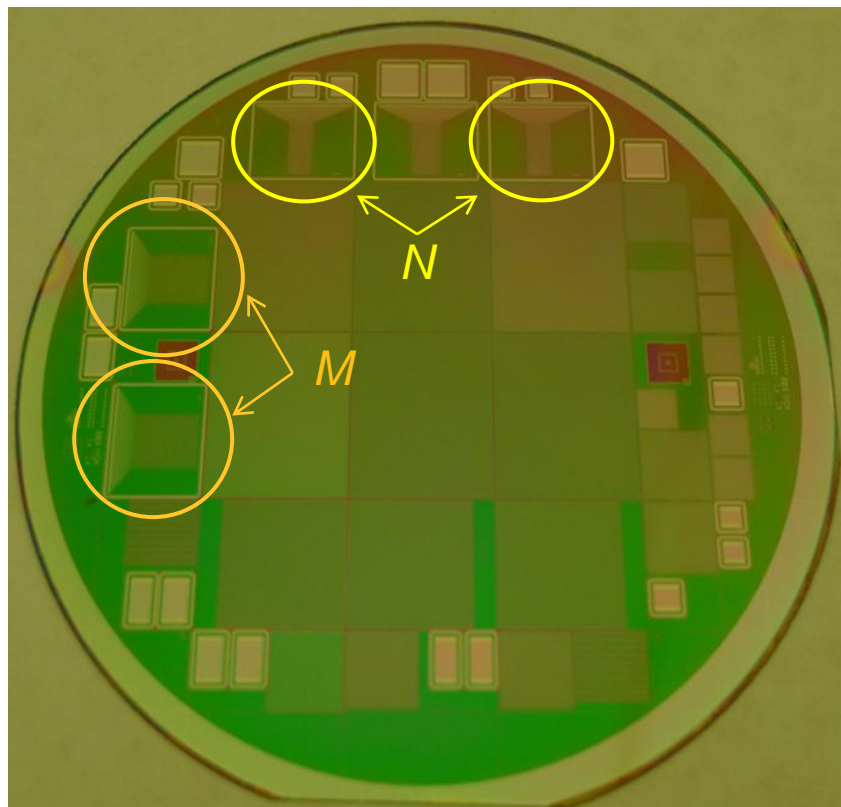


Charge Collection Efficiency of proton-irradiated small-cell 3D strip sensors up to $1.7E16 n_{eq}/cm^2$ equivalent fluence



32nd RD50 Workshop
Hamburg
June 5th, 2018

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The Team



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[1] IFCA (CSIC-UC)



IFCA

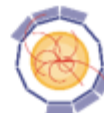
[2] IMB-CNM (CSIC)



[3] CERN



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



AIDA²⁰²⁰

Outline

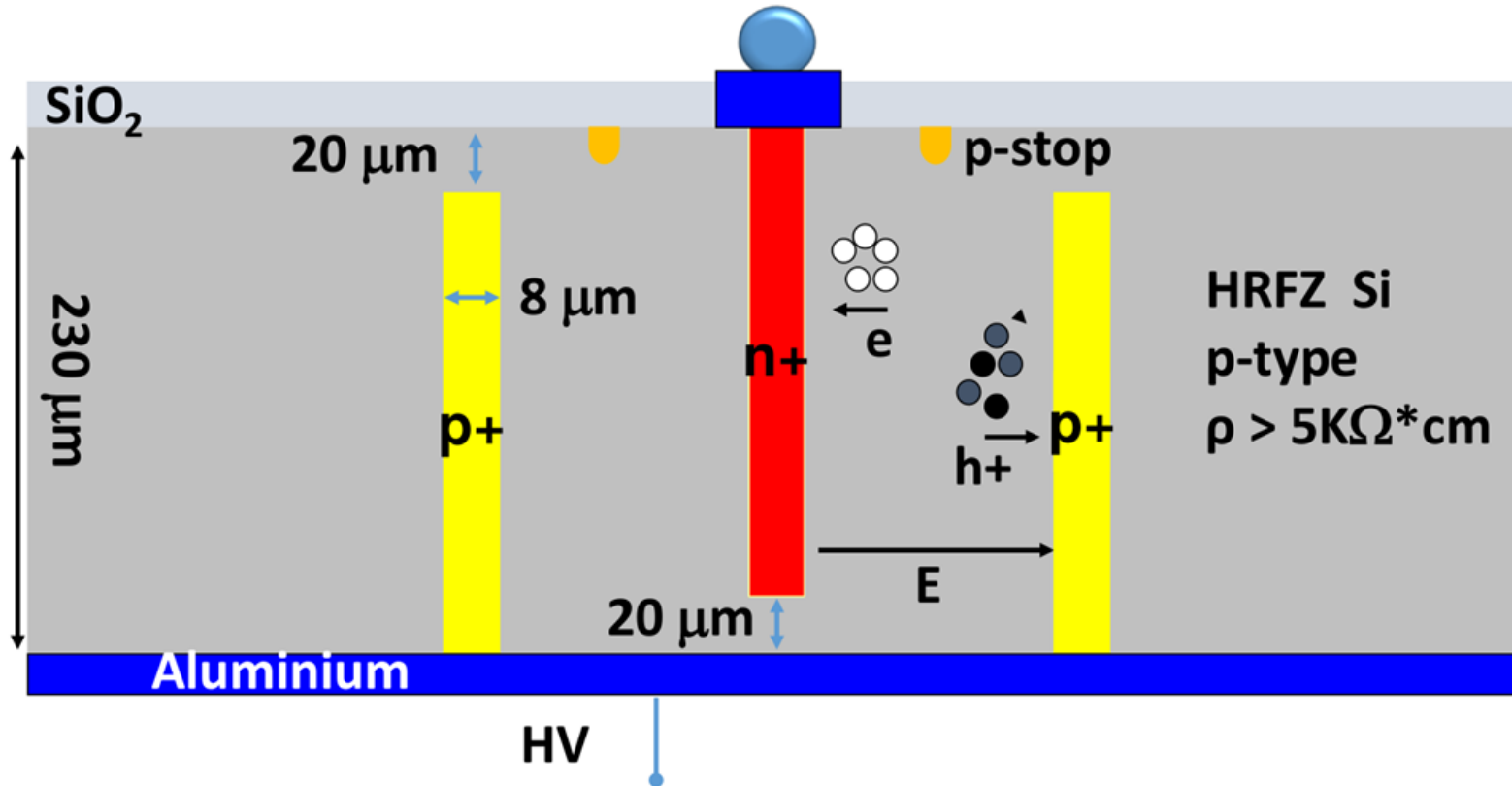


- Motivation
- Sensor description
- Samples and experimental setup
- Results:
 - Charge collection
 - Power dissipation studies
- Conclusion

Radiation tolerance of 3D sensors: strips and pads.

- **Strip 3D sensors:** avoid irradiation of the electronics and study charge collection efficiency.
- **Pixel 3D sensors with pixel electronics (ROC4SENS):**
 - Trento workshop February 2018. Gervasio Gómez
<https://indico.cern.ch/event/666427/contributions/2881255/>
 - RD50 workshop November 2017. Esteban Currás
<https://indico.cern.ch/event/663851/contributions/2788172/>
 - Paper submitted to arXiv and to be submitted to NIM:
First study of small-cell 3D Silicon Pixel Detectors for the High Luminosity LHC
<https://arxiv.org/abs/1806.01435>
- **Pad 3D sensors:** estimate current and capacitance per pixel, and power dissipation (critical for the operating conditions of the sensor).

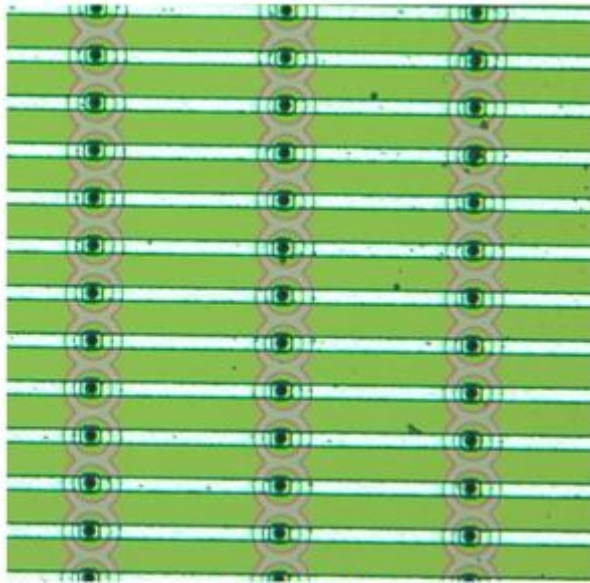
Sensor description



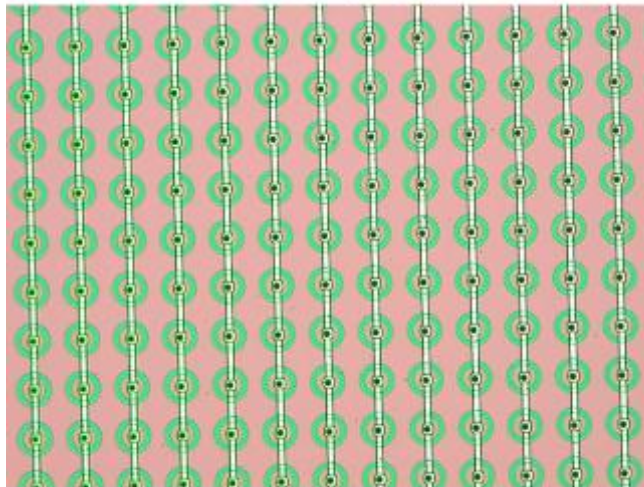
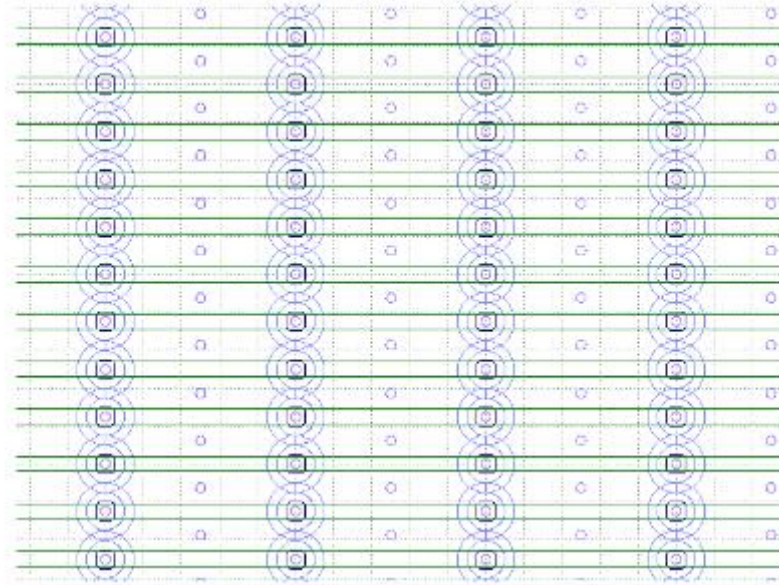
*CNM 3D Double-Sided n-on-p
230 μm thick*

*50 μm x 50 μm
25 μm x 100 μm*

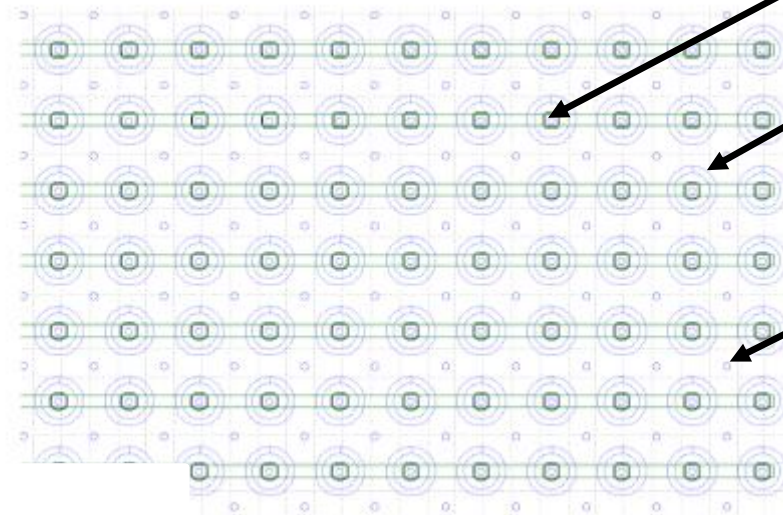
Sensor description. 3D pixel strips



25×100 (1E) μm^2
N1-3, N1-7, N1-8



50×50 (1E) μm^2
M1-5, M2-3



*N (union)
column*

P stop

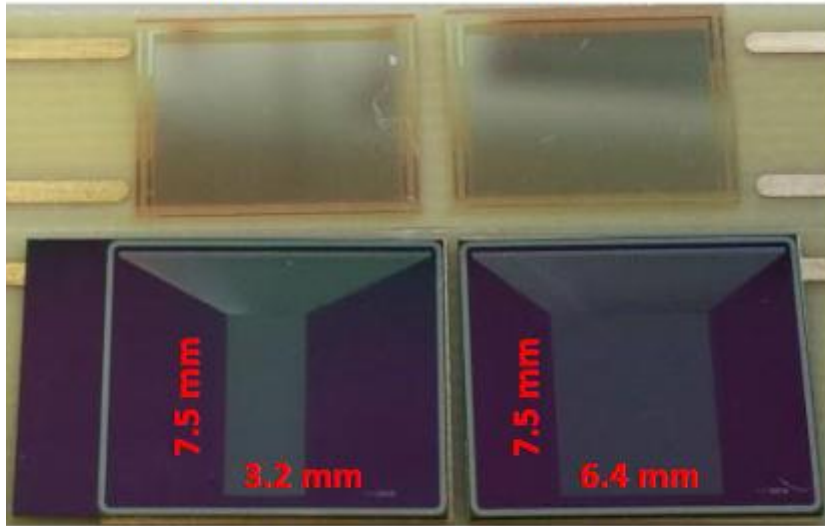
*P (ohmic)
column*

Sensor design. Readout system

Strip geometries tested

FAN AC

FAN AC

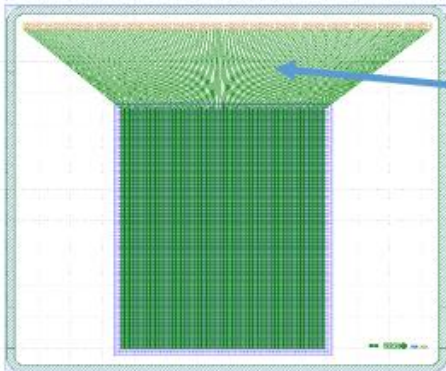


$25 \times 100 \mu\text{m}^2$

128 75-pixel strips

$50 \times 50 \mu\text{m}^2$

128 150-pixel strips



Metal routing to fit
 $80 \mu\text{m}$ pitch electronics
(Alibava Systems).

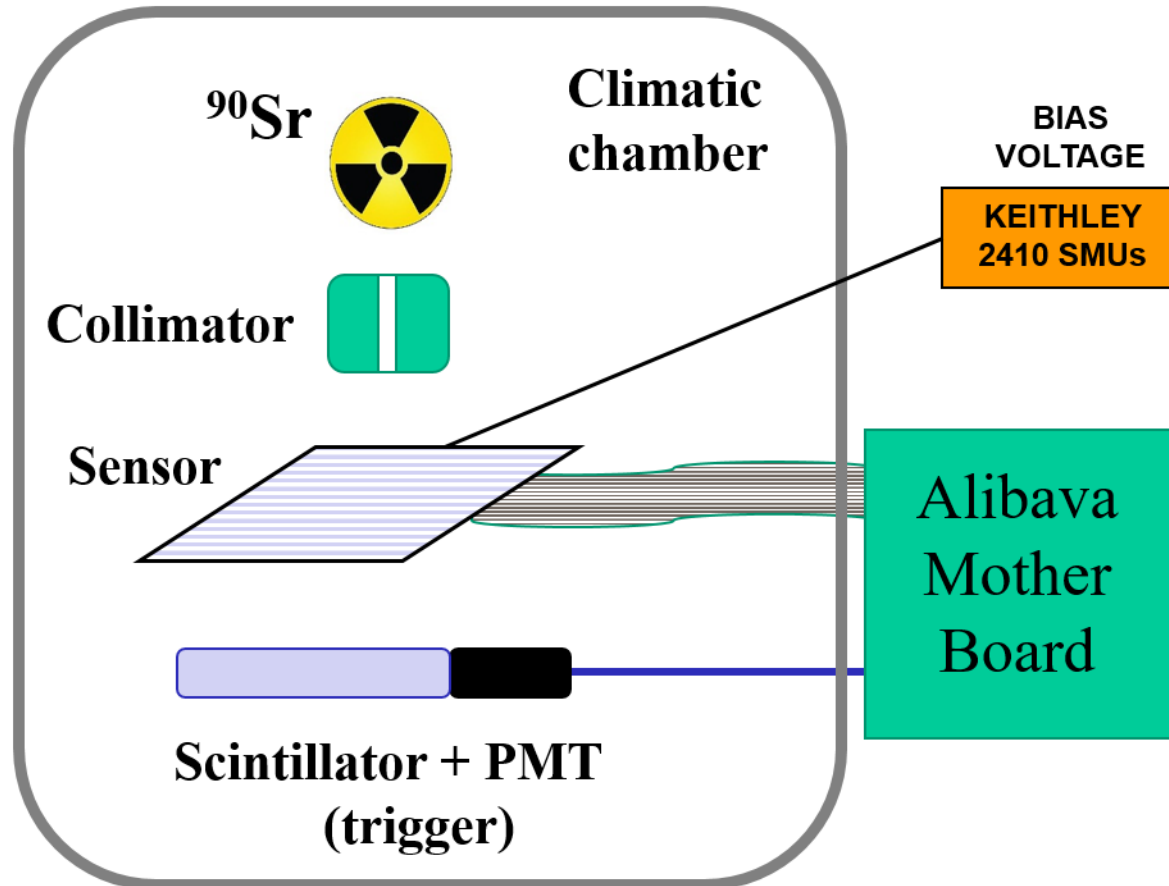
Connected through fan AC

Alibava daughter board
with 2 beetle (strip)
ROCs

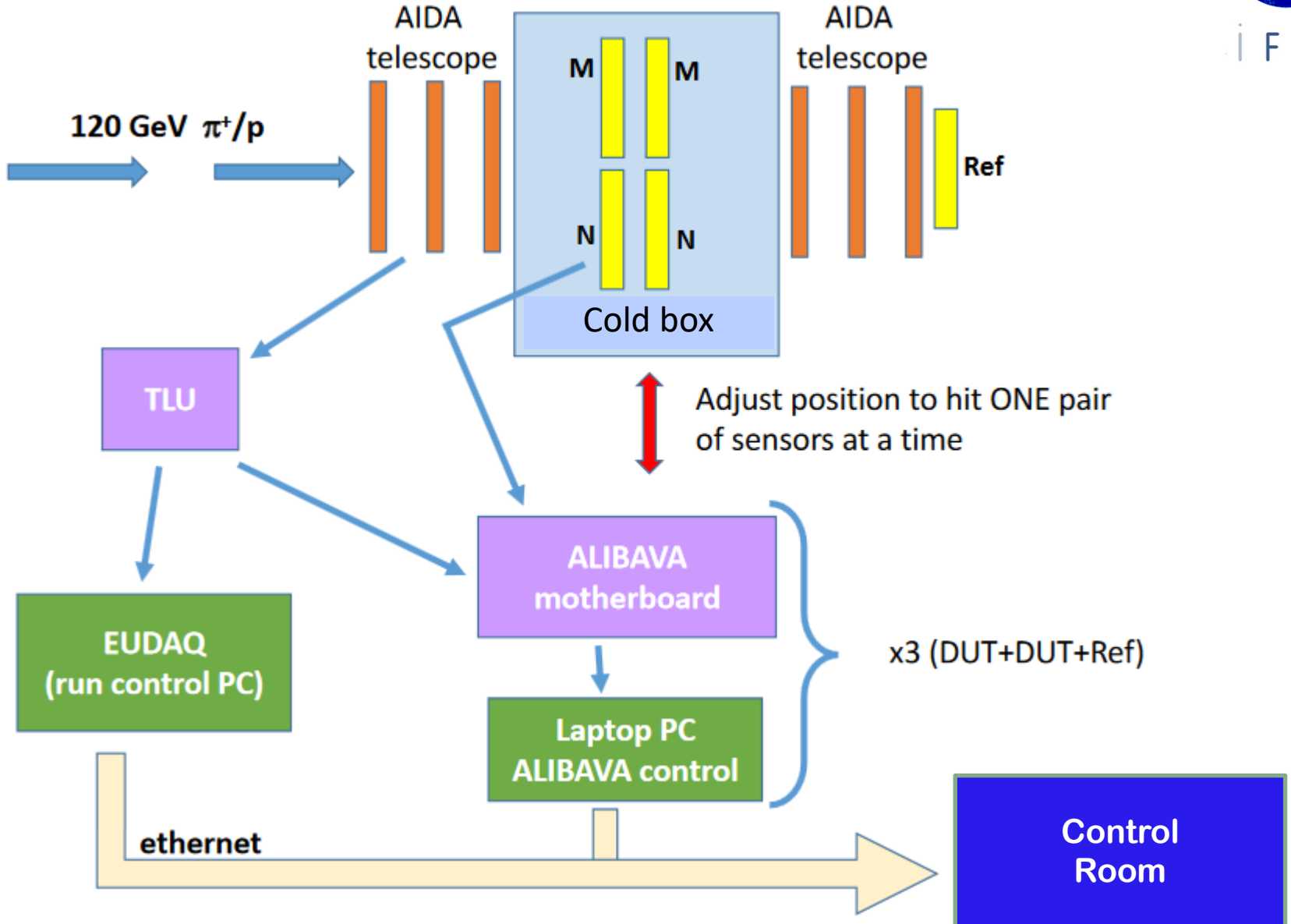


Device	Fluence / n_{eq}/cm^2	Geometry / μm^2	Number of samples	Test
Strip 3D	0	25 x 100	1	<p>Test Beam at CERN SPS:</p> <ul style="list-style-type: none"> ➤ π/p^+ E ~ 120 GeV ➤ Temperature -25°C <p>Radioactive source ^{90}Sr:</p> <ul style="list-style-type: none"> ➤ Temperature -25°C
		50 x 50	1	
	5.7E15	25 x 100	1	
	1.72E16	25 x 100	1	
50 x 50		1		
Pad 3D	0	50 x 50	5	<p>Electrical characterization (IV and CV) Temperature -20°C</p>
		25 x 100 (2E)	5	
	4.2E15	50 x 50	5	
		25 x 100 (2E)	5	
	1E16	50 x 50	5	
		25 x 100 (2E)	5	

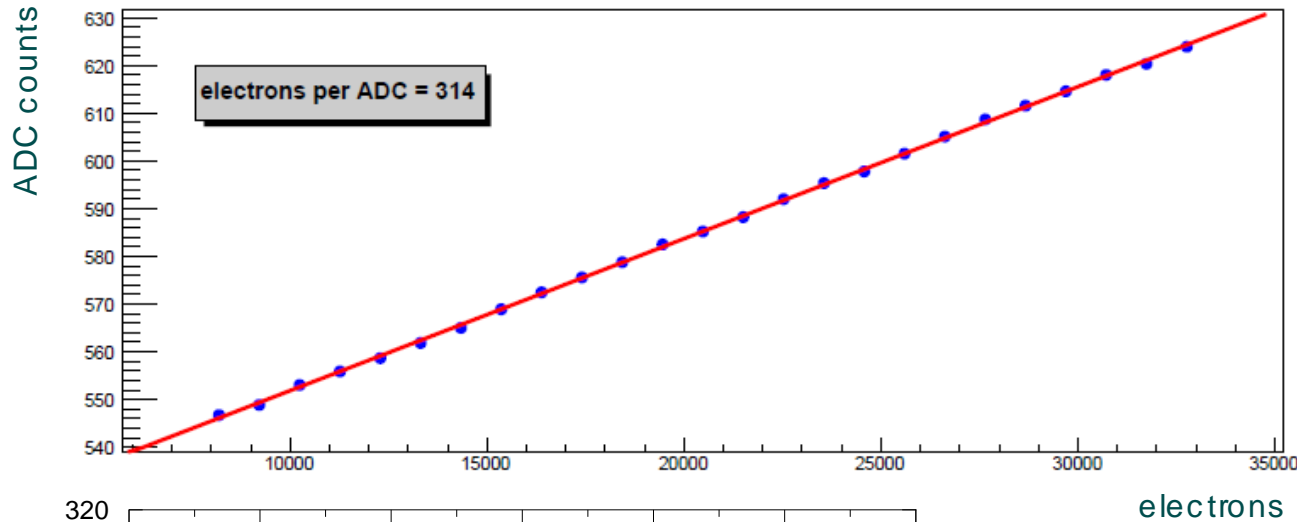
Experimental setup: Radioactive source



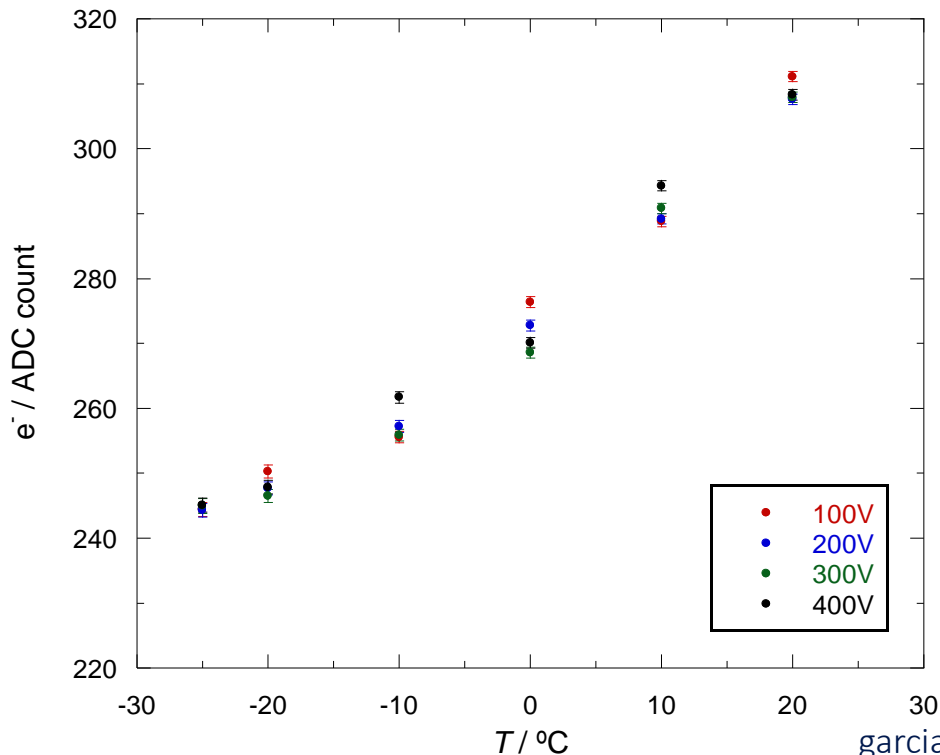
Experimental setup: Test beam



Results: Calibration of the beetle. ADC units charge



Example of a calibration regression for one channel



Calibration factor dependence with bias voltage and temperature

Is the calibration circuit trustworthy to estimate the charge?

Results: Unirradiated sensors charge collection uncertainty



From unirradiated sensor MPV dispersions, error associated to the charge injection for 3D sensors is determined, comparing with theoretically expected charge collected value.

- Theoretical value 230 μm thick sensor: 17.48 ke (76 e⁻ h⁺ / μm)

50x50 230 μm 3D sensor $T = -25^\circ\text{C}$ $\overline{\text{MPV}} = 19.14$ ke correction = 17.48/19.14 = 0.9133

25x100 230 μm 3D sensor $T = -25^\circ\text{C}$ $\overline{\text{MPV}} = 16.25$ ke correction = 17.48/16.25 = 1.0757

Mean value of the correction = 0.9945

Uncertainty in the MPV:

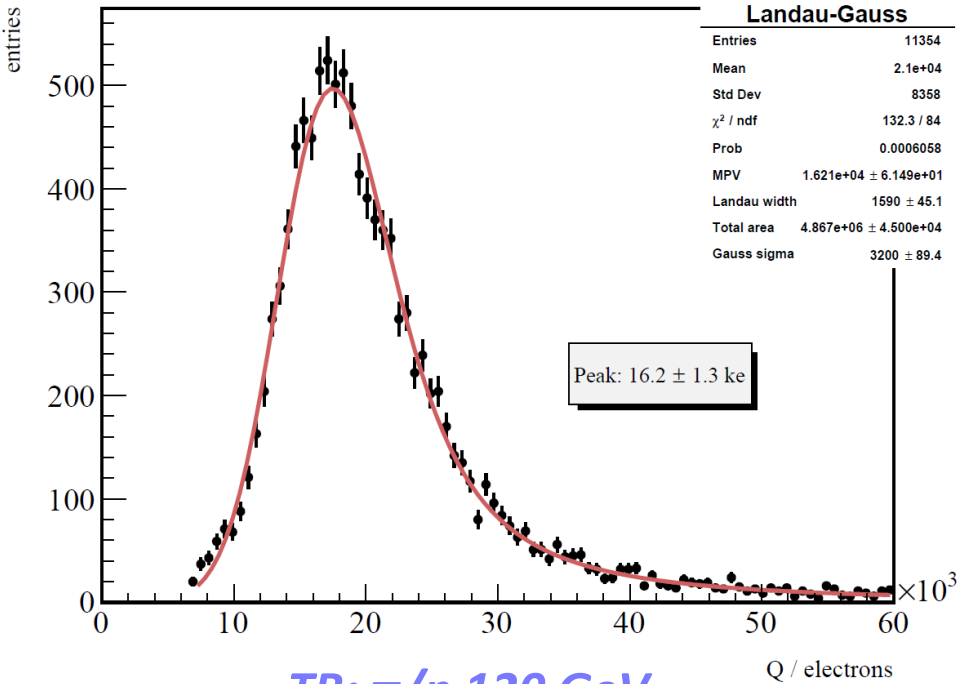
$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{m=1}^N (x_e - x_m)^2} = \sqrt{\frac{1}{2} [(1 - 0.9133)^2 + (1 - 1.0757)^2]} = 0.081 \Rightarrow \boxed{8\%}$$

Results: Calibrated collected charge distributions.

Unirradiated 3D sensor

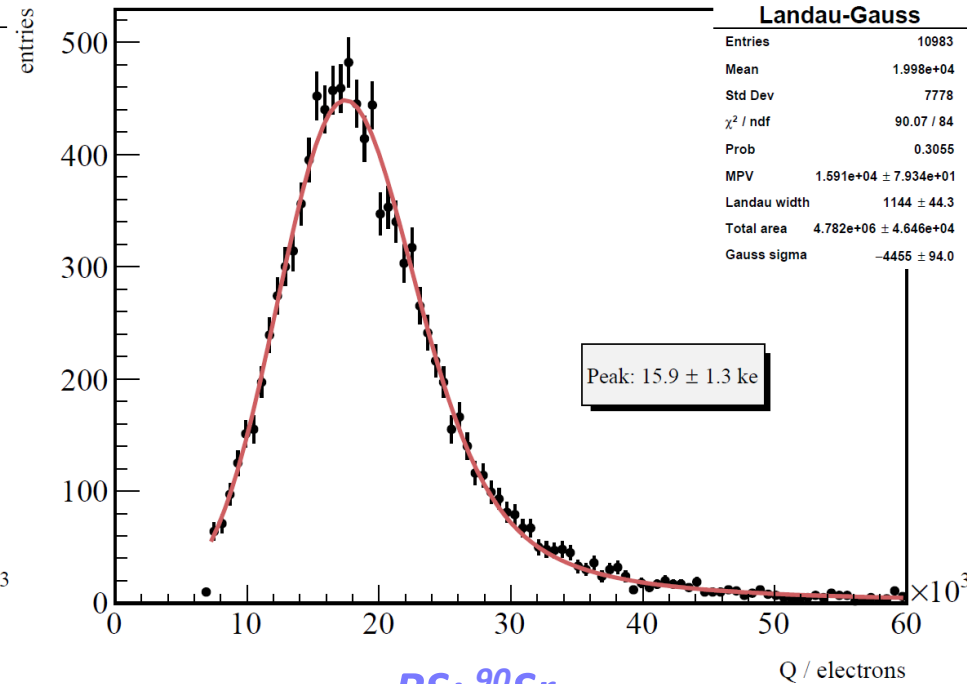


TB2017cern Sensor N1-3 run 401 T=-25C V=-50V Calibrated charge. 9.4375 < time window < 13.4375



TB: π/p 120 GeV
25 x 100 μm^2
T = -25°C
V = -50V

RS2017cern Sensor N1-3 run 0007 T=-25C V=-30V Calibrated charge. 3.2275 < time window < 7.2275



RS: ^{90}Sr
25 x 100 μm^2
T = -25°C
V = -30V

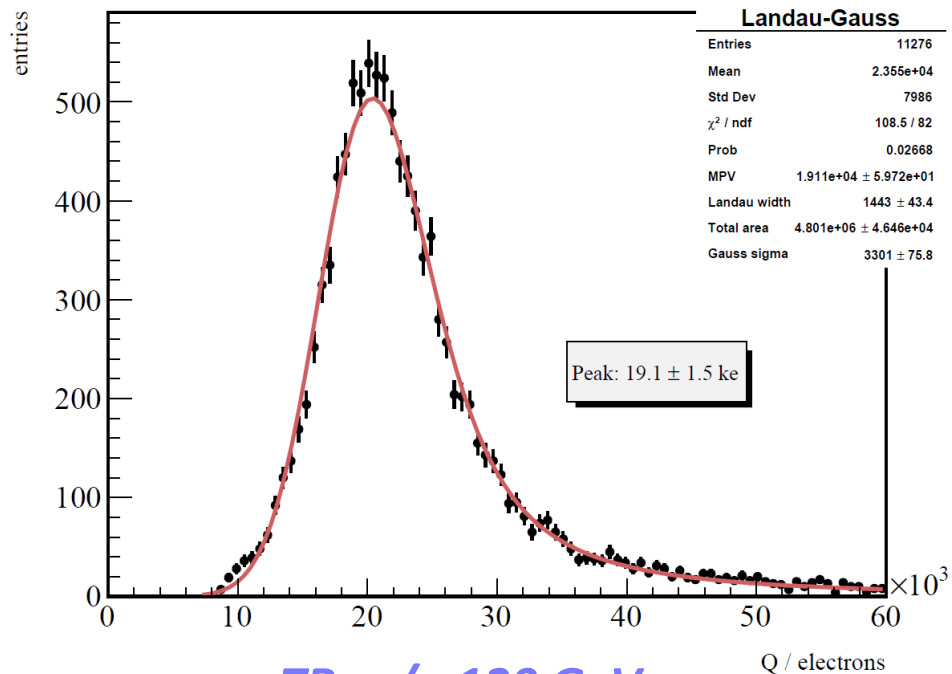
Depletion voltage $\sim -10\text{V}$

Results: Calibrated collected charge distributions.

Unirradiated 3D sensor

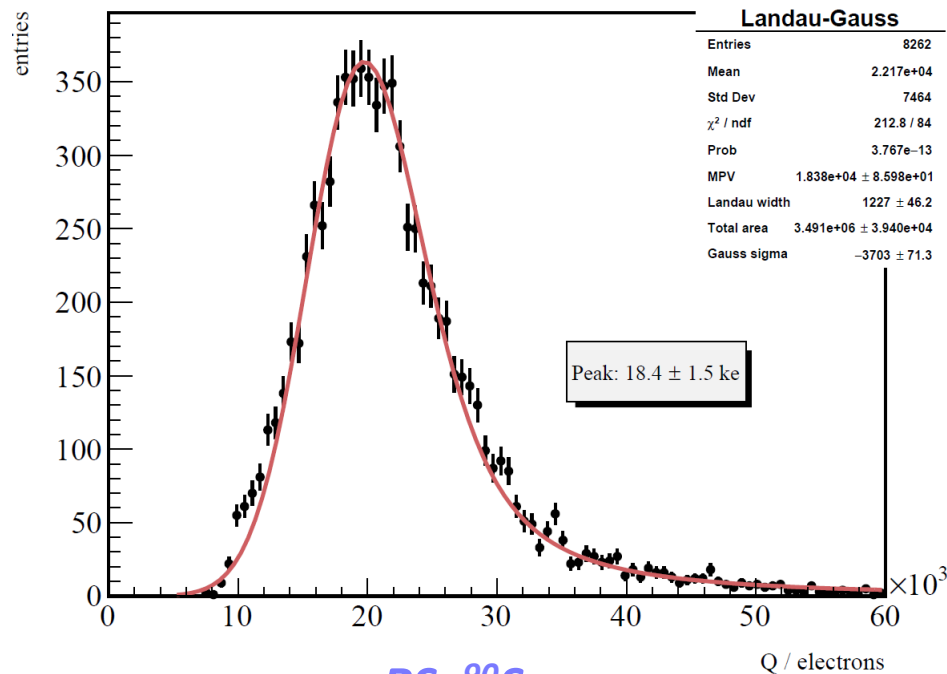


TB2017cern Sensor M1-5 run 381 T=-25C V=-30V Calibrated charge. 9.9775 < time window < 13.9775



TB: π/p 120 GeV
50 x 50 μm^2
T = -25°C
V = -30V

RS2017cern Sensor M1-5 run 0012 T=-25C V=-30V Calibrated charge. 3.4975 < time window < 7.4975



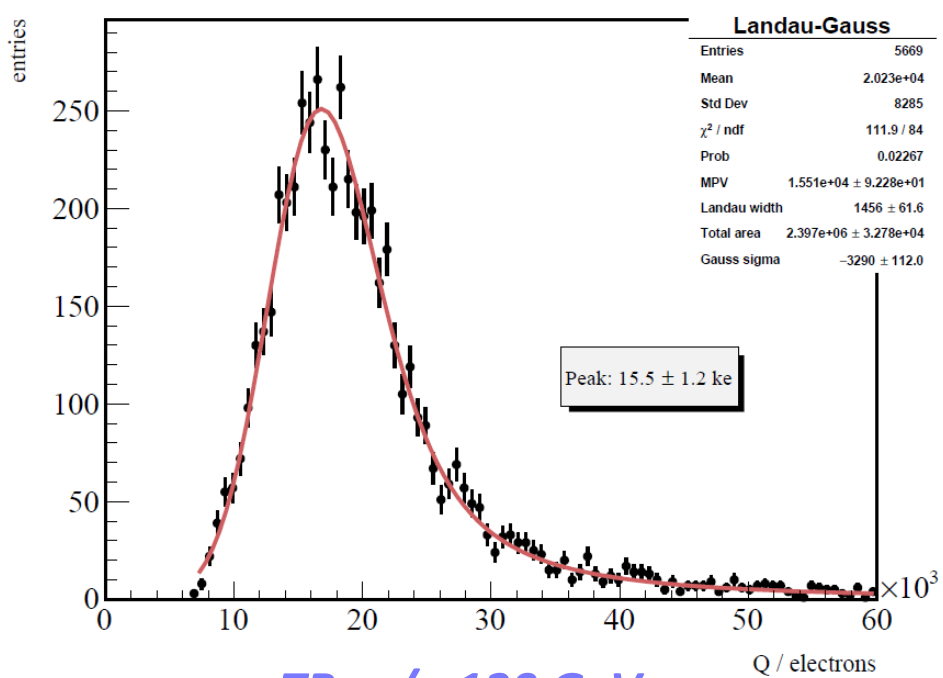
RS: ^{90}Sr
50 x 50 μm^2
T = -25°C
V = -30V

Results: Calibrated collected charge distributions.

Irradiated 3D sensor at $5.7E15 \text{ n}_{eq}/\text{cm}^2$

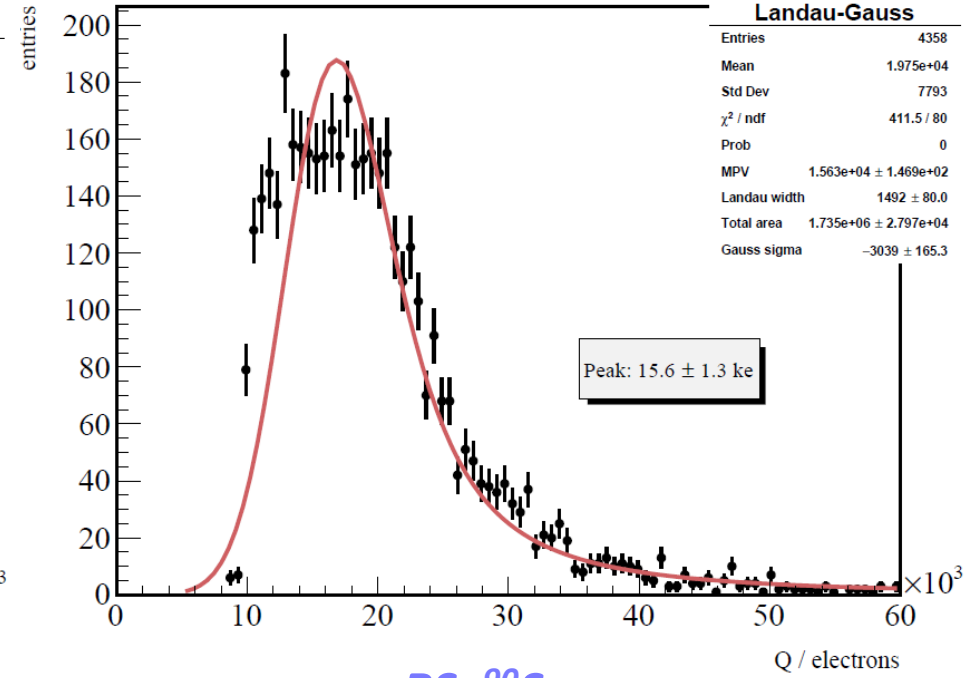


TB2017 Sensor N1-7 run 362 T=-25C V=-180V Calibrated charge. 10.3825 < time window < 14.3825



TB: π/p 120 GeV
25 x 100 μm^2
T = -25°C
V = -180V

RS2017cern Sensor N1-7 run 0005 T=-25C V=-180V Calibrated charge. 2.4175 < time window < 6.4175



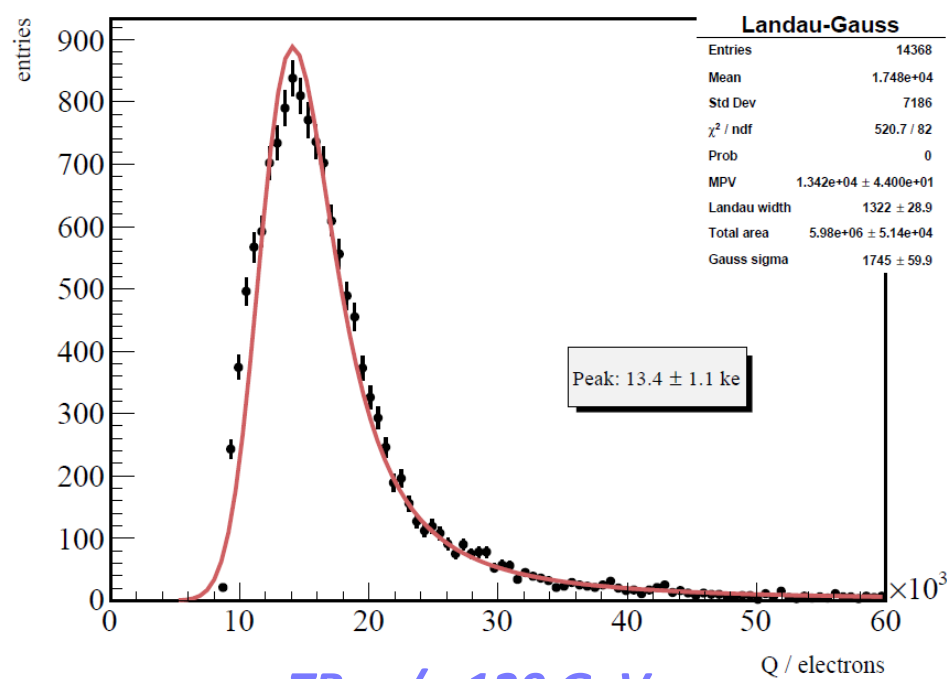
RS: ^{90}Sr
25 x 100 μm^2
T = -25°C
V = -180V

Results: Calibrated collected charge distributions.

Irradiated 3D sensor at $1.72E16 n_{eq}/cm^2$

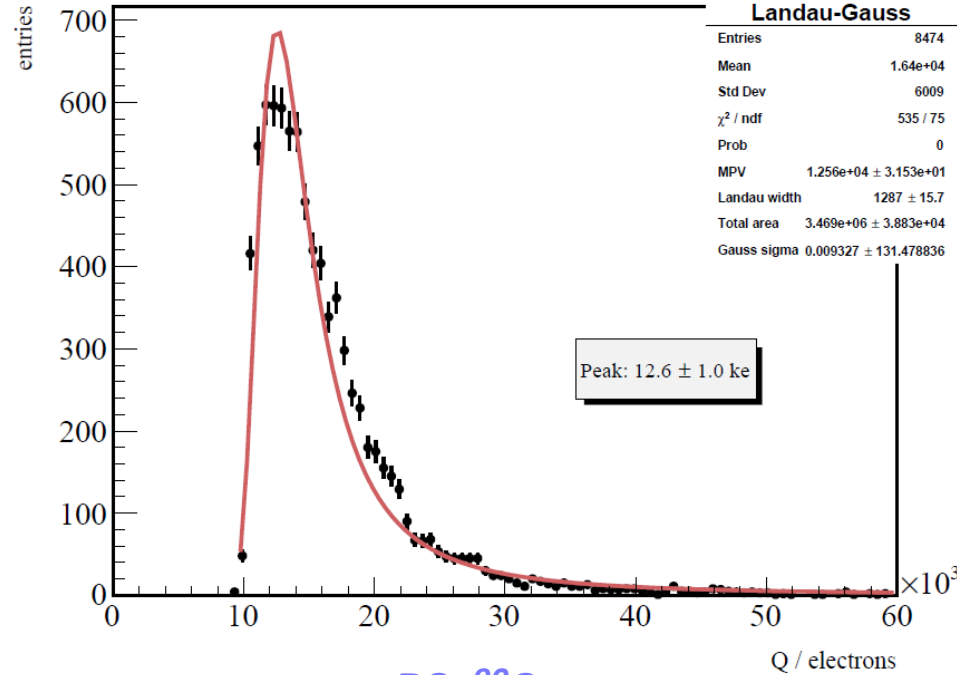


TB2017 Sensor M2-3 run 362 T=-25C V=-175V Calibrated charge. 10.1125 < time window < 14.1125



TB: π/p 120 GeV
 $50 \times 50 \mu m^2$
 $T = -25^\circ C$
 $V = -175V$

RS2017cern Sensor M2-3 run 0004 T=-25C V=-175V Calibrated charge. 2.6875 < time window < 6.6875



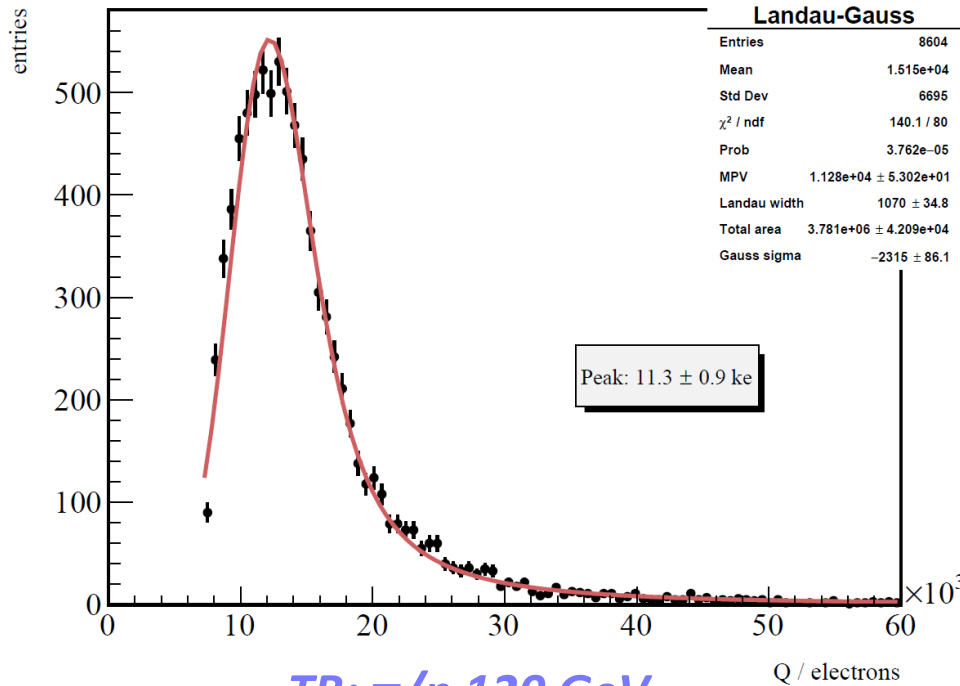
RS: ^{90}Sr
 $50 \times 50 \mu m^2$
 $T = -25^\circ C$
 $V = -175V$

Results: Calibrated collected charge distributions.

Irradiated 3D sensor at $1.72E16 n_{eq}/cm^2$

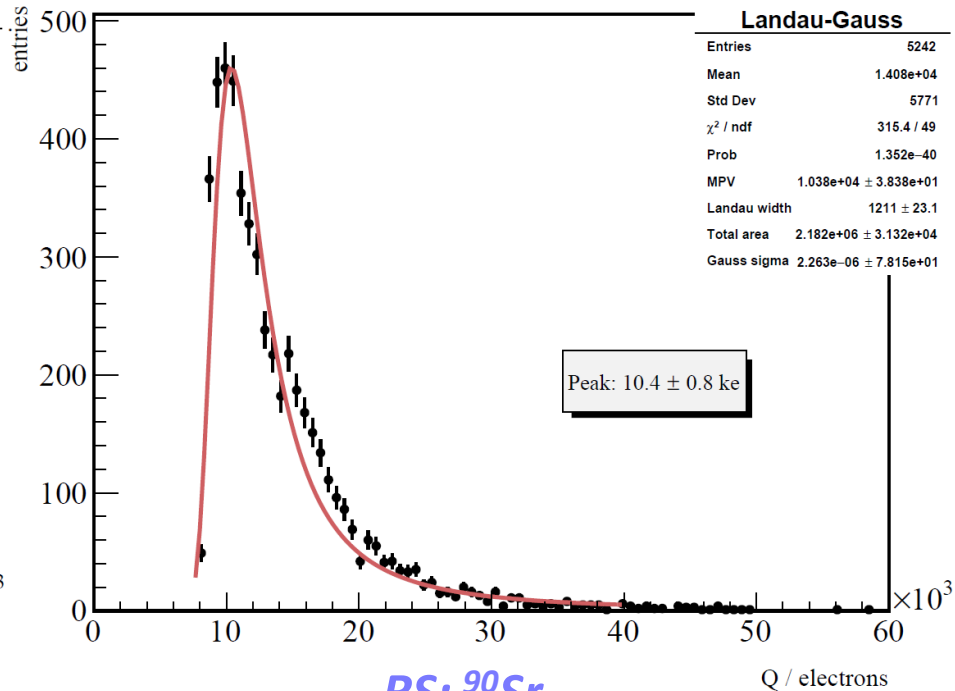


TB2017 Sensor N1-8 run 403 T=-25C V=-175V Calibrated charge. 9.3025 < time window < 13.3025



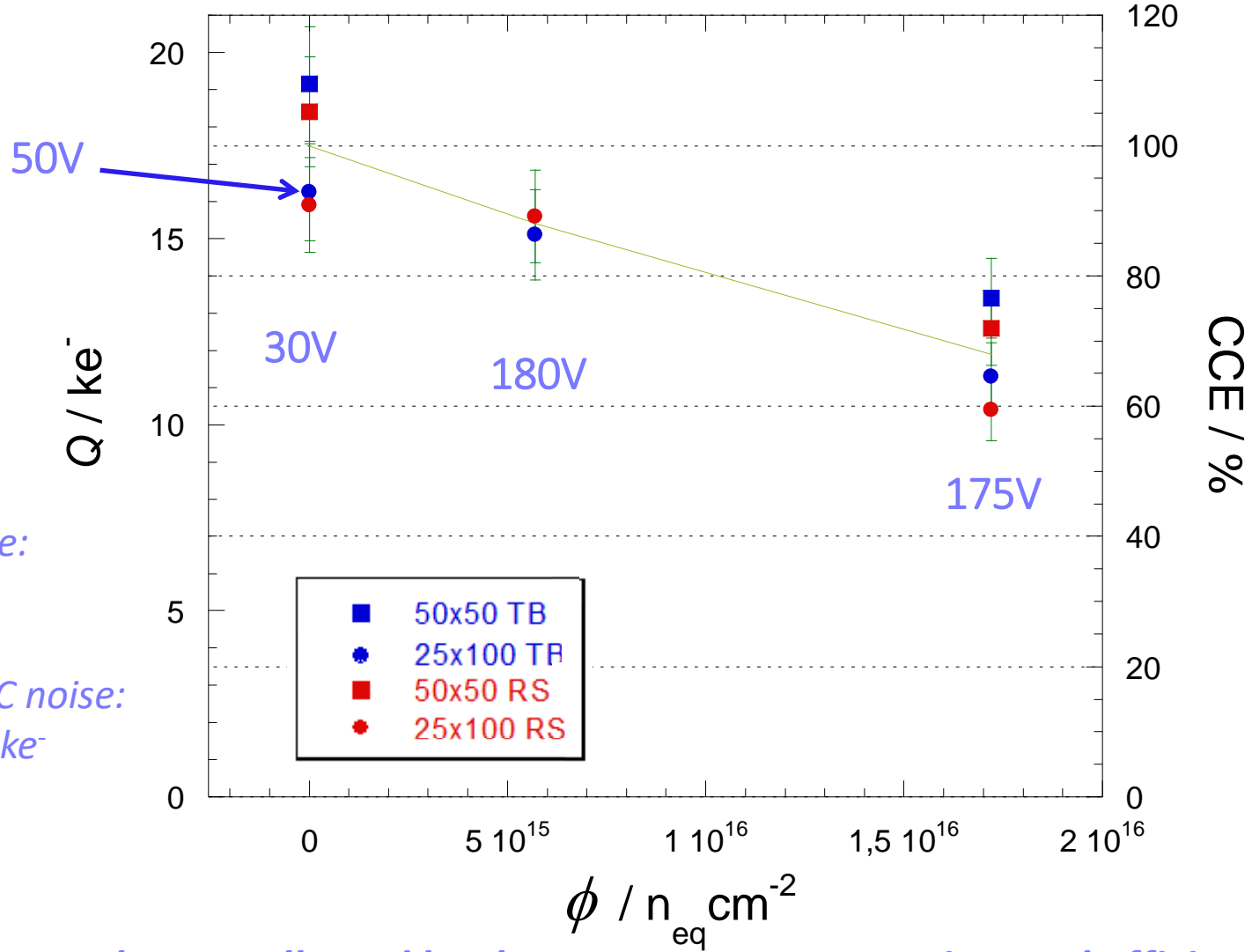
TB: π/p 120 GeV
 $25 \times 100 \mu m^2$
 $T = -25^\circ C$
 $V = -175V$

RS2017cern Sensor N1-8 run 0006 T=-25C V=-175V Calibrated charge. 2.1475 < time window < 6.1475



RS: ^{90}Sr
 $25 \times 100 \mu m^2$
 $T = -25^\circ C$
 $V = -175V$

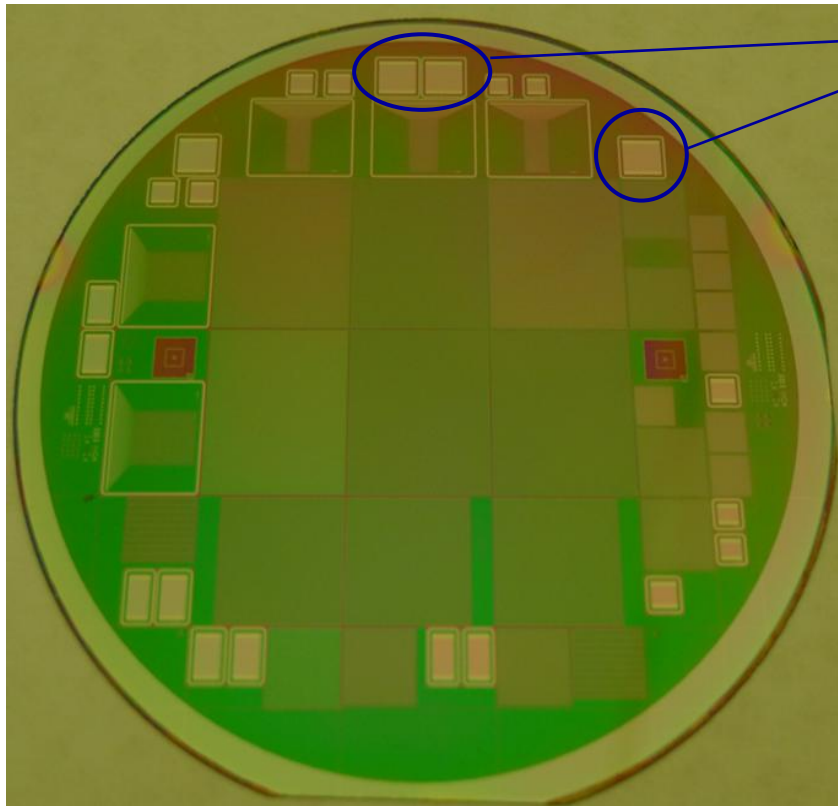
Results: Charge collection variation with fluence



- *RD53 noise:*
300 e⁻
- *Beetle ROC noise:*
1.5 – 2 ke⁻

Charge collected by the two sensor geometries, and efficiency at TB and RS, for the three fluence values.

Results: Power dissipation studies. Pads

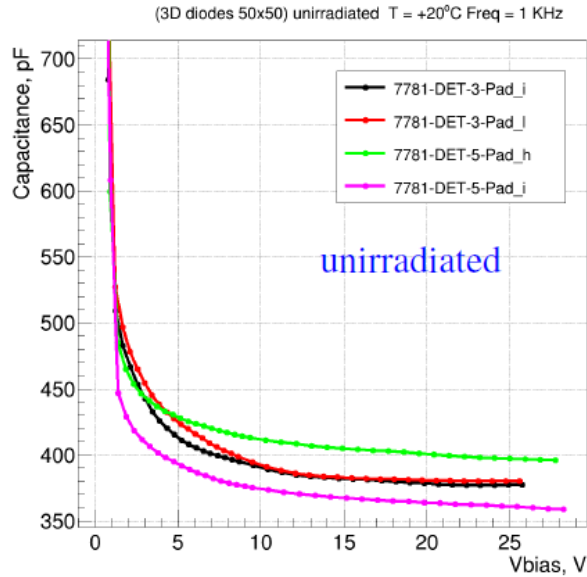


5 pad sensors of $50 \times 50 \mu\text{m}^2$

Fluence values:

- ✓ Unirradiated
- ✓ $4.2 \text{ E}15 \text{ n}_{\text{eq}}/\text{cm}^2$
- ✓ $1 \text{ E}16 \text{ n}_{\text{eq}}/\text{cm}^2$

Results: CV characterization 50x50 pads

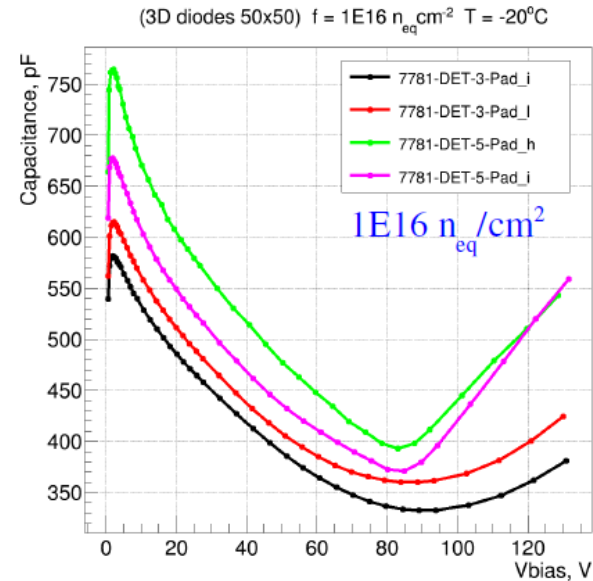
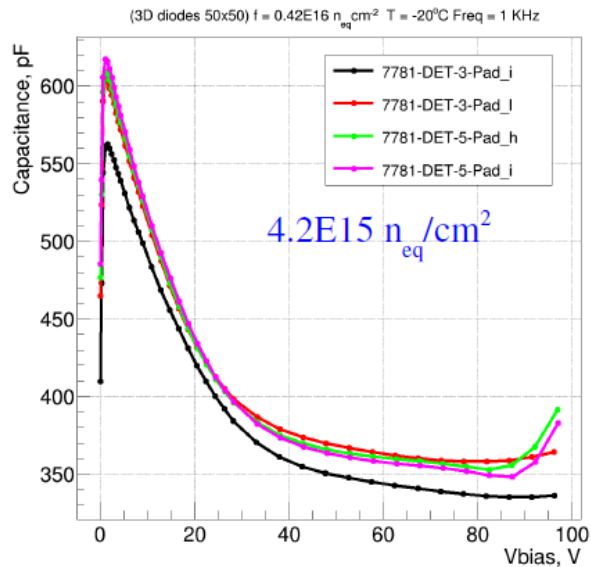


Unirradiated $C_{end} \rightarrow$ around 35-40 fF per pixel.

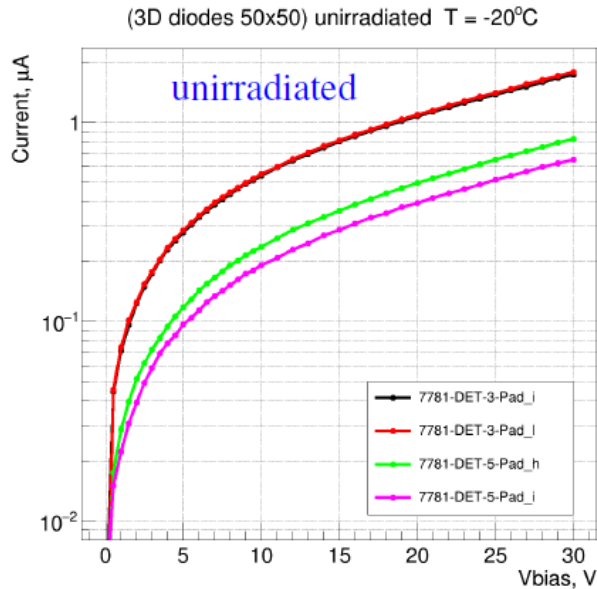
Irradiated ($4.2E15 n_{eq}/cm^2$) $C_{end} \rightarrow$ around 35 fF per pixel.

Irradiated ($1E16 n_{eq}/cm^2$) $C_{end} \rightarrow$ around 35-40 fF per pixel.

Specified max. capacitance of RD53: around 100 fF per pixel



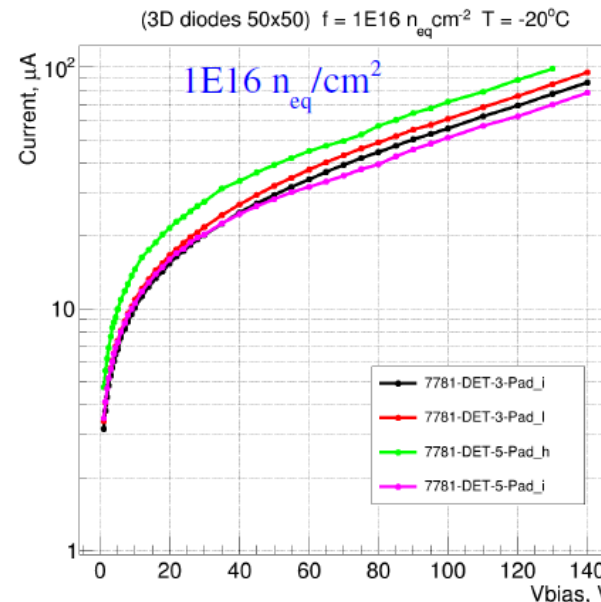
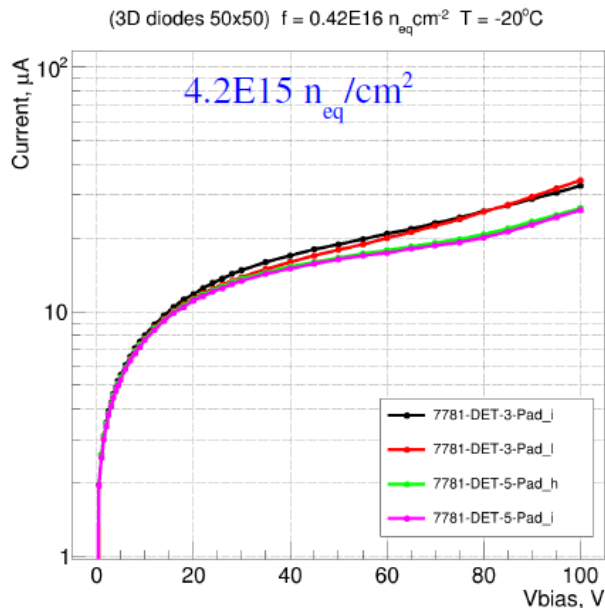
Results: IV characterization 50x50 pads



- Unirradiated at 30 V → around 60-150 pA per pixel
- $4.2\text{E}15 n_{\text{eq}}/\text{cm}^2$ at 100 V → around 3 nA per pixel
- $1\text{E}16 n_{\text{eq}}/\text{cm}^2$ at 100 V → around 6 nA per pixel

Sensor consumption: 14 mW/cm²

RD53 chip estimated dissipation: 2.37 W/chip
0.6 W/cm²



- Charge collection efficiency of strip 3D sensor:
 - Small size 3D strip sensors present a large charge collection efficiency (65%) when reaching high irradiation fluences.

- Electrical characterization of pad 3D sensors:
 - Power dissipation much lower (2%) than the chip maximum value at half the final fluence.

**Thank you for
your attention**

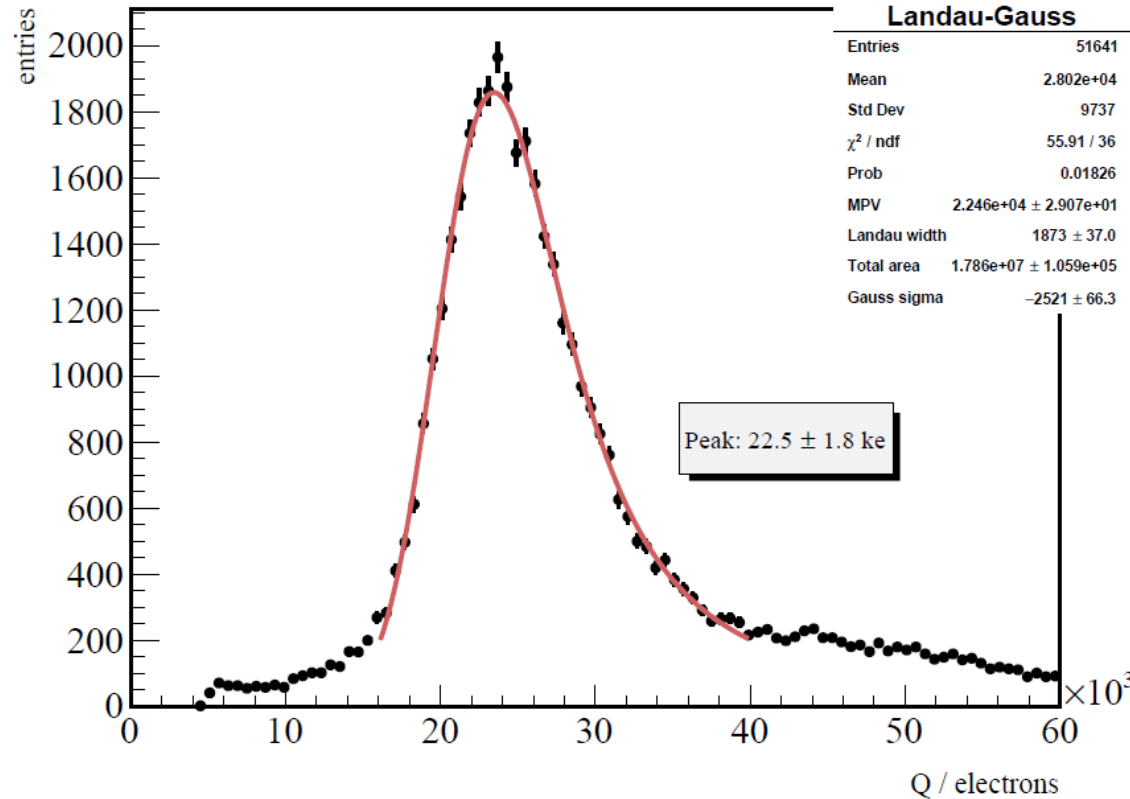
BACKUP

Results: Calibrated collected charge distributions.

Reference planar sensor 300 μm thick



TB2017cern Sensor REF run 403 T=20C V=-200V Calibrated charge. 14.0275 < time window < 18.0275



Expected collected charge value for 300 μm: 22.8 ke⁻

*Unirradiated planar sensor at TB measurement
T = +20°C ; V = -200V*

Results: Charge collection variation with fluence



Sensor	Q / ke	Fluence	
M1-5 TB	19.15	0	-30V
M1-5 RS	18.4	0	-30V
N1-3 TB	16.25	0	<u>-50V</u>
N1-3 RS	15.9	0	-30V
N1-7 TB	15.1	5.7E15	-180V
N1-7 RS	15.6	5.7E15	-180V
M2-3 TB	13.4	1.72E16	-175V
M2-3 RS	12.6	1.72E16	-175V
N1-8 TB	11.3	1.72E16	-175V
N1-8 RS	10.4	1.72E16	-175V

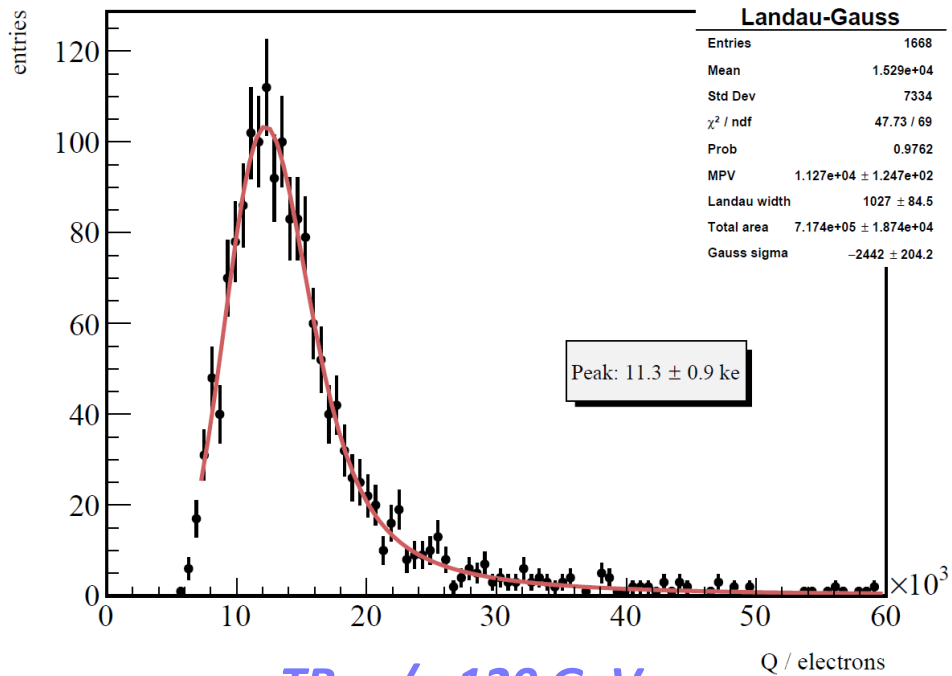
Charge collected by the sensors for the three fluence values.

Results: Calibrated collected charge distributions.

Irradiated 3D sensor at $5.7E15 \text{ n}_{eq}/\text{cm}^2$

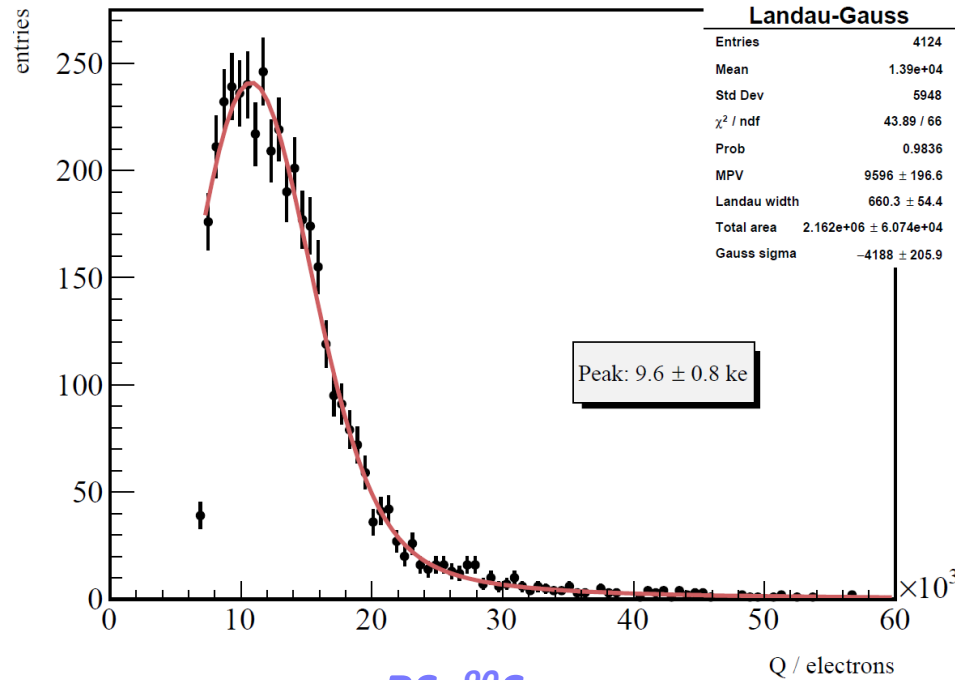


TB2017 Sensor N1-7 run 314 T=-25C V=-120V Calibrated charge. 10.1125 < time window < 14.1125



TB: π/p 120 GeV
 $25 \times 100 \mu\text{m}^2$
 $T = -25^\circ\text{C}$
 $V = -120\text{V}$

RS2017cern Sensor N1-7 run 0002 T=-25C V=-120V Calibrated charge. 2.0125 < time window < 6.0125



RS: ^{90}Sr
 $25 \times 100 \mu\text{m}^2$
 $T = -25^\circ\text{C}$
 $V = -120\text{V}$

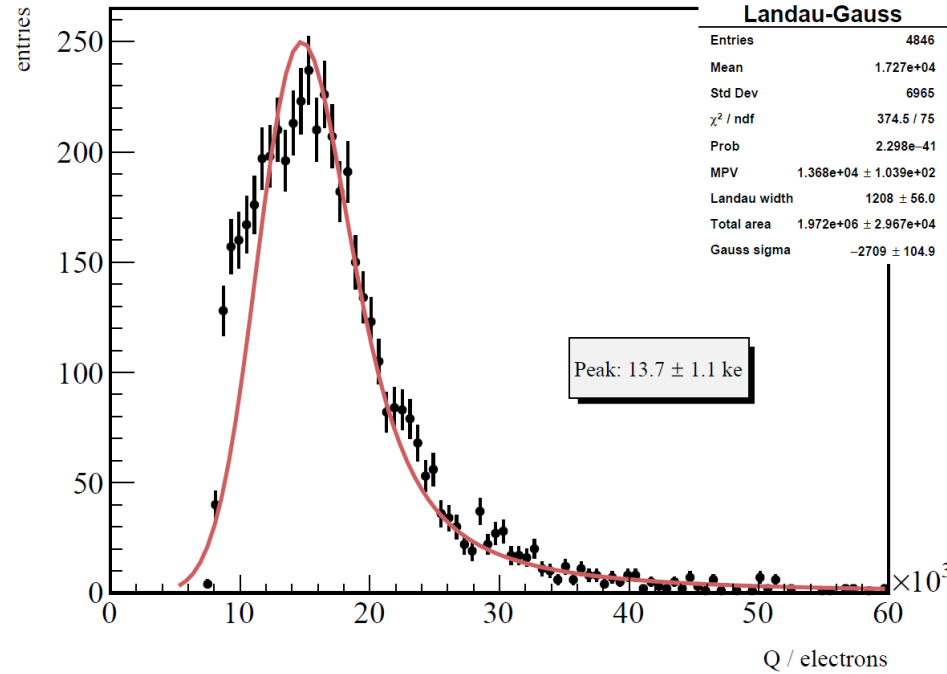
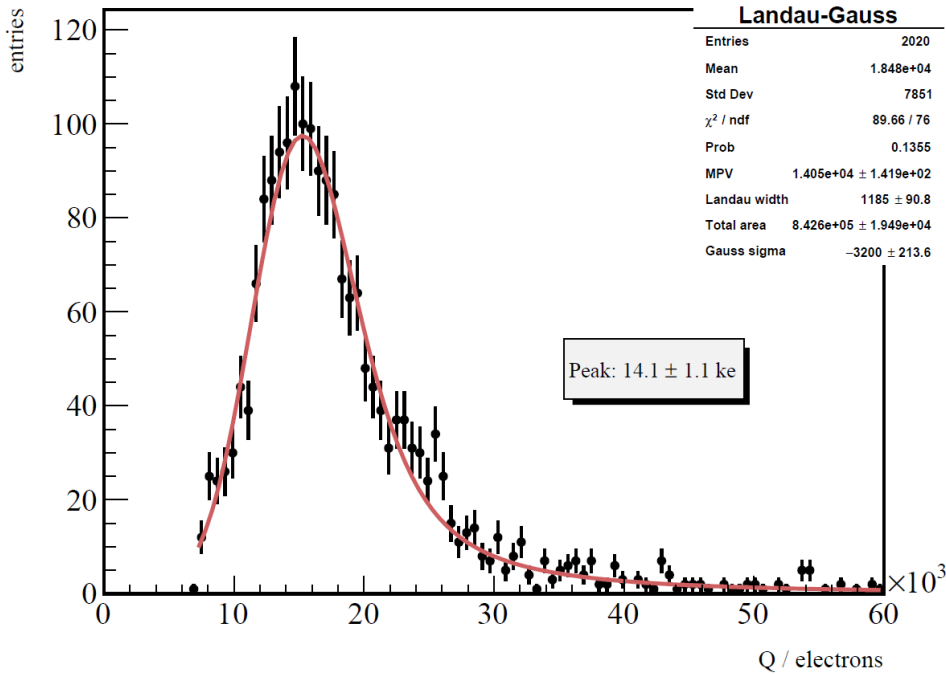
Results: Calibrated collected charge distributions.

Irradiated 3D sensors at $5.7E15 \text{ n}_{eq}/\text{cm}^2$



TB2017 Sensor N1-7 run 308 T=-25C V=-160V Calibrated charge. 10.5175 < time window < 14.5175

RS2017cern Sensor N1-7 run 0004 T=-25C V=-160V Calibrated charge. 2.8225 < time window < 6.8225



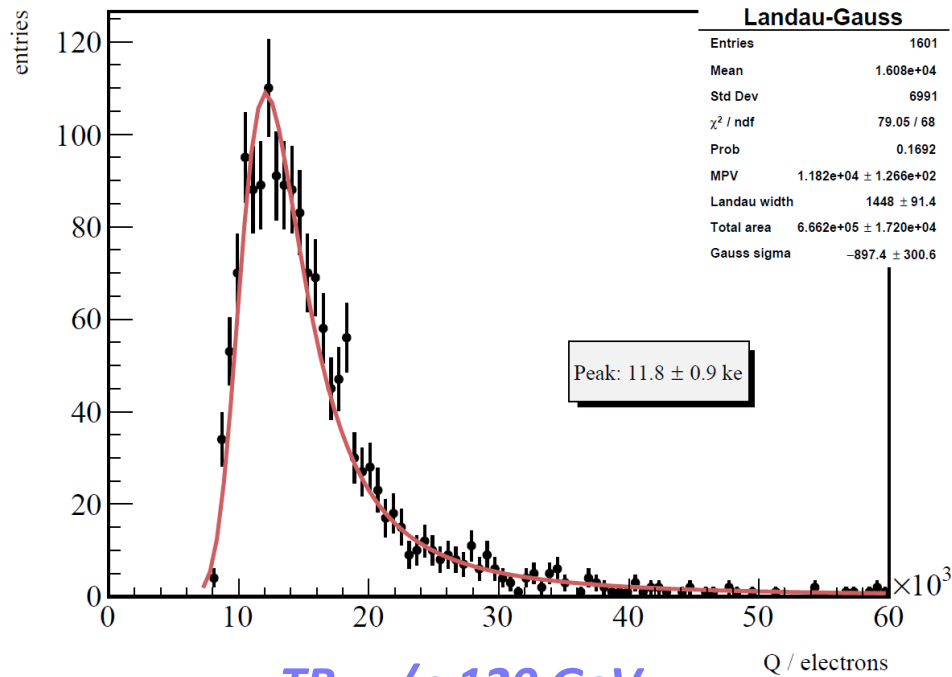
Irradiated 3D sensor N1-7 at TB and RS measurements
 $T = -25^\circ\text{C}$; $V = -160\text{V}$

Results: Calibrated collected charge distributions.

Irradiated 3D sensor at $1.72E16 n_{eq}/cm^2$

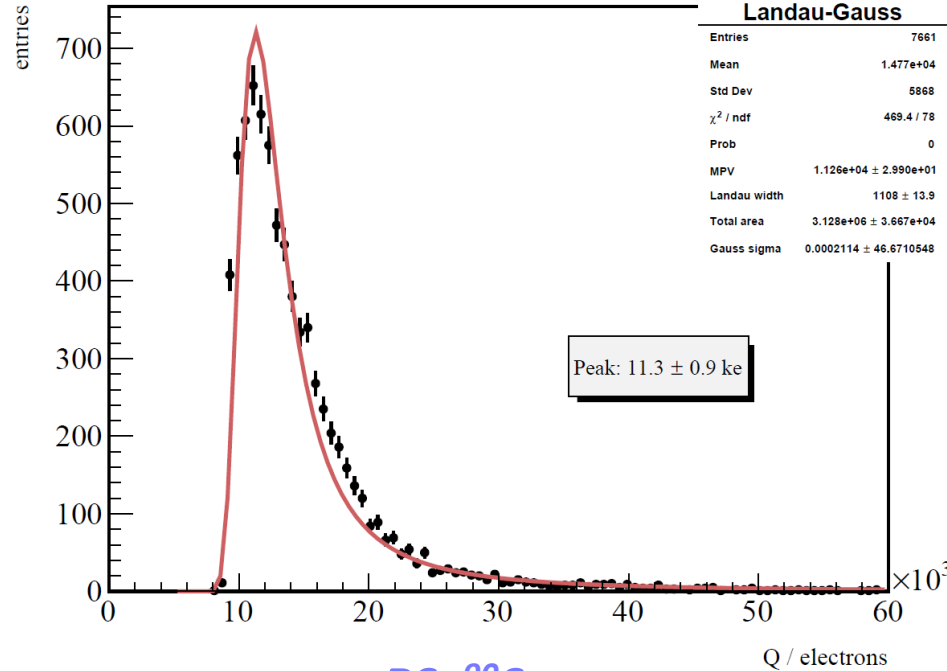


TB2017 Sensor M2-3 run 307 T=-25C V=-150V Calibrated charge. 9.8425 < time window < 13.8425



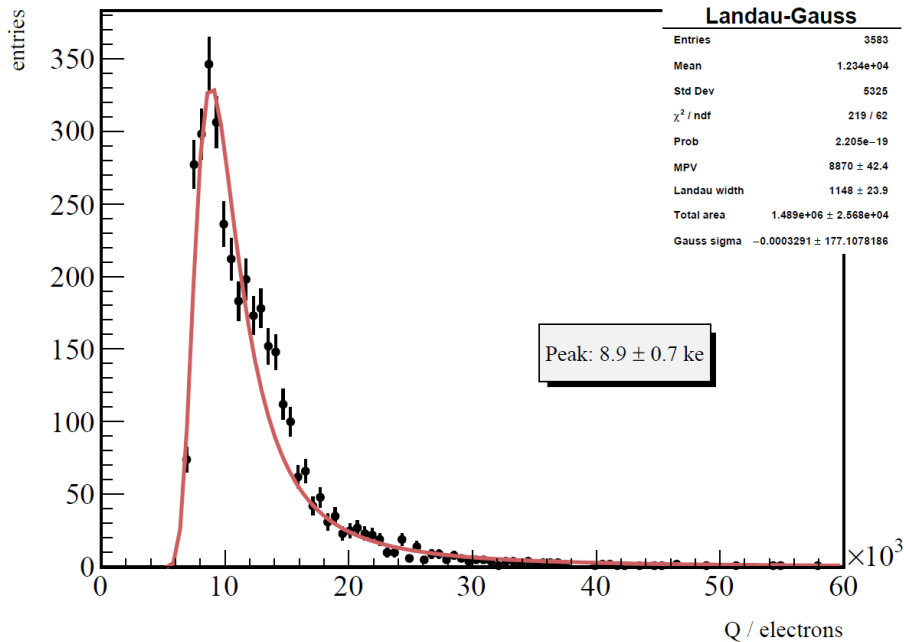
TB: π/p 120 GeV
 $50 \times 50 \mu m^2$
 $T = -25^\circ C$
 $V = -150V$

RS2017cern Sensor M2-3 run 0003 T=-25C V=-150V Calibrated charge. 2.2825 < time window < 6.2825

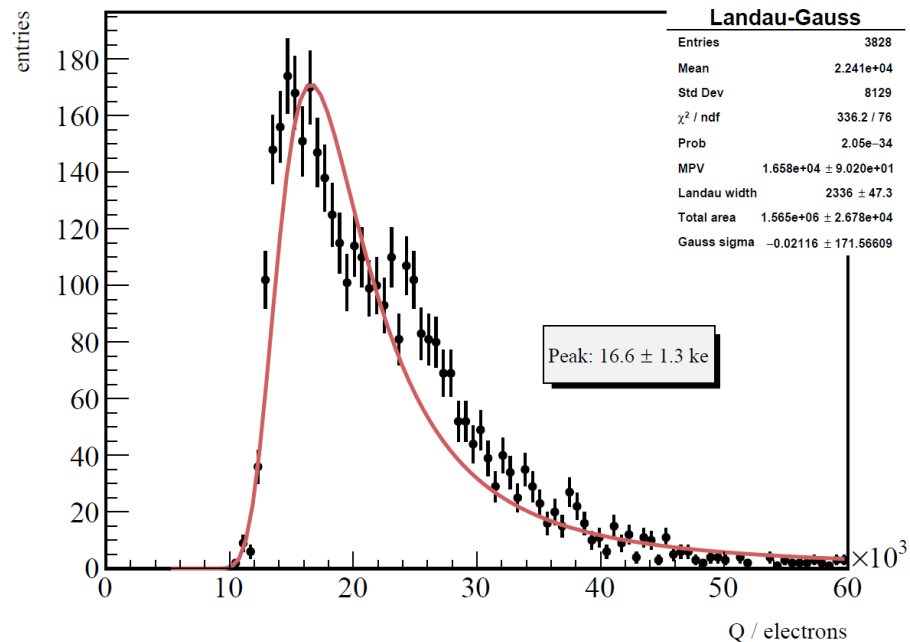


RS: ^{90}Sr
 $50 \times 50 \mu m^2$
 $T = -25^\circ C$
 $V = -150V$

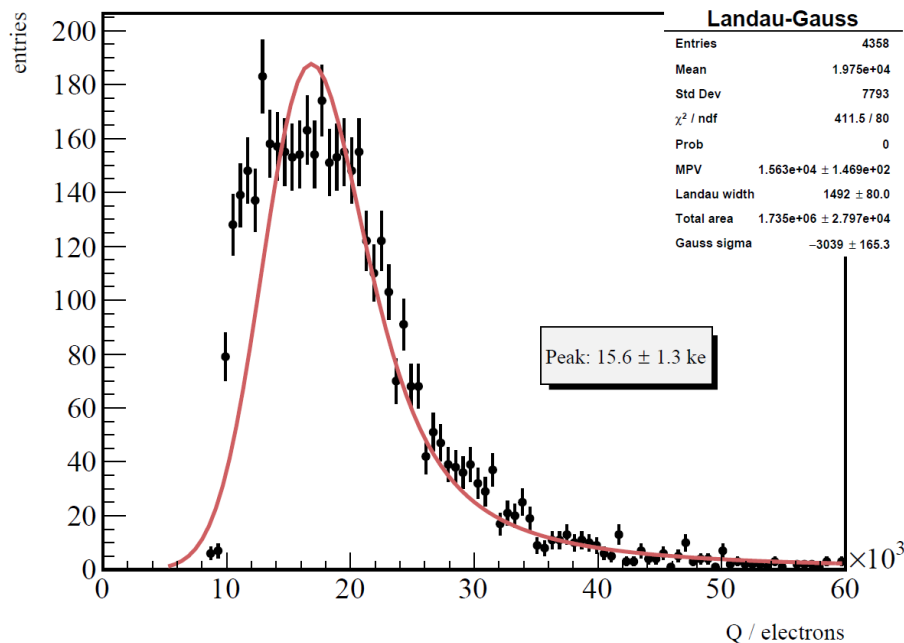
RS2017cern Sensor N1-7 run 0001 T=-25C V=-100V Calibrated charge. 2.5525 < time window < 6.5525



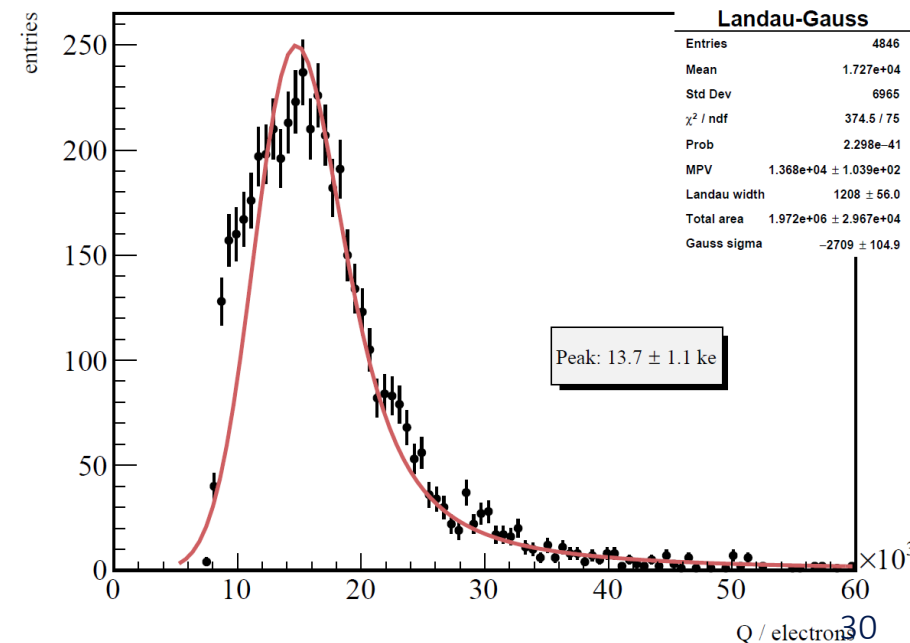
RS2017cern Sensor N1-7 run 0006 T=-25C V=-200V Calibrated charge. 2.6875 < time window < 6.6875



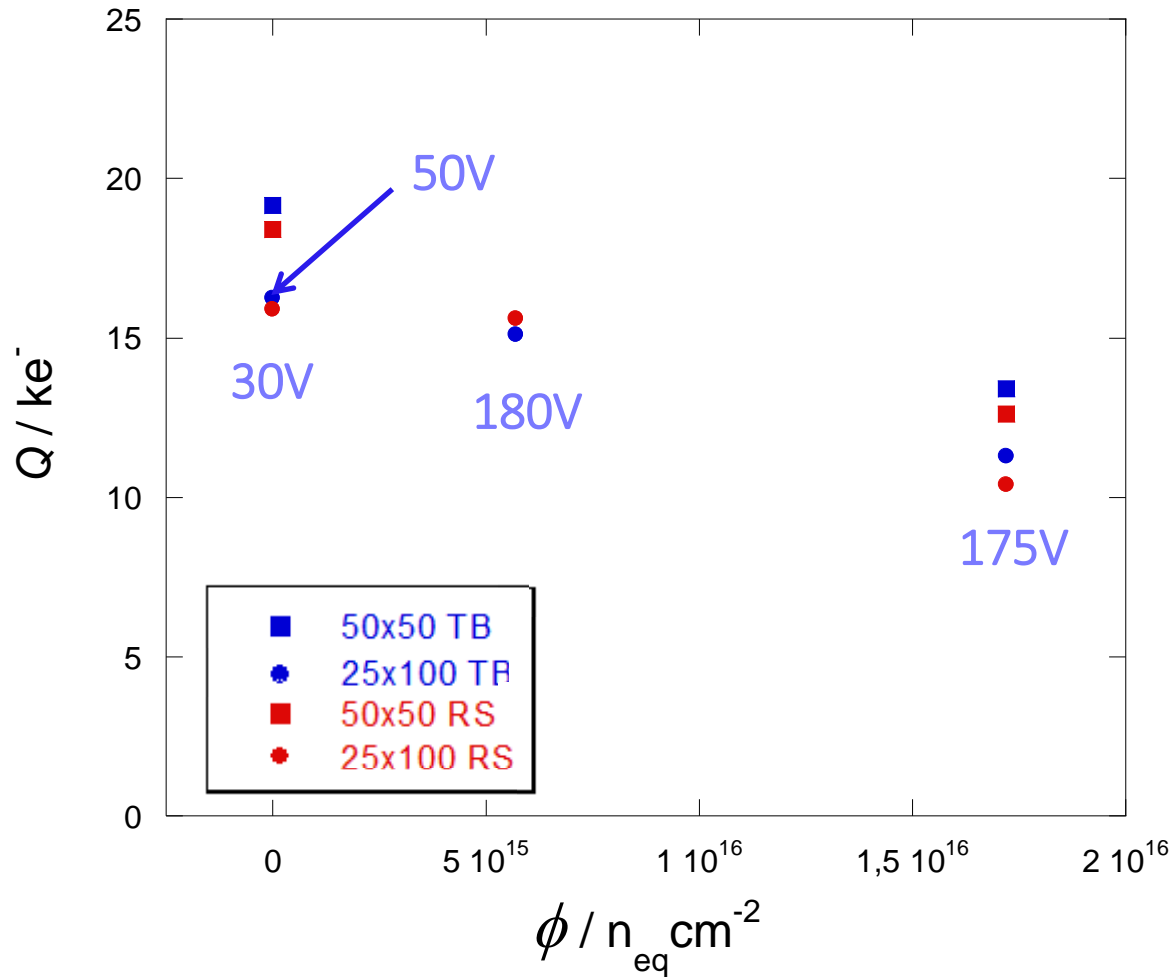
RS2017cern Sensor N1-7 run 0005 T=-25C V=-180V Calibrated charge. 2.4175 < time window < 6.4175



RS2017cern Sensor N1-7 run 0004 T=-25C V=-160V Calibrated charge. 2.8225 < time window < 6.8225



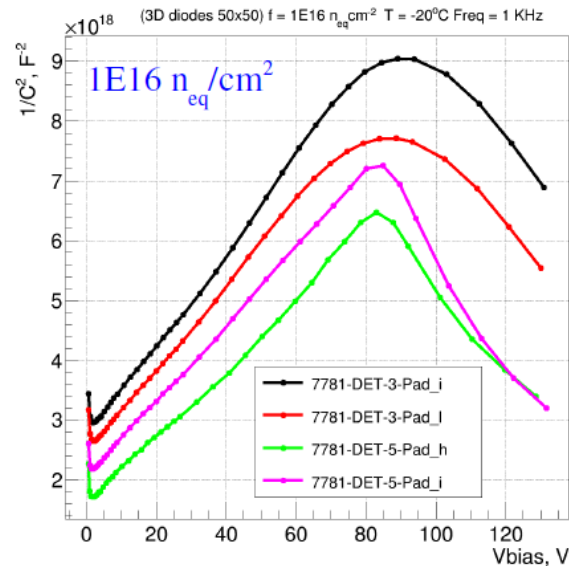
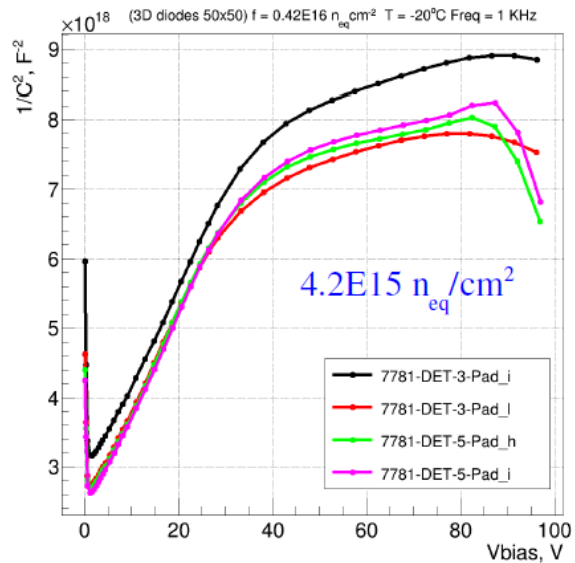
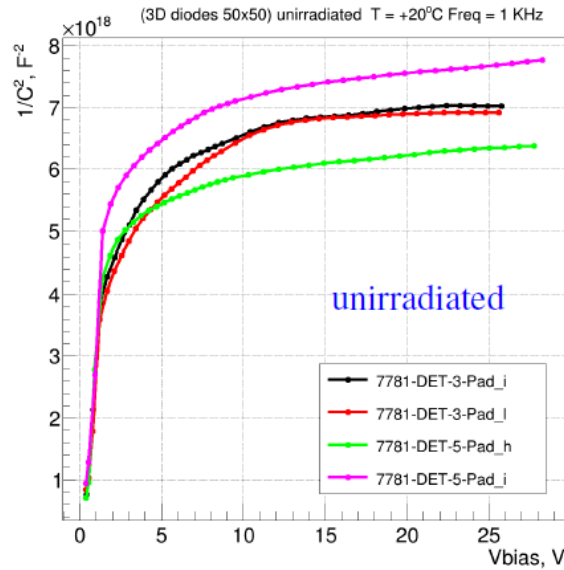
Results: Charge collection variation with fluence



Charge collected by the two sensor geometries at TB and RS, for the three fluence values.

Results: Electrical characterization of pads

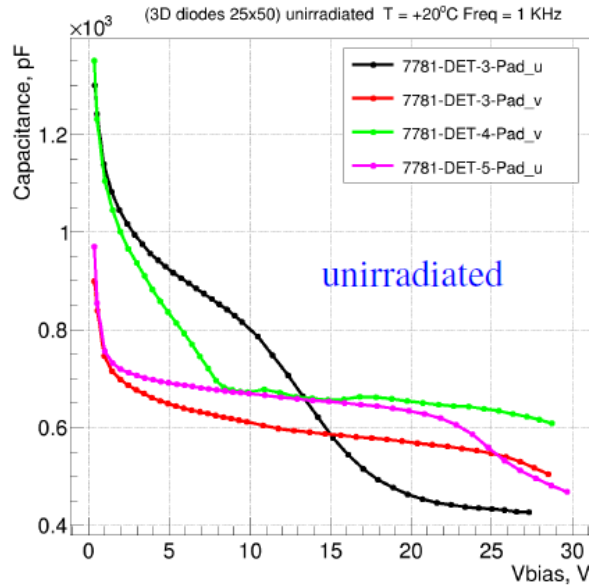
CV characterization 50x50



Results: Electrical characterization of pads



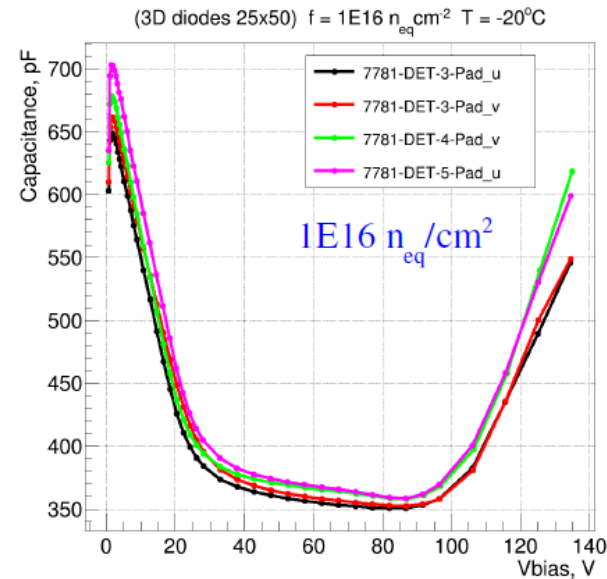
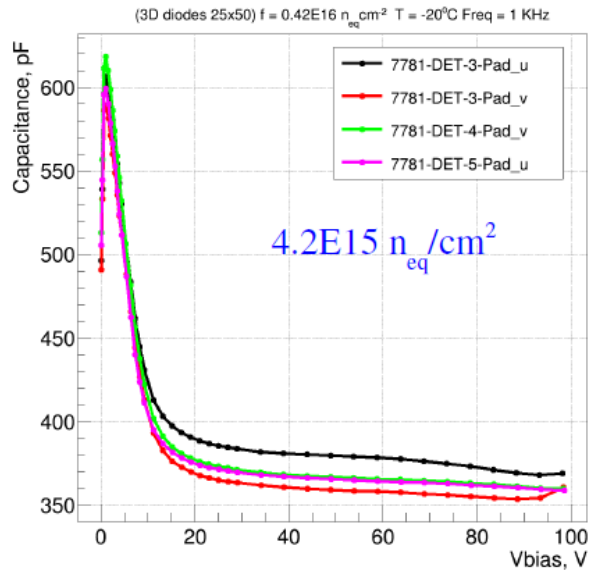
CV characterization 25x50



Unirradiated C_{end} → around 50-70 fF per pixel.

Irradiated ($4.2E15 \text{ n}_{eq}/\text{cm}^2$) C_{end} → around 35-38 fF per pixel.

Irradiated ($1E16 \text{ n}_{eq}/\text{cm}^2$) C_{end} → around 35 fF per pixel.



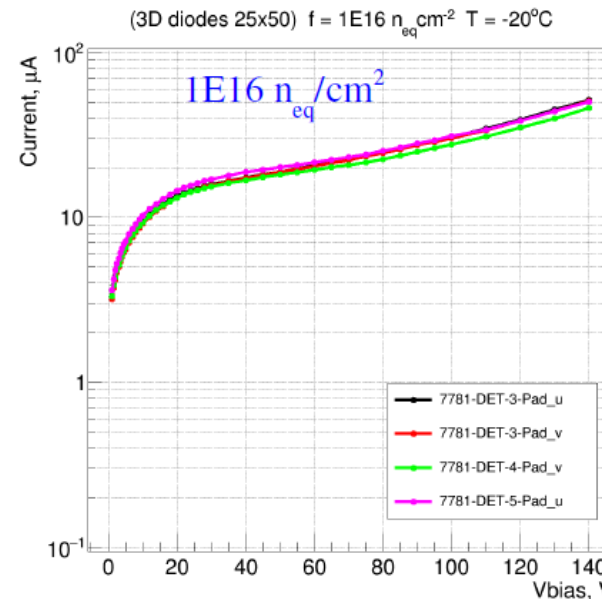
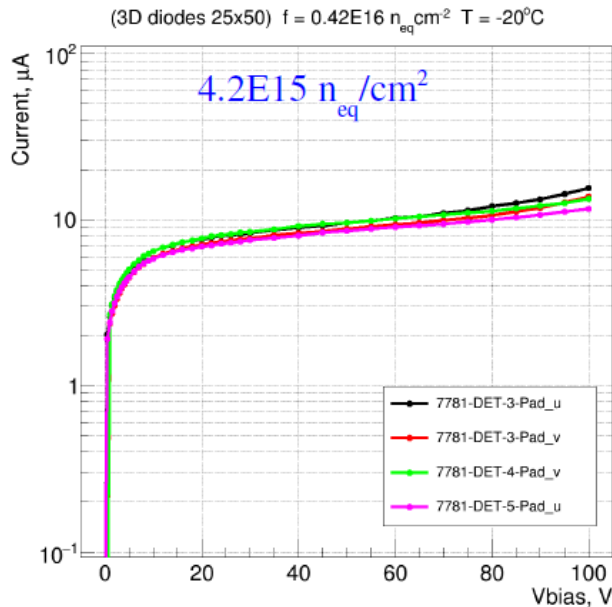
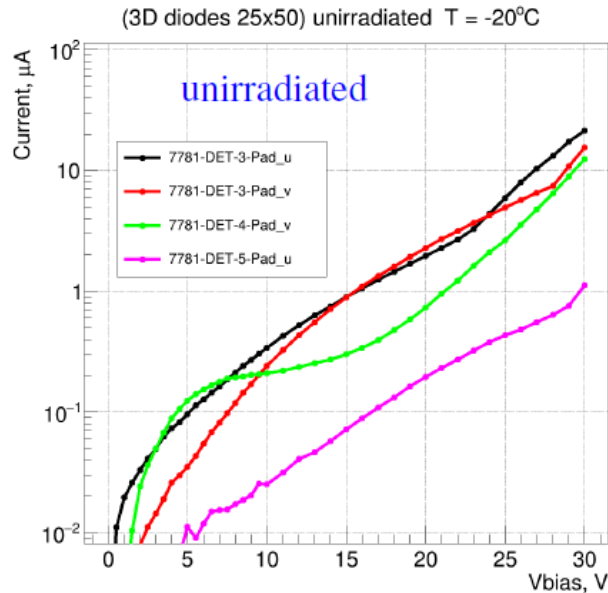
Results: Electrical characterization of pads

IV characterization 25x50

Unirradiated at 20 V → around 20-200 pA per pixel.

Irradiated ($4.2E15 \text{ n}_{\text{eq}}/\text{cm}^2$) at 60 V → around 1 nA per pixel.

Irradiated ($1E16 \text{ n}_{\text{eq}}/\text{cm}^2$) at 60 V → around 2 nA per pixel.



Results: Electrical characterization of pads



CV characterization 25x50

