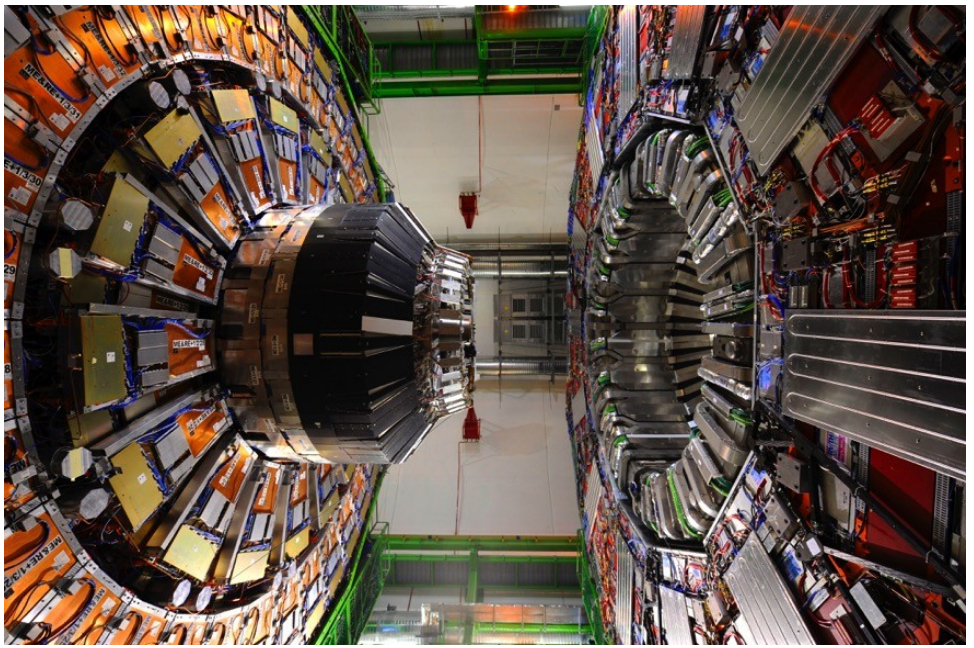
Radiation hardness and precision timing study of Silicon Detectors for the CMS High Granularity Calorimeter (HGC)



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Outline

- High Granularity Calorimeter (HGCal)
- Diodes under study
- Summary of the characterization of dd-FZ diodes after neutron irradiation
- Characterization of the epitaxial diodes after neutron irradiation:
  - IV, CV and CCE
- Radioactive source measurements (^{90}Sr)
- Precision timing capabilities for the unirradiated diodes and preliminary results with the irradiated.
- Summary and future activities

High Granularity Calorimeter (HGCAL)

593 m^2 of Silicon in a high radiation environment.

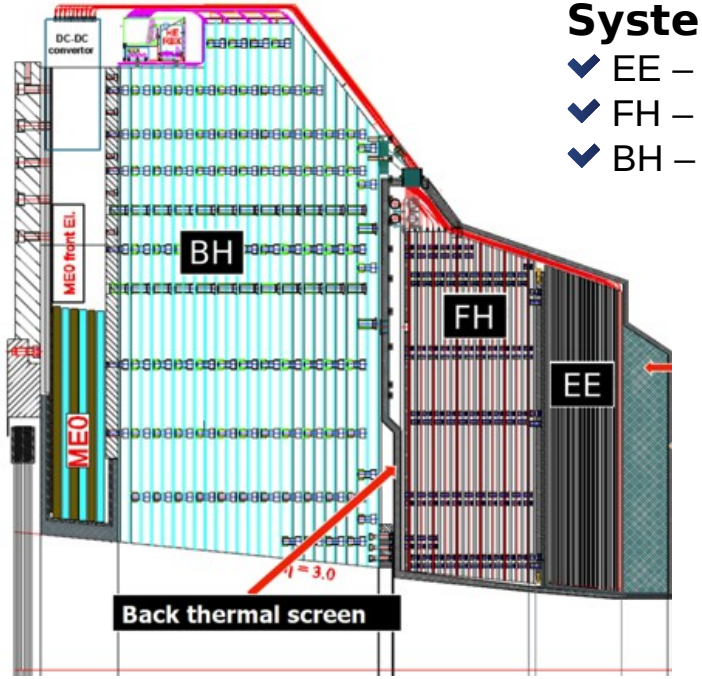
- Cost.
- Very high radiation levels – need to plan for 1.5×10^{16} neutrons/cm^2

Cooling.

- We need a compact calorimeter with small gaps between absorber plates.
- We need to operate at – 30°C
- Power at end of life 120 kW → main contribution: front-end electronics
  → sensor leakage current ~25% power

Data and Trigger

- Channel count is 6M, with 21.5K detector modules and 40 Si planes. Producing an enormous amount of data.
- Data used in the Level- 1 CMS event trigger.



System Divided into three separate parts:

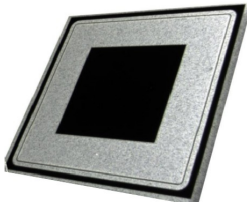
- EE – Silicon with tungsten absorber – 28 sampling layers – 25 Xo + ~1.3 λ
- FH – Silicon with brass absorber – 12 sampling layers – 3.5 λ
- BH – Scintillator with brass absorber – 11 layers – 5.5 λ

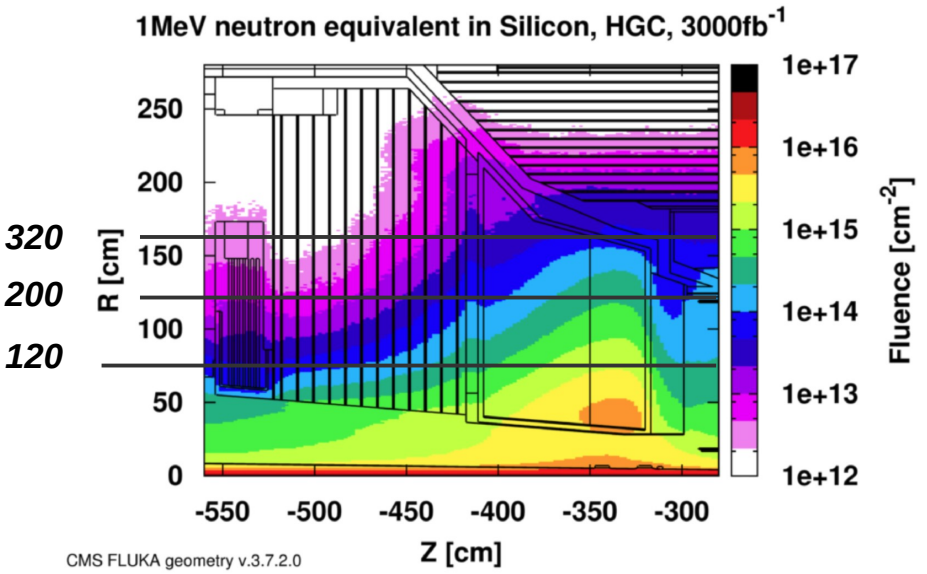
EE and FH are maintained at – 30°C.
BH is at room temperature (or -30°C)

Diodes under study

Same technology used for the CMS tracker upgrade (CMS HPK sensor characterization)

- ✔ Silicon growth technique (Epi: epitaxial layer, dd-FZ: float zone deep diffusion)
- ✔ Polarity: n-on-p (p-type), p-on-n (n-type)
- ✔ Active thickness:
  - ✔ FZ: 320, 200 and 120 um
  - ✔ Epi: 100 and 50 um
- ✔ Size:
  - ✔ Large diodes : 5 × 5 mm²





Investigate sensor performance after **neutron irradiation** with neutron equivalent fluences up to $1.5 \cdot 10^{16}$n/cm²

List of sensors and status:

Fluence n/cm2	Thickness (um)				
	Float zone			Epitaxial	
	320	200	120	100	50
4.00E+014	1 n-on-p, 1 p-on-n				
6.00E+014	2 n-on-p, 2 p-on-n				
9.00E+014	1 n-on-p, 1 p-on-n				
1.50E+015		1 n-on-p, 1 p-on-n			
2.50E+015		2 n-on-p, 2 p-on-n			
4.00E+015		1 n-on-p, 1 p-on-n			
6.25E+015			2 n-on-p, 2 p-on-n	2 n-on-p	
1.00E+016			1 n-on-p, 1 p-on-n	2 n-on-p	2 n-on-p, 2 p-on-n
1.60E+016			1 n-on-p, 1 p-on-n		2 n-on-p, 2 p-on-n

Characterization after neutron irradiation

Properties to be measured:

- Bulk current I(U, Φ, h) → power consumption, noise
- Capacitance (1 MHz signal): C(U, Φ, h) → capacitance seen by electronics
  (455 Hz signal) → depletion voltage.
- Charge collection efficiency CCE(U, Φ, thickness) → signal with a laser
- MIP studies with beta source → Landau parameters distribution
- Test beam → Timing performance
- Effect of annealing on the properties (up to 3 months at room temperature)

Work already presented:

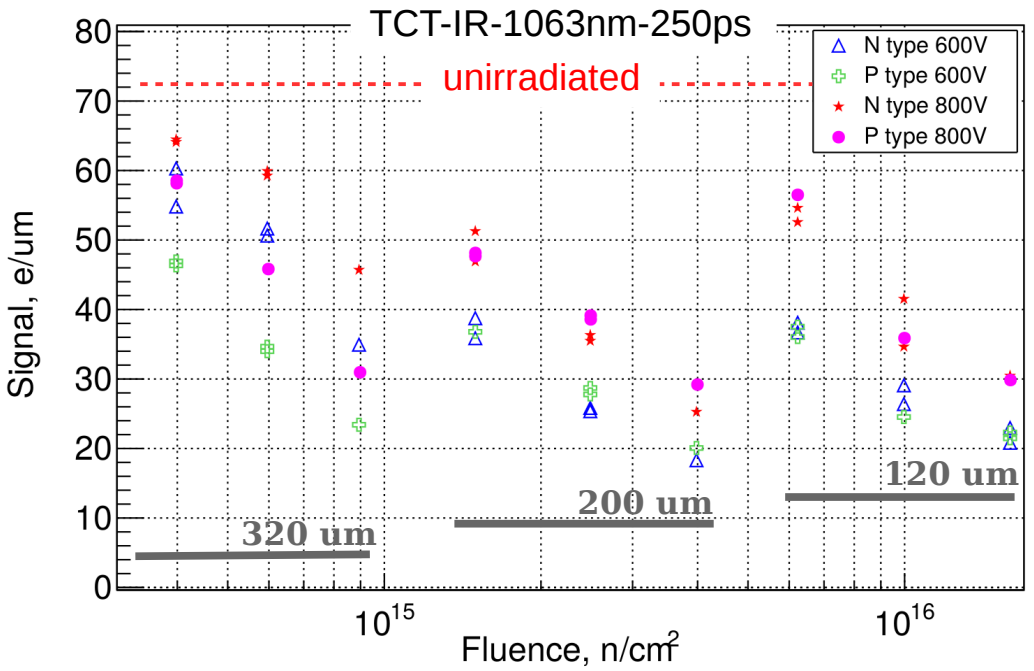
- IV and CV characterization after irradiation for the dd-FZ
- CCE with IR laser for the dd-FZ
- Radiative source setup for MIP studies.
- First test beam for timing capabilities for the unirradiated sensors (dd-FZ)

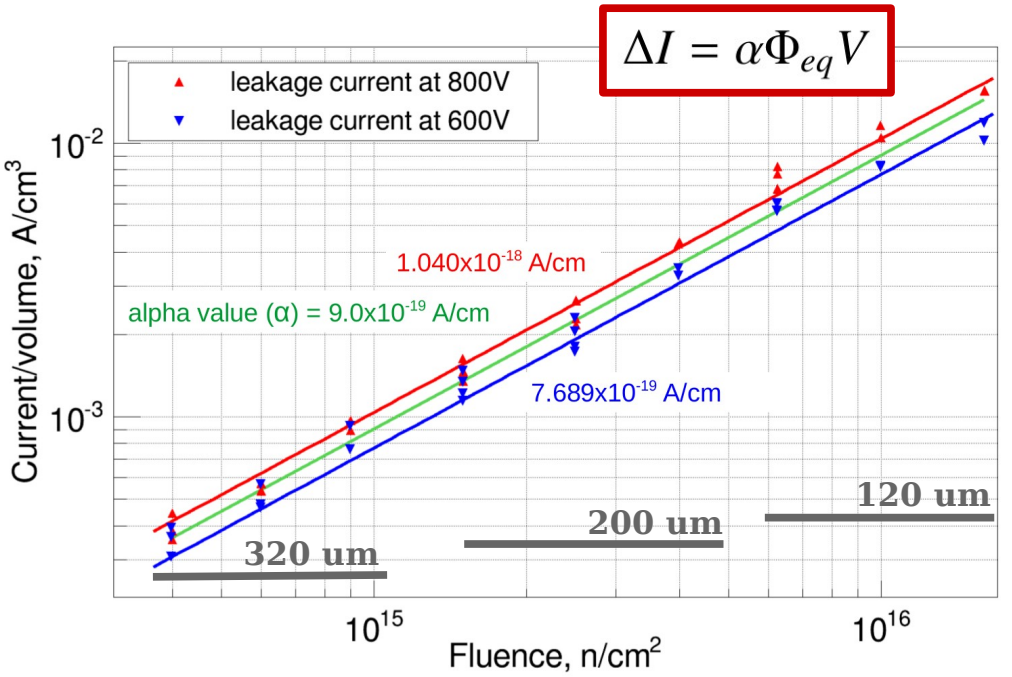
New results:

- IV and CV characterization after irradiation for the Epitaxial diodes.
- CCE with IR laser for the Epitaxial diodes.
- Firs result of MIP characterization with ^{90}Sr for dd-FZ and Epitaxial
- Timing capabilities of dd-FZ unirradiated diodes. A new test-beam has been done for the irradiated → **preliminary results**.

Characterization after neutron irradiation dd-FZ

-20ºC and annealing of 10min@60ºC



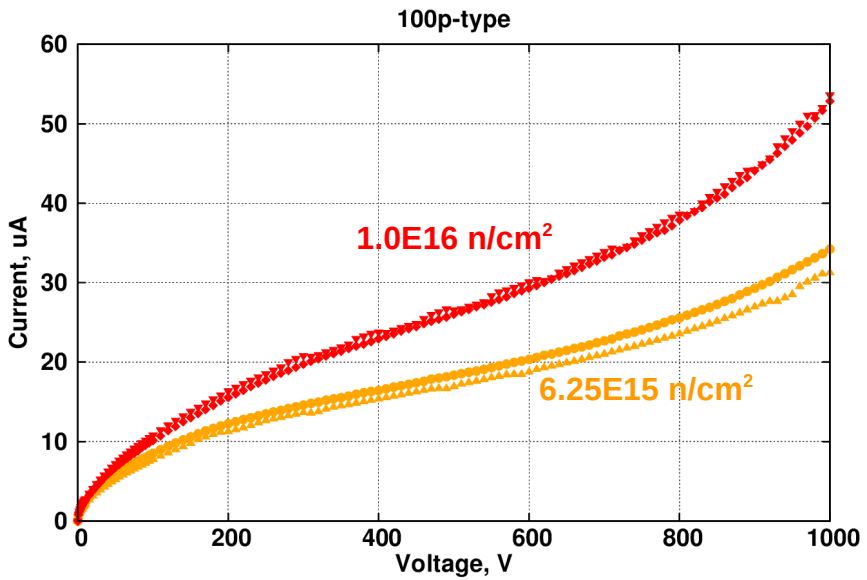


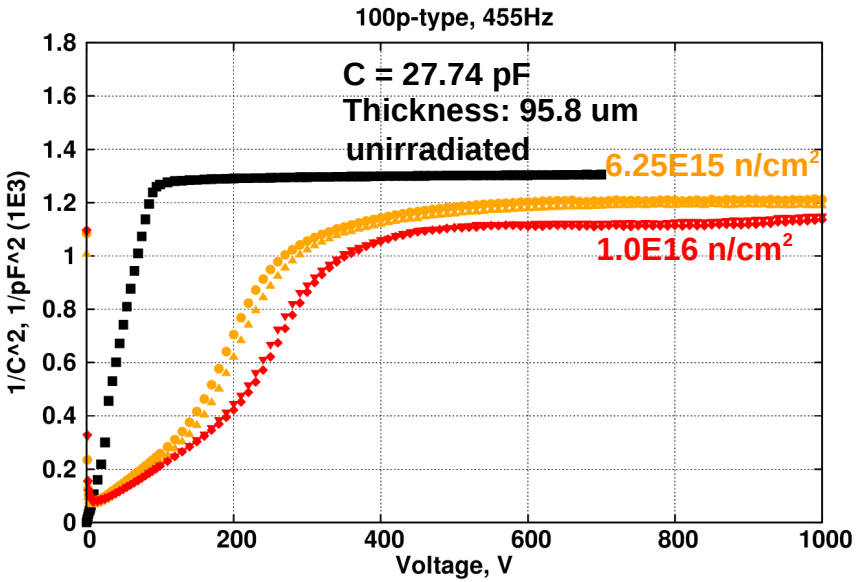
- Charge collection efficiency for 300 µm, low fluences, p-type diodes show lower values. For 200 µm and 120 µm both are closer as expected.

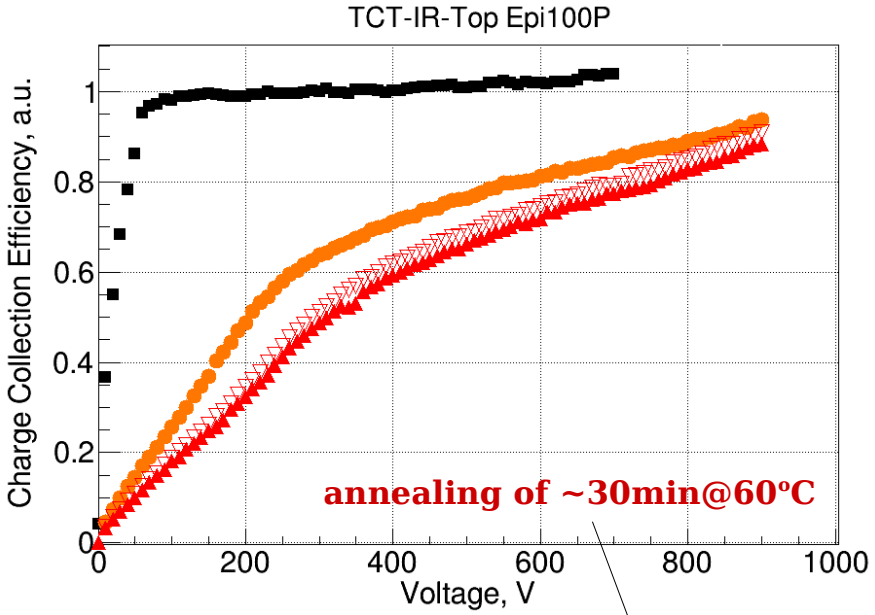
- Leakage current normalized by the volume of the diode (for all thicknesses and two type of bulk doping) increases proportional to the fluence
- At very high fluences the current still continue to scale linearly with the volume and the fluence.

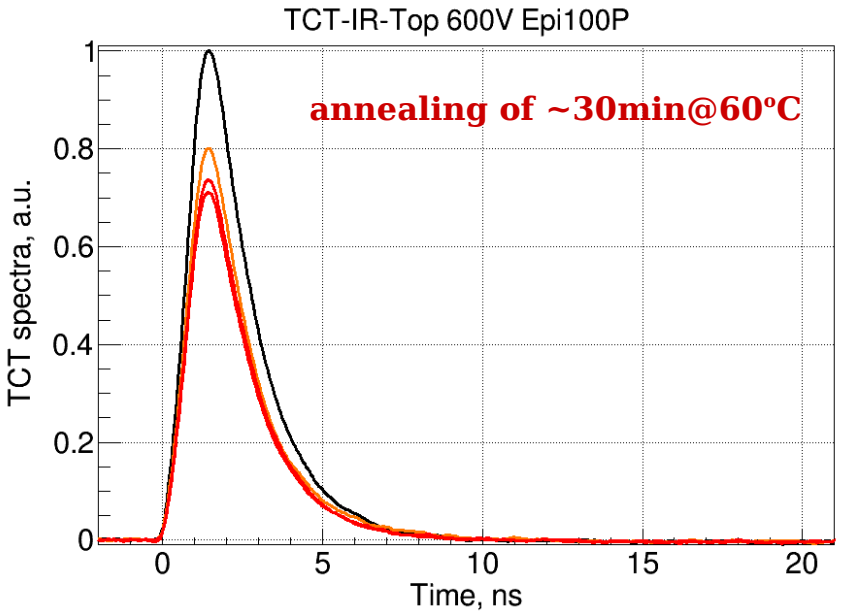
Characterization after neutron irradiation

Epitaxial 100um p-type, -20ºC and annealing of 10min at 60ºC (guard ring not connected)





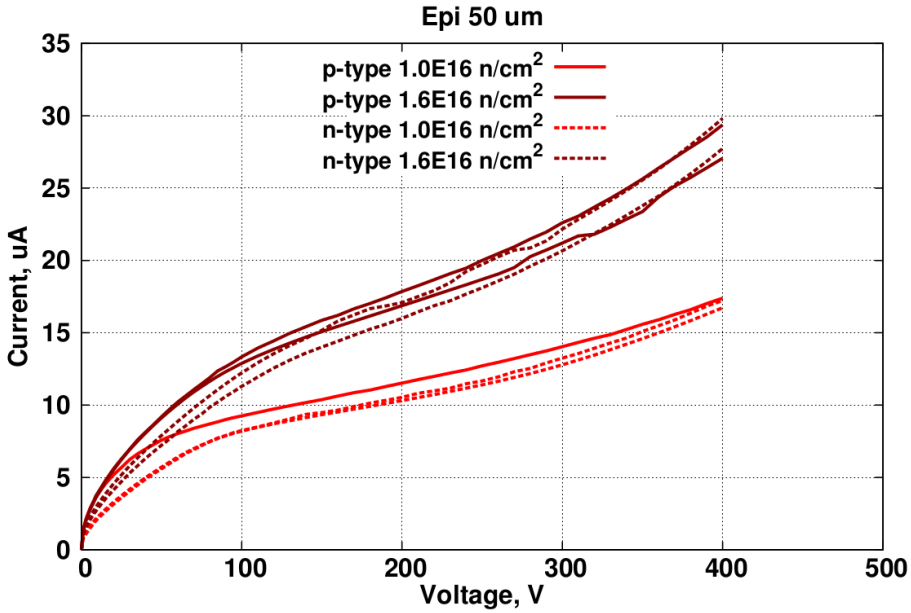


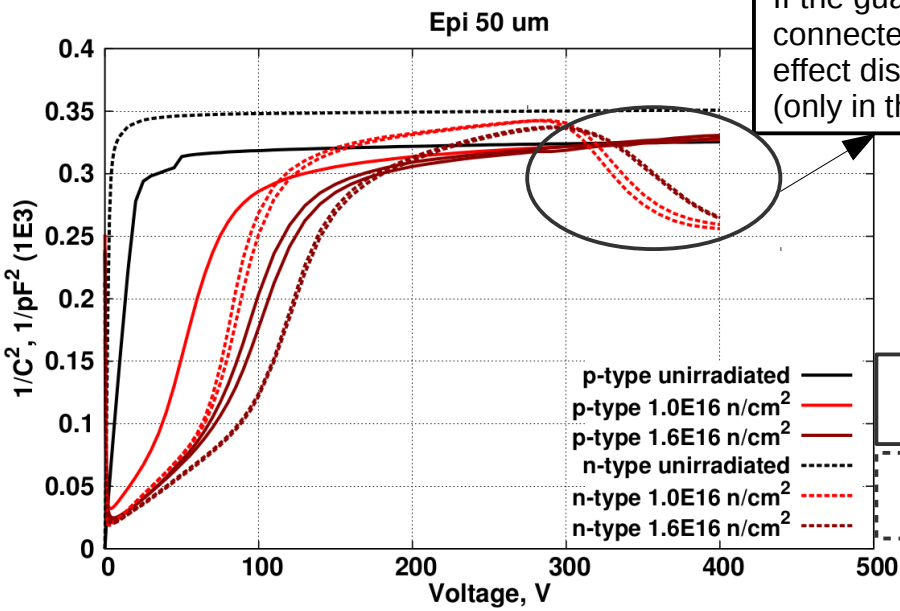


Room temperature during ~5 days

Characterization after neutron irradiation

Epitaxial 50um, -20ºC and annealing of 10min at 60ºC (guard ring not connected)

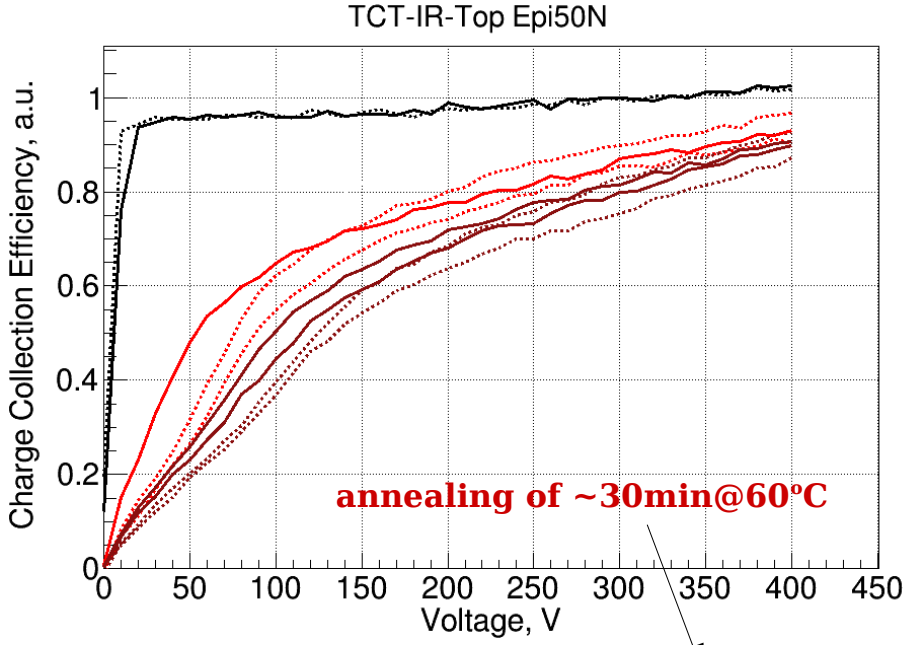


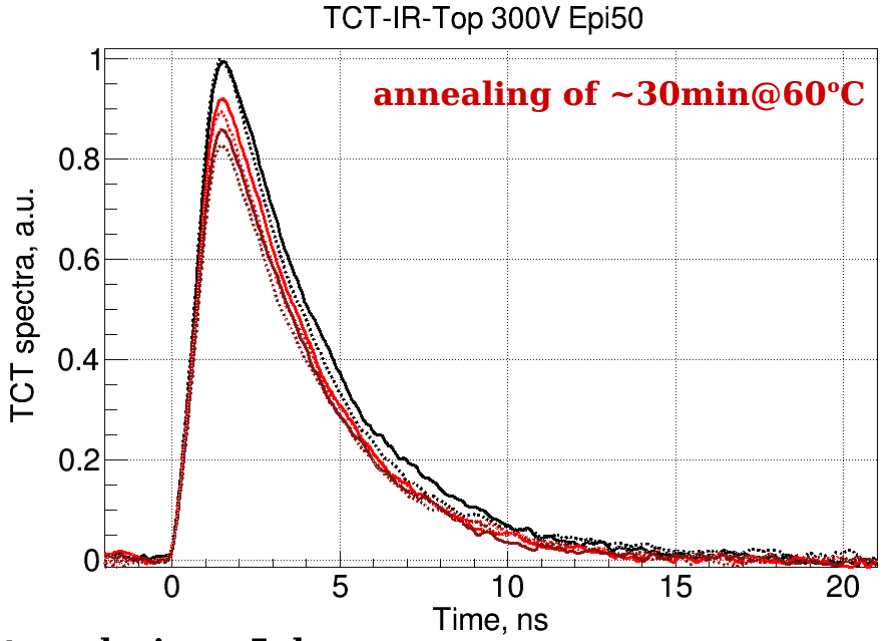


If the guard ring is connected this effect disappears (only in the n-type)

C = 55.5 pF (47.81 um)

C = 53.4 pF (49.7 um)





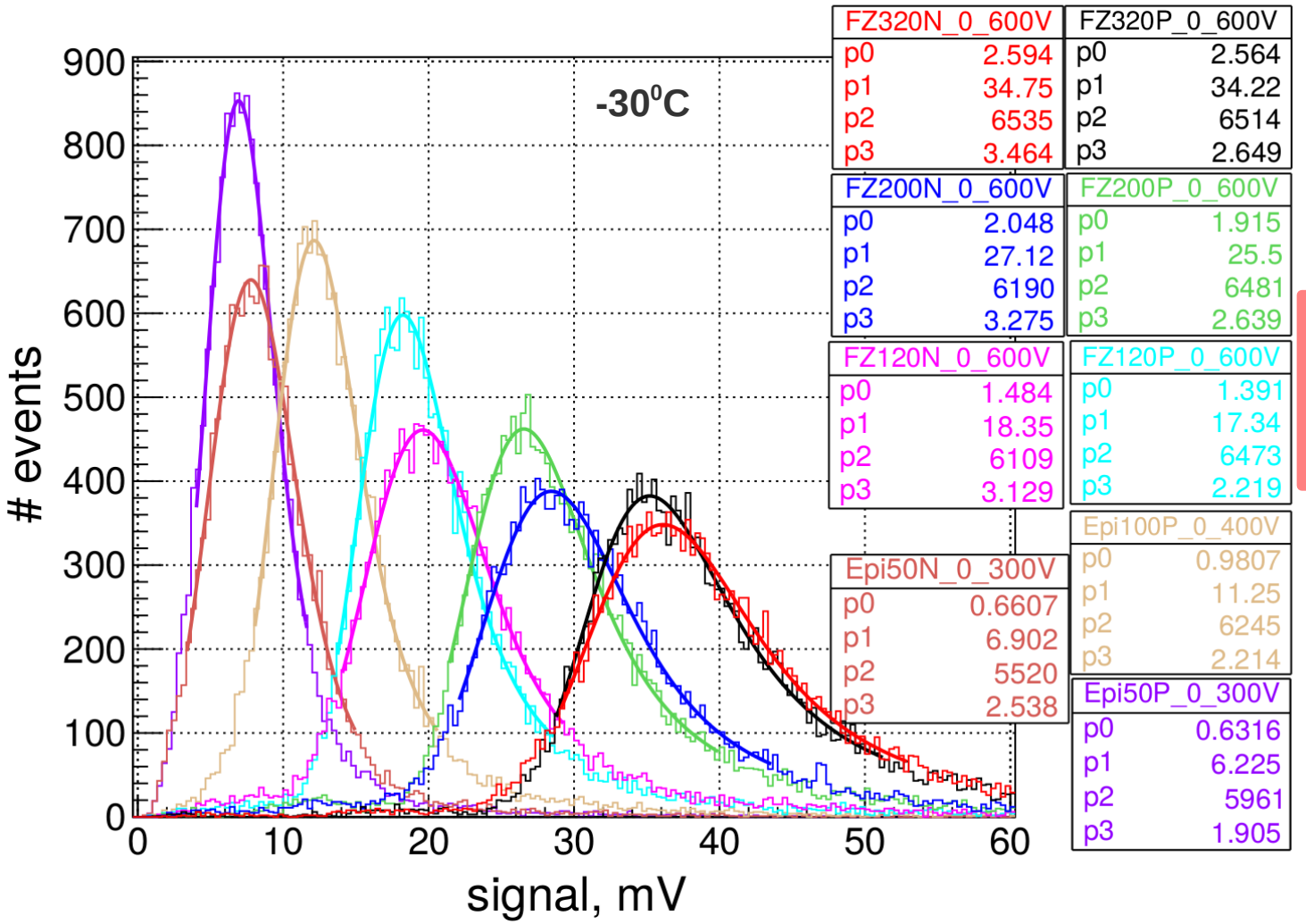
Room temperature during ~5 days

Characterization after neutron irradiation

^{90}Sr measurements → Mip study

- All sensors were measured at -20°C and -30°C
- Voltage steps from 0V up to 1000V (400V for the epitaxial 50um diodes) in steps of 20V.
- 20.000 events collected. Enough statistics for the landau reconstruction in each step.

All uniradiated diodes fitted using a convoluted Landau + Gauss Fit

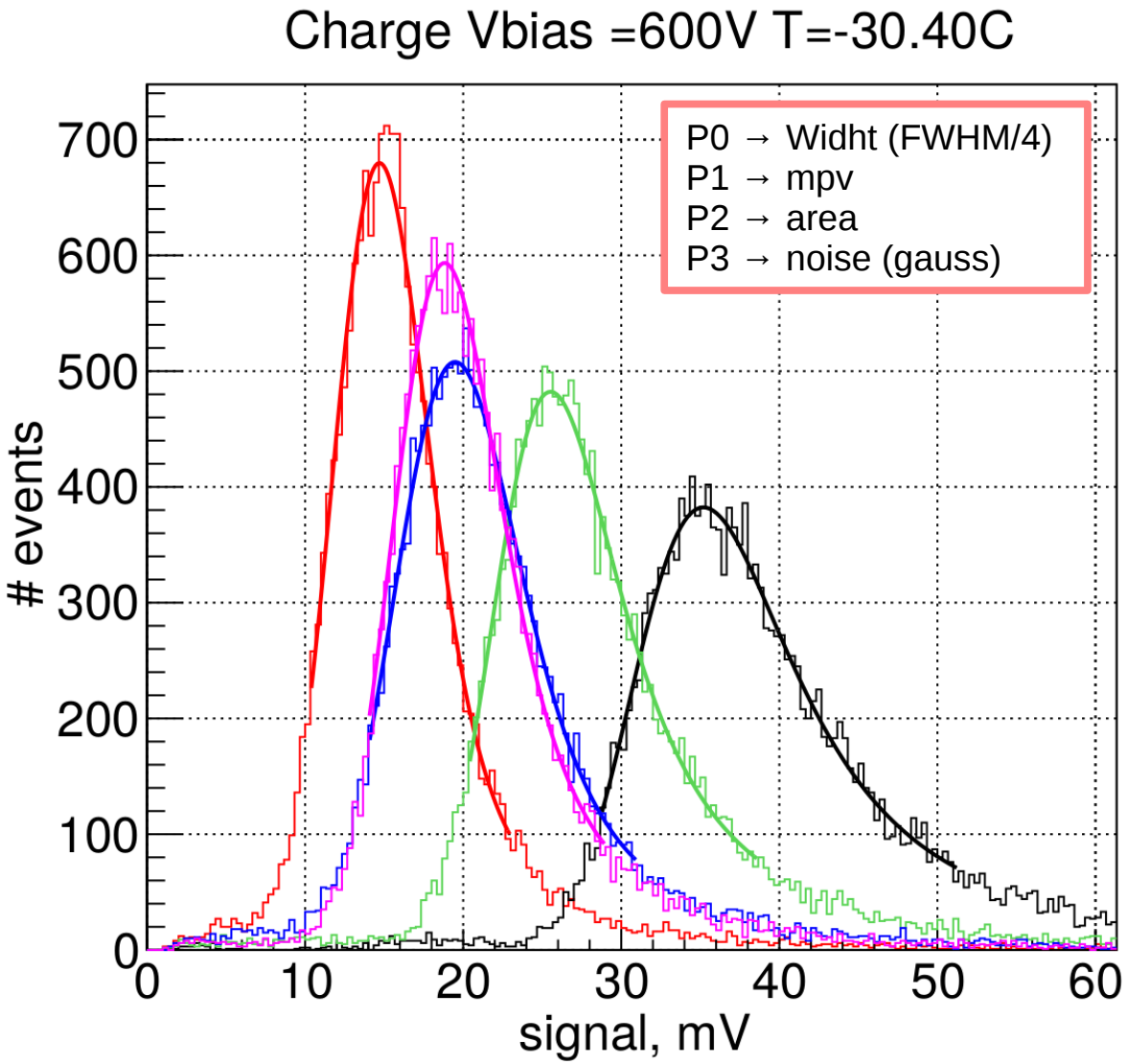


P0 → Width (FWHM/4)
P1 → MPV
P2 → Area
P3 → Noise (gauss)

Characterization after neutron irradiation

^{90}Sr measurements → Mip study

Charge distribution for the 300 um thickness n-on-p diodes at 600V and -30°C

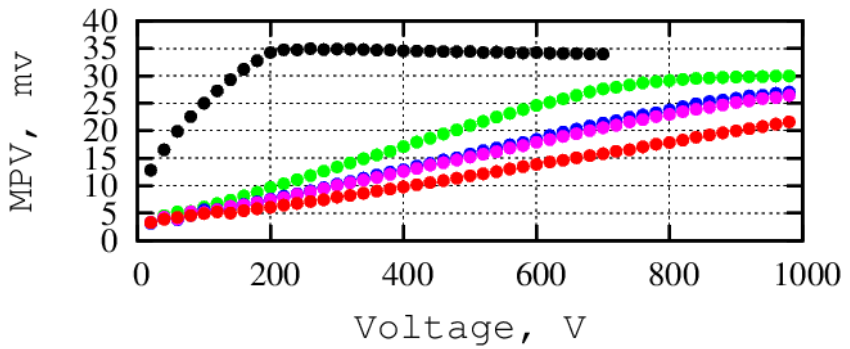


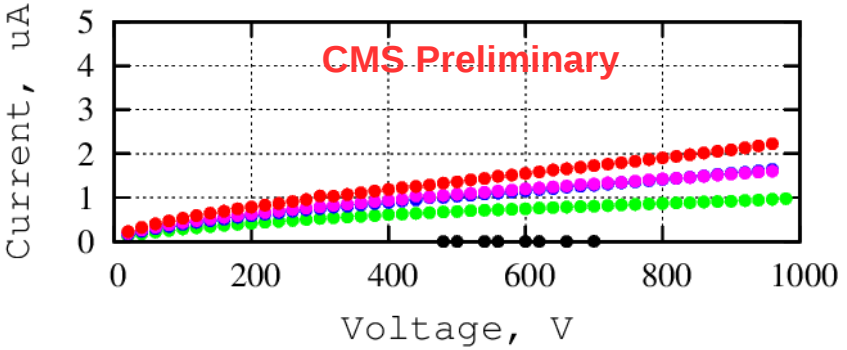
FZ320P_0_600V		reference
p0	2.564	
p1	34.22	
p2	6514	
p3	2.649	
FZ320P_1_600V		4E14 n/cm²
p0	1.874	
p1	24.6	
p2	6407	
p3	2.367	
FZ320P_2_600V		6E14 n/cm²
p0	1.328	
p1	18.28	
p2	6329	
p3	3.06	
FZ320P_3_600V		6E14 n/cm²
p0	1.215	
p1	17.79	
p2	6474	
p3	2.587	
FZ320P_4_600V		9E14 n/cm²
p0	0.8428	
p1	13.77	
p2	6228	
p3	2.474	

Characterization after neutron irradiation

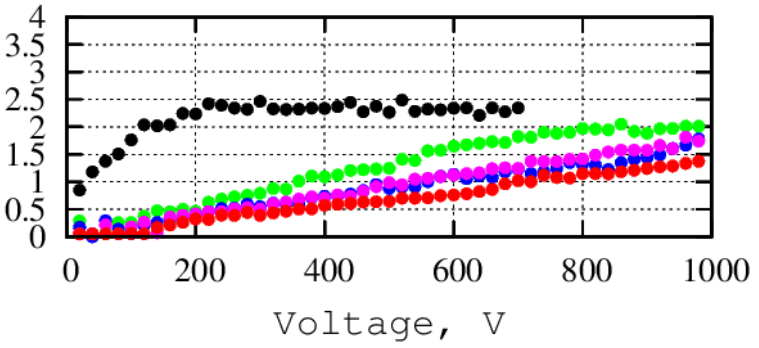
^{90}Sr measurements → Mip study

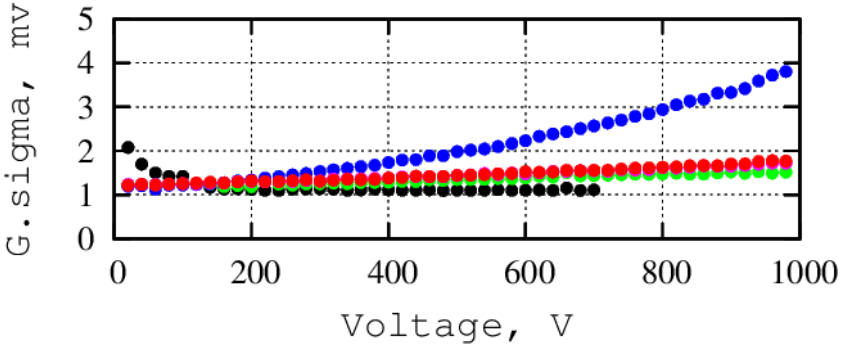
- Charge distribution for the 300 um thickness n-on-p at -30°C
  Unirradiated, 4E14, 6E14, 6E14, 9E14 n/cm^2



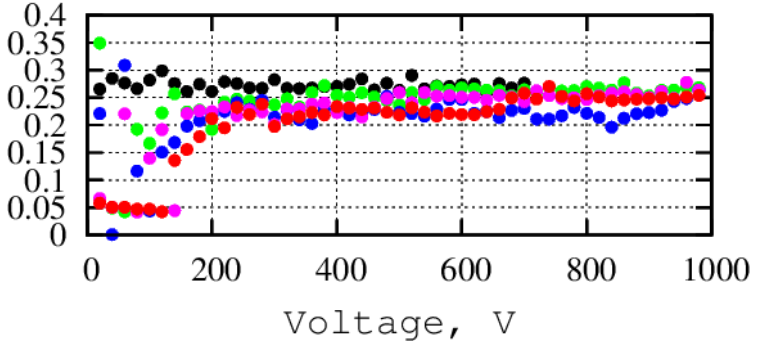


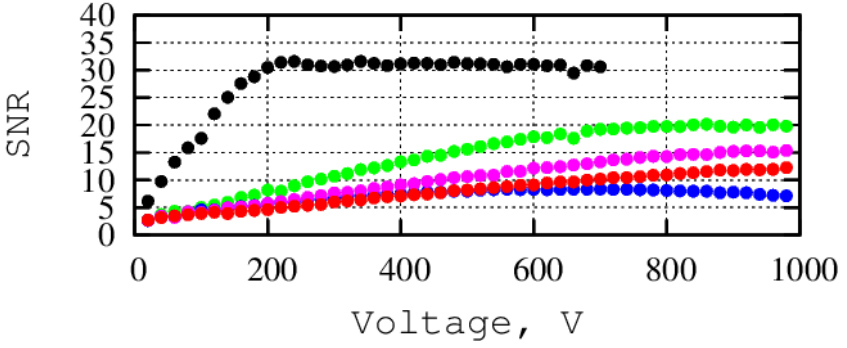
L.Width, mv





FWHM/MPV





Algorithm for the fitting needs to be improved. Landau width parameter is very sensible, especially for the irradiated diodes with low SNR

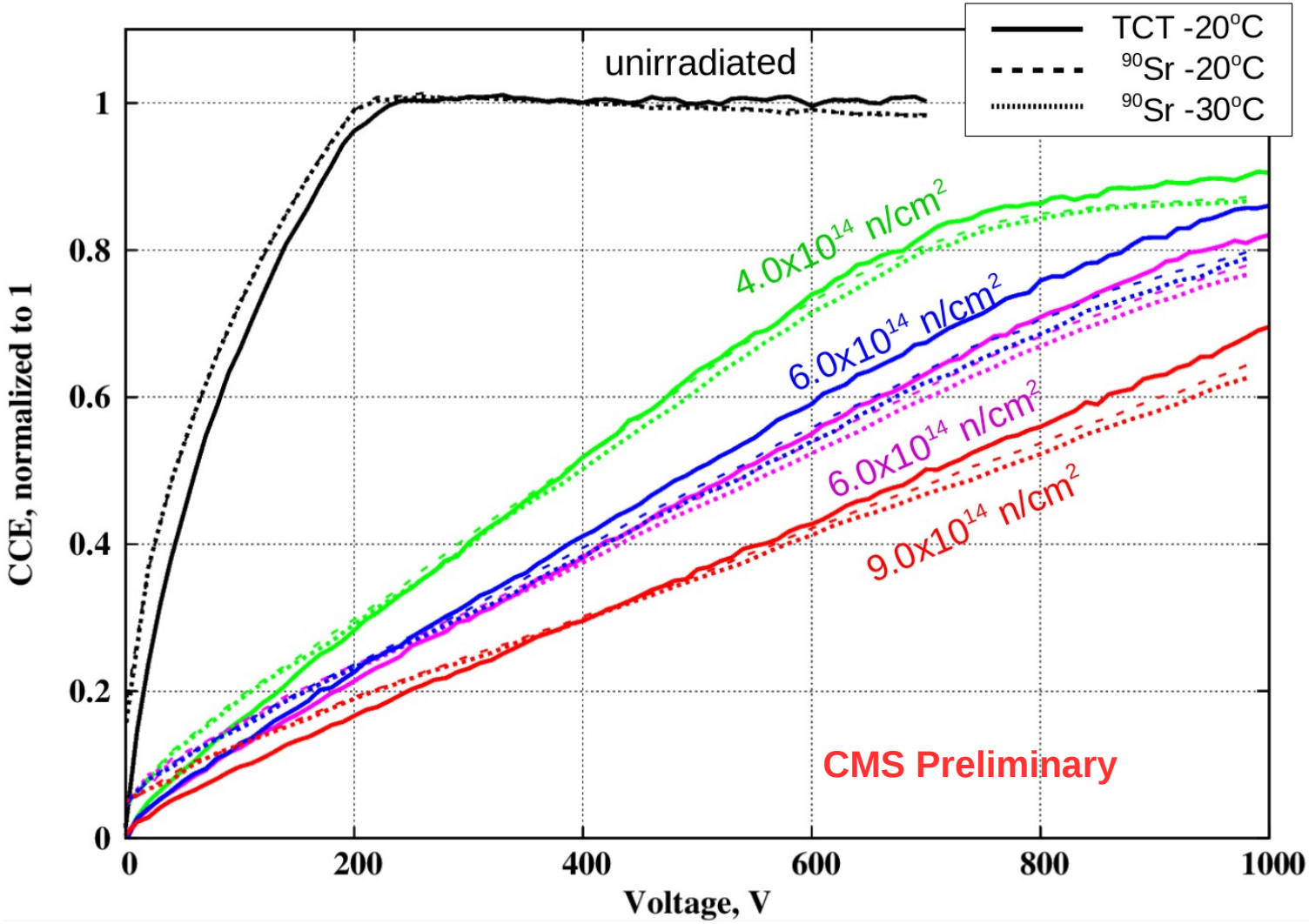
Characterization after neutron irradiation

^{90}Sr measurements → Mip study

Comparison between the charge collected with ^{90}Sr and the TCT with the infrared laser for the dd-FZ 300 μm n-on-p silicon diodes:

1 - Very similar results comparing TCT results (~40 MIP) with ^{90}Sr (1 Mip)

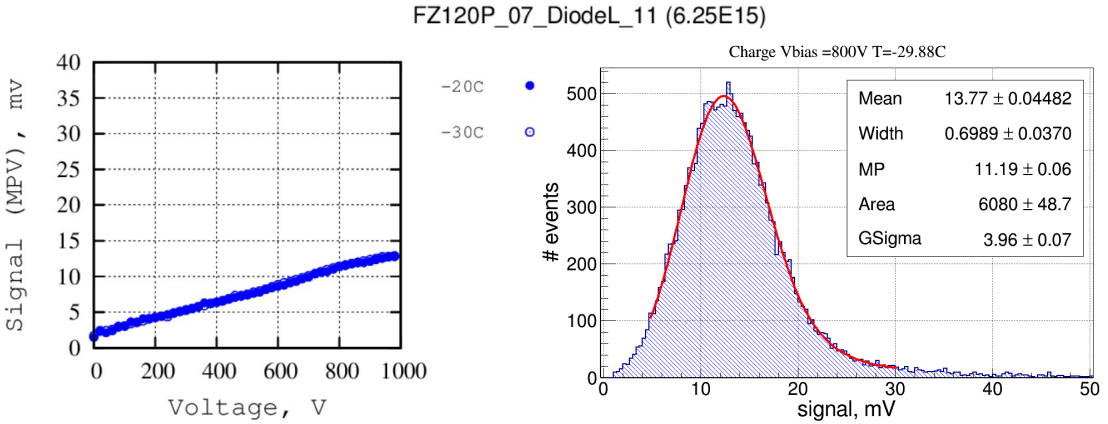
2 - Charge collected at -20^{o}C and at -30^{o}C is almost the same.

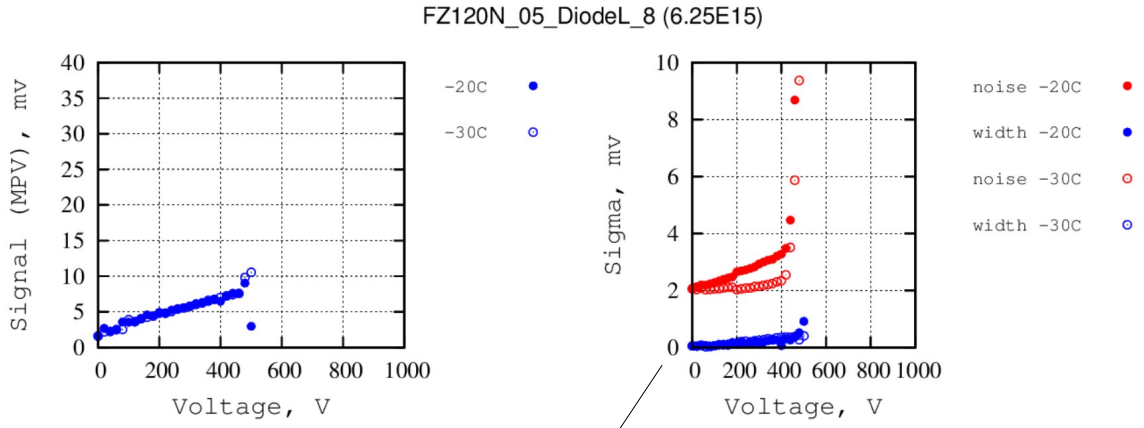


Characterization after neutron irradiation

^{90}Sr measurements → Mip study

All sensors were measured and we have data even for the thinner ones, analysis is ongoing ...

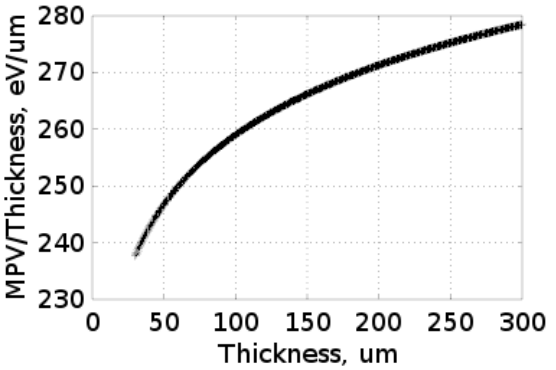




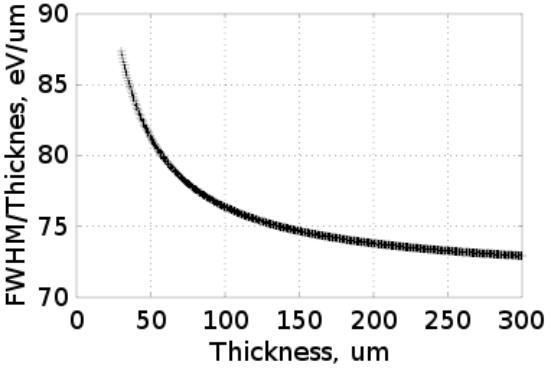
Problems with all the n-types, at certain voltage (random) the noise starts to increase and it is not possible to measure them above that voltage.

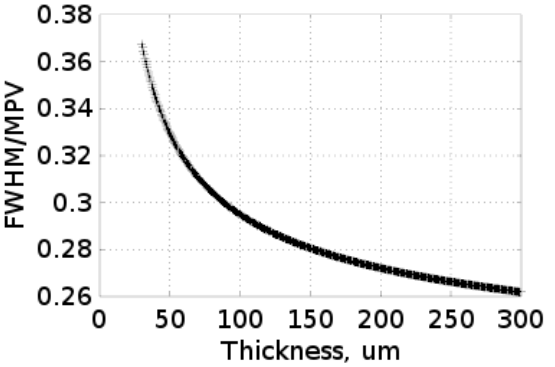
Theoretical predictions about the MPV and the FWHM have to be checked:

$$_L\Delta_p = \xi\left[ln\frac{2m_ec^2\beta^2\gamma^2}{I^2} + ln\frac{\xi}{I} + 0.2 - \beta^2 - \delta\right]$$



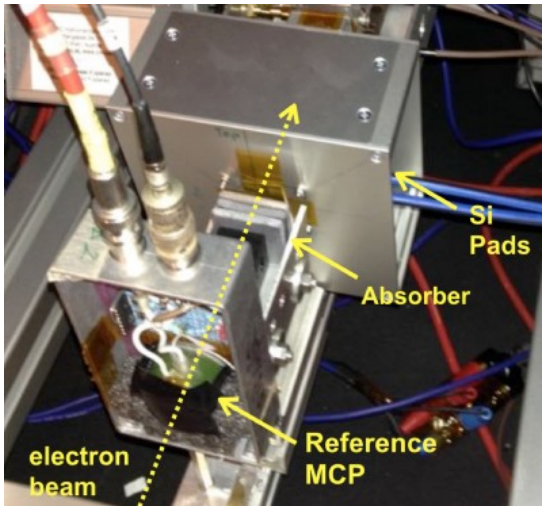
Protons with momentum > 28 GeV/c

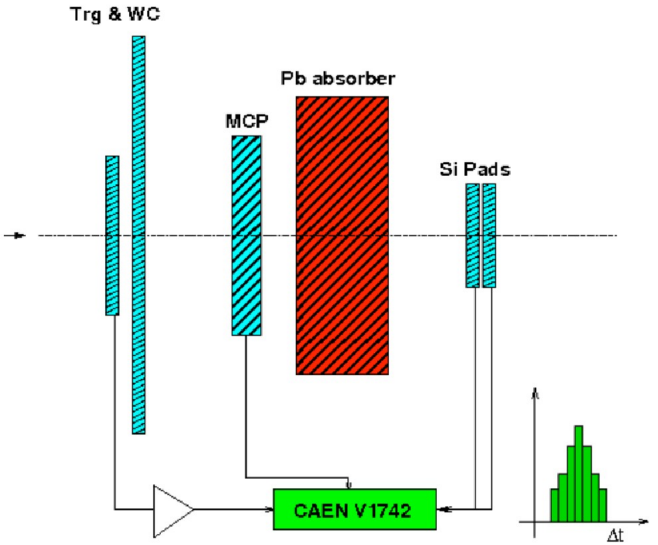


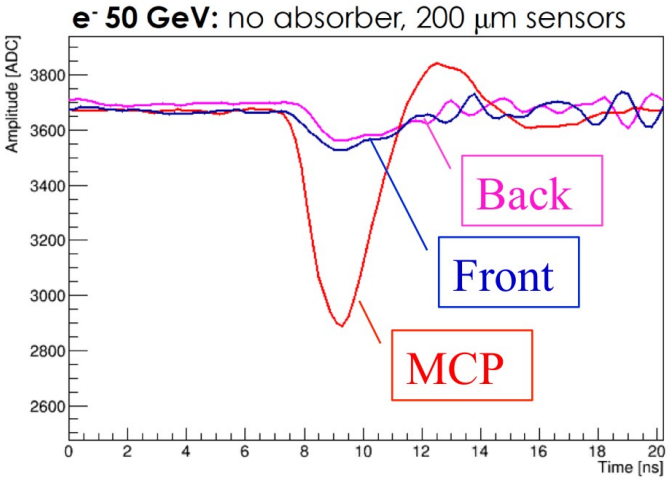


Precision timing test beam

Test of time response with **unirradiated** Si PAD (CERN h2 Jul 2015)





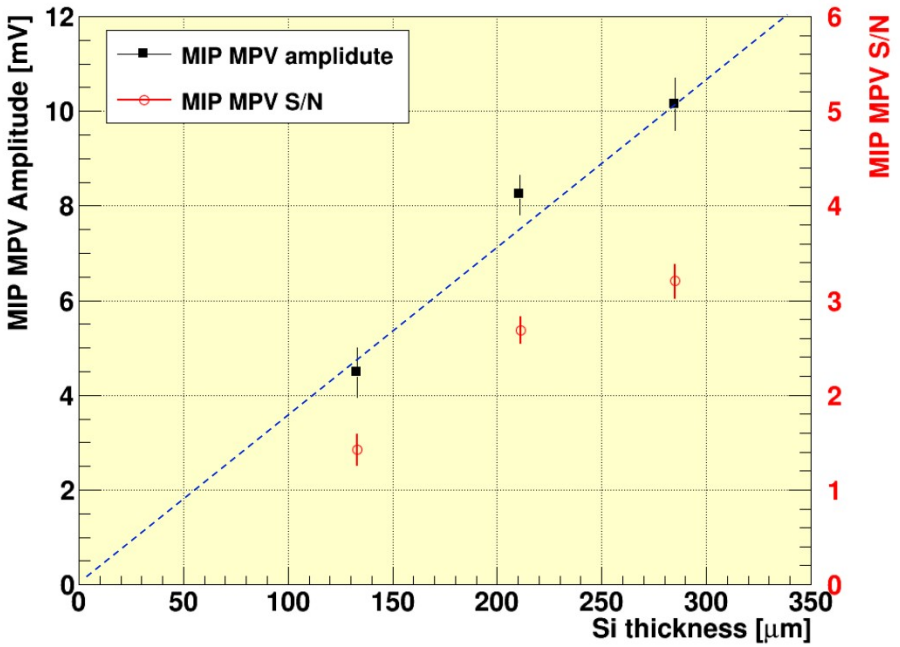


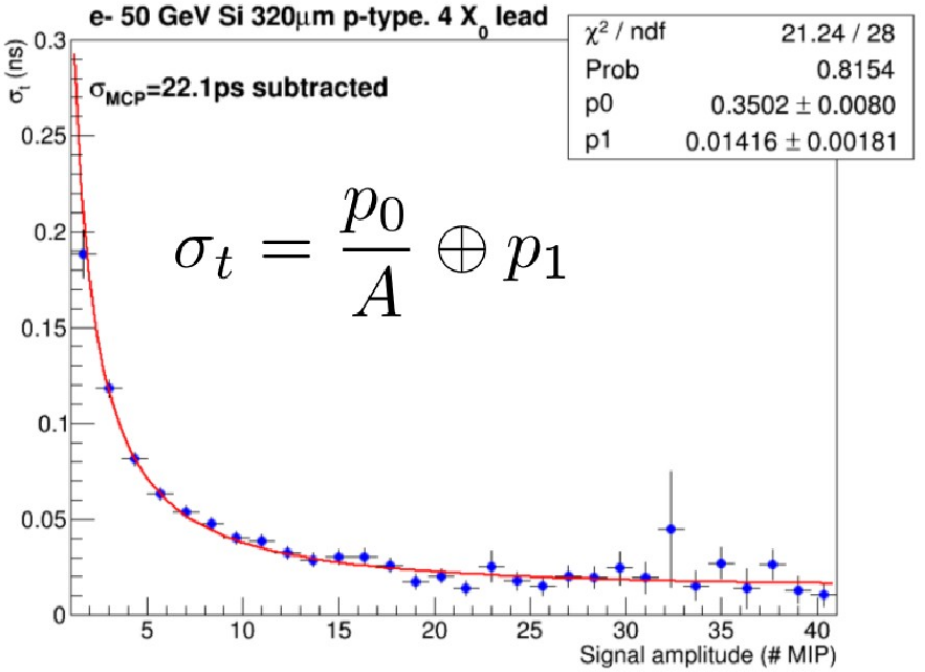
- **Goal: measure intrinsic time capabilities for EM shower and MIPs for unirradiated Si pads**
  - MCP: used as trigger and time reference, also studied in previous test beams
  - Thin Si pads: understand intrinsic timing capabilities of HGCAL sensors
- **Re-use most of the available I-MCP infrastructure**
  - 60x60x120 cm light tight box, with an aluminium rail to align several timing devices
  - Readout using H4DAQ: V1742 fast (5GS/s) digitizer,12 bit, ~700MHz bandwidth, ~ 5 ps precision, up to 32 channels
  - 2×2 cm 2 trigger counter and (xy) wire chamber space resolution ~1 mm

Precision timing test beam

Test of time response with **unirradiated** Si PAD (CERN H2 Jul 2015)

- 2 sensors of the same type were tested at the same time
  - 320, 200 and 120 um thick sensors, 5x5 mm^2 size, p and n type and unirradiated.
- Run with absorber (e^- + absorber → generate signal from 1 to ~100 MIPs):
  - Estimate <# of MIPs> from the signal amplitude relative to one MIP
  - Measure the time resolution as a function of MIPs multiplicity (<signal amplitude>)

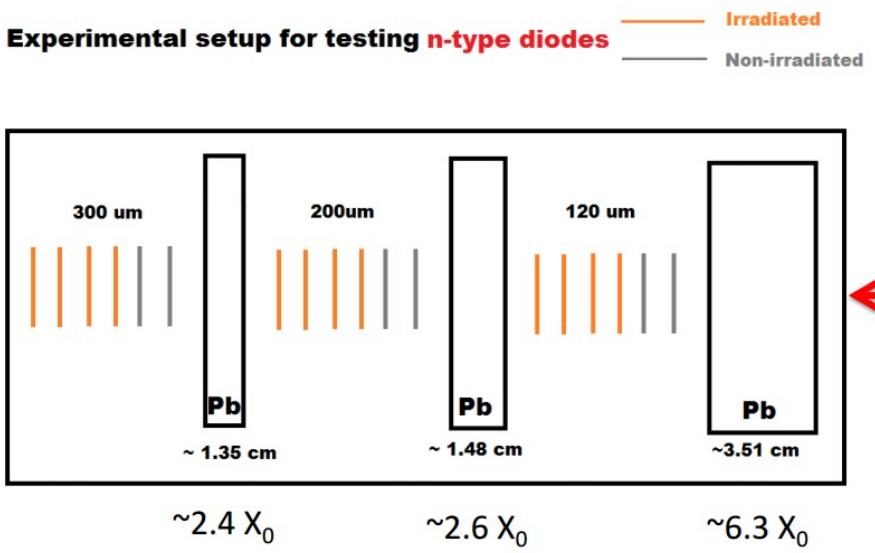




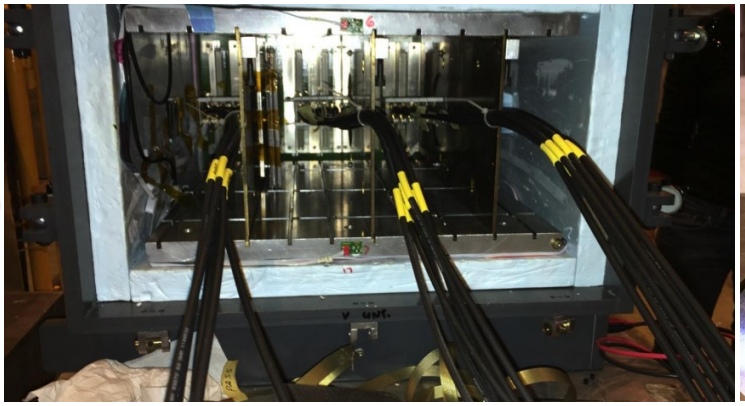
I. *Timing resolution is < 20 ps for S > 20 MIPs*
II. *Single MIP signal is resolvable from noise*
III. *Sensor response is linear within 4% for N < 4 MIP*
IV. *Application of timing capabilities of silicon sensors to time-*
V. *Application of timing capabilities of silicon sensors to time-resolve showers may provide new capabilities (e.g. pile-up mitigation in CMS HGCAL at the HL-LHC)*

Precision timing test beam

Test of time response with **irradiated** Si PAD (CERN H2 Apr-May 2016)



Cold box (-25^{0}C)

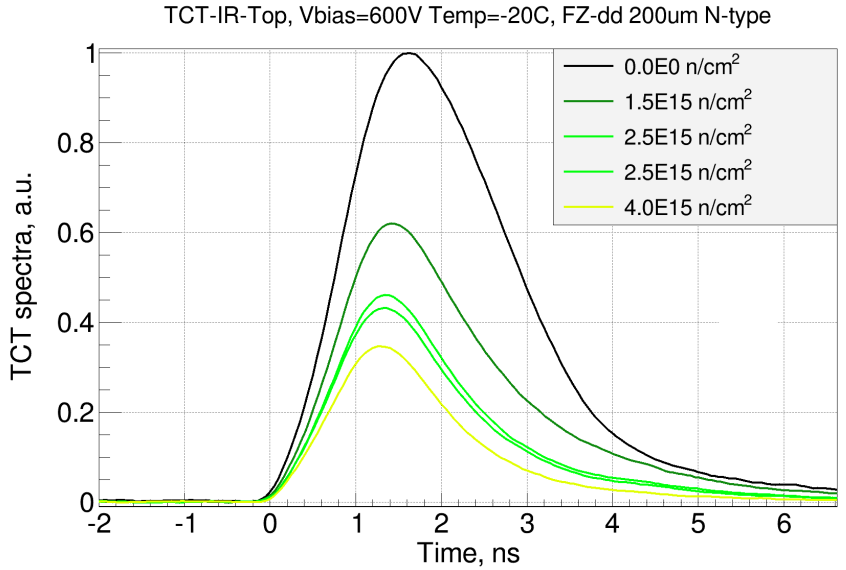


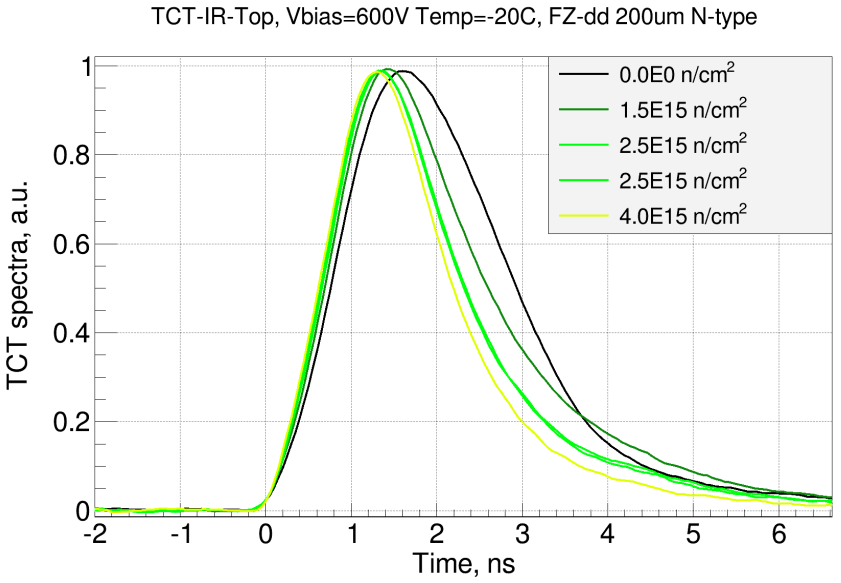
120 um set

- **Same goal but this time with irradiated: measure intrinsic time capabilities for EM shower and MIPs for irradiated Si pads**
  - Same DAQ: 2×2 cm 2 trigger counter and (xy) wire chamber space resolution ~1 mm. Readout using H4DAQ: V1742 fast (5GS/s) digitizer,12 bit, ~700MHz bandwidth, ~ 5 ps precision, up to 32 channels
  - Two unirradiated diodes at the beginning of each set for timing reference instead of the MCP
  - Analysis ongoing ...

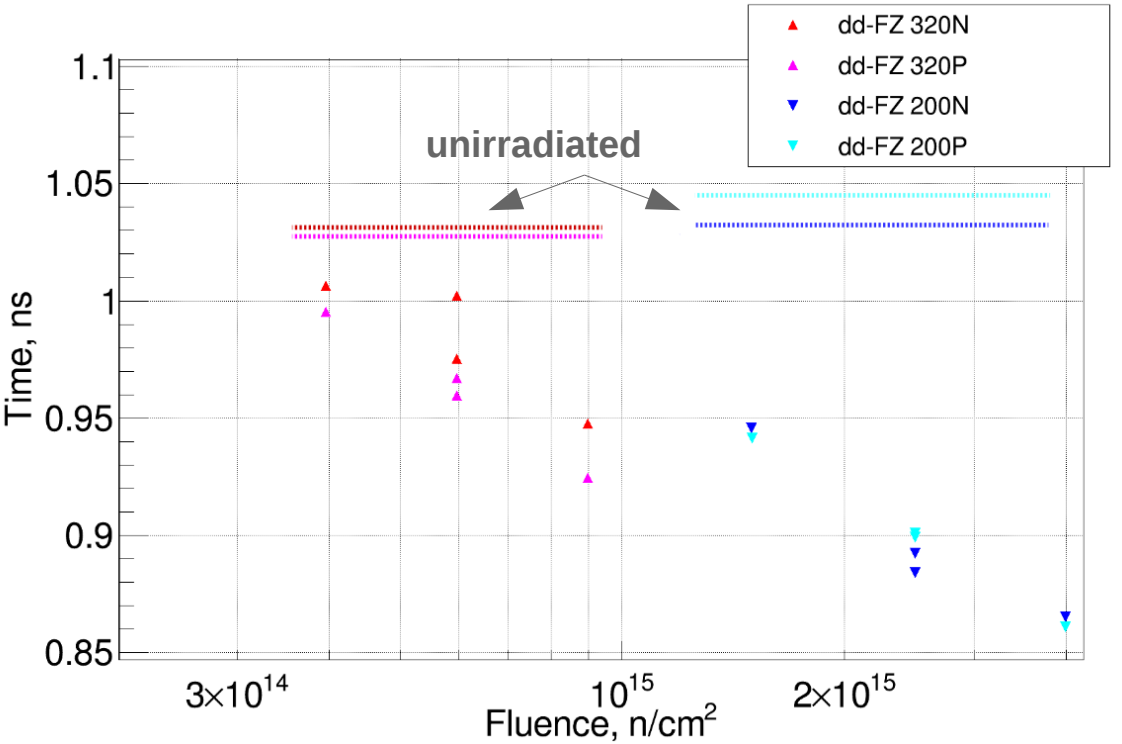
Precision timing and test beam

Test of time response with **irradiated** Si PAD (CERN H2 Apr-May 2016)





Rise time of the TCT-IR pulses (from 10% max to 90% max) at 600V and -20^{0}C



We know that neutron irradiation results in

- reduction of pulse amplitude
- reduction of pulse rise-time

Summary and future activities

- ✓ Characterization after neutron irradiation: IV, CV and CCE done for all the diodes. Why the CCE for the dd-FZ 300 um p-type after neutron irradiation is lower than the n-type ones needs to be better understood.

- ✓ Measurements with the ^{90}Sr source finished for all the diodes. Study of the Landau parameters and comparison with the literature ongoing.

- ✓ Fast time test beam for unirradiated proved the timing capability of these diodes. Test beam for the irradiated diodes just finished and the analysis is ongoing.

- ✓ To do: annealing studies (80min at 60^{0}C)