Radiation hardness of small-pitch 3D pixel sensors up to HL-LHC fluences

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RD50 Workshop, Kraków, 5 June 2017

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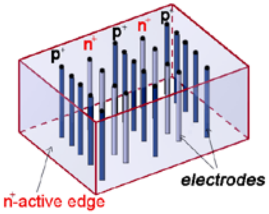
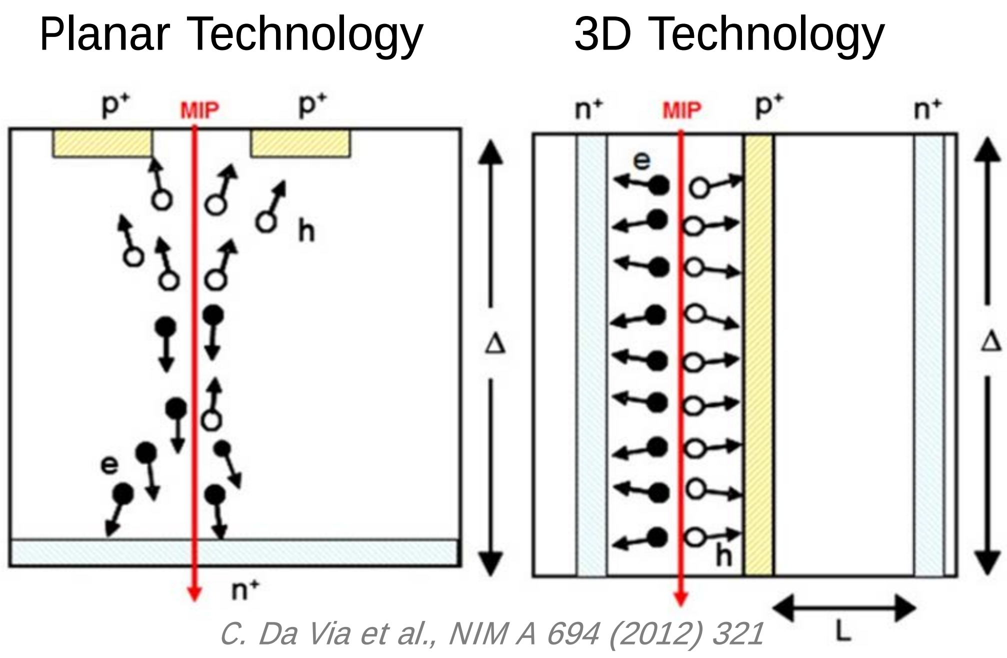
ATLAS

3D Detector Principle





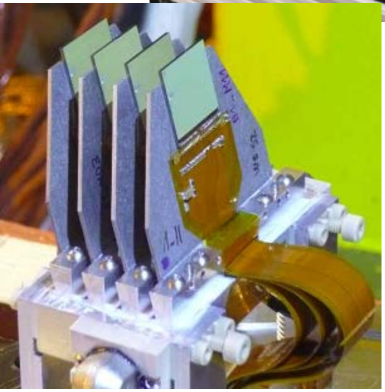
C. Da Via et al., NIM A 694 (2012) 321

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°

Applications of 3D Silicon Pixel Detectors

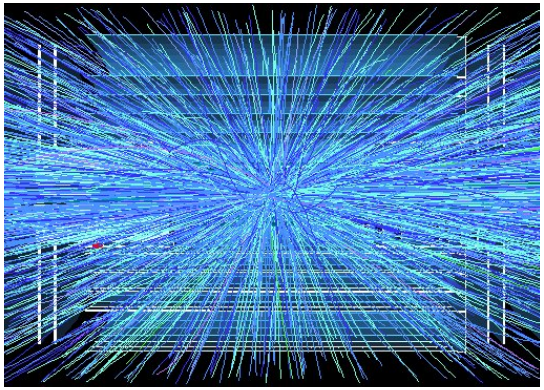
- ATLAS IBL
  - 25% 3D FEI4 detectors (CNM+FBK sensors)
  - Running since June 2015



- ATLAS Forward Proton (AFP)
  - CNM sensors, 3D pixel modules produced by IFAE
  - Running in LHC since March 2016, upgraded in March 2017

S. Grinstein et al.,
JINST 12 (2017) C01086

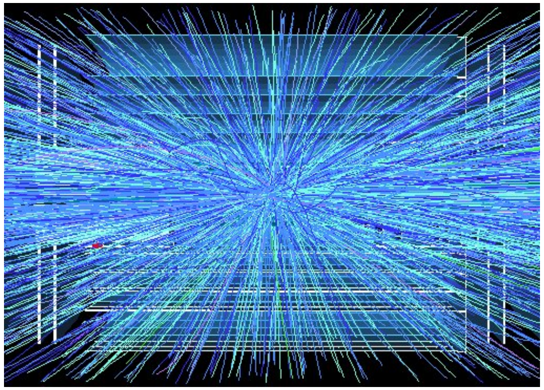
- CMS-TOTEM PPS
  - CNM sensors
  - Installed in March 2017



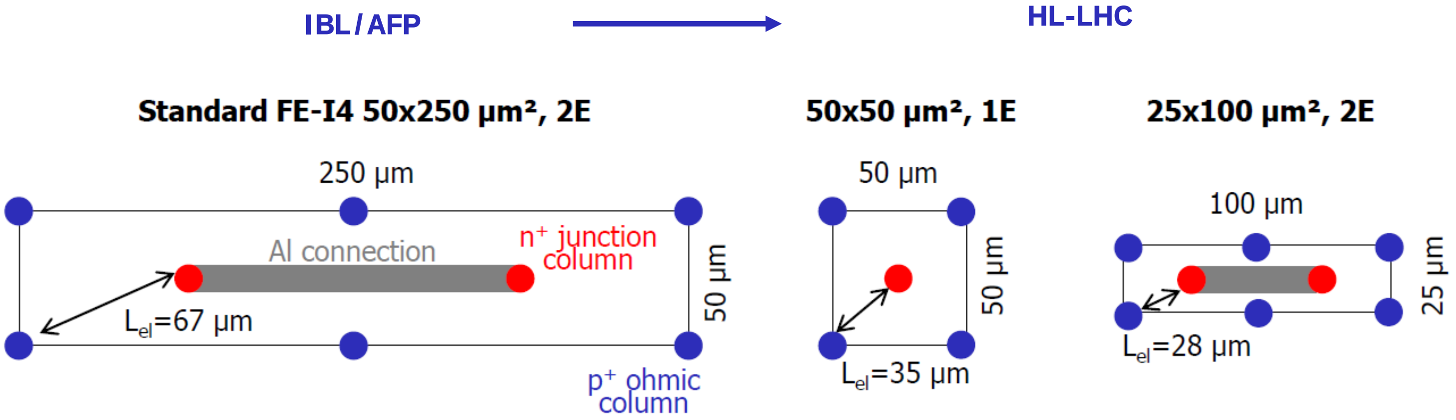
- HL-LHC pixel detectors
  - Possible installation 2024, sensor qualification for Pixel TDRs 2017
  - Radiation hardness: 1-2e16 n_{eq}/cm^2 required
  - Reduced pixel size: 50x50 μm^2 or 25x100 μm^2
  - 3D promising candidate for innermost layer(s)

This talk

Development of HL-LHC 3D Pixel Detectors



- Radiation hardness: 1-2e16 n_{eq}/cm^2 required
- Reduced pixel size due to occupancy: 50x50 μm^2 or 25x100 μm^2
  - RD53 readout chip under development
- Reduced 3D inter-electrode distance L_{el}
  → less trapping, V_{dep}
  → more radiation hard
  (but higher C_{det} and more dead material)
- Possibly reduced thickness (75-150 µm single-sided)
  - Lower occupancy, I_{leak}, C_{det} (but also lower signal)
  - But here only 230 µm studied



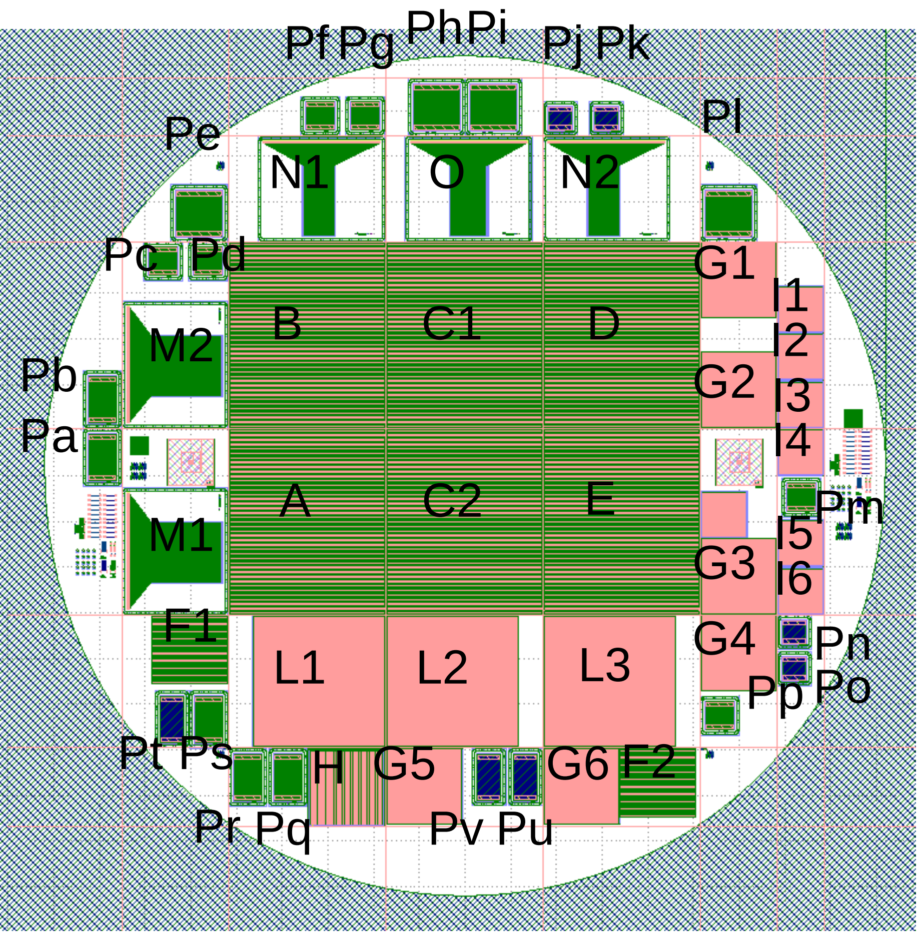
IBL/AFP → **HL-LHC**

Standard FE-I4 50x250 µm², 2E

50x50 µm², 1E

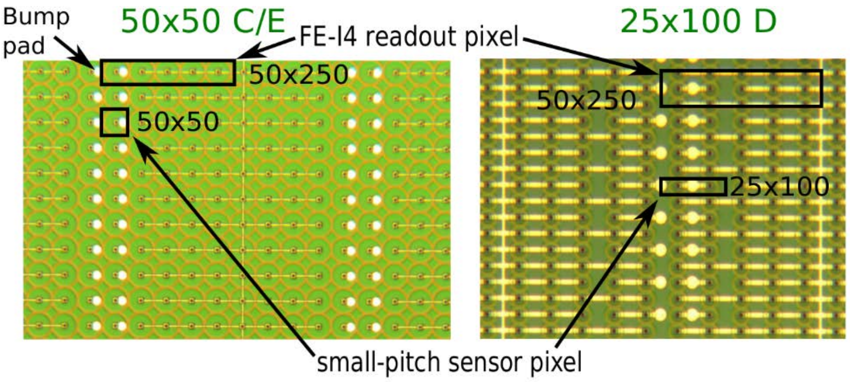
25x100 µm², 2E

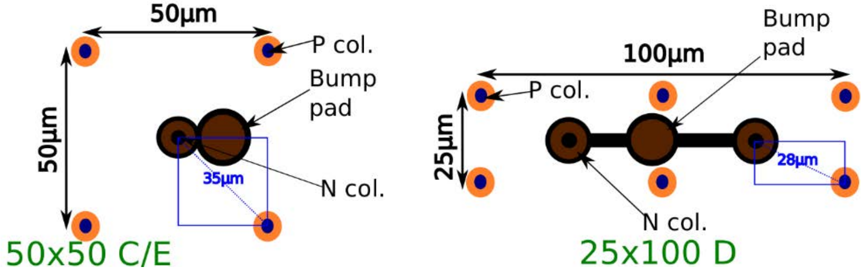
First Small-Pixel CNM Run for HL-LHC



D. Vázquez Furelos et al., 2017 JINST 12 C01026
J. Lange et al., 2016 JINST 11 C11024

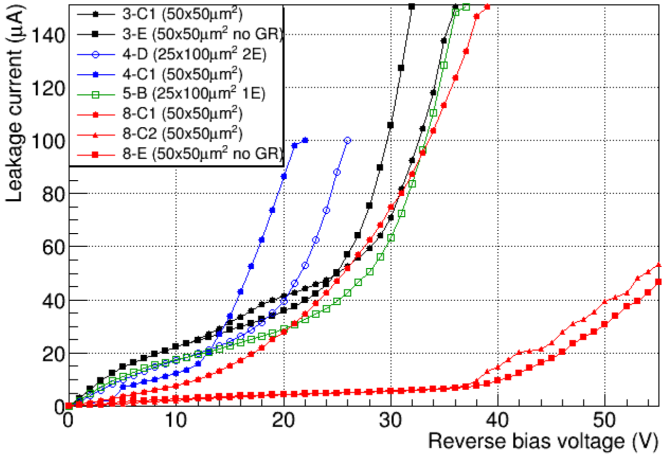
- Run 7781 finished in Dec 2015 (RD50 project)
- 5x 4” wafers, p-type, 230 μm double-sided, non-fully-passing-through columns (a la IBL)
- Increased aspect ratio 26:1 (column diameter 8 μm)
- **First time small pixel size 25x100+ 50x50 μm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and diodes down to 25x25 μm² 3D unit cell





Sample Characterisations

Pixel IV

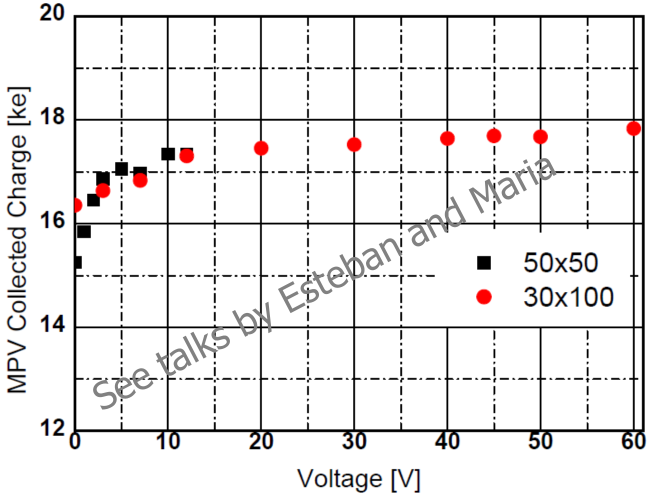


Pixel Geom.	C/el. [fF] (*)	C/pixel [fF] (*)	Noise [e]
25x100 2E	42	84	160
50x50 1E	37	37	105-140

(*) from pad diodes

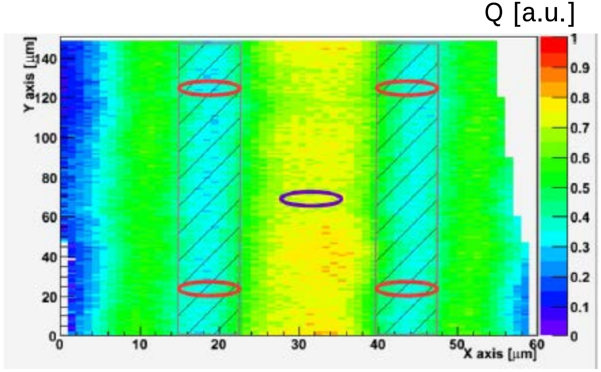
D. Vázquez Furelos et al.,
2017 JINST 12 C01026

Strips charge collection (unirr.)



See talks by Esteban and Maria

Strips laser scan
25x100 µm², 1e16, 150 V



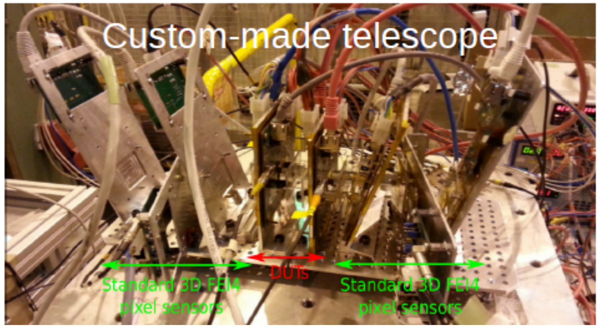
L. Simon

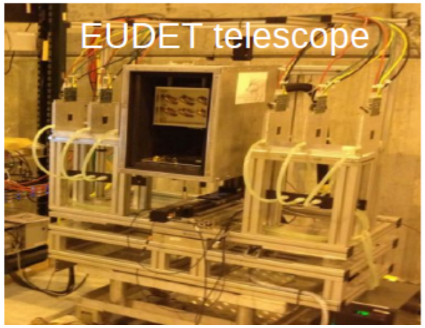
- Pixel devices bump-bonded and assembled at IFAE
- IVs
  - V_{BD} ~ 15-40 V
  - Improved in new productions after CNM process optimization
    S. Grinstein et al., JINST 12 (2017) C01086
- C <100 fF/pixel (within RD53 limit)
- Noise 100-160 e similar to standard 3D FEI4s
- Sr90 source scans on pixels
  - Similar charge as in standard FEI4s
- Sr90 and laser scans on strips
  - 17 ke charge as expected for both 50x50 µm² and 30x100 µm² (unirr.)
  - Almost full charge even at 0-2 V → low V_{dep} due to low L_{el}
  - Uniform even after 1e16 n_{eq}/cm^2
  - Measurements up to 2e16 n_{eq}/cm^2 in progress

Beam Tests and Irradiations

- Irradiation at KIT (uniform) and PS IRRAD (non-uniform)
- Beam tests at CERN SPS H6, 120 GeV pions

Beam Test period	Telescope	Reconstruction framework	Sensor geometry (μm^2)	Irradiation (n_{eq}/cm^2)
May 2016	Custom-made 3D FEI4	Judith	50x50 + 25x100	Not irradiated
Nov 2016	EUDET	EUTelescope + TBmon2	50x50 + 50x50	5e15 (uniformly 23 MeV p^+ - KIT)
Sept 2016	EUDET	EUTelescope + TBmon2	50x50	1.4e16 (non uniformly 23 GeV p^+ - CERN PS)

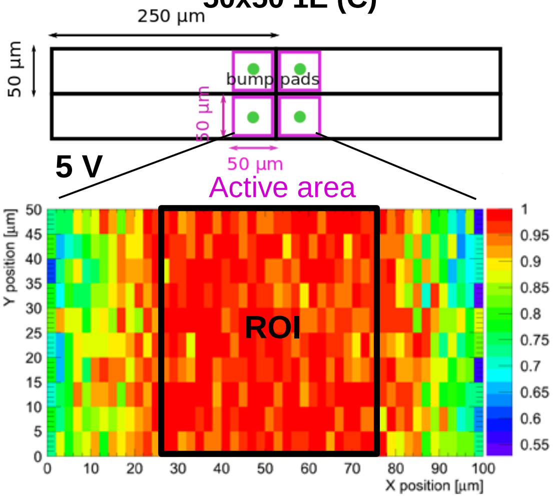




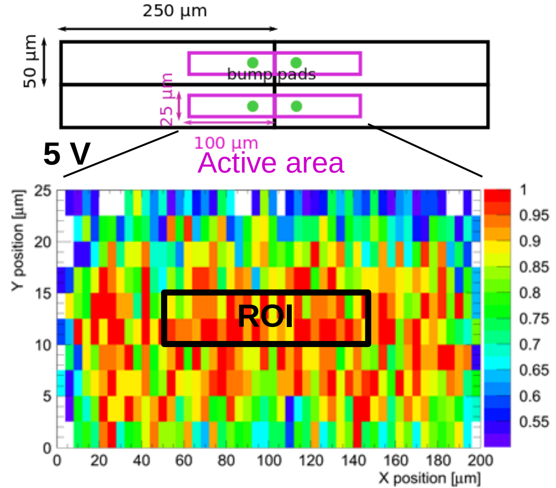
Efficiency before Irradiation

In-Pixel Efficiency (0° tilt)

50x50 1E (C)

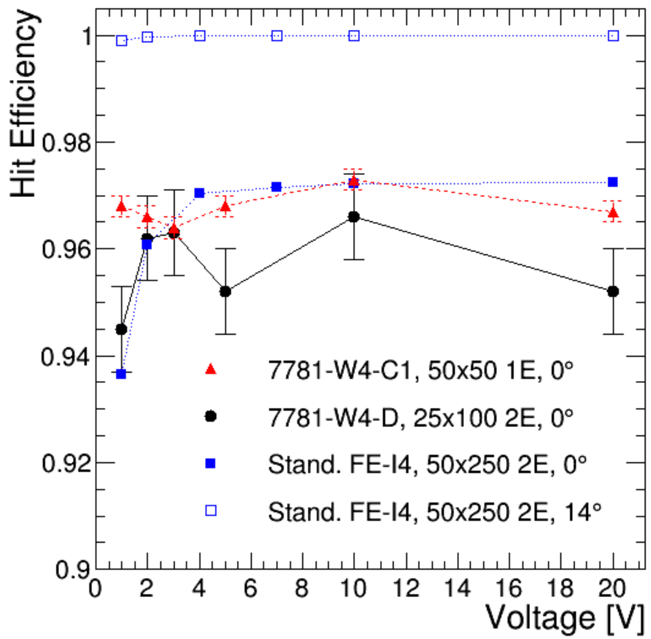


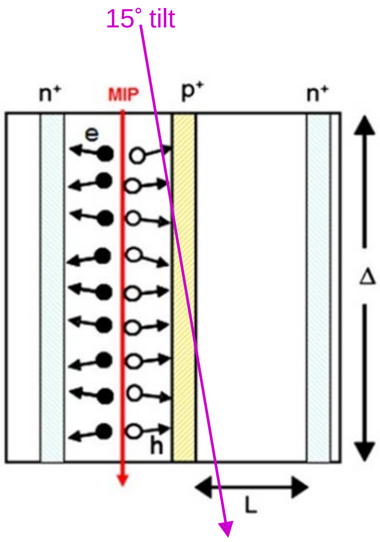
25x100 2E (D)



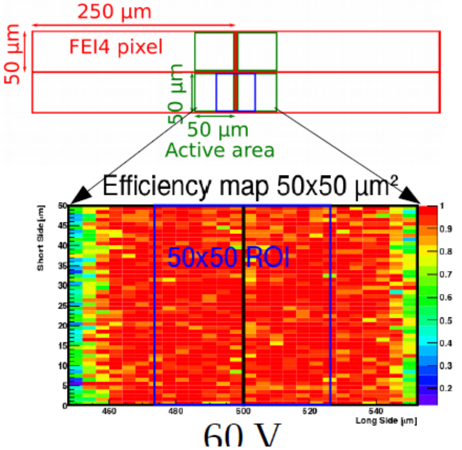
- Select ROI within active region
  → avoid inactive area + telescope smearing
- Efficiency in ROI
  - 97% already from 1 V at 0°: very early depleted due to small electrode distance
  - Improvable by tilting: avoids hitting only low-efficiency regions

J. Lange et al., 2016 JINST 11 C11024

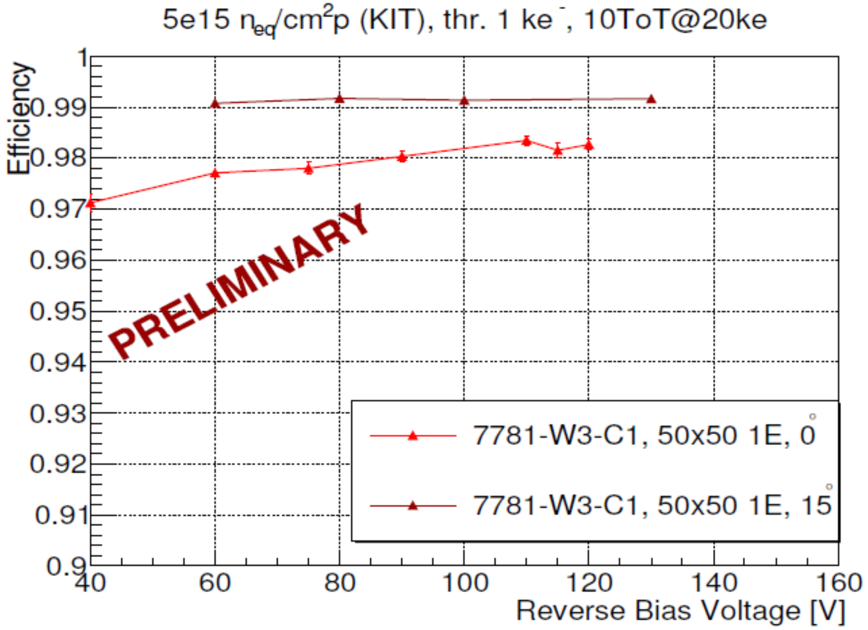


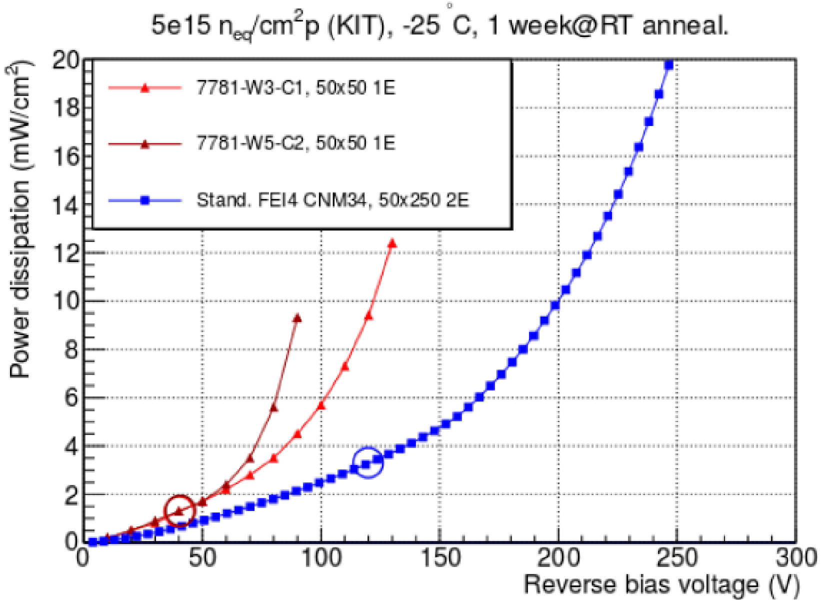


Uniform Irradiation to 5e15 n_{eq}/cm²

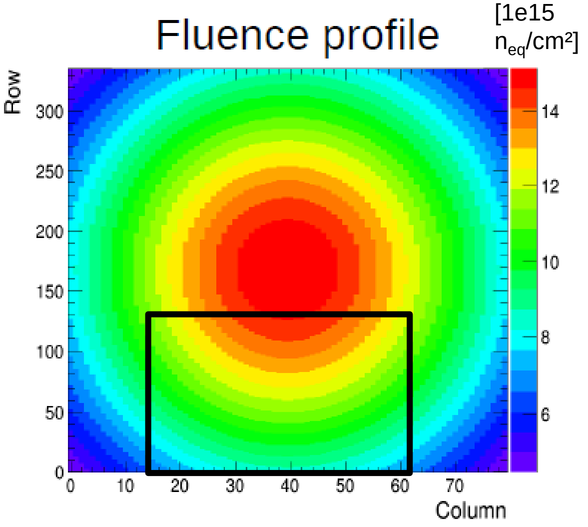


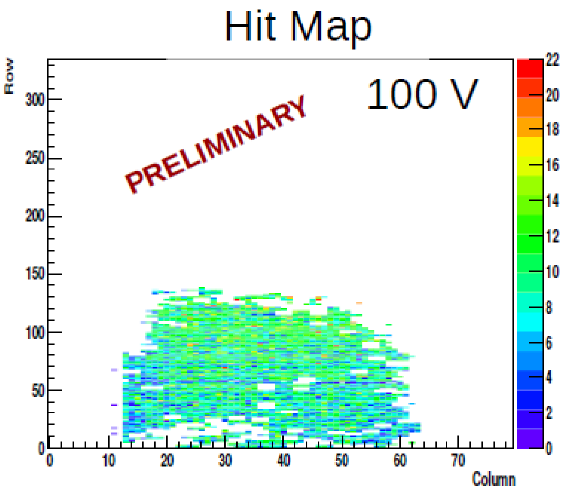
- 2 3D pixel devices of 50x50 µm²
- Irradiated uniformly to 5e15 n_{eq}/cm² at KIT
- Already 97% efficiency at 40 V (0° tilt)!
  - Compare to standard IBL/AFP FEI4: 120 V
  - Improves to 99% at 15° tilt
- Low V_{op} → advantage for power dissipation
  - 1.5 mW/cm²

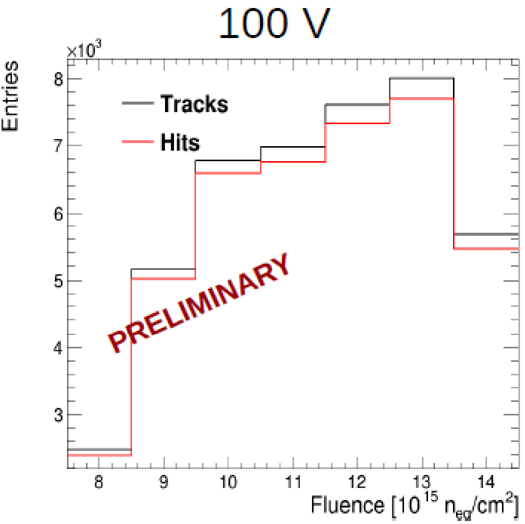


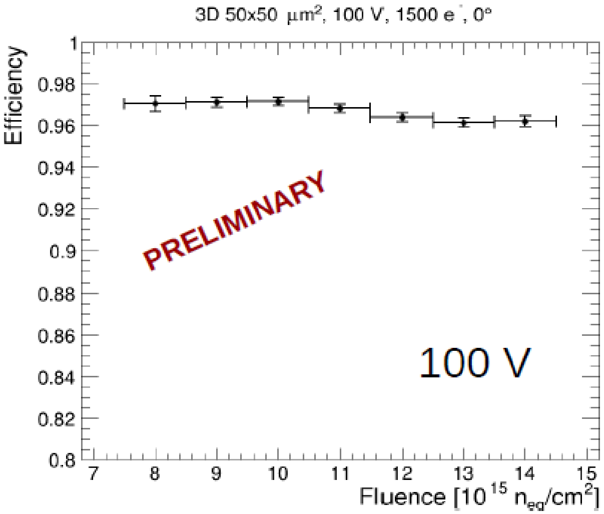


Non-Uniform Irradiation to 1.4e16 n_{eq}/cm²





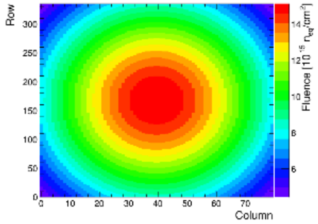




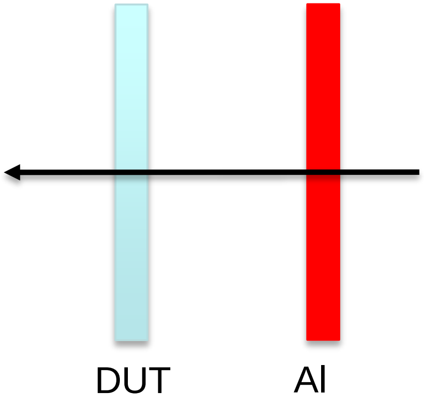
- Non-uniform irradiation at CERN-PS (23 GeV p) with 20x20 mm² beam
  - Can sample range of fluences on single device: 0.8 – 1.4e16 n_{eq}/cm²
  - Estimation of systematic fluence uncertainty from variations of beam width and position by 1 mm:
    - 11% at 1.4e16 n_{eq}/cm²
    - 24% at 8e15 n_{eq}/cm²
- Only part of device with connected bumps (bad UBM)
  → Analysis in localised region

Non-Uniform Irradiation - Methodology

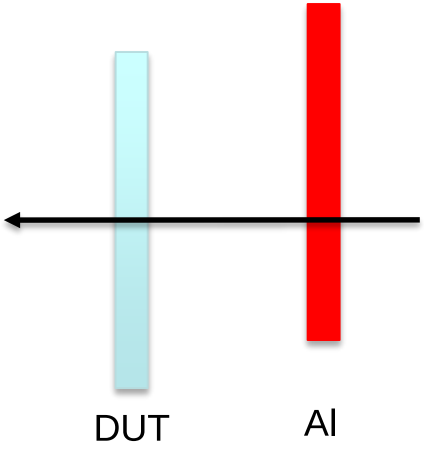
- Fluence profile default value
  - Fluence normalization obtained with 20x20 mm² Al dosimetry foil: 1.1e16 n_{eq}/cm²
    - Cross-checks with central 5x5 and 10x10 mm² Al foil consistent
    - In future also cross-checks with segmented Al foil
  - Assume perfect alignment of Al foil with DUT and beam centre
  - Assume beam FWHM as measured by IRRAD (BPM3): 20.4x18.3 mm²



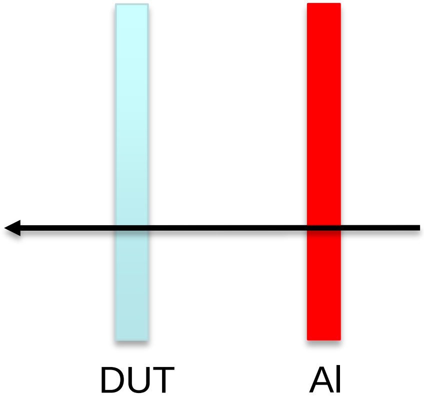
- Systematic uncertainty assessment
  - Introduce variations by +/- 1 mm in beam FWHM, beam centre offset, Al foil offset (both x, y)
  - Vary in all combinations
  - Determine maximum deviation from default value (envelope) for all variation combinations -> take as systematic uncertainty (conservative)



Default



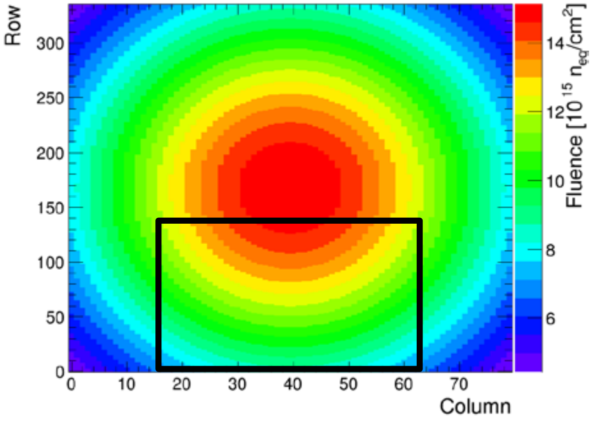
Al foil variation



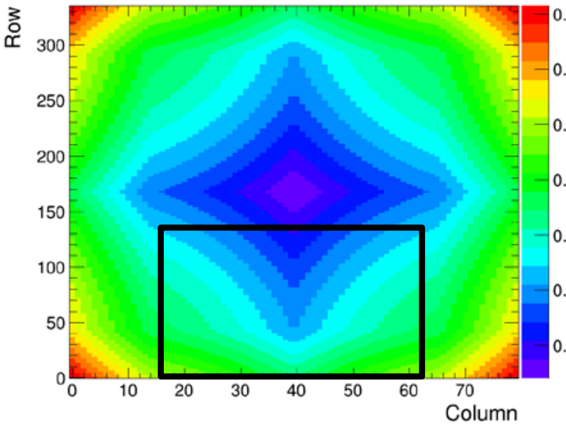
Beam centre variation

Non-Uniform Irradiation - Uncertainties

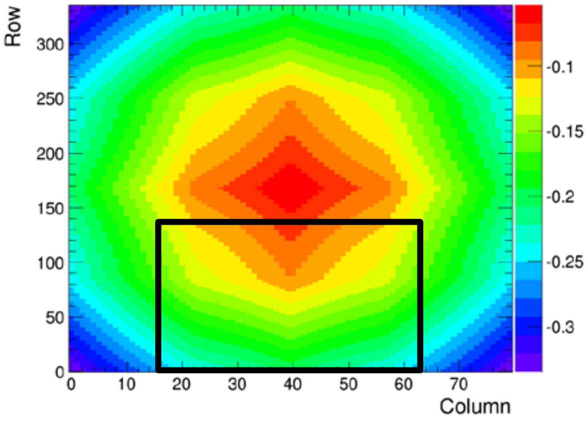
Default

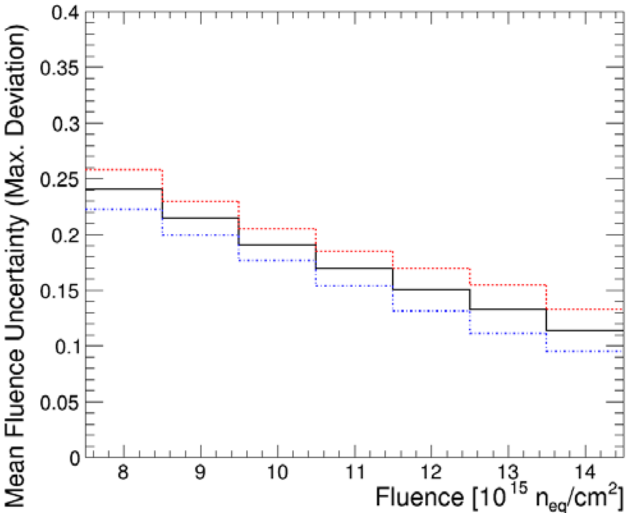


Max. Dev. Up



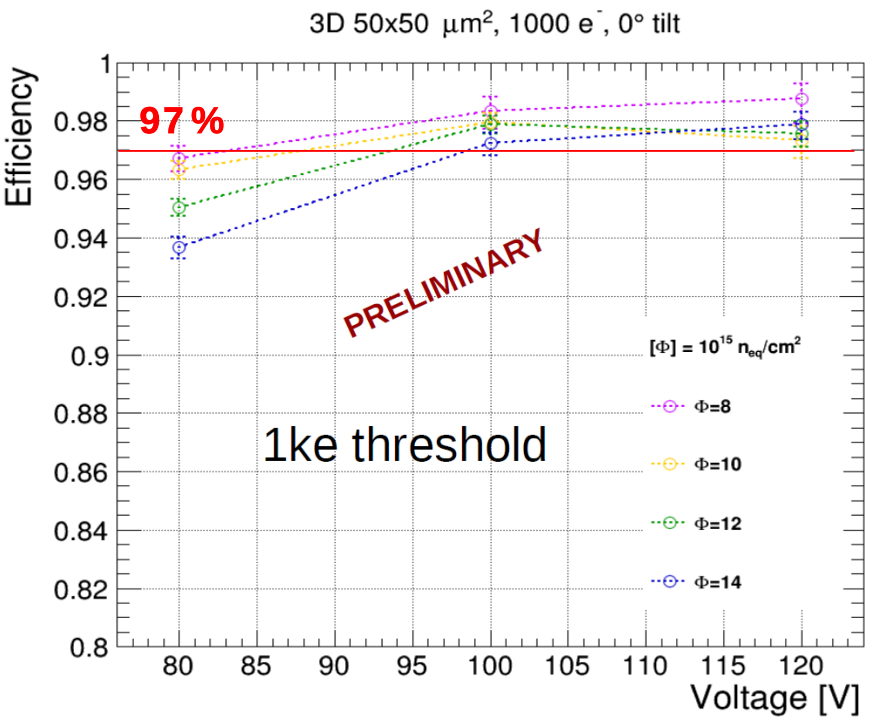
Max. Dev. Down



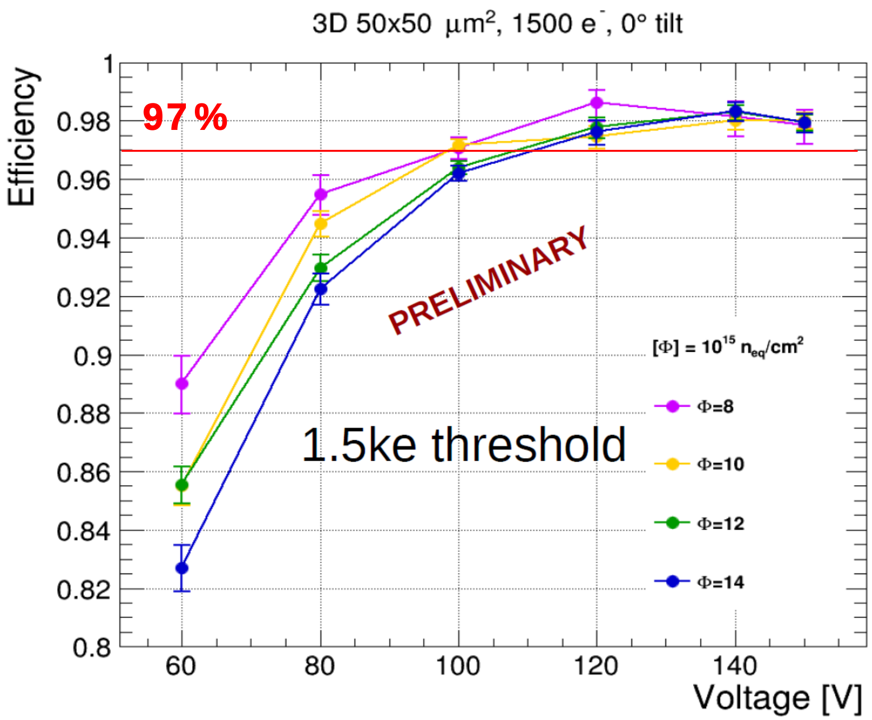


- Shape fluence uncertainties 11-24% in fluence range of interest
- Plus 7% normalisation uncertainty

Efficiency for Non-Uniform Irradiation



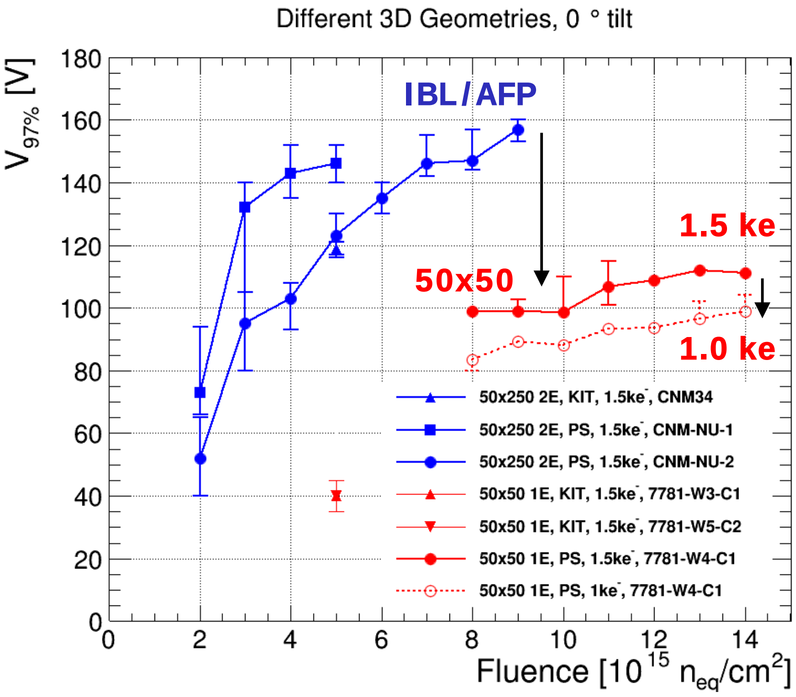
3D 50x50 µm², 1000 e⁻, 0° tilt



3D 50x50 µm², 1500 e⁻, 0° tilt

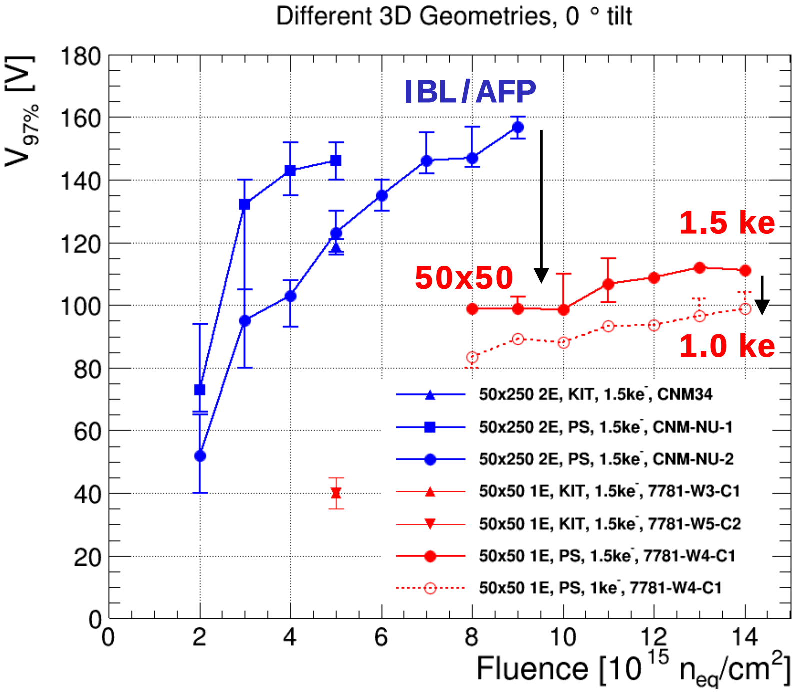
- Efficiency improves with lower threshold
- 97% efficiency already at 100 V (1 ke threshold) after 1.4e16 n_{eq}/cm²!

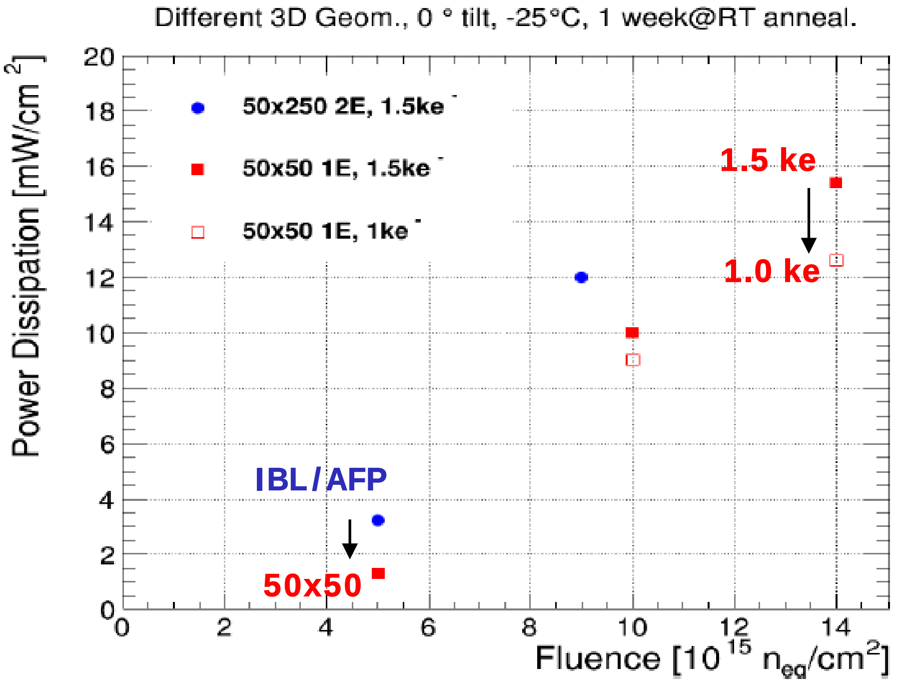
Comparison IBL to Small Pitch



- Highly improved operation voltage for 50x50 µm² 3D compared to IBL/AFP generation

Comparison IBL to Small Pitch





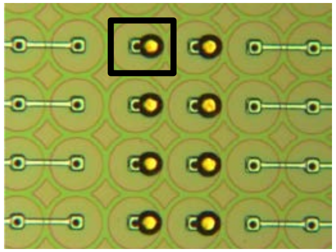
- Highly improved operation voltage for 50x50 µm² 3D compared to IBL/AFP generation
- Also improves power dissipation
  - Despite higher current for 50x50 µm² (still under investigation, might improve after optimisations)
  - 9 (13) mW/cm² at 1e16 (1.4e16) n_{eq}/cm²
  - Considerably lower than for 100 µm planar devices* with ≥25 mW/cm² at 1e16 n_{eq}/cm² (V_{op}=500 V)

* N. Savic et al., 28th RD50 Workshop, Torino, Italy, 6-8 June 2016

Conclusions and Outlook

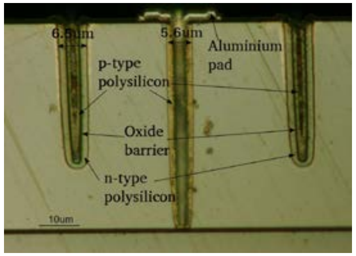
- Studied first CNM 3D production with small pixel size up to 1.4e16 n_{eq}/cm²
  - Highly reduced operational voltage and power dissipation wrt. IBL/AFP generation (and planar) after irradiation
    - 100 V for 1.4e16 n_{eq}/cm²
  - Irradiation to higher fluences of 2-3e16 n_{eq}/cm² on-going at IRRAD → ultimate HL-LHC fluence after 4000 fb^{-1} with safety factor 1.5

50x50 µm²



- Also productions and promising results from FBK and SINTEF

- Single-sided thin (72-150 µm) 3D productions under way at CNM
  - Also with RD53 geometry

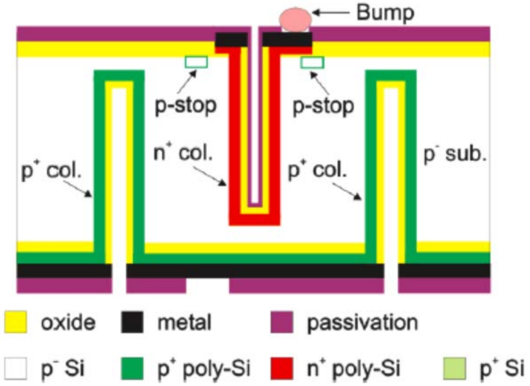


Excellent radiation hardness of 3D pixel detectors demonstrated

BACKUP

Different 3D Technologies

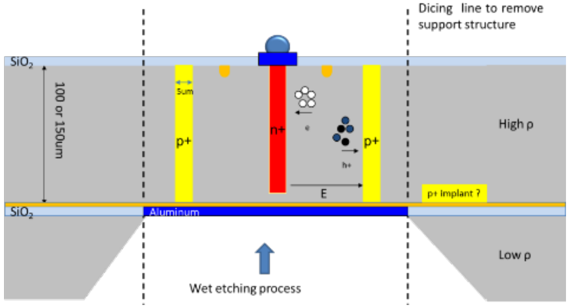
- Double sided (available at CNM)
  - IBL/AFP-proven technology
  - No handling wafers needed
    → thickness limited to ≥200 µm and wafers to 4”
  - 3D columns ~8 µm diameter



Double-sided

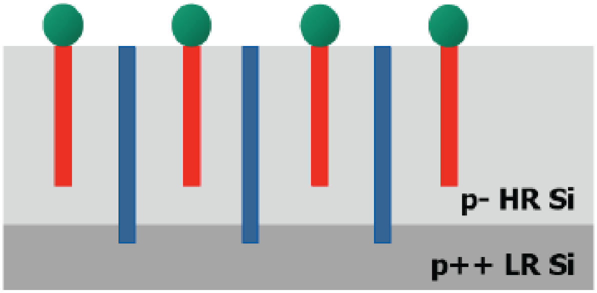
G. Pellegrini, CNM

- Single sided (available at FBK, SINTEF, CNM)
  - On handling wafer (SOI or Si-Si bonding)
    → 6” possible (FBK, SINTEF)
  - Active thickness range 50-150 µm being explored
  - Narrow 3D columns ~5 µm possible



SOI

G. Pellegrini, CNM



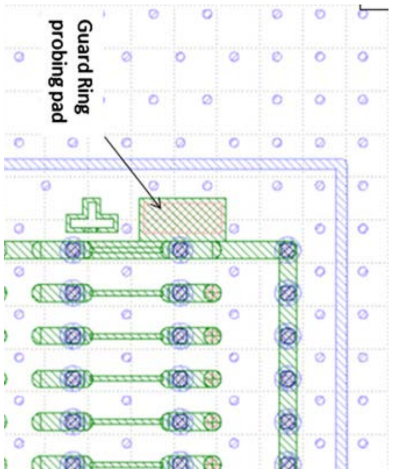
Si-Si bonding

M. Boscardin, FBK

State of the Art: IBL/AFP Generation

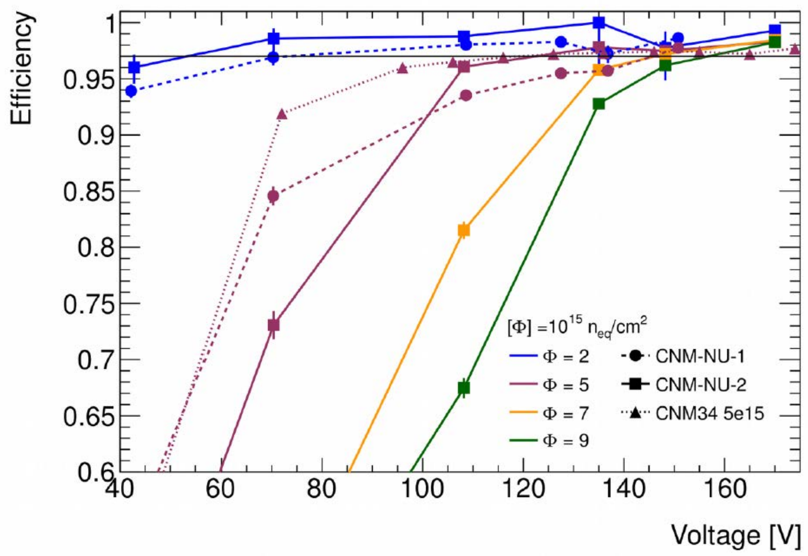
- 230 µm thick sensors by CNM and FBK (double-sided)
- FEI4s: 50x250 µm² 2E, 67 µm inter-el. distance
- Radiation hardness up to 5e15 n_{eq}/cm^2 established (IBL)
- Explored limits further with irradiations up to HL-LHC fluences
  - At 9.4e15 n_{eq}/cm^2 : 97.8% efficiency at 170 V!
  - Power dissipation 15 mW/cm^2 at 1e16 n_{eq}/cm^2 and -25°C

→ Good performance at HL-LHC fluences even for existing 3D generation



J. Lange et al., 2016 JINST 11 C11024

p-irradiated FEI4, 0° tilt



Standard FE-I4 50x250 µm², 2E