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

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RD50 Workshop CERN, 21 November 2017

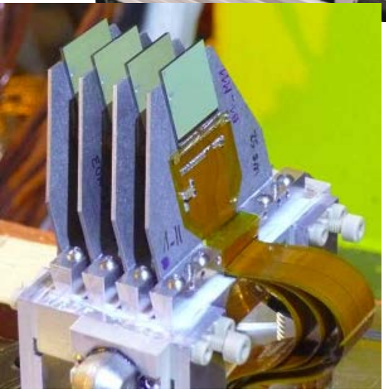
Institut de Física d'Altes Energies

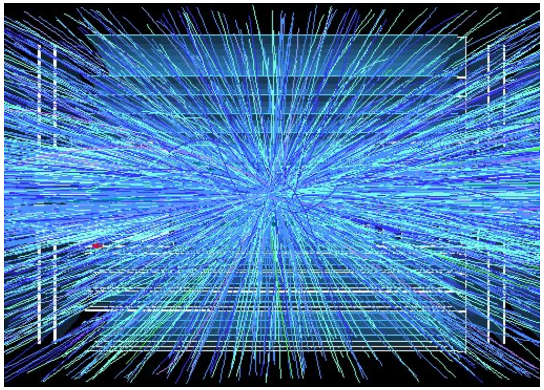
EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

ATLAS

Applications of 3D Silicon Pixel Detectors





- ATLAS IBL 2015
  - 25% 3D FEI4 detectors (CNM+FBK sensors)
- ATLAS Forward Proton (AFP) 2016
  - CNM sensors, 3D pixel modules produced by IFAE

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

- CMS-TOTEM PPS 2017
  - CNM sensors
- HL-LHC pixel detectors 2024

This talk

  - Sensor qualifications 2017-2018 for ATLAS Inner Tracker (ITk) upgrade
  - Huge particle density and occupancies
  - Reduced pixel size: 50x50 μm^2 or 25x100 μm^2
  - Radiation hardness:
    - Full 4000 fb^{-1}: 2.5e16 n_{eq}/cm^2 innermost layer
    - But FE chip not expected to be so radiation hard
      → Baseline requirement: 1.3e16 n_{eq}/cm^2 (1 replacement of 2 inner layers)
  - 3D promising candidate for innermost layer(s)

3D Pixel Strategy Barcelona

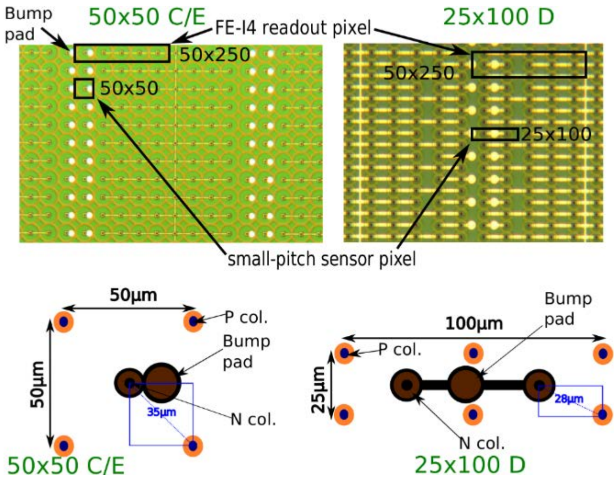
1. Test IBL/AFP generation
   - 230 µm thick, double-sided process, 50x250 µm^2 2E FEI4 pixels
   - Radiation hardness demonstrated up to ITk fluence (9e15 n_{eq}/cm^2)

J. Lange et al., 2016 JINST 11 C11024

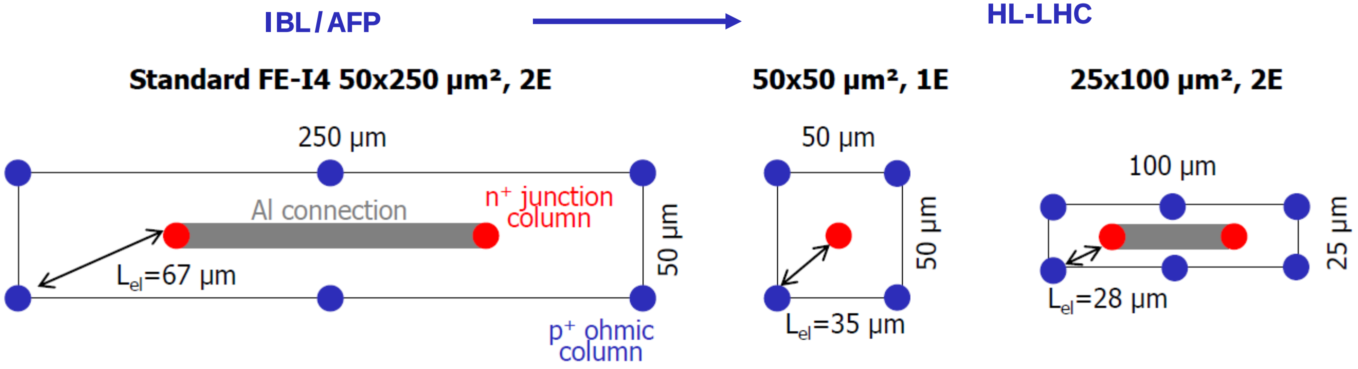
2. Develop prototype small-pitch 3D pixels matched to FEI4
   - Pixel size 50x50 and 25x100 µm^2
     - Reduced electrode distance → more radiation hard
   - Double-sided 230 µm CNM run well-studied
     - Good performance up to 1.4e16 n_{eq}/cm^2 (ATLAS ITk baseline scenario, 1 replacement)
     - Exploring up to 3e16 n_{eq}/cm^2 (full ITk fluence and beyond)
   - Recently produced thinner 100-150 µm single-sided 3D

J. Lange et al., arXiv:1707.01045

3. Produce RD53A 3D pixels (on-going)
   - “Real” 50x50 and 25x100 µm^2



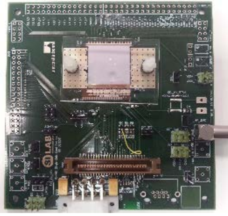
D. Vázquez Furelos et al., 2017 JINST 12 C01026



IBL/AFP → **HL-LHC**

Standard FE-I4 50x250 µm^2, 2E | **50x50 µm^2, 1E** | **25x100 µm^2, 2E**

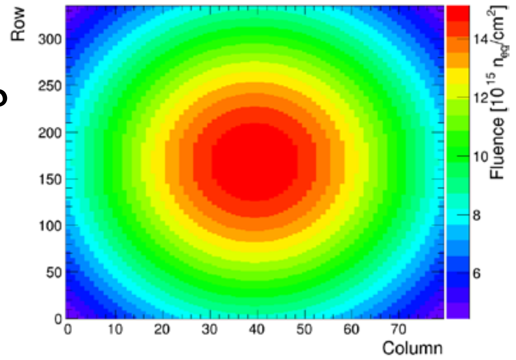
Beam Tests and Irradiations



- 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

PS1 20 mm FWHM

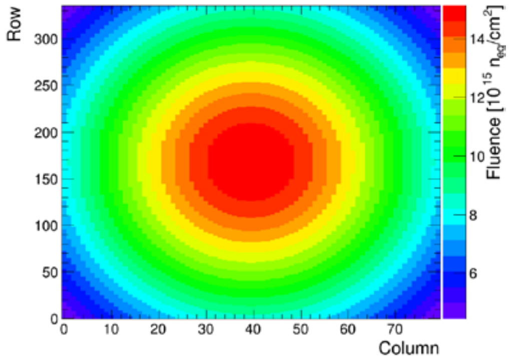


- Many beam tests at CERN SPS H6, 120 GeV pions

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	KIT 2016	0.5	0.5	8d@RT	Nov2016
	PS3 20mm 2017	1.0	1.5	18d@RT	Not working
7781-W3-C1, 50x50	KIT 2016	0.5	0.5	8d@RT	Nov 2016
	PS2 12mm 2016	0.7	1.2	15d@RT	
	PS3 20mm 2017	1.1	2.2	18d@RT	July 2017
	PS4 20mm 2017	0.6	2.8	15d@RT	Oct 2017
	PS5 20mm 2017	~0.5	~3.3	Just finished	2018?
7781-W4-E, 50x50	KIT 2017	1.0	1.0	as irrad.	July2017
				7d@RT	Sep+Oct 2017
7781-W3-E, 50x50	Unirr.				Sep 2017

Beam Tests and Irradiations

- This talk: KIT uniform up to 1e16 n_{eq}/cm^2


PS1 20 mm FWHM

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
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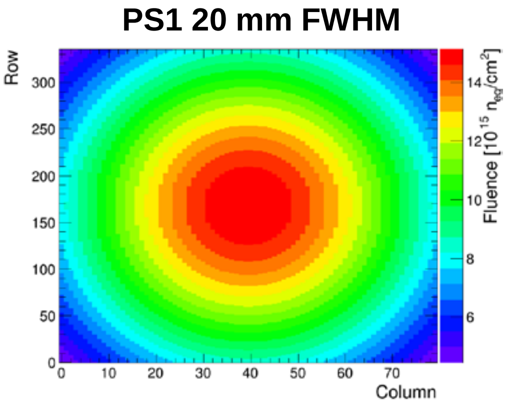
	PS4 20mm 2017	0.6	3.1	15d@RT	Not working
7781-W5-C2, 50x50	KIT 2016	0.5	0.5	8d@RT	Nov2016
	PS3 20mm 2017	1.0	1.5	18d@RT	Not working
7781-W3-C1, 50x50	KIT 2016	0.5	0.5	8d@RT	Nov 2016
	PS2 12mm 2016	0.7	1.2	15d@RT	
	PS3 20mm 2017	1.1	2.2	18d@RT	July 2017
	PS4 20mm 2017	0.6	2.8	15d@RT	Oct 2017
	PS5 20mm 2017	~0.5	~3.3	Just finished	2018?
7781-W4-E, 50x50	KIT 2017	1.0	1.0	as irrad.	July2017
				7d@RT	Sep+Oct 2017
7781-W3-E, 50x50	Unirr.				Sep 2017

Beam Tests and Irradiations

- This talk: PS non-uniform up to 2.5e16 n_{eq}/cm^2


PS1 20 mm FWHM

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
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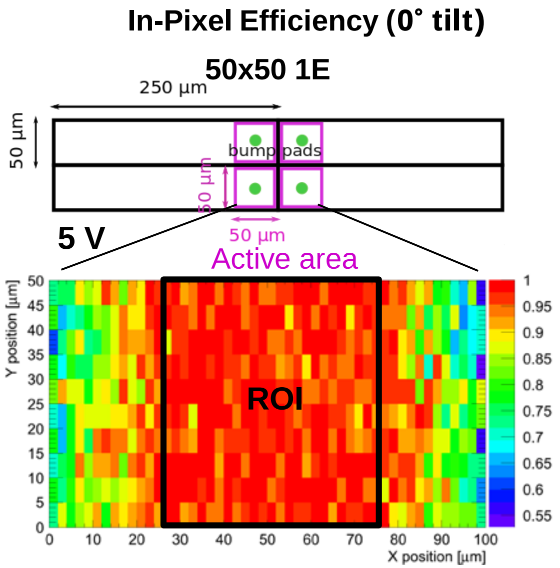
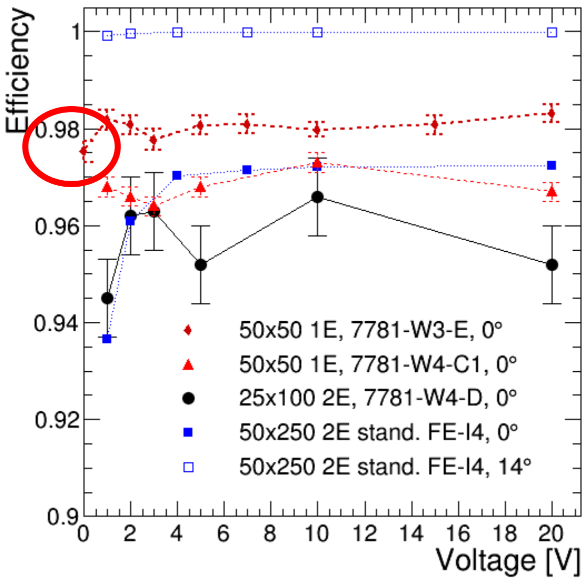
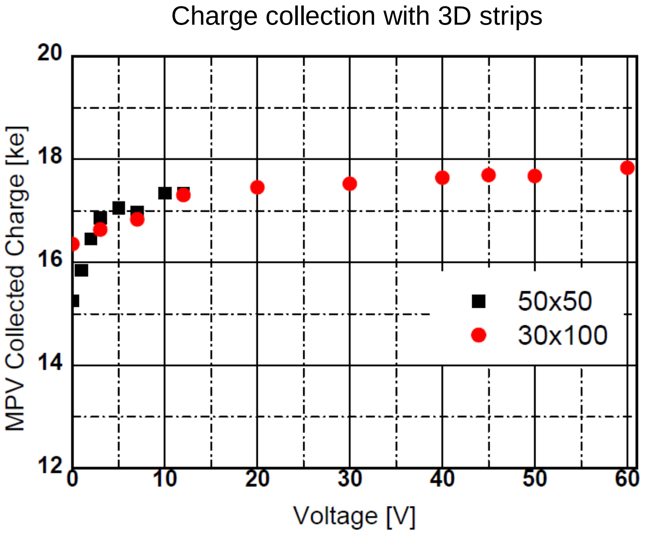
	PS5 20mm 2017	~0.5	~3.3	Just finished	2018?
7781-W4-E, 50x50	KIT 2017	1.0	1.0	as irrad.	July2017
				7d@RT	Sep+Oct 2017
7781-W3-E, 50x50	Unirr.				Sep 2017

Efficiencies before Irradiation



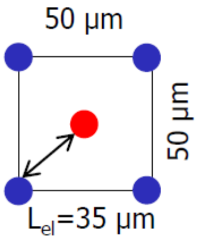


J. Lange et al., 2016 JINST 11 C11024 (plus new data)



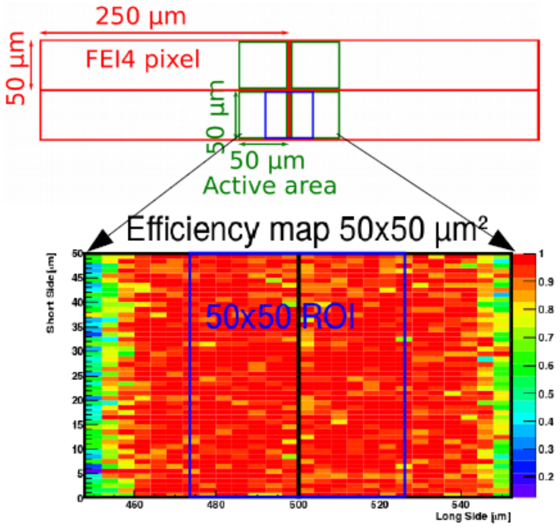
M. Manna, 30th RD50 Workshop Krakow 2017

- Test beam with reference tracks from telescope: select Region of Interest within active region
- Previous meas. with non-ideal devices + ad-hoc telescope
- New meas. with very good device + EUDET-type telescope (high res.), down to 0 V
- 98% plateau efficiency starting at **0 V!**
  - Consistent with high charge collection at 0V in small-pitch 3D strips
  - Thanks to small electrode distance (28-35 µm)

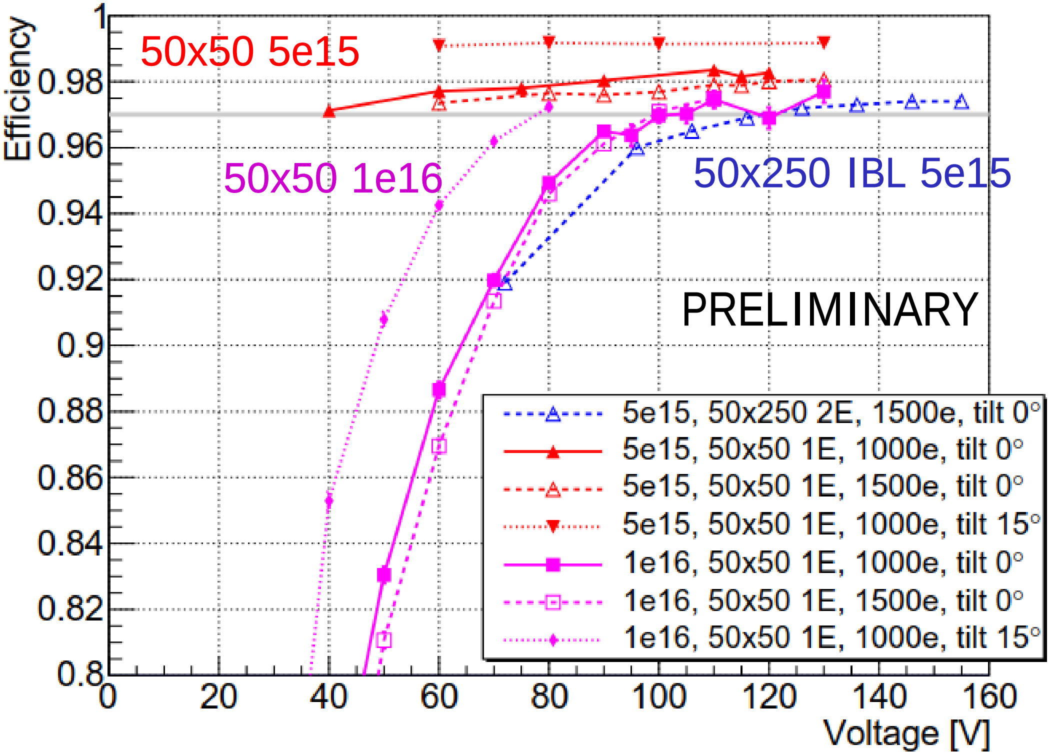


Uniform Irradiation at KIT

5e15, 60 V



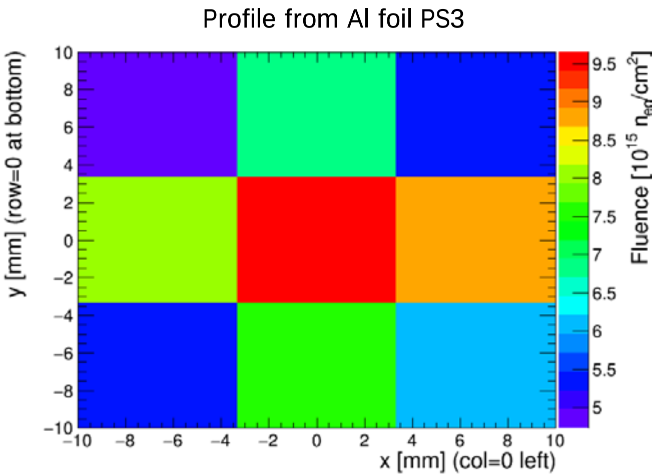
CNM 230 µm, p irrad (KIT)



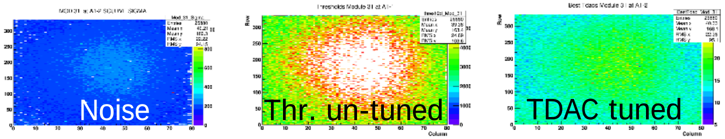
- 5e15
  - Already 97% efficiency at 40 V and 0° tilt!
  - Compare to standard IBL/AFP FEI4: 120 V
  - Very uniform over pixel (no effect of 3D columns visible)
  - Improves to 99% at 15° tilt
- 1e16
  - Already 97% efficiency at 100 V (80 V) at 0° (15°) tilt!

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.)

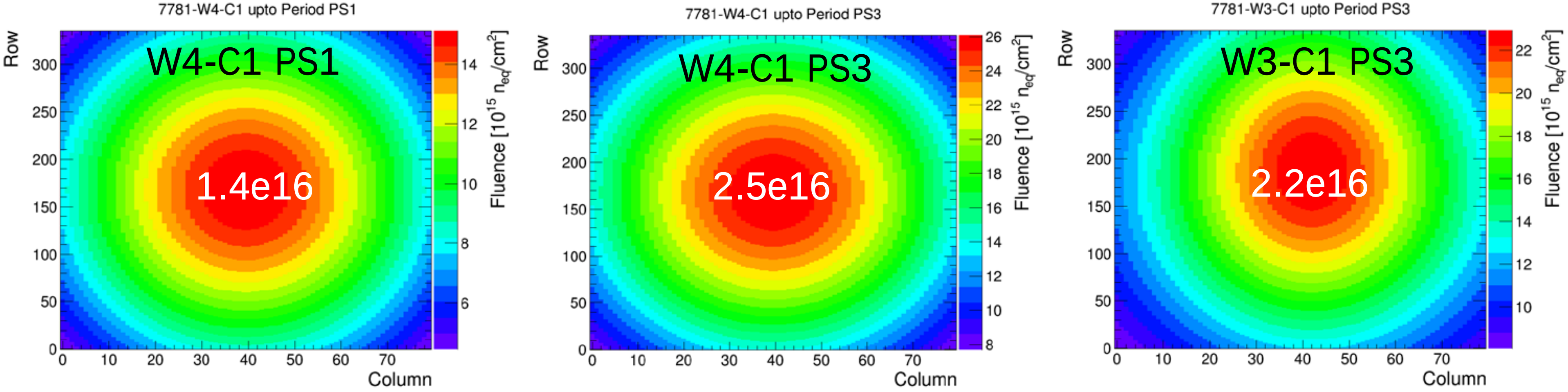


Profile from Al foil PS3



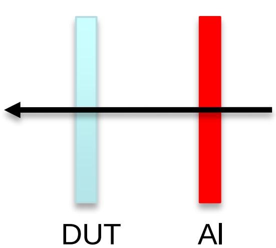
PS2, 7781-W3-C1

Final fluence maps for analysed data

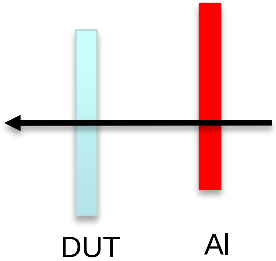


PS Non-Uniform Irradiation - Uncertainties

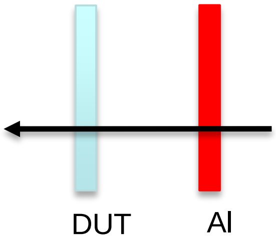
- Introduce variations by +/- 1 mm in beam σ, beam centre offset, Al foil offset (both x, y)
- Vary in all combinations
- Determine maximum deviation from default value (envelope) for all variation combinations
  → take as systematic uncertainty (conservative)
- 15% uncertainty at highest fluence, 45%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



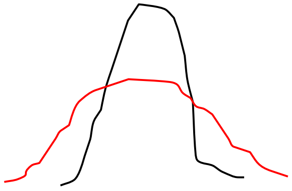
Default



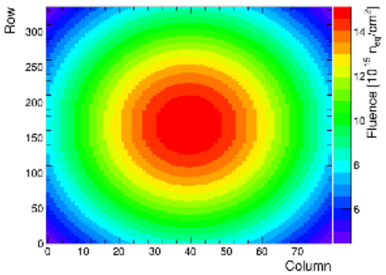
Al foil variation

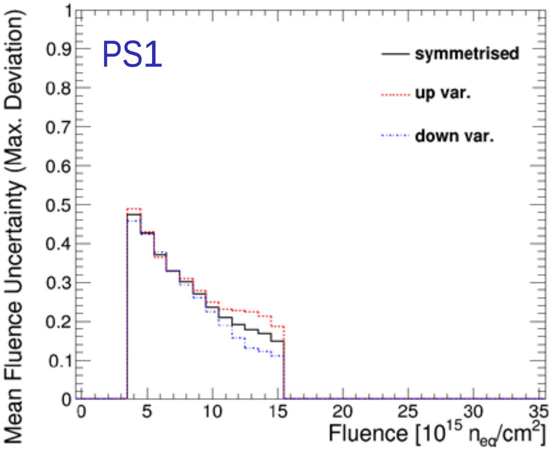


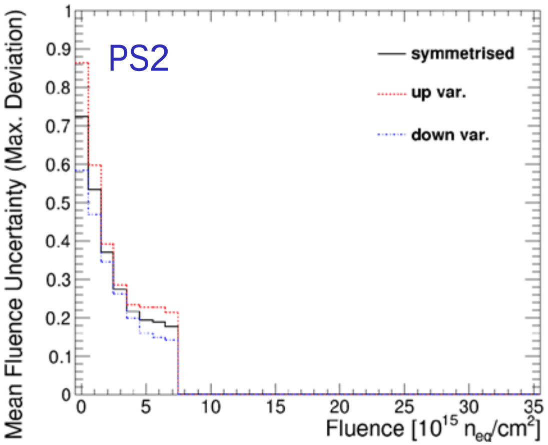
Beam centre variation

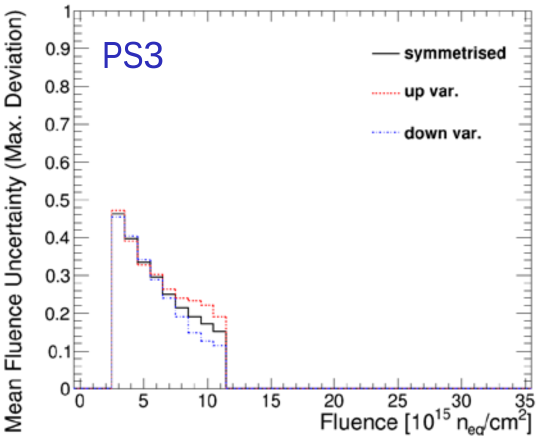


Beam width variation



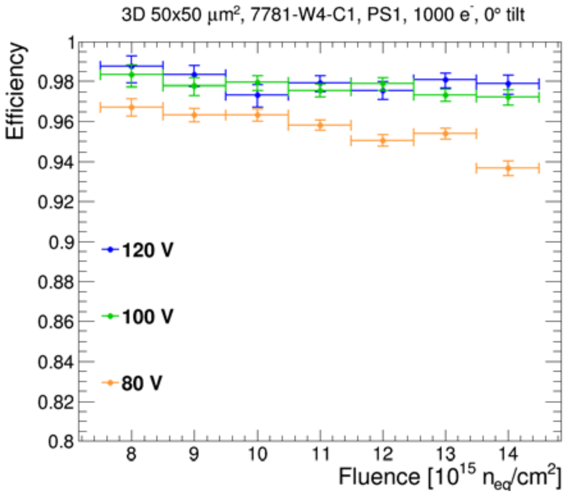


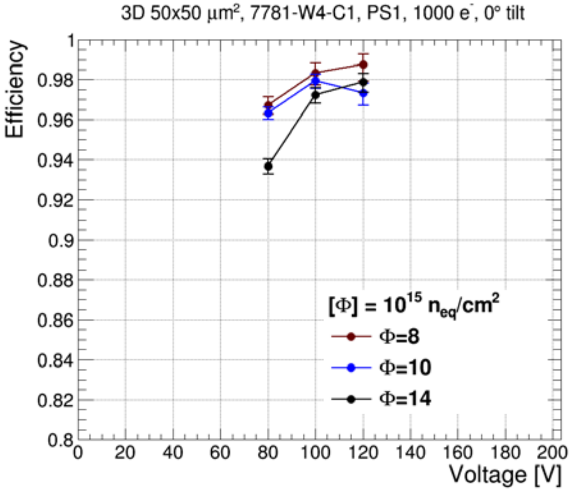




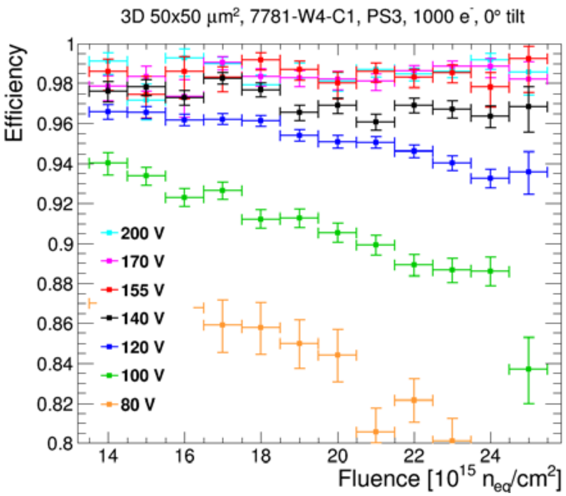
Efficiency vs. Fluence and V

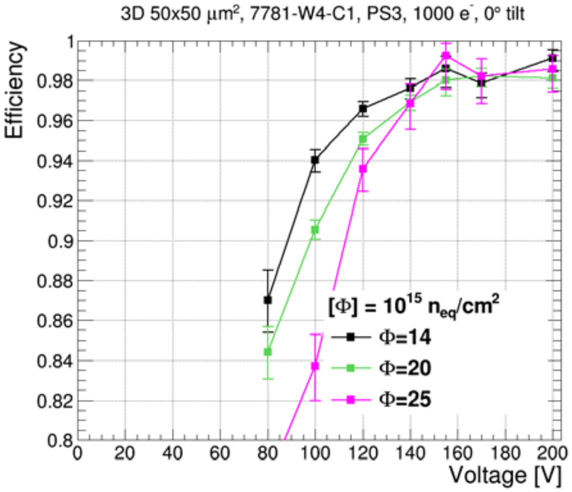
W4-C1 PS1



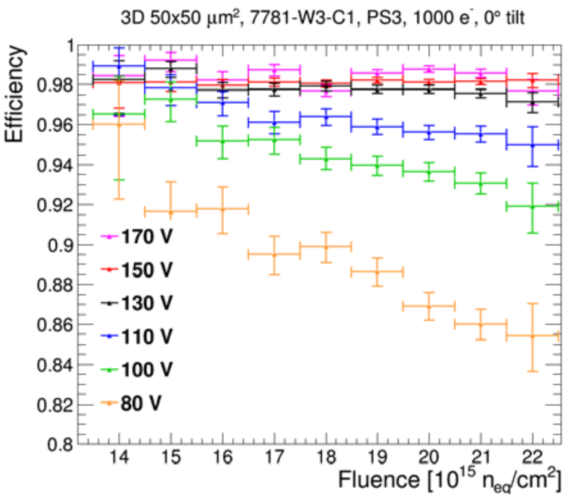


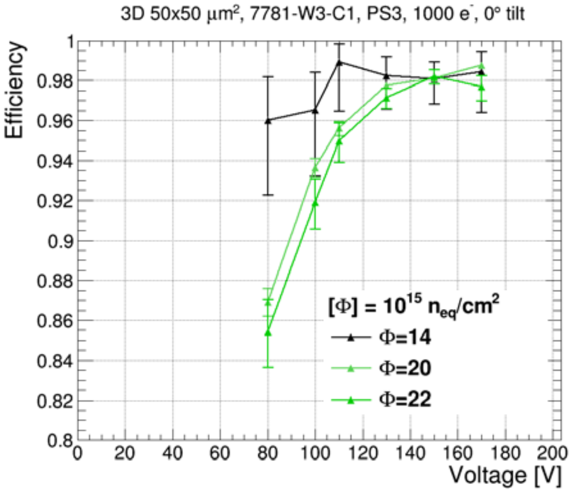
W4-C1 PS3





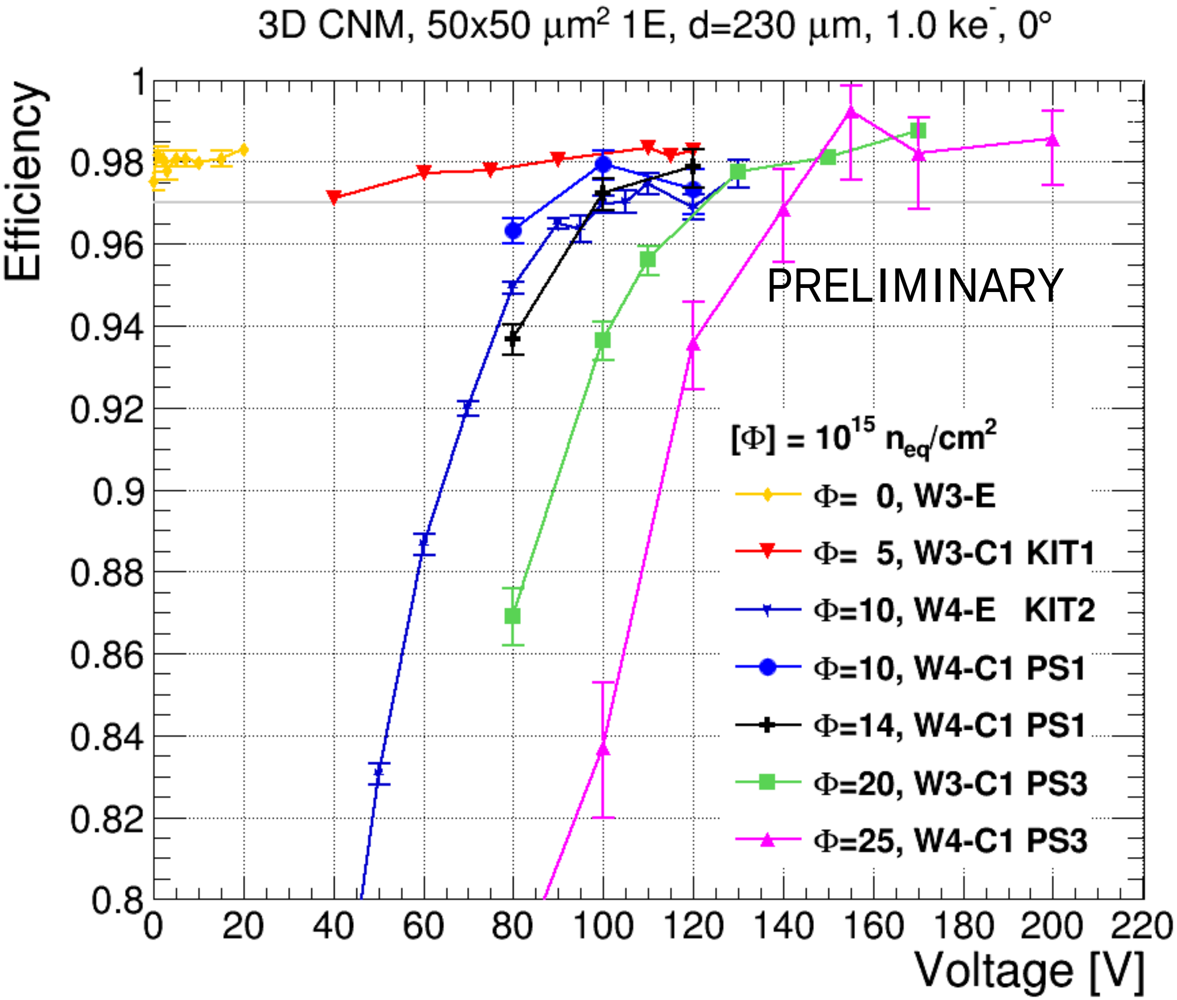
W3-C1 PS3





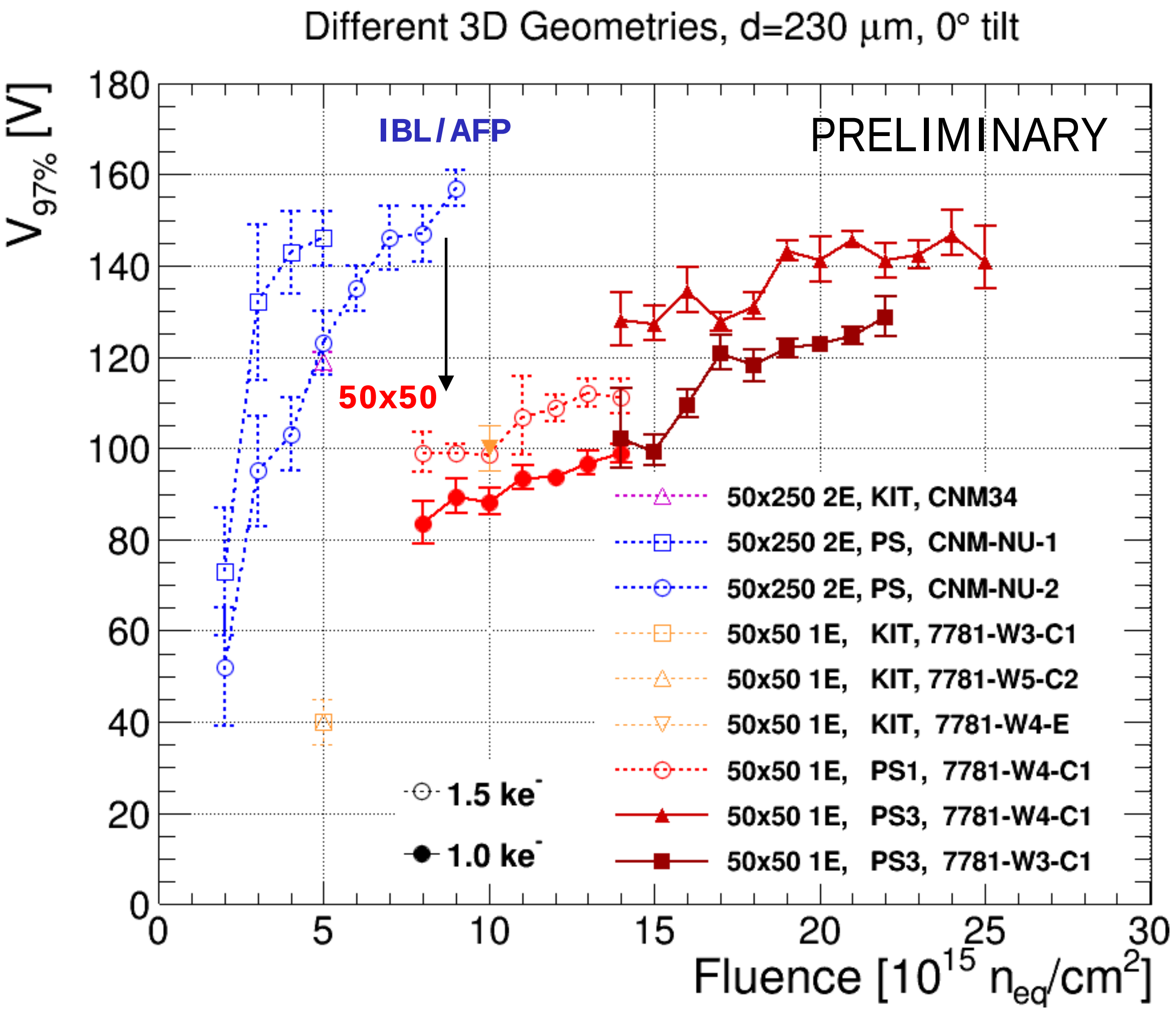
- Efficiency improves with voltage and decreases with fluence

Efficiency vs. V Compilation



- Fluence uncertainty very high at lowest fluence of non-uniform device (~50%)
  → plot only at (or close to) highest fluence with ~15% uncertainty
- Also KIT uniform irradiation added
  - PS+KIT agree well at 1e16 n_{eq}/cm²
- **98% plateau efficiency reached even after 2.5e16 n_{eq}/cm²**

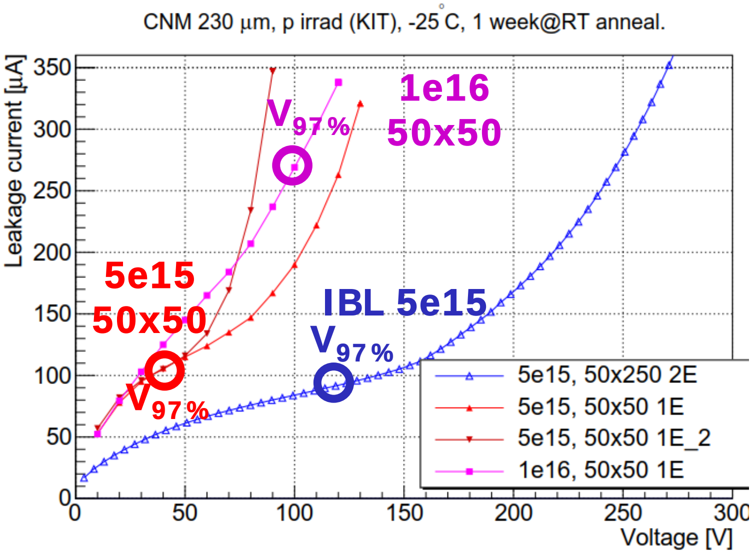
Operation Voltage vs. Fluence

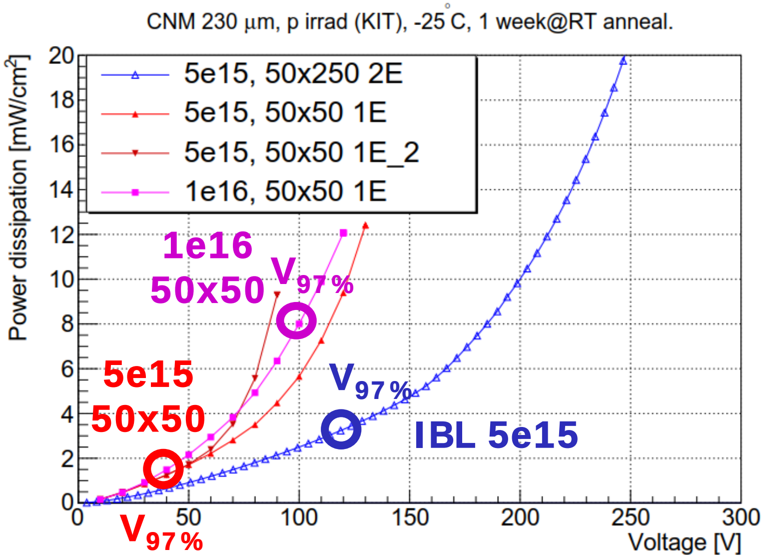


- Take $V_{97\%}$ as estimate of operation voltage
- Highly improved operation voltage for 50x50 μm² 3D compared to IBL/AFP generation
- At ITk baseline fluence of 1.3e16 n_{eq}/cm^2 only 100 V needed
  - Thin planar needs >=500 V

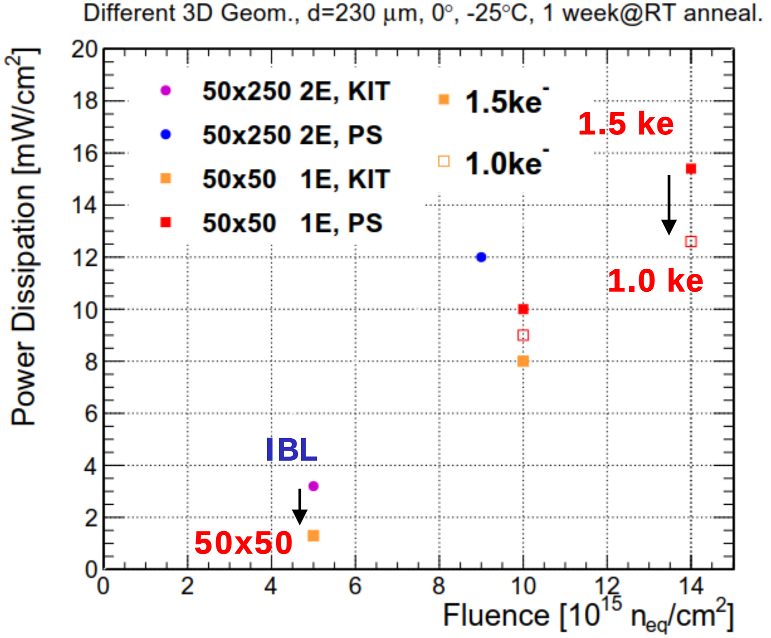
    N. Savic et al., 28th RD50 Workshop, Torino, Italy, 6-8 June 2016
- **Even at 2.5e16 n_{eq}/cm^2: $V_{97\%}$ < 150 V**

IV and Power Dissipation



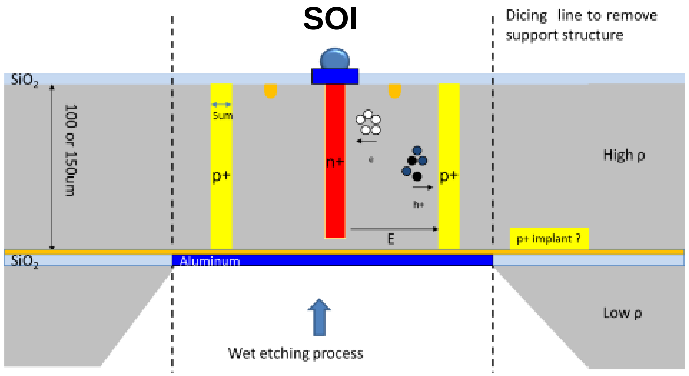


- From one pixel device only extractable for uniform irrad. (KIT)
  - At fixed V, 50x50 μm² has higher I_{leak}, but same at $V_{97\%}$
  - Power dissipation improves due to lower $V_{97\%}$
- For non-uniform PS irradiation PS, $V_{97\%}$ from test beam efficiency combined with n-irradiated 3D strip IV
- Low power dissipation
  - 8 (13) mW/cm² at 1.0e16 (1.4e16) n_{eq}/cm²
  - Considerably lower than for planar devices and IBL 3D gen.

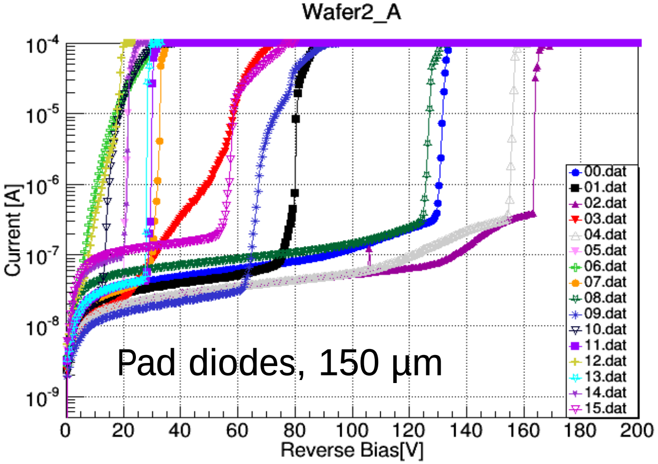


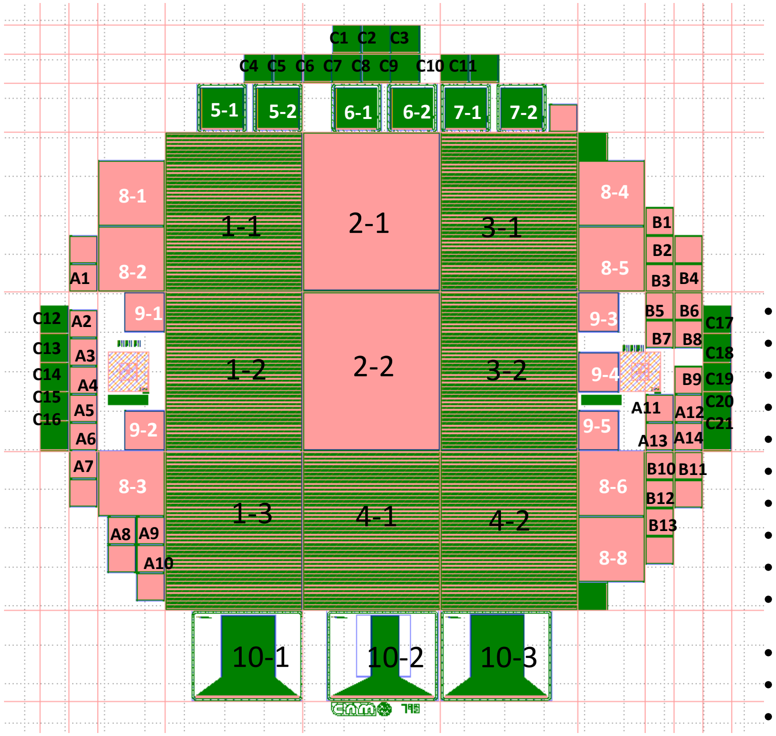
J. Lange et al., arXiv:1707.01045 (plus new data)

New CNM 3D Runs I: Thin small-pitch FEI4



- Thin 3D run with small-pitch FEI4 prototypes **just finished**
- 100 and 150 µm single-sided on SOI
- Probing on-going, various quality classes
- UBM+flip-chipping to be done in-house by CNM + IFAE

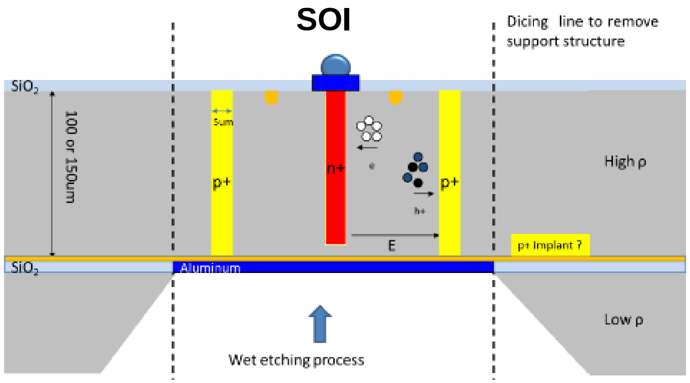




- 1-X FE-I4 standard (50x125um^2)
- 2-X FE-I4 50x50um^2
- 3-X FE-I4 50x50um^2 part of the pixel shorted
- 4-X FE-I4 25x50um^2 part of the pixel shorted
- 5-x Diodes 25x50um^2
- 6-x Diodes 50x50um^2
- 7-x Diodes 50x125um^2
- 8-x CMS PSI 50x50um^2
- 9-X Fermilab chip 30x50um^2
- 10-X strips 50x50, 25x50, 50x125um^2

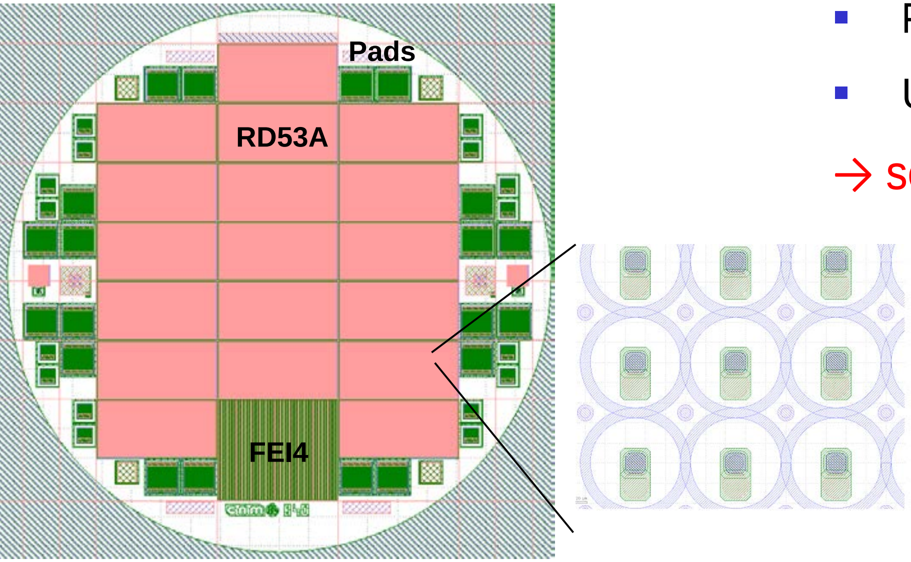
- A-X 50x50um^2, (64x64)
- B-X 25x50um^2, (64x64)
- C-X 50x50um^2, (64x64)

New CNM 3D Runs II: RD53A



- Runs with RD53A 3D pixel devices
  - Single-sided 72, 100+150 µm on SOI
  - Double-sided 200 µm
- Devices
  - 14 RD53A 50x50 µm² 1E
  - 4 RD53A 25x100 µm² (2x 1E, 2x 2E)
  - 1 FEI4 50x50 µm² 1E (equivalent to 7781 C)
  - Pad diodes of 50x50 µm² and 25x100 µm²
- Production on-going → expected for end of year
- UBM + flip-chip to be done in-house by CNM + IFAE

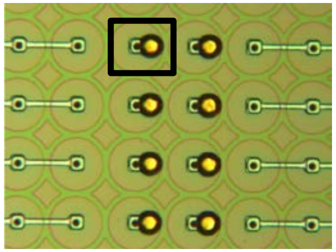
→ sensors expected on time for arrival of RD53A

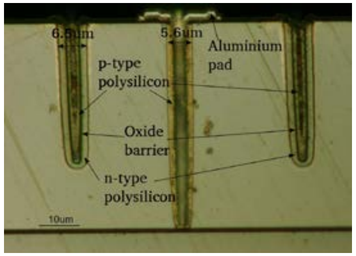


Conclusions and Outlook

- Studied 230 µm CNM 3D production with small pixel size up to **unprecedented fluences of 3e16 n_{eq}/cm^2** 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}/cm^2 → safe operation at ITk baseline fluence (1 replacement)
    - 97% efficiency reached at <150 V after 2.5e16 n_{eq}/cm^2
    - No indication that limit has been reached...

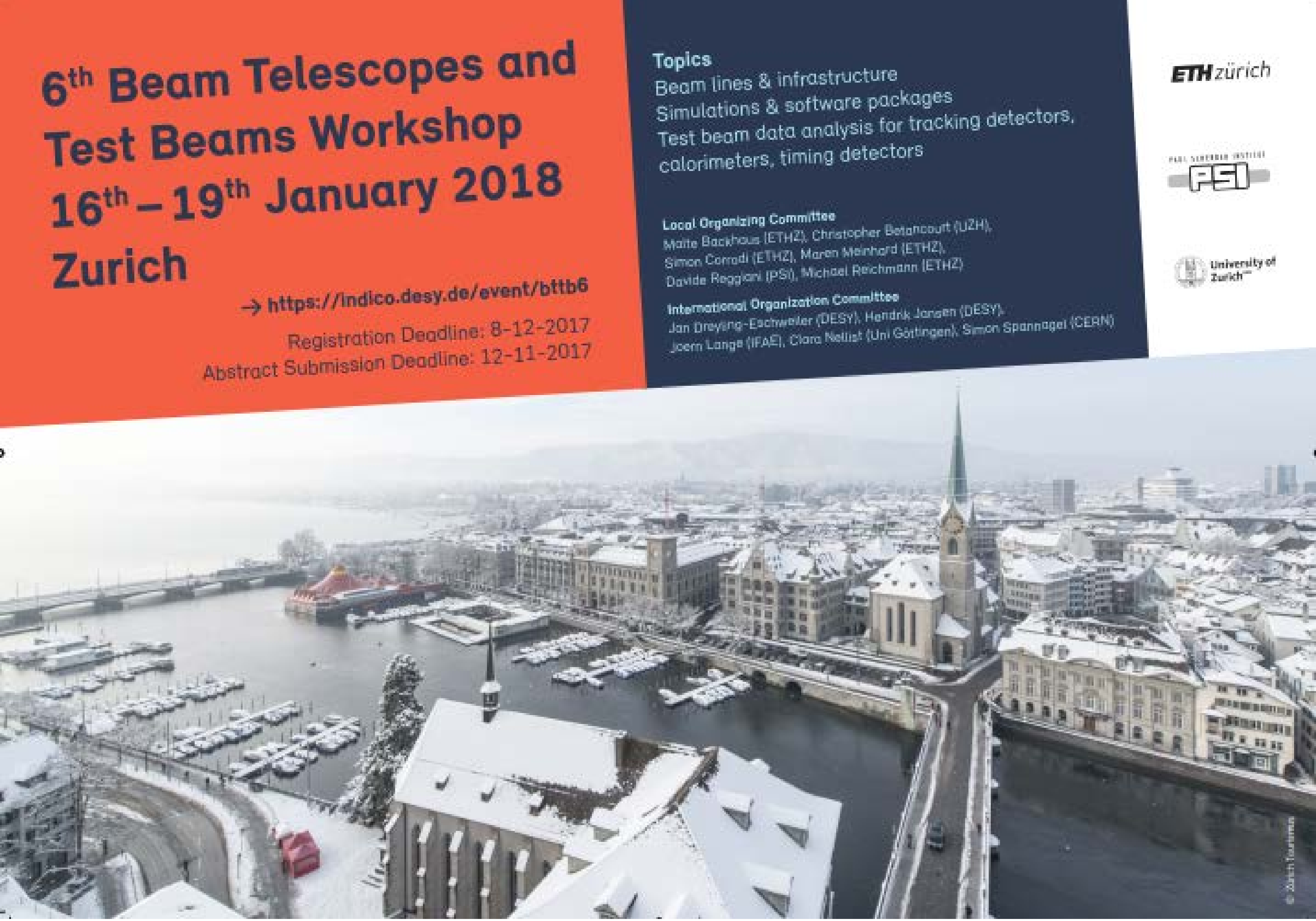
50x50 µm²





- 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



6th Beam Telescopes and Test Beams Workshop

16th – 19th January 2018

Zurich

→ https://indico.desy.de/event/bttb6

Registration Deadline: 8-12-2017

Abstract Submission Deadline: 12-11-2017

Topics

Beam lines & infrastructure

Simulations & software packages

Test beam data analysis for tracking detectors, calorimeters, timing detectors

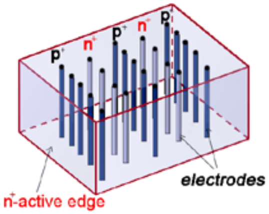
Local Organizing Committee

Malte Backhaus (ETHZ), Christopher Betancourt (UZH), Simon Corrodi (ETHZ), Maren Meinhard (ETHZ), Davide Reggiani (PSI), Michael Reichmann (ETHZ)

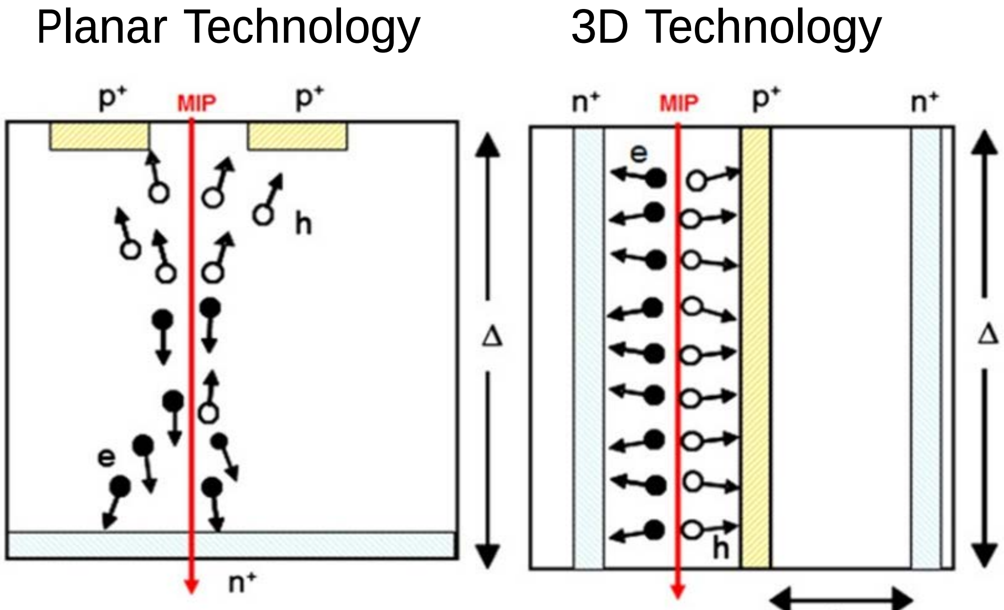
International Organization Committee

Jan Dreyling-Eschweiler (DESY), Hendrik Jansen (DESY), Joern Lange (IFAE), Clara Nellist (Uni Göttingen), Simon Spannagel (CERN)

BACKUP



3D Detector Principle



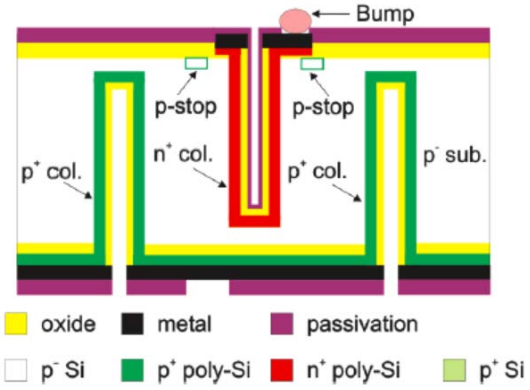
C. Da Via et al., NIM A 694 (2012) 321

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°

Different 3D Technologies

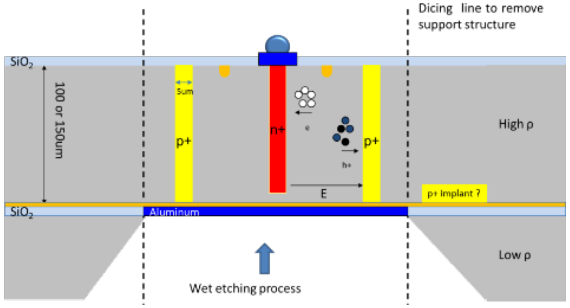
- Double sided (available at CNM)
  - IBL/AFP-proven technology
  - No handling wafers needed
    → thickness limited to ≥200 µm and wafers to 4”
  - 3D columns ~8 µm diameter



Double-sided

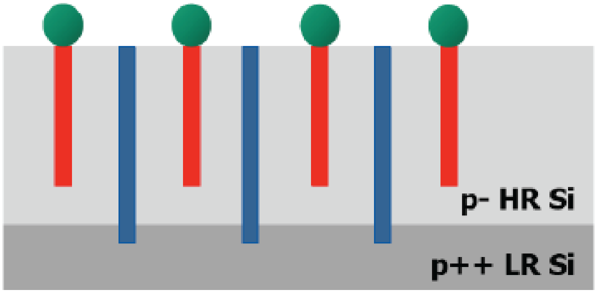
G. Pellegrini, CNM

- 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

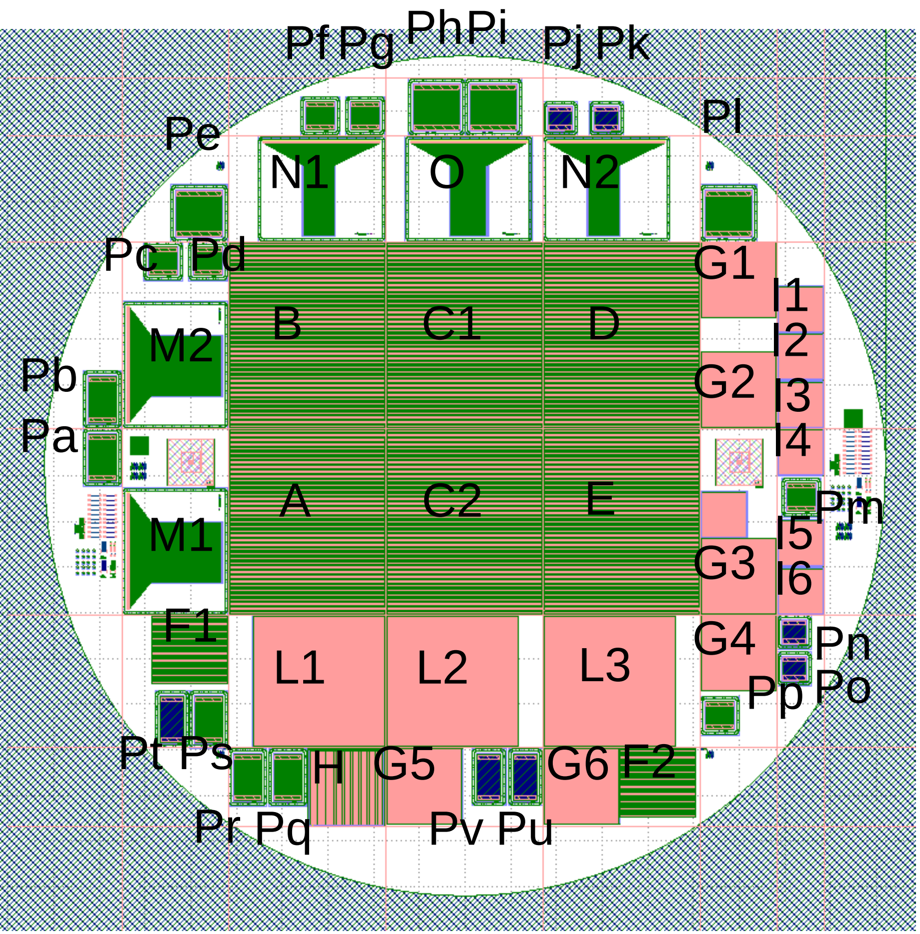
G. Pellegrini, CNM



Si-Si bonding

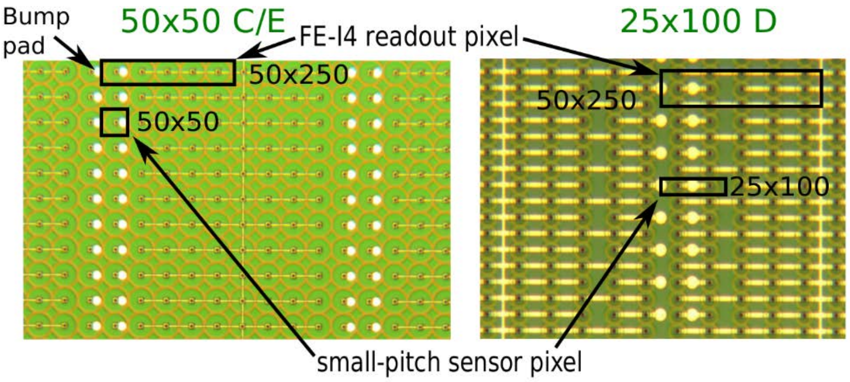
M. Boscardin, FBK

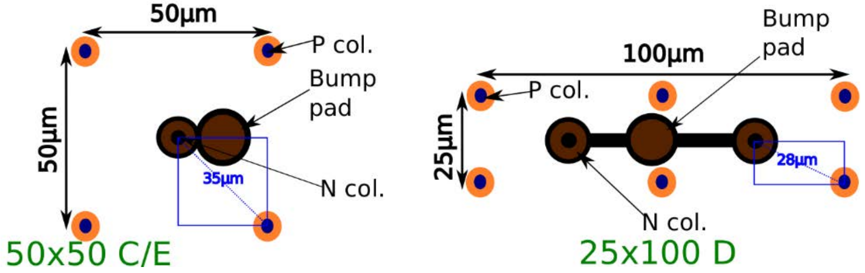
First Small-Pixel CNM Run for HL-LHC



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

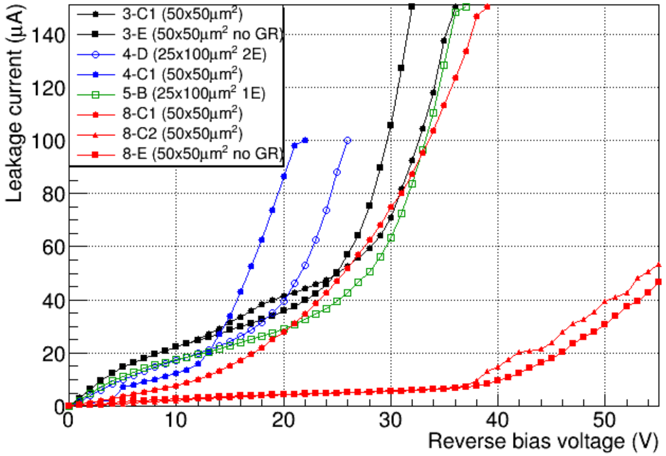
- Run 7781 finished in Dec 2015 (RD50 project)
- 5x 4” wafers, p-type, 230 µm double-sided, non-fully-passing-through columns (a la IBL)
- Increased aspect ratio 26:1 (column diameter 8 µm)
- **First time small pixel size 25x100 + 50x50 µm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and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





Sample Characterisations

Pixel IV

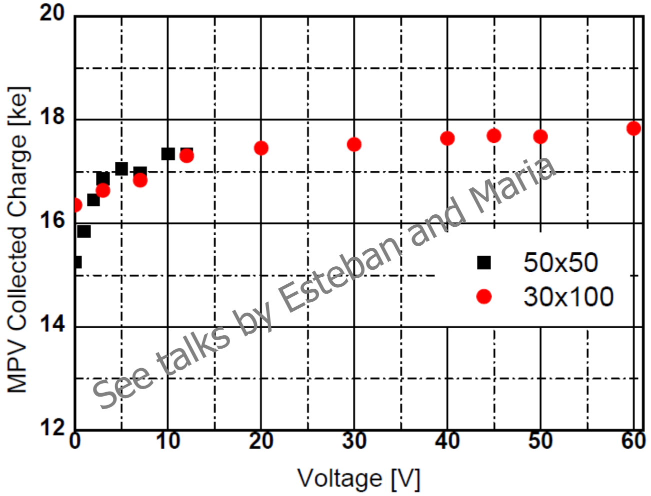


Pixel Geom.	C/el. [fF] (*)	C/pixel [fF] (*)	Noise [e]
25x100 2E	42	84	160
50x50 1E	37	37	105-140

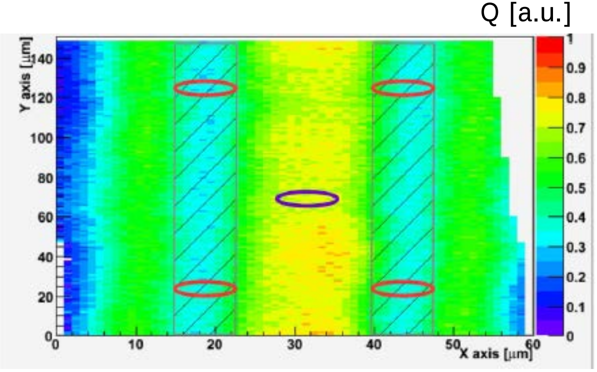
(*) from pad diodes

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

Strips charge collection (unirr.)



Strips laser scan
25x100 μm^2, 1e16, 150 V



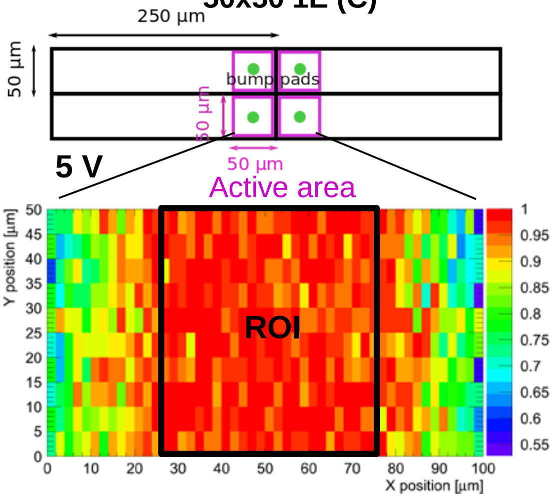
L. Simon

- 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 μm^2 and 30x100 μm^2 (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

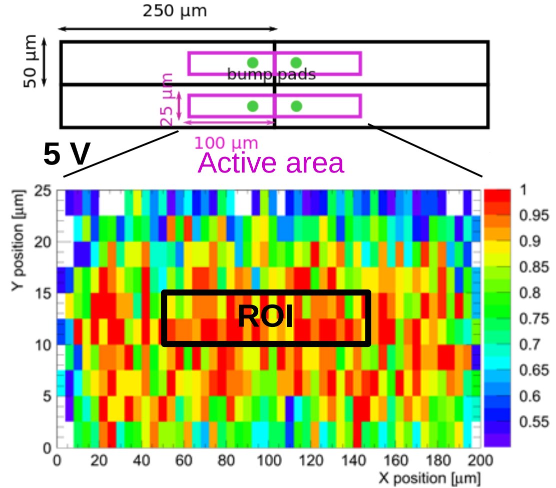
Efficiency before Irradiation

In-Pixel Efficiency (0° tilt)

50x50 1E (C)

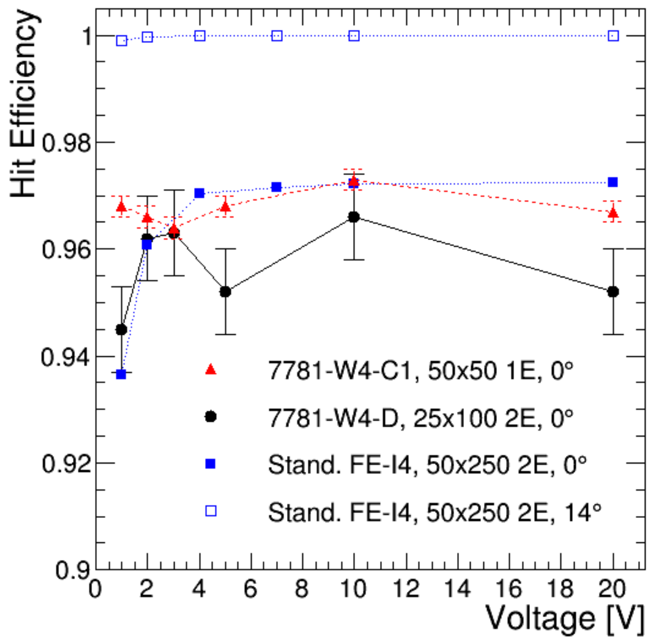


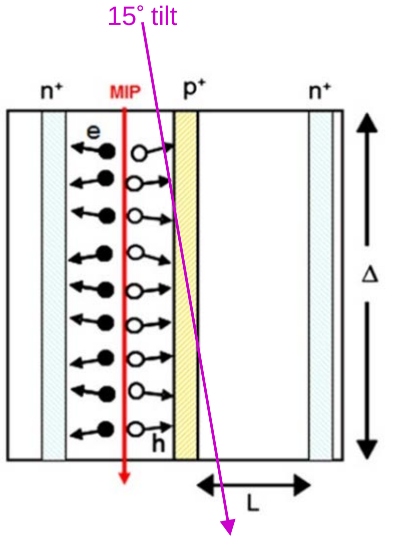
25x100 2E (D)



- 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

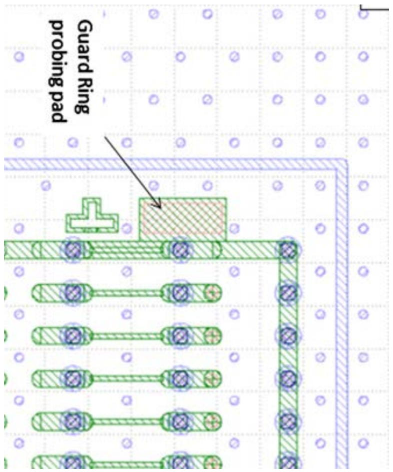




State of the Art: IBL/AFP Generation

- 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