33rd RD50 workshop – CERN, 26-28/11/2018

Performance of thin planar n-on-p silicon pixels after HL-LHC radiation fluences

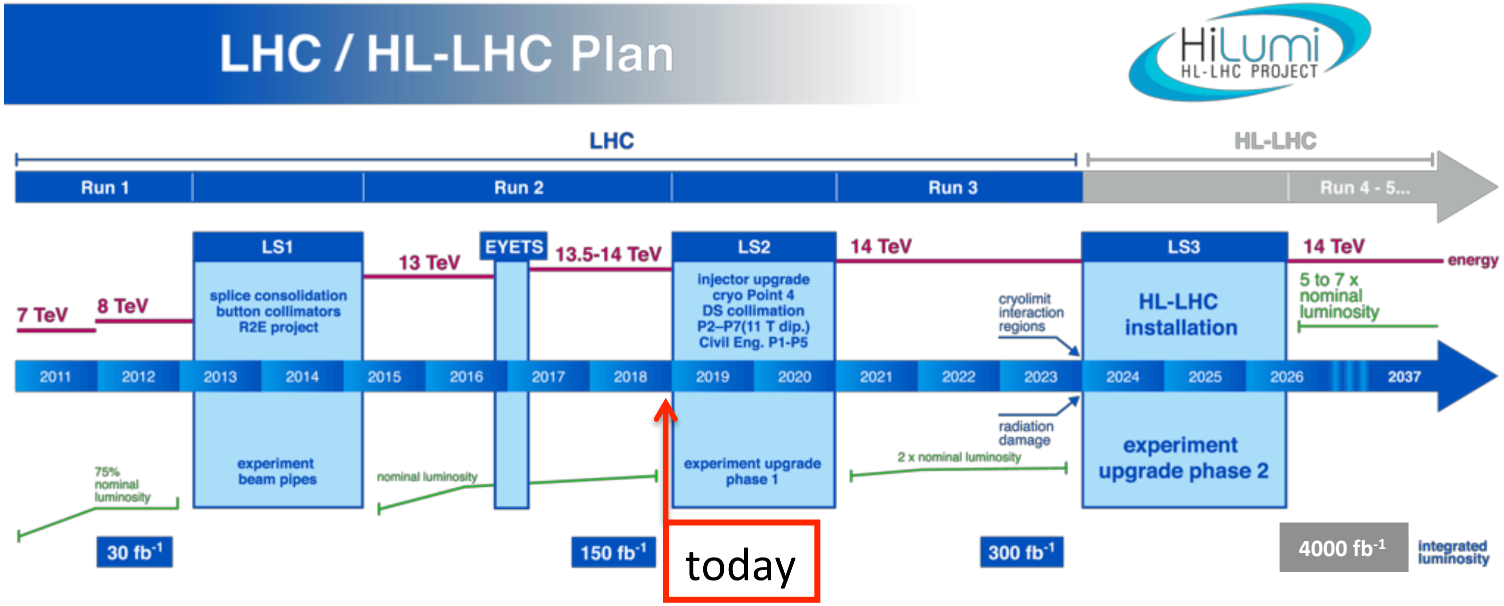
M. Bomben, G. Calderini, A. Ducourthial,
R. Taibah, F. Crescioli, L. D'Eramo,
I. Luise and G. Marchiori
LPNHE & UPD, Paris

Outline

- Introduction on the LPNHE planar pixel productions
- Second production: radiation hardness of thin pixel detectors
- Third production: edge efficiency and radiation hardness of thin pixel detectors
- All productions: comparison of biasing structures
- Conclusions and outlook

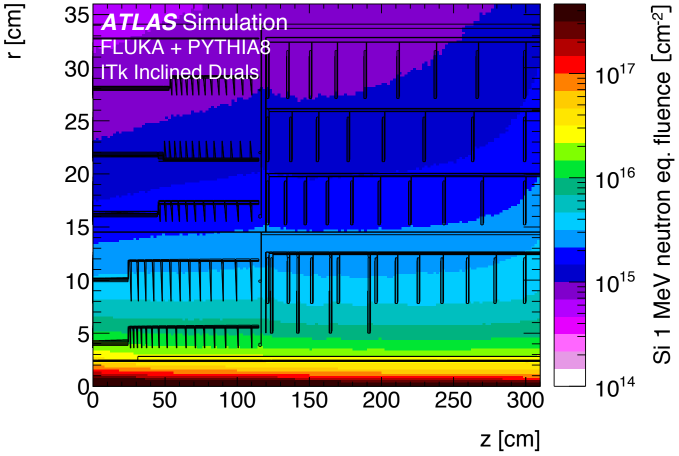
INTRODUCTION

High Lumi LHC (HL-LHC) challenges



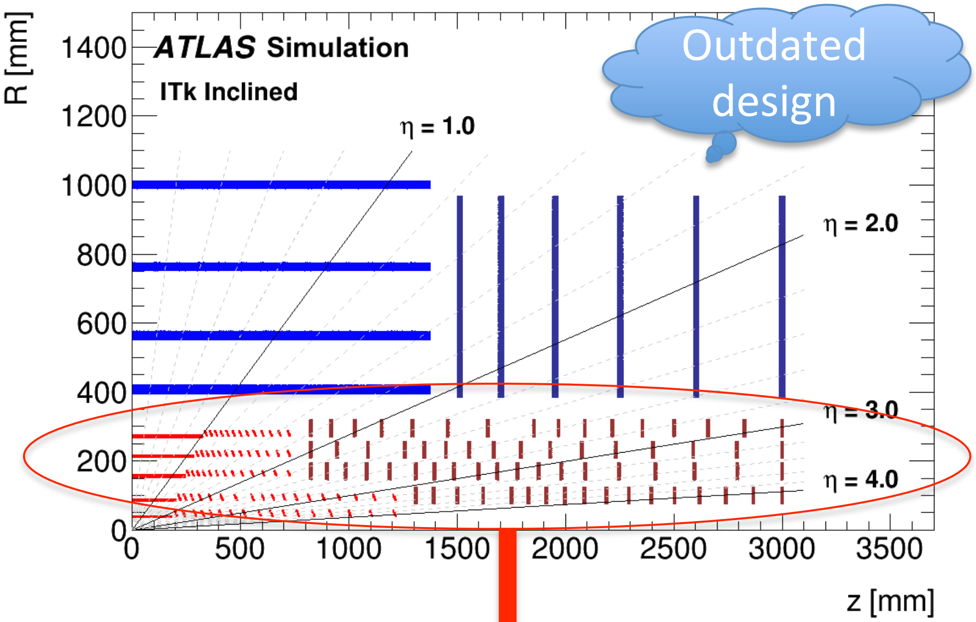
Higher luminosity to fully exploit LHC physics reach potential

Parameter	LHC	HL-LHC
instantaneous luminosity L [cm^{-2}s^{-1}]	1.0×10^{34}	7.5×10^{34}
average number of pile-up events μ	25	200
track rate density for the innermost pixel layer $\mathcal{N}$ [MHz cm^{-2}]	0.25	2
fluence to the innermost pixel layer Φ [1 MeV n_{eq}/cm^2]	5×10^{15}	2×10^{16}
total ionising dose to the innermost pixel layer TID [MRad]	160	1700

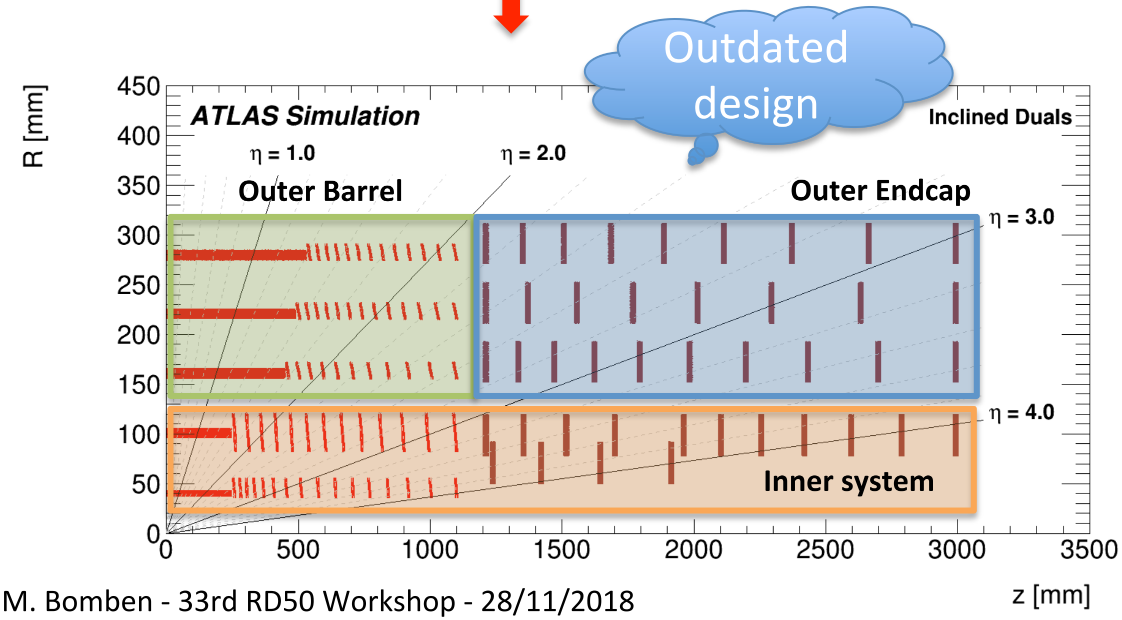


Much harsher environment in terms of:
- Event rate
- Number of collisions
- **Radiation damage to tracking detectors**

ATLAS Inner Tracker (ITk)



Outdated design



Outdated design

- Replacement of Inner Detector
- All Silicon system (pixels+strips)
- Coverage down to |η|=4

- **Pixels detector**: > 10 m^2 of 50x50 μm^2 pixels
- New inclined geometry:
- ✓ Larger coverage
- ✓ Less material

- ➢ Radiation hardness:

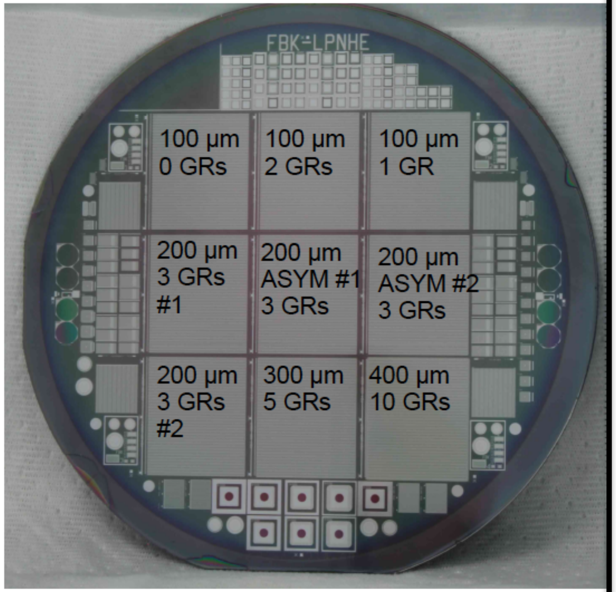
- ➢ 3D for innermost layers

- ➢ **Thin planar everywhere else**

- ➢ **ITk requirement: hit eff. > 97%**

LPNHE planar pixel productions

PAE1

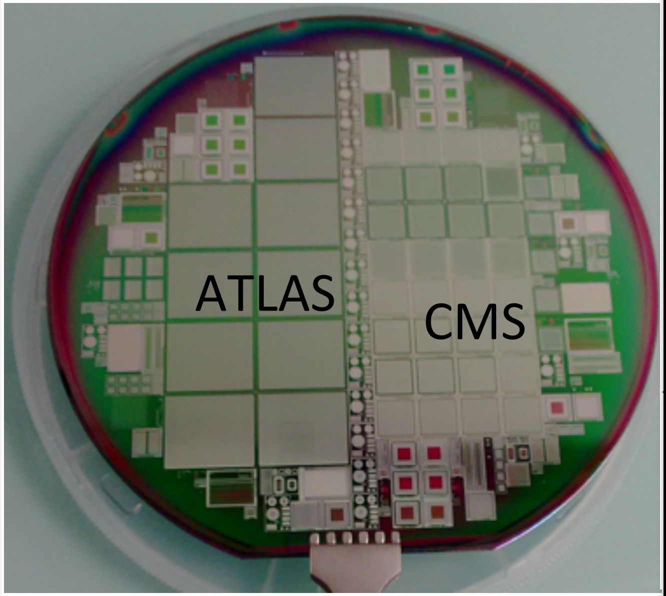


4” 200 µm thick n-on-p
Active Edge technology
Pixel-to-edge down to 100 µm
Tested extensively on beam

NIM A 712 (2013) 41–47

JINST 12 P05006 (2017)

P2

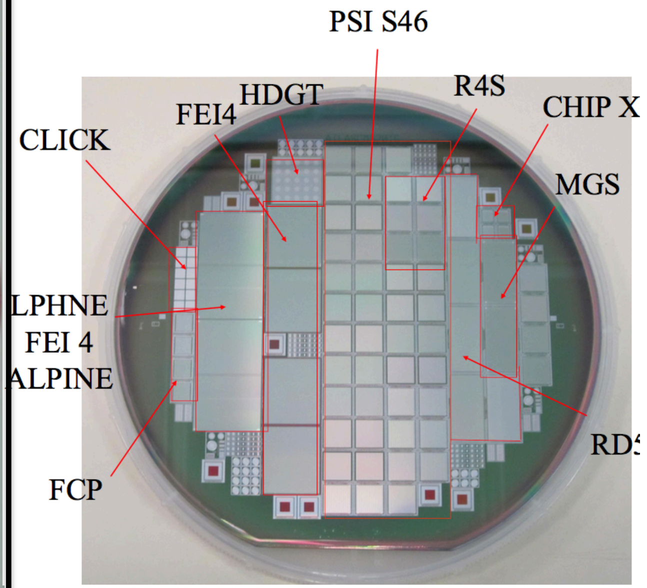


6” 130 µm thick n-on-p
INFN ATLAS/CMS project
Tested extensively on beam,
after irradiation too

2017 JINST 12 C12038

arXiv:1810.07279

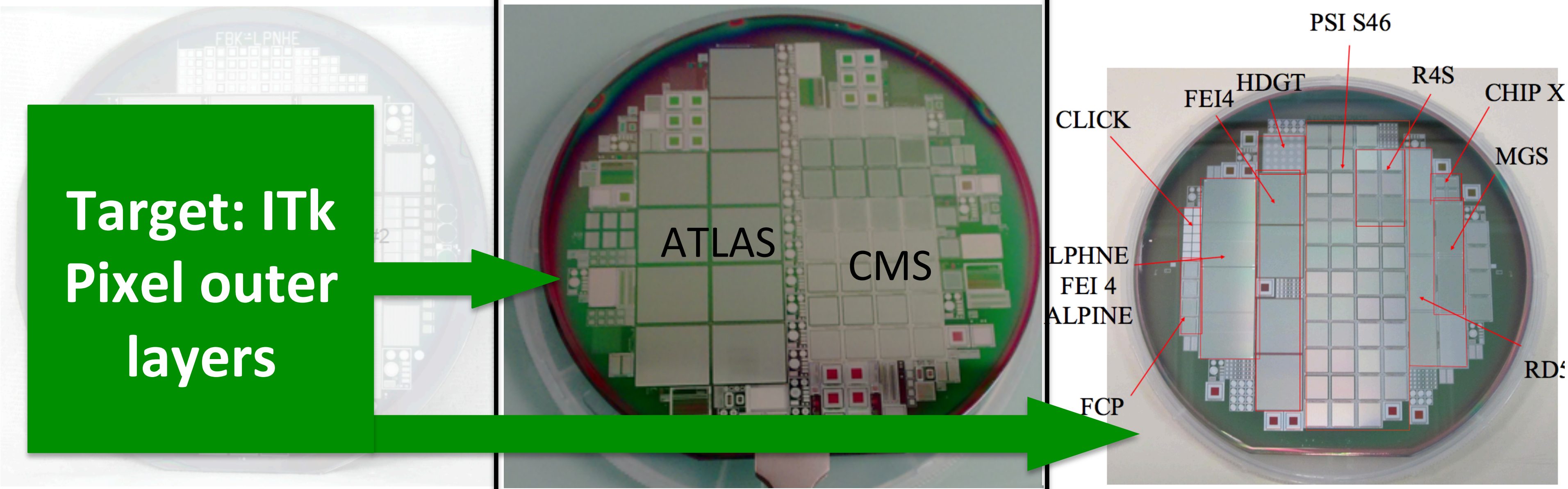
PAE3



6” 130 µm thick n-on-p
INFN ATLAS/CMS project
Active Edge technology
Pixel-to-edge down to 50 µm
RD53 compatible sensors
Measured on beam,
after irradiation too

NIM A 2018 – in press

LPNHE planar pixel productions



Target: ITk Pixel outer layers

PAE1

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NIM A 712 (2013) 41–47

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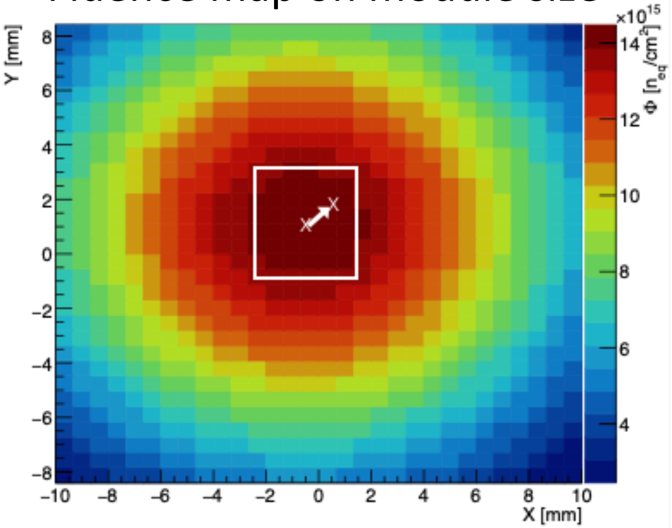
NIM A 2018 – in press

SECOND PRODUCTION: RADIATION HARDNESS OF THIN PIXEL DETECTORS

Irradiated pixel detectors

Fluence map on module size

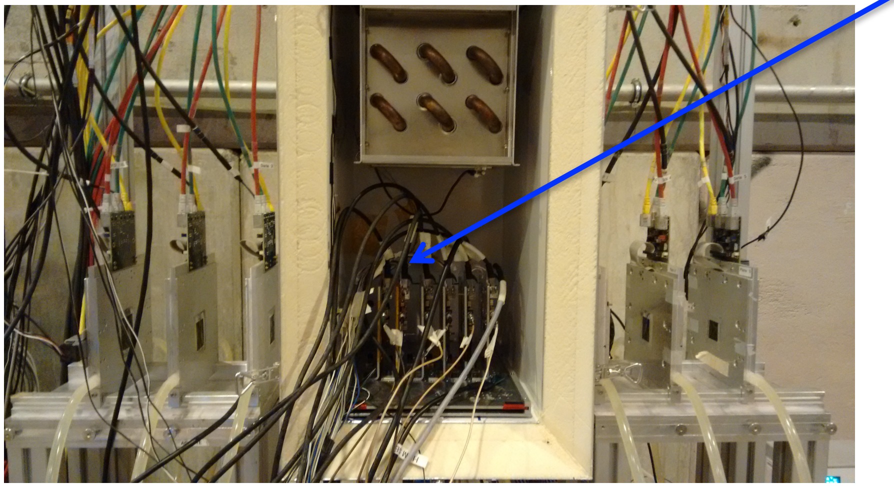


130 µm thick FE-I4 detector irradiated up to 1.4e16 n_{eq}/cm^2 at CERN IRRAD (24 GeV/c protons)

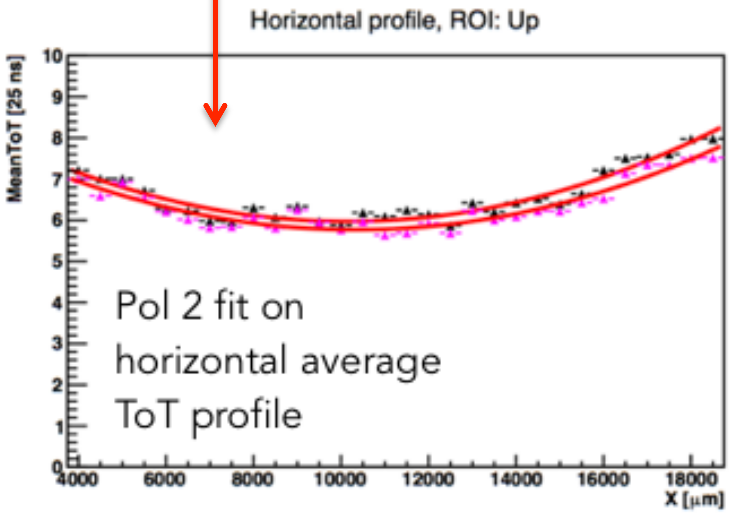
Gaussian beam profile (20 x 20 mm^2 FWHM)

Position unc. ~ 2 x 2 mm^2 (for ref. white box in the map)

Peak position re-calculated on data (white arrow in the map)



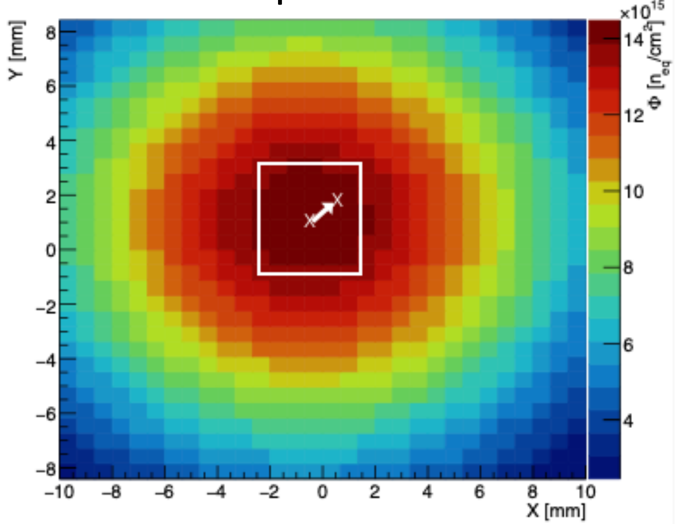
Module measured w/ 120 GeV π



Pol 2 fit on horizontal average ToT profile

Irradiated pixel detectors

Fluence map on module size



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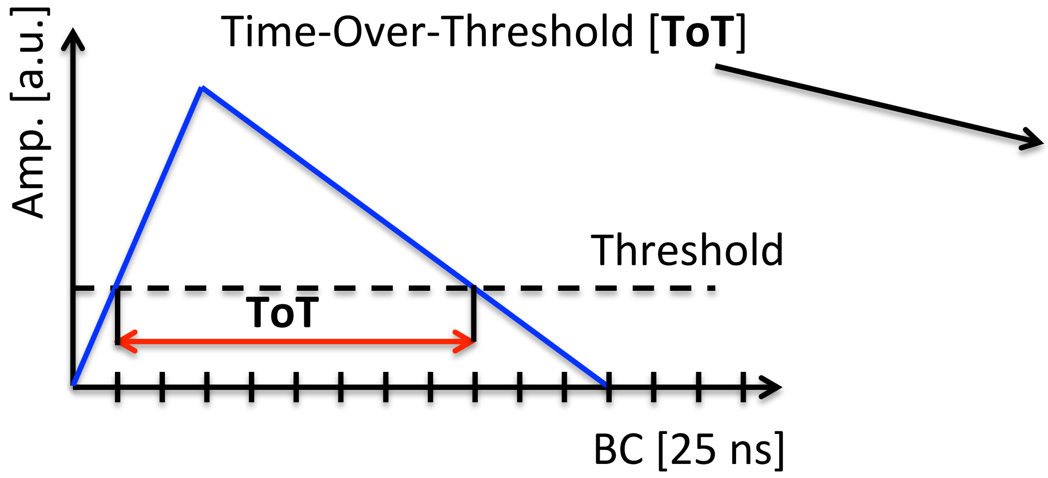

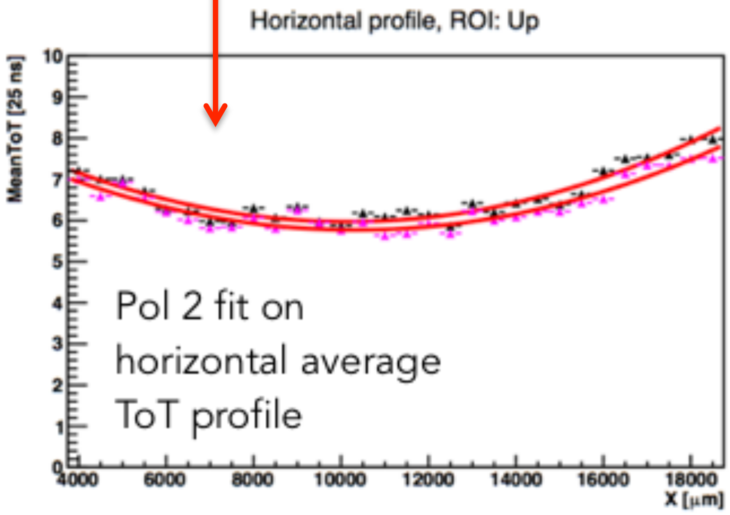

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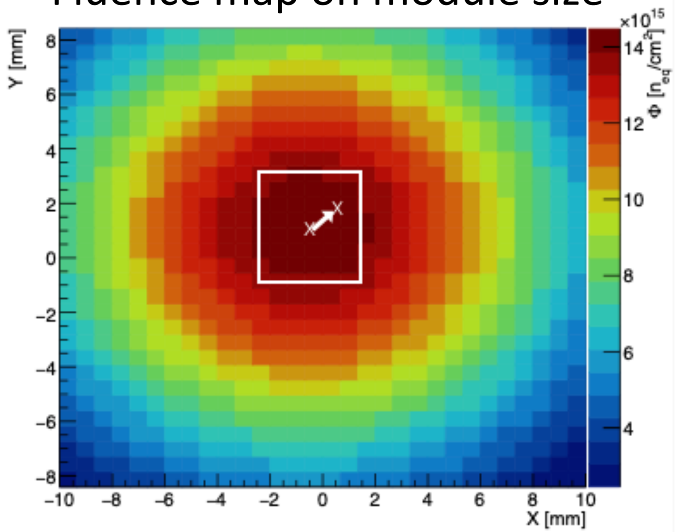

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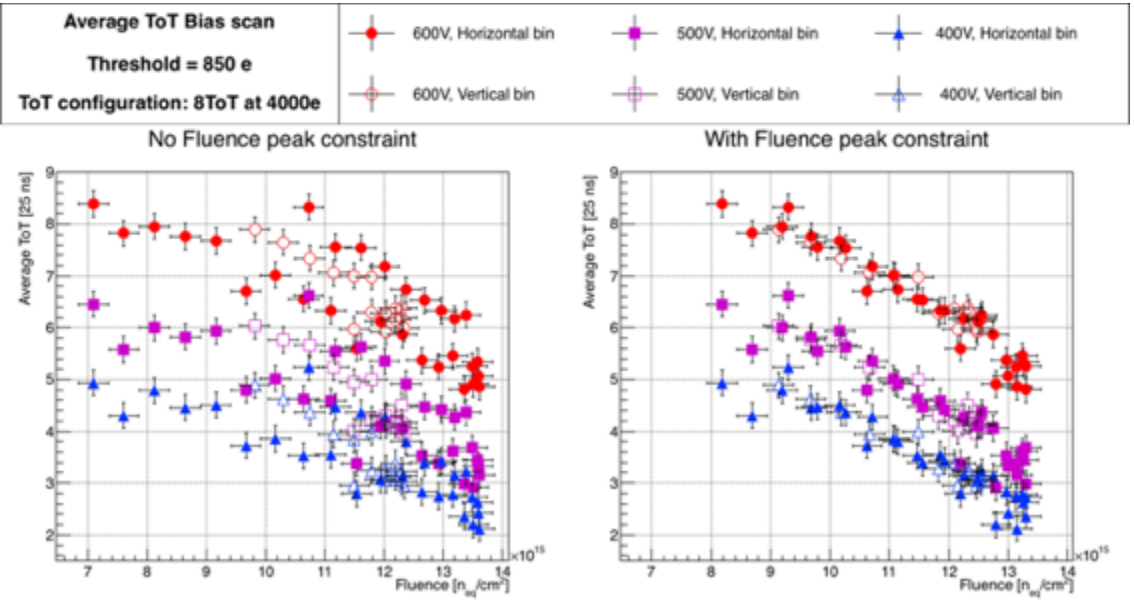


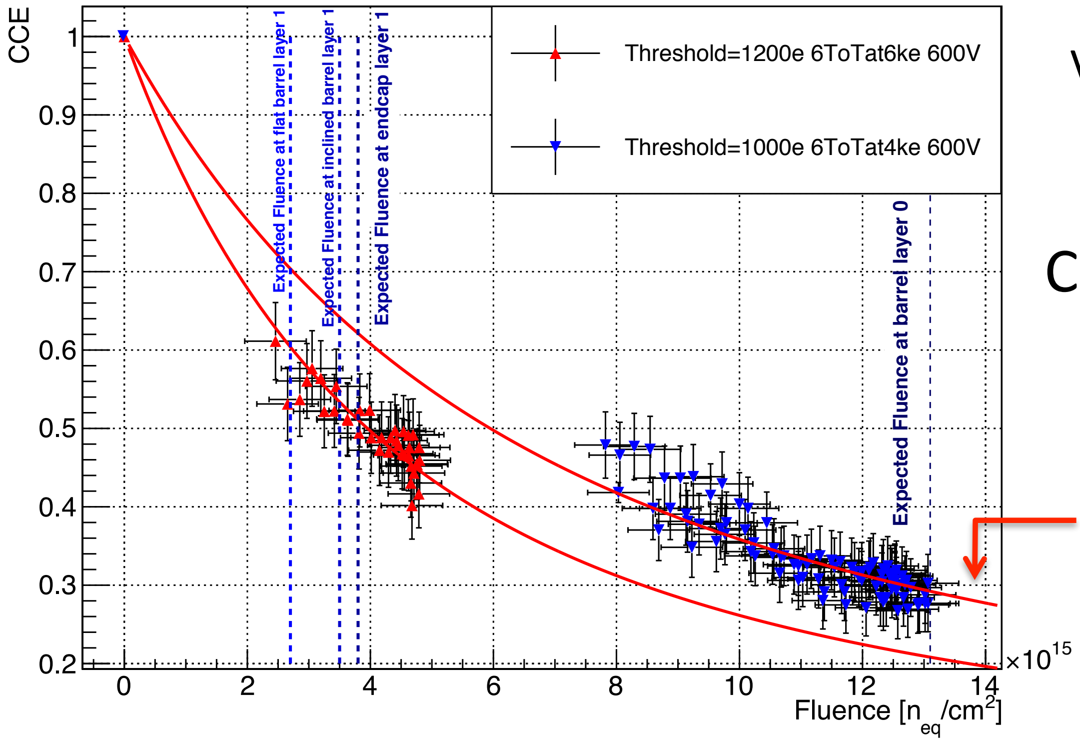
No Fluence peak constraint

With Fluence peak constraint

- ➢ Data-driven approach
- ➢ Adjustment within uncertainties
- ➢ Much less charge dispersion

Thin pixel performance

Charge Collection Efficiency (CCE)



Hor. uncertainty bar ➔ fluence

Ver. uncertainty bar ➔ ToT dispersion

CCE down to 50% for innermost planar pixel layer

Fit with Hecht formula*
β = (3.6x10^{-16} ± 0.1) cm^{2}/ns
for large fluences
To be interpreted as a lower limit

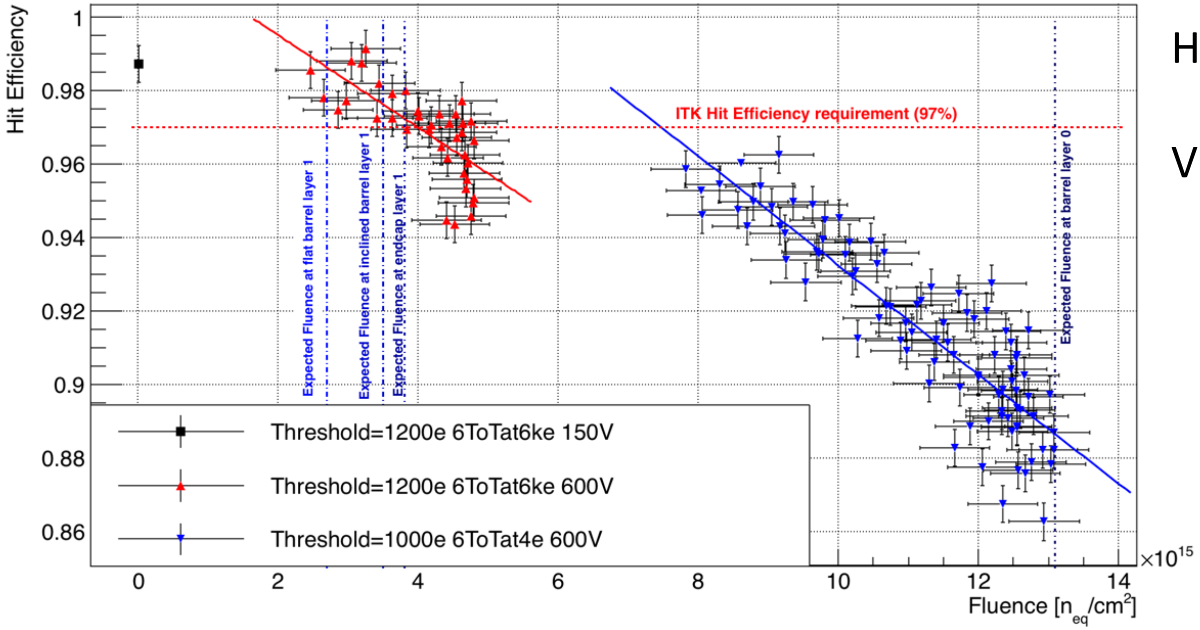
Calibration	Fluences ($\Phi = 1 \times 10^{15} \mathrm{n_{eq}/cm^2}$)			
	2.7	3.5	3.8	13.1
Thr.=1200e, 6ToT at 6000e, CCE =	61%	53%	51%	21%
Thr.=1000e, 6ToT at 4000e, CCE =	71%	64%	62%	29%

arXiv:1810.07279

*Zeit. Physik. (1932) 77:235

Thin pixel performance

Hit efficiency



Hor. uncertainty bar ➔ fluence

Ver. uncertainty bar ➔ statistical

Hit eff. > 97% for fluence ≤ 7.5e15 n_{eq}/cm^2

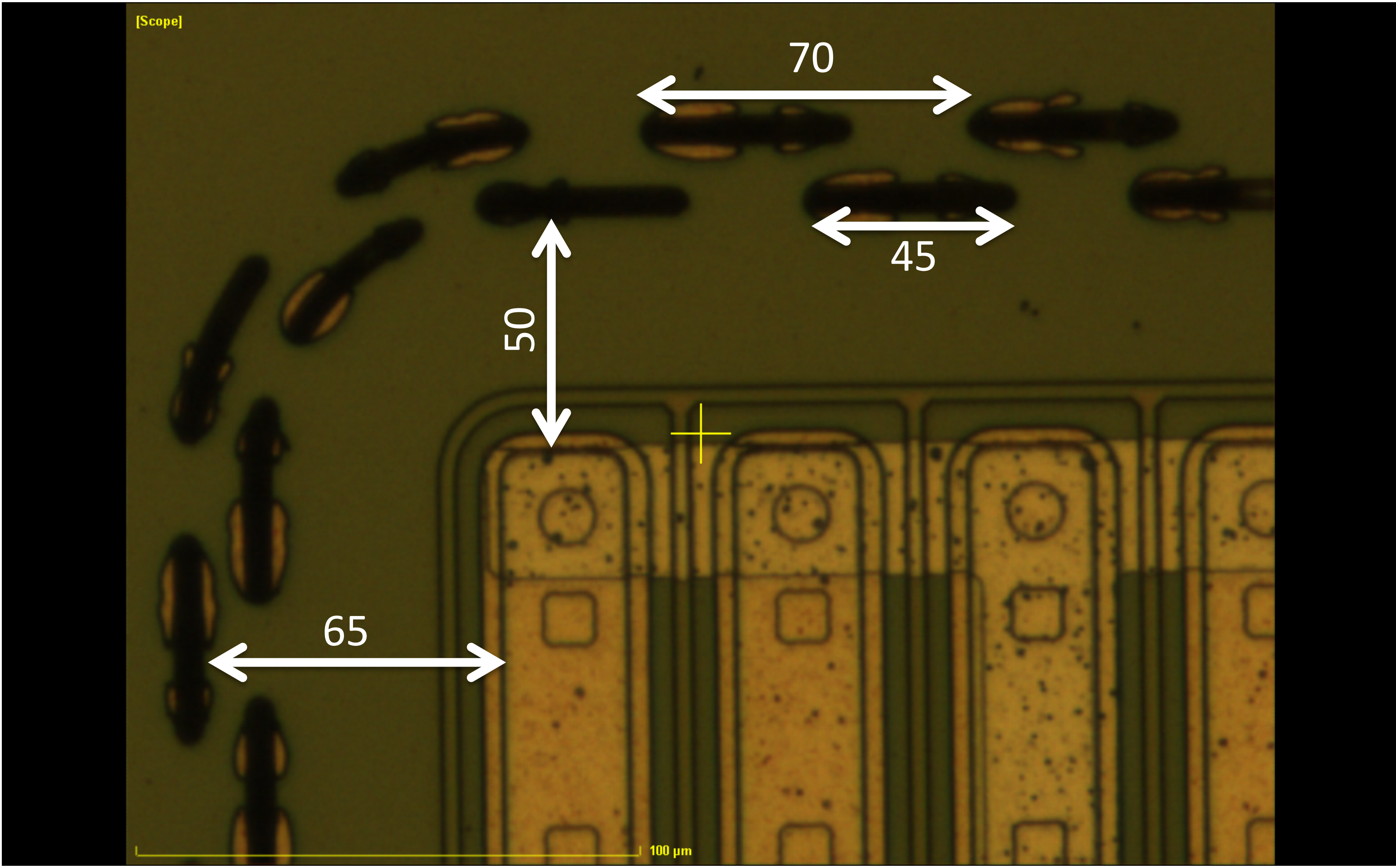
Fully qualified for ITk

arXiv:1810.07279

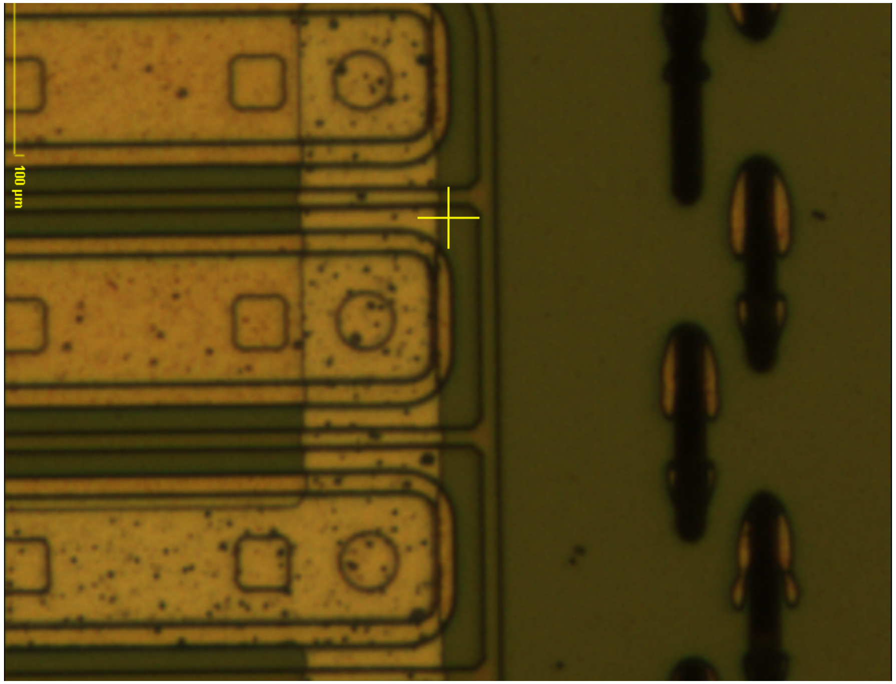
Fluence ($\Phi = 1 \times 10^{15} n_{eq}/cm^2$)	2.7	3.5	3.8	7.45	13.1
Threshold (electrons)	1200	1200	1200	1000	1000
ToT tuning (ToT corresponding to ke-)	6 at 6	6 at 6	6 at 6	6 at 4	6 at 4
Extrapolated Hit Efficiency (%)	98.6	97.6	97.2	97.0	88.6

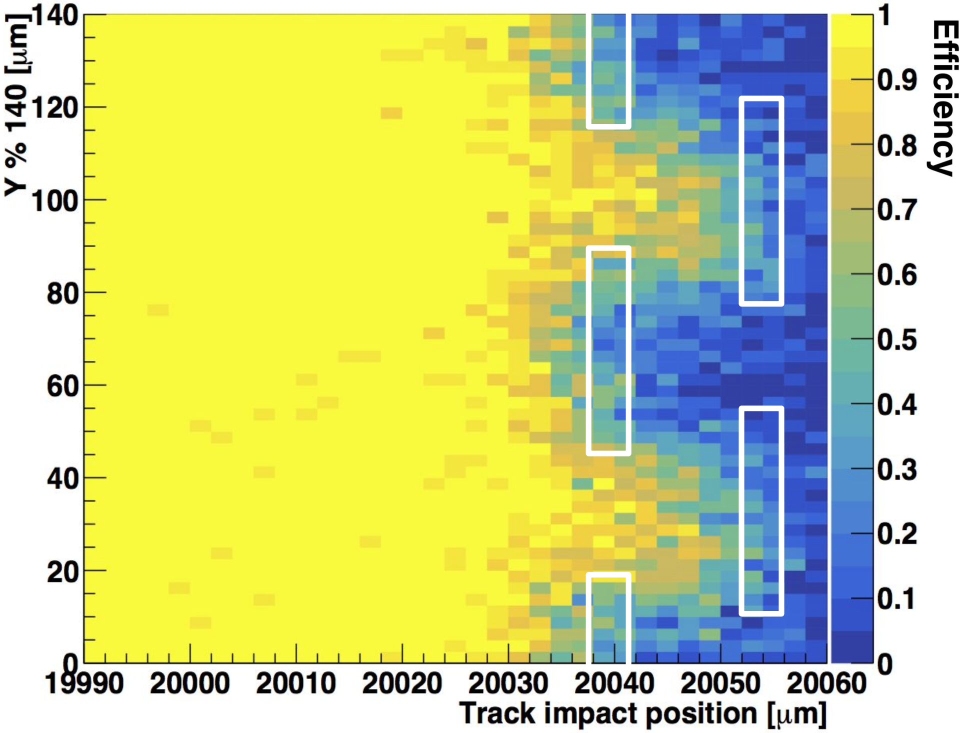
THIRD PRODUCTION: EDGE EFFICIENCY AND RADIATION HARDNESS OF THIN PIXEL DETECTORS

PAE3 sensor with staggered trenches



Active-edge performance before irradiation





130 µm thick sensor with **staggered trenches**, no GRs, ~50 µm last pixel to last edge 2 fences of discontinued edges (such sensors do not require a support wafer)

The efficiency follows the edge pattern

The efficiency is higher than 50% up to 44 µm from the last pixel

Active-edge performance after irradiation

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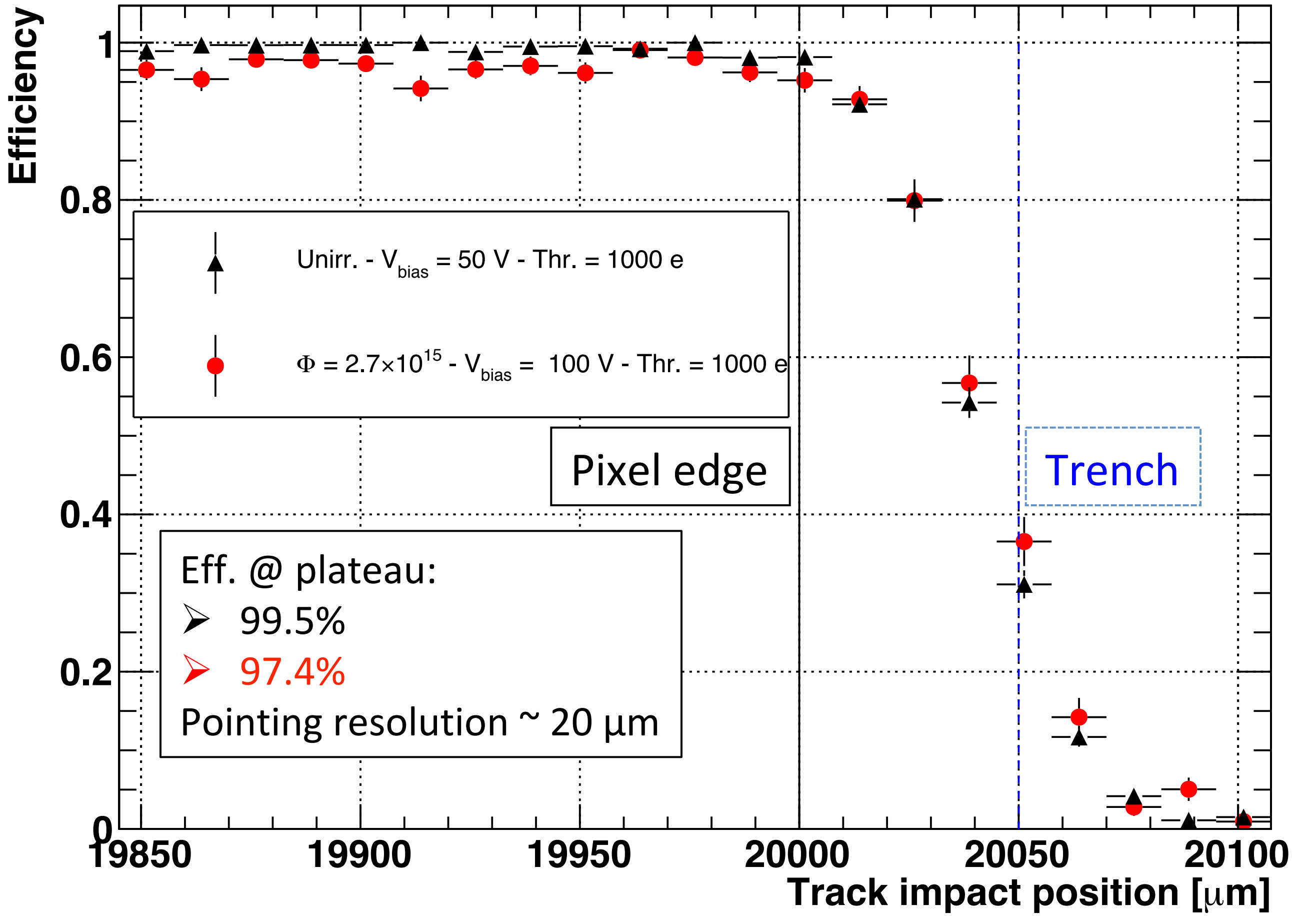
Uniform irradiation at KIT (23 MeV p)
$\Phi = 2.7\text{x}10^{15}\ n_{eq}/cm^2$



Eff. @ plateau:
- 99.5%
- 97.4%

Pointing resolution ~ 20 μm

Edge efficiency after **irradiation** + in soft BD conditions:

Comparable to **unirradiated** performance

Efficiency higher than 80% up to 25 μm from last pixel

Module measured w/ 4 GeV electrons

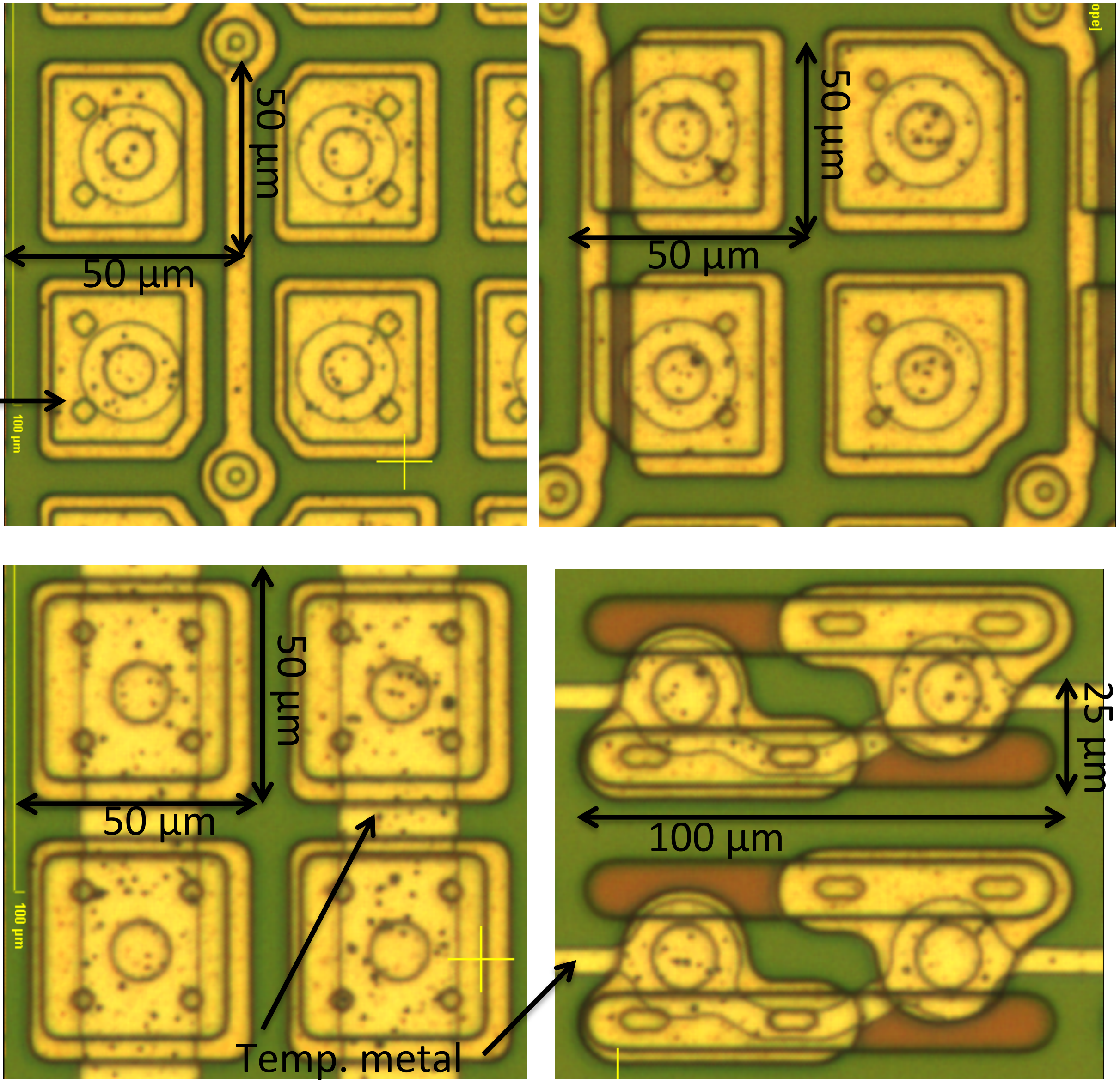
RD53A compatible sensors

Different solutions implemented on the wafer;

2 designs with bias dot

Temporary metal for
50x50 µm^2 and 25x100 µm^2

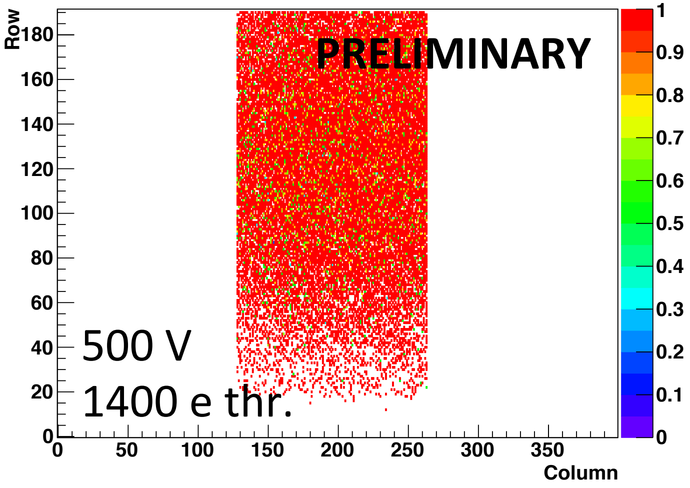
In the following preliminary results after irradiation of this design (50x50 µm^2 & bias dot)

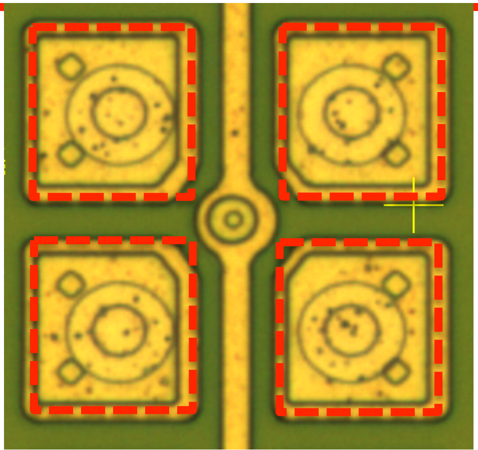


Results in preparation also for the 25x100 design

Performance of irradiated RD53A

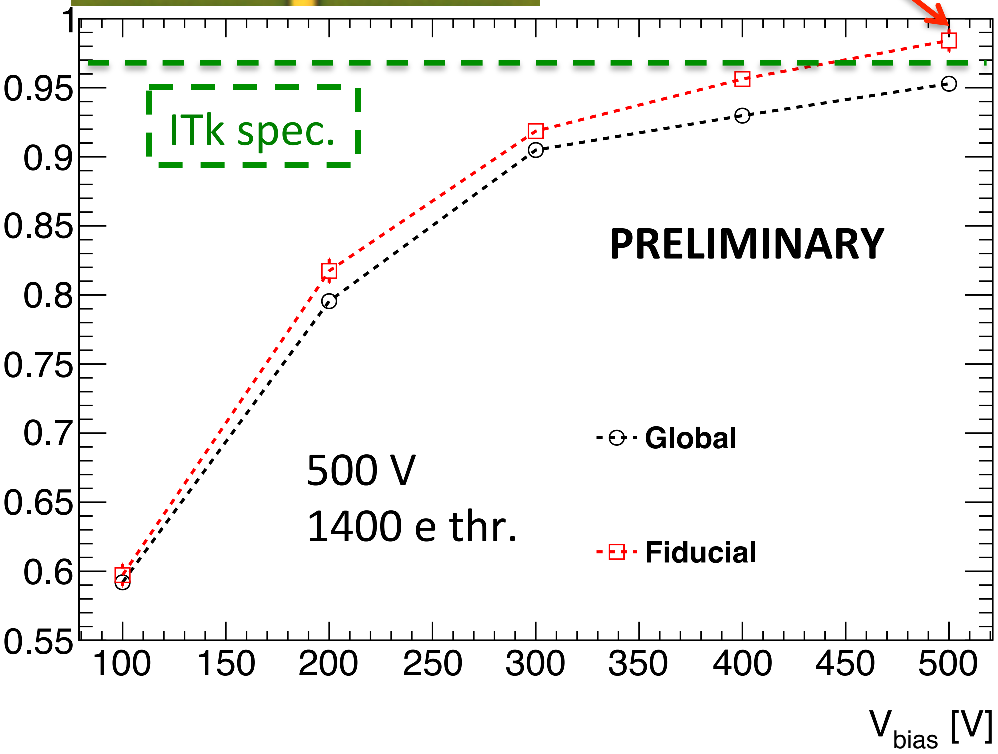
Irr. at CERN IRRAD @ **$\langle\Phi\rangle = 5\times10^{15}\ n_{eq}/cm^2$**
Fluence map being reconstructed





Inner (fiducial) region

98.4% @ 500 V

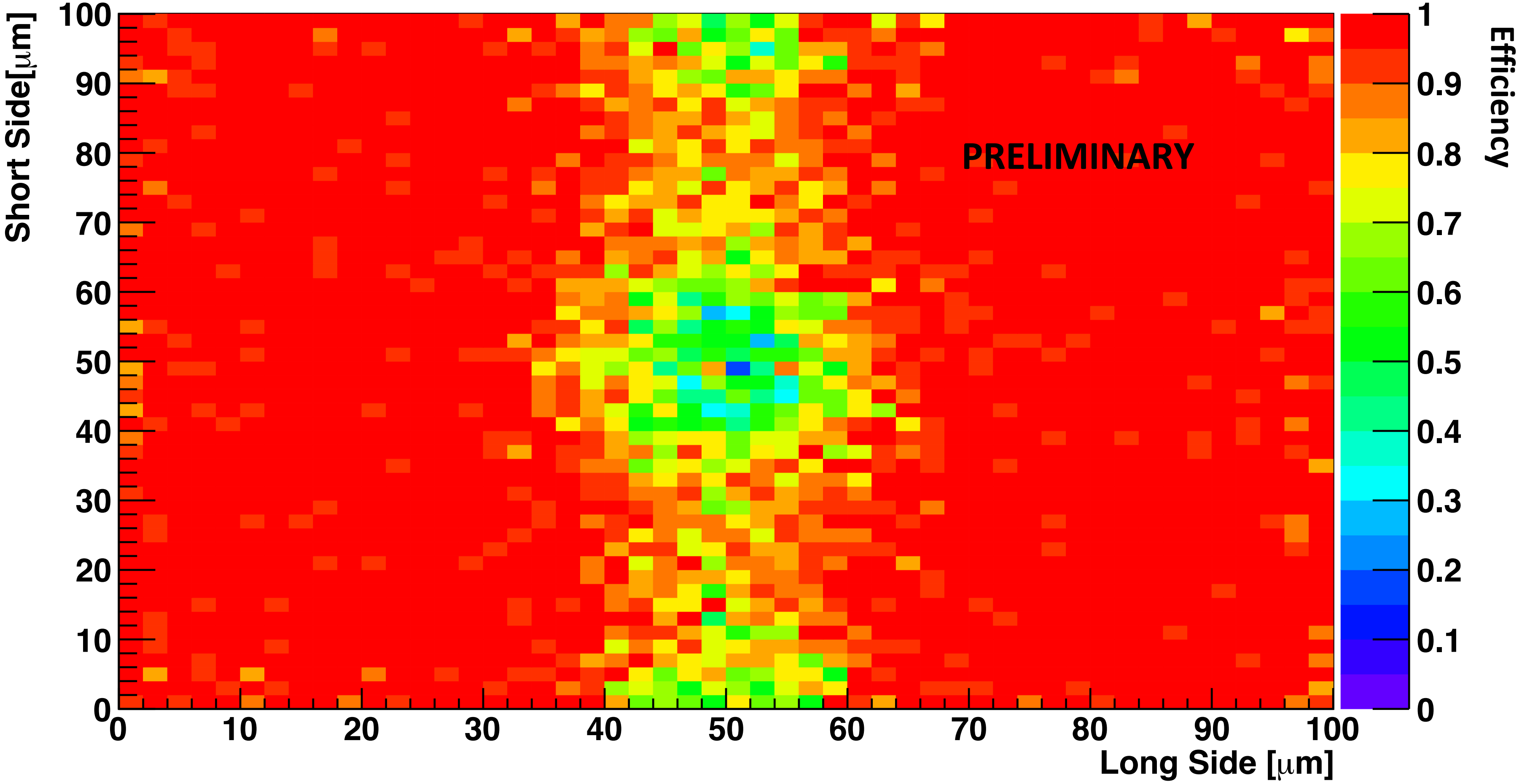


Significant efficiency loss when whole matrix is considered

Restricting analysis to the inner part of the cell brings back > 97% hit efficiency

Hit efficiency map

500 V
1400 e thr.



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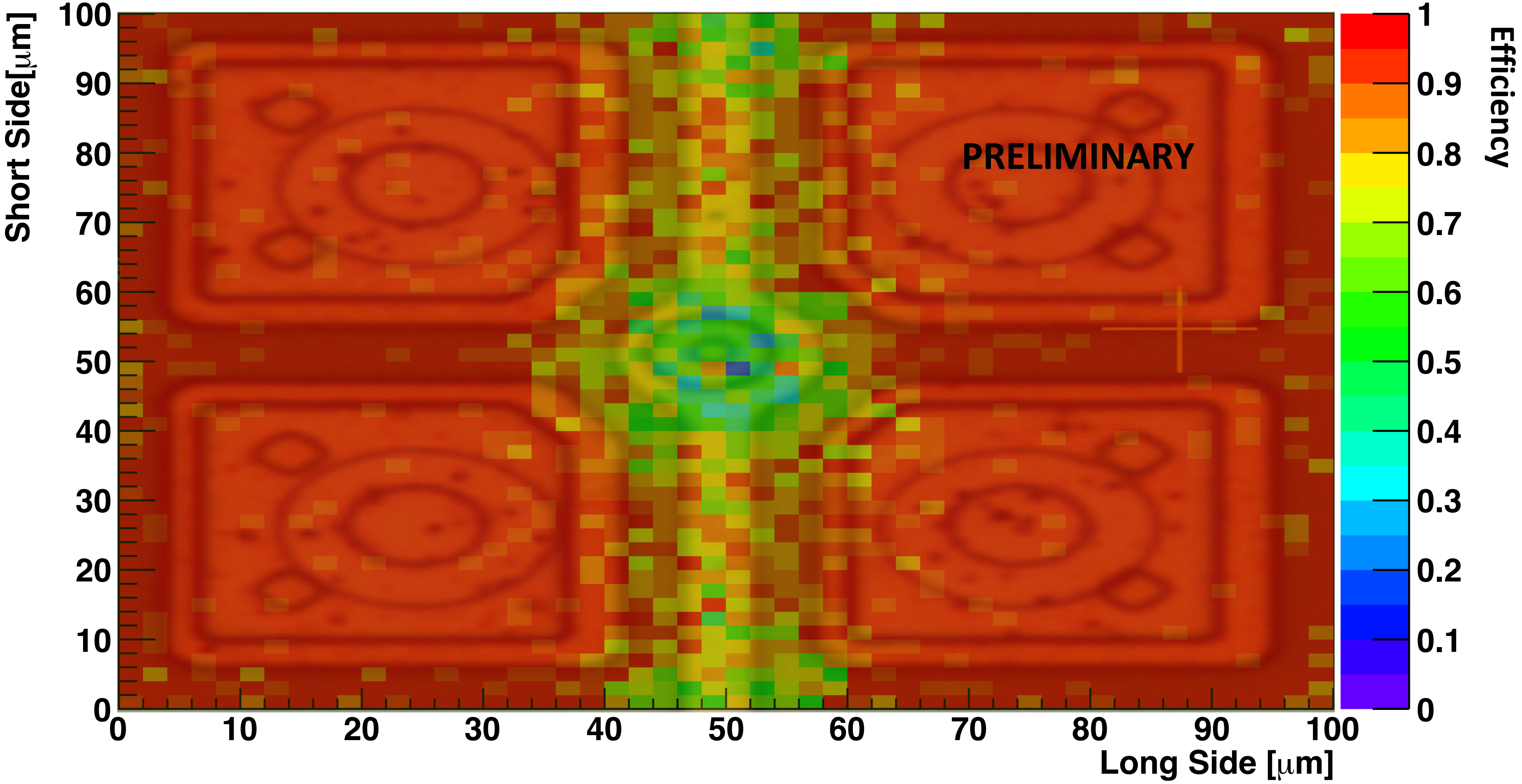
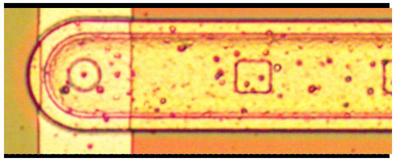
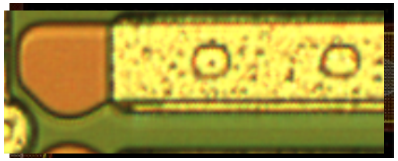
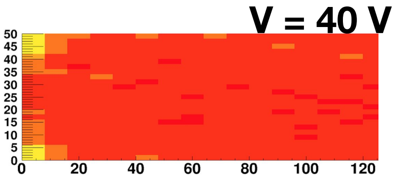
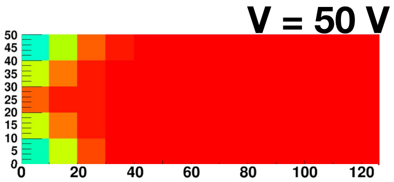
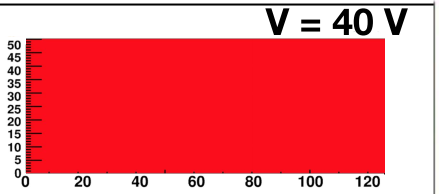
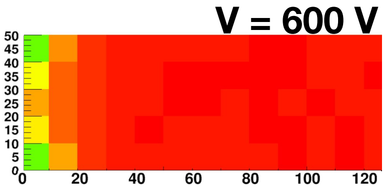
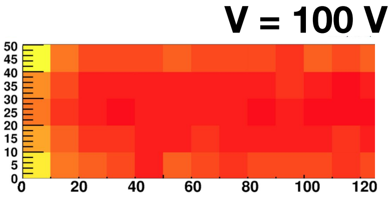
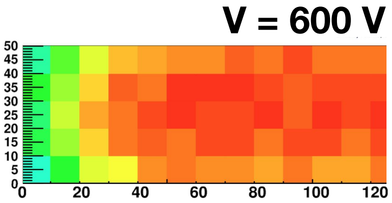
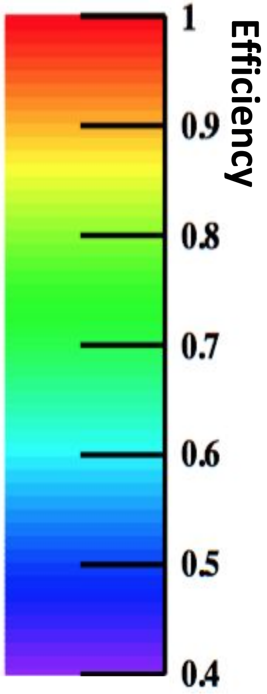


ALL PRODUCTIONS: COMPARISON OF BIASING STRUCTURES

Biasing structures

	LPNHE 7 - PAE1 **Temporary Metal**	**W80 - P2** **Bias Dot**	**M1.4 - PAE3** **Temporary Metal**
			
Un-irradiated			
Fluence **3 x 10^{15} n_{eq}/cm^2**			
Fluence **1 x 10^{16} n_{eq}/cm^2**			



Temporary metal considered for ITk. We were the first to propose it for planar

CONCLUSIONS & OUTLOOK

Conclusions & outlook

- Unprecedented HL-LHC radiation fluences demand for radiation hard pixel detectors
- Thin n-on-p planar pixels sensors produced at FBK by LPNHE proved to meet the stringent ATLAS Inner Tracker specifications after HL-LHC like fluences
- New small pitch pixels show once more the interest of using temporary metal as biasing solution, assuring large and uniform hit-efficiency, after irradiation too
- Next steps: test more prototypes and improve pixel cell design

Acknowledgments

The second and third production were supported by the Italian National Institute for Nuclear Physics (INFN), Projects ATLAS, CMS, RD-FASE2 (CSN1):

Principal investigators: Marco Meschini, Gian Franco Dalla Betta, Maurizio Boscardin, Giovanni Darbo, Gabriele Giacomini, Sabina Ronchin, Alberto Messineo

Irradiations and testbeam supported by AIDA-2020 Project EU-INFRA Proposal no. 654168

Many thanks to all ITk pixel testbeam community

THANK YOU
FOR YOUR ATTENTION!

Backup

Hecht formula

$$\mathrm{CCE} = \frac{\mathrm{Q}}{\mathrm{Q}_0} = \left[\frac{d_e + d_h}{w}\right] - \left(\frac{d_e}{w}\right)^2\left(1 - e^{-\frac{w}{d_e}}\right) - \left(\frac{d_h}{w}\right)^2\left(1 - e^{-\frac{w}{d_h}}\right)$$

$$d_e = v_e^{(sat)}\,\tau_e = \frac{v_e^{(sat)}}{\beta_e\ \phi}$$

Same for holes

(Brutal) approximations:

- saturated velocities
- 1D Ramo potential
- (From TCAD) same saturation velocity for electrons and holes

Full derivation also here:
M. Bomben - 2018
https://tel.archives-ouvertes.fr/tel-01824535