R&D for new high radiation tolerant pixel sensors for the high-luminosity phase of the CMS experiment at LHC

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On behalf of the CMS – Pixel R&D INFN Collaboration

13th Trento Workshop on Advanced Silicon Radiation Detectors

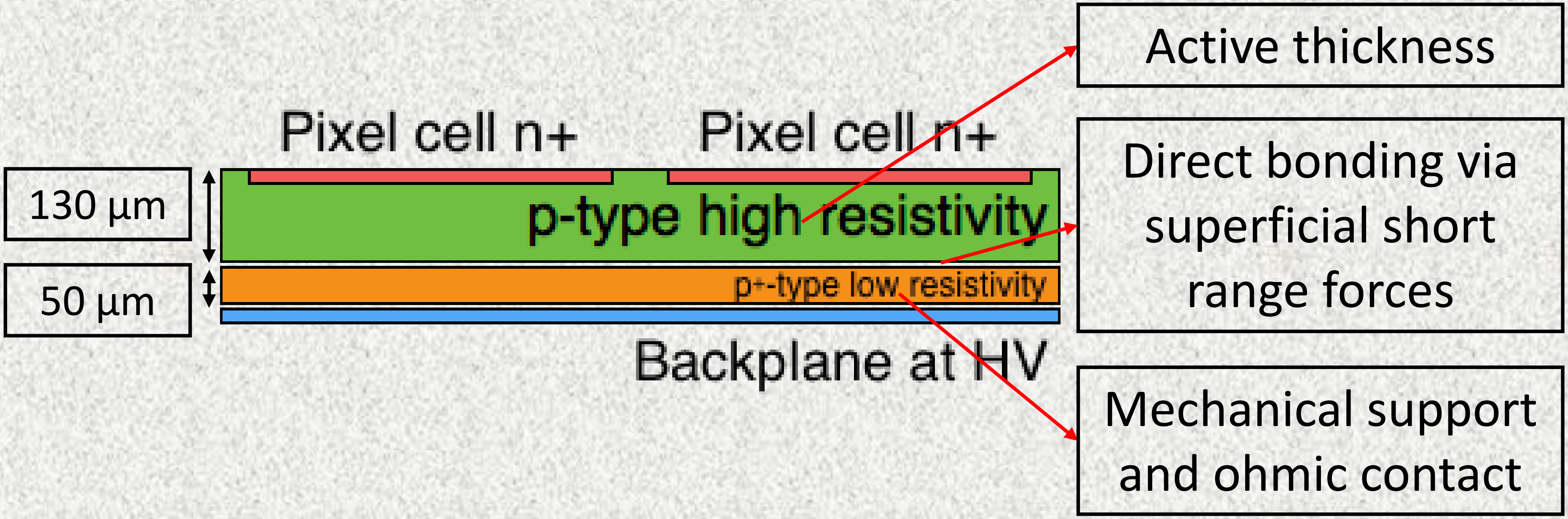
Munich 19-21 February 2018

INFN Pixel R&D: Main Design Features

High Luminosity upgrade of the CERN-LHC: operation conditions	Sensor design contraints
Luminosity $5x10^{34}/(cm^2 \cdot s)$, up to 200 events/25 ns bunch crossing	Maintain occupancy at % level and increase the spatial resolution ➜ pixel cell size ~ 25x100 µm² or 50x50 µm² currently 100x150 µm² CMS
Radiation level for first pixel layer at 3000 fb^{-1} ~$2x10^{16}$ n_{eq}/cm^2 (~10 years) ➜ carriers lifetime ~0.3 ns, mean free path ~30 µm for electrons at saturation velocity	Reduce electrodes distance to increase electric field and thus the signal ➜ thin planar or 3D columnar technologies

FBK-INFN Planar Sensors

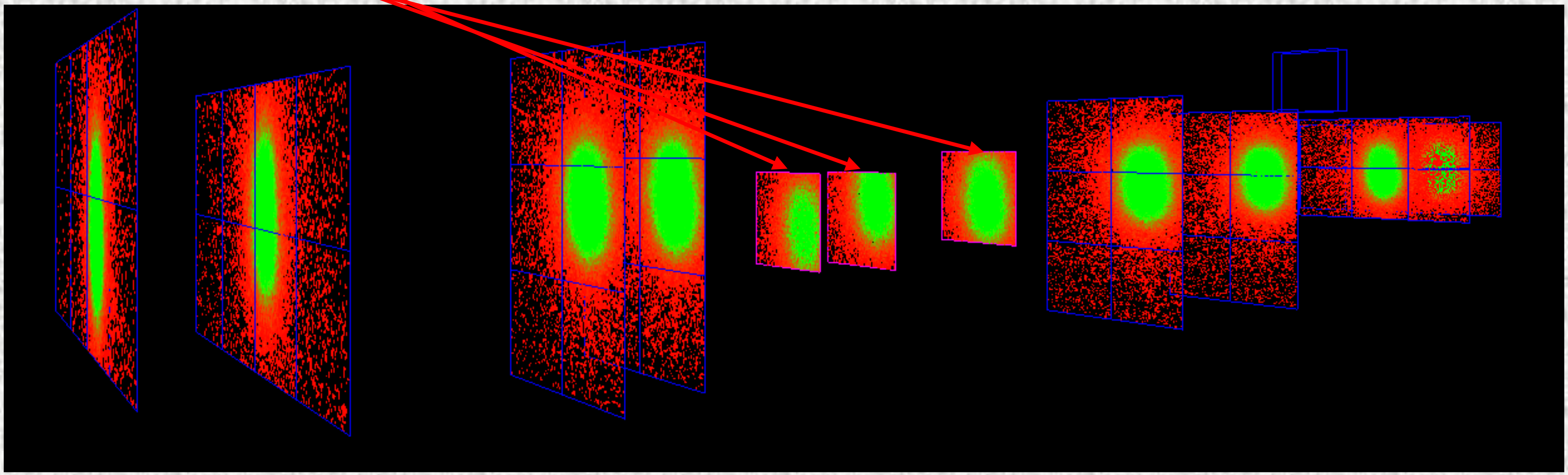
New thin n-in-p planar sensors have been designed by an FBK-INFN collaboration exploiting the Direct Wafer Bonding (DWB) technology, with different active thicknesses (100 and 130 µm) and total thicknesses (180, 200 and 285 µm).



Wafers produced by IceMOS Technology

Test Beam Facility

- Planar sensors bonded to the PSI46dig Read-Out Chip (PbSn Bump Bonds @IZM) have been tested at the Fermilab Test Beam Facility using 120 GeV protons.
- Track reconstruction is based on a telescope composed by 8 pixel planes. Resolution on both transverse coordinates at the Devices Under Test is approximately 9 µm.



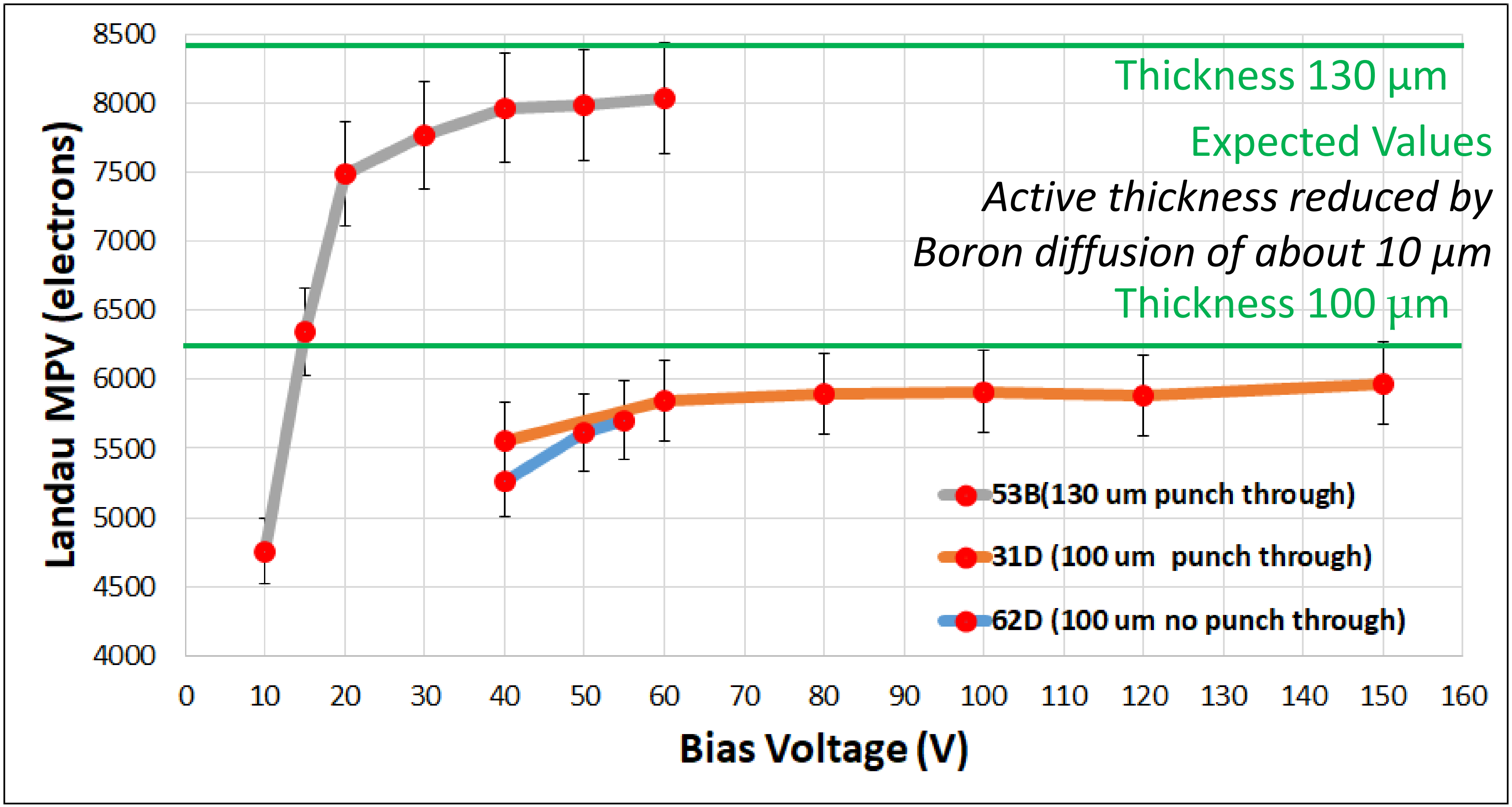
In this talk…

ID Chip	Active Thickness (µm)	P-stop (around cell)	n.GR/P-stop between GR	Punch-Through	BCB mask	Irradation Dose (neq/cm2)
62D	100	yes	1/no	no	frame	3.10E+15
31D	100	no	1/no	yes	frame	5.02E+15
11C	130	yes	10/yes	yes	frame	3.10E+15
53B	130	yes	10/yes	yes	none	1.19E+15
43A	100	no	1/yes	yes	full	5.02E+15

We'll refer to the detectors using this ID

"Frame" in column "BCB mask" means that an insulating layer is applied both on sensor (frame from guard ring to cutting edge) and on ROC everywhere excluding bump bond area and wire bond pads.
"Full" means that the insulating layer is applied on both sensor and ROC everywhere but on bump bond pads

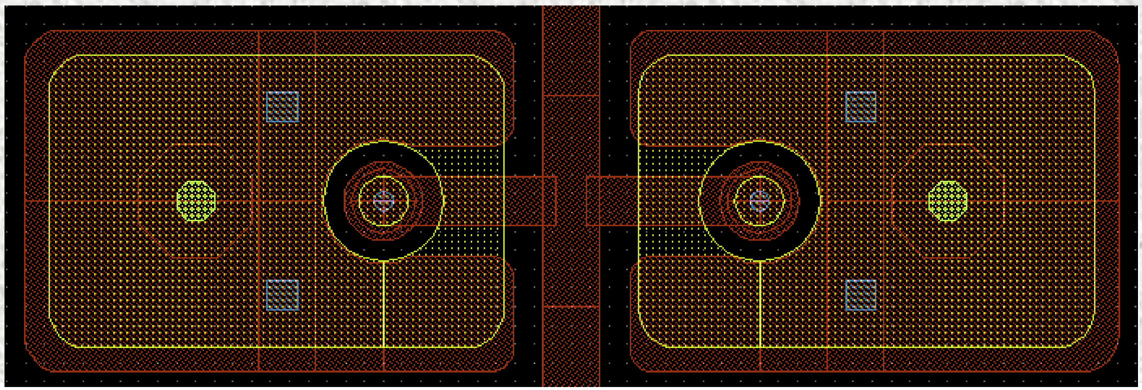
Performance before irradiation: MPV vs. Vbias

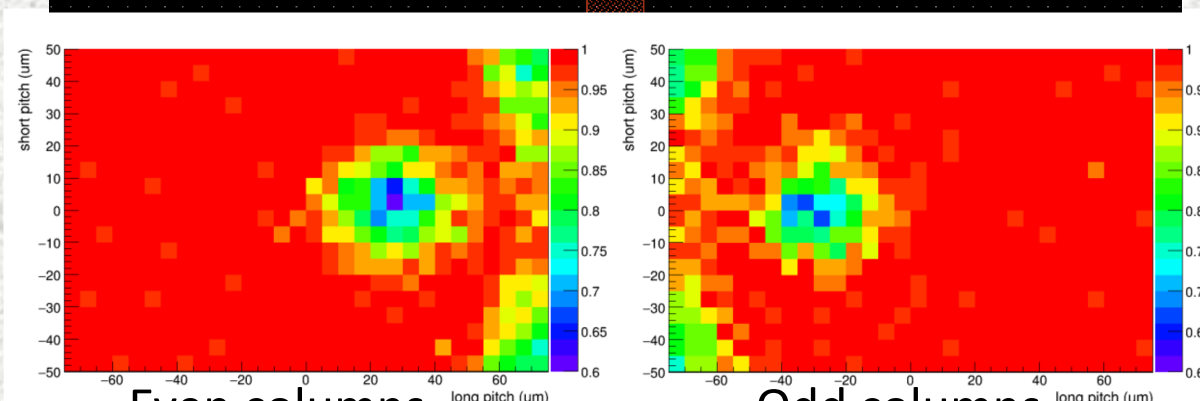


N.B. Detection efficiency is close to 100% (> 99.8%)

Detector thickness 100 µm/31D: Punch Through (Before Irradiation)

Map of the efficiency as a function of the impact point of the reconstructed tracks on the cell of this sensor shows losses in the region where punch through and its bias grid are present: detection efficiency reaches 96.8% at 150V.

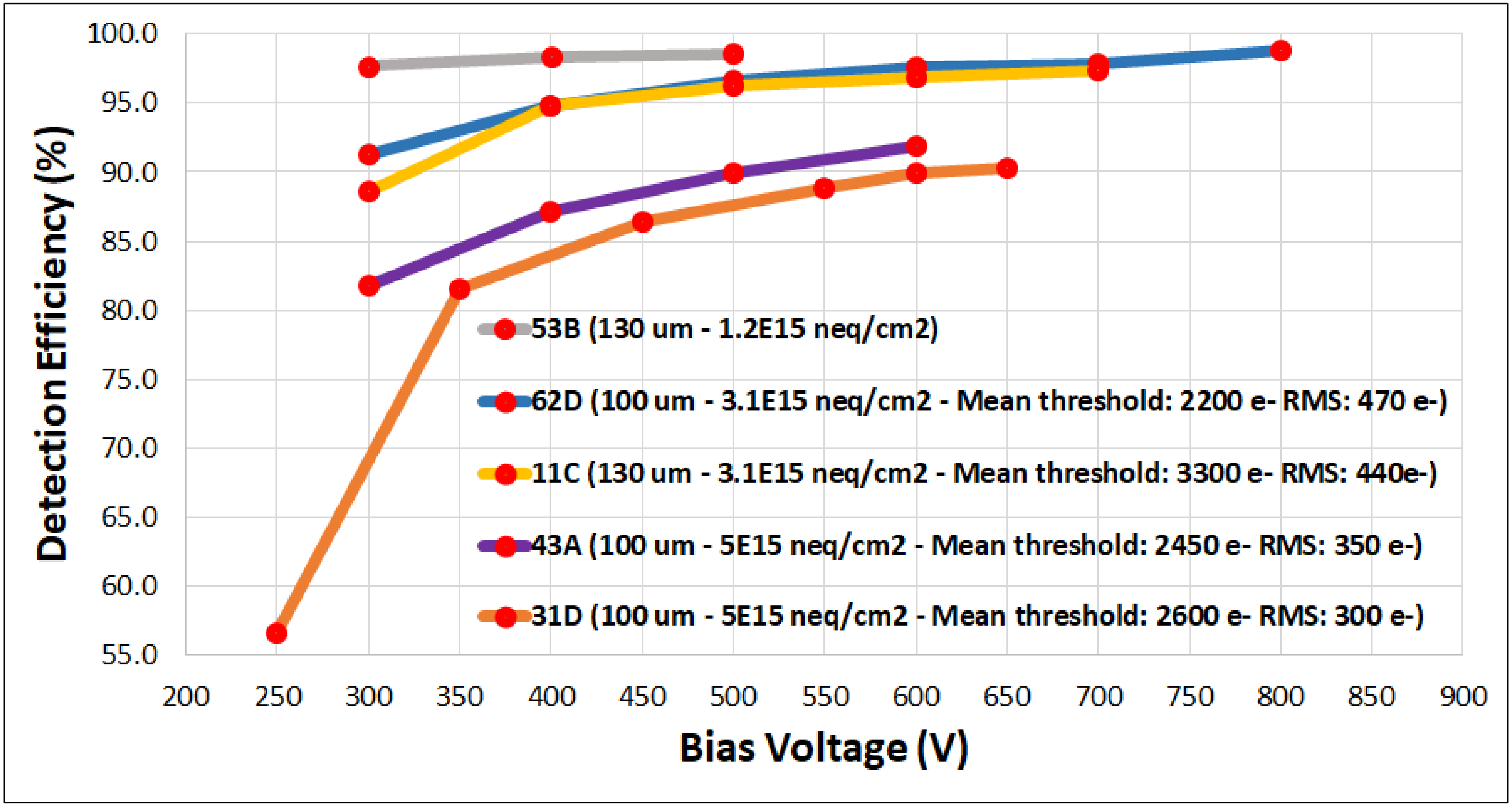




Even columns

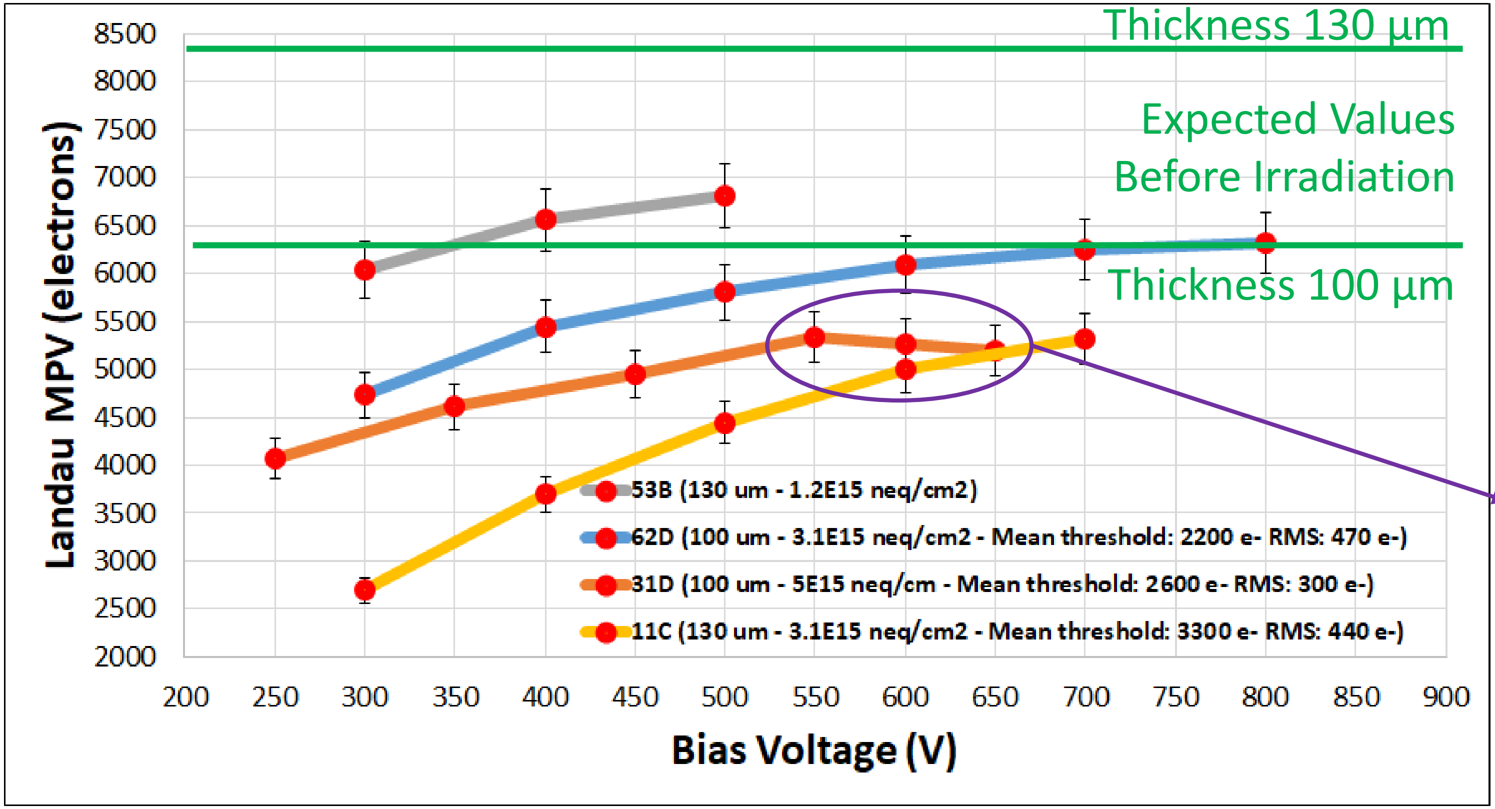
Odd columns

Performance after irradiation: Efficiency vs. Vbias



Thresholds have been chosen in order to minimize the out-of-time noise of the DUT

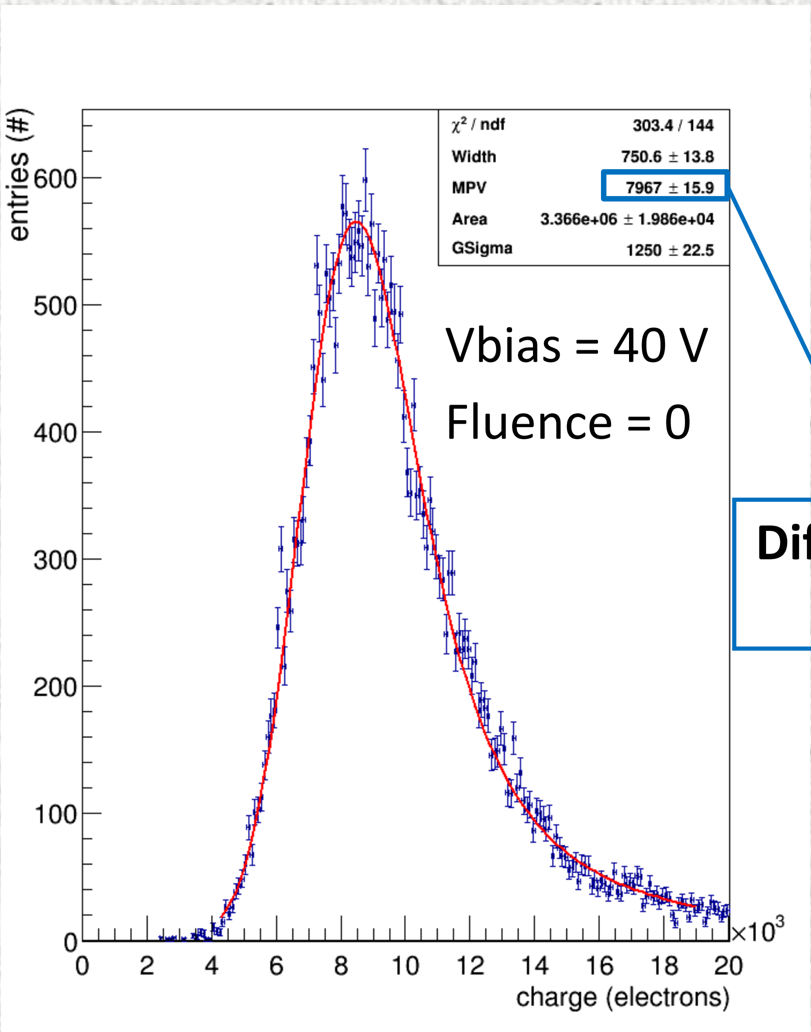
Performance after irradiation: MPV vs. Vbias



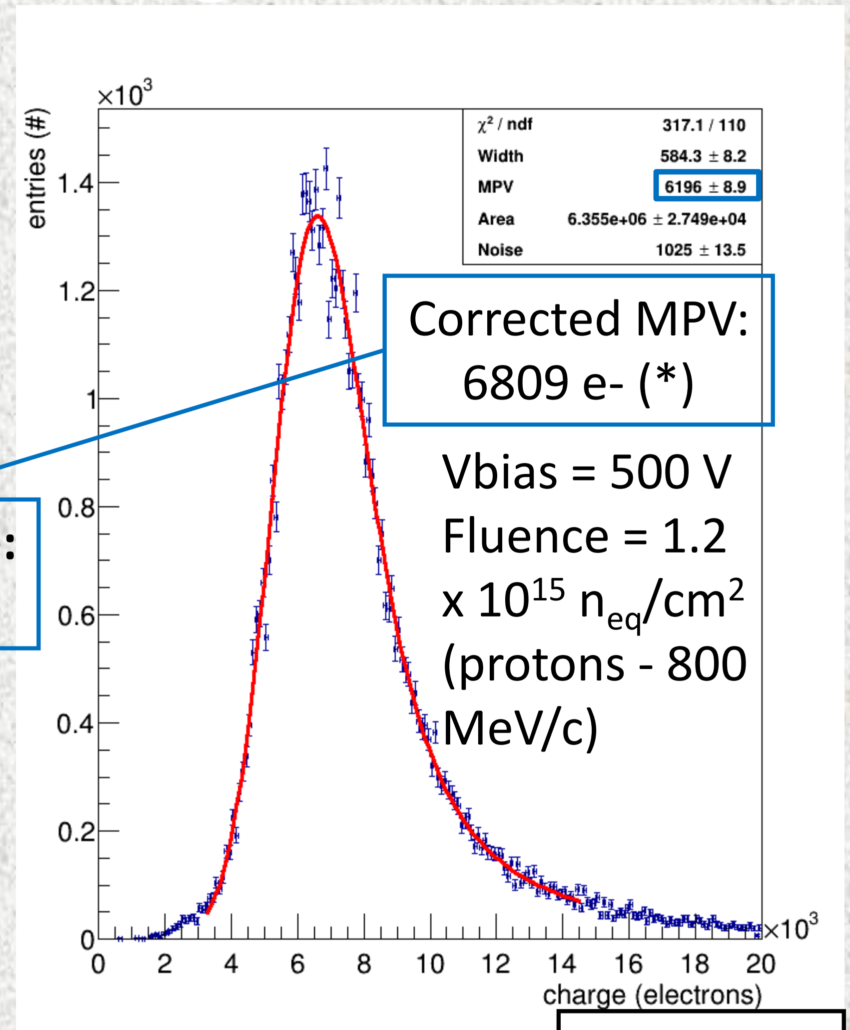
Gain of the chip is affected by sensor leakage current (165 µA @ 650V)

Landau MPV values have been corrected to account for the band-gap reference voltage variation as a function of irradiation dose

Detector thickness 130 µm/1.2E15: Collected charge



Difference: 15%



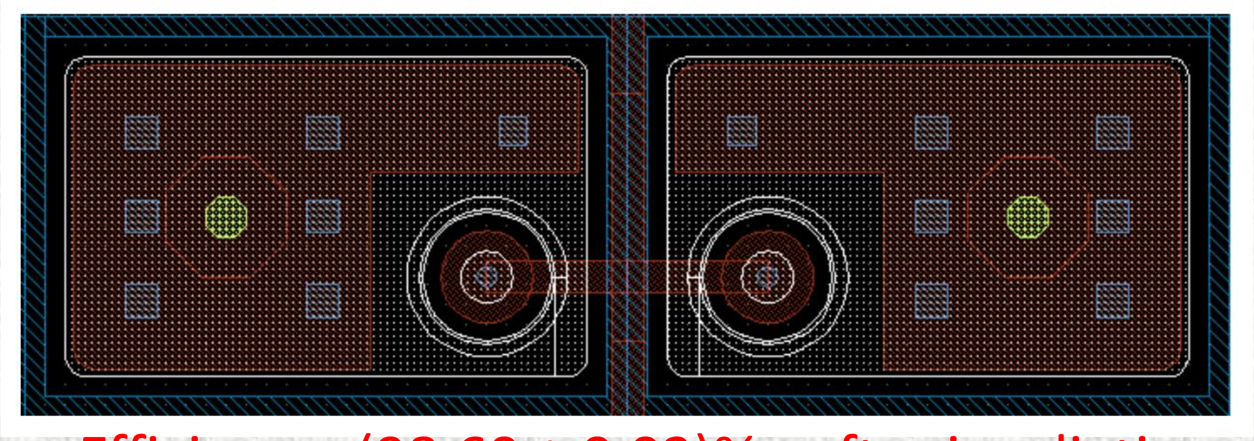
Corrected MPV: 6809 e- (*)

Vbias = 500 V
Fluence = 1.2 x 10^{15} n_{eq}/cm^2 (protons - 800 MeV/c)

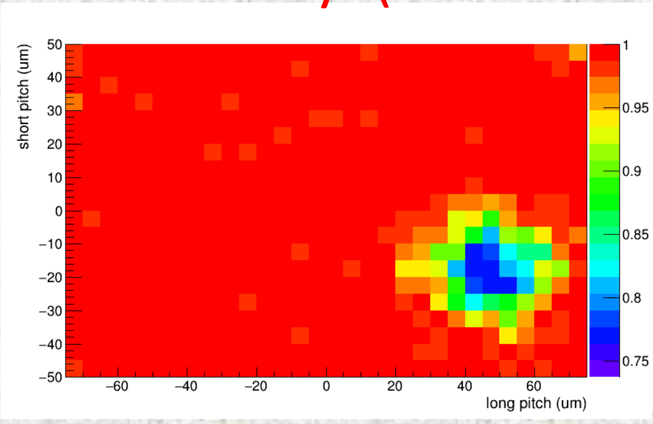
(*) See slide 9

Detector thickness 130 µm/1.2E15: Efficiency

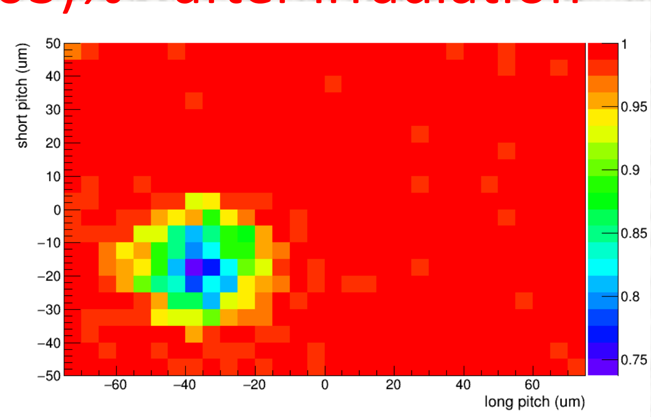
Vbias = 500 V - Fluence = 1.2 x 10^{15} n_{eq}/cm^2 (protons - 800 MeV/c)



Efficiency: (98.60 ± 0.03)% - after irradiation



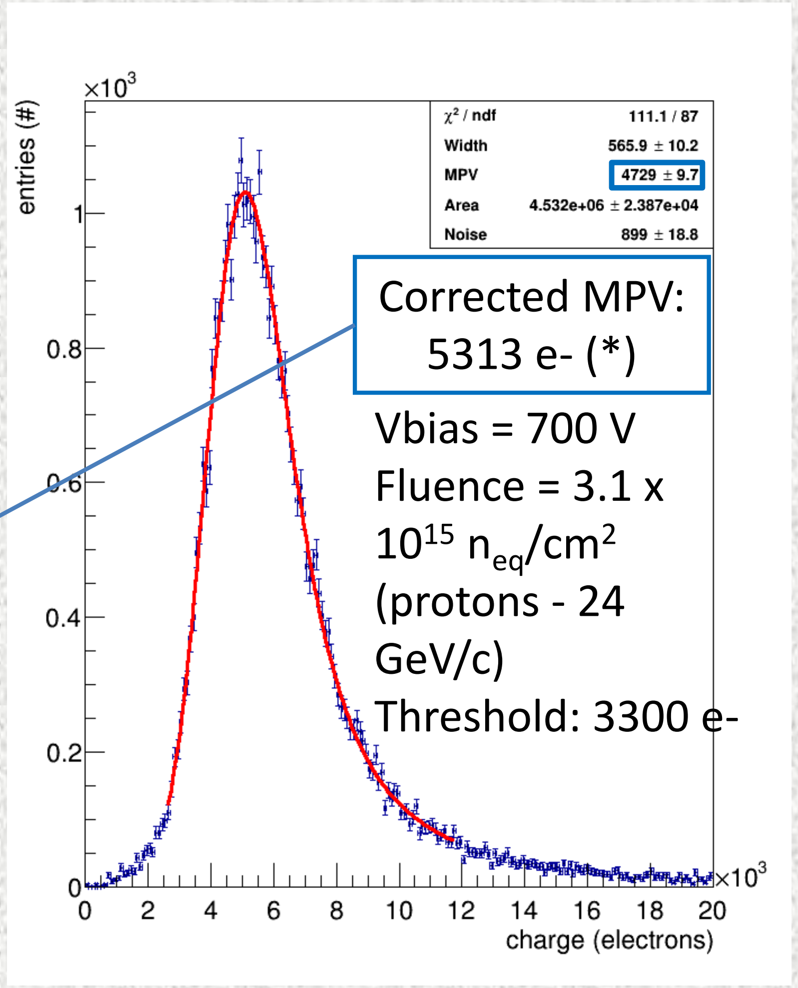
Even columns



Odd columns

Detector thickness 130 µm/3.1E15: Collected Charge

Not tested before irradiation!



Corrected MPV: 5313 e- (*)

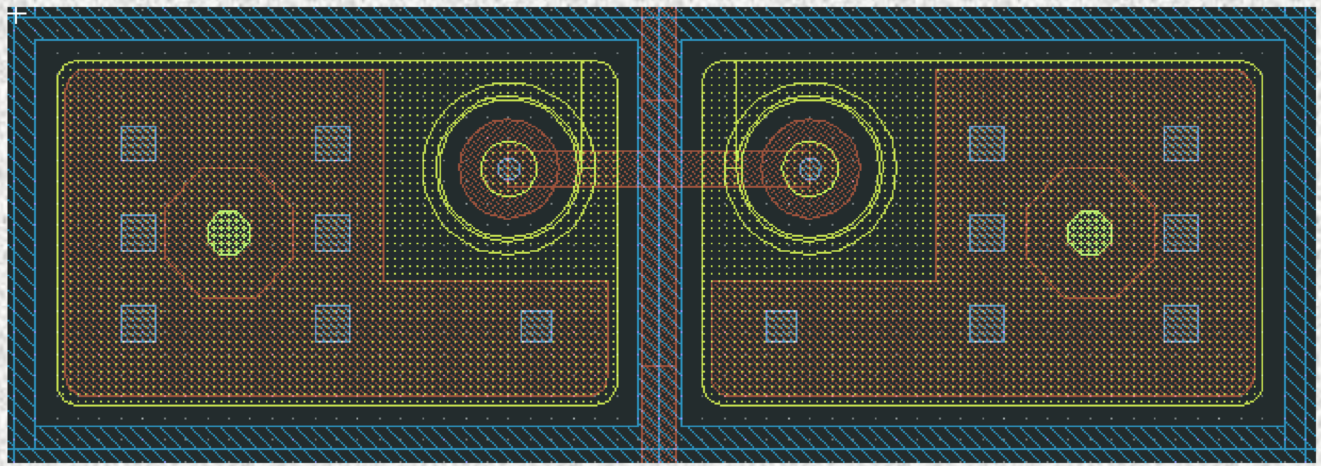
Vbias = 700 V
Fluence = 3.1 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c)
Threshold: 3300 e-

Assuming 8000 e-, as measured for the other 130 µm sensor before irradiation, charge loss is 34%

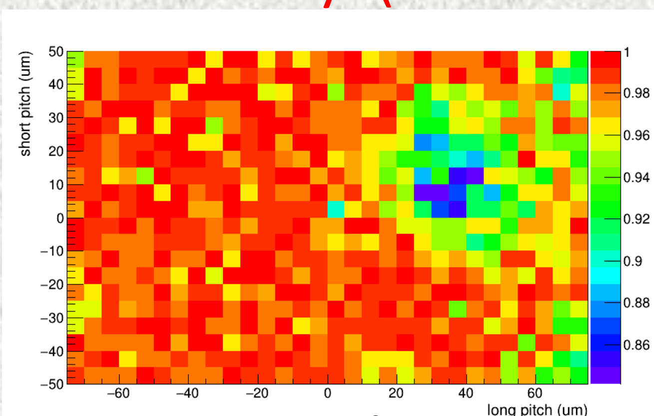
(*) See slide 9

Detector thickness 130 µm/3.1E15: Efficiency

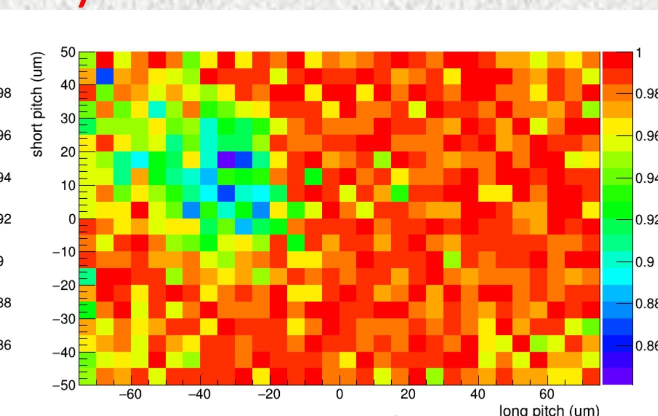
Vbias = 700 V - Fluence = 3.1 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 3300 e



Efficiency: (97.33 ± 0.03)% - after irradiation

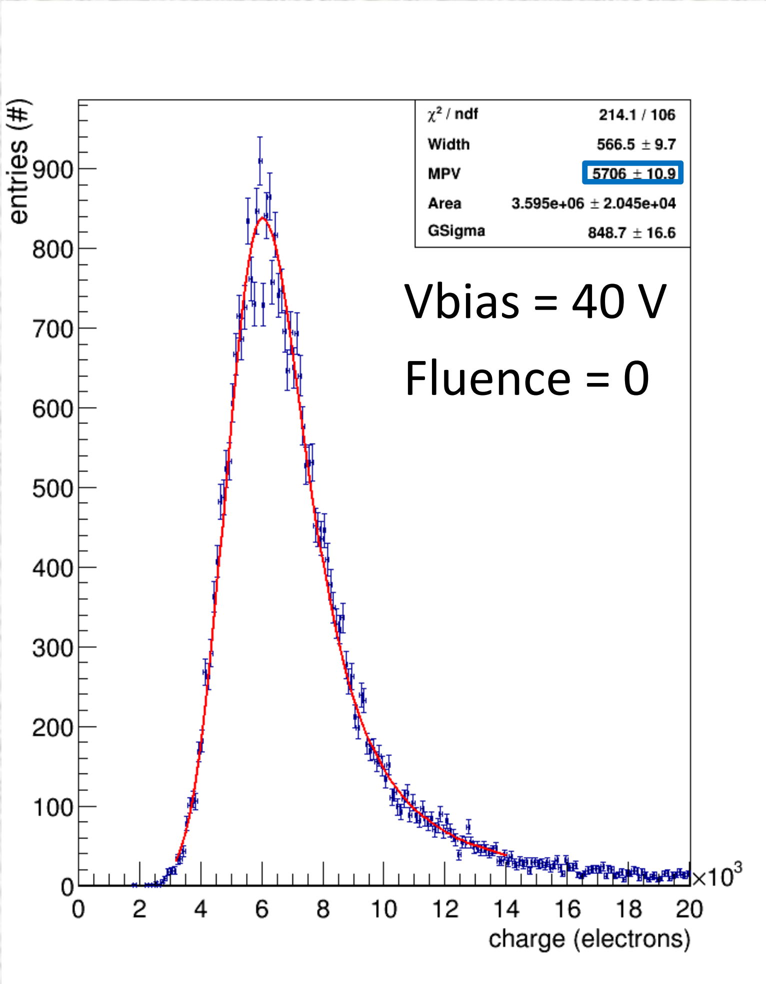


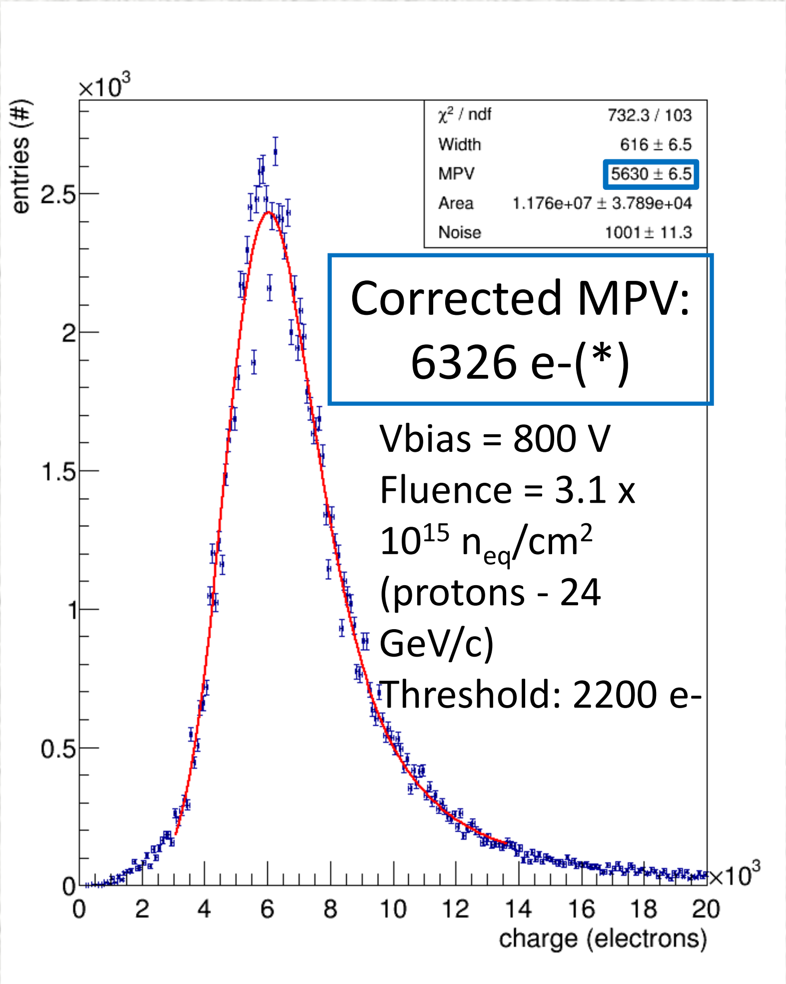
Even columns



Odd columns

Detector thickness 100 µm/3.1E15: Collected charge





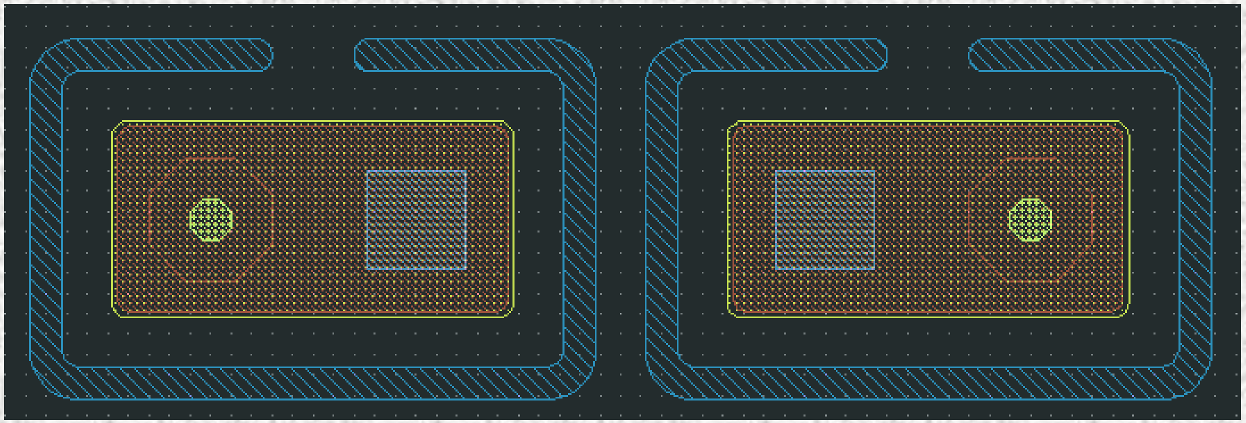
Full charge collection after irradiation!!!

(*) See slide 9

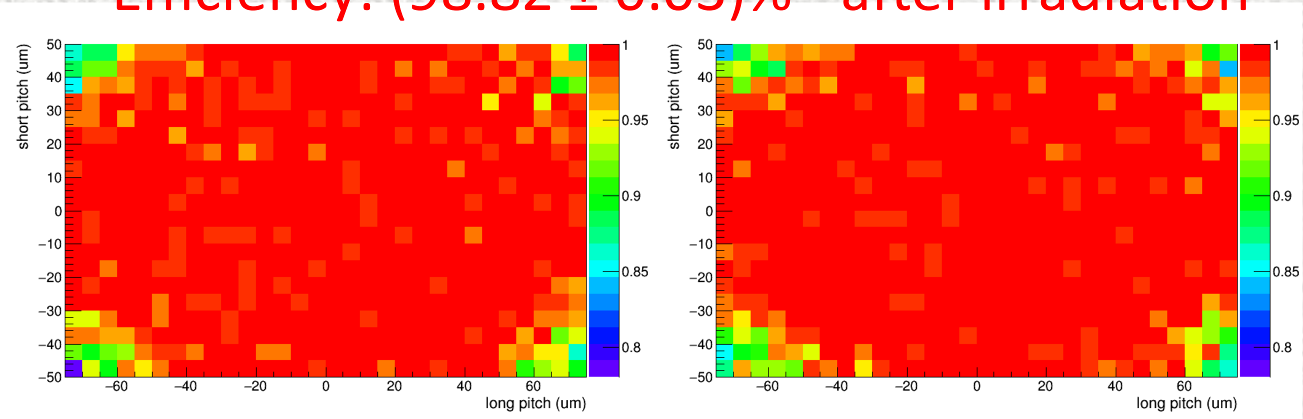
Detector thickness 100 µm/3.1E15: Efficiency

Vbias = 800 V - Fluence = 3.1 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 2200 e-

Sensor without punch through



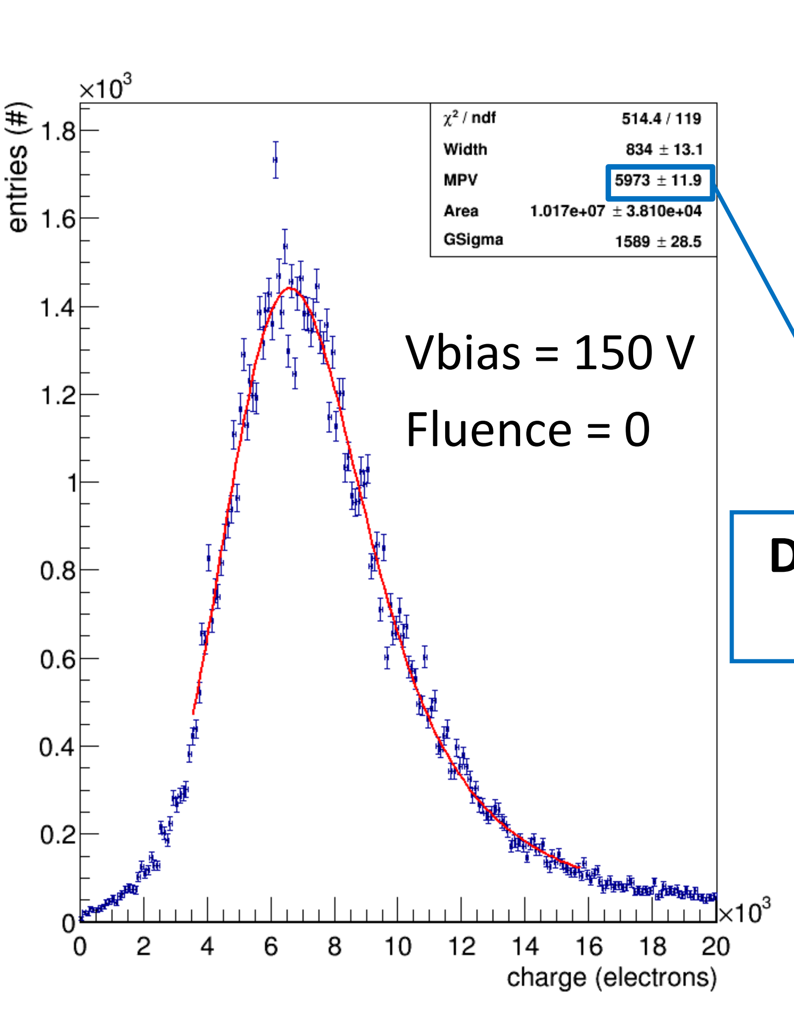
Efficiency: (98.82 ± 0.03)% - after irradiation



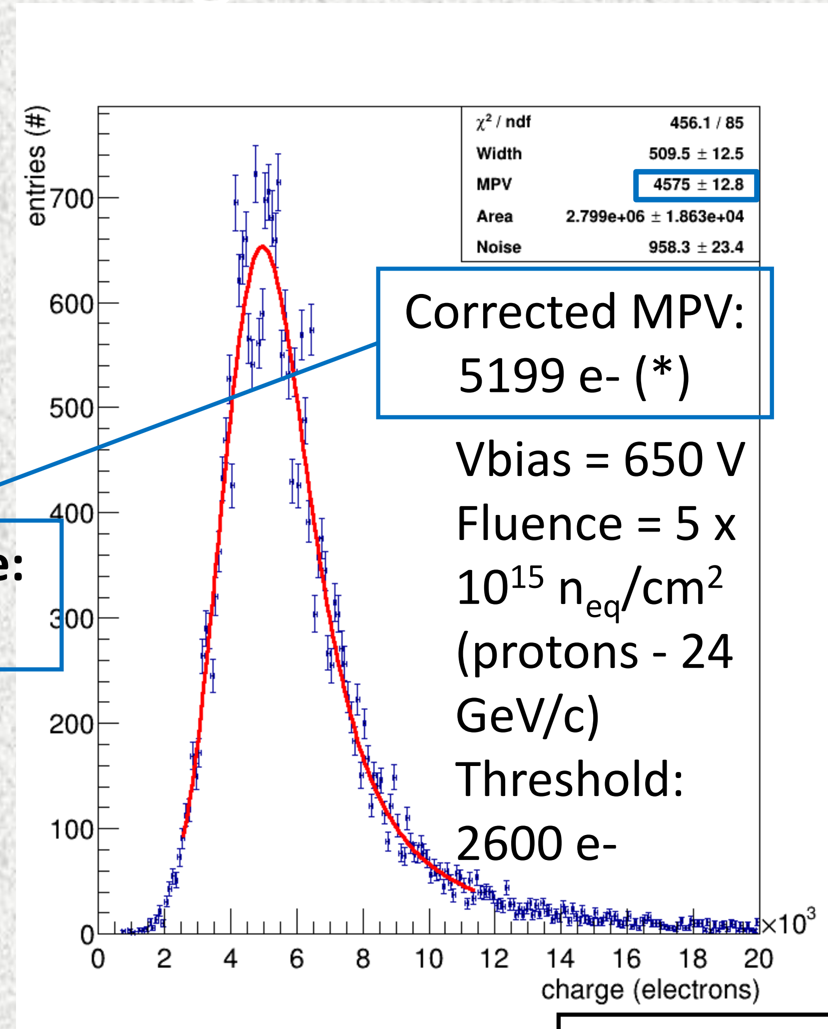
Even columns

Odd columns

Detector thickness 100 µm/5E15/31D: Collected charge



Difference: 13%



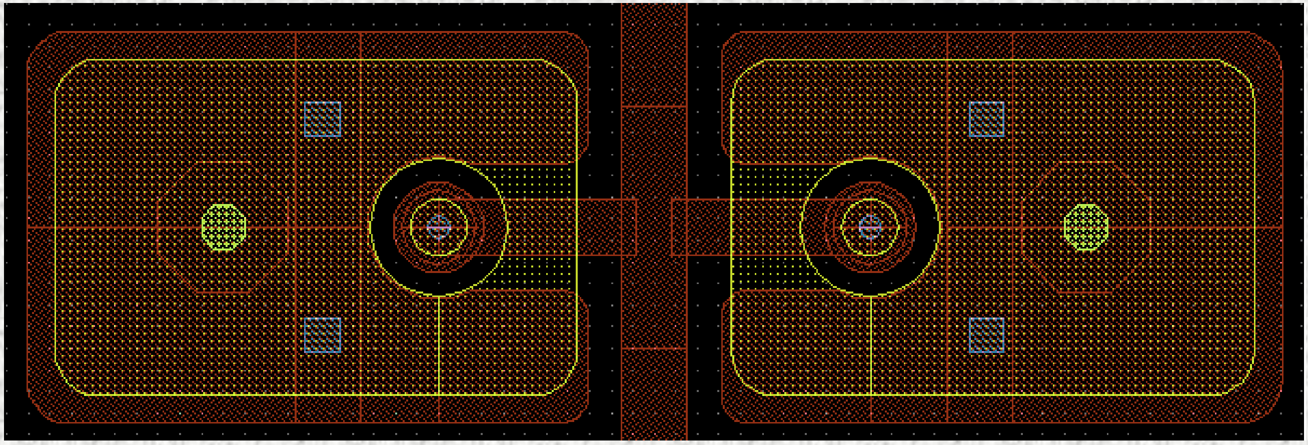
Corrected MPV: 5199 e- (*)

Vbias = 650 V
Fluence = 5 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c)
Threshold: 2600 e-

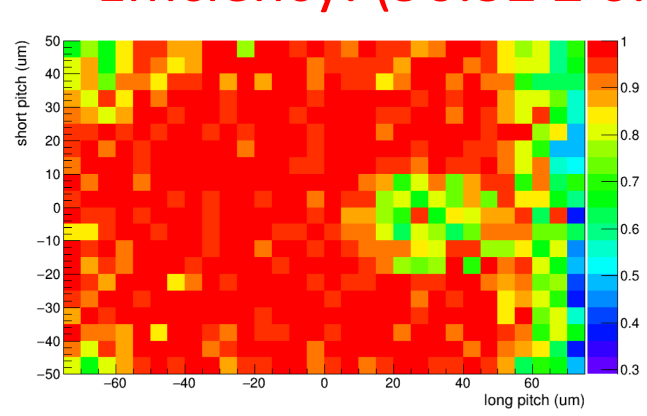
(*) See slide 9

Detector thickness 100 µm/5E15/31D: Efficiency

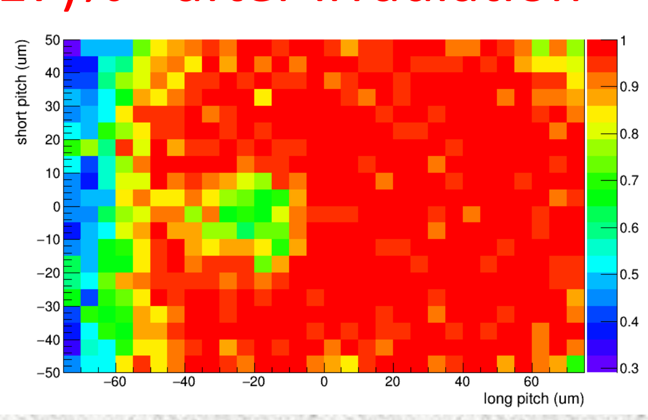
Vbias = 650 V - Fluence = 5 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 2600 e-



Efficiency: (90.32 ± 0.17)% - after irradiation



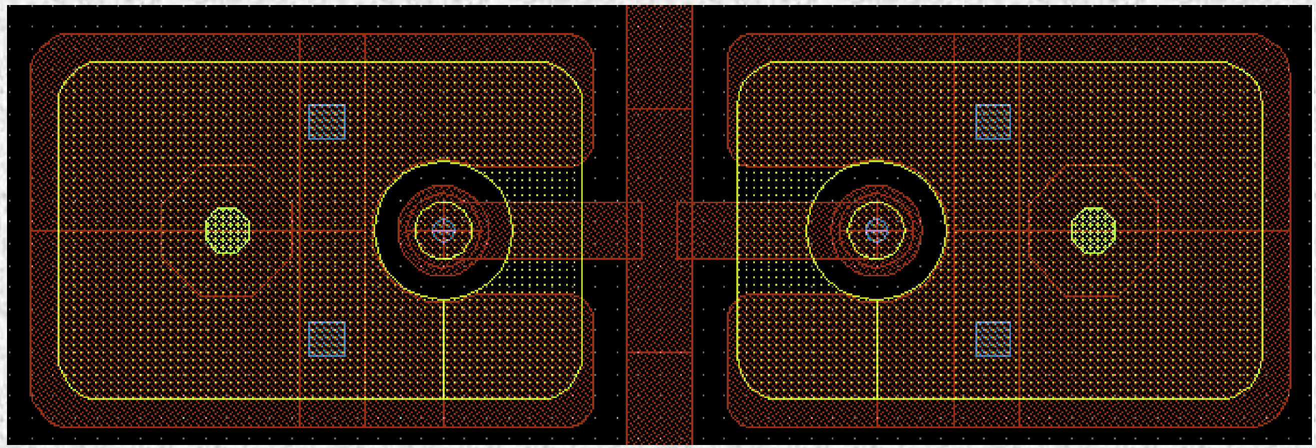
Even columns



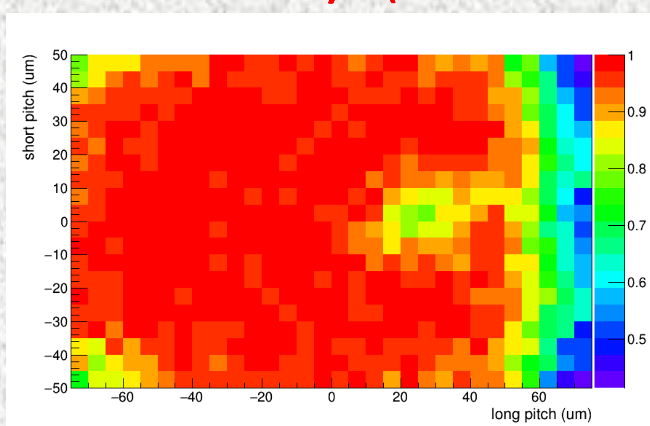
Odd columns

Detector thickness 100 µm/5E15/43A: Efficiency

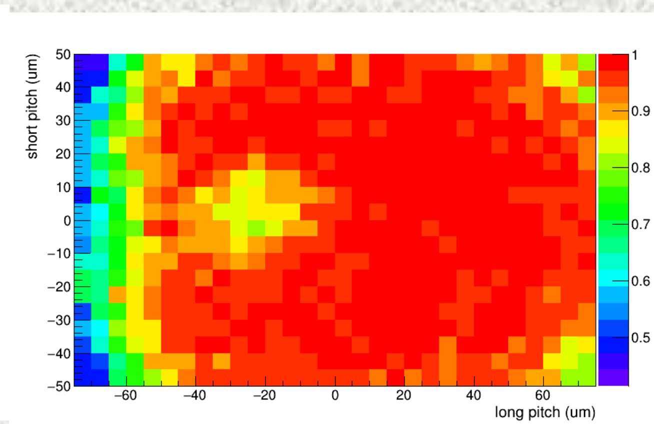
Vbias = 600 V - Fluence = 5 x 10^{15} n_{eq}/cm^2 (protons - 24 GeV/c) – Threshold: 2450 e-



Efficiency: (91.85 ± 0.06)% - after irradiation



Even columns



Odd columns

To Summarize…

ID Chip	Active Thickness (µm)	Punch-Through	Irradation Dose (neq/cm2)	Collected Charge (e-)	Detection Efficiency (%)
62D	100	no	3.10E+15	6326 @800 V	98.82 @800 V
31D	100	yes	5.02E+15	5189 @650 V	91.85 @650 V
43A	100	yes	5.02E+15	///	90.32 @600 V
53B	130	yes	1.19E+15	6809 @500 V	98.60 @500 V
11C	130	yes	3.10E+15	5313 @700 V	97.33 @700 V

- Expected value of collected charge before irradiation: 6300 e- and 8400 e- for 100 and 130 µm active thickness sensors respectively → sensor 62D collects the same charge before and after irradiation
- Lower efficiency for irradiation dose of 5.02E15 n_{eq}/cm^2 is determined both by losses due to the punch through bias grid and by the relatively high threshold

Conclusions

- Results on irradiated planar sensors produced in collaboration with FBK using the new DWB technology are very promising for the realization of thin high radiation-hard sensors
- Use of punch through structures should be questioned on the base of its effect on the cell efficiency, as showed in this presentation
- Irradiation of these sensors bonded to the PSI46dig ROC is limited to 5E15 n_{eq}/cm^2 by the ROC radiation hardness
- We look forward to bonding our sensors to the new RD53 ROC in order to exploit it's higher radiation hardness and lower thresholds

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

AIDA 2020

Many thanks to…

M. Dinardo, D. Menasce, L. Moroni (Univ. & INFN Milano Bicocca)

M. Meschini, L. Viliani (Univ. & INFN Firenze)

G. Darbo (INFN Genova)

A. Messineo (Univ. & INFN Pisa)

G. Giacomini, S. Ronchin (FBK)

G.F. Dalla Betta (Univ. & TIFPA-INFN Trento)

M. Boscardin (FBK & TIFPA-INFN Trento)

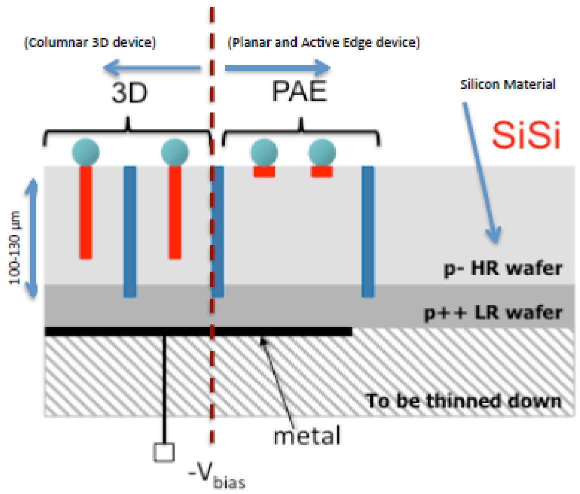
I. Zoi (Univ. Hamburg)

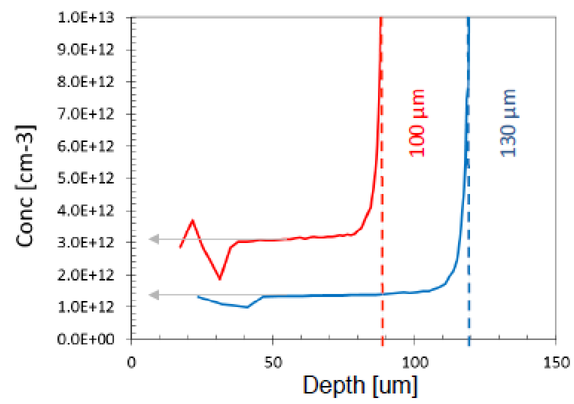
R. Rivera, L. Uplegger (FNAL)

Backup

Charge Collection Features

Material features: active thickness





- Doping concentration profile measurement
  - effective thickness reduced by the Boron diffusion (for SiSi) from wafer carrier deep about 10 µm.

- dE/dx reduced for "thin silicon"
  - Down to ~ 60% of most probable energy loss (388 eV/µm)

- Charge collection reduced by Boron diffusion
  - At Beam test 6000-8000 electrons expected
    - Measure by ROC PSI45dig: threshold 1500 e + dispersion 120 e

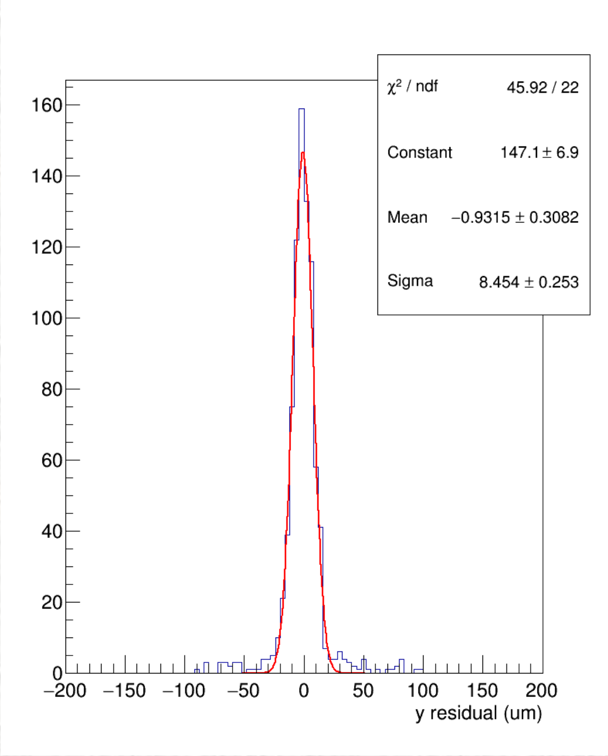
βγ	100 (~90)	130 (~120)
~3.	5919	8068
~1000.	6535	8885

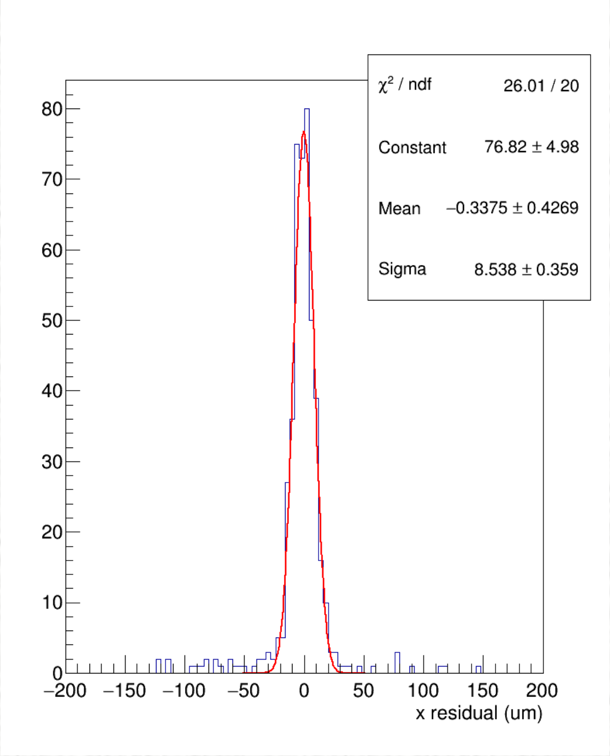
Charge collected from theory

14/02/17 Pixel Phase II meeting: A. Messineo 5

Resolution

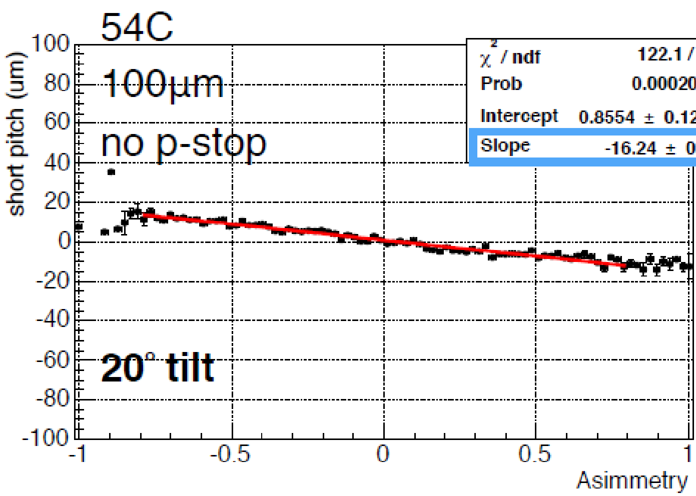
Selecting tracks with double hits on all the telescope planes (best resolution), we measured the residuals with respect to the double hits coordinate on the DUT, reconstructed from the measured charge division charecteristic.

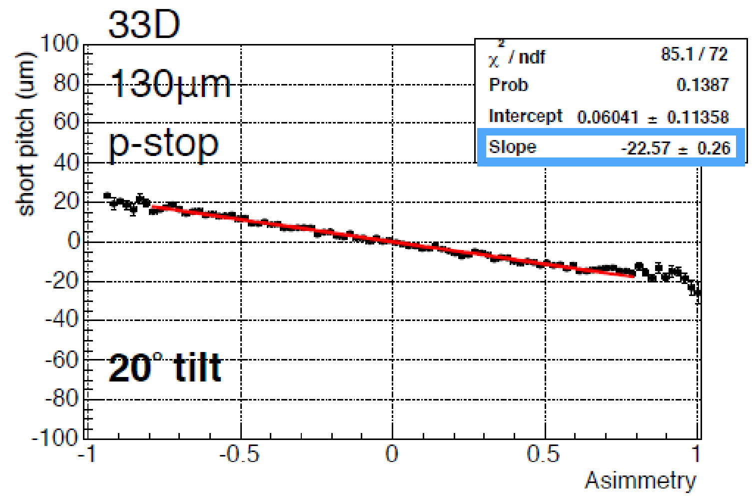




Subracting the expected telescope resolution of 7.3 µm we measured a resolution of 4.3 µm on both transverse coordinates for this DUT

Tilted Sensors Before Rad





Ratio Slope@130µm / Slope@100µm is ~1.4

Back of an envelope calculations for ***Slope*** *at non-zero incidence angle:*

$w/2 \cdot \tan(\theta) + x \sim \text{charge}_L$

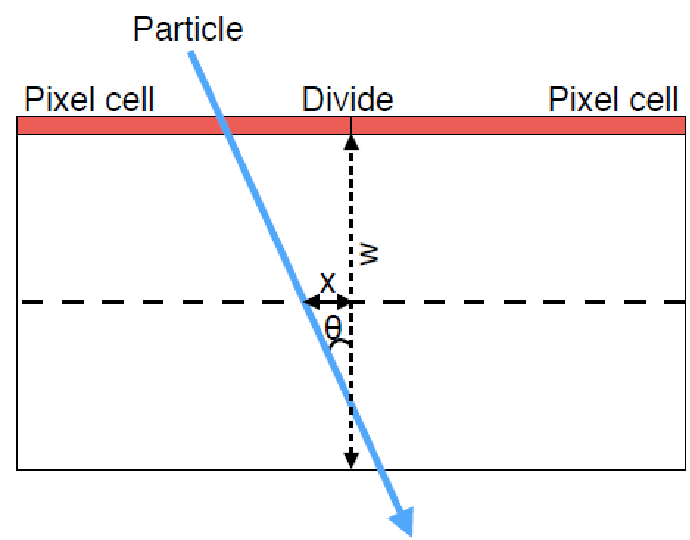
$w/2 \cdot \tan(\theta) - x \sim \text{charge}_R$

Asymmetry = $2x / (w \cdot \tan(\theta))$

Slope = x/Asymmetry = $w/2 \cdot \tan(\theta)$

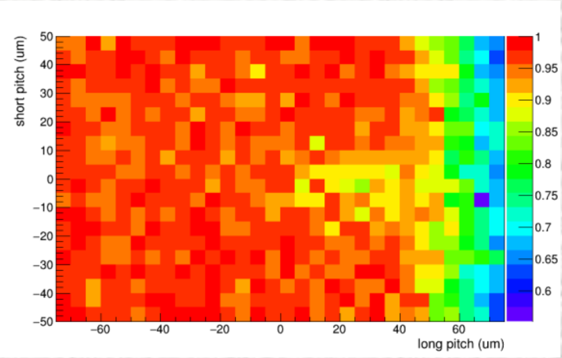
- w = 100 µm ➜ Slope = 18.2 µm/asymmetry
- w = 130 µm ➜ Slope = 23.7 µm/asymmetry

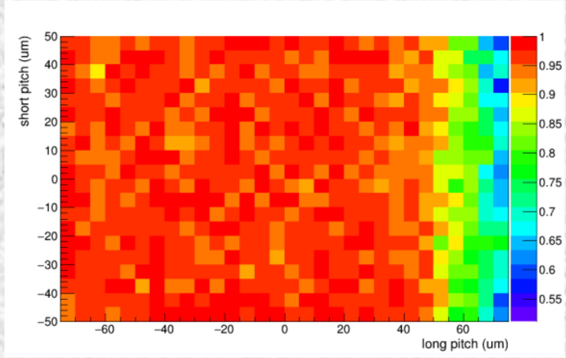
Amazingly close to our measurements

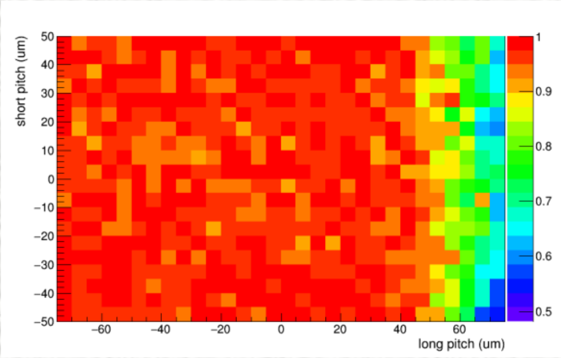


Tilted Sensors After Rad Efficiency Maps

Even Columns





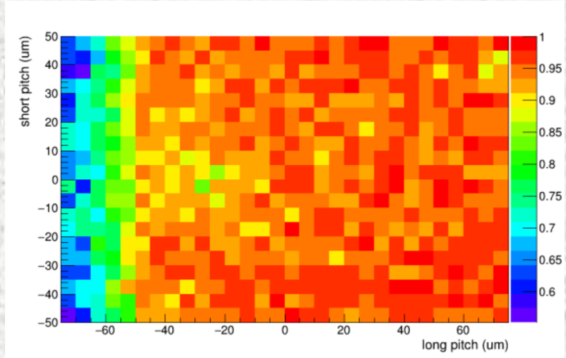


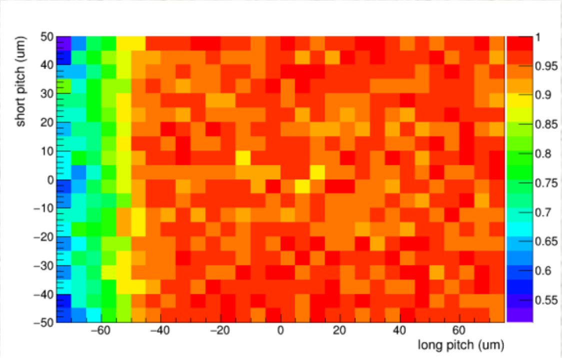
5°

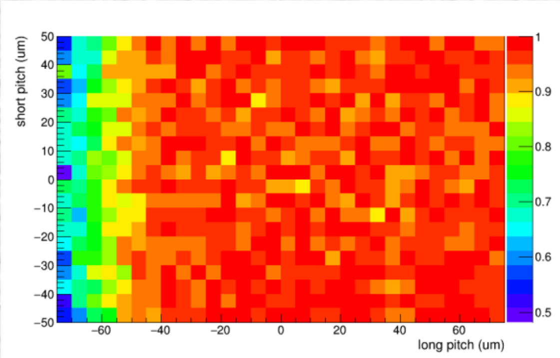
10°

20°

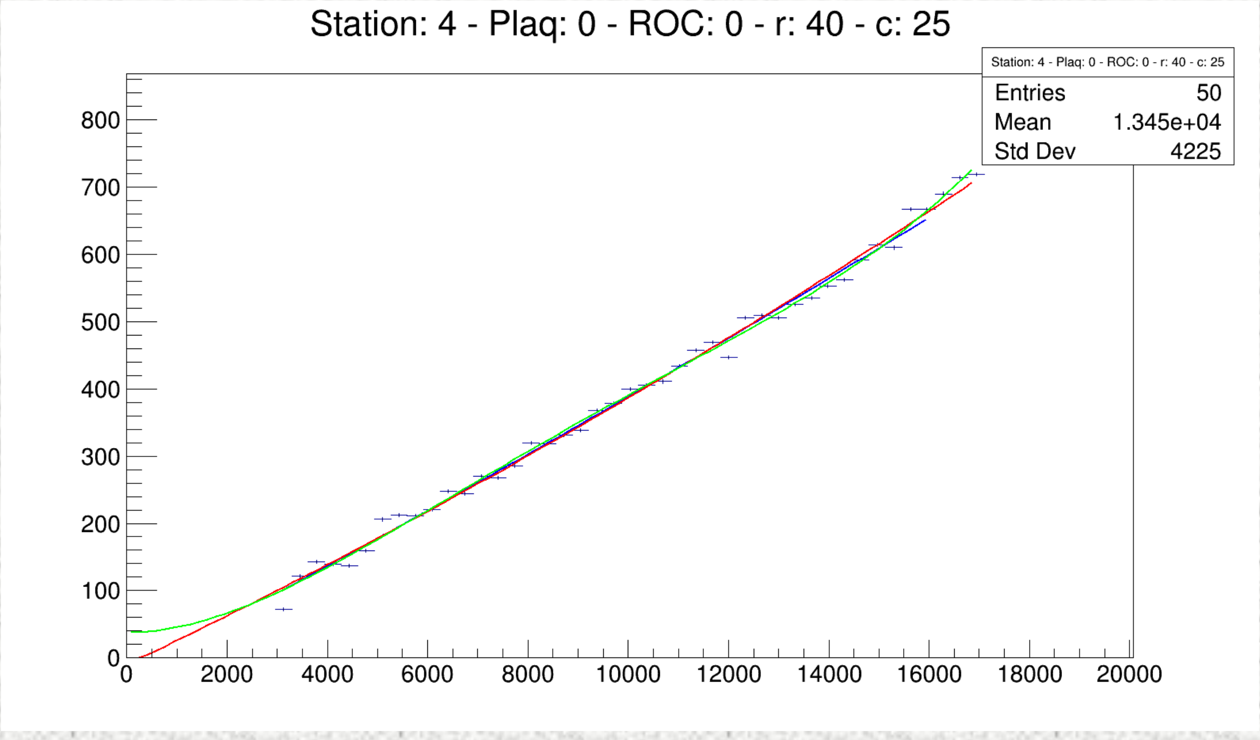
Odd Columns







Calibration Issues



PSI46dig was designed for operations with 300 µm sensors, collecting approximately 22500 e^-.

New sensors reach 100 µm thickness, hence lowest collected charge is 6000 e^-.

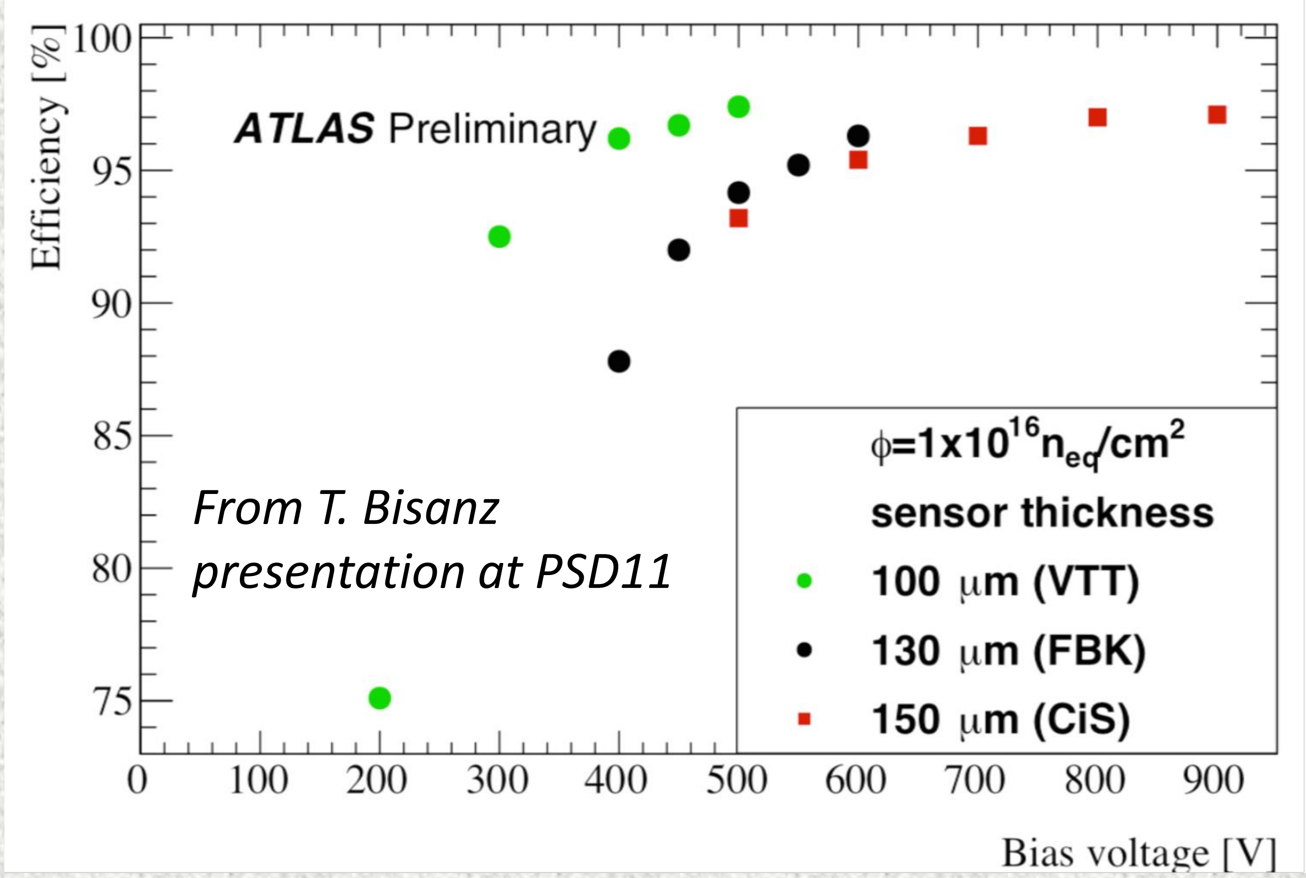
Lower values are reached once detectors are irradiated.

Now we are operating with this ROC in a heavily non linear region of the gain curve.

Determination of the collected charge is very hard!!

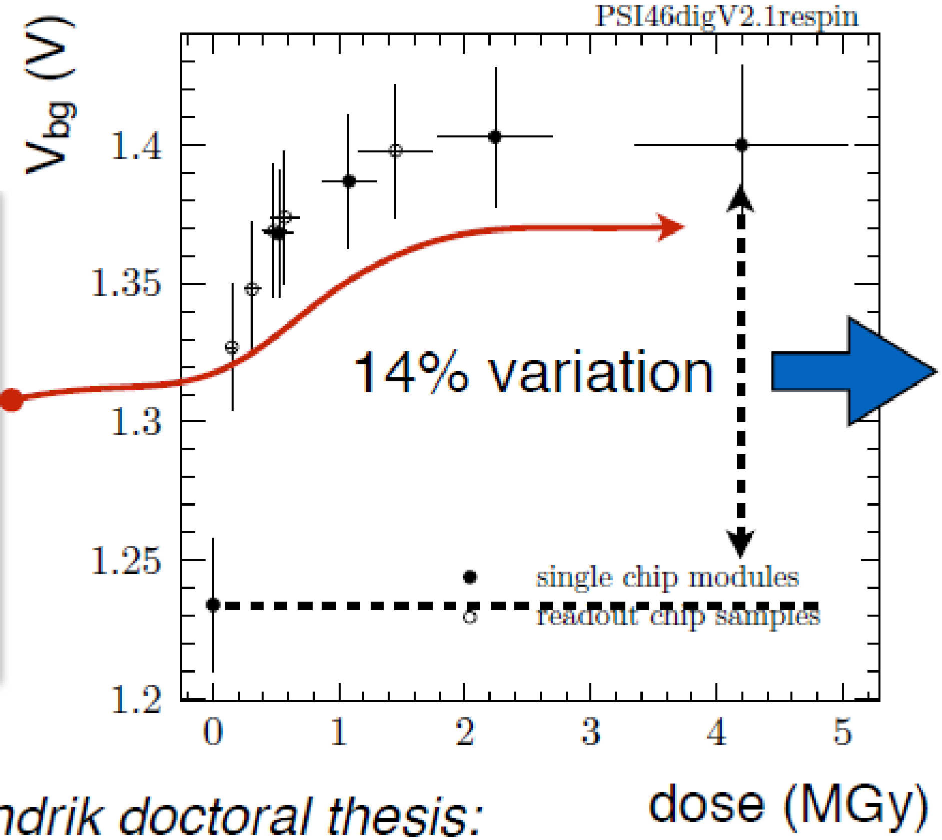
Comparison with other results

ATLAS results obtained at higher irradiation fluences are in agreement with our results in terms of efficiency.



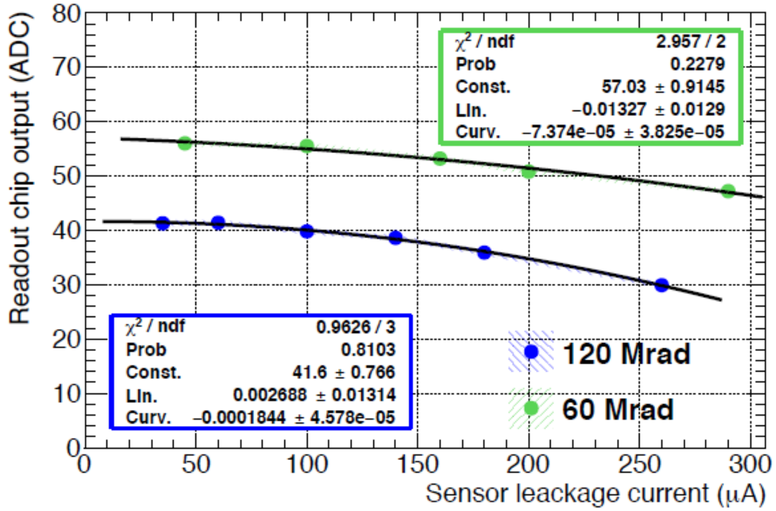
Band-gap reference voltage variation

Variation of band gap reference voltage with irradiation ➜ ADC to electron conversion must be corrected



[Hoß, Jan Hendrik doctoral thesis: https://doi.org/10.3929/ethz-b-000182698]

Chip gain variation



- PSI46 digital chip with same sensors as those installed right now in CMS (300 μm active thickness)
- Irradiated with 23 MeV proton beam at Zyklotron AG Karlsruhe
- 120 Mrad corresponds to ~0.8×10^{15} n_{eq}/cm^2
- 60 Mrad corresponds to ~0.4×10^{15} n_{eq}/cm^2

[many thanks to Malte B. and ETH team for providing the sample and the setup]

1. Fit all gain curves (i.e. ADC output vs injected charge) with a second degree polynomial
2. For every ROC and for every voltage (i.e. leakage current), histogram the ADCs for an injected charge of 6 000 electrons

The mean of such an histogram is what is shown in the plot versus leakage current

The gain of the PSI46 digital chip is affected by the leakage current of the sensor

2 Mauro Dinardo, Universita` degli Studi di Milano Bicocca and INFN