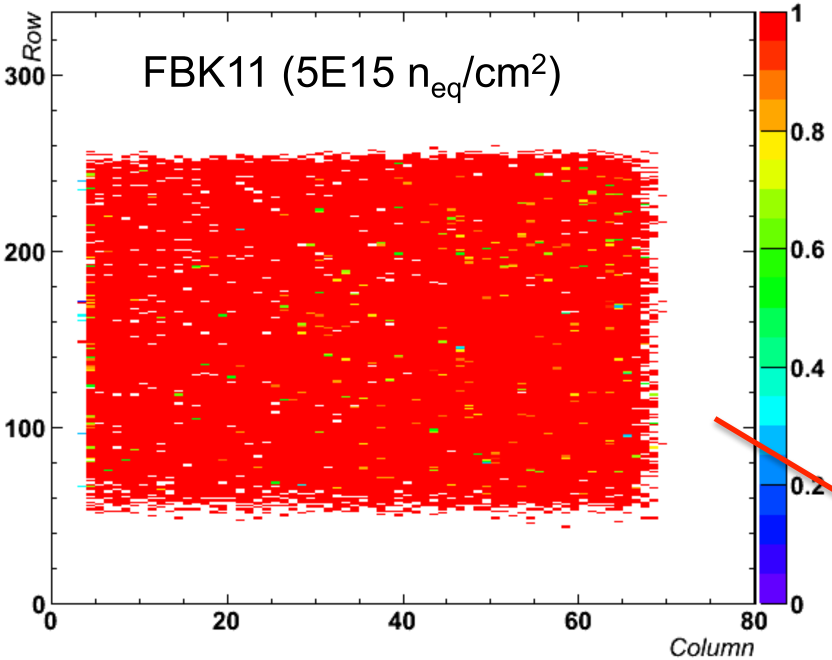


- 3D devices can be operated at threshold of 1500e (current detector 3200e)
- 3D noise ~150e (slightly higher for FBK, planar ~120e)
- Charge collection verified
  - FBK depletes at lower bias
  - But lower Vbd (FBK future: partially pass-through)
- Optimal high voltage for 3D devices: ~ 160 V

Device Performance: Test-beams

- Test beam measurements **critical** to study performance of IBL devices (sensor decision!)
  - ✓ **Efficiency** and position resolution
- Several test-beam periods carried out (DESY, CERN), and different devices tested
  - EUDET and ACONITE telescopes
  - Partially supported by AIDA

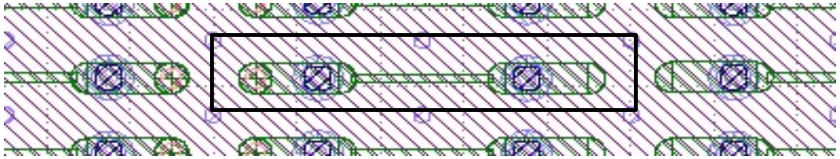




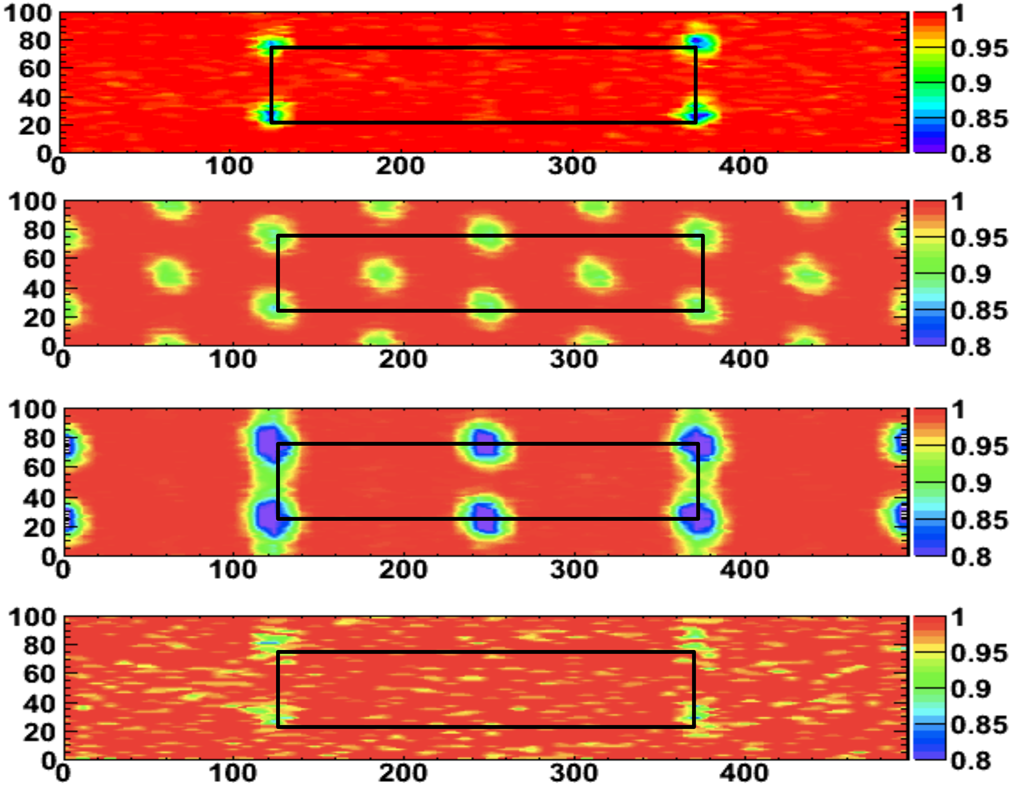
- Only part of the FE-I4 device covered by telescope planes
- 15 deg tilt in rφ (expected in IBL)
- Noisy, dead pixels masked out
- Efficiency determined from extrapolated track on devices (3x3 matching window)

Overall efficiency: 98.3%

Test-beam Results



Pixel efficiency map: fold efficiency to “single” pixel



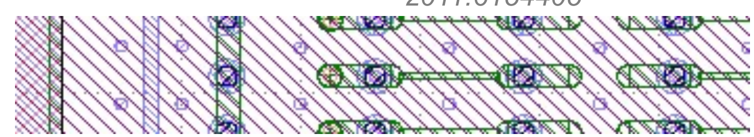
SCC55 **CNM-3D**: un-irrad
HV = 20V, Φ = 0 deg, 1500e threshold
Eff.=99.4%

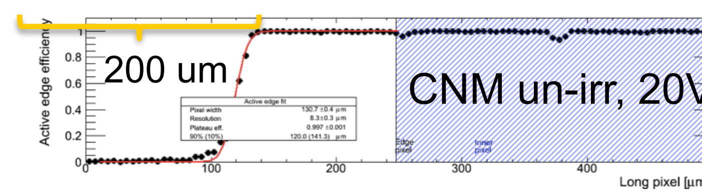
SCC105 **FBK-3D**: un-irrad
HV = 20V, Φ = 0 deg, 1500e threshold
Eff.=98.77%

SCC81 **CNM-3D**: n-irrad (5E15 n_{eq}/cm^2)
HV = 160V, Φ = 0 deg, 1500e threshold
Eff.=97.46%

SCC34 **CNM-3D**: p-irrad (5E15 n_{eq}/cm^2)
HV = 160V, Φ = 15 deg, 1500e threshold
Eff.=98.96%

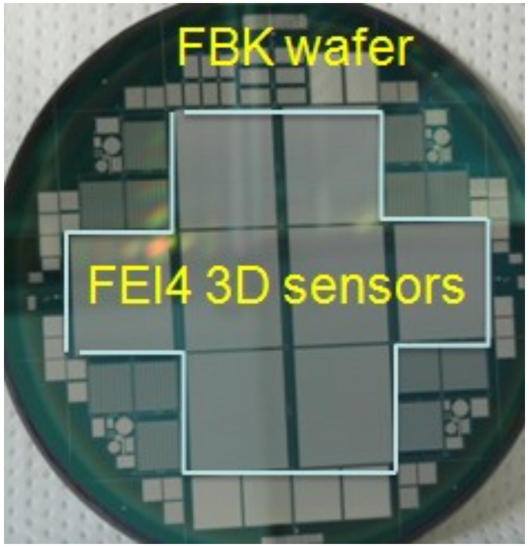
IEEE NSS, 2011, 10.1109/NSSMIC.2011.6154405





- Cooling to -15C (measured on PCB at 1cm from assembly)
- High efficiency (>97%) after irradiation (5E15 n_{eq}/cm^2) has been achieved
- Slim edge: 200 μm *(less for FBK!, see slide 25)*

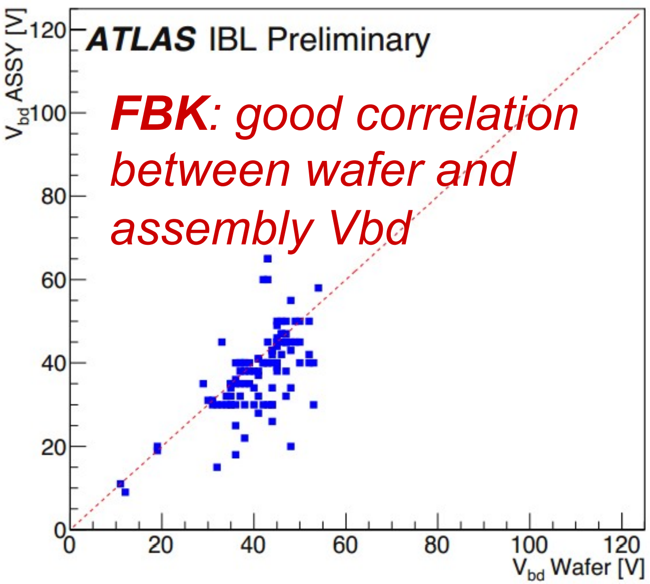
IBL 3D Productions

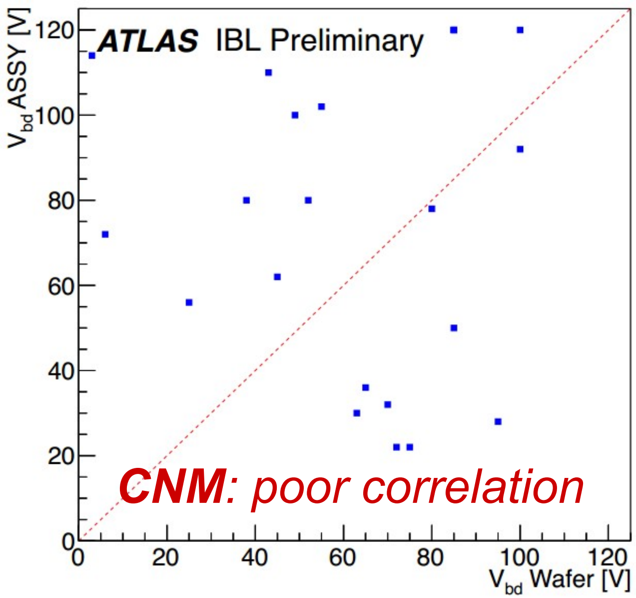


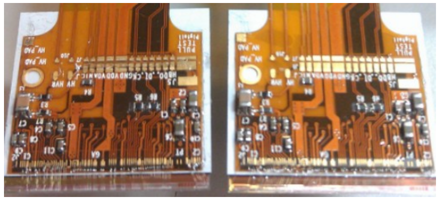
Productions yields:

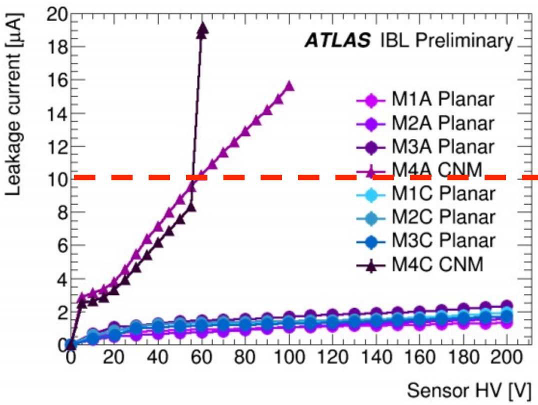
- FBK: 57% (on 33 selected wafers, ≥ 3 good sensors)
    - Based on temporary metal measurements at wafer level
- CNM: 72% (on 40 selected wafers, ≥ 3 good sensors)
    - Based on 3D-GR method at wafer level!

Evaluate devices (Vbd) **after** hybridization:





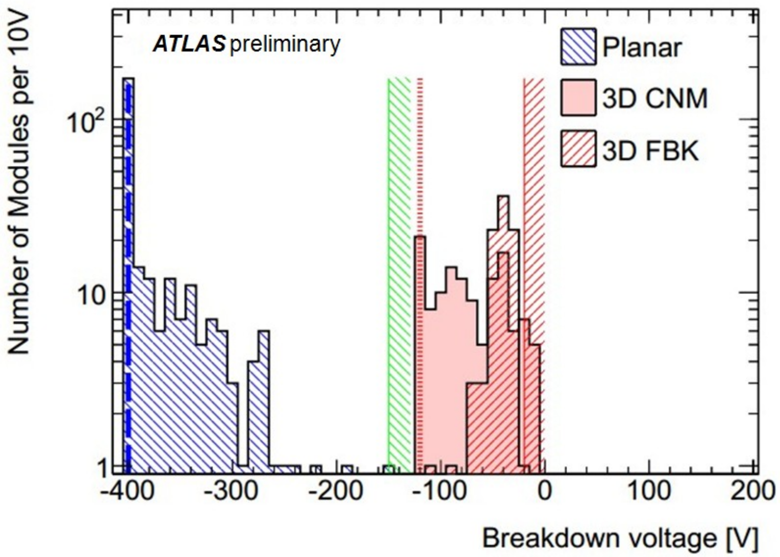




➢ 3D-Guard Ring evaluation method not good enough!

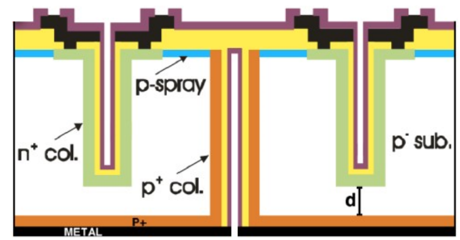
- Little statistics because QA made with too low bias current limit…
- CNM implementing poly-silicon bias structure for new productions

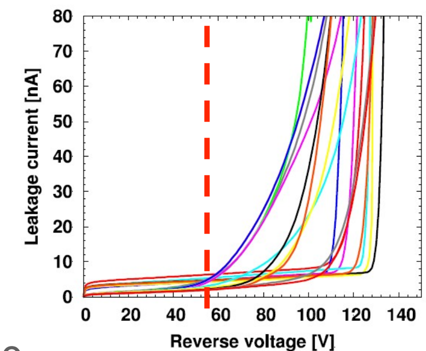
IBL 3D Modules



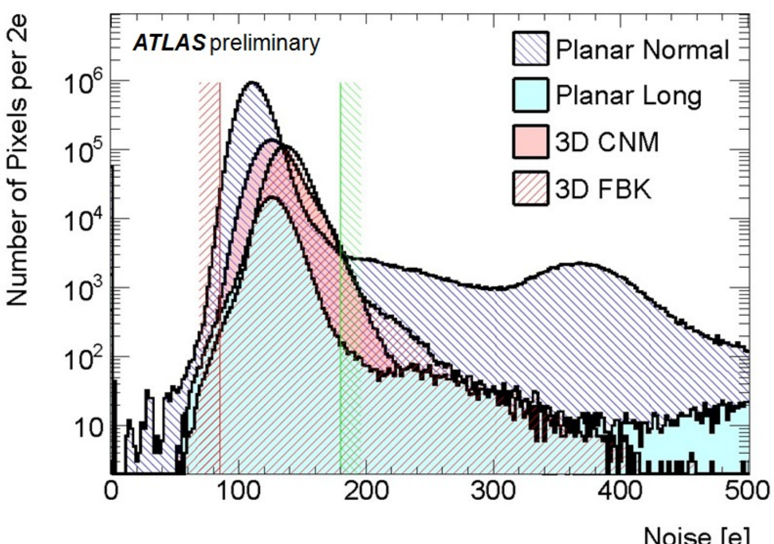
FBK assemblies have lower Vbd than CNM

- Modified process: partially etched junction columns





10.1109/NSSMIC.2013.6829540



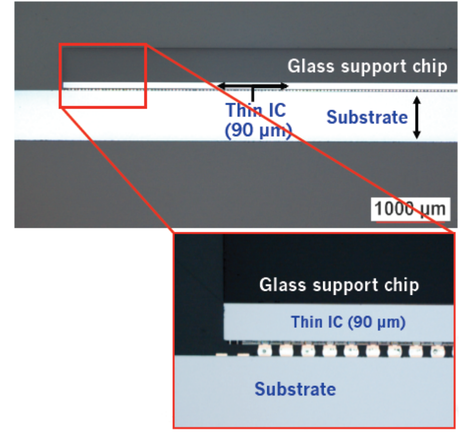
ATLAS publication in preparation
ATL-INDET-INT-2014-003

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

- Calibration: 10ToT @ 16ke
- Threshold: 3000e
- Temperature: -15C

- 3D devices higher noise than planar: higher sensor capacitance 110fF vs 170fF (NIMA 714 (2013) 83)
- FBK noise slightly higher than CNM, due to larger column overlap

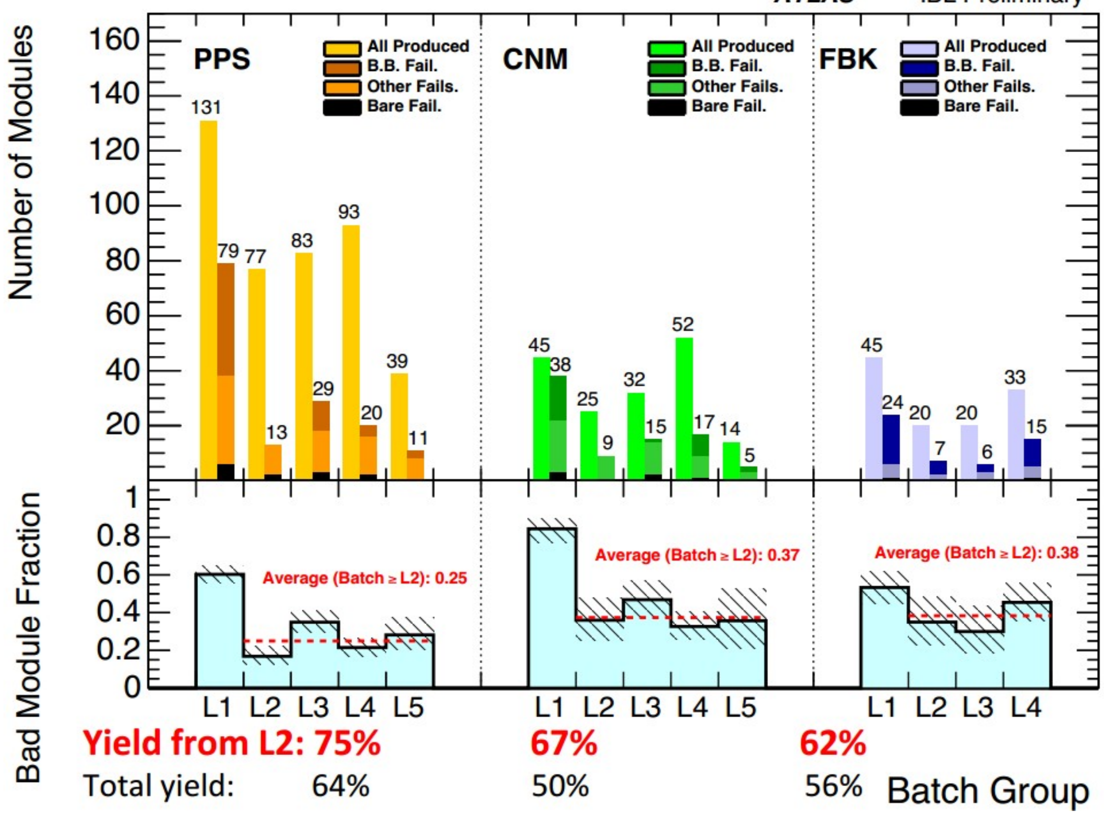
Bump-Bonding and Assembly



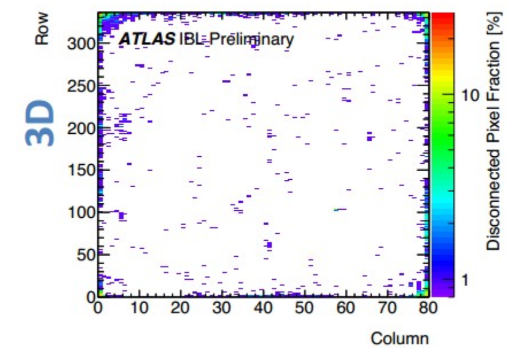
Initial problems with bump-bonding yield

- CNM affected by Vbd (3D GR selection method)
- FBK more affected by bump-bonding yield (not understood)
  - *Temporary metal?*

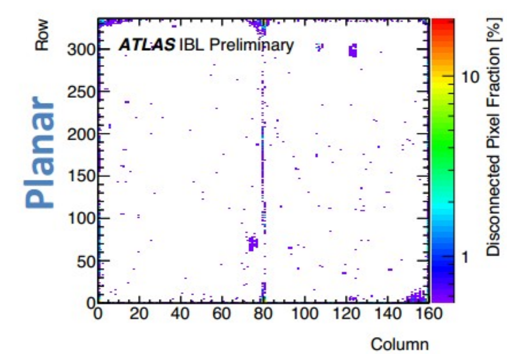
Module failures in production by categories



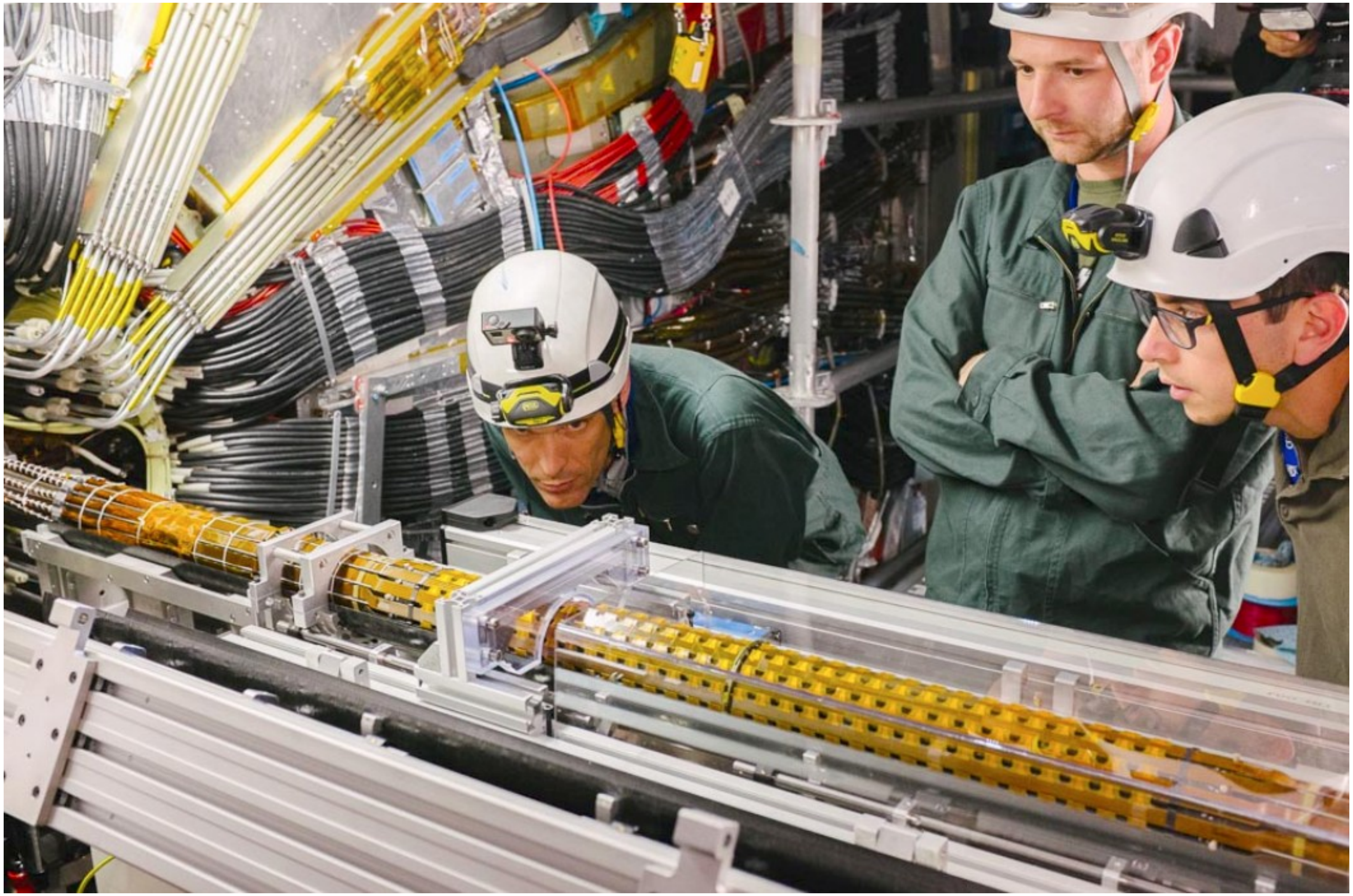
Map of disconnected pixel for all modules on the 14 IBL staves



Dead pixel fraction on IBL: 0.09 %



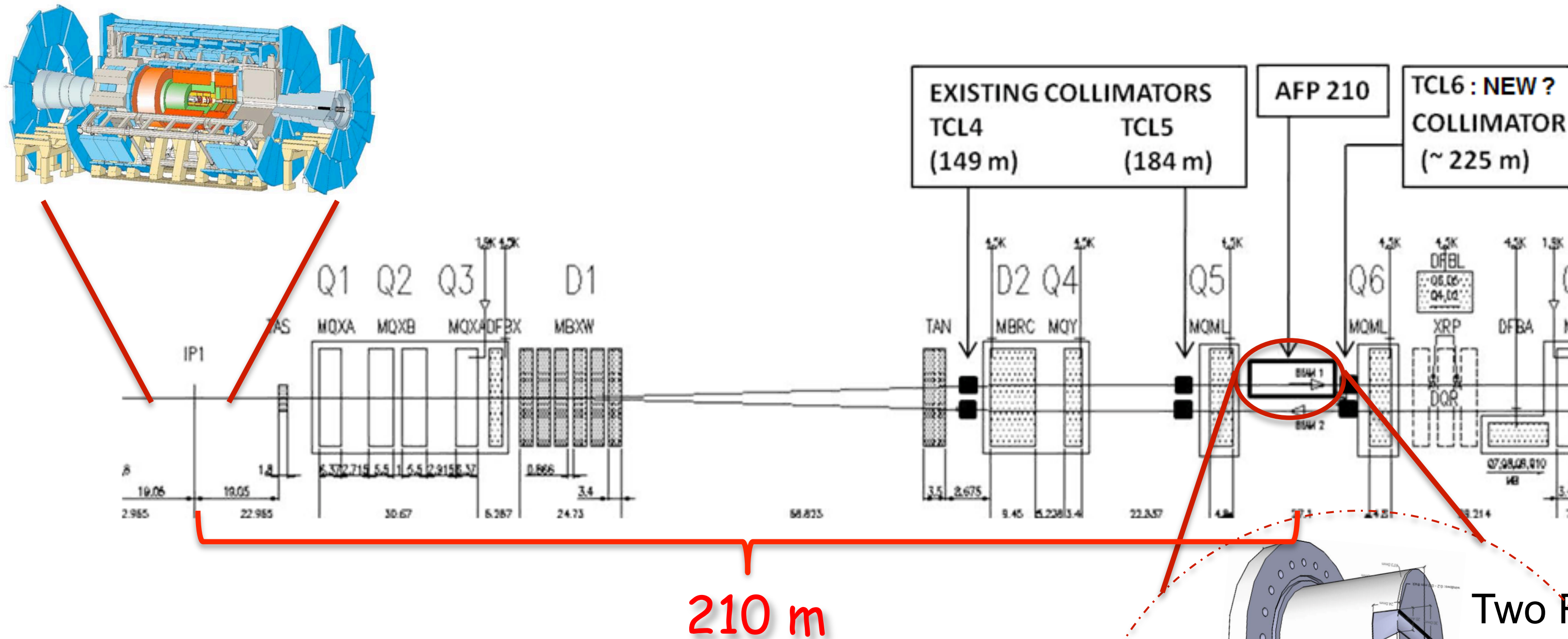
IBL Installation

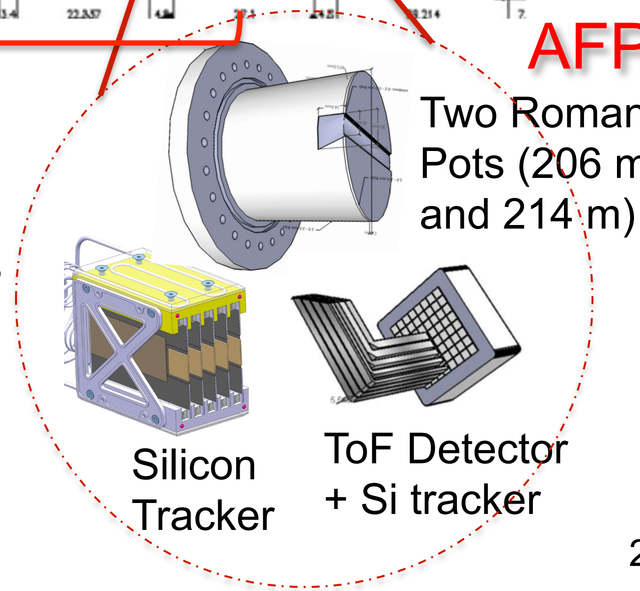


- See Alessandro's talk
- 3D detectors installed and working for the 1st time in an experiment!
    - 112 3D modules

AFP Introduction

- AFP will study events in which intact protons emerge from ATLAS inelastic collisions, with detectors close to the LHC beam at 210 m from the IP





Many interesting scattering processes characterized by protons emitted at very low angles

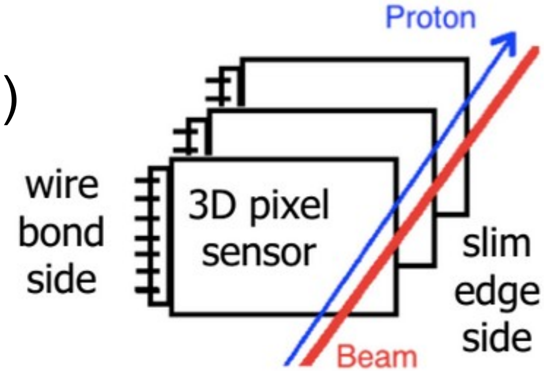
- **Tracker** for momentum measurements
- **ToF** to reduce background (at high luminosity)

AFP recently passed ATLAS internal physics and technical reviews.

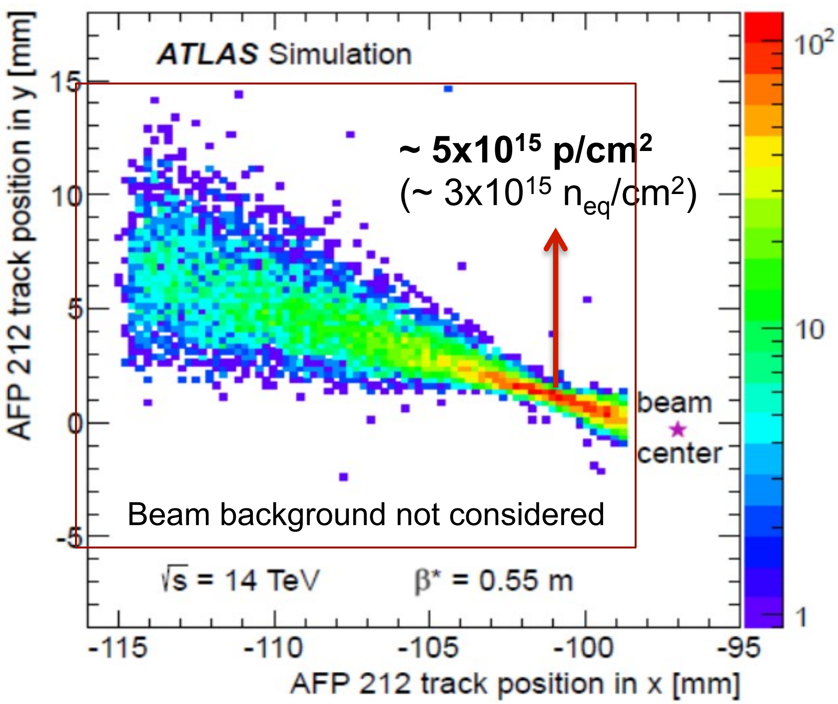
S. Grinstein - ICHEP 2014

AFP Tracker

- Mounted as close as possible to the beam to increase physics sensitivity (allow mass resolution of ~5 GeV)
- Run luminosity scenarios:
  - Low-μ: dedicated runs (100/nb, *proposed program*)
  - High-μ: possible upgrade (100/fb)



Expected radiation profile on the tracker sensor for 100/fb (with 2 RP per side):



[Trzebinski M., CERN-THESIS-2013-166]

Tracker requirements:

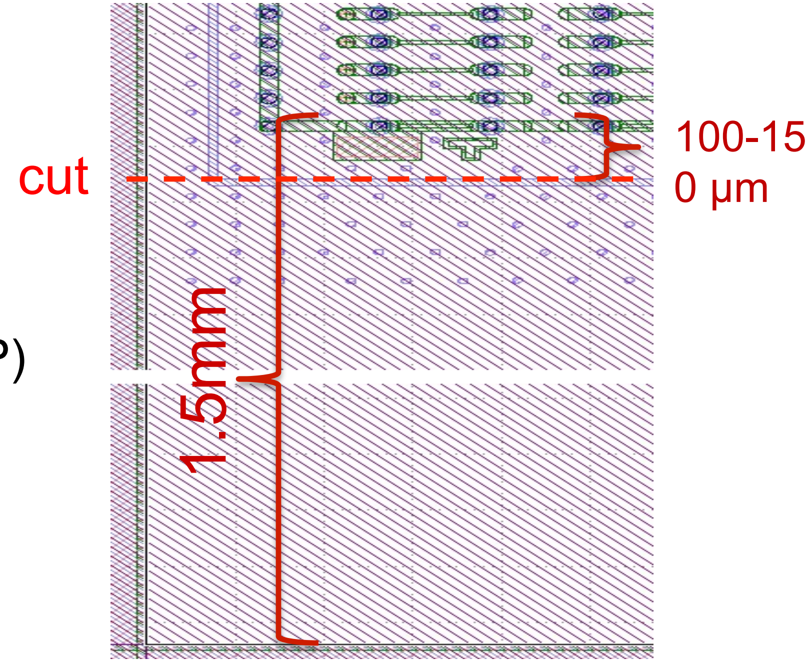
- Position resolution of 10 μm (in *x*)
- Detector with no inactive edge
- Radiation hard (and cope with non-uniform dose) – for high luminosity operation

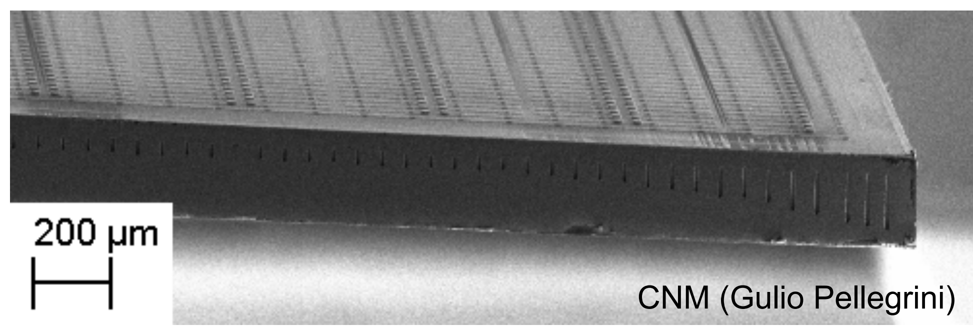
Silicon detectors:

- 3D pixel sensors
- FE-I4 readout ($2x2cm^2$)

Slim Edge for AFP

- Edge slimming:
  - Cut IBL sensors ~1.5mm inactive edge down to 100-150 µm (FE-I4 chip: 80 µm dead region)
  - Investigated: Scribe-Cleave-Passivate (SCP) slimming with promising results
    NIM A 731 (2013) 198
  - Technique used to make AFP prototypes: standard diamond-saw cut
  - Used IBL sensors of low quality





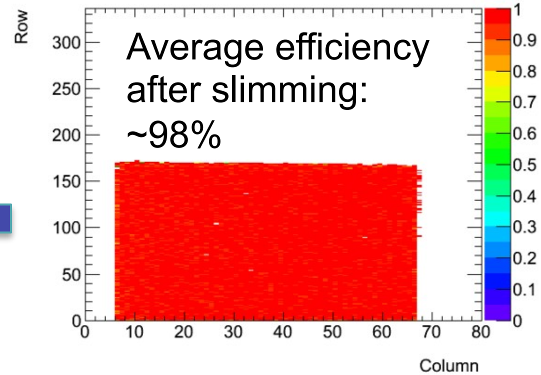
➢ AFP 3D pixel prototypes ready for testing!

AFP Tracker: Performance

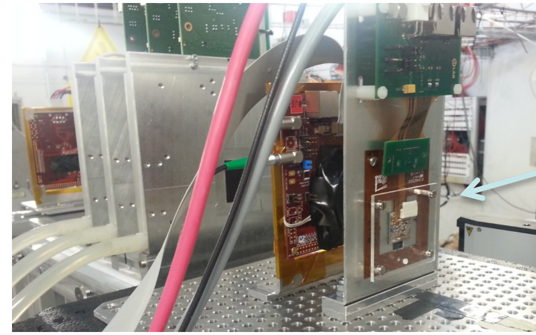
S. Grinstein - Vertex 2014

Beam test campaign at DESY during 2013/14

Is the edge efficiency affected by the diamond saw cut?

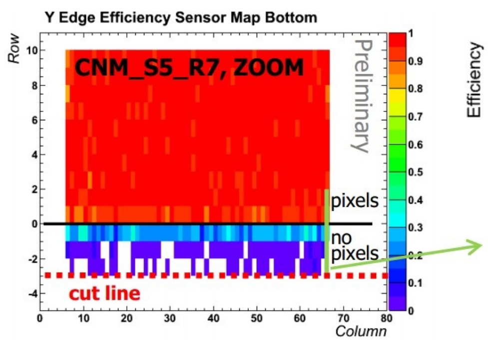


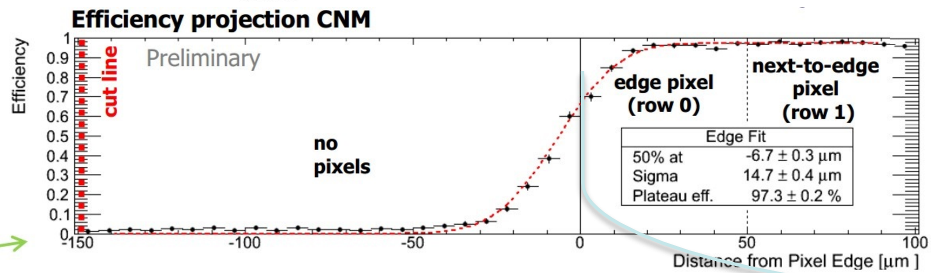
Track reconstruction with EUDET telescope (AIDA support)

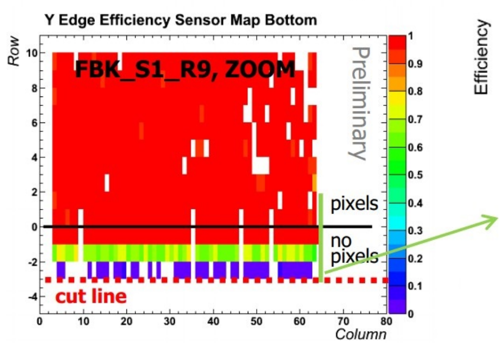


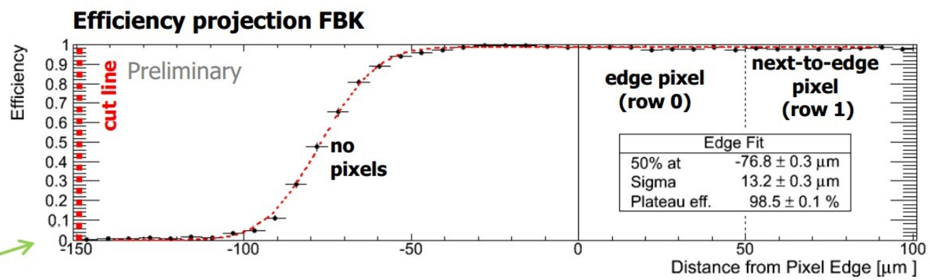
AFP prototype

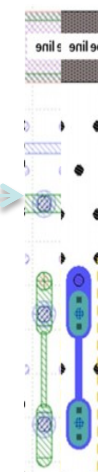
June/July 2013 DESY
- 5 GeV electron beam
- 0 deg incidence
- 2000e thr., 30V bias
- 10ToT @ 20ke











CNM 3D GR restricts the active area compared to FBK fences-only

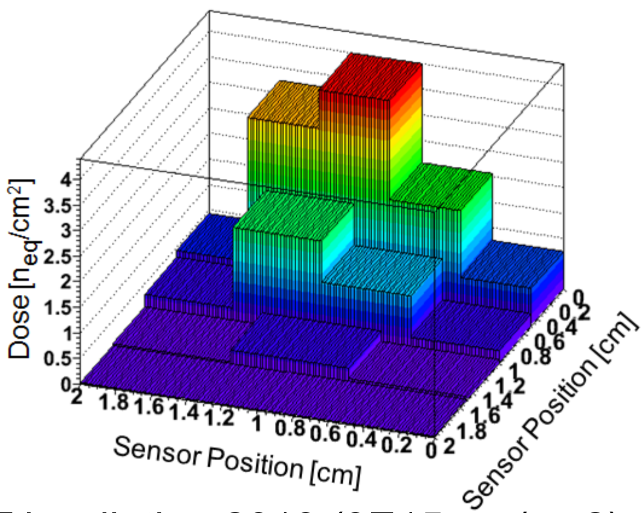
J. Lange, Pixel 2014

AFP prototypes slimed to ~150 um show excellent efficiency until last pixel row

AFP Tracker: Radiation Hardness

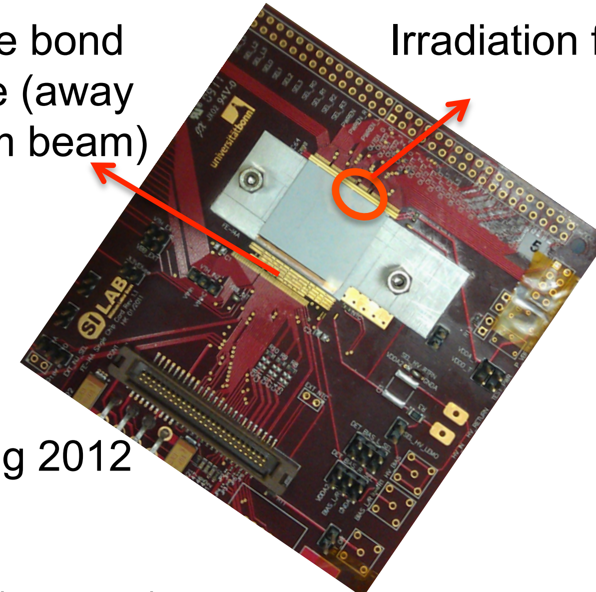
For **high luminosity** program:
Evaluate effect of non-uniform irradiations

Device irradiated at **IRRAD1** (CERN) to 4E15 neq/cm2



Wire bond side (away from beam)

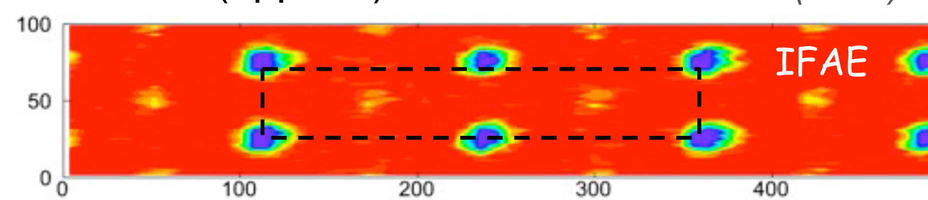
Irradiation focused here



S. Grinstein - Vertex 2014

Beam tests CERN Aug 2012
- Threshold: 1700e
- Bias voltage: 130V
- Temperature: -20C (approx.)

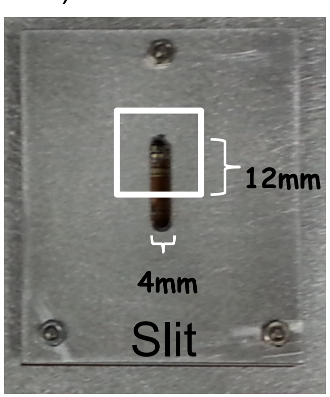
NIMA 730 (2013) 28

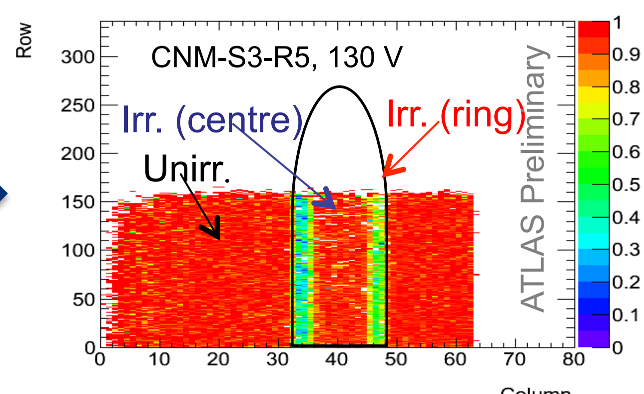


Efficiency: **98.0%** (irradiated side)

KIT irradiation 2013 (3E15neq/cm2)
(AIDA)

See J. Lange, Pixel 2014

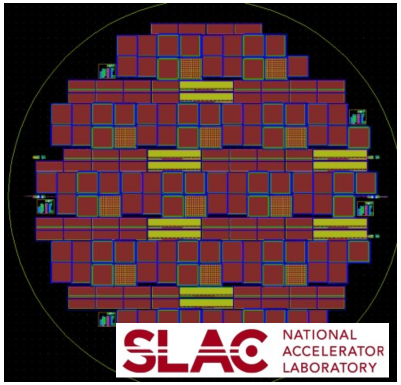


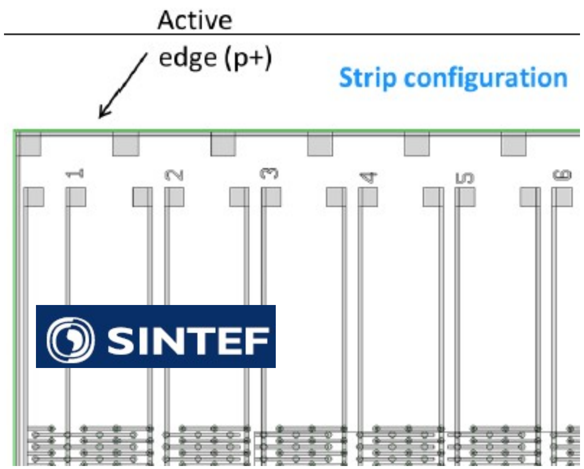


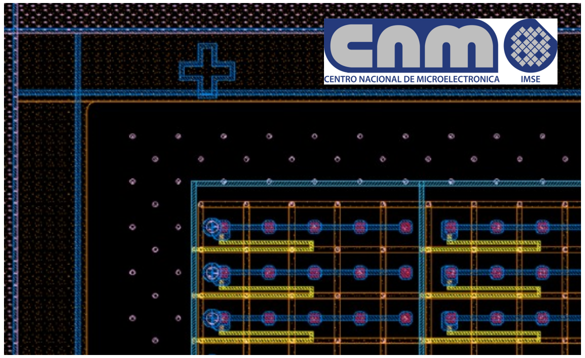
Good efficiency in irradiated region of AFP prototypes

Outlook: future 3D sensors

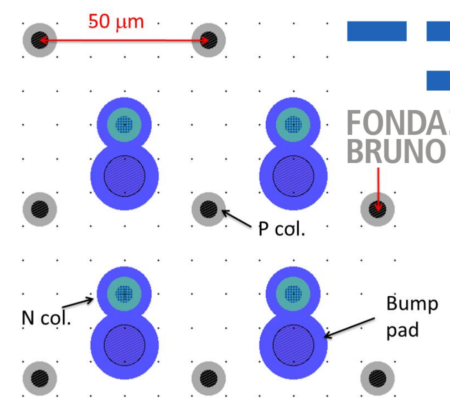
- Front-end for LHC Phase-II pixels, RD53 *(from M. Garcia-Sciveres)*
    - 50x50 um^2 , 25x100 um^2 ?
    - C_{det}<100fF
    - Threshold~1000e
    - Ideal: Ileak< 5nA/pixel
- Next generation of 3D sensors being developed at *SLAC (SNF), CNM* (within the RD50 collaboration), *FBK* and *Sintef*
    - ➢ Thinner substrate (narrower columns), active edges, on-wafer sensor selection (poly-silicon), improved Vbd, 6 inch wafer productions (FBK, Sintef),…

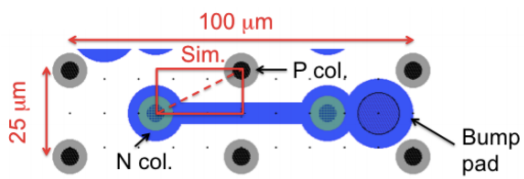






FONDAZIONE BRUNO KESSLER





Summary

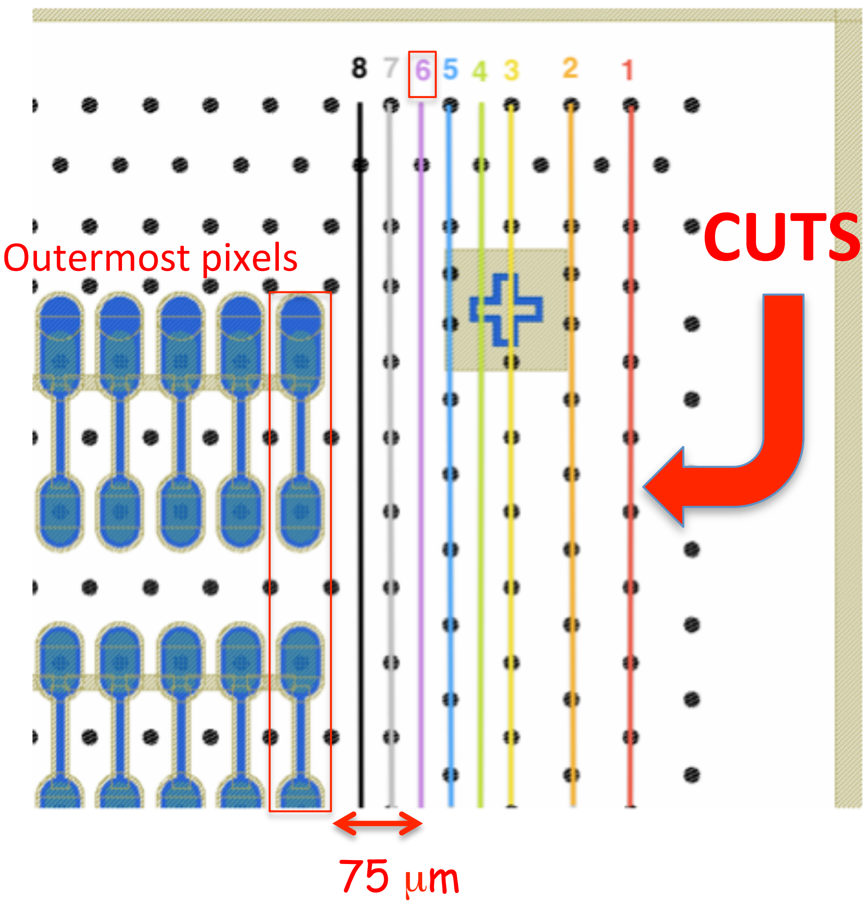
- Big progress made recently on 3D pixel sensors by ATLAS: from R&D to industrialization *(ATLAS 3D R&D collaboration)*
- 3D pixels selected for 25% of ATLAS new pixel layer (IBL)
  - High efficiency (>97%) after irradiation (5E15 n_{eq}/cm^2) has been achieved
  - Inactive edges of ~ 200 um
- 3D sensor productions at CNM and FBK completed in time and with good yield*, lessons
  - 3D-GR not good enough for sensor selection
  - Not passing through columns better for Vbd and Q collection
- Promising results for Forward Physics
  - Diamond saw cut can reduce inactive edge to 100 µm
  - Obtained high efficiency for non-uniform irradiation (7E15neq/cm2)
- Other experiments at LHC interested in 3D pixel technology

Back-up Slides

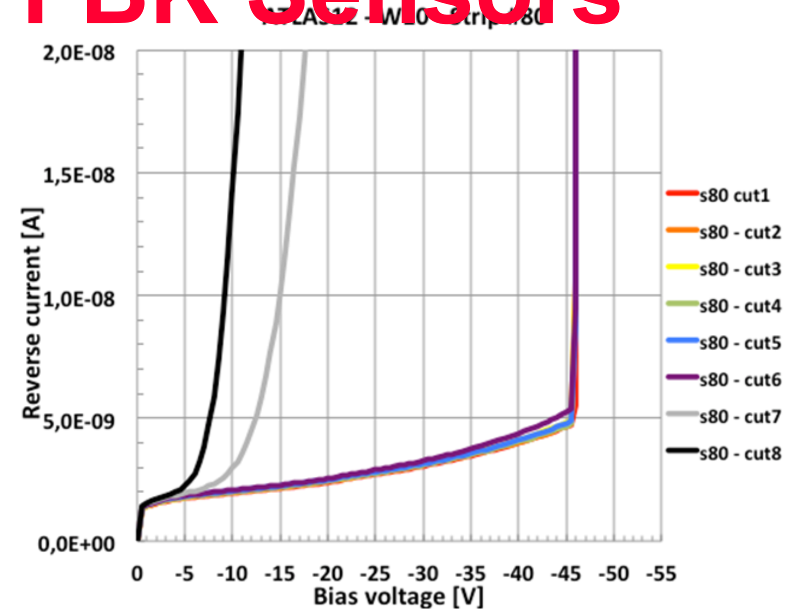
Edge Studies with FBK Sensors

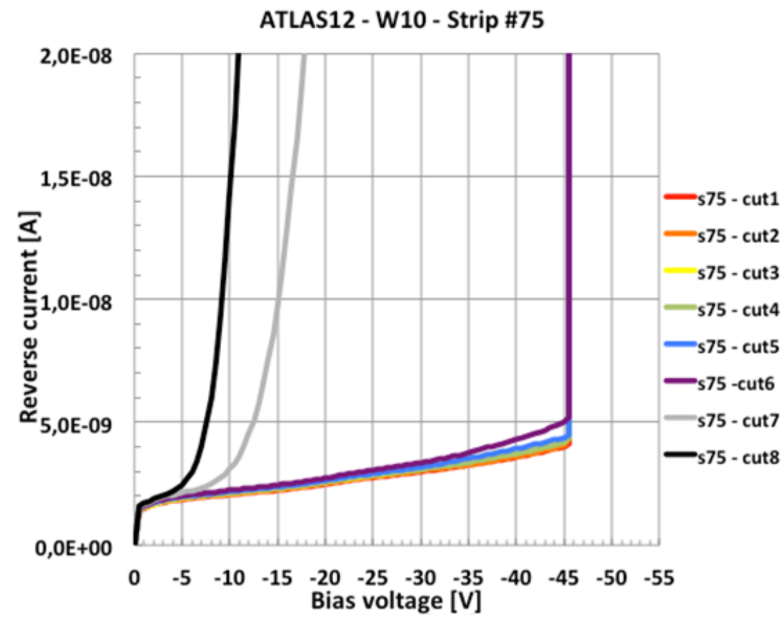
- Slim edge studies with FEI4 sensors

JINST 7 (2012) C01015



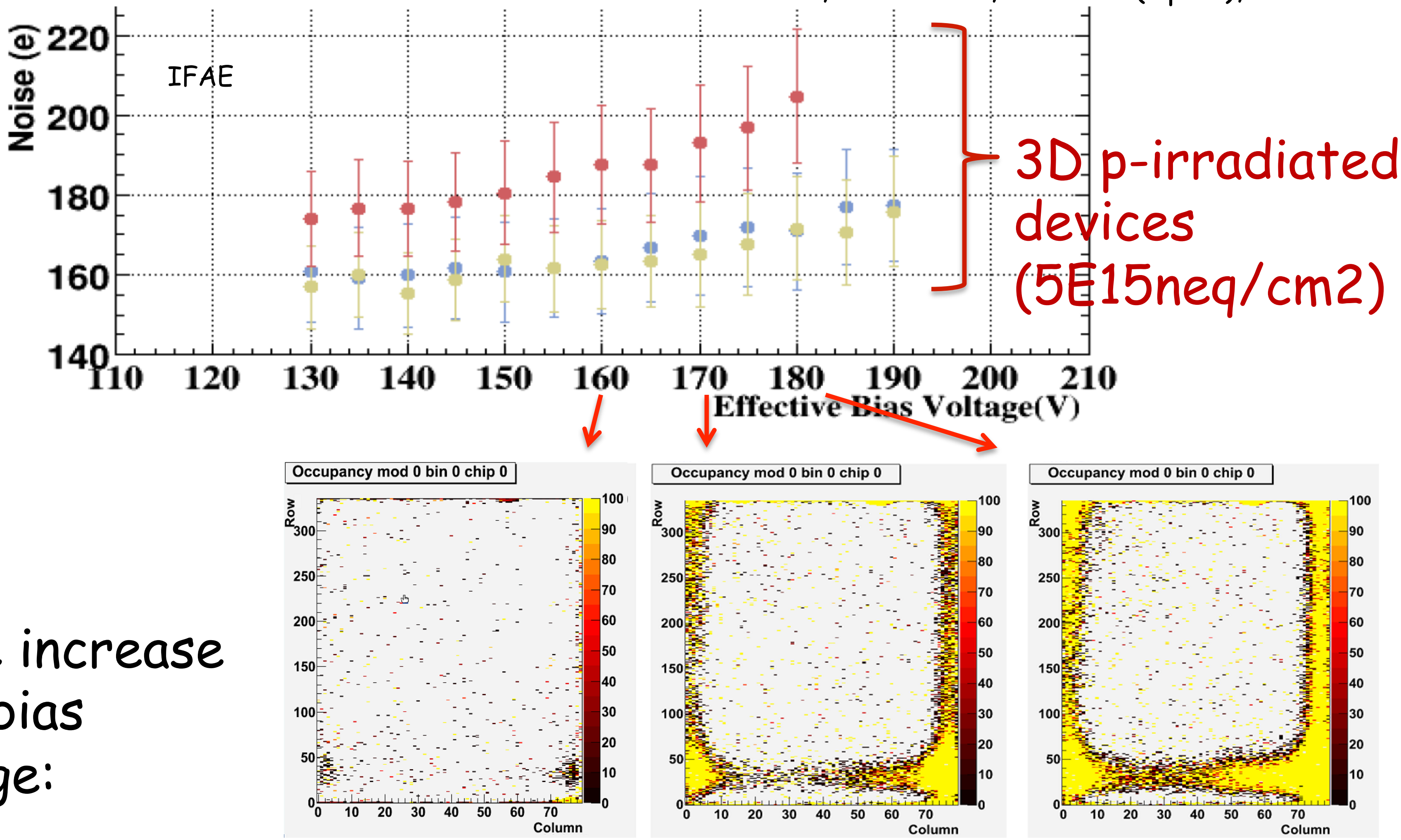
- Standard diamond-saw cuts
- Repeated cuts and I-V curve after each cut
- Negligible change in I-V curve up to cut #6
- Edge area can be safely reduced to ~75 um





Device Performance (laboratory)

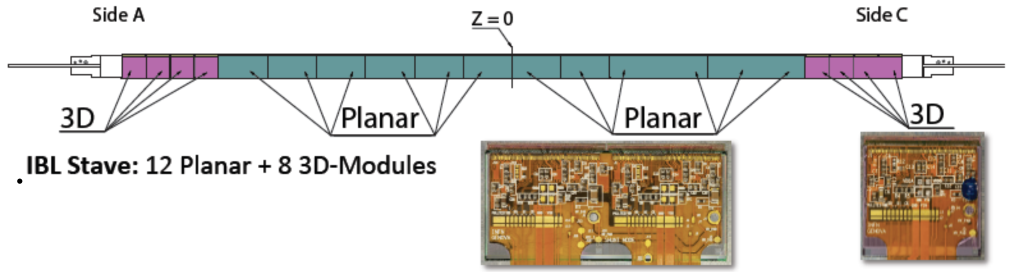
S. Grinstein, IEEE NSS, Valencia (Spain), 2011

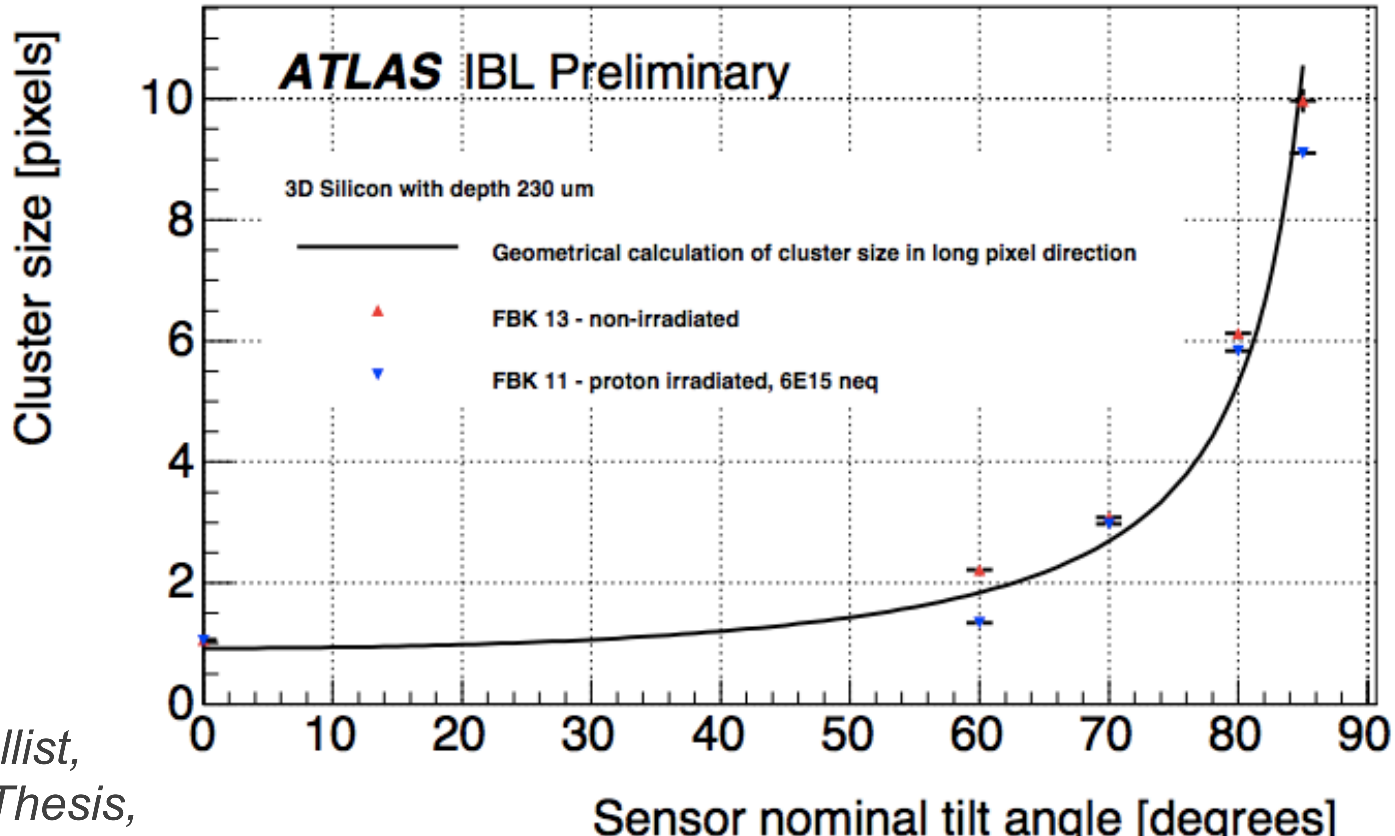


Noise increase with bias voltage:

➢ So does charge collection: <u>which is the optimal bias voltage for 3D devices</u>?

High Eta studies with 3D Sensors





C. Nellist, PhD Thesis, Manchester 2013