Analysis of 3D pixel sensors test beam data

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on behalf of the ATLAS and CMS Tracker Groups

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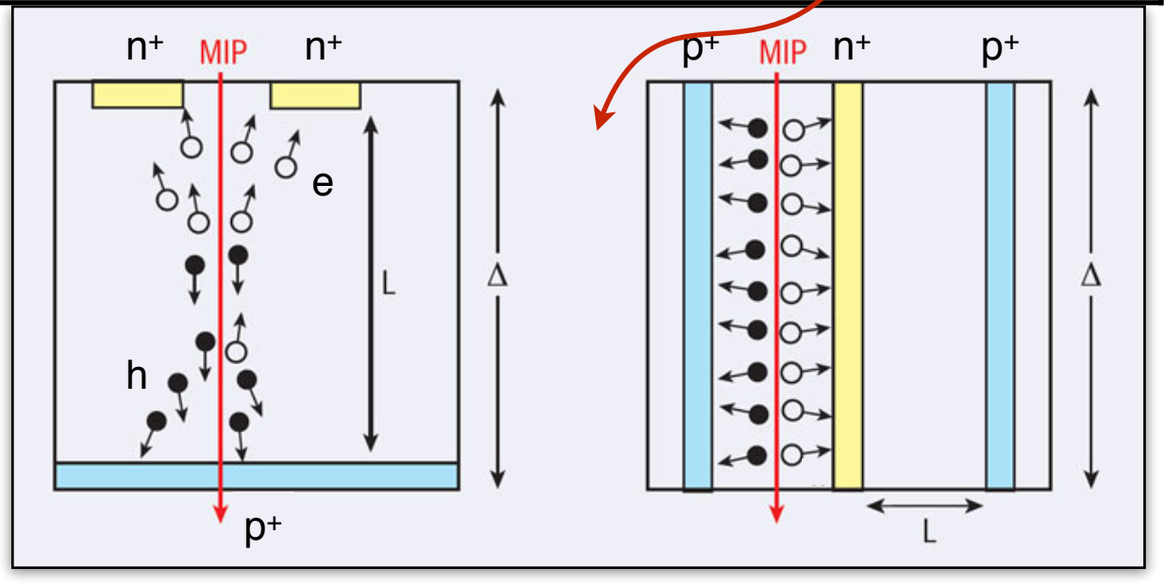
Design implications for the sensors of the pixel detector

HL-LHC operation conditions	Sensor design contraints
Luminosity $7.5 \times 10^{34}/(cm^2 s)$ Up to **200 events/25 ns** bunch crossing	Maintain occupancy at ‰ level and increase spatial resolution ➜ pixel cell size ~ 25x100 μm^2 or 50x50 μm^2
Fluence **~2.3x10^{16} n_{eq}/cm^2** for first pixel layer at 3000 fb^{-1} (~10 years) ➜ carriers lifetime ~0.3 ns, **mean free path ~30 µm** for electrons at saturation velocity	Reduce electrodes distance (**L**) to increase electric field and the signal ➜ thin planar or 3D columnar technologies

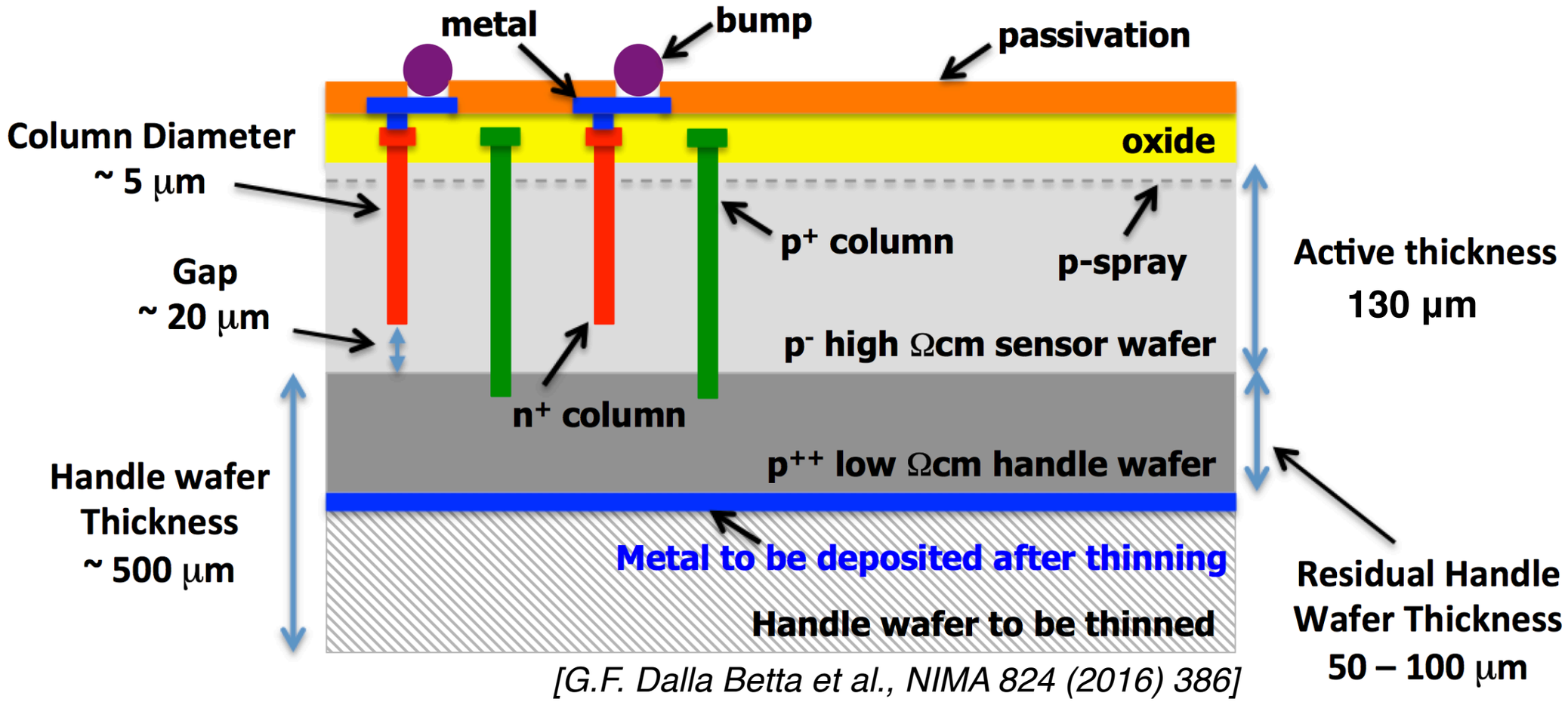
Joint ATLAS-CMS INFN collaboration, partnership with Fondazione Bruno Kessler-**FBK** (Trento, Italy), for the development of **thin planar** and **3D columnar n-in-p** sensors on **6" FZ wafers** with **Direct Wafer Bond**(1)



[C. Da Vià et al, NIMA (2012)]

(1) IceMos Technology, Belfast

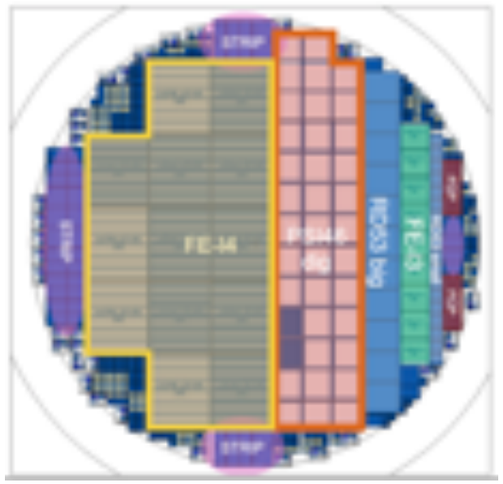
3D pixel @ FBK

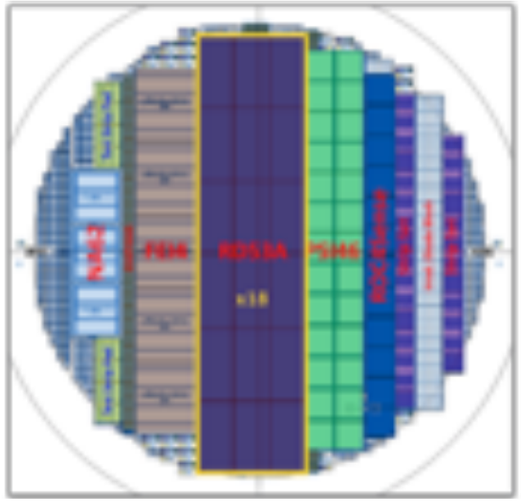


[G.F. Dalla Betta et al., NIMA 824 (2016) 386]

- 3D single sided process, optimised by FBK
- Ohmic columns/trenches depth > active layer depth (for bias)
- Junction columns depth < active layer depth (for higher Vbreakdown)
- Reduction of columns diameter to ~5 μm
- Holes (at least partially) filled with poly-Si
  - Two wafers, high and low resistivity, bonded together

FBK 3D productions



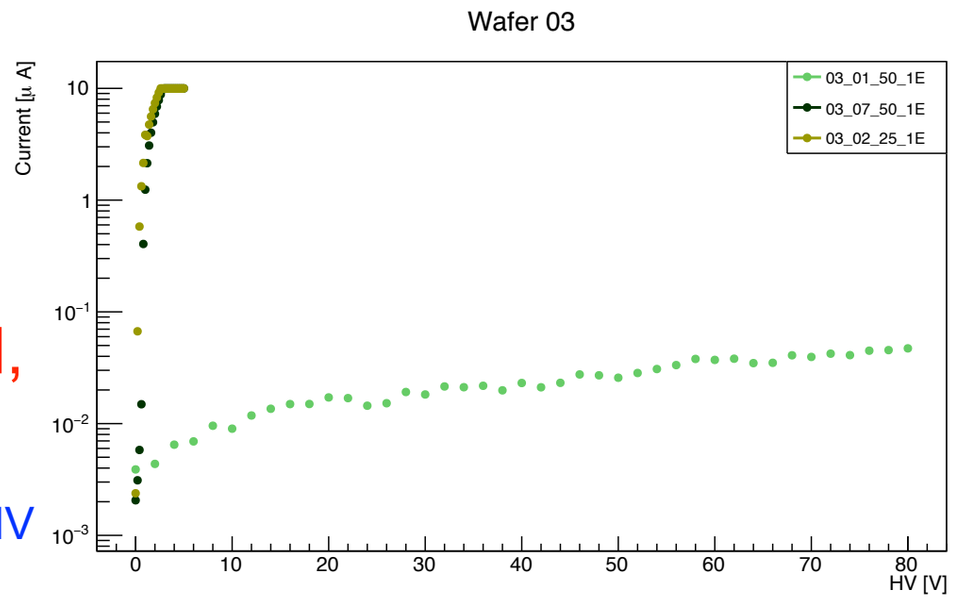


Shared between ATLAS and CMS

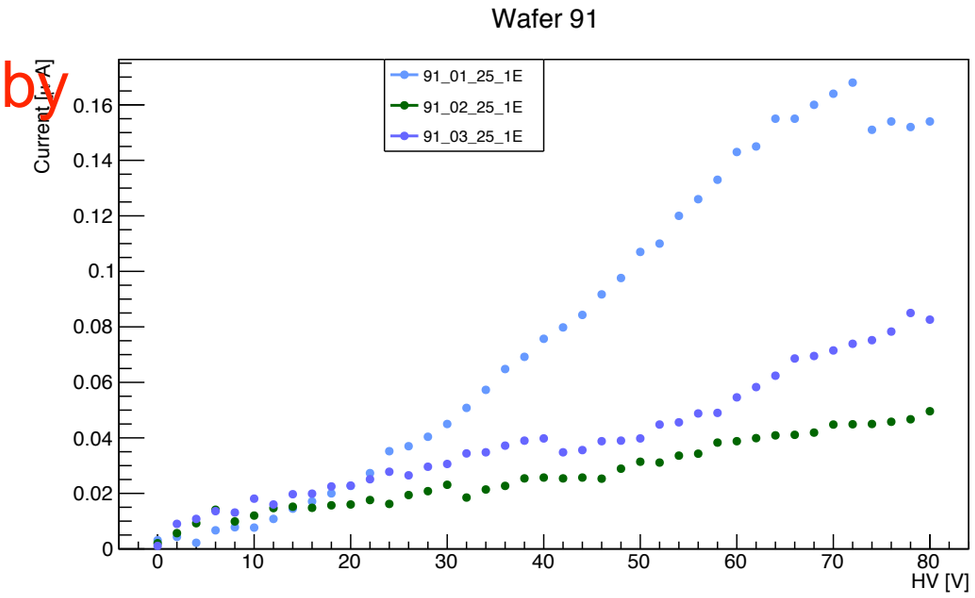
- 1st production batch (2015—2016) for Pixel TDR
  - For ATLAS: 13 FEI4s per wafer:
  - Test-beam performance evaluation up to 1e16 neq/cm2 irradiation
  - Active thickness: 130 μm
- 2nd production batch (2017—): post-TDR
  - Active thickness: 130 μm
  - 18× RD53a single: 50×50(1E) and 25×100(1E,2E)
    - 2 shipped to Leonardo (ATLAS), 3 to IZM (CMS)
    - 2× Non-irrad test-beam (FEI4-Leonardo/RD53a-IZM)
    - 1× irradiated test-beam (R53a-IZM)
- 3rd production batch (Coming up in 2019)
  - Active thickness: 150 μm
  - New stepper for improved lithography precision
  - Layout: 47 RD53a sensors / wafer

2nd batch RD53a @ IZM: Laboratory measurement

- Received 6 modules in Genova from wafers 03 and 91
  - 2 out of 6 sensors have breakdown voltage significantly decreased wrt wafer measurement
- Modules assembled in Genova on SCC Bonn card, unexpected problems in operation
  - 4 out of 6 modules have been found in LV short after bonding – no HV applied
  - The other 2 of 6 modules have functioned for a while but then developed a LV short after some tests.

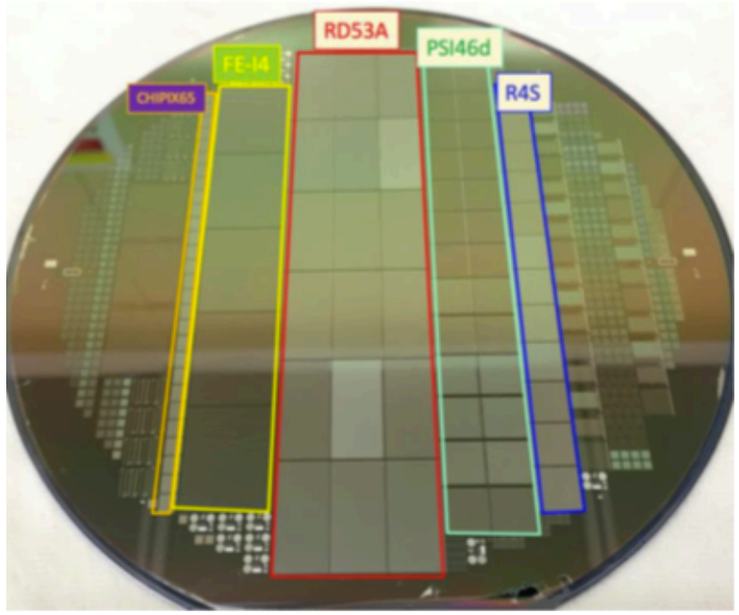


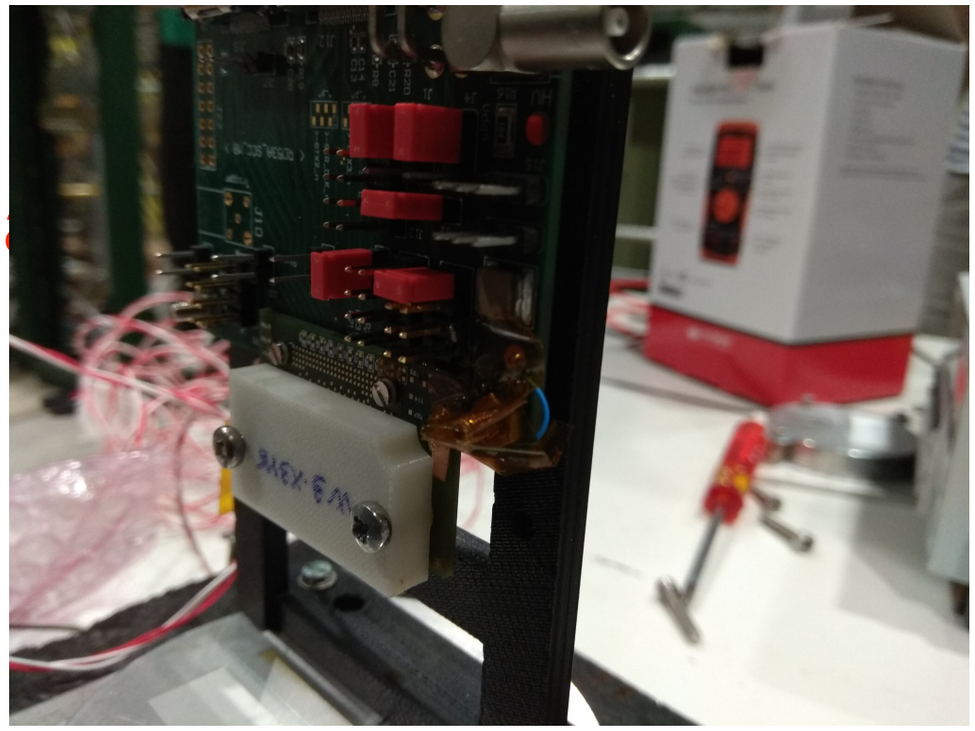
- Turned out to be most probably shorts generated by the wire bonding:
  - Few bare RD53a recently assembled with thin wedge tool
    - chips works fine
  - Rebonding of the six 3D modules on-going
    - at least one found working fine, so chips were not really dead. More to be hopefully fixed!



3D pixel sensors

- 25x100 um^2 and 50x50 um^2
  - 130 um FZ active Thickness, 6” DWB wafers, resistivity > 3 kOhm cm, on a 500 um CZ low resistivity handle wafer
    - Wafer thinned down to a total of 200 um thickness and bonded to a RD53A chip
    - Modules mounted on both Bonn and Rice cards
  - Also a 2E sensor has been analyzed, but did not survive the test beam …
- Performance measured before and after irradiation
  - Both at CERN and FNAL test beam facilities
  - Not 100% sure on the irradiation dose
    - very near 1E16 n_{eq}/cm^2

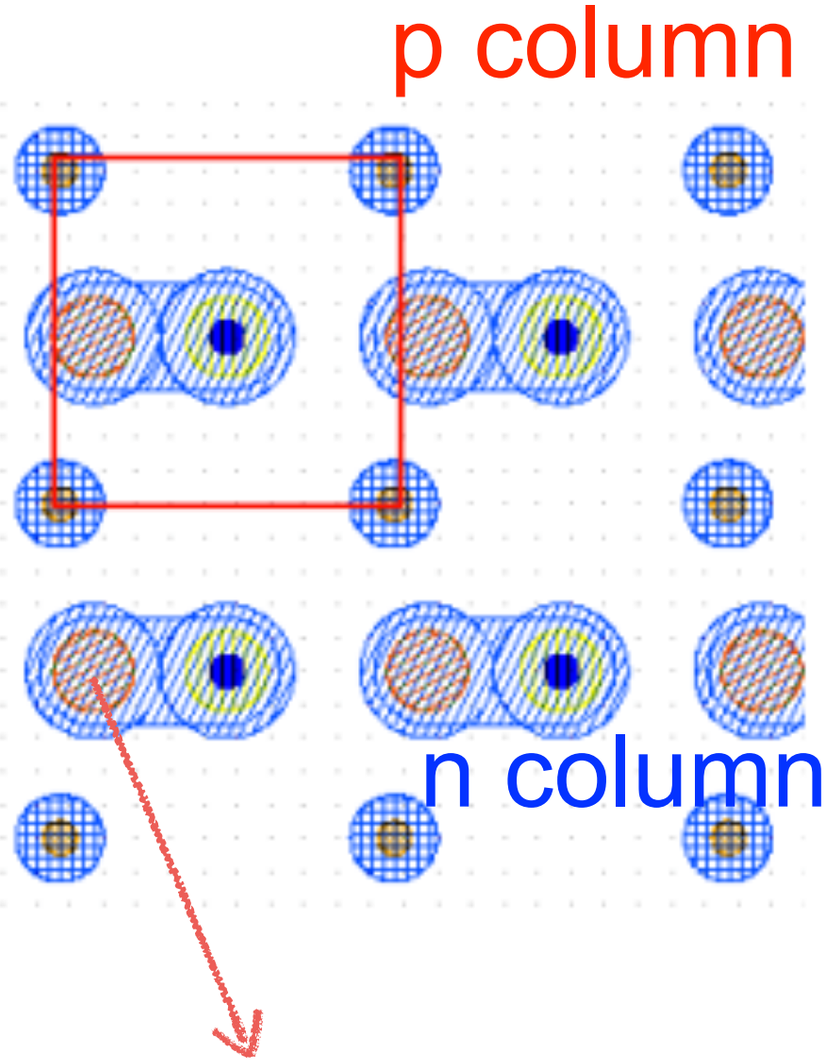




Sensors specification

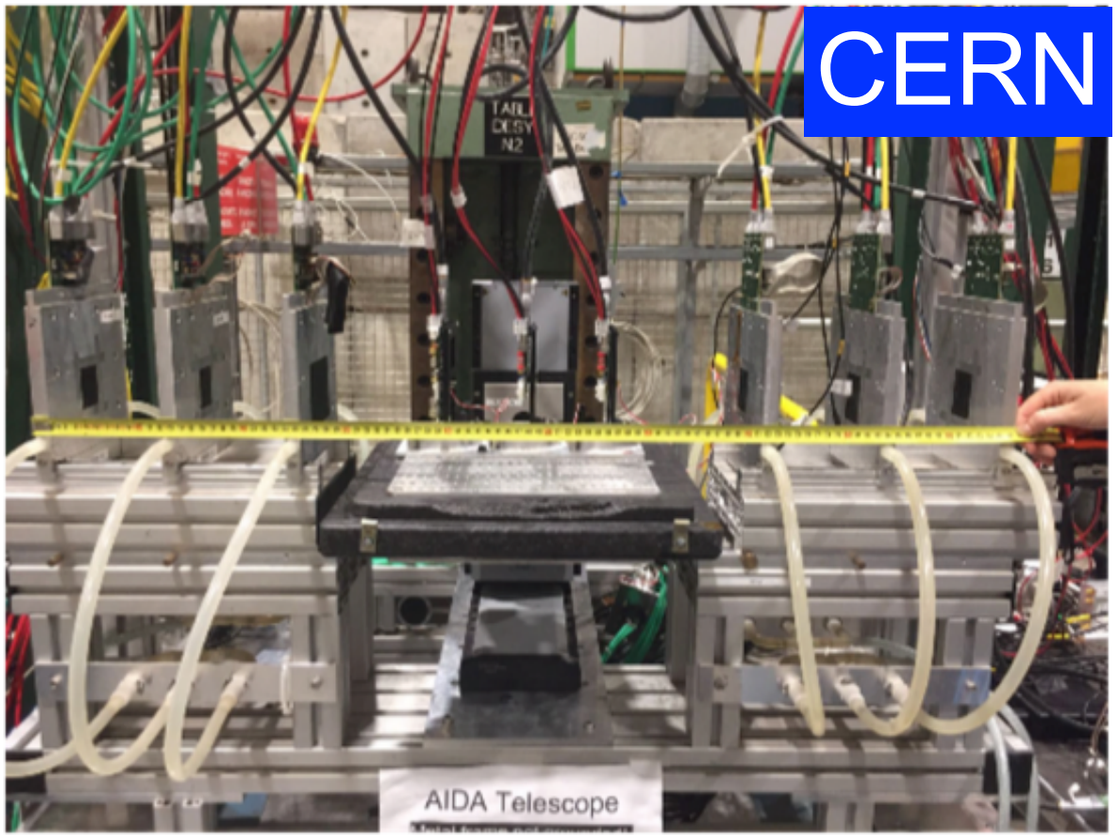
Name	Geometry	Tested **before** irradiation	Tested **after** irradiation
w91 x1y3	50x50	CERN	CERN
w91 x2y3	50x50	CERN	CERN/ FNAL/ ATLAS
w3 x3y1	25x100	CERN/ FNAL/ ATLAS	
w3 x3y2	25x100		CERN/ FNAL

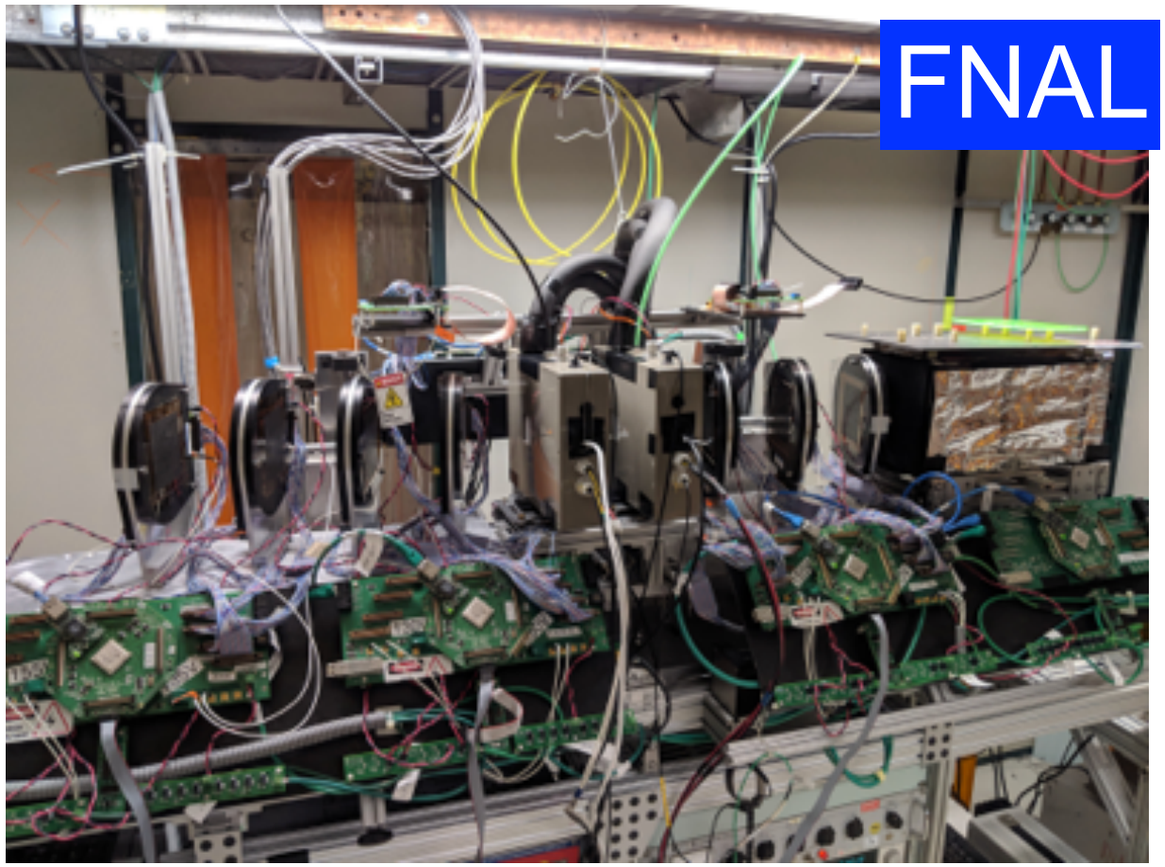
For the 25x100 case two different sensors have been used but from the same family



Test beam set up

- CERN
  - Data acquisition and tracking based on the Mimosa Telescope, with the Bonn setup
    - Reconstruction based on EUTelescope code
  - Higher spatial resolution with respect the FNAL set up but **not able to perform any calibration**
- FNAL
  - Data acquisition based on OTS-DAQ , with the YARR system and tracking made with strip silicon sensors
  - higher rate, and **able to perform calibrations**





Efficiency definition

- All noisy/dead channels are masked before computing the efficiency
  - i.e. they do **not** enter in either the numerator or the denominator
- The track is fitted with only the telescope detectors
  - a hit on the DUT is considered as associated to the track if it lays nearby the extrapolated position of the track into the sensor
  - we also tried different definitions for associating the hit to the track and they all give comparable efficiency
- Only “good" tracks are considered as denominator
  - i.e. they are timed in with the crossing particles and the chi2 is not too far from 1.
  - The borders of the sensors are excluded from the fiducial volume
    - exact definition depends on the test beam set up
    - anyway we found efficiency values in good agreement between the two set of measurements

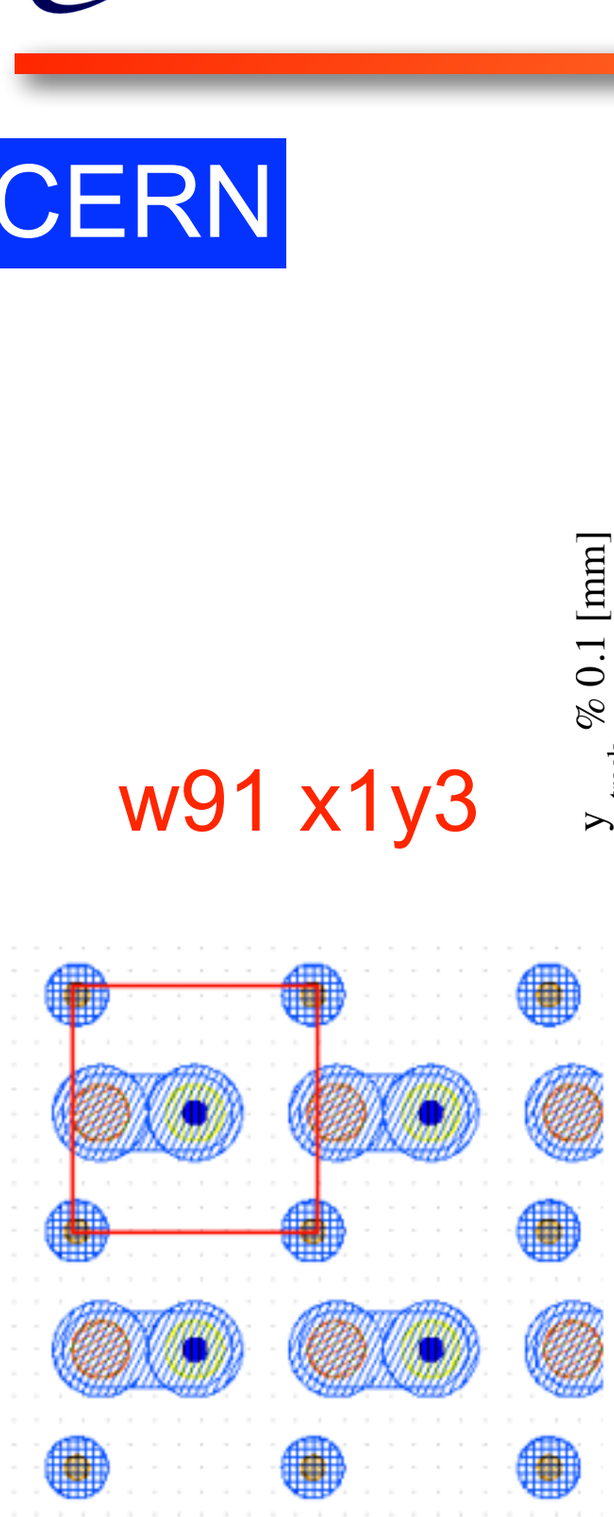
3D hit efficiency before irradiation

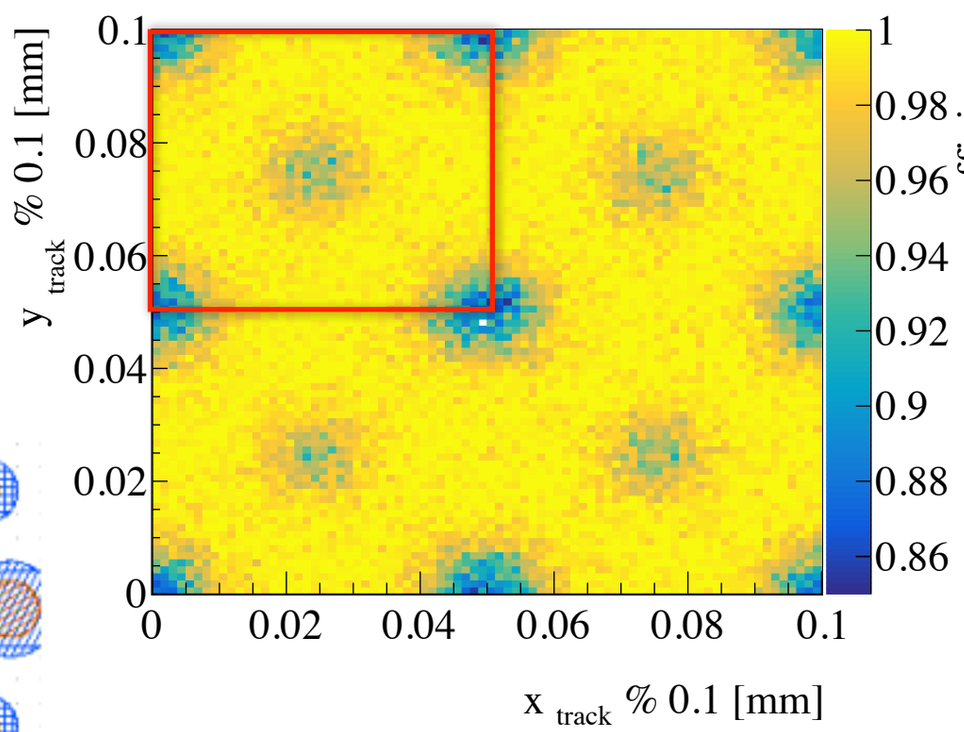
CERN

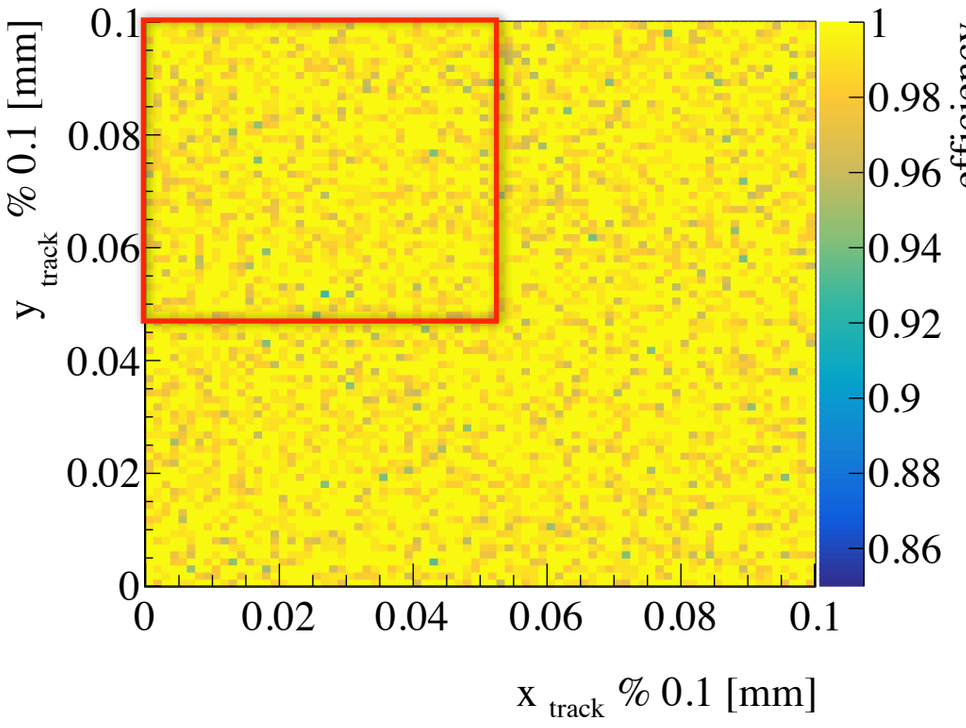
3D 50x50, Bias = **14 V**
0 deg tilt, Eff=98.6%

3D 50x50, Bias = **34 V**
34 deg tilt, Eff=99.3%

w91 x1y3



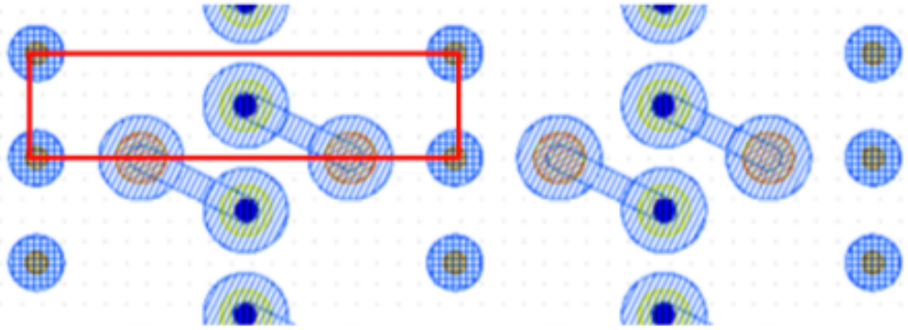




3D hit efficiency before irradiation

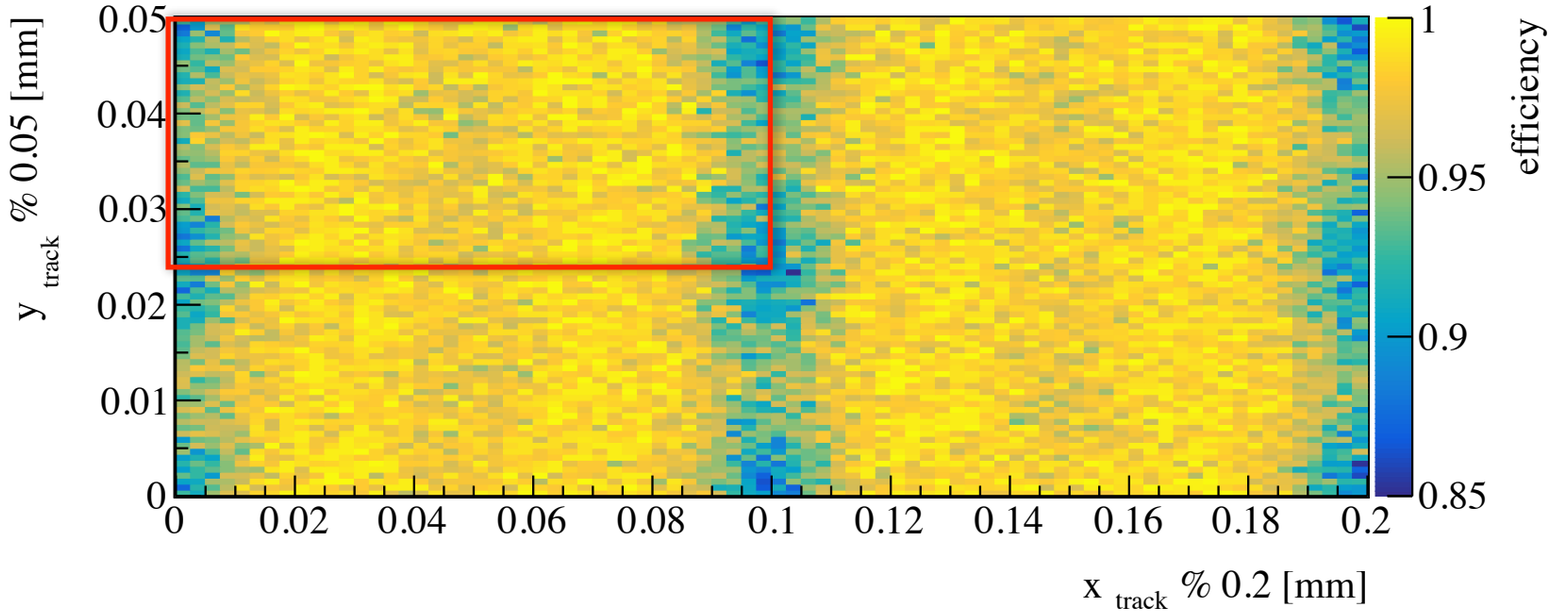
CERN

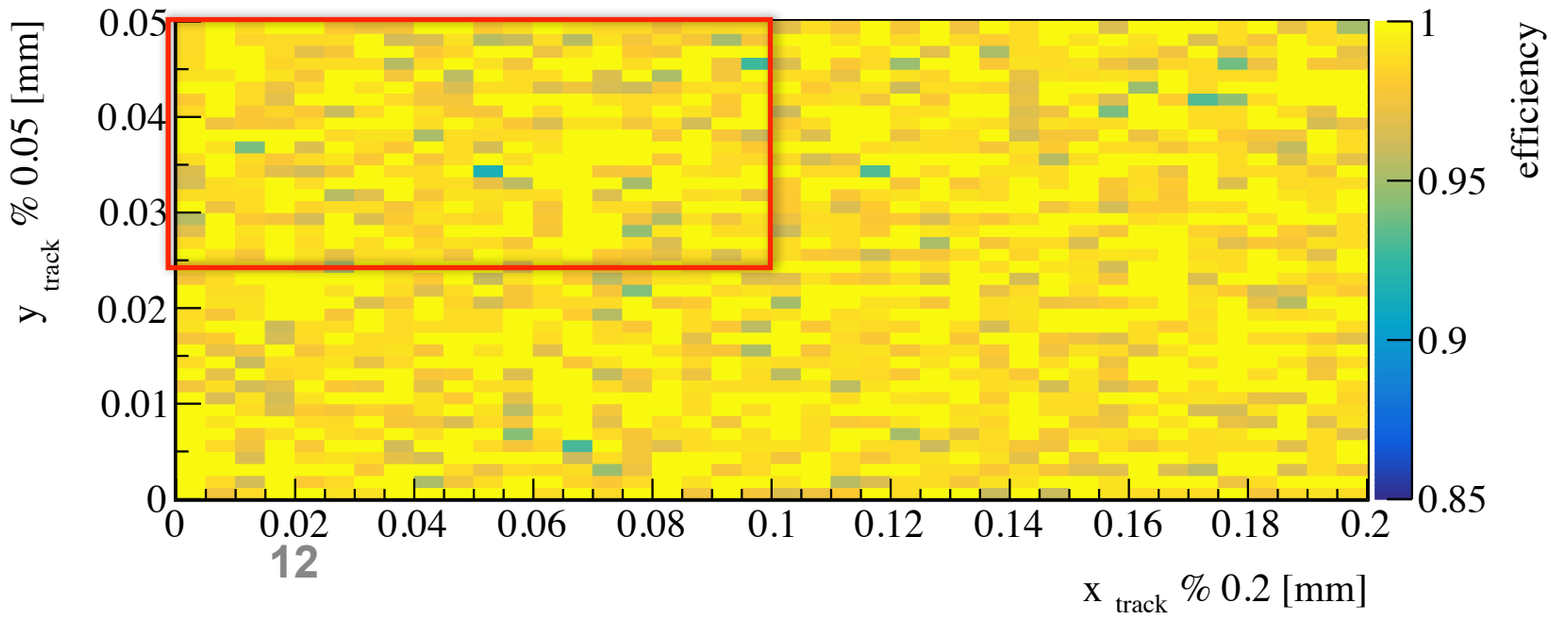
w3 x3y1



3D 25x100, Bias = **3V (!)**
34 deg tilt, Eff=**99.4**%

3D 25x100, Bias = **3V (!)**
0 deg tilt, Eff=**97.3**%



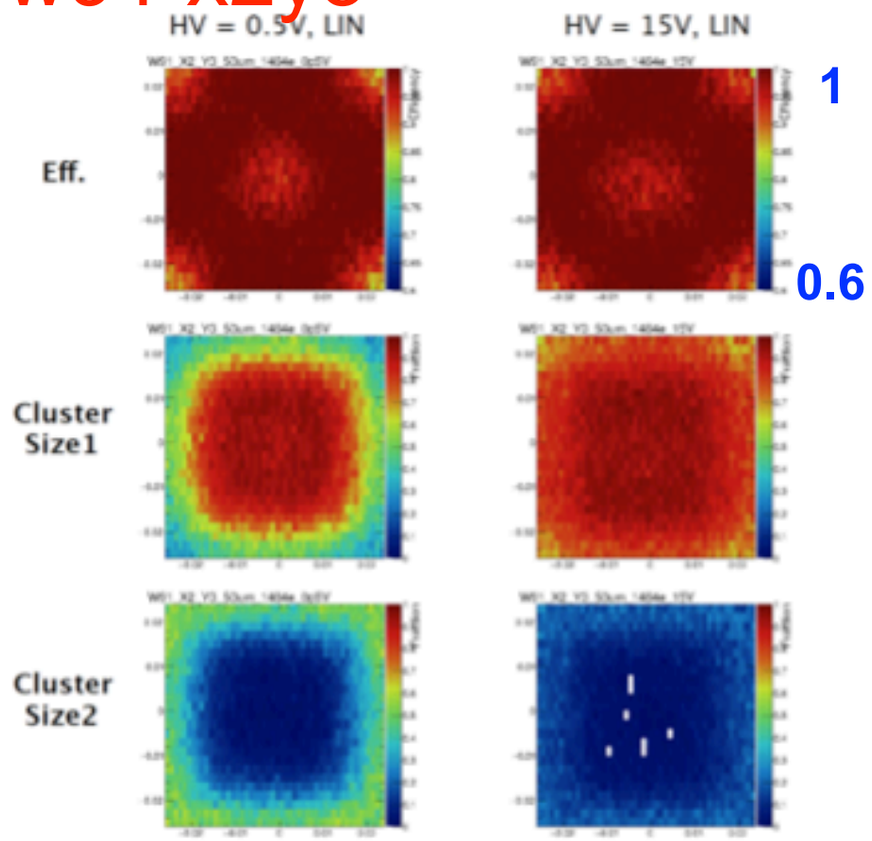


2nd batch RD53a @ IZM Test beam measurement (before irradiation)

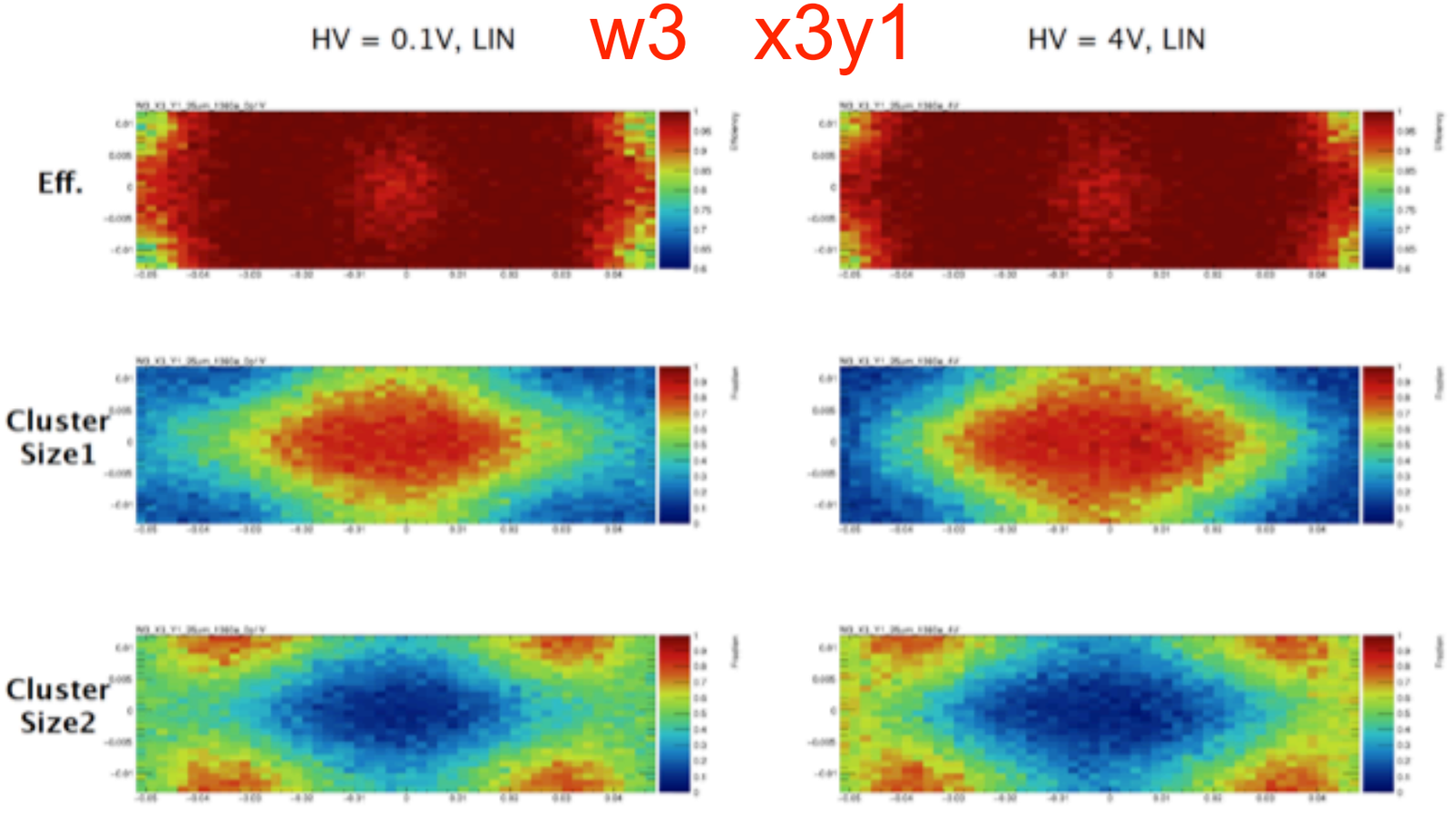
- Two modules by CMS samples were used in the July TB CERN SPS H6.
  - 50x50(1E) and 25x100(1E), normal incidence angle
    - Local pixel efficiency vs cluster size:

ATLAS results

w91 x2y3



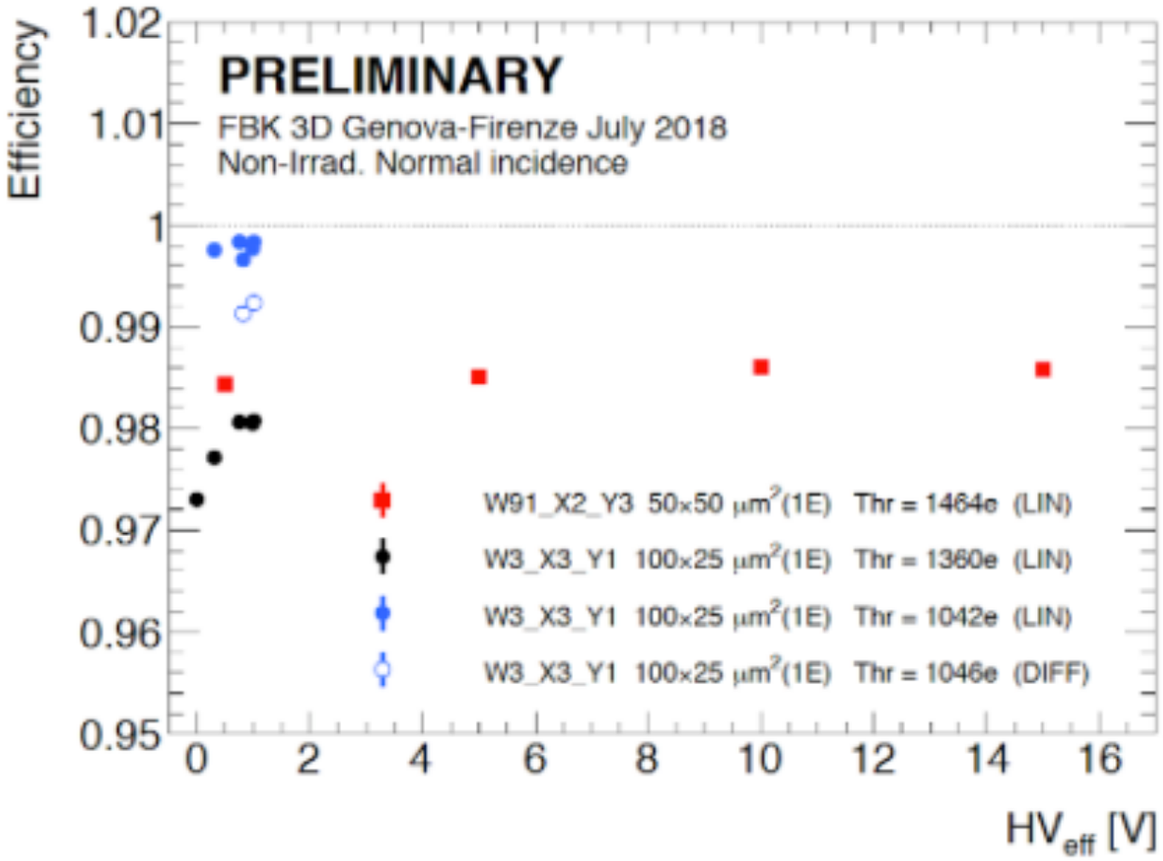
w3 x3y1

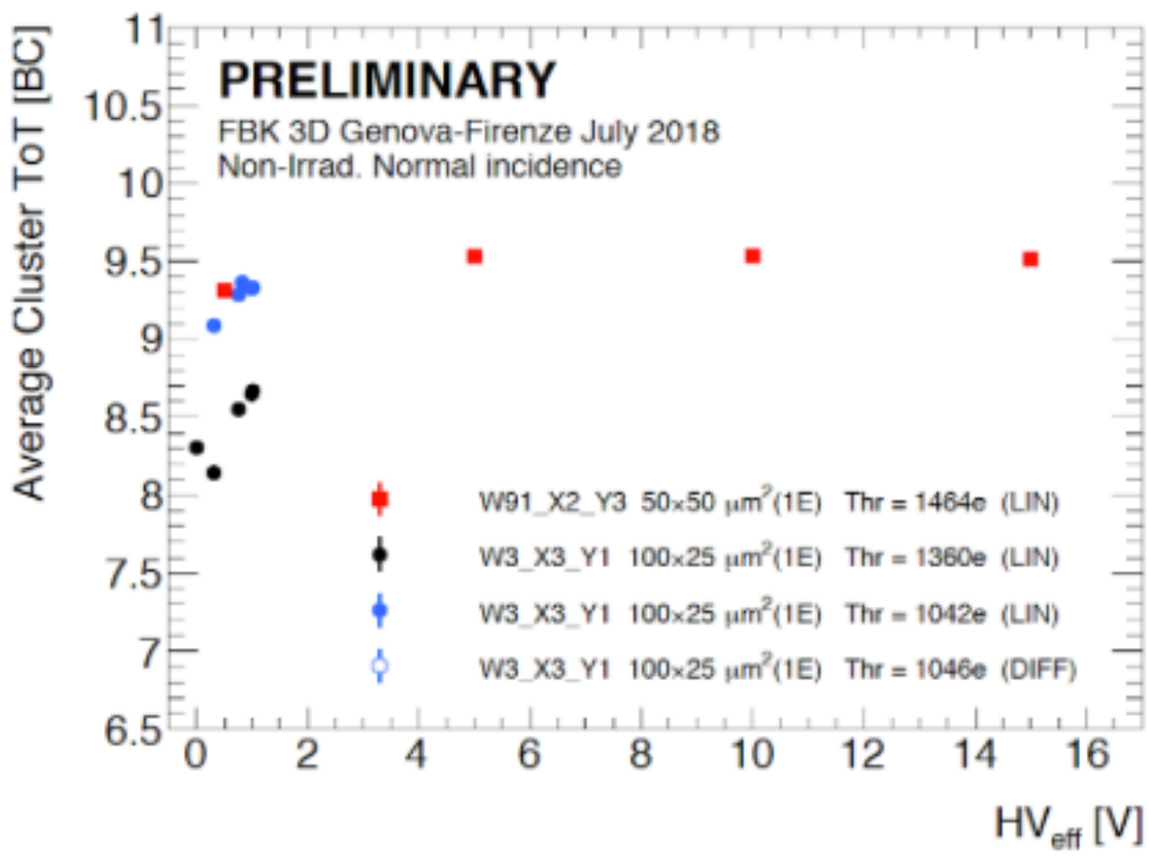


2nd batch RD53a @ IZM Test beam measurement (before irradiation)

- Two modules by CMS samples were used in the July TB CERN SPS H6.
  - 50x50(1E) and 25x100(1E), normal incidence angle
    - Average efficiency and Average cluster ToT:

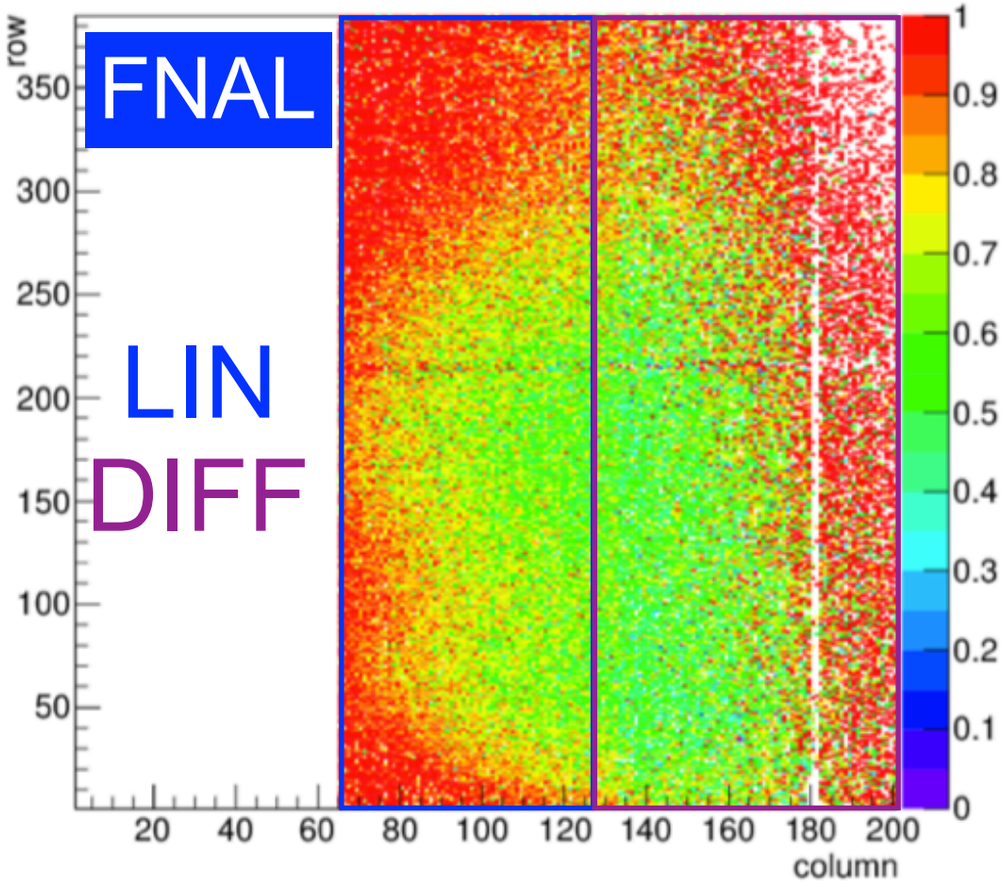
ATLAS results





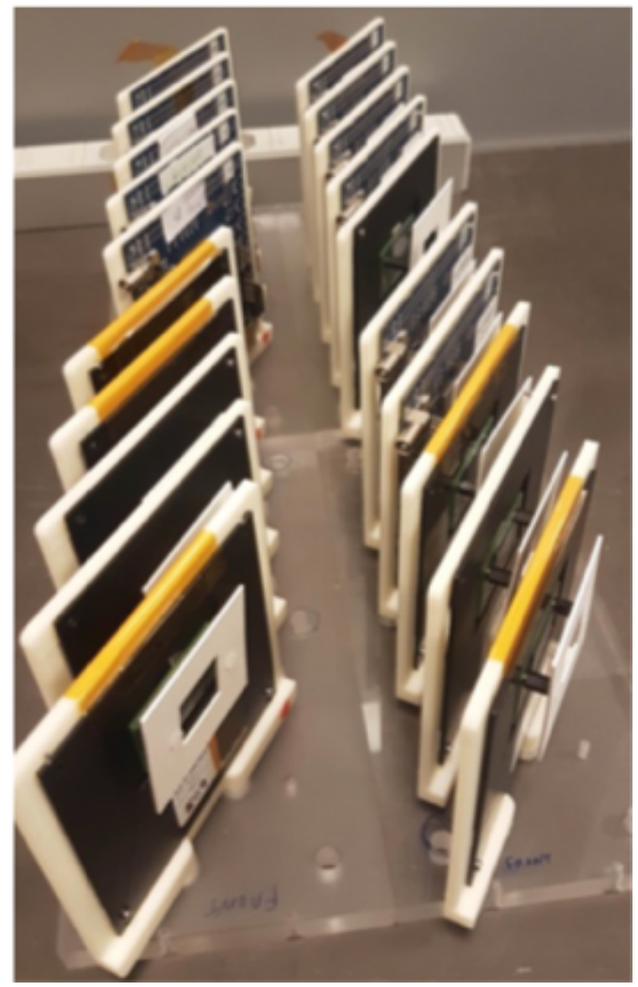
Module irradiation

- Irradiation dose up to about 1E16 n_{eq}/cm^2
  - Corresponding dose of 6 MGy
    - No cross check on the absorbed dose have been made
- Sensors were tilted by 55 degrees to have more uniform irradiation



Irradiation was done at "room temperature", no cooling, so it would be better say "unknown temperature"
No LV or bias was applied to the modules

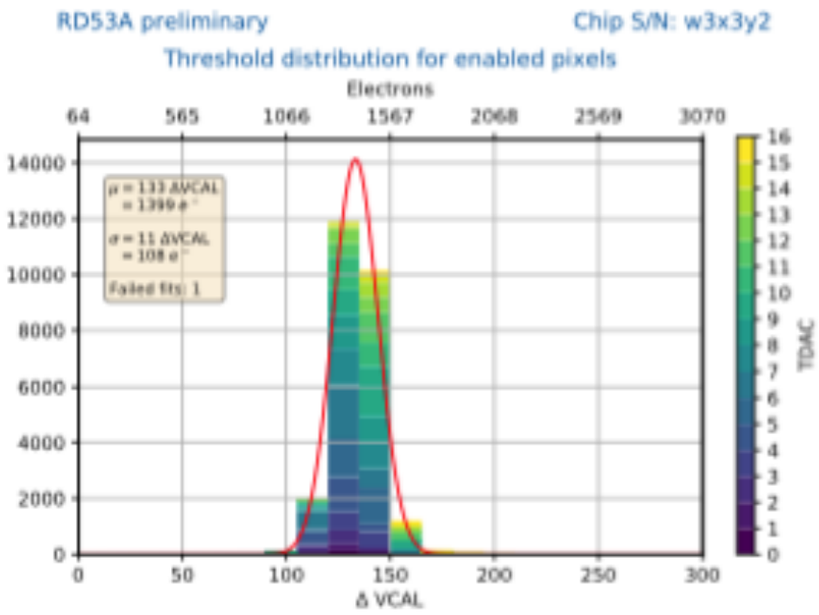
3D, 25x100 under depleted irradiated area clearly visibile in green

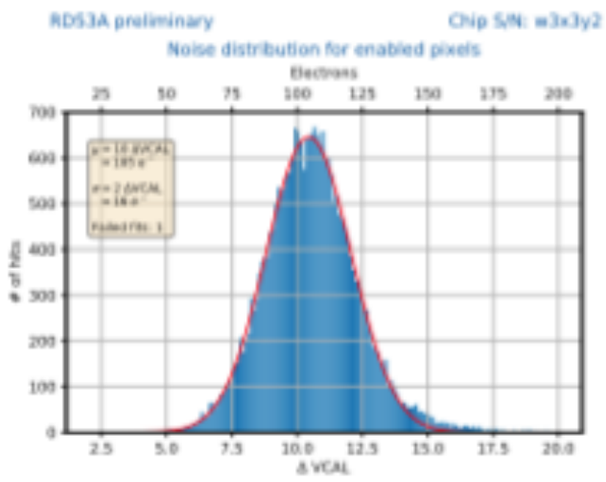


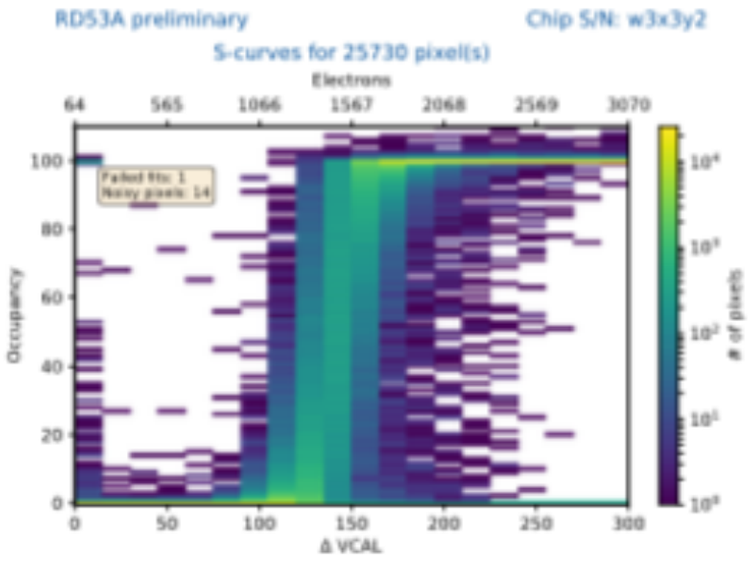
Thresholds and noise after irradiation

CERN

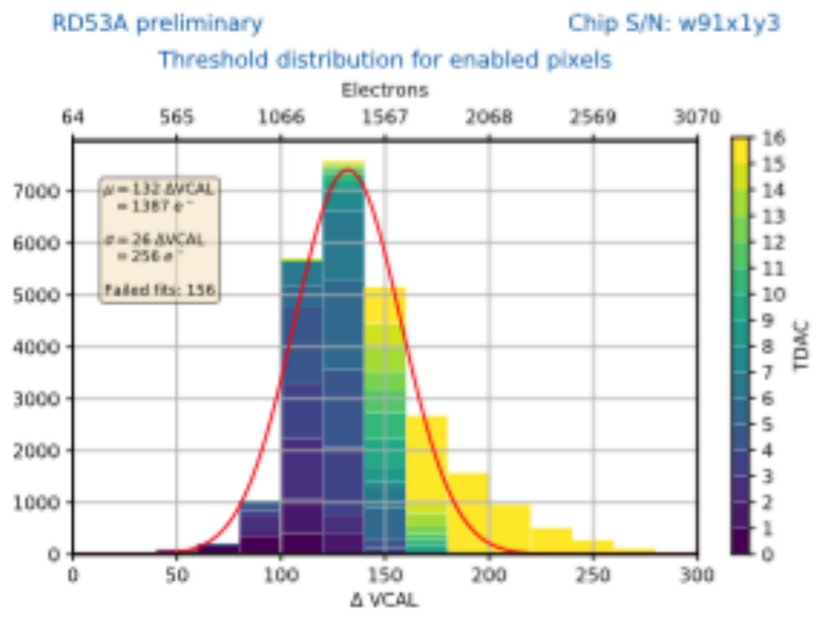
25x100: Threshold ~1400 e⁻, noise = 105 e⁻

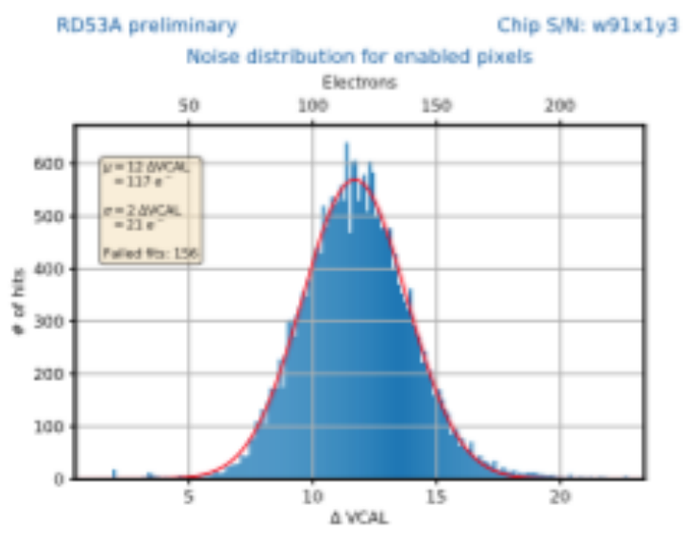


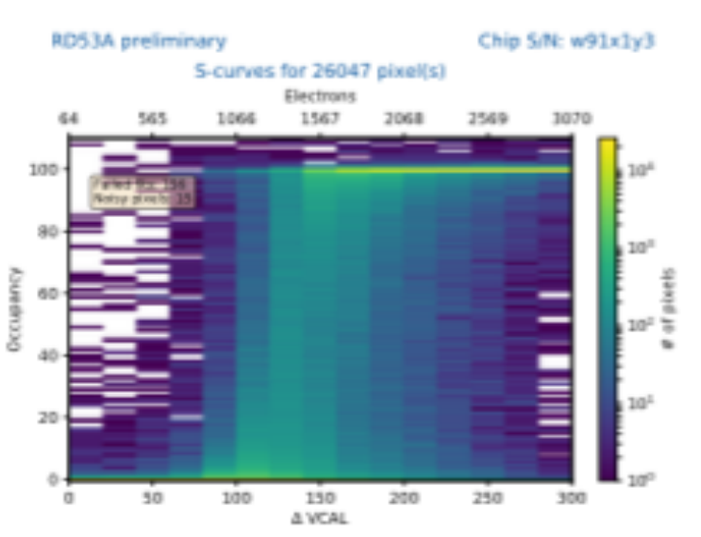




50x50: Threshold ~1400 e⁻, noise = 120 e⁻ Tuning difficult, too many pixels stuck @ Tdac 15



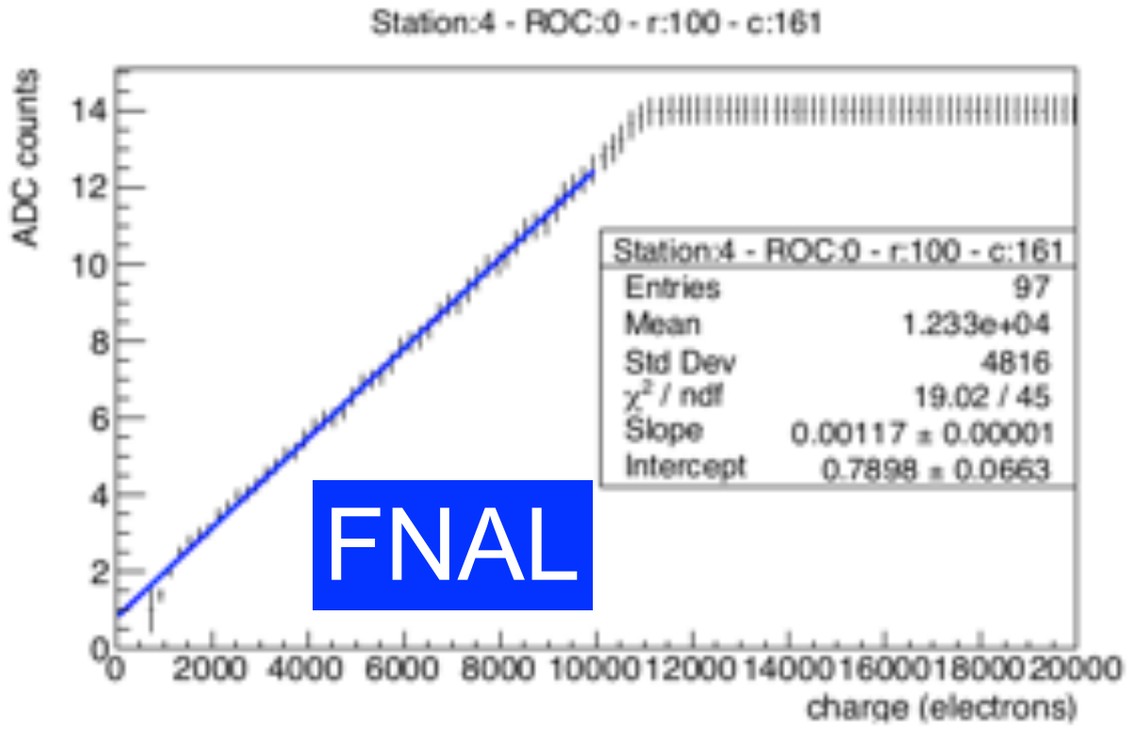




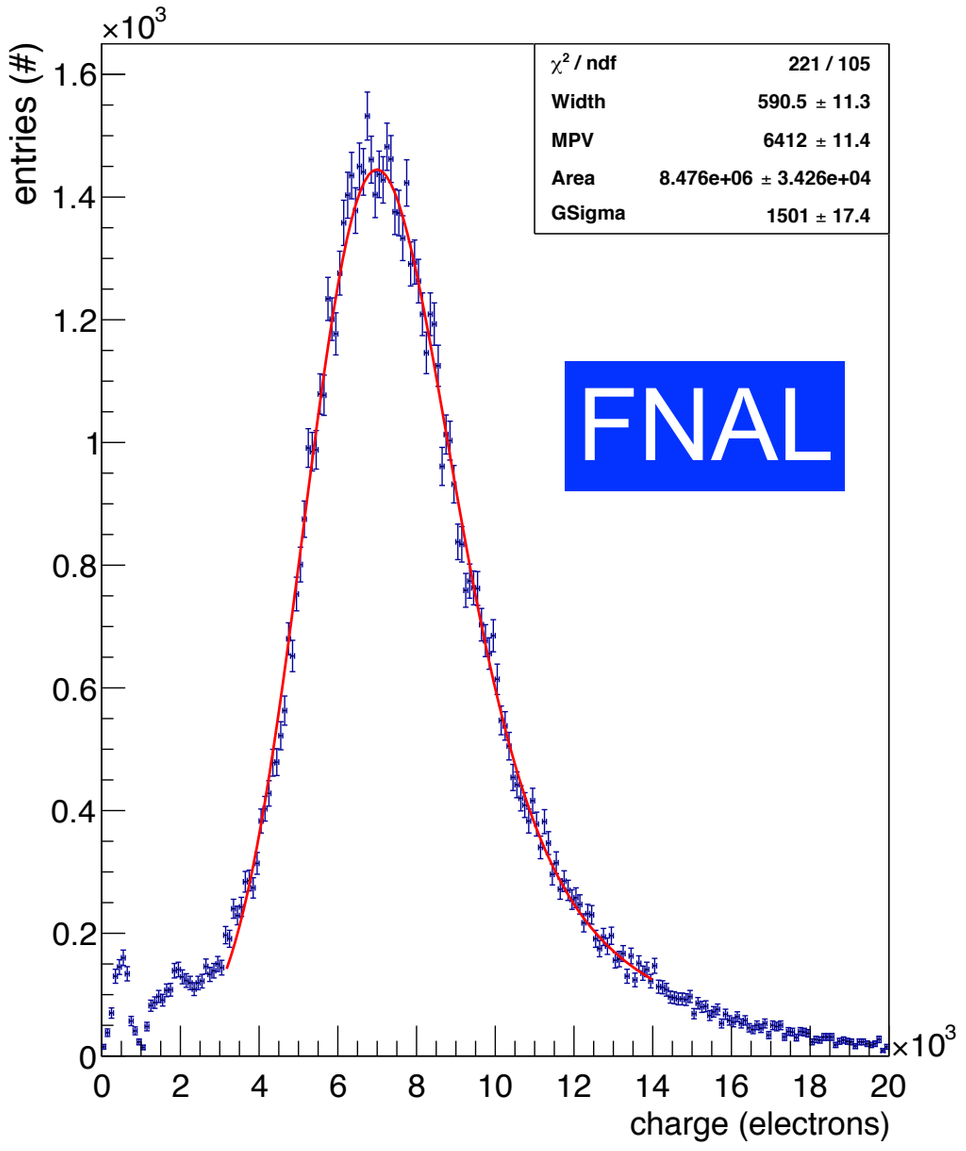
Gain calibrations

- RD53A modules were read out using the YARR system
  - All calibrations have been taken with the modules mounted on the test beam and in the same temperature conditions of the data taking
- Enabling the three FE simultaneously the whole system was extremely noisy
  - we took all the data with the Sync FE disabled in order to get rid of this noise
- While Linear FE calibration went on smoothly, no calibration was applied for the Differential

Linear FE



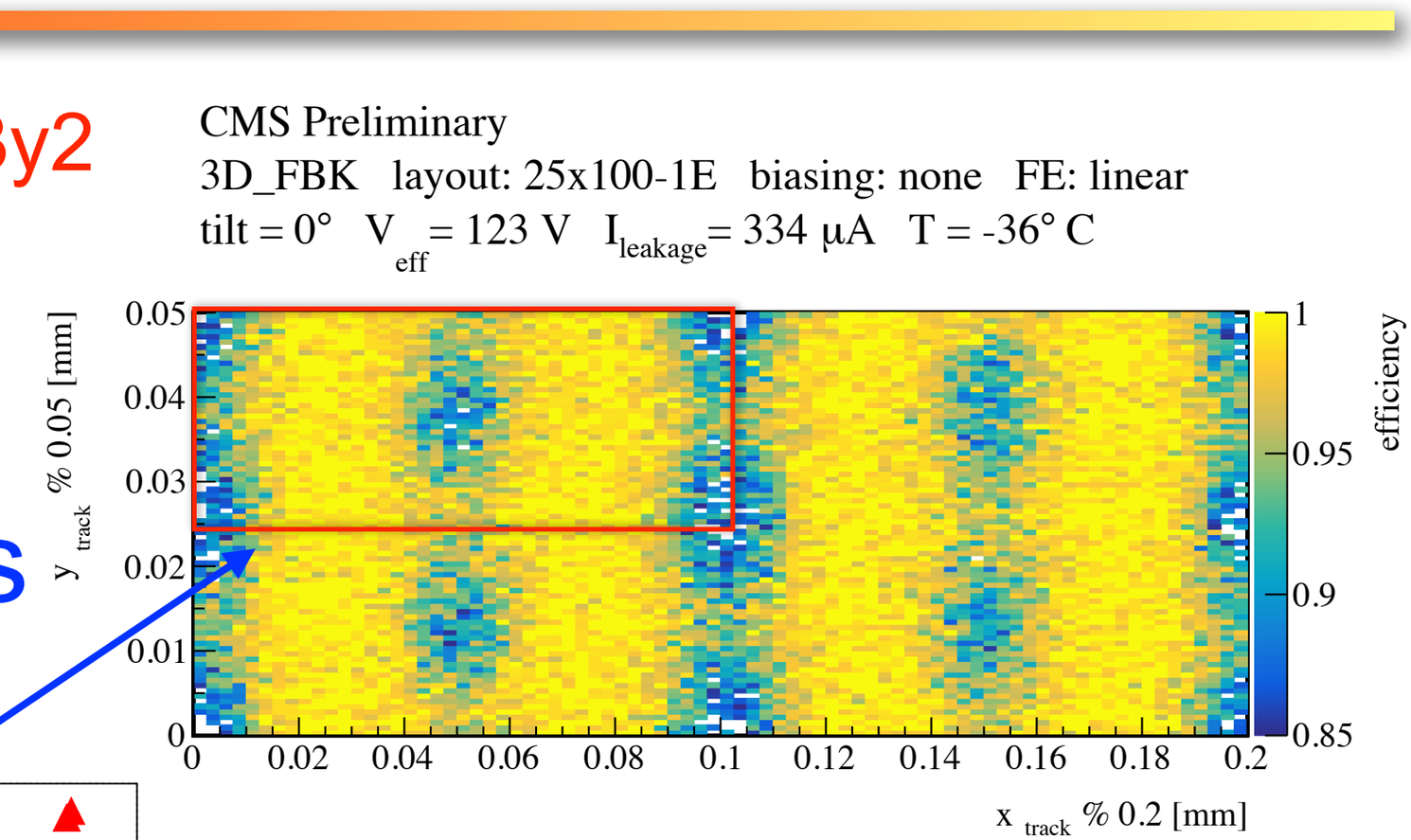
3D, irrad to 10^{16} $n_{e.q.}/cm^2$



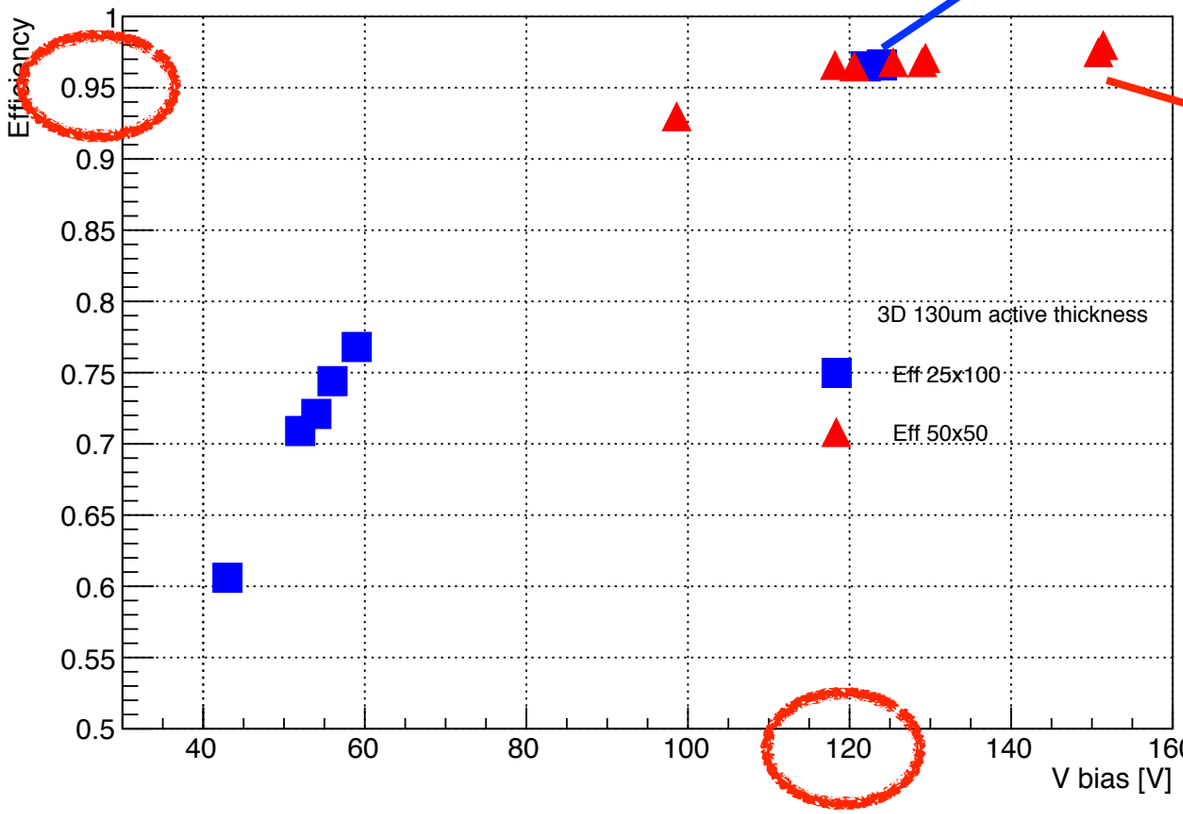
Efficiency vs V bias

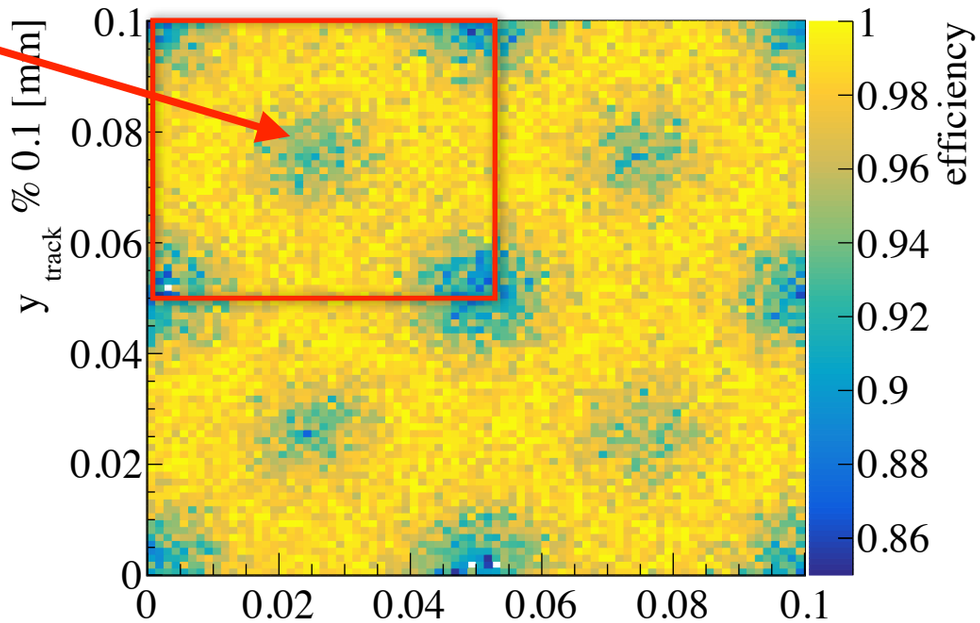
CERN

w3 x3y2



Irradiated Modules

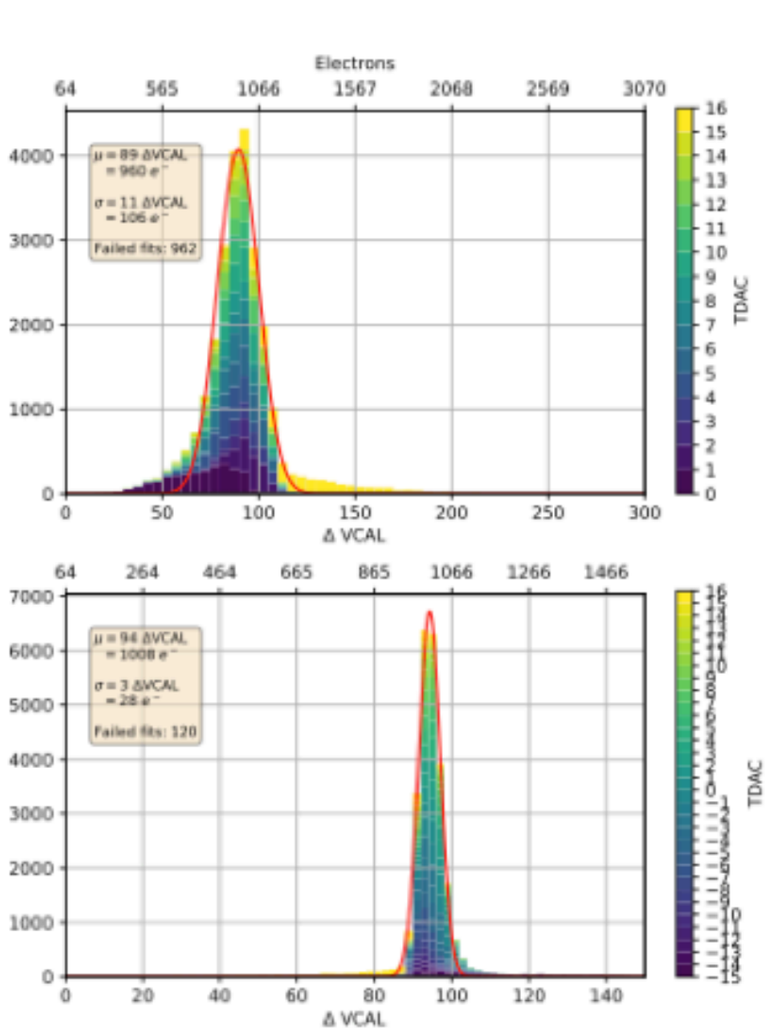


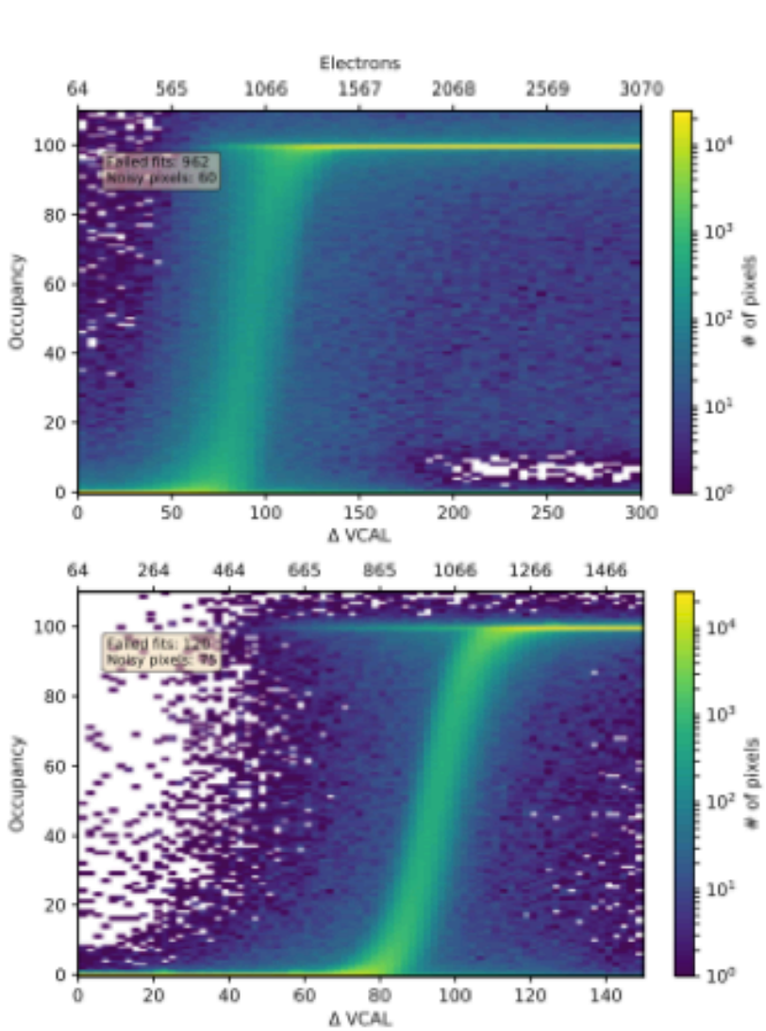


w91 x1y3

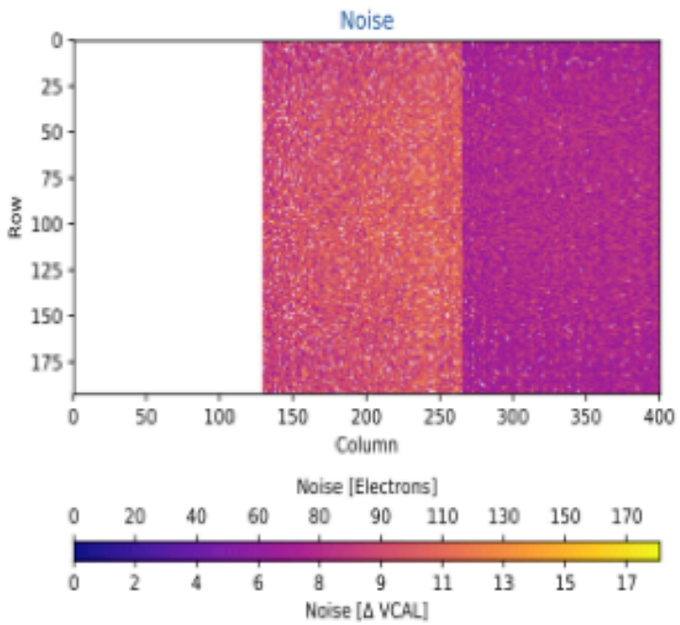
2nd batch RD53a @ IZM Test beam measurement (post irradiation)

- Test beam @CERN SPS H6A in Oct 24-31. 50x50(1E) module W91_X2_Y3_50
- Irradiation profile is common to other modules, but some non-ideal profile may be present.
  - Brief counting of activity after test-beam indicated ~2x difference of residual activity between SYNC-side and DIFF-side of the sensor
- Tuning: targeted ~1000e threshold for both LIN and DIFF with BDAQ53.
  - Quite clean tuning with <1% noisy pixels for both FEs.





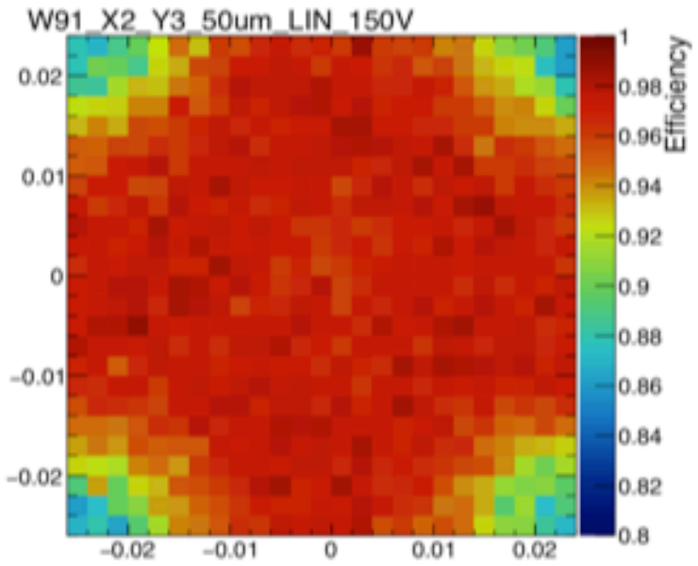
ATLAS results



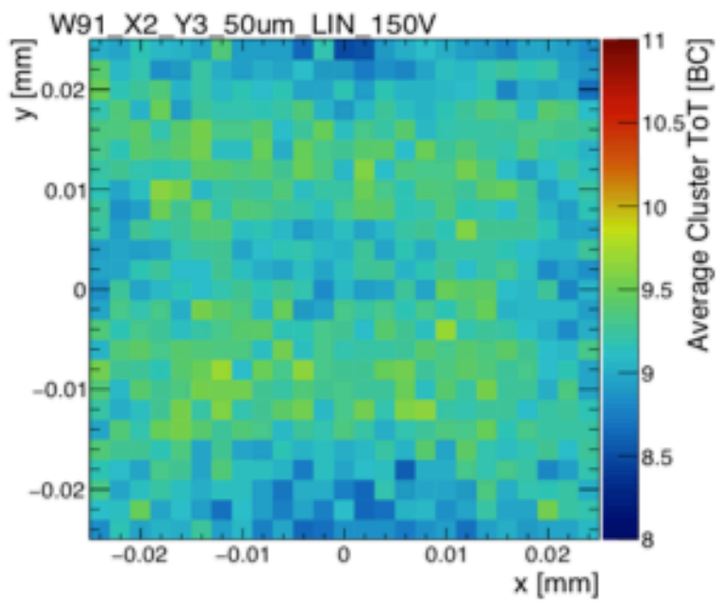
2nd batch RD53a @ IZM Test beam measurement (post irradiation)

- Datasets
  - HV scan at normal angle: { 50, 75, 90, 100, 115, 125, 135, 140, 155, 160, 165, 175 } V
  - HV scan at 15deg tilt angle: { 20, 30, 40, 50, 60, 70, 80, 90, 100 } V
    - Comment: LIN FE became quite noisy and masked in this round;
  - HV scan at 100V as at higher voltage DIFF is also noisy.
  - At least 1M events per each HV point.
- Tuning threshold at ~960 e
- Efficiency: ~96.2% @150 V after masking dark pixel (masked and their adjacent)

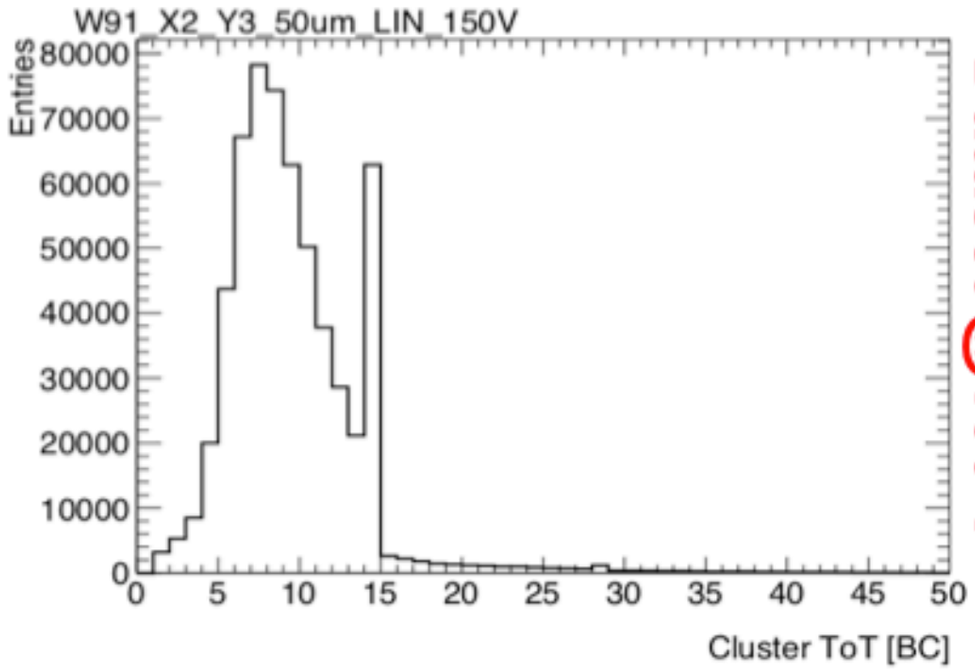
ATLAS results



Local Efficiency

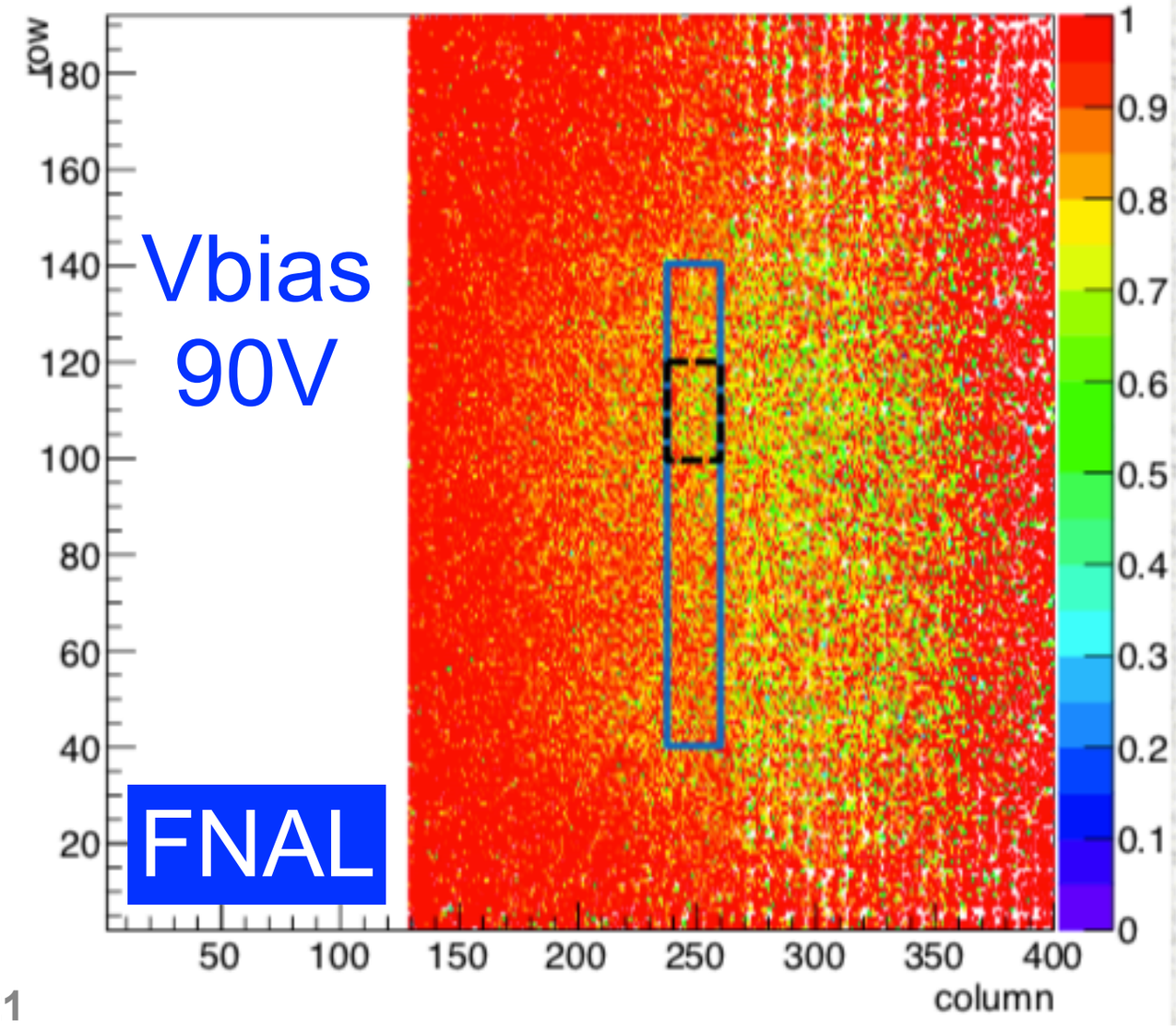


Average cluster ToT



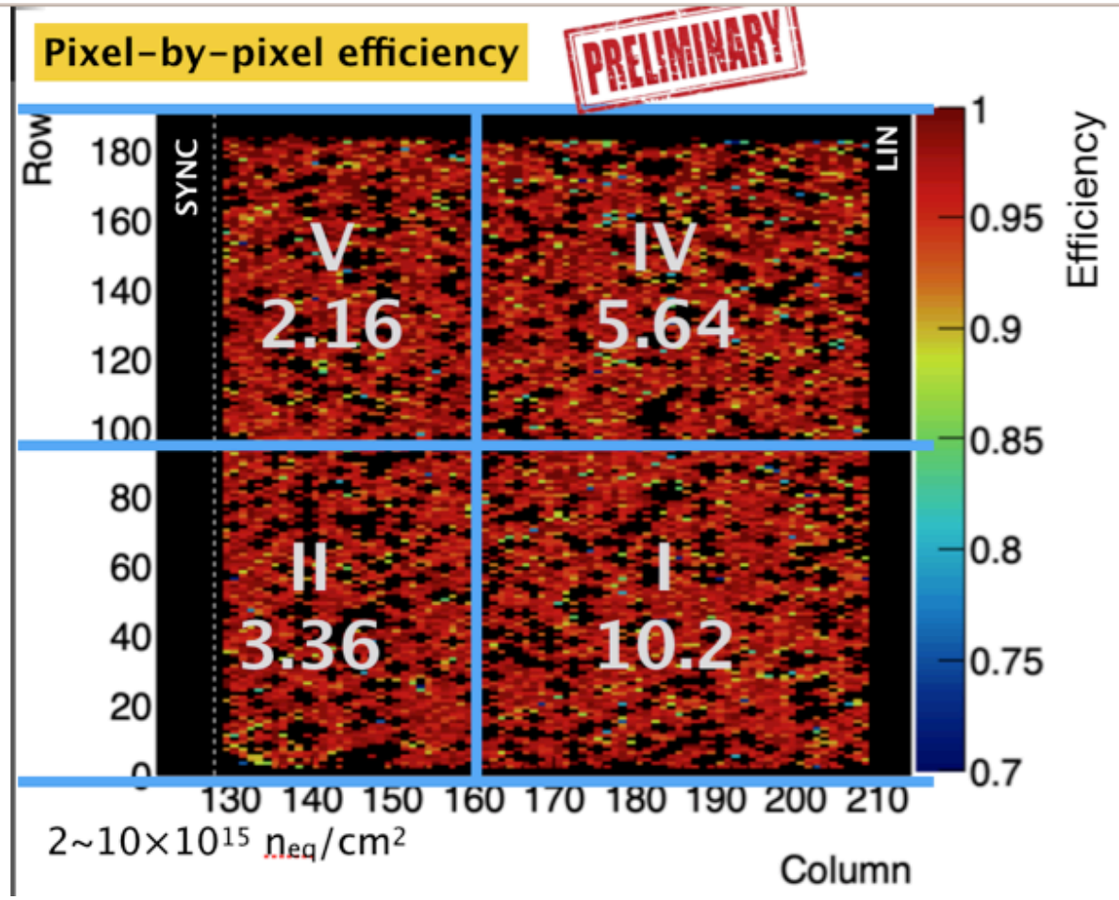
A good news

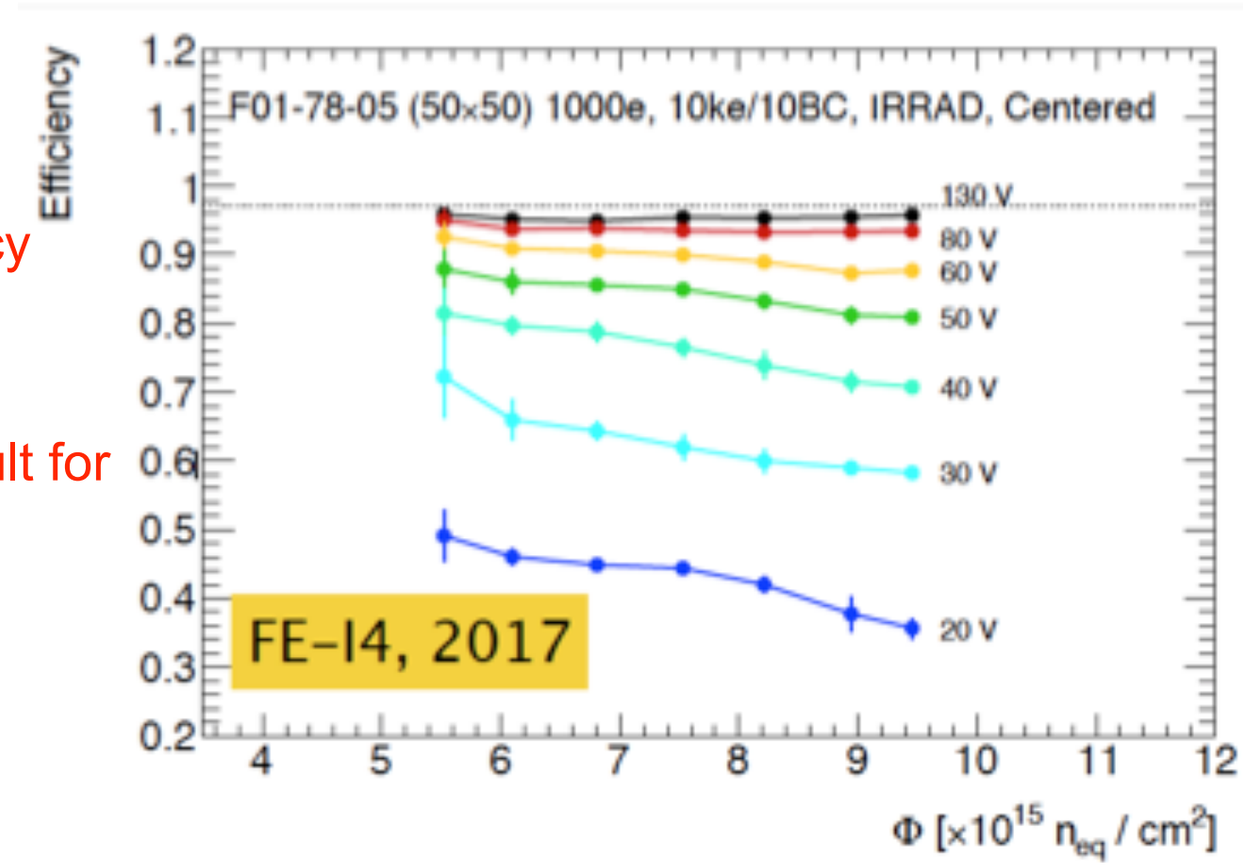
- The irradiation spot was also visible in the 2D efficiency distribution
  - 3D 50 x 50 module, at a bias voltage of 90 V to show the irradiated area
- We can select two small regions of the linear FE corresponding to the center of the irradiation spot to analyse the data for the highest bias voltage (**120 V**)
  - efficiency of **97.4%** (black region) and **97.8%** (blue region)
- Irradiation dose in these regions is the closest to 1E16 neq/cm^2 !!!

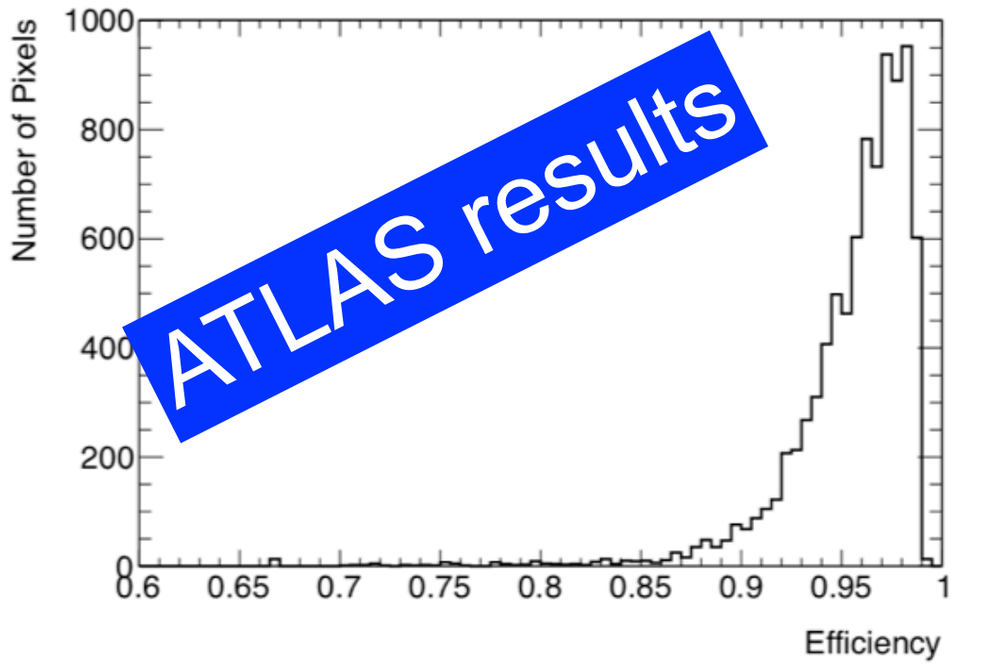


2nd batch RD53a @ IZM Test beam measurement (post irradiation)

- Efficiency reaching around 96.2%
  - after removing low-eff pixels.
- At 150V and for the LIN FE region, the efficiency is almost flat
  - strong position dependence isn't observed.
- Seems consistent with the previous FEI4's result for 50x50 μm².
  - Rough consistency with FEI4 also for lower voltages

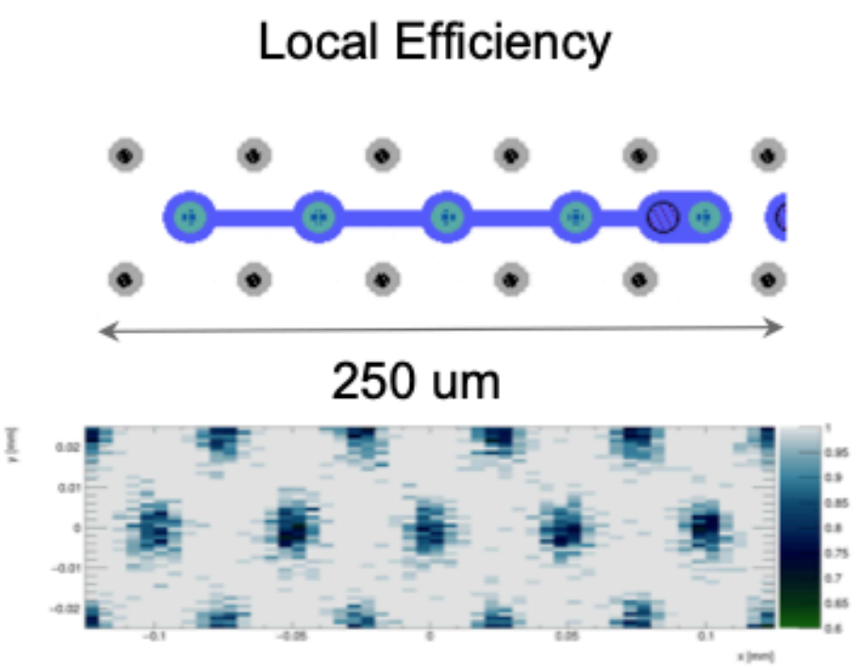


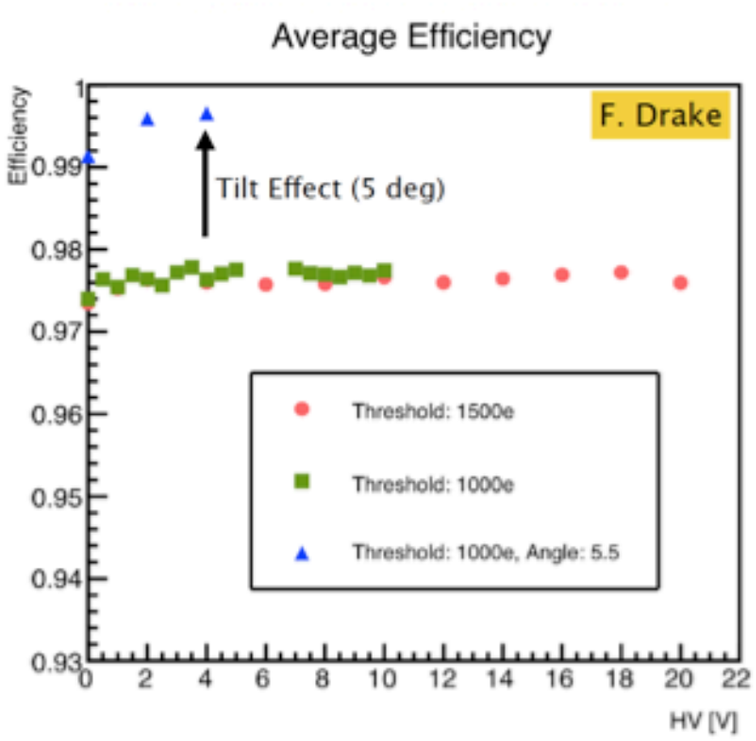


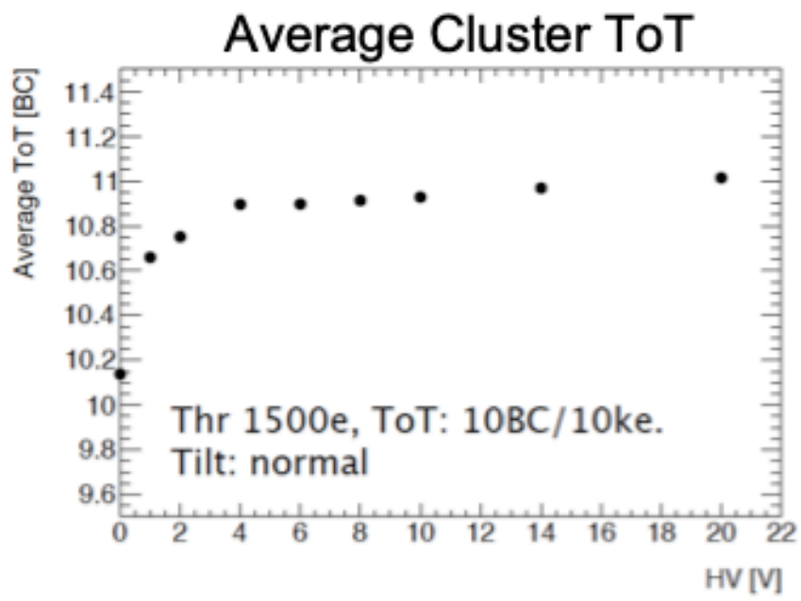


2nd batch FEI4 @ Leonardo

- Sample: FEI4 50x250 (5E)
  - embedding 5 of 50x50 cells in the IBL pixel dimension
- Test-beam at CERN SPS H6A. Configurations:
  - Thr 1500e, ToT: 10BC/10ke. Tilt: normal
  - Thr 1000e, ToT: 10BC/10ke. Tilt: normal, 5 deg
  - HV scan 0-20V







Conclusions

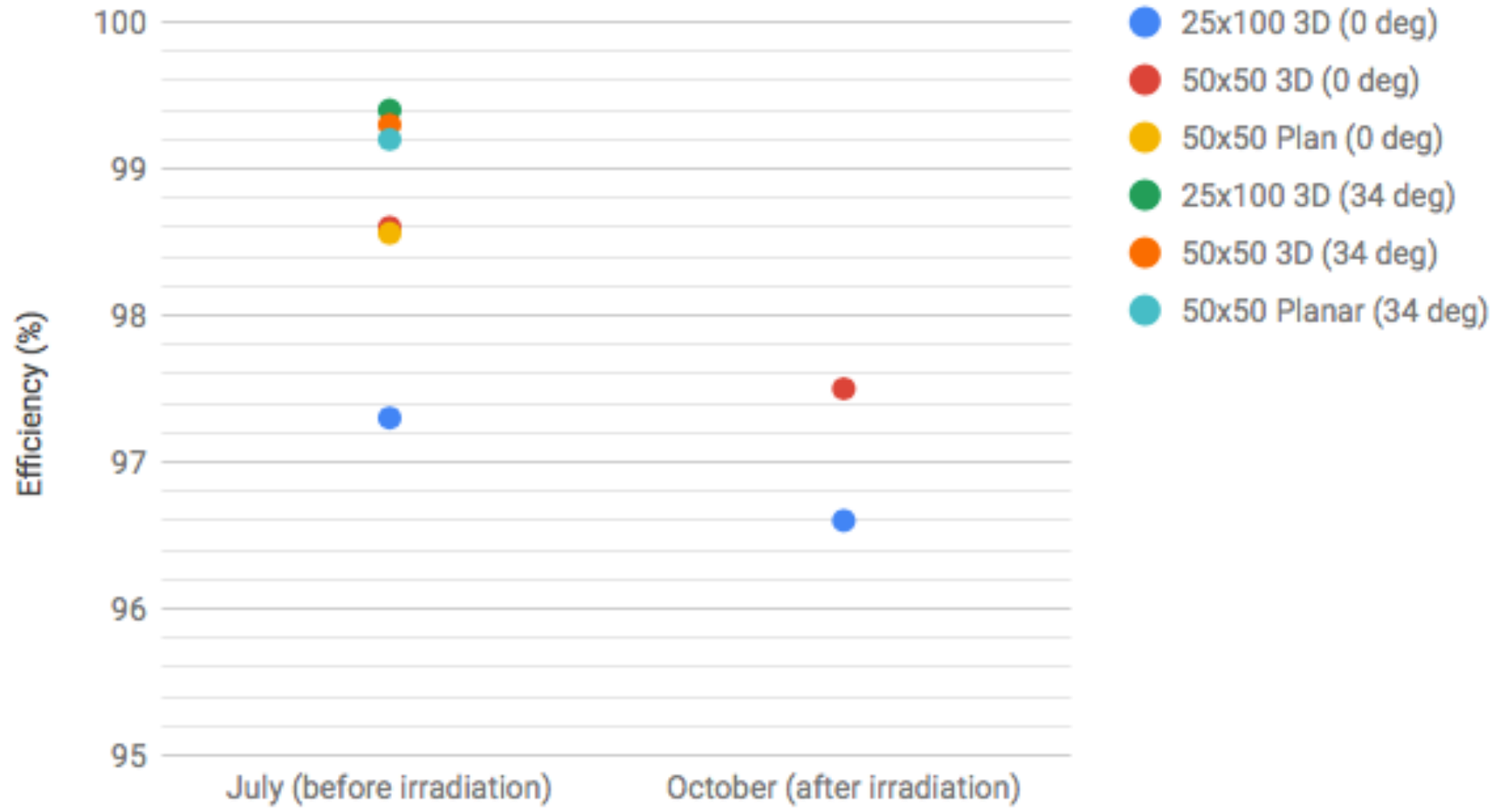
- Several test beams have been made in 2018
  - large effort of a small crew!
- Collected a large set of data
  - 3D and planar sensors
    - 50x50, 25x100
  - before / after irradiation
- Irradiation dose very near 1e16 n_{eq}/cm^2
  - FNAL test beam analysis revealed that we should not be far from the center of the beam in the LIN FE area.
- Efficiency after irradiation are compatible with those before irradiation already at moderate voltage even at high irradiation dose
  - everywhere **below 150 V**

	25x100 3D (0 deg)	**50x50 3D (0 deg)**
July (before irradiation)	97,3	98,6
October (after irradiation)	96,6	97,5

Back-up

Efficiency comparison

- Comparison before and after irradiation
  - slightly smaller efficiency after irradiation for zero degrees incident particles

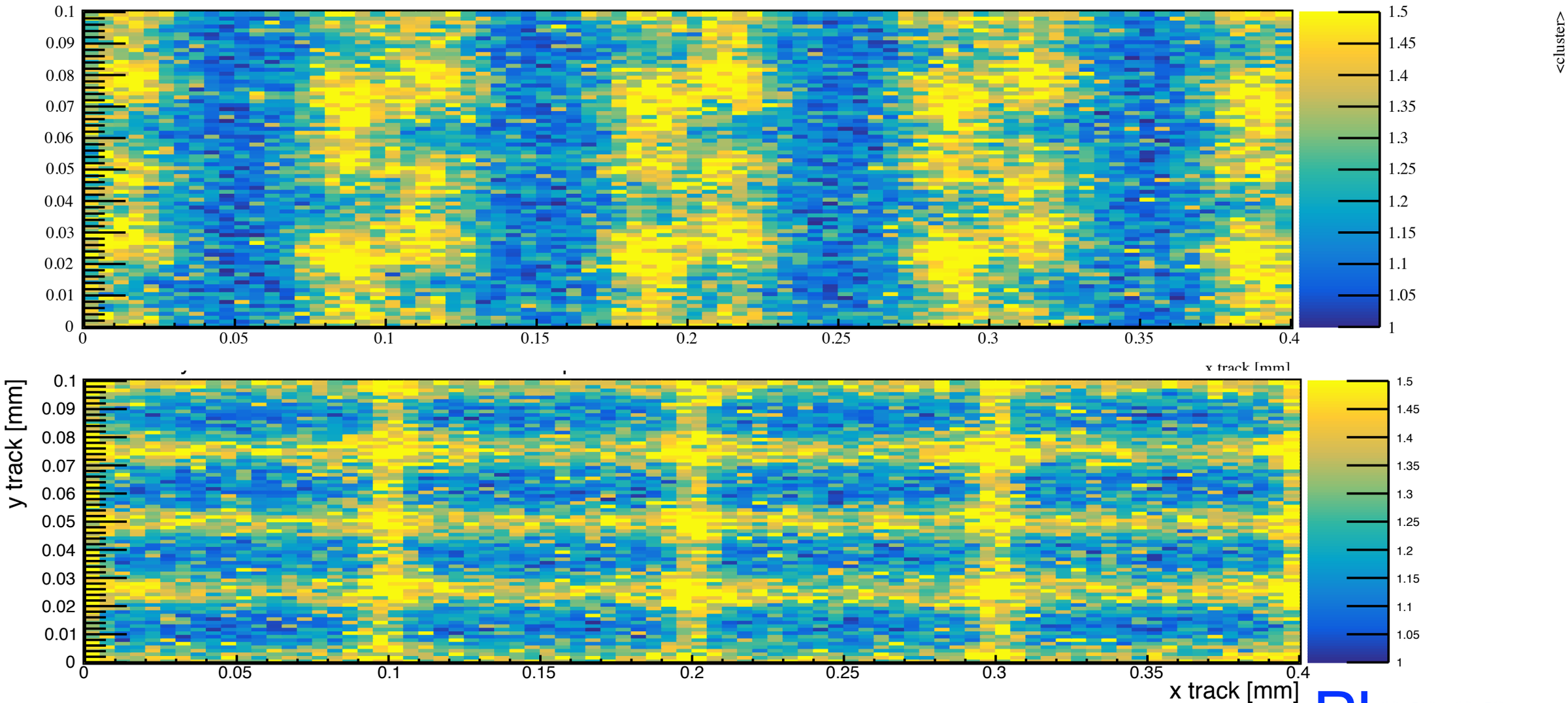


CERN

Possible x-talk effect

- Correlation between even and odd row clearly present
  - apparently we do see a pattern in the cluster size
  - whether it is significant or not still has to be quantified.

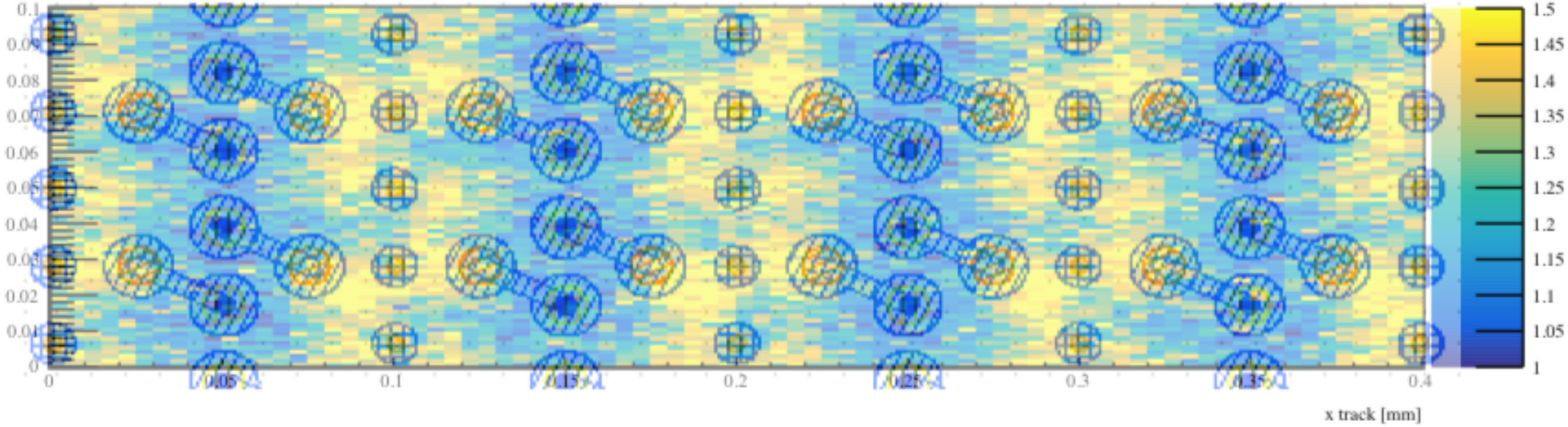
3D



Planar

Possible x-talk effect

- Correlation between even and odd row clearly present
  - apparently we do see a pattern in the cluster size
  - whether it is significant or not still has to be quantified.



M. Meschini

Gain calibrations

- Performed with YARR system (many thanks to Susan)
- **VCal** scan from **0** to **2000** in steps of **20**
- **100** injections at a time
- **tune_globalpreamp.json** calibration ran with options: **7/8000** electrons as target charge for **ToT = 8**
- Conversion VCal to electrons performed with the formula:

$$(-10^{-3} + 0.195 \cdot 10^{-3} \cdot \mathbf{VCal} \cdot 10^{-3}) \;/\; -1.6 \cdot 10^{-19} \cdot 8.2 \cdot 10^{-15}$$

Where:

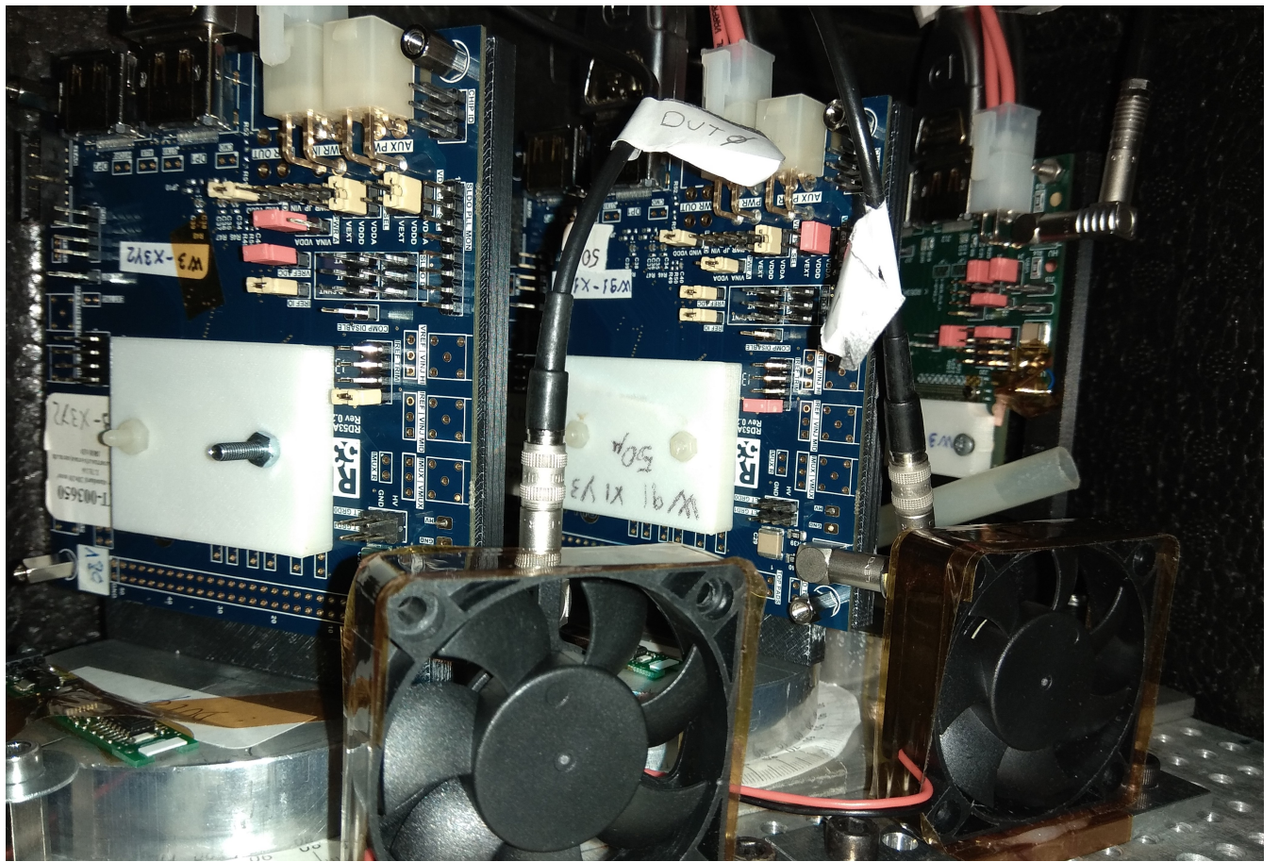
-10^{-3} and $0.195 \cdot 10^{-3}$: standard constants

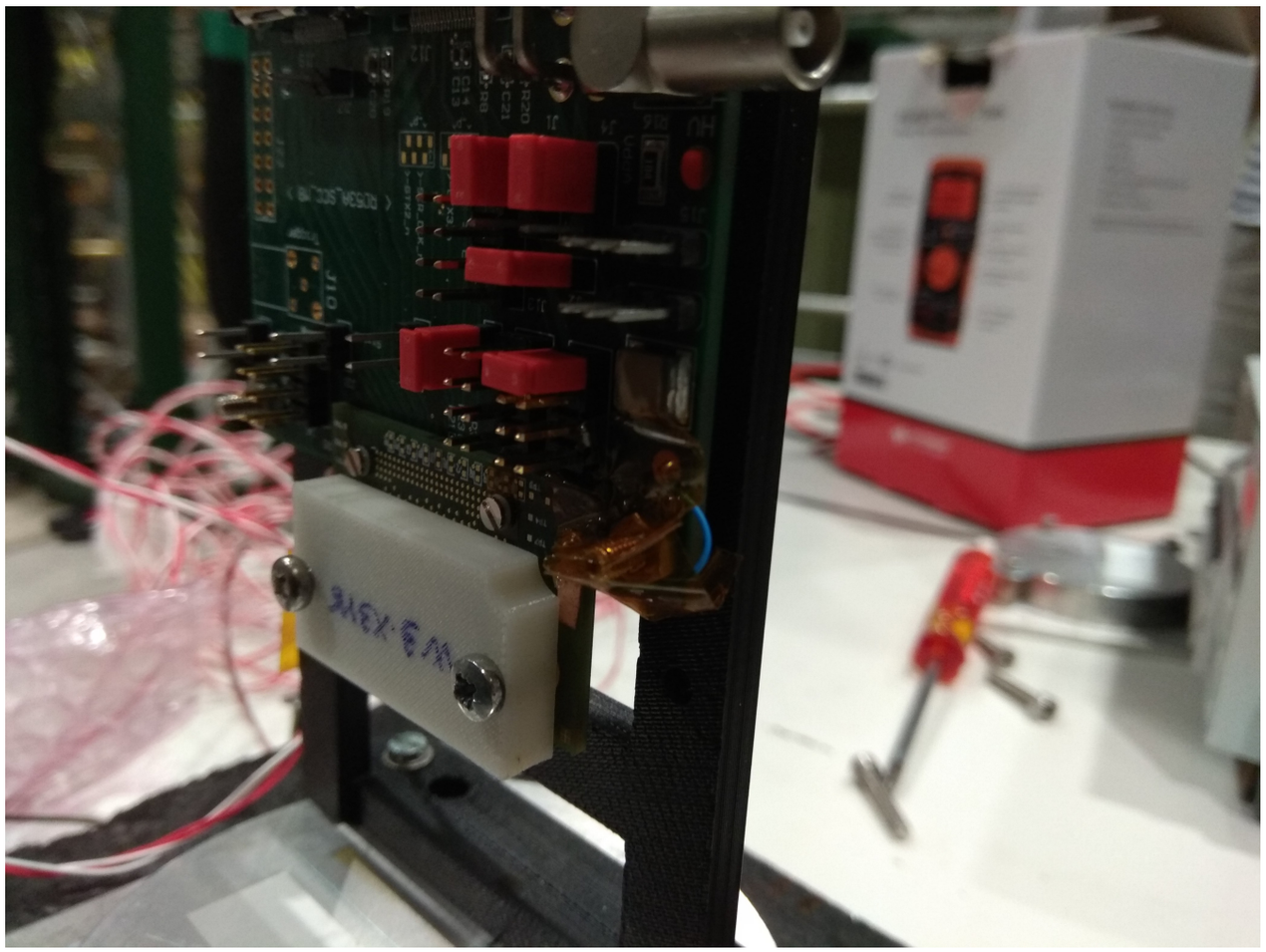
$8.2 \cdot 10^{-15}$: injection capacitance

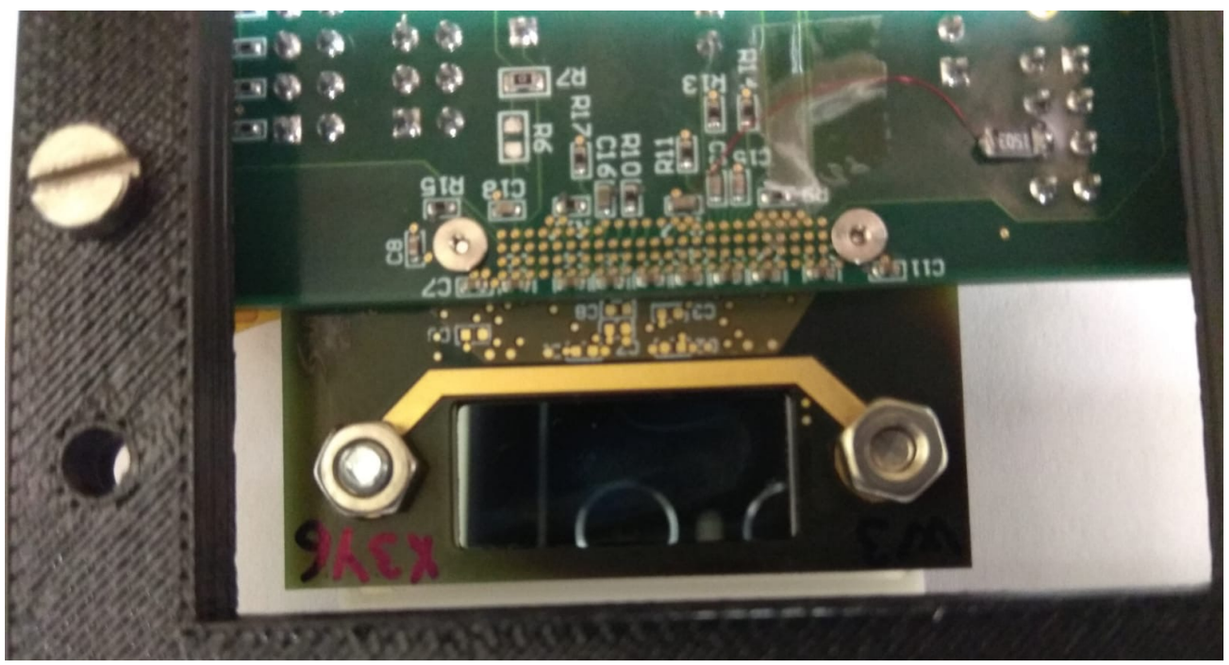
$-1.6 \cdot 10^{-19}$: electron charge

as from here: https://gitlab.cern.ch/YARR/YARR/blob/master/src/libRd53a/Rd53aCfg.cpp#L14

Sensors mounted on Bonn and Rice cards

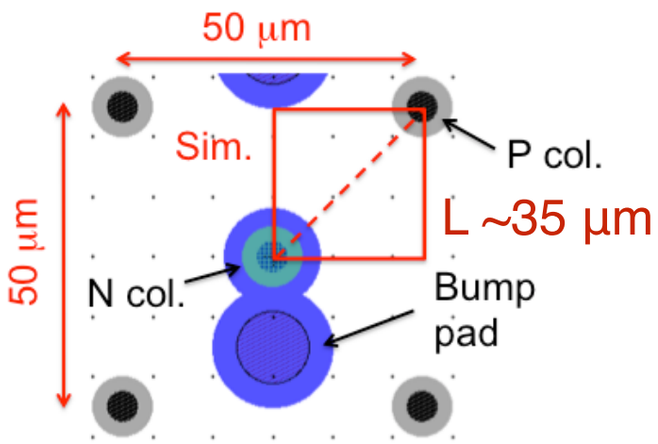




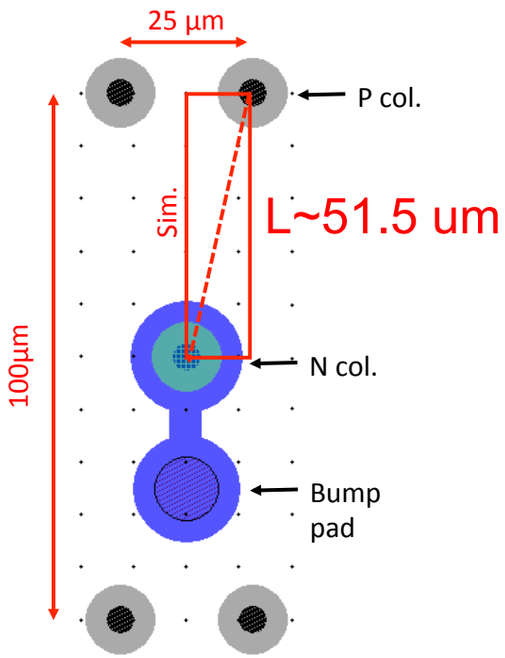


3D pixel sensors

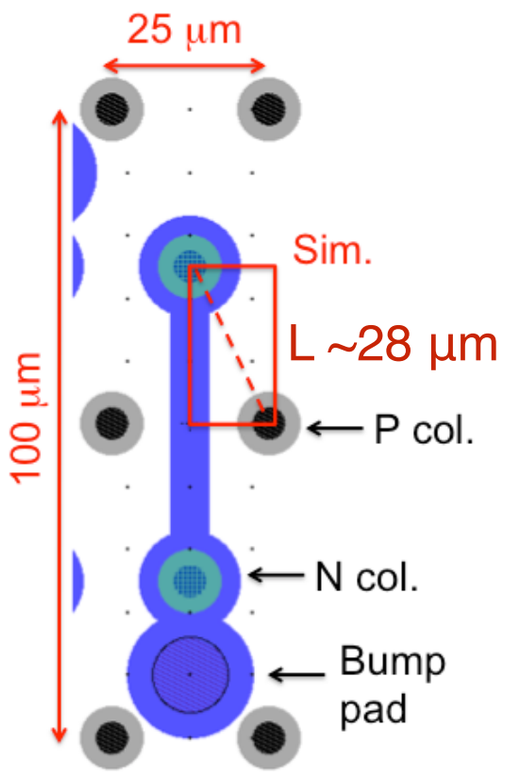
50x50 µm² 1E



25x100 µm² 1E



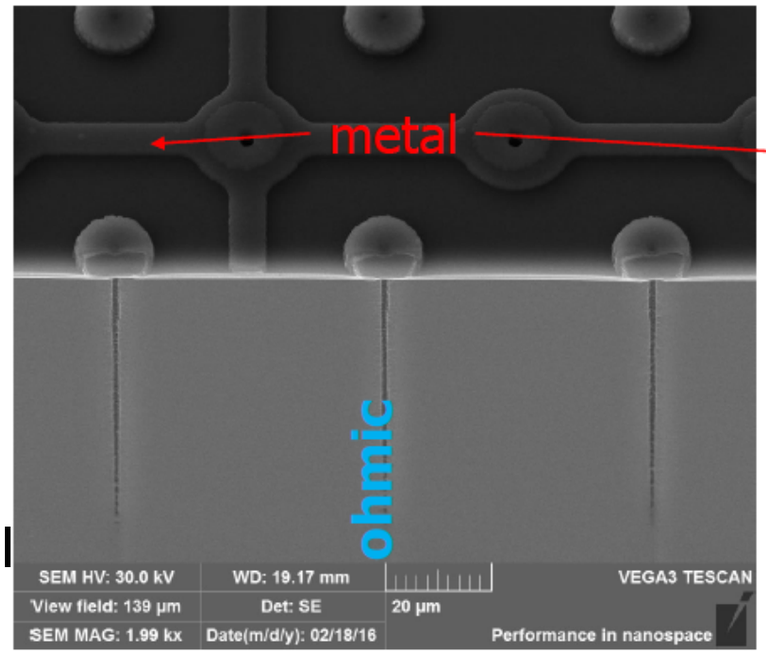
25x100 µm² 2E

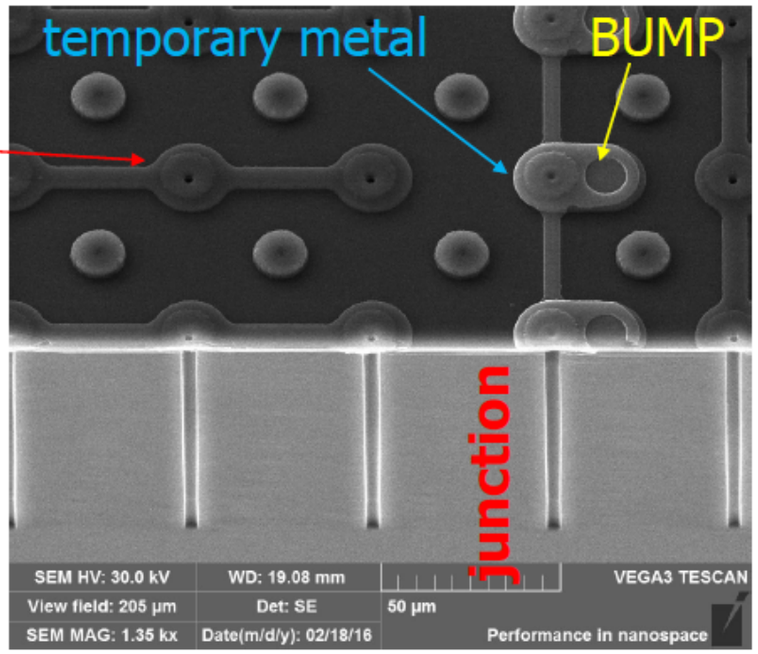


- **50x50 µm²** with 1 junction electrode (**1E**) and **25x100 µm²** with 1 junction electrode (**1E**) enough space for bump pad

- **25x100 µm²** with 2 junction electrodes (**2E**) has bump pad too close to ohmic columns ➜ under test **bumps on-columns**

- **100x150 µm²** cell sizes made for compatibility with current CMS pixel readout chip (i.e. PSI46 digital)





[G.F. Dalla Betta et al., PoS (Vertex2016) 028]

Efficiency comparison

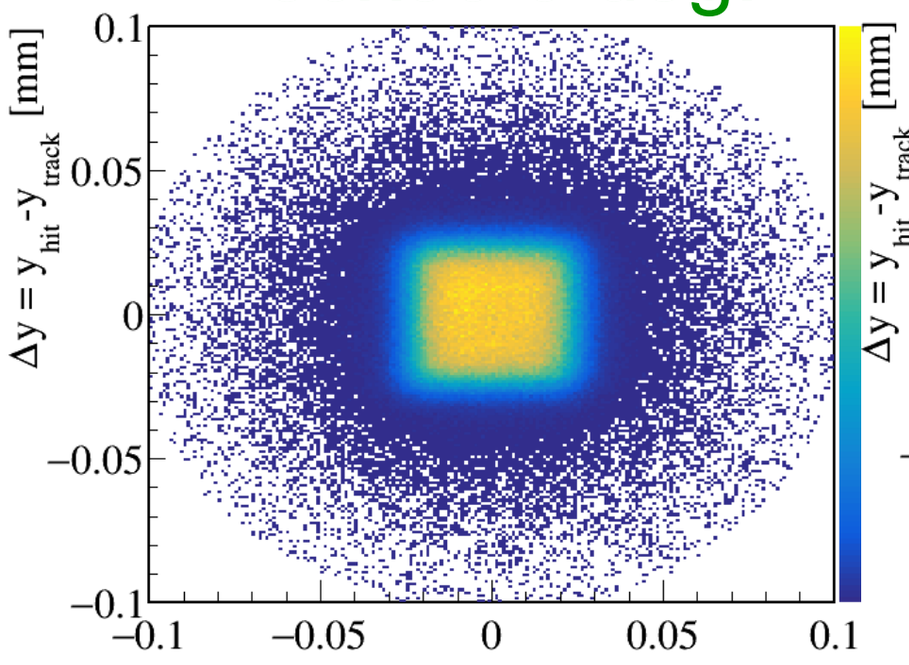
- Comparison before and after irradiation

	25x100 3D (0 deg)	50x50 3D (0 deg)	50x50 Plan (0 deg)	25x100 3D (34 deg)	50x50 3D (34 deg)	50x50 Planar (34 deg)
July (before irradiation)	97,3	98,6	98,6	99,4	99,3	99,2
October (after irradiation)	96,6	97,5				

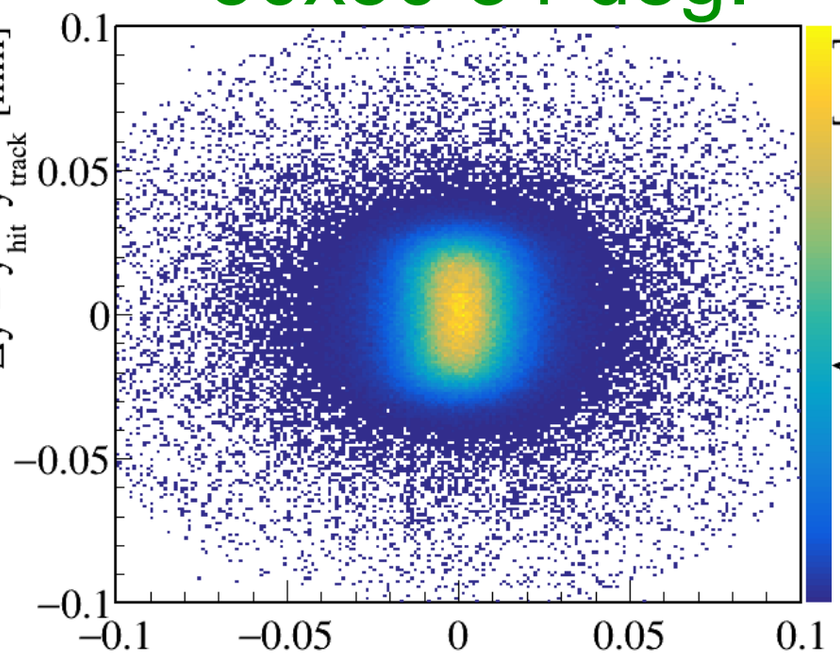
Residuals

CERN

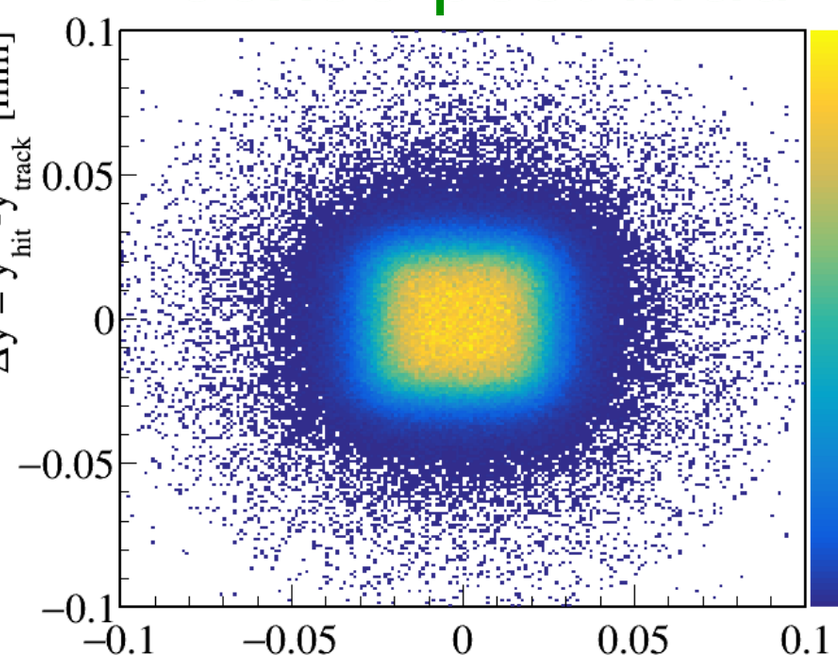
50x50 0 deg.



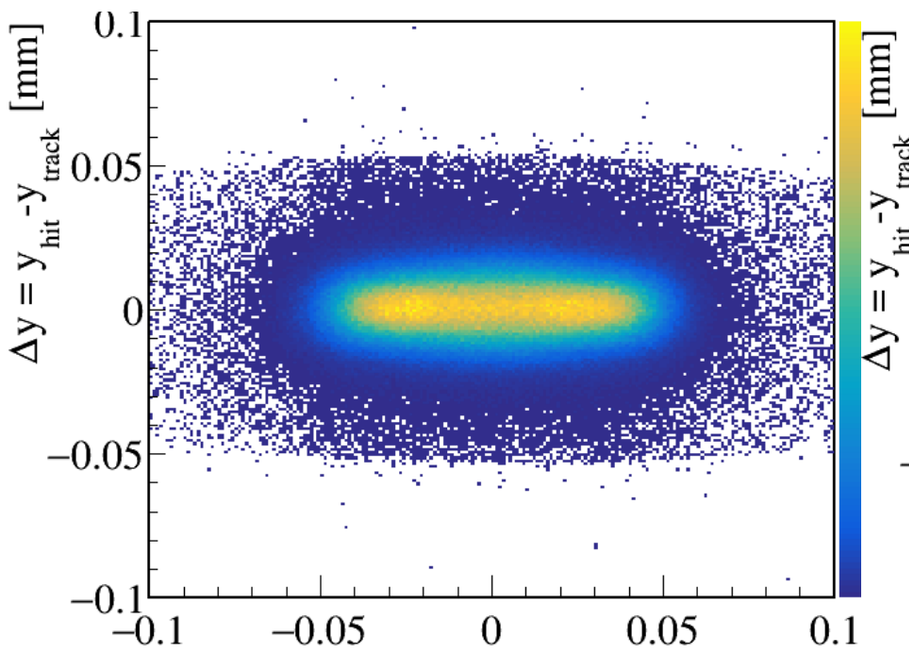
50x50 34 deg.



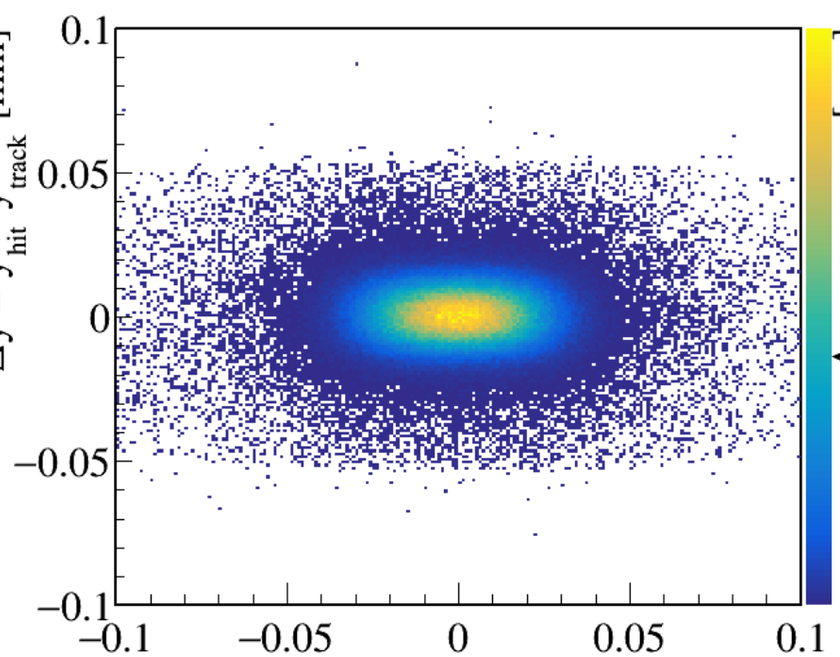
50x50 post-irrad



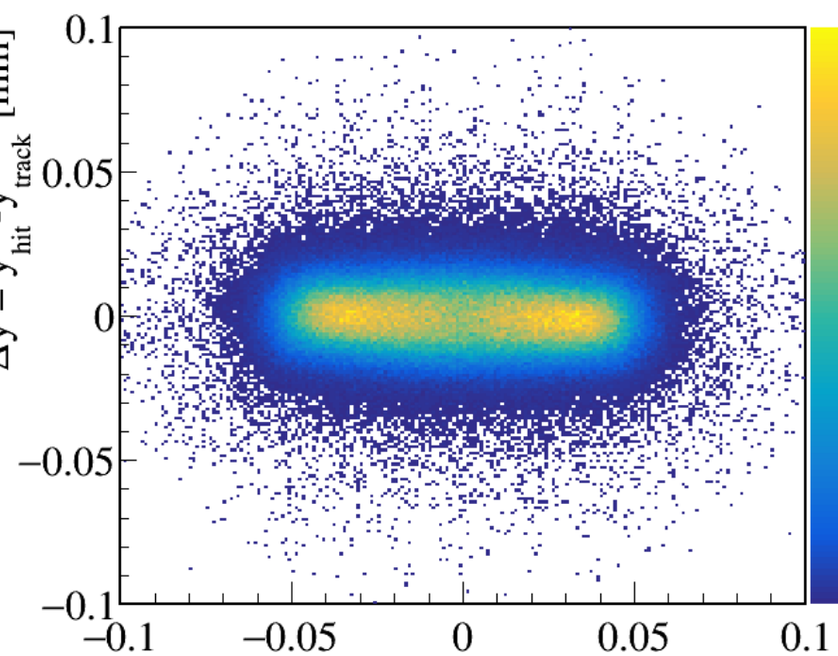
25x100 0 deg.



25x100 34 deg.



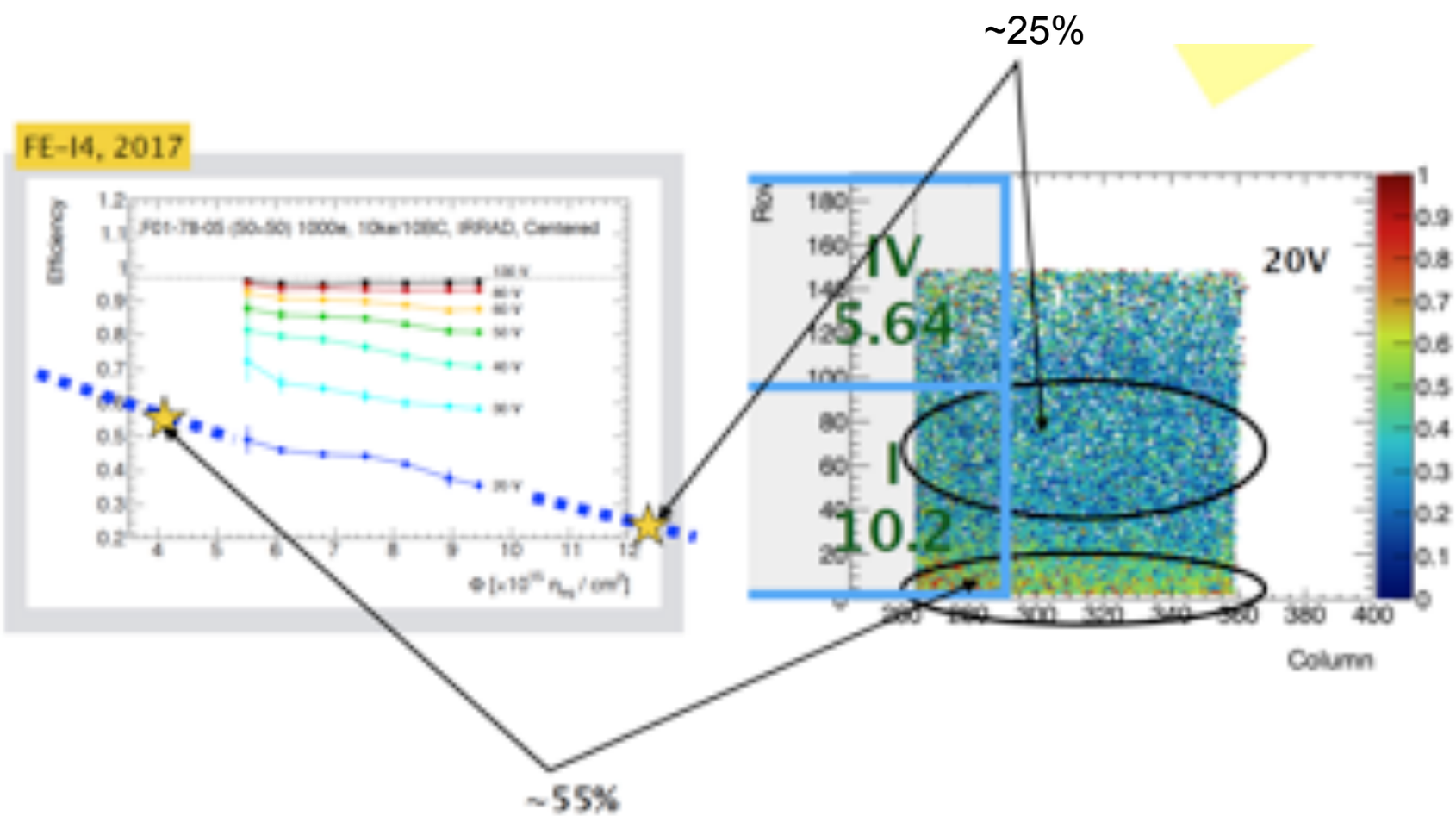
25x100 post-irrad



2nd batch RD53a @ IZM Test beam measurement (post irradiation)

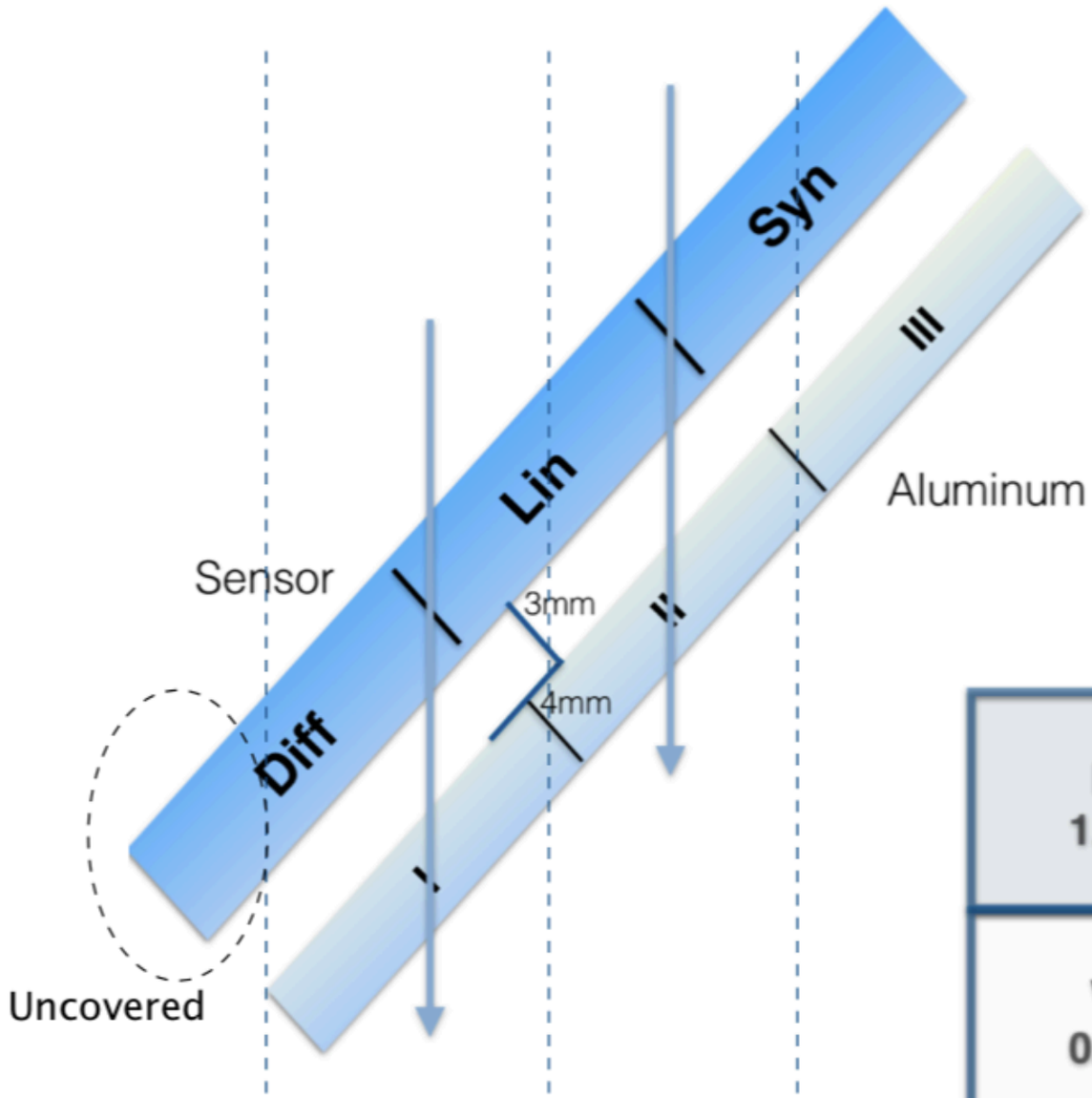
SPARE

- Seems consistent with the previous FEI4's result for 50x50 μm².
  - Rough consistency with FEI4 also for lower voltages
    i. Example for 20 V



Irradiation ATLAS

CERN IRRAD configuration and fluence measurement



- **Aluminum foil placed on the back** of sensor during irradiation
  - Modules **tilted of 55°** with respect to the beam in order to achieve uniform irradiation
  - Assuming 3mm of distance from the assembly this introduces **a shift of ~4 mm** on the X direction

***10^{15} n_{eq}/cm^2**

III 1.14	II 3.36	I 10.02
VI 0.78	V 2.16	IV 5.64

Slide provided from S. Terzo, G. Giannini

Overview of the 2nd production

Good RD53a (out of 18)	**8**	**8**	**10**	**9**	**8**
~77% **50x50(1E)** (out of 8)	6	7	6	7	5 (TB-Jul:1)
~73% **25x100(1E)** (out of 3)	2	1	3	2	3
~5% **25x100(2E)** (out of 7)	0	1	1 (TB-Jul:1)	0	0
Good FEI4 (out of 5)	**2**	**2** (TB-May:1)	**4**	**3**	**1**