Beam test measurements of irradiated 3D pixel sensors with 50x50 μm² pixel size

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  - Non irradiated sensors
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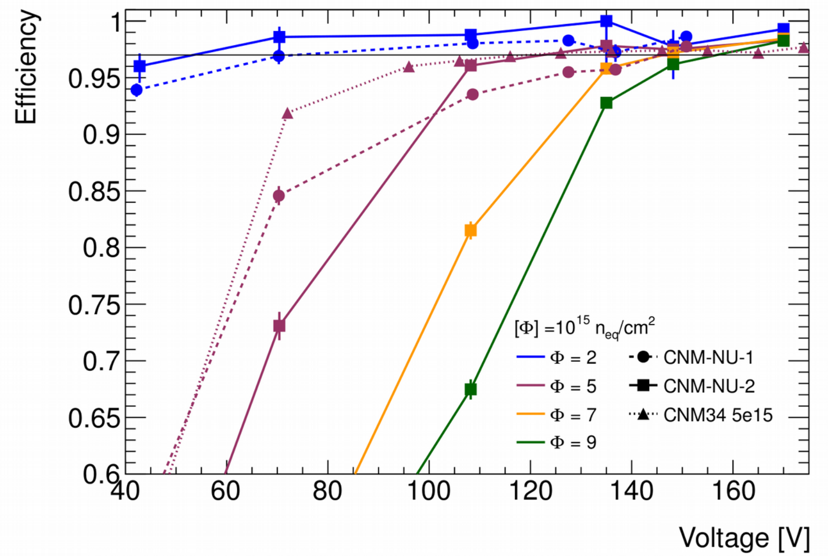
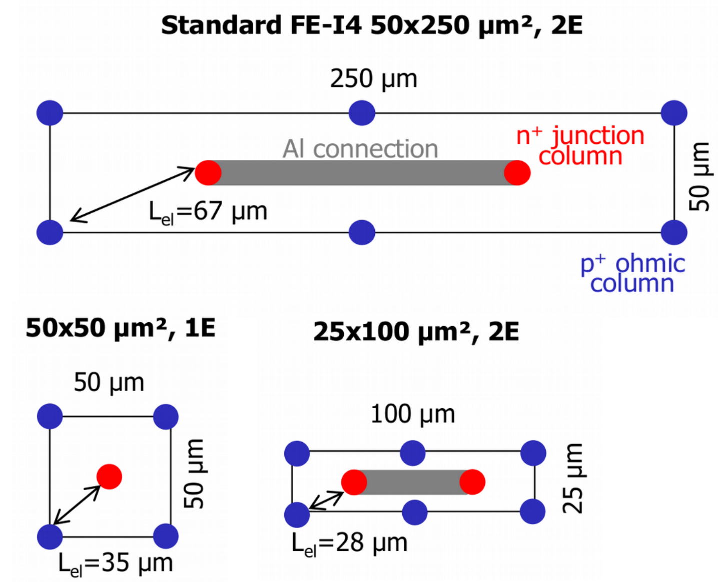
- Summary

3D pixel sensors

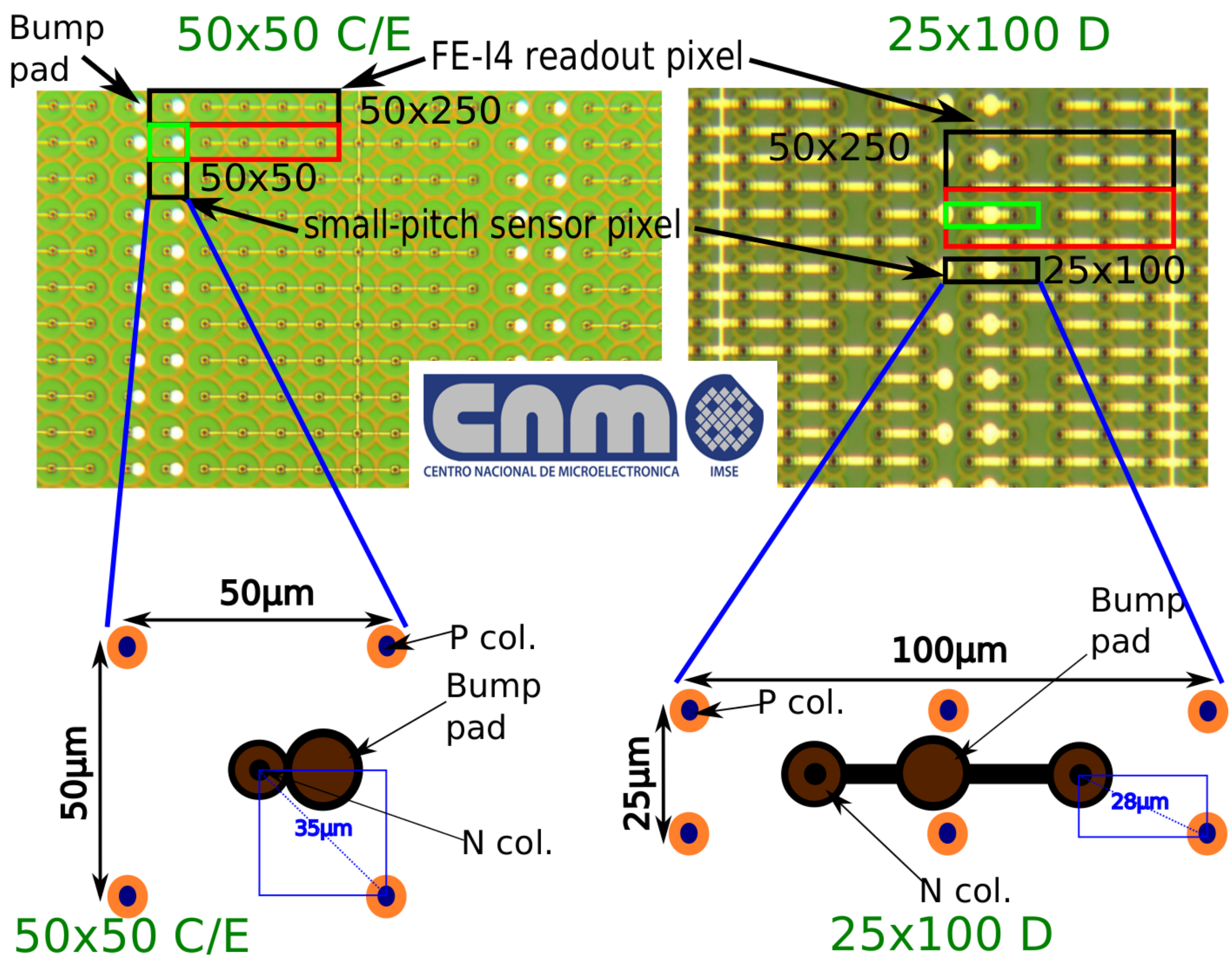
- 3D pixel sensors (using FEI4 chip) installed in current innermost layer (IBL) of ATLAS detector and in the ATLAS Forward Proton Detector (AFP)
  - Array of 336x80 pixels
  - Pixel size 50x250 µm² (inter-electrode distance L_{el} = 67 µm)
  - Radiation hardness of IBL-type devices proven at least up to 9e15 n_{eq}/cm^2 (J. Lange et al., 2016 JINST 11 C11024)
- Upgrade for high luminosity LHC
  - 3D pixel sensors good candidate for innermost layers
  - Need smaller pixel size to cope with higher occupancy and increased radiation levels (up to 2e16 n_{eq}/cm^2)
  - Proposed pixel sizes 50x50 and 25x100 µm² (L_{el} = 35 and 28 µm)





First small-pitch run at CNM

- CNM RD50 Run7781: p-type, 230 µm thick, 8 µm 3D columns diameter, double-sided technology (G. Gómez’s talk)
- **RD53A** chip being developed for small pixel sensors
  - Chip has 50x50 µm² pixel size
  - Compatible with sensors with 50x50 and 25x100 µm² pixel size
  - Expected for mid 2017
- **FEI4** chip used to test first production of small pixel sensors
  - Similar productions between FBK and CNM (H. Oide’s talk)
  - 50x50 and 25x100 µm² sensors need a **special structure** to use the FEI4 chip
  - One small size pixel (sensor pixel) connected to each FEI4 pixel (readout pixel)
    - The rest are connected to ground
    - **80% insensitive area** to take into account

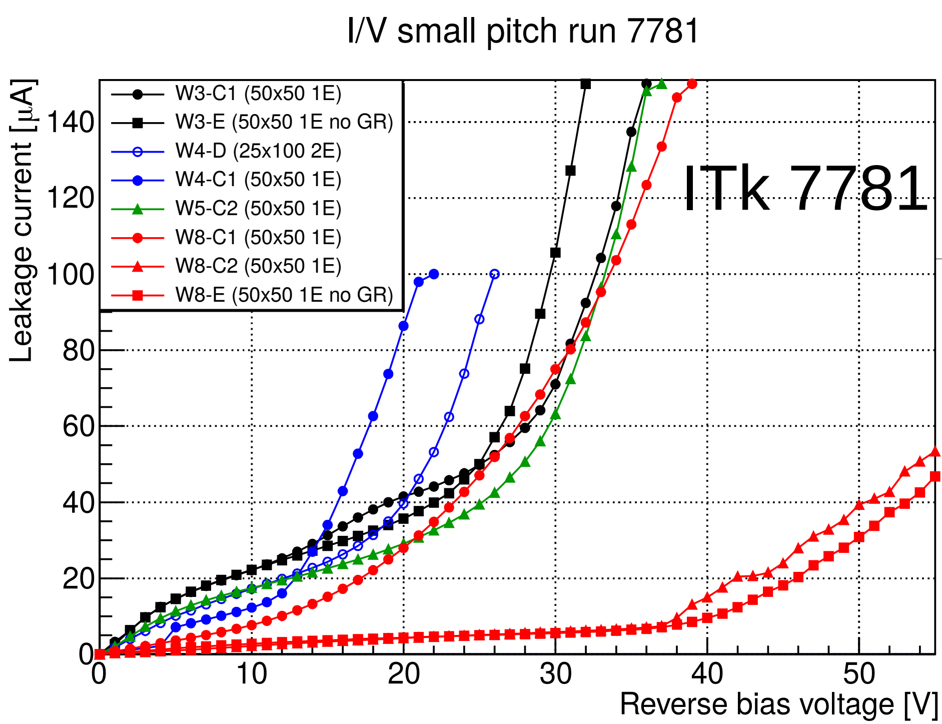


L_{el} = 35 µm

L_{el} = 28 µm

Lab measurement before irradiation

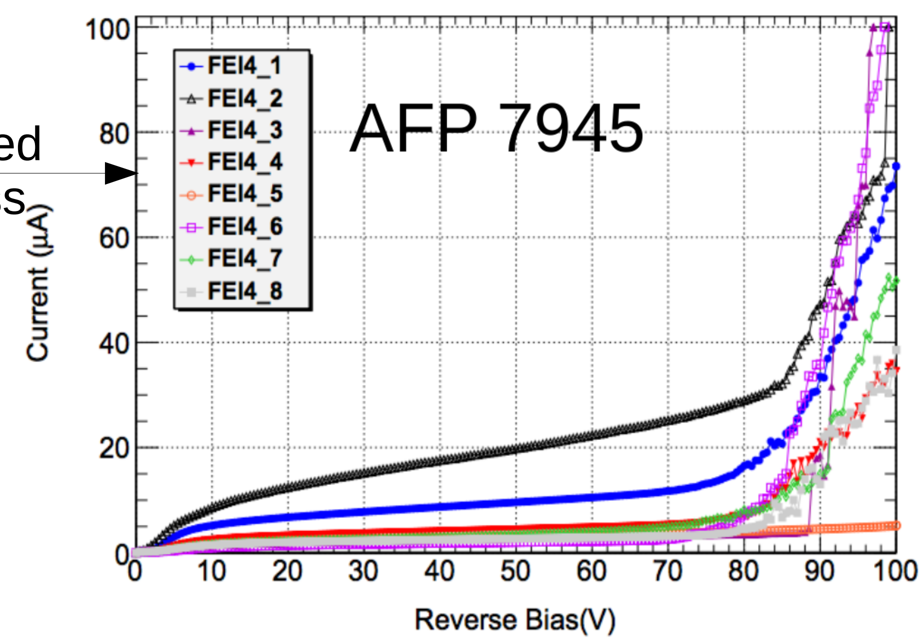
D. Vázquez Furelos et al., 2017 JINST 12 C01026



Improved process

Vbd

S. Grinstein et al., 2017 JINST 12 C01086

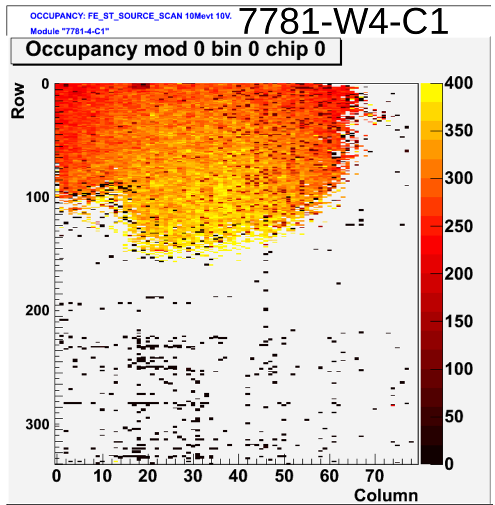


- 8 devices successfully flip-chipped and tested at IFAE
- Breakdown voltage ~ 15-40V
  - Expected improvements after optimized process in next productions
    - AFP production 7945: V_{bd} > 80 V

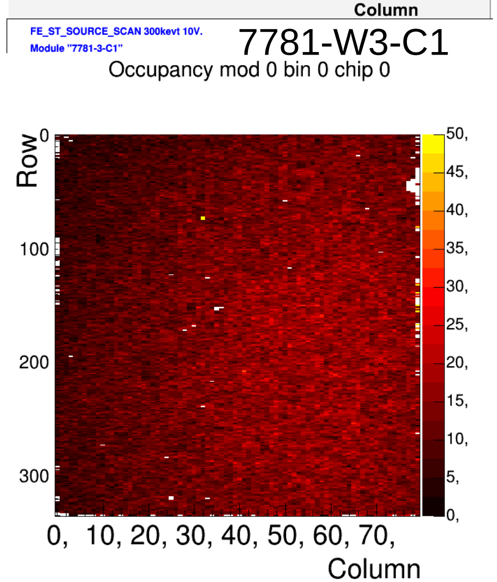
Charge collection

- UBM done at CNM
- Sensors from a first batch have big disconnected areas due to not optimized UBM

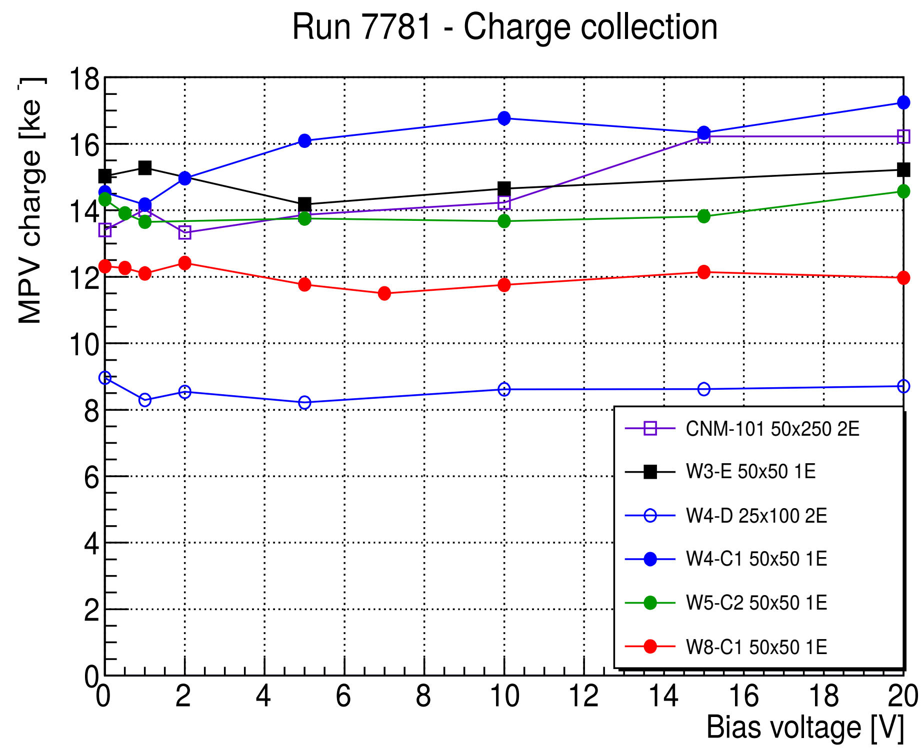
^{90}Sr occupancy



- Second batch with better UBM → almost no disconnected areas



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

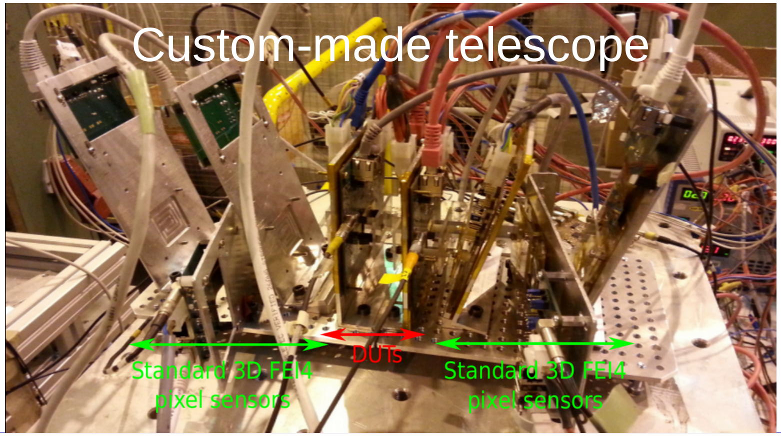


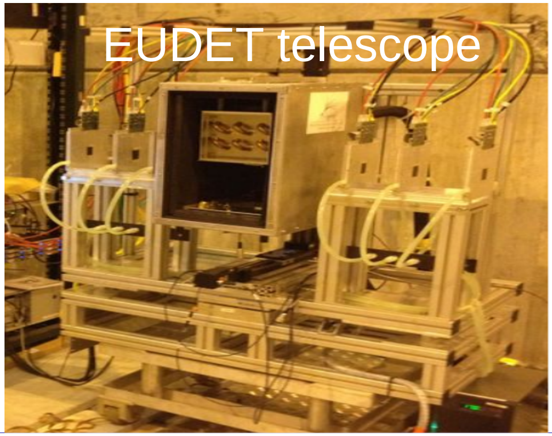
- Even on sensors with bad UBM, the collected charge can be measured
- Similar results between small pitch and IBL-generation sensors

Summary of Beam Tests

- Beam Tests with small pitch sensors (in CERN SPS)

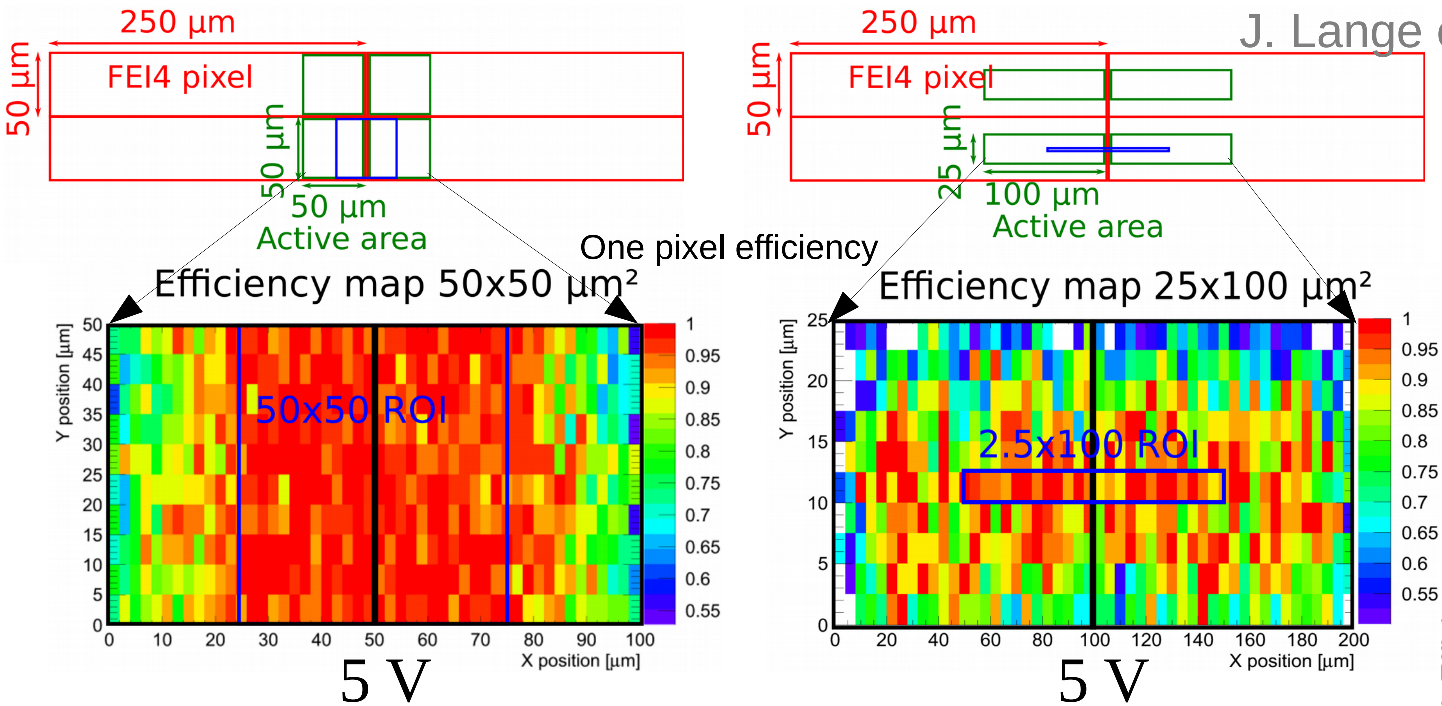
Beam Test period	Telescope	Reconstruction framework	Sensor geometry (μm^2)	Irradiation (n_{eq}/cm^2)
May 2016	Custom-made 3D FEI4	Judith	50x50 + 25x100	Not irradiated
Nov 2016	EUDET	EUTelescope + TBmon2	50x50 + 50x50	5e15 (uniformly 23 MeV p^+ - KIT)
Sept 2016	EUDET	EUTelescope + TBmon2	50x50	1.4e16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



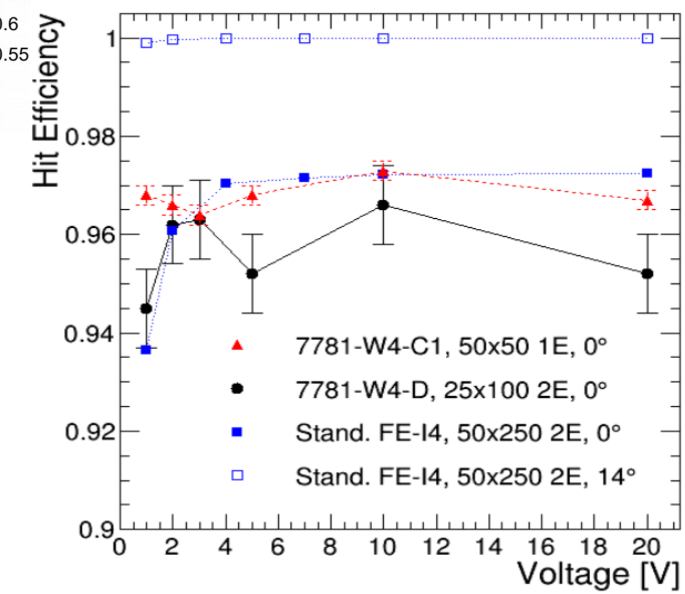


Beam Test before irradiation

J. Lange et al., 2016 JINST 11 C11024



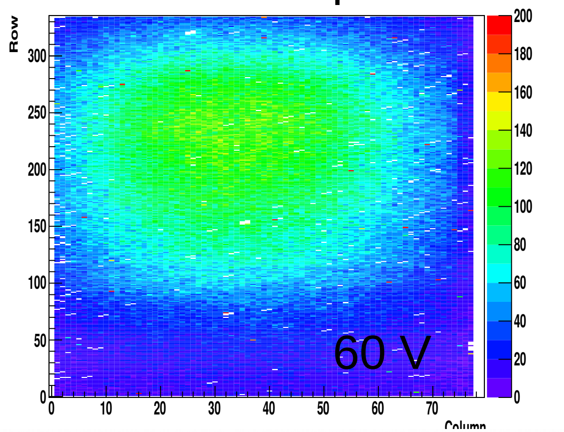
- Beam Test during May
- Custom made 3D FEI4 telescope
- Measured three 50x50 µm² and one 25x100 µm²

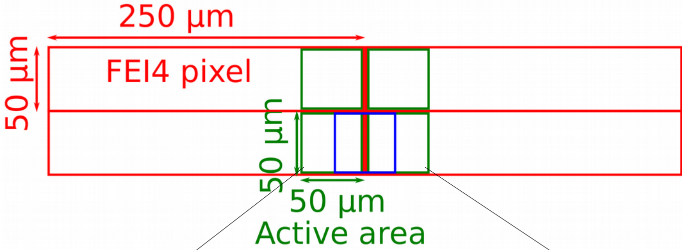


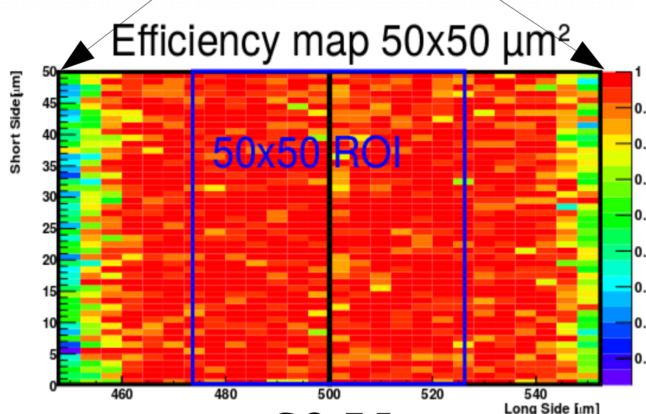
- Selected region of interest inside the active area of the pixels
  - Avoid the charge sharing to inactive pixels and telescope resolution effects
- Already **96-97% efficiency at 1-2 V** with 1.5ke threshold
  - Similar efficiency to standard 3D FEI4 which needs 4-5V to reach the plateau
- Tilt (14º) can improve the efficiency up to 99.9% as already demonstrated in standard FEI4 → still under study for small pitch

Beam Test after uniform irradiation 5e15 n_{eq}/cm^2

Hit Map

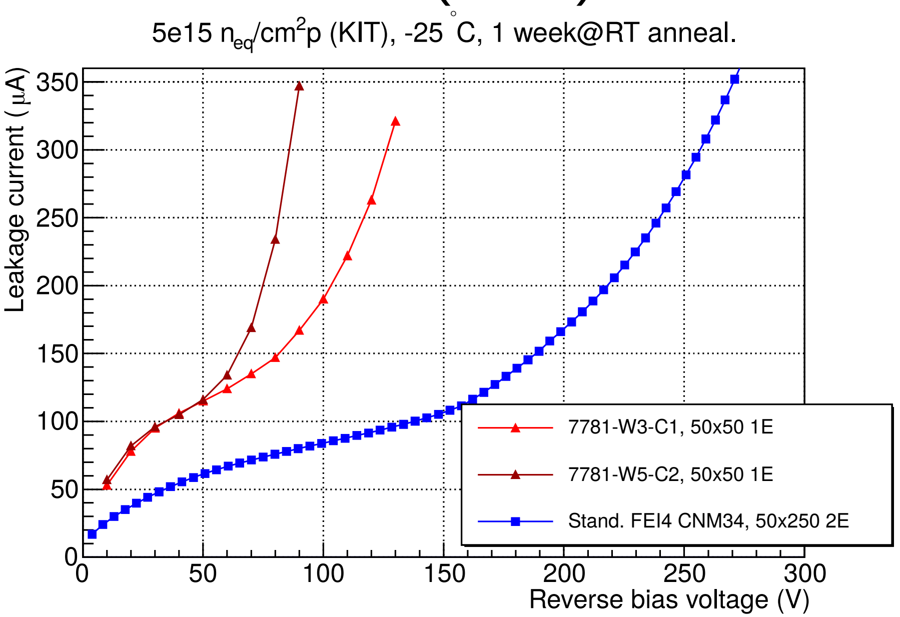




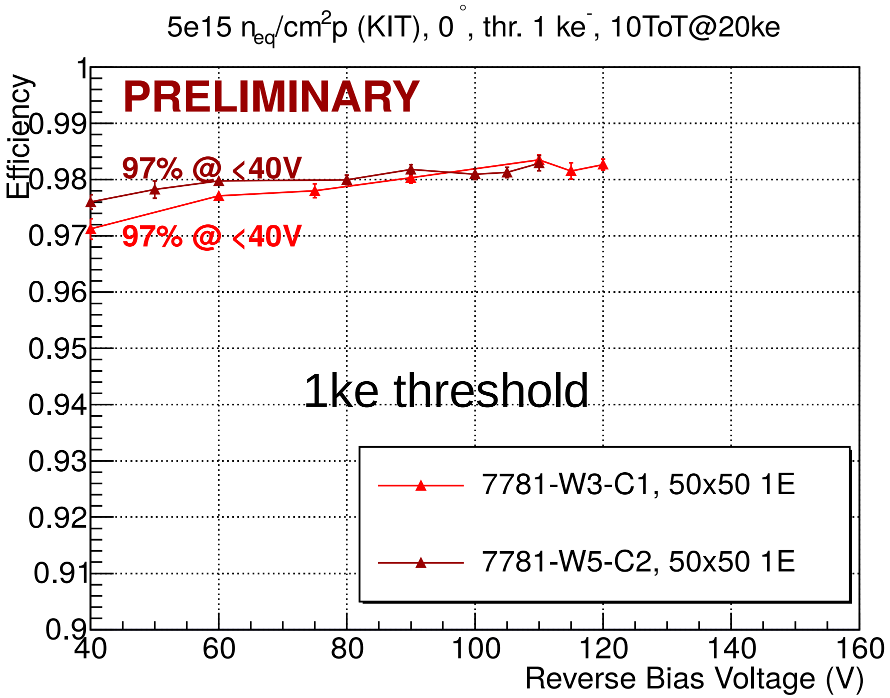


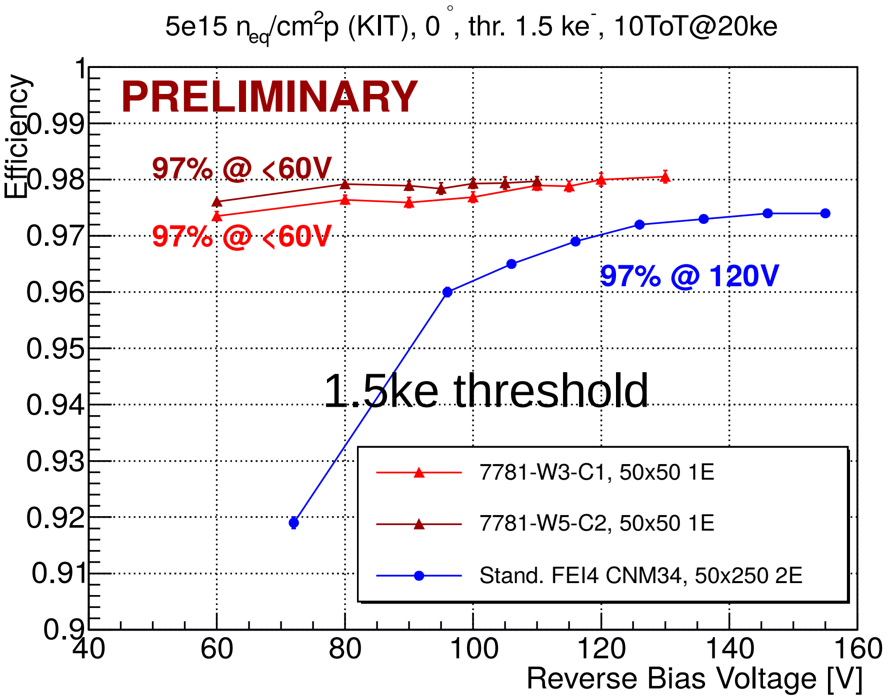
60 V

- Beam Test during Nov 2016
- EUDET telescope
- Two small pitch 50x50 µm² sensors (good UBM) **irradiated uniformly** to **5e15 n_{eq}/cm^2**
  - IBL radiation hardness benchmark
- Higher leakage current for small pitch than standard IBL sensors (but...)



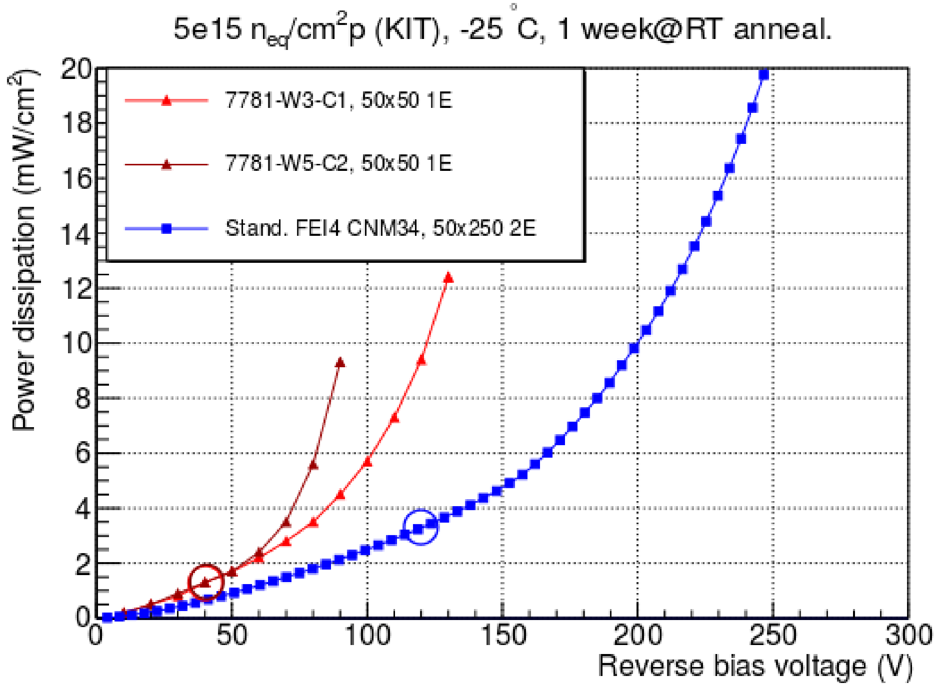
Efficiency (uniform irradiation 5e15 n_{eq}/cm^2)





- Devices tunned to 1ke and 1.5ke thresholds (10ToT@20ke) at -40 ºC and -50 ºC (temperature on chip between -20 ºC and -35 ºC)
- **Efficiency over 97% at 40 V with 1ke threshold**
- Similar efficiencies at 1ke and 1.5ke threshold within 0.5%
- Perpendicular incidence (expected improvement for 14º tilt)

Power dissipation (uniform irradiation 5e15 n_{eq}/cm^2)

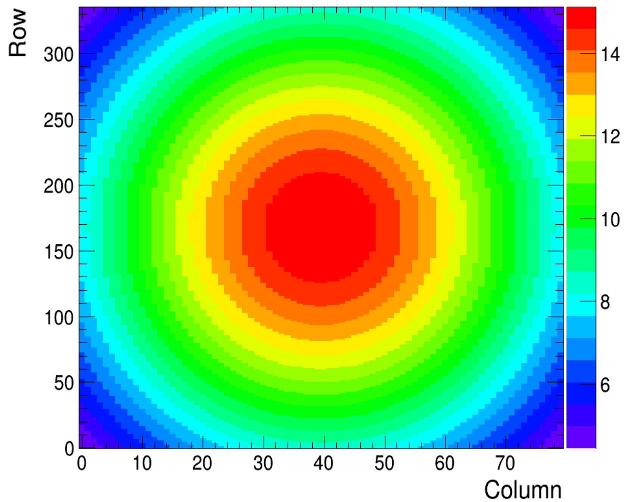


- At 40 V operation voltage, power dissipation improves compared to IBL-type devices
- Reduction in electrode distance achieves lower power dissipation even with poorer IV curve

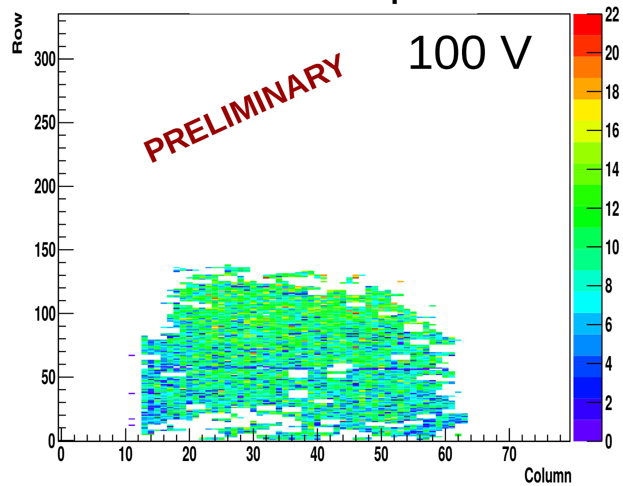
Small pitch power dissipation 1.5 mW/cm^2 at 5e15 n_{eq}/cm^2

Beam Test after non uniform irradiation ($1.4e16\ n_{eq}/cm^2$)

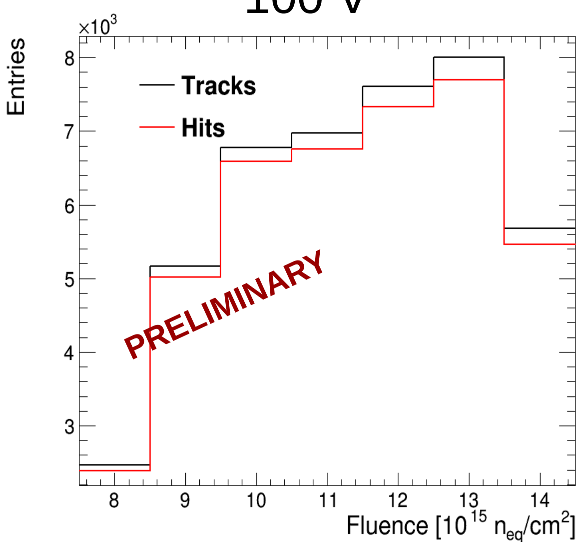
Fluence profile

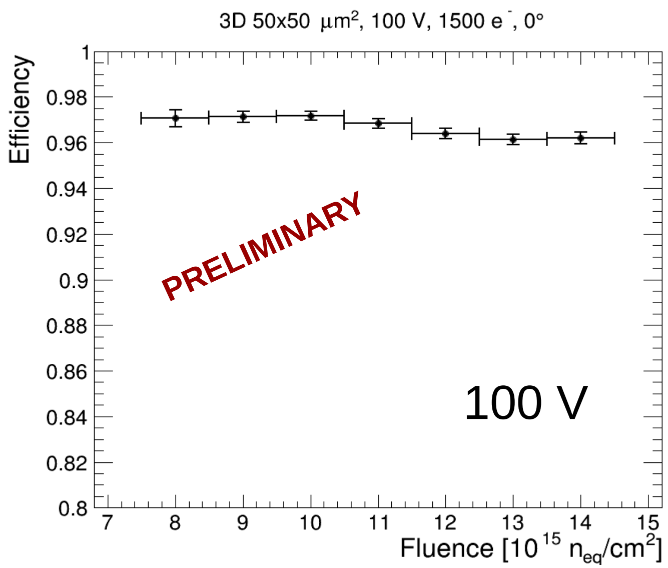


Hit Map



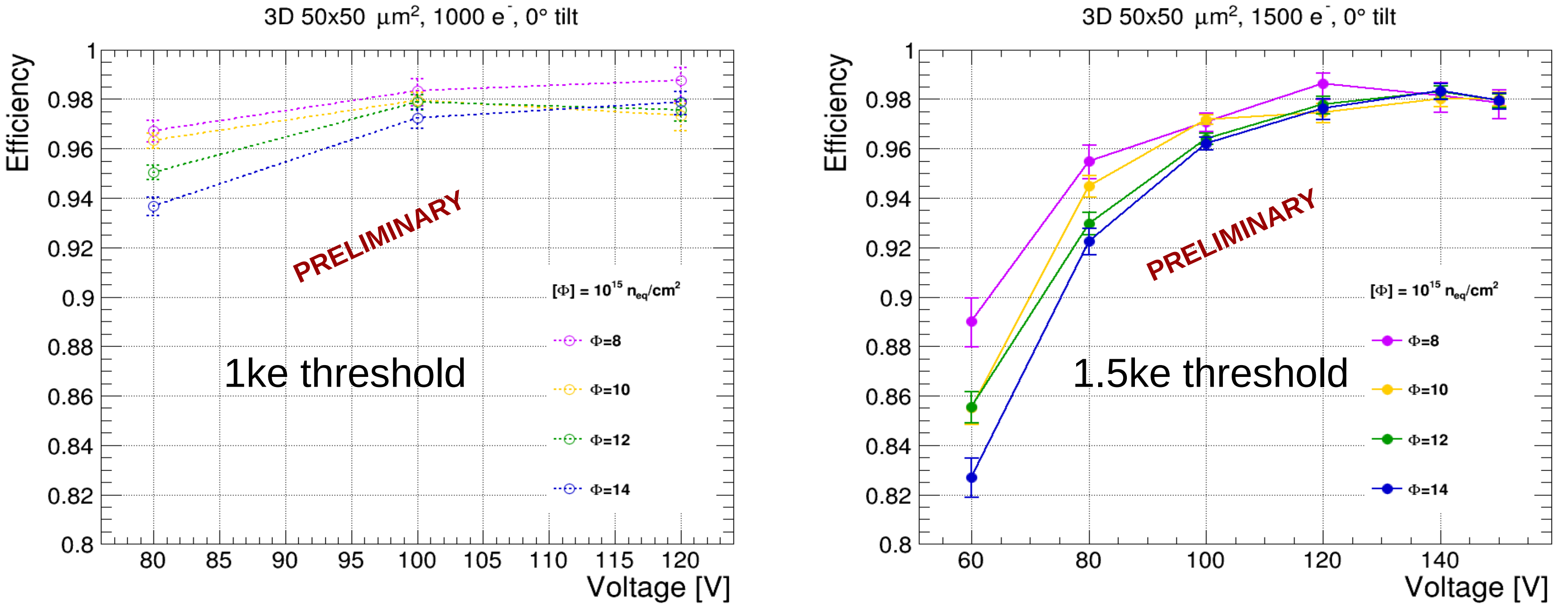
100 V





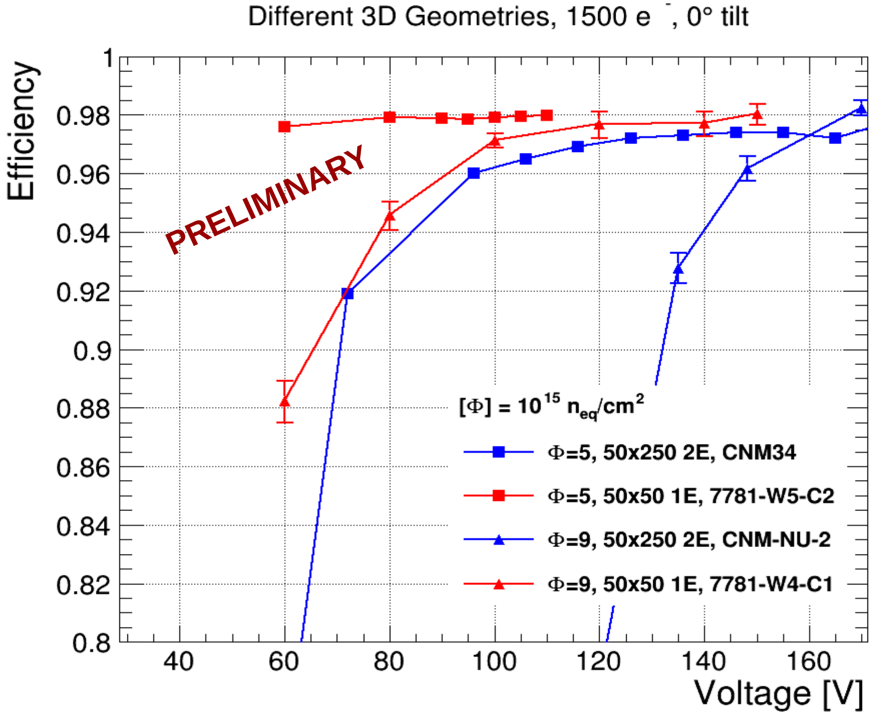
- Beam Test during Sept 2016
- EUDET telescope
- One small pitch 50x50 µm² sensors (bad UBM) **irradiated non-uniformly** up to **$1.4e16\ n_{eq}/cm^2$**
  - Can study the efficiency for different fluences
  - Due to the non-uniform irradiation, the power dissipation cannot be precisely obtained
- Fluence normalization based on monitoring Al foils
- Fluence range 0.8 to $1.4e16\ n_{eq}/cm^2$ in the active area of the sensor
- For each fluence the efficiency can be extracted combining the fluence profile with the active area of the sensor

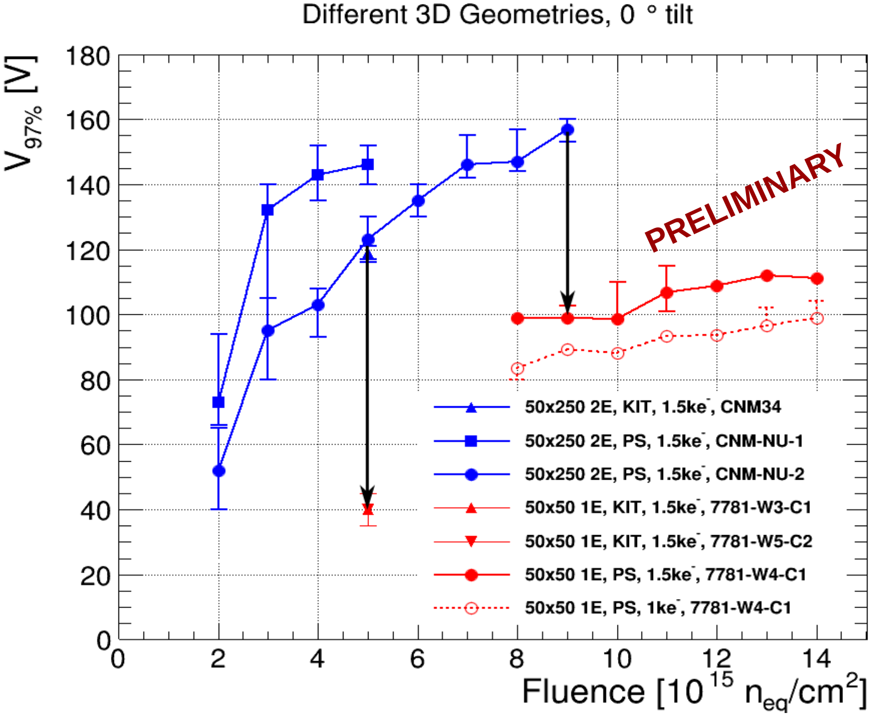
Efficiency
(non uniform irradiation 1.4e16 n_{eq}/cm^2)



- First estimation of the **operation voltage:** <=**100 V** for **1ke threshold** for all the fluences from **0.8 to 1.4e16** $\mathbf{n_{eq}/cm^2}$
  - Similar operation voltage for 1.5ke threshold (100-120 V)

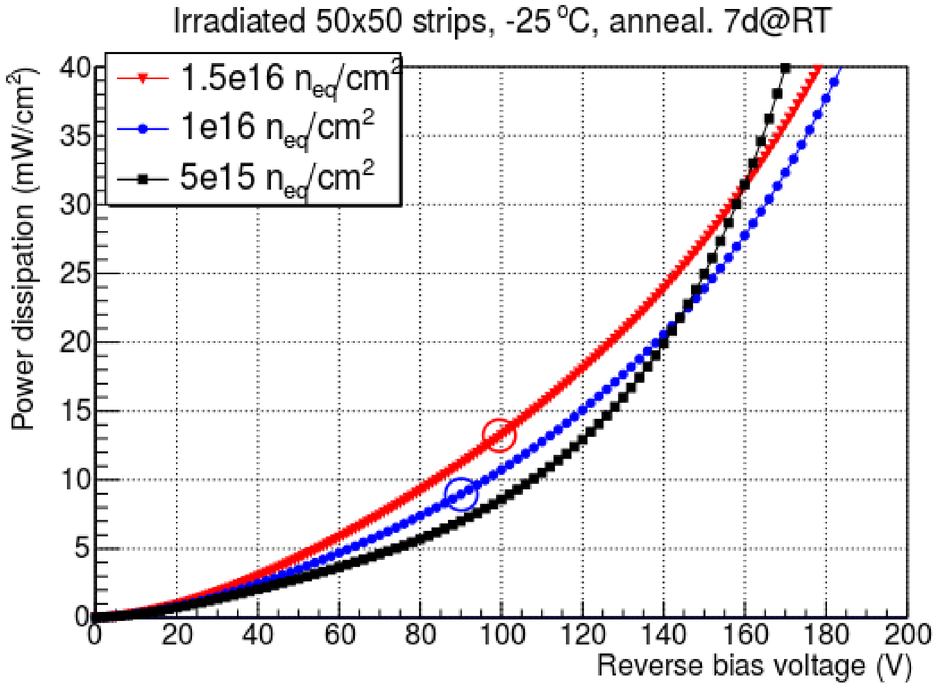
Summary: small-pitch vs IBL-type

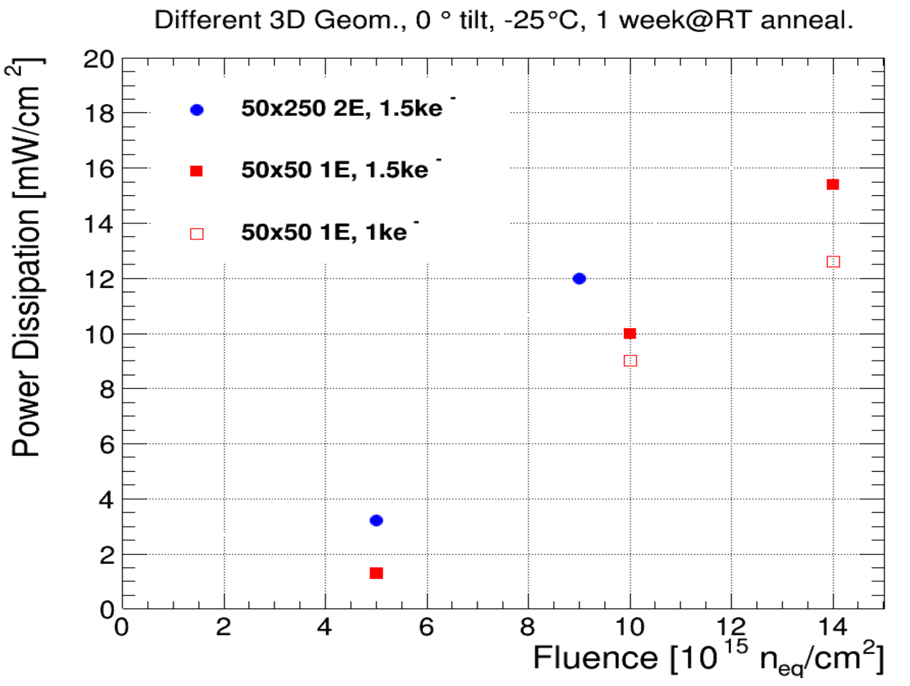




- **Improved operation voltage at 5e15 n_{eq}/cm^2 from 120 V to 40 V**
- **At 9e15 n_{eq}/cm^2 the voltage needed for 97% efficiency is 100 V compared with IBL-type 160 V**

Power dissipation (non uniform irradiation 1.4e16 n_{eq}/cm^2)





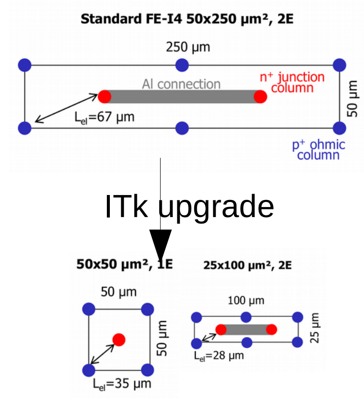
- Power dissipation cannot be directly measured on the pixel sensor due to the non uniform irradiation
- Estimate the power dissipation from strips irradiated to 1 and 1.5e16 n_{eq}/cm^2 using operation voltage calculated on Beam Tests

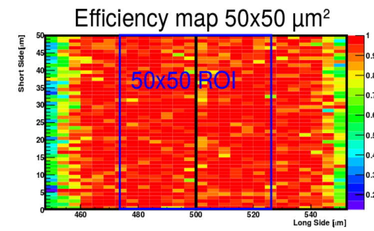
Small pitch power dissipation 9 mW/cm² at 1e16 n_{eq}/cm^2 ($V_{97\%}$ = 90 V)

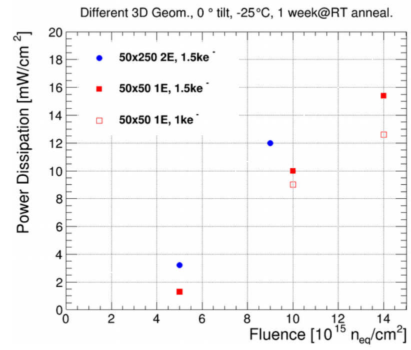
Small pitch power dissipation 13 mW/cm² at 1.4e16 n_{eq}/cm^2 ($V_{97\%}$ = 100 V)

Summary

- First 3D production of small pixel structures
  - Need to use FEI4 chip due to RD53 chip unavailability
- Efficiency of **non irradiated small pitch** sensors ~**96-97% at 1-2 V**
  - Comparable with IBL-type which needs 4-5 V
  - Expected higher efficiency with tilted sensors (14º)
- Small pitch sensors **operation voltage** of **40 V** after irradiation of **5e15 n_{eq}/cm²**
  - Much lower than IBL generation irradiated to the same fluence (IBL 120 V at 1.5k threshold)
  - **Power dissipation 1.5 mW/cm²**
- Small pitch sensors irradiated non uniformly up to 1.4e16 n_{eq}/cm²
  - **Operation voltage** for **1.4e16 n_{eq}/cm²** of **100 V**
  - Comparison at **fluence** of **9e15 n_{eq}/cm²** give **operation voltage of 100 V** vs IBL-type 160 V
  - **Estimated power dissipation from strips 13 mW/cm²**
- Measurements done at perpendicular incidence with 230 µm thick sensors
  - Incoming productions with thinner devices





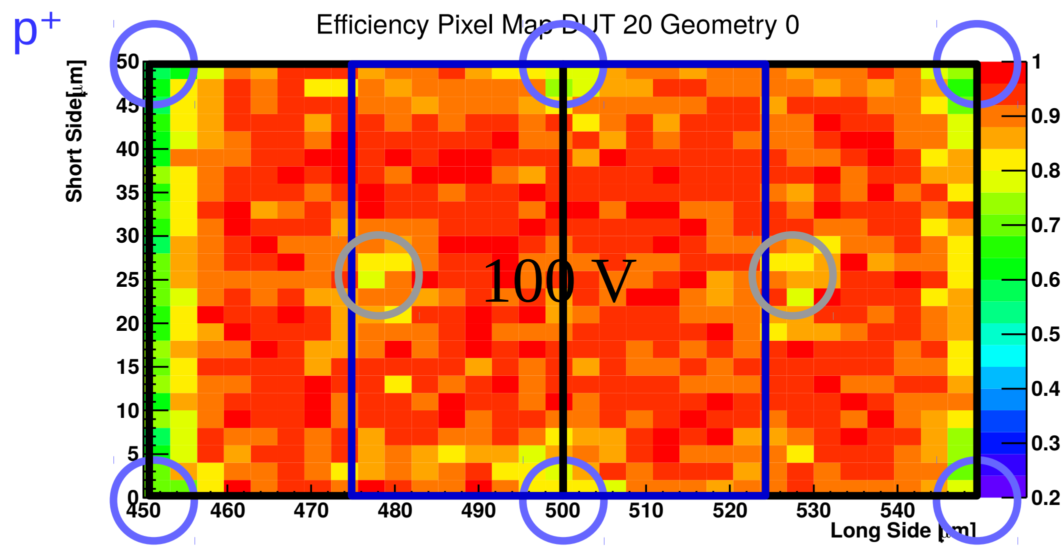


Thanks for your attention

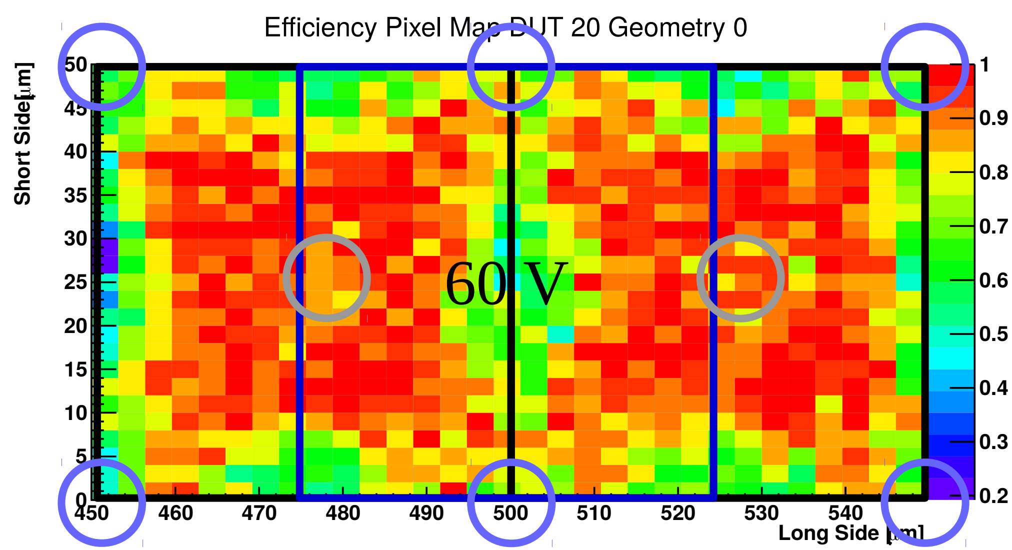
Backup

Non uniform irradiated in-pixel maps

- Map for 100 V (all the fluences included)
- p^{+} & n^{+} columns visible

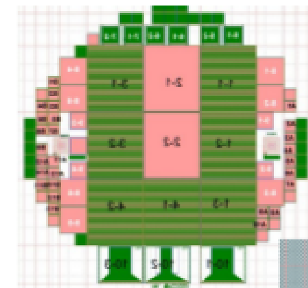


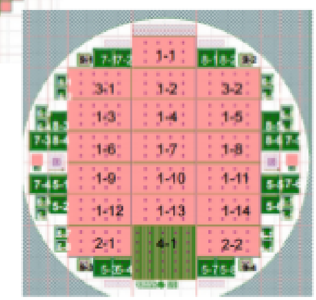
- Map for 60 V (all the fluences included)
- p^{+} & n^{+} columns visible
- Low field regions visible

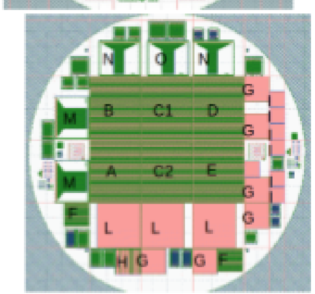


Next productions

- Run **9052**
  - Single sided on thin SOI wafers
  - “Small pitch” sensors, compatible with FEI4 chips
- Runs **9761**
  - Single sided on thin SOI wafers
  - RD53 sensors (50x50, 25x100 and 1 FEI4)
- Run 9194
  - Double sided, 200 μm thick, same mask as 7781 (1st small pitch)
  - Improved production process

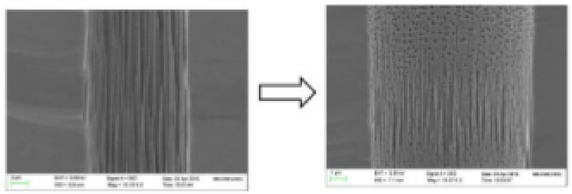


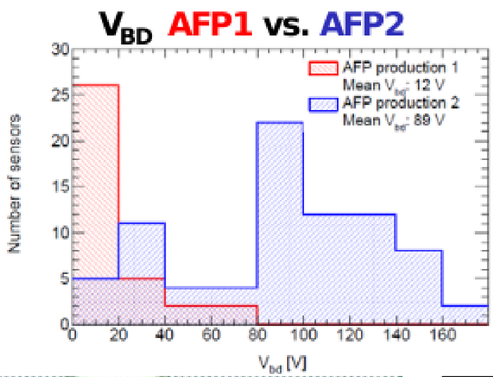


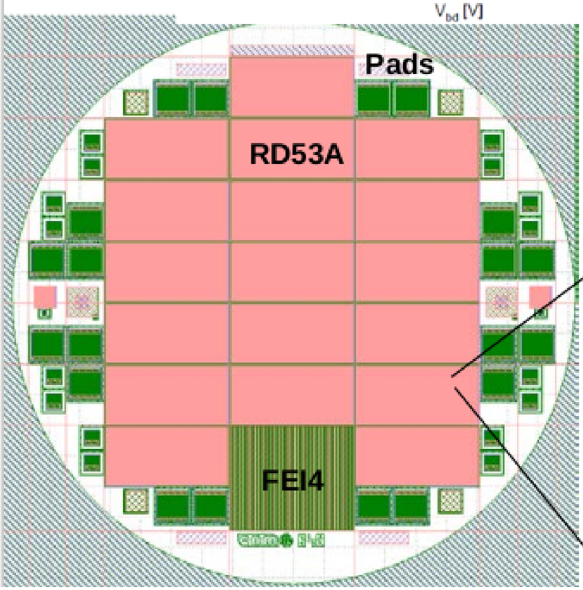


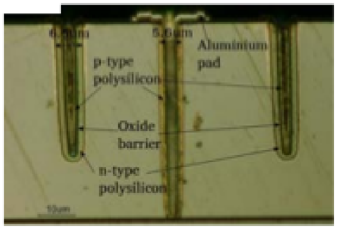
Next productions

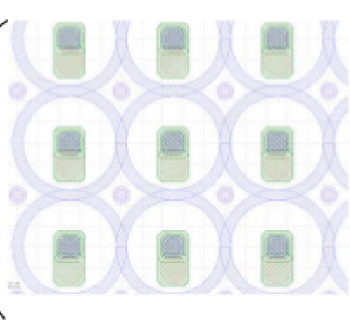
IBL/AFP1/7781 AFP2/CT-PPS











- CNM largely improved 3D process
  - Better DRIE process reduced side wall defects, also edge protection → **huge yield improvement** in AFP2 run (85%)
    S. Grinstein et al., arXiv:1611.01005
- New run as copy of 7781 with improved process
  - Production on-going → expected for February 2017
- Thin 3D runs with 7781 mask (100-150 µm on SOI)
  - Production on-going → expected for February 2017
- Runs with RD53A pixel devices
  - Single-sided 72, 100+150 µm: expected for mid 2017
  - Double-sided 200 µm planned later (AIDA2020)
  - 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
- Investigating collaboration with Glasgow
  - Could transfer part of DRIE processing to Glasgow to increase production capabilities for 3m² scenario

Temperatures in Beam test