Radiation hardness of 3D pixel sensors up to unprecedented fluences of 3e16 n_{eq}/cm^2

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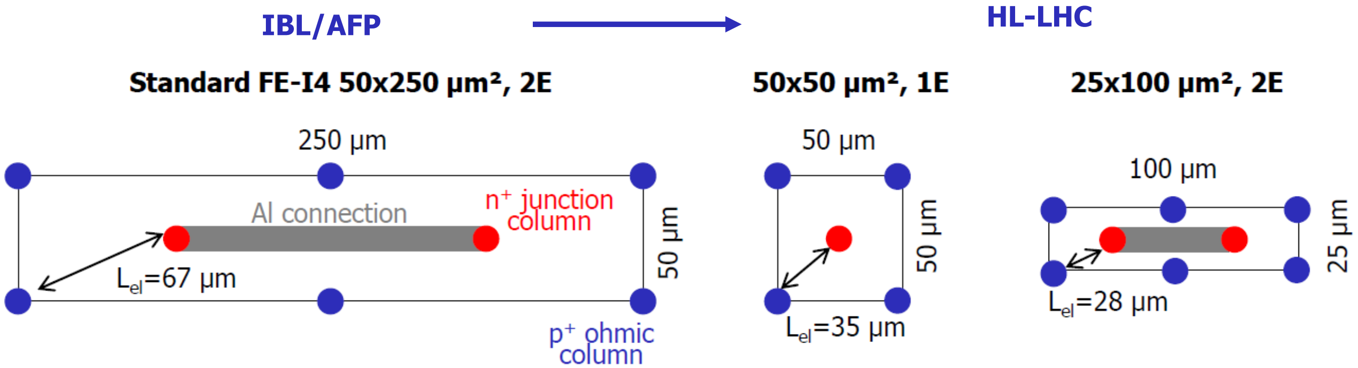
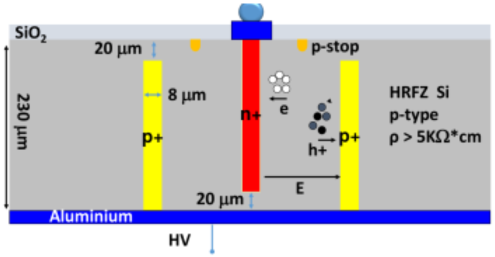
Towards Radiation-Hard 3D

Experiment	Fluence
ATLAS IBL/AFP	5e15 n_{eq}/cm^2
ITk 4 ab^{-1} (full)	2.5e16 n_{eq}/cm^2
ITk 2 ab^{-1} (1 repl.)	1.3e16 n_{eq}/cm^2
LHCb 2030?	1e17 n_{eq}/cm^2
FCC-hh ?	7e17 n_{eq}/cm^2



1. Tested IBL/AFP generation
   - 230 µm thick, double-sided CNM process, 50x250 µm² 2E FEI4 pixels
   - Radiation hardness demonstrated up to ITk fluence (9e15 n_{eq}/cm^2)

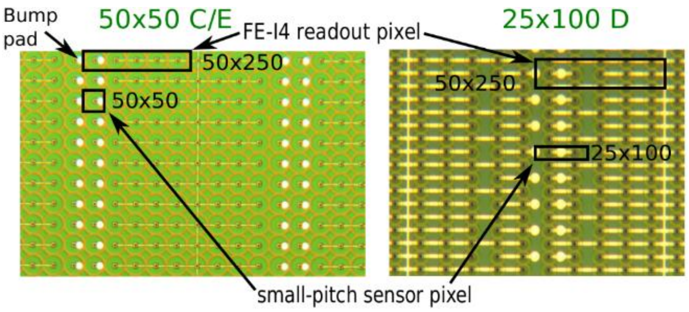
J. Lange et al., 2016 JINST 11 C11024



2. Develop prototype small-pitch 3D pixels matched to FEI4
   - Pixel size 50x50 and 25x100 µm²
     - Reduced electrode distance → more radiation hard
     - Matched to 50x250 µm² chip pixel → 20% active area
   - Double-sided 230 µm CNM run

J. Lange et al., arXiv:1707.01045

     - This study: tested up to 3e16 n_{eq}/cm^2 beyond full HL-LHC fluence



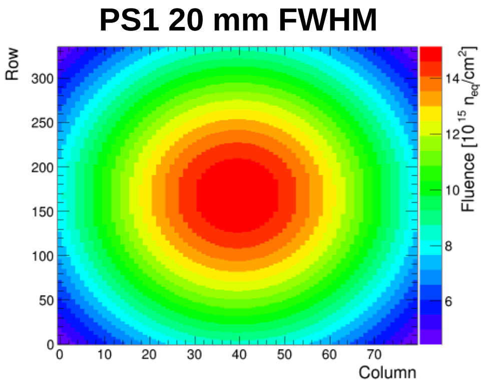
D. Vázquez Furelos et al., 2017 JINST 12 C01026

3. Produce RD53A 3D pixels (on-going)
   - “Real” 50x50 and 25x100 µm²
   - Different thicknesses 72-200 µm

Beam Tests and Irradiations

- Irradiations
  - KIT 23 MeV p: uniform 5e15 and 1e16 n_{eq}/cm^2
  - PS IRRAD 23 GeV p: non-uniform 12 or 20 mm beam
    → allows probing a large range of fluences on single pixel device
    - Reached up to 3e16 n_{eq}/cm^2
  - FEI4 chip survived harsh doses beyond specs in many cases! (though not all)

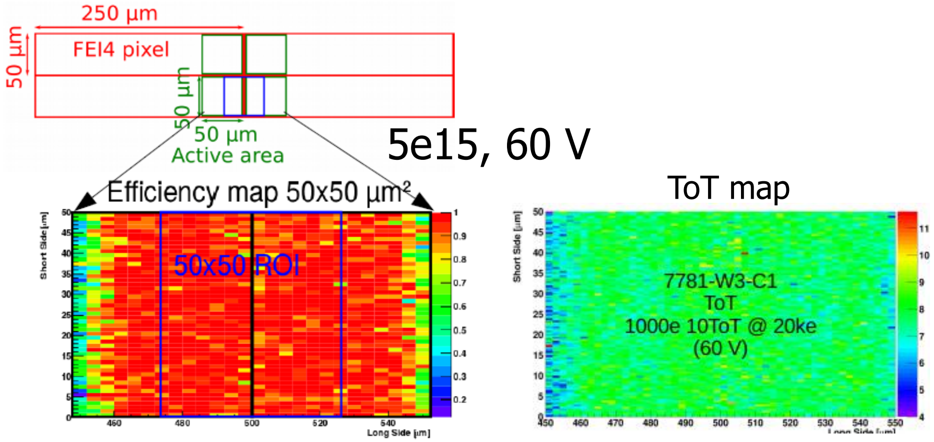
Many thanks to
F. Ravotti, G. Pezzullo,
F. Bögelspacher,
A. Dierlamm



- Many beam tests at CERN SPS H6, 120 GeV pions

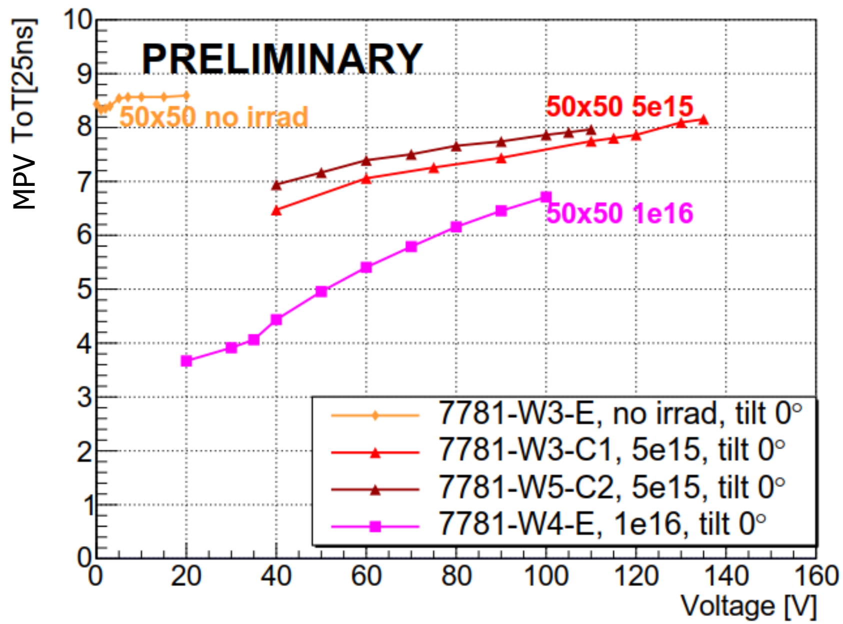
Device	Irradiations	Fluence peak step	Fluence peak total	Annealing	Beam test
		[1e16 n_{eq}/cm^2]	[1e16 n_{eq}/cm^2]		
7781-W4-C1, 50x50	PS1 20mm 2016	1.5	1.5	7d@RT	Sep 2016
	PS3 20mm 2017	1.1	2.6	18d@RT	July 2017
	PS4 20mm 2017	0.6	3.1	15d@RT	Not working
7781-W5-C2, 50x50	KIT1 2016	0.5	0.5	8d@RT	Nov2016
	PS3 20mm 2017	1.0	1.5	18d@RT	Not working
7781-W3-C1, 50x50	KIT1 2016	0.5	0.5	8d@RT	Nov 2016
	PS2 12mm 2016	0.7	1.2	15d@RT	
	PS3 20mm 2017	1.1	2.3	18d@RT	July 2017
	PS4 20mm 2017	0.5	2.8	15d@RT	Oct 2017
	PS5 20mm 2017	0.3	3.1	21d@RT	2018
7781-W4-E, 50x50	KIT2 2017	1.0	1.0	as irrad.	July2017
				7d@RT	Sep+Oct 2017
7781-W3-E, 50x50	Unirr.				Sep 2017

Before and After Uniform Irradiation

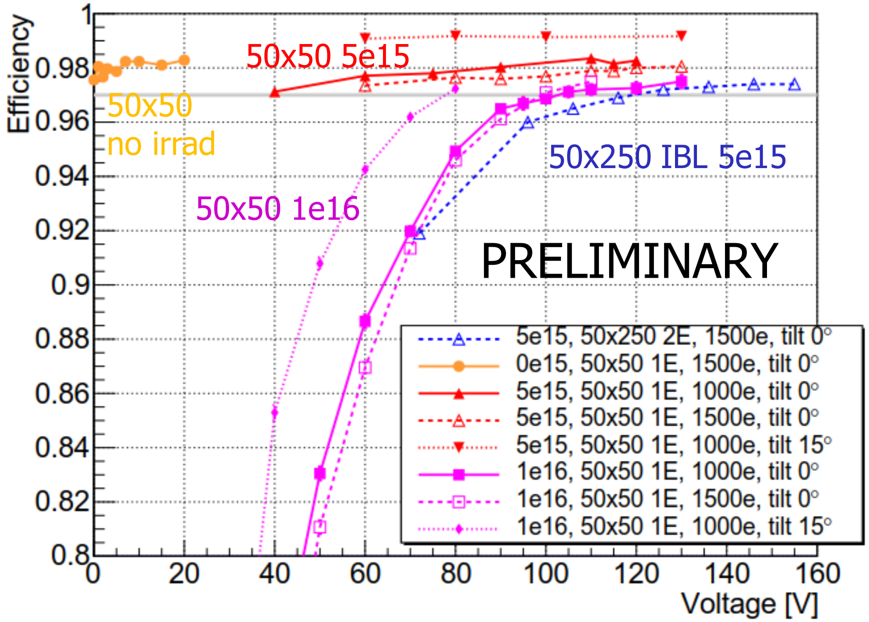


- ToT and efficiency very uniform over pixel
- ToT: high charge collection efficiency after irrad.
- Efficiency:
  - No bias voltage needed before irradiation: 98% at 0 V
  - 97% at 40 (100) V for 5e15 (1e16) n_{eq}/cm^2 at 0° tilt
    - Significantly better than for standard IBL/AFP FEI4
    - Further improves at 15° tilt

3D CNM, 50x50 µm² 1E, d=230 µm, 1ke⁻ 10ToT@20ke, p irrad (KIT)



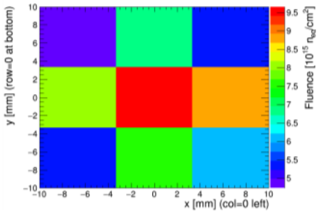
CNM 230 µm, p irrad (KIT)



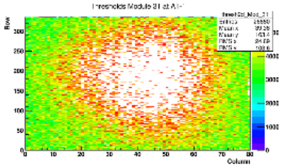
PS Non-Uniform Irradiation - Methodology

- Fluence normalization obtained with 20x20 mm² Al dosimetry foil
- Profile from
  - Beam profile monitors: 12-20 mm FWHM
  - Fluence maps by pixelating Al foil → fit
  - Beam centre from Al foil or in-situ for 1st period (thr., noise etc.)
- Fluence uncertainty
  - Estimated from 1 mm variations in beam centre, width, Al position
  - 15-20% uncertainty at highest fluence, but ~50% at lowest fluence
- Efficiency as function of fluence on 1 device!
  - Expected behaviour
  - For compilation use only at (or close to) highest fluence with lowest uncertainty

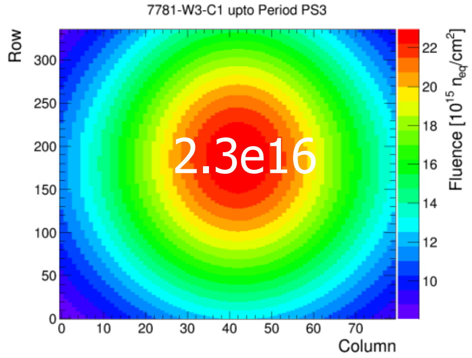
Profile from Al foil PS3

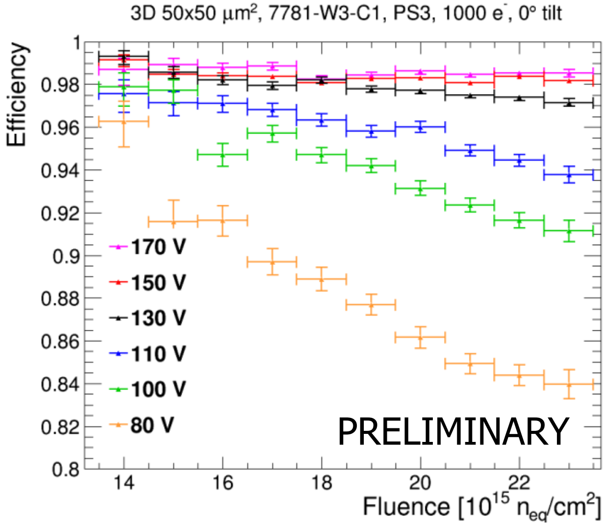


Thr. un-tuned

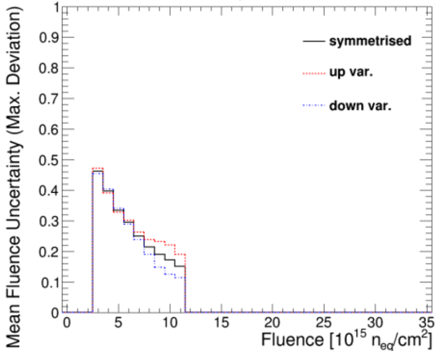


Fluence map W3-C1 PS3

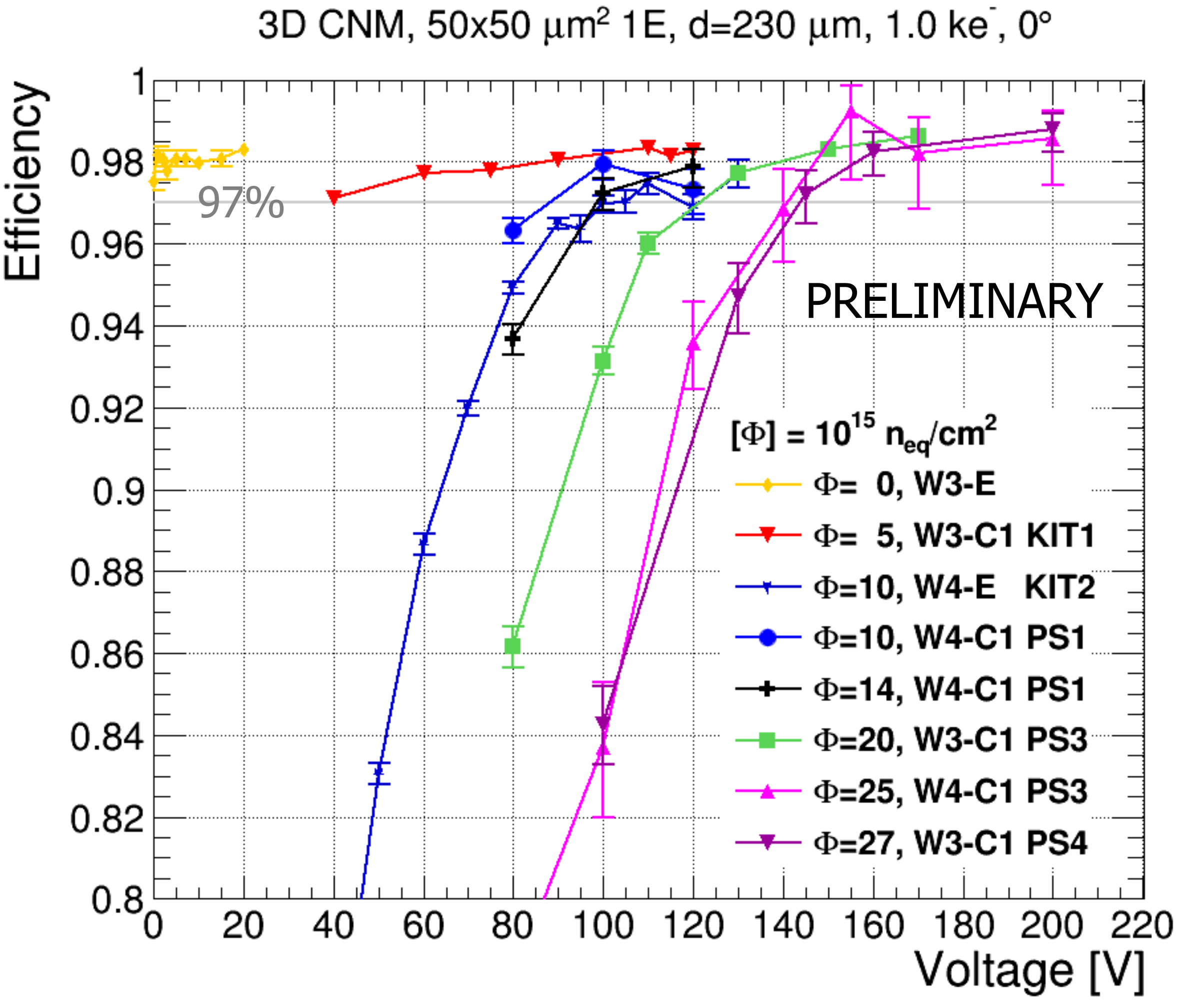




Uncertainty PS3

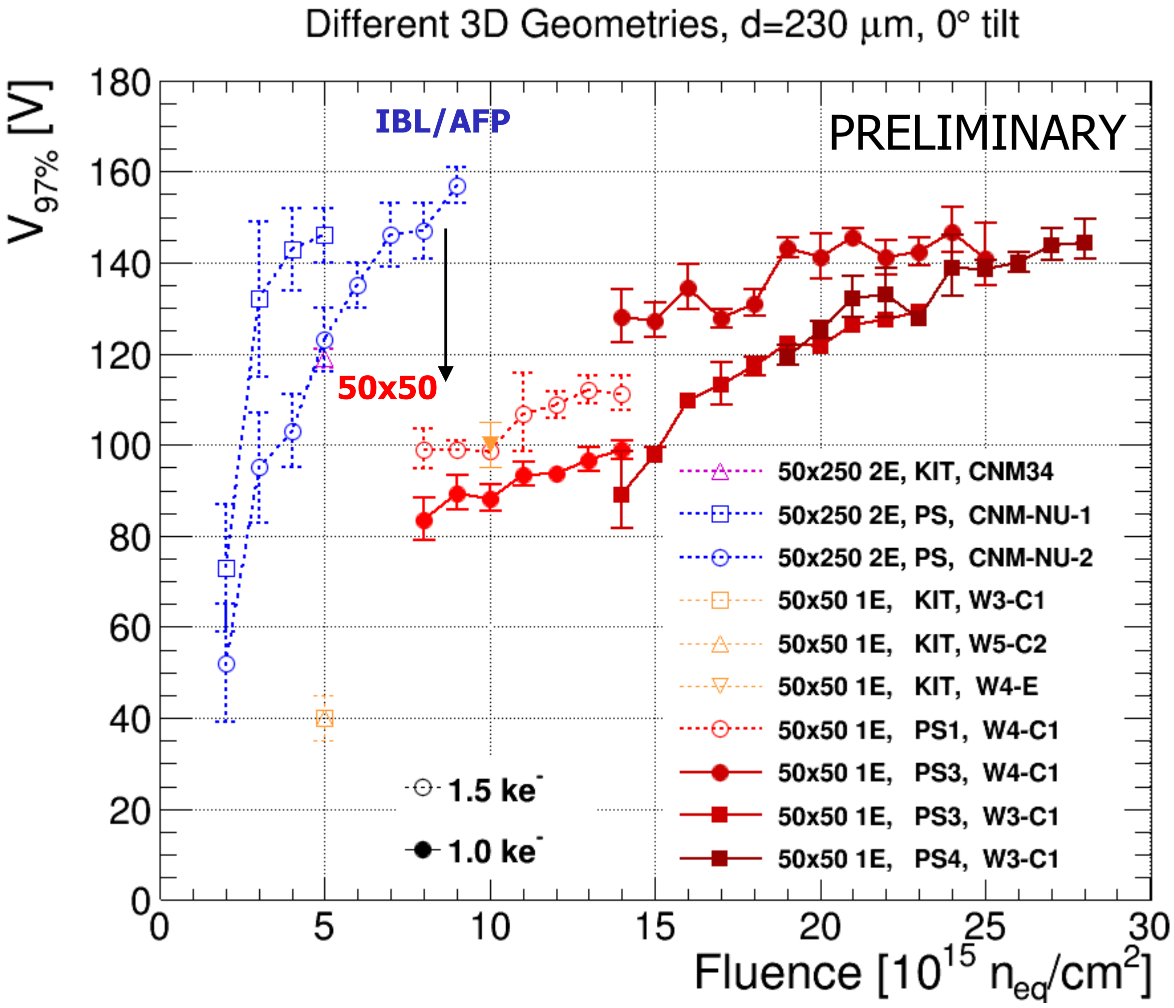


Efficiency vs. V Compilation



- Uniform irradiation (KIT) + non-uniform (PS) at highest fluence with lowest fluence uncertainty (~15-20%)
- PS+KIT agree at 1e16 n_{eq}/cm^2
- **98% plateau efficiency reached even after 2.7e16 n_{eq}/cm^2**

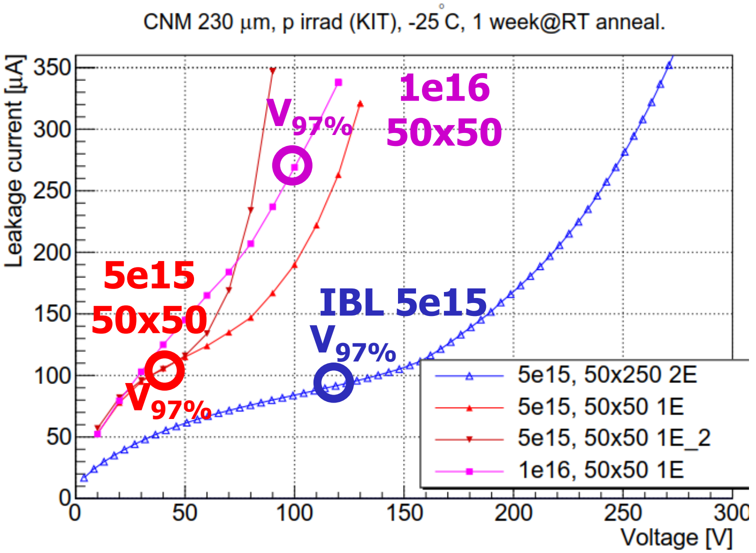
Operation Voltage vs. Fluence

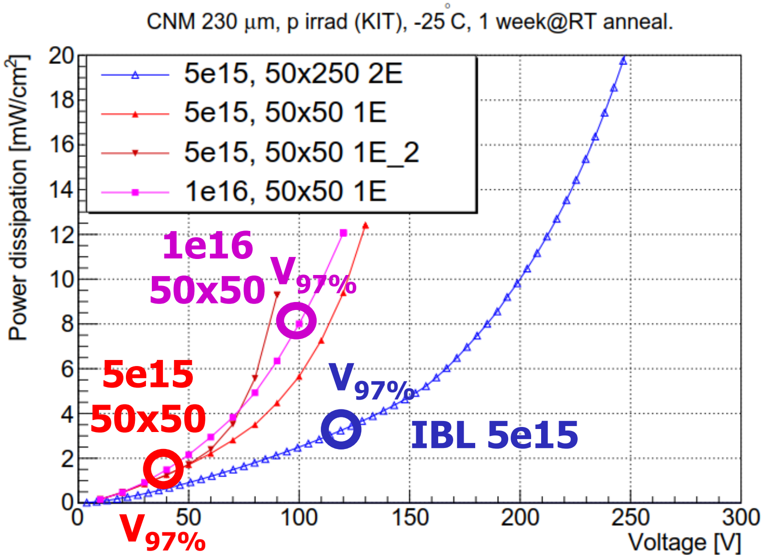


- $V_{97\%}$: estimate of operation voltage
- Highly improved operation voltage for 50x50 μm² 3D compared to IBL/AFP generation
- At ITk baseline fluence of 1.3e16 n_{eq}/cm² only 100 V needed
  - Thin planar needs ~500 V

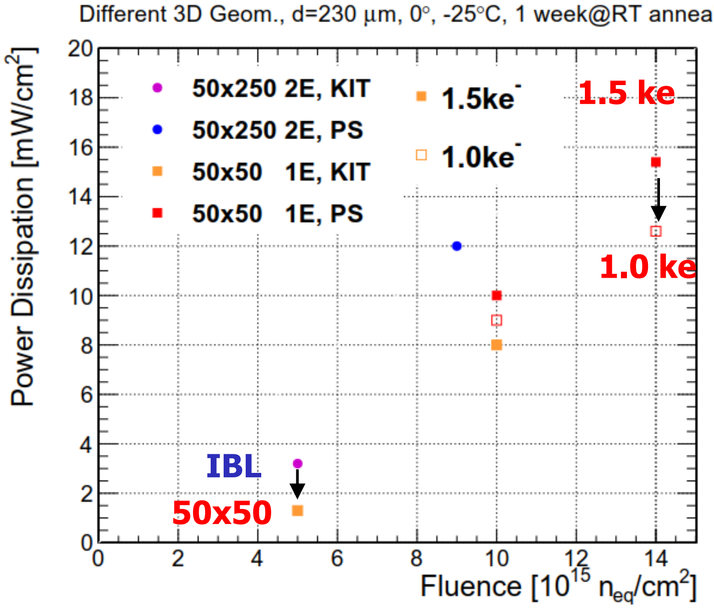
    N. Savic et al., JINST 11 (2016) C12008
- **Even at 2.7e16 n_{eq}/cm²: $V_{97\%}$ < 150 V**

IV and Power Dissipation



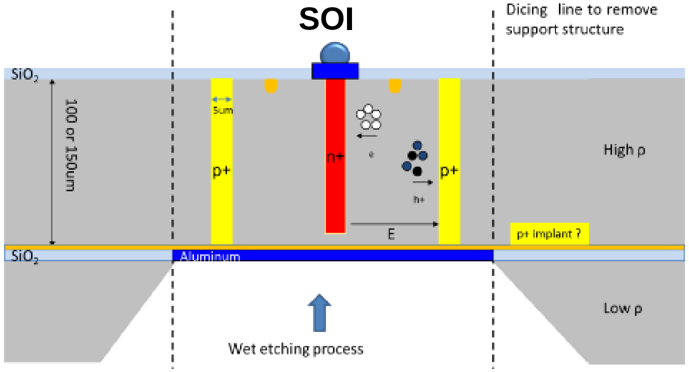


- Important parameters for thermal run away
- From one pixel device only extractable for uniform irrad. (KIT)
  - At fixed V, 50x50 µm² has higher I_{leak}, but same at $V_{97\%}$
  - Power dissipation improves due to lower $V_{97\%}$
- For non-uniform PS irradiation PS, $V_{97\%}$ from test beam efficiency combined with n-irradiated 3D strip IV
- Considerably lower P than for IBL 3D gen. and planar devices (25 mW/cm² at 1e16 n_{eq}/cm²) N. Savic et al., JINST 11 (2016) C12008

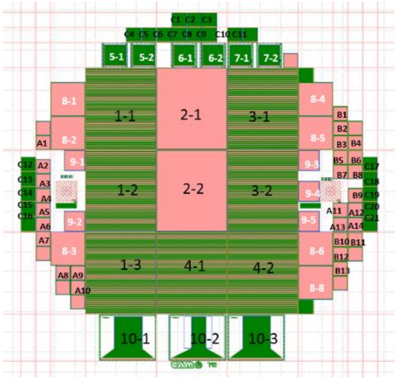


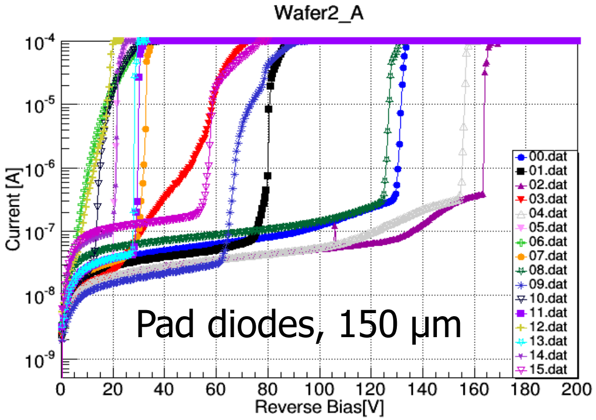
J. Lange et al., arXiv:1707.01045 (plus new data)

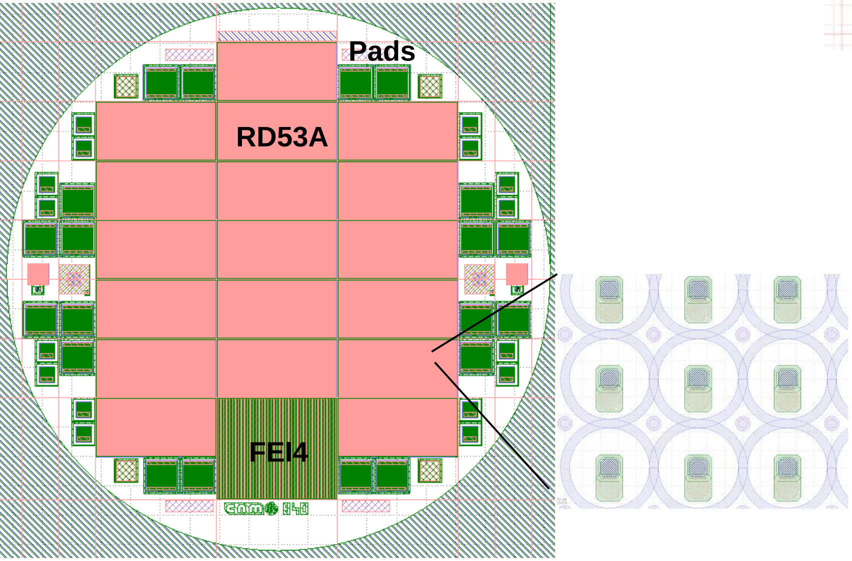
New CNM 3D Runs: Thin + RD53A



- Thin 3D run with small-pitch FEI4 prototypes just finished
  - 100 and 150 µm single-sided on SOI wafers
  - Probing and dicing on-going







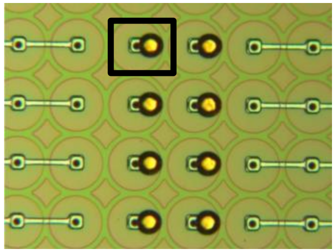
- 3D runs with RD53A sensors on-going
  - Single-sided 72, 100+150 µm on SOI and double-sided 200 µm
  - 50x50 µm² 1E, 25x100 µm² 1E and 2E
  - UBM + flip-chip to be done in-house by CNM + IFAE

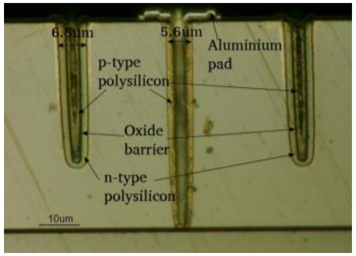
→ expected to finish within 1-2 months

Conclusions and Outlook

- Studied 230 µm CNM 3D production with small pixel size up to **unprecedented fluences of 3e16 n_{eq}/cm²** beyond full ITk fluences
  - First time pixel devices irradiated to such high fluences (and survived)
  - Highly reduced operational voltage and power dissipation wrt. IBL/AFP generation and planar after irradiation
    - 98% efficiency at 0 V before irradiation
    - 97% efficiency at 100 V and 13 mW/cm² for 1.4e16 n_{eq}/cm²
      → safe operation at ITk baseline fluence (1 replacement)
    - 97% efficiency reached at <150 V after 2.7e16 n_{eq}/cm²
    - No indication that limit has been reached…

50x50 µm²



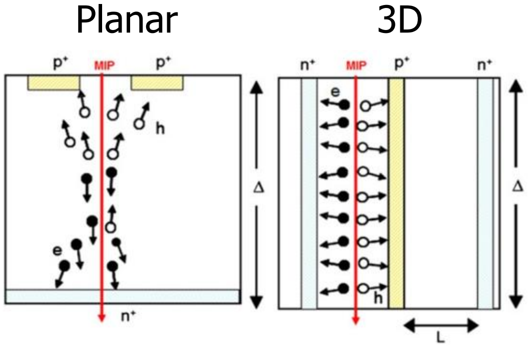


- Single-sided thin (72-150 µm) 3D productions under way at CNM
  - Also with RD53A-chip geometry in addition to FEI4 prototypes
    → expected to have even better performance with new optimised readout chip

Unprecedented radiation hardness of 3D pixel detectors demonstrated

BACKUP

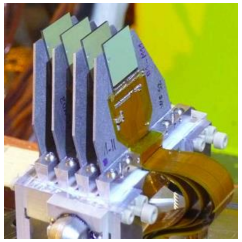
3D Silicon Pixel Detectors Overview


Planar

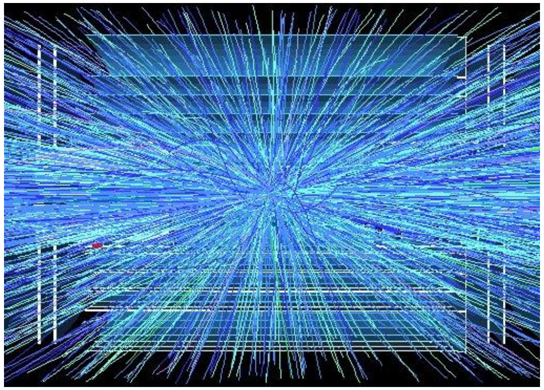
3D

IBL

AFP



HL-LHC

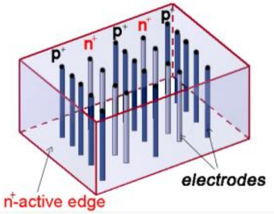


- 3D Silicon detectors: radiation-hard sensor technology
  - Electrode distance decoupled from thickness → fast charge collection, trapping reduced S. Parker et al.
- Already applied in ATLAS IBL, AFP, CT-PPS
  - Radiation hardness up to 5e15 n_{eq}/cm^2 required and proven
- Future HEP applications require more radiation hardness and small pixel sizes
  - HL-LHC pixel detectors (2024)
    - Full 4000 fb^{-1}: 2.5e16 n_{eq}/cm^2 innermost layer (ATLAS ITk) L. Rossi's talk
    - But FE chip not specified to be so radiation hard M. Garcia-Sciveres' talk → Baseline requirement: 1.3e16 n_{eq}/cm^2 (replacement of 2 inner layers)
    - 50x50 µm² or 25x100 µm² pixel size to cope with occupancy
  - FCC-hh (far future)
    - 7e17 n_{eq}/cm^2 G. Kramberger's talk
- Aim: Develop new generation of ultra-radiation-hard 3D pixel detectors

see also H. Oide's talk for FBK

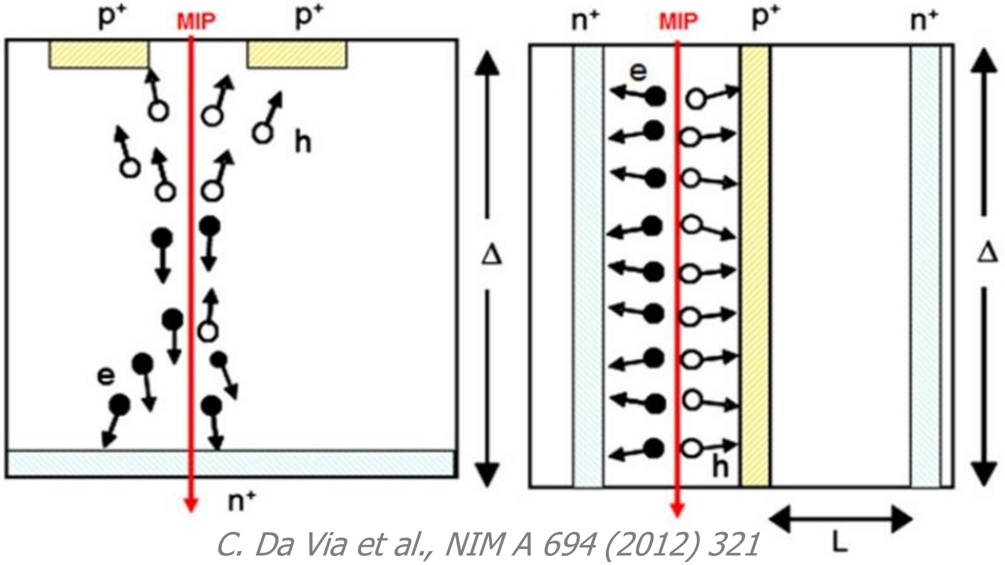
  - In the framework of ATLAS HL-LHC pixel upgrade
  - But exploring limits of technology

3D Detector Principle



Planar Technology

3D Technology



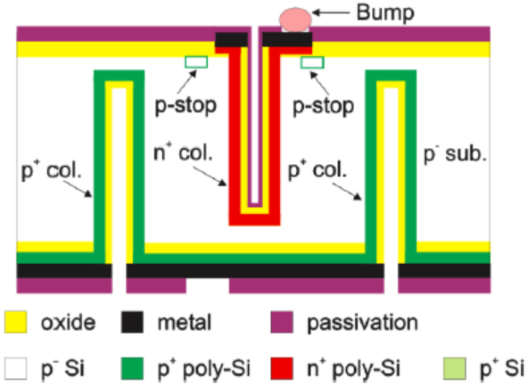
C. Da Via et al., NIM A 694 (2012) 321

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

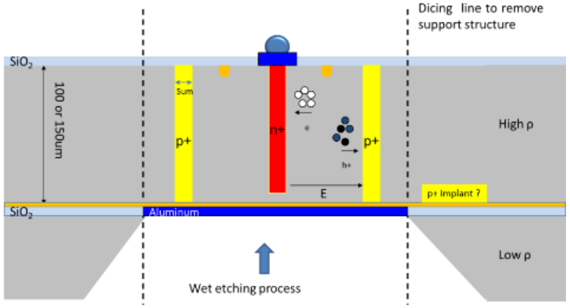
- Double sided (available at CNM)
  - IBL/AFP-proven technology
  - No handling wafers needed
    → thickness limited to ≥200 µm and wafers to 4”
  - 3D columns ~8 µm diameter



Double-sided

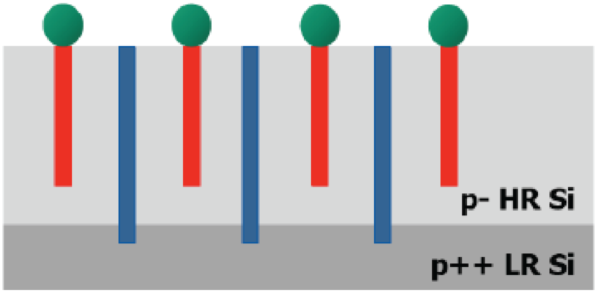
G. Pellegrini, CNM

- 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

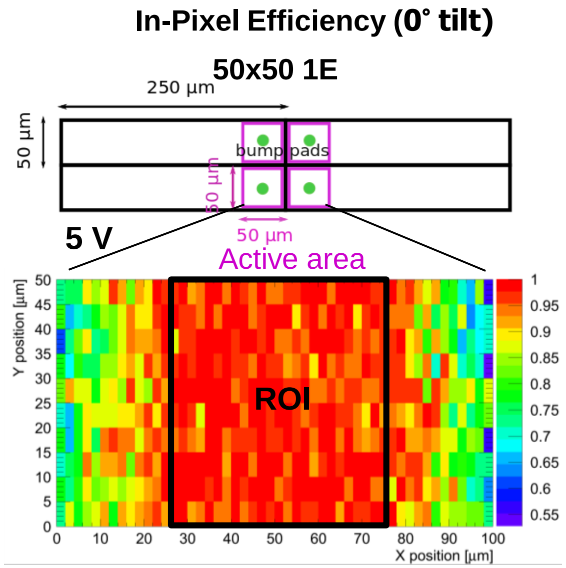
G. Pellegrini, CNM

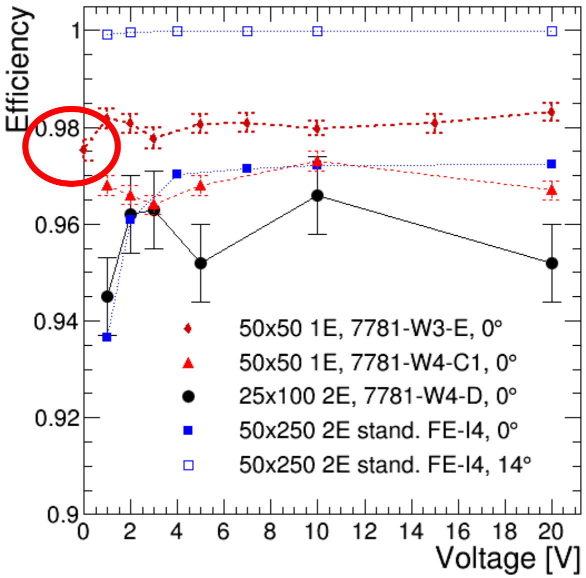


Si-Si bonding

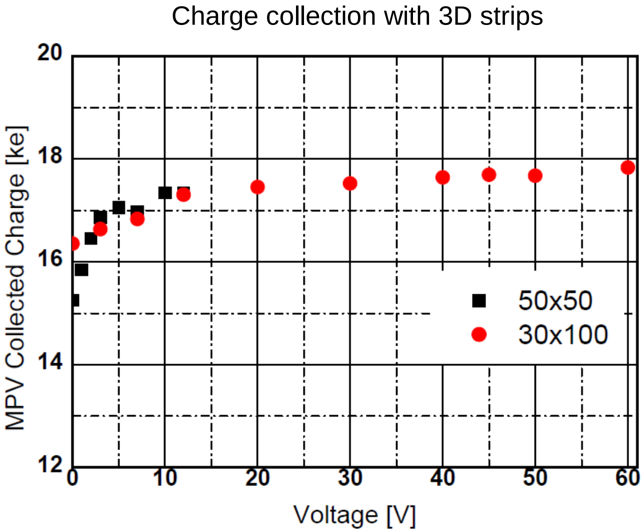
M. Boscardin, FBK

Efficiencies before Irradiation



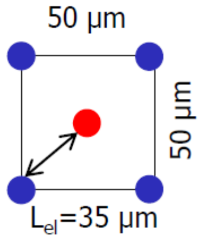


J. Lange et al., 2016 JINST 11 C11024 (plus new data)

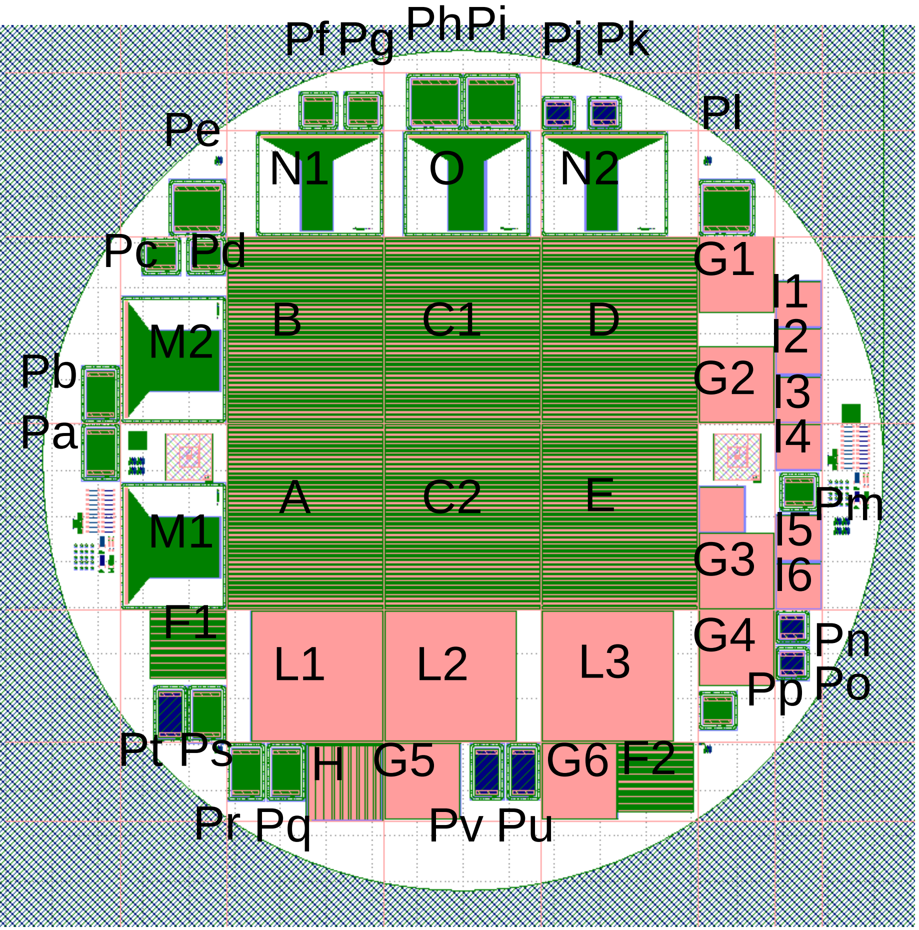


M. Manna, 30th RD50 Workshop Krakow 2017

- Test beam with EUDET/AIDA telescope
  - Reference tracks with few µm resolution
    → select Region of Interest (ROI) within active region
    and away from telescope resolution effects
- 98% plateau efficiency starting at **0 V!**
  - Consistent with high charge collection at 0 V in small-pitch 3D strips
  - Thanks to small electrode distance (28-35 µm)



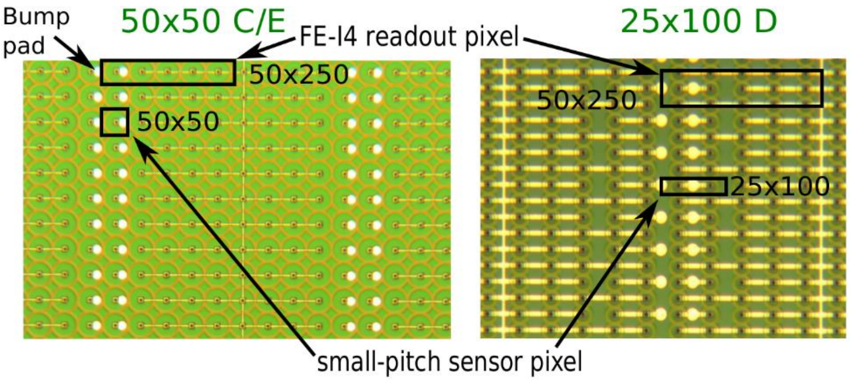
First Small-Pixel CNM Run for HL-LHC

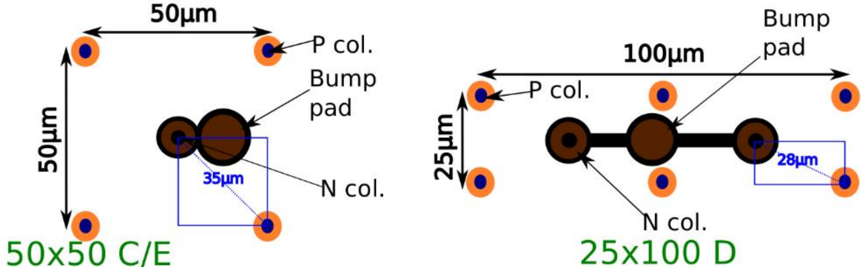


D. Vázquez Furelos et al., 2017 JINST 12 C01026

J. Lange et al., 2016 JINST 11 C11024

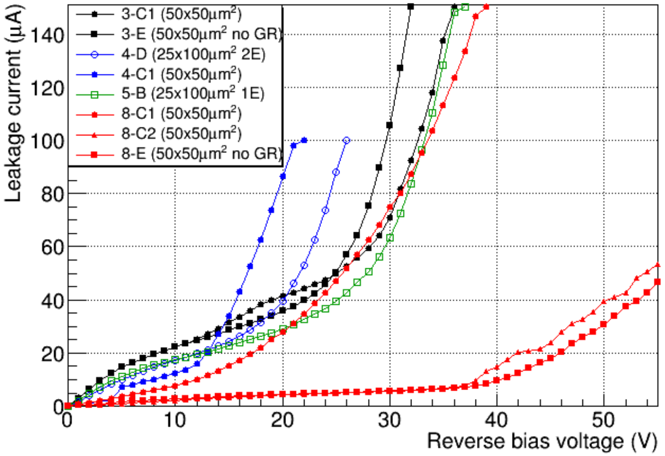
- Run 7781 finished in Dec 2015 (RD50 project)
- 5x 4" wafers, p-type, 230 µm double-sided, non-fully-passing-through columns (a la IBL)
- Increased aspect ratio 26:1 (column diameter 8 µm)
- **First time small pixel size 25x100+ 50x50 µm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and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





Sample Characterisations

Pixel IV

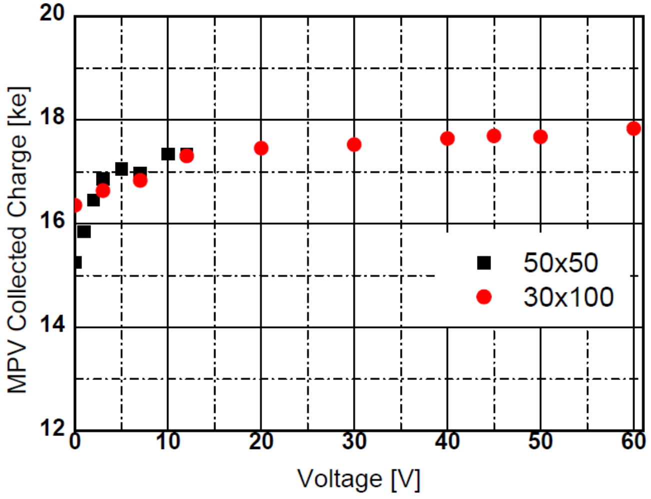


Pixel Geom.	C/el. [fF] (*)	C/pixel [fF] (*)	Noise [e]
25x100 2E	42	84	160
50x50 1E	37	37	105-140

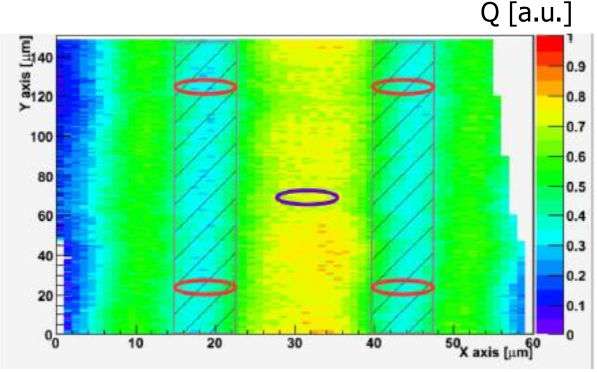
(*) from pad diodes

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

Strips charge collection (unirr.)



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



L. Simon

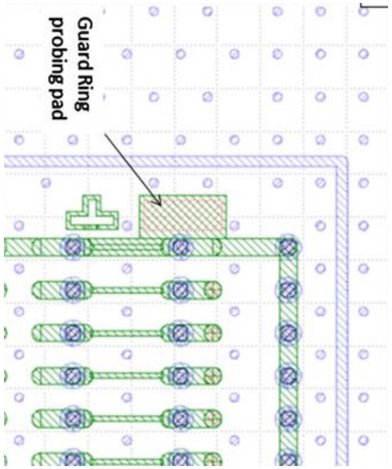
- Pixel devices bump-bonded and assembled at IFAE
- IVs
  - V_{BD} ~ 15-40 V
  - Improved in new productions after CNM process optimization

    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}/cm²
  - Measurements up to 2e16 n_{eq}/cm² in progress

State of the Art: IBL/AFP Generation

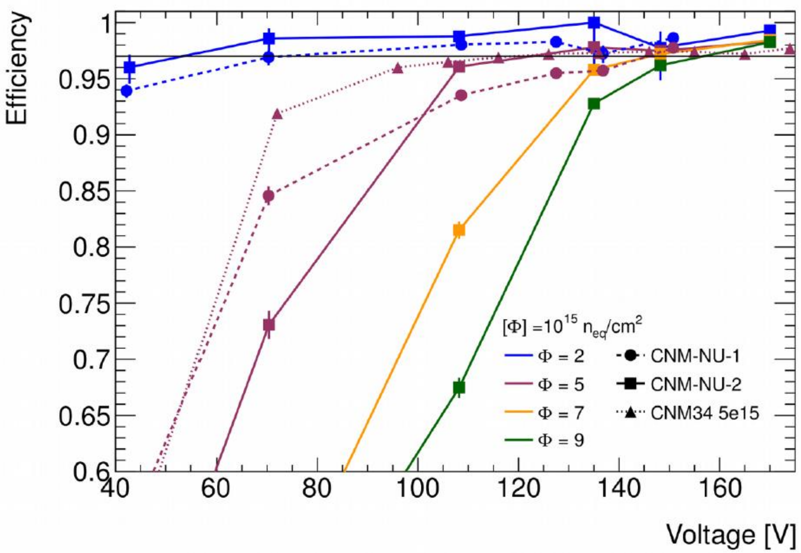
- 230 µm thick sensors by CNM and FBK (double-sided)
- FEI4s: 50x250 µm² 2E, 67 µm inter-el. distance
- Radiation hardness up to 5e15 n_{eq}/cm^2 established (IBL)
- Explored limits further with irradiations up to HL-LHC fluences
  - At 9.4e15 n_{eq}/cm^2 : 97.8% efficiency at 170 V!
  - Power dissipation 15 mW/cm² at 1e16 n_{eq}/cm^2 and -25°C

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

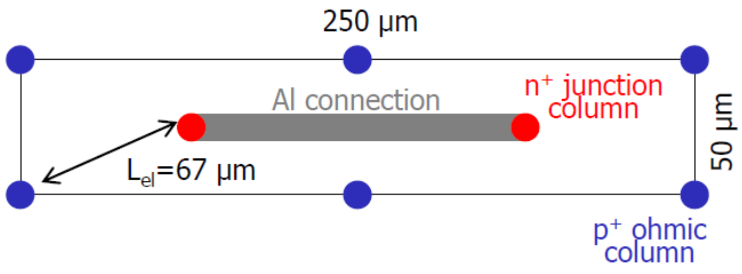


J. Lange et al., 2016 JINST 11 C11024

p-irradiated FEI4, 0° tilt

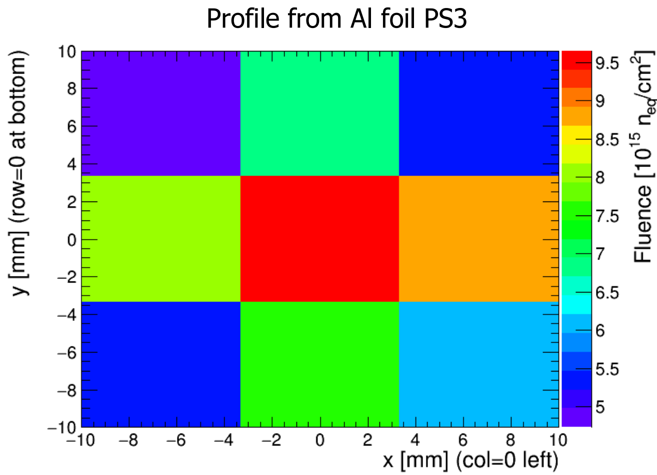


Standard FE-I4 50x250 µm², 2E

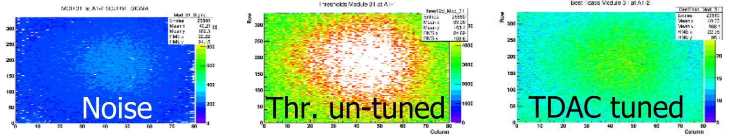


PS Non-Uniform Irradiation - Methodology

- Fluence normalization obtained with 20x20 mm² Al dosimetry foil
- Profile from
  - Beam profile monitors: 12-20 mm FWHM
  - Also made fluence maps by pixelating Al foil
- Beam position
  - From Al foil profile
  - For first irradiations also in-situ from pixel measurements (eff., noise, threshold before tuning, TDAC after tuning etc.)

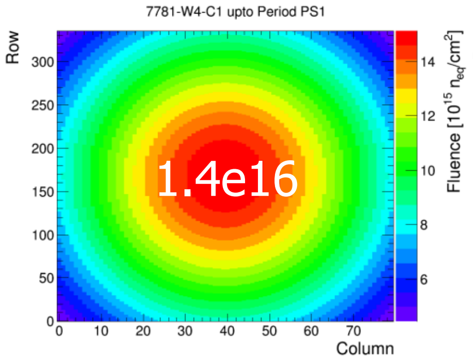


PS2, 7781-W3-C1

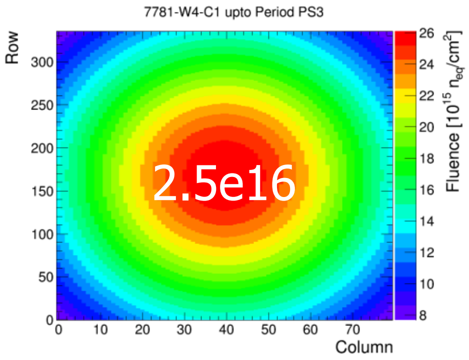


Final fluence maps for analysed data

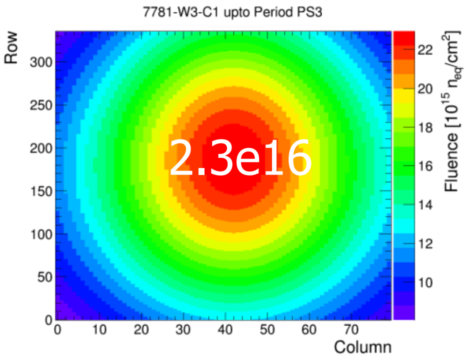
W4-C1 PS1



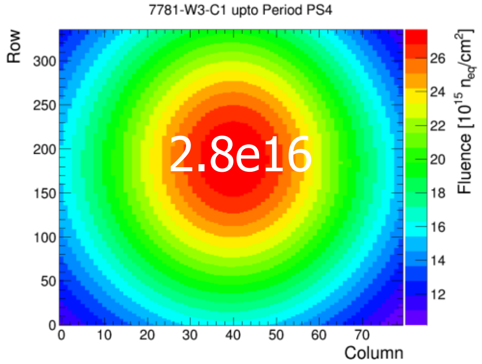
W4-C1 PS3



W3-C1 PS3

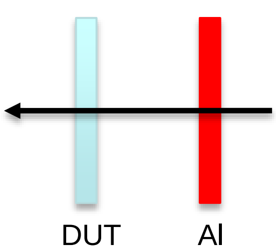


W3-C1 PS4

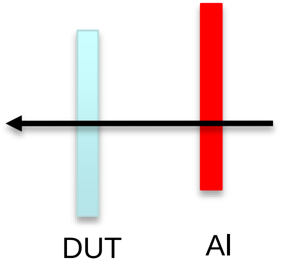


PS Non-Uniform Irradiation - Uncertainties

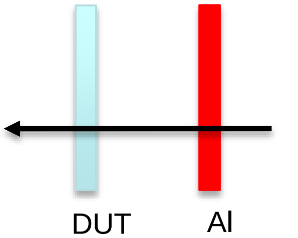
- Introduce variations by +/- 1 mm in beam σ, beam centre offset, Al foil offset (both x, y)
- Vary in all combinations
- Determine maximum deviation from default value (envelope) for all variation combinations → take as systematic uncertainty (conservative)
- 15-20% uncertainty at highest fluence, 45% (70%) at lowest fluence for 20 (12) mm beam



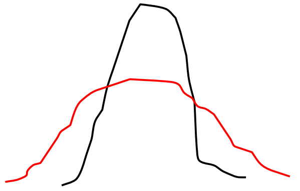
Default



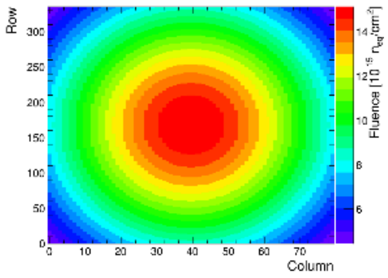
Al foil variation

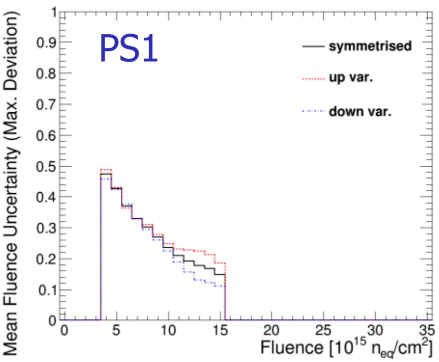


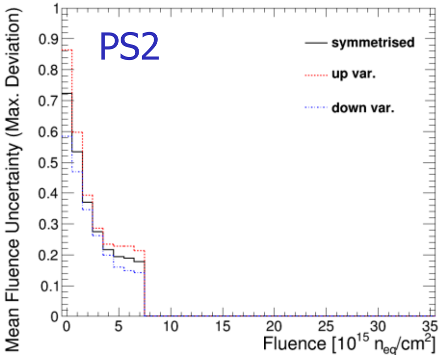
Beam centre variation

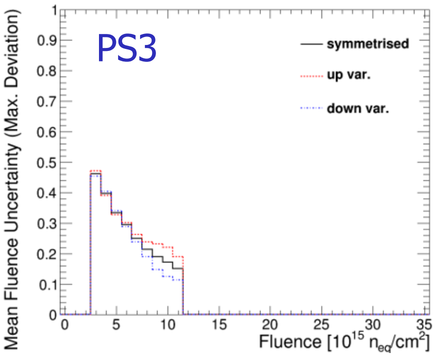


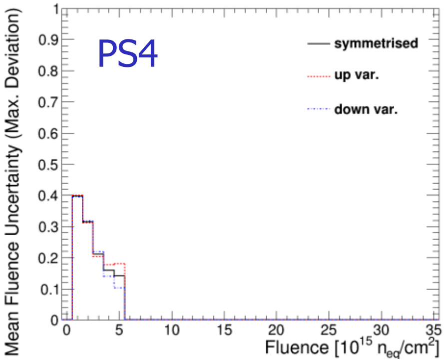
Beam width variation





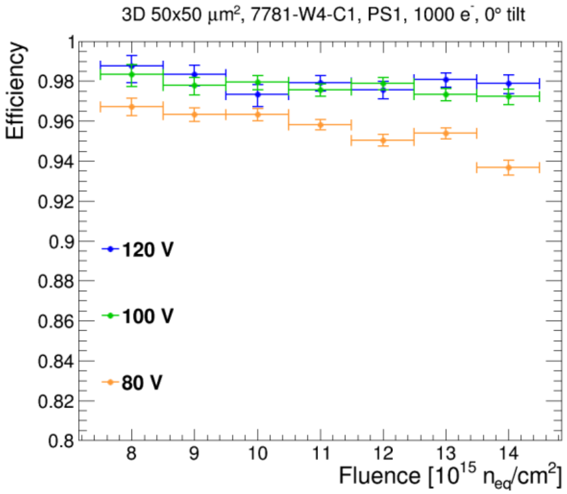




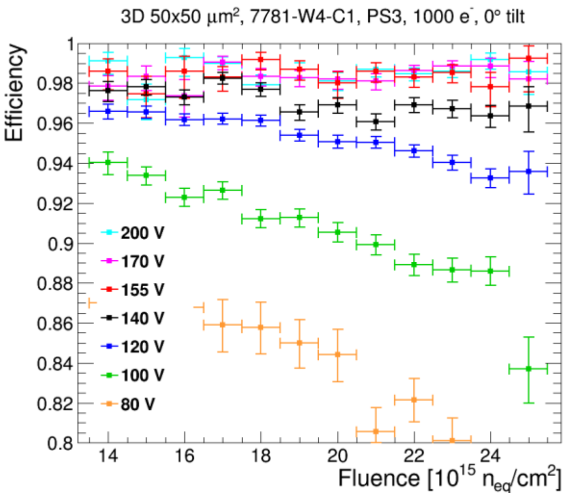


Efficiency vs. Fluence

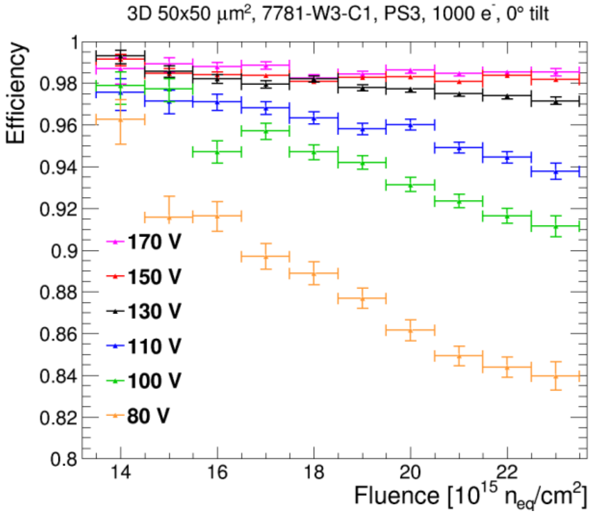
W4-C1 PS1



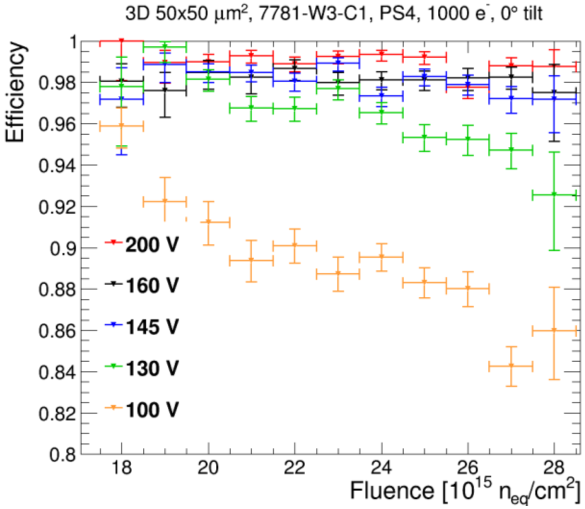
W4-C1 PS3



W3-C1 PS3



W3-C1 PS4



- Large range of fluence on single device
- Efficiency decreases with fluence at low voltage
- Efficiency improves with voltage
- NB: Fluence uncertainties large at low fluence range (~50%)