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

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14th Vienna Conference on Instrumentation
Feb 15-19, 2016

Outline

- High Granularity Calorimeter (HGCAL)
- HGCAL silicon sensors
- Results of the characterization after neutron irradiation:
  - IV (Leakage current vs Voltage), CV (Capacitance vs Voltage)
  - CCE (charge collection efficiency)
  - MIP studies
- Precision timing and test beam
- Summary and future activities

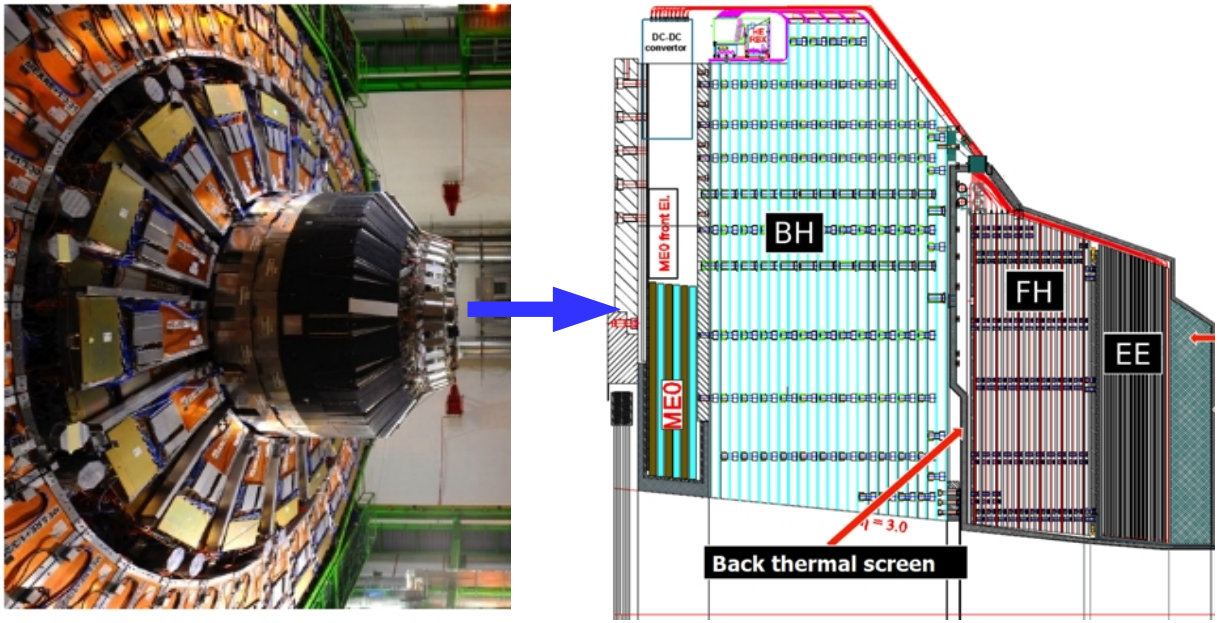
High Granularity Calorimeter (HGCAL)

CMS needs to replace End-cap Electromagnetic and Hadronic calorimeters for Phase II due to radiation damage. This opens a new possibility for the Calorimeter design and the **HGCAL has been the technology chosen for this upgrade**.

We are working for the future implementation of the High Granularity Calorimeter with ~6M channels of silicon pads, integrating EE and HE functions (CALICE concept) with a Back HE to capture energy tails.

We expect that with such detailed information from the calorimeter, coupled with a precision silicon tracker, we will be able to measure physics objects with high precision, in a high pileup and very dense environment, with a robust technology

The CMS End-Cap calorimeters need to be replaced for the HL-LHC:
A Challenge, and an Opportunity



High Granularity Calorimeter (HGCAL)

Major Engineering Challenges

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

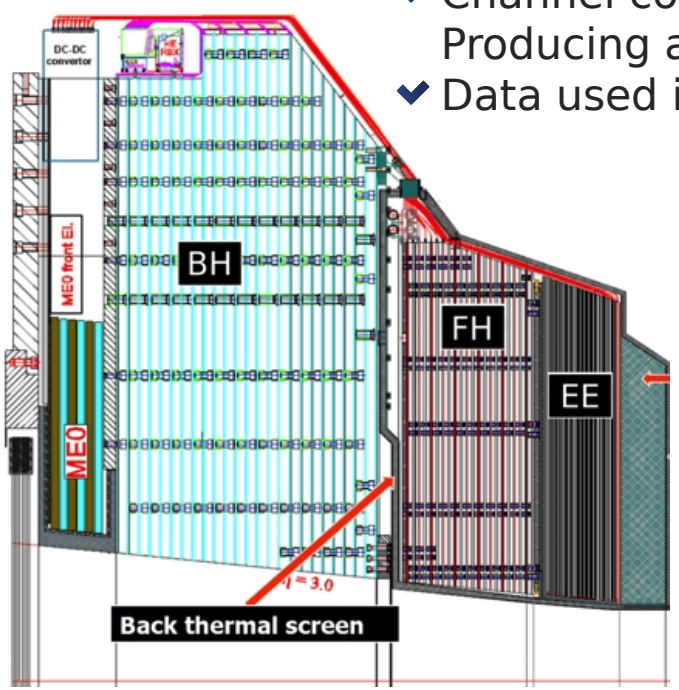
- Cost.
- Very high radiation levels – need to plan for 1.5x10^{16} neutrons/cm^2

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

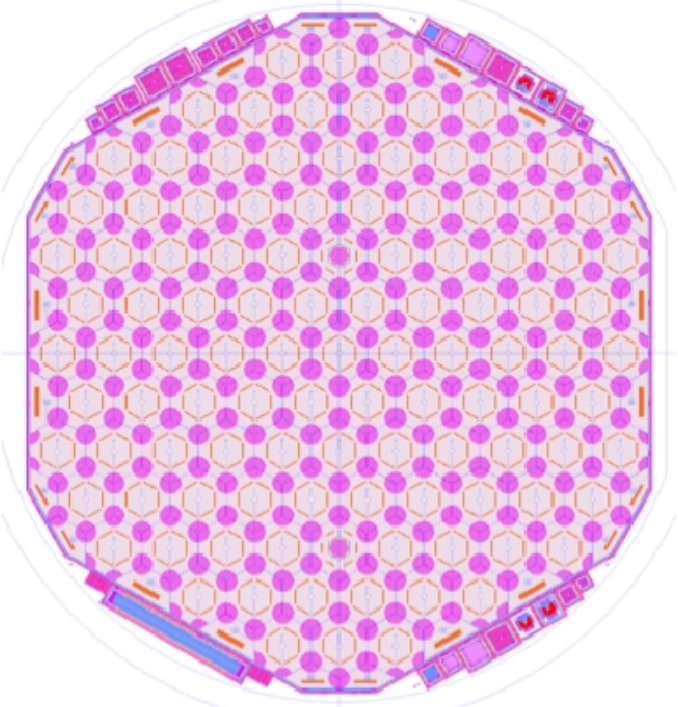
EE and FH are maintained at – 30°C.
BH is at room temperature (or -30°C)

HGCAL Silicon sensors

Radiation tolerance study of large area pad diodes as active sensor for a High Granularity Electromagnetic Endcap Calorimeter for PhaseII Upgrade

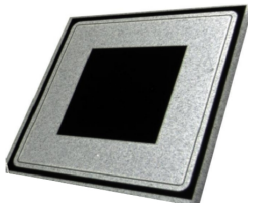
Investigate sensor performance after **neutron irradiation** with neutron equivalent fluences up to $1.5 \cdot 10^{16} n/cm^2$

Hexagonal sensor geometry based on SiD design



Diodes under investigation:

- Same technology used for the CMS tracker upgrade (CMS HPK sensor characterization)
- Silicon growth technique (Epi: epitaxial layer, FZ: floating 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 mm^2
  - Small diodes : 2×2 mm^2



HGCAL operating conditions:

- Temperature (T) $< -30^\circ$C: $\sim -35^\circ$C
- Bias voltage (U): 600 ÷ 800 V

Cell size ~1cm^2 for 300um & 200um
→ Cell capacitance 40~60pF

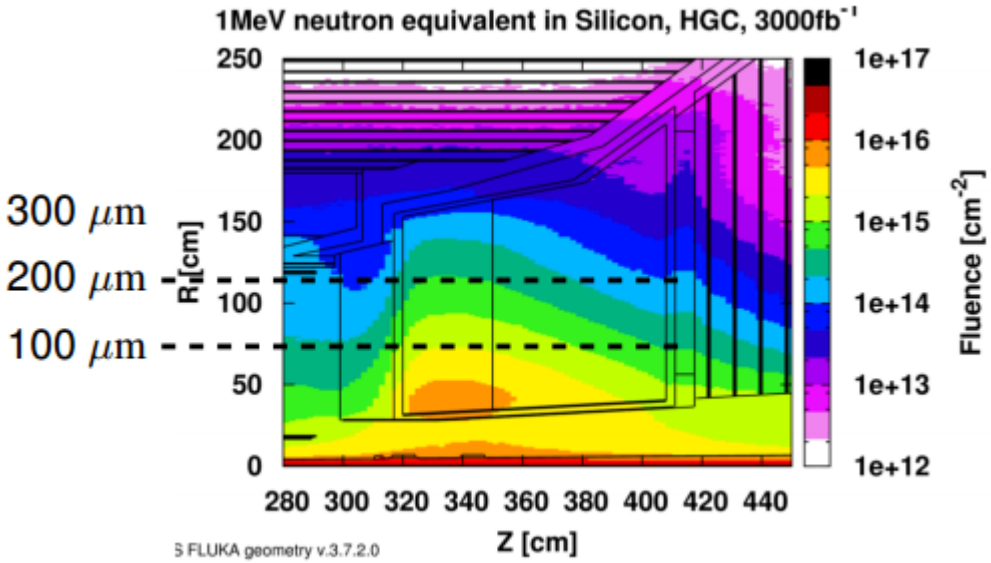
Cell size ~0.5cm^2 for 120um
→ Cell capacitance ~ 50pF

HGCAL Silicon sensors

Available sensors

- Sensors irradiated in Ljubljana
- Sensors initially measured at Hamburg and then shipped to CERN

- The study carried out for the CMS tracker upgrade with protons irradiation now is extended to neutrons irradiation



List of sensors, only Floating Zone:

Status during the first measurements

	Thickness (um)		
Fluence n/cm²	320	200	120
4.00E+014	2 N-type, 2 P-Type		
6.00E+014	2 N-type, 2 P-Type		
9.00E+014	0		
1.50E+015		2 N-type, 2 P-Type	
2.50E+015		2 N-type, 2 P-Type	
4.00E+015		0	
6.25E+015			2 N-type, 2 P-Type
1.00E+016			2 N-type, 2 P-Type
1.60E+016			2 N-type, 2 P-Type

Status during the second measurements

	Thickness (um)		
Fluence n/cm²	320	200	120
4.00E+014	1 N-type, 1 P-Type		
6.00E+014	2 N-type, 2 P-Type		
9.00E+014	1 N-type, 1 P-Type		
1.50E+015		1 N-type, 1 P-Type	
2.50E+015		2 N-type, 2 P-Type	
4.00E+015		1 N-type, 1 P-Type	
6.25E+015			1 N-type, 1 P-Type
1.00E+016			2 N-type, 2 P-Type
1.60E+016			1 N-type, 1 P-Type

After

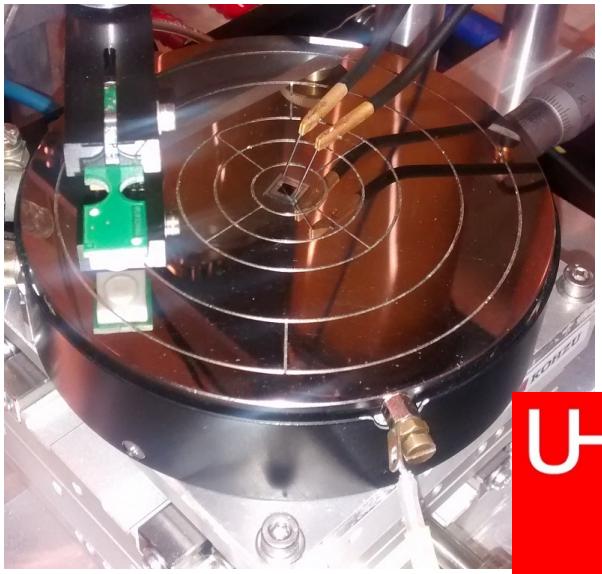
re-irradiation

Characterization after neutron irradiation

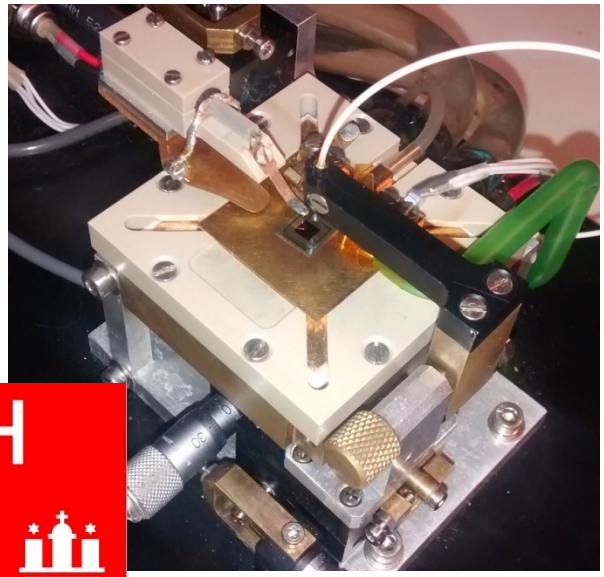
Properties to be measured:

- 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
- Effect of annealing on the properties (up to 3 months at room temperature)

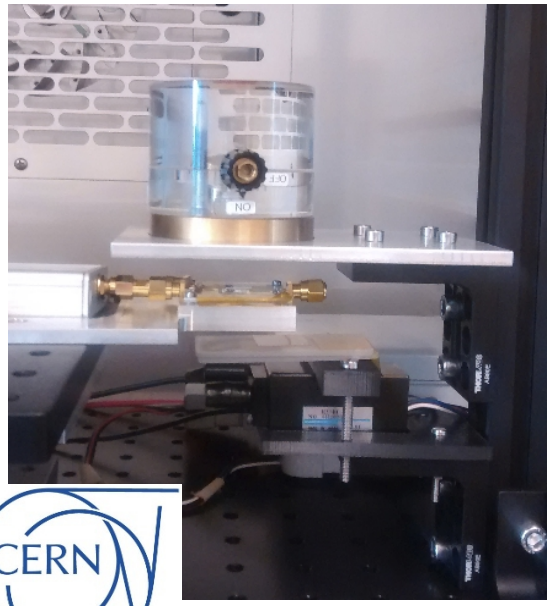
IV/CV set-up



TCT set-up for CCE
IR laser (1063 nm)

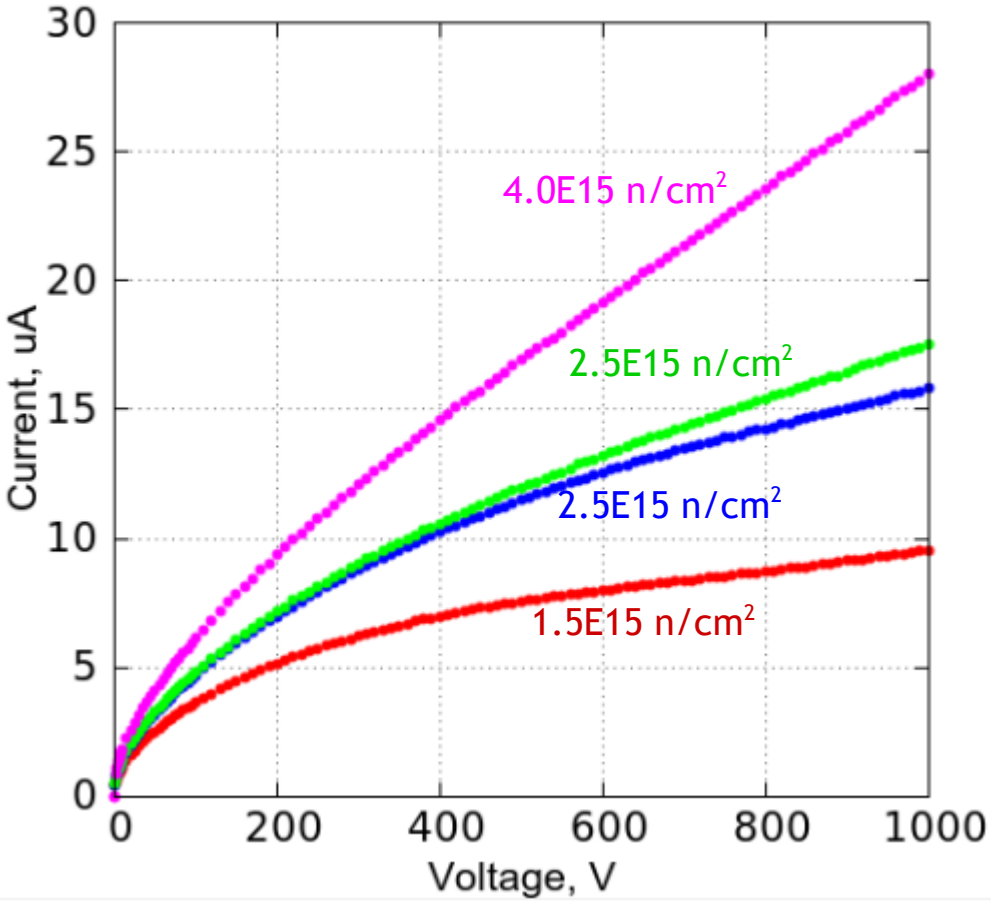


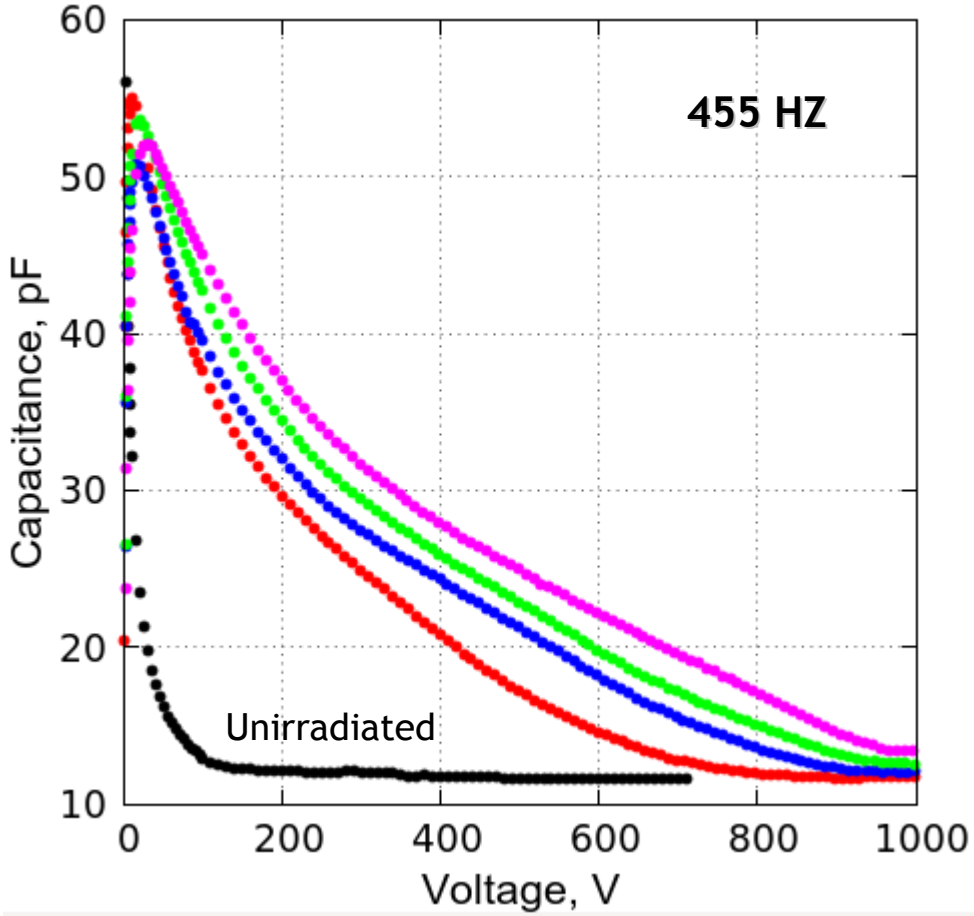
MIP sensitivity with RS



Characterization after neutron irradiation

Examples of IV and CV measurements: FZ 200um N-type, at -20^{0}C

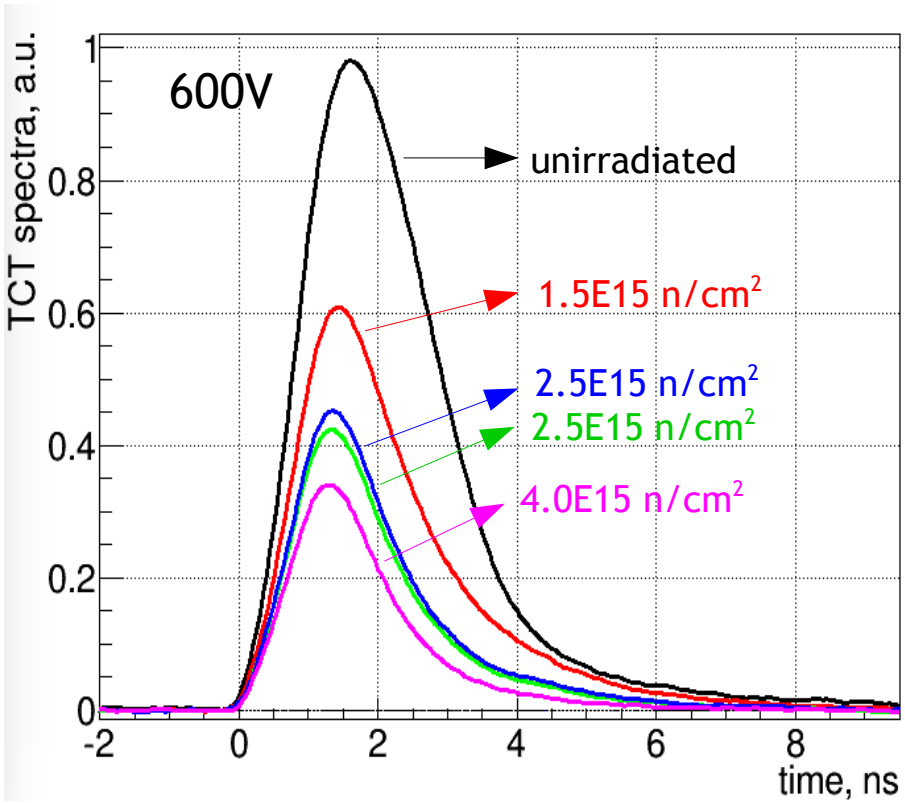


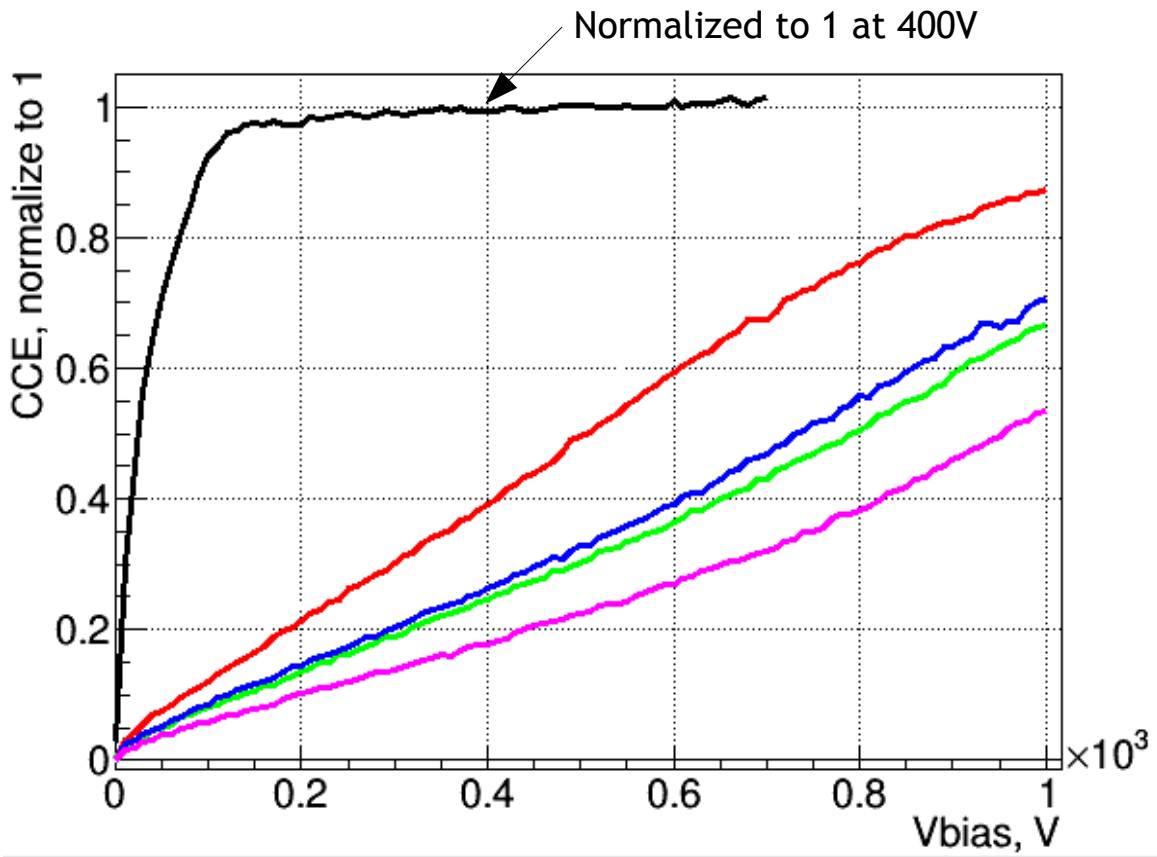


- The higher the fluence, the higher is the leakage current
- Higher is the fluence higher is the capacitance, depletion voltage increases with fluence --> capacitance increase.

Characterization after neutron irradiation

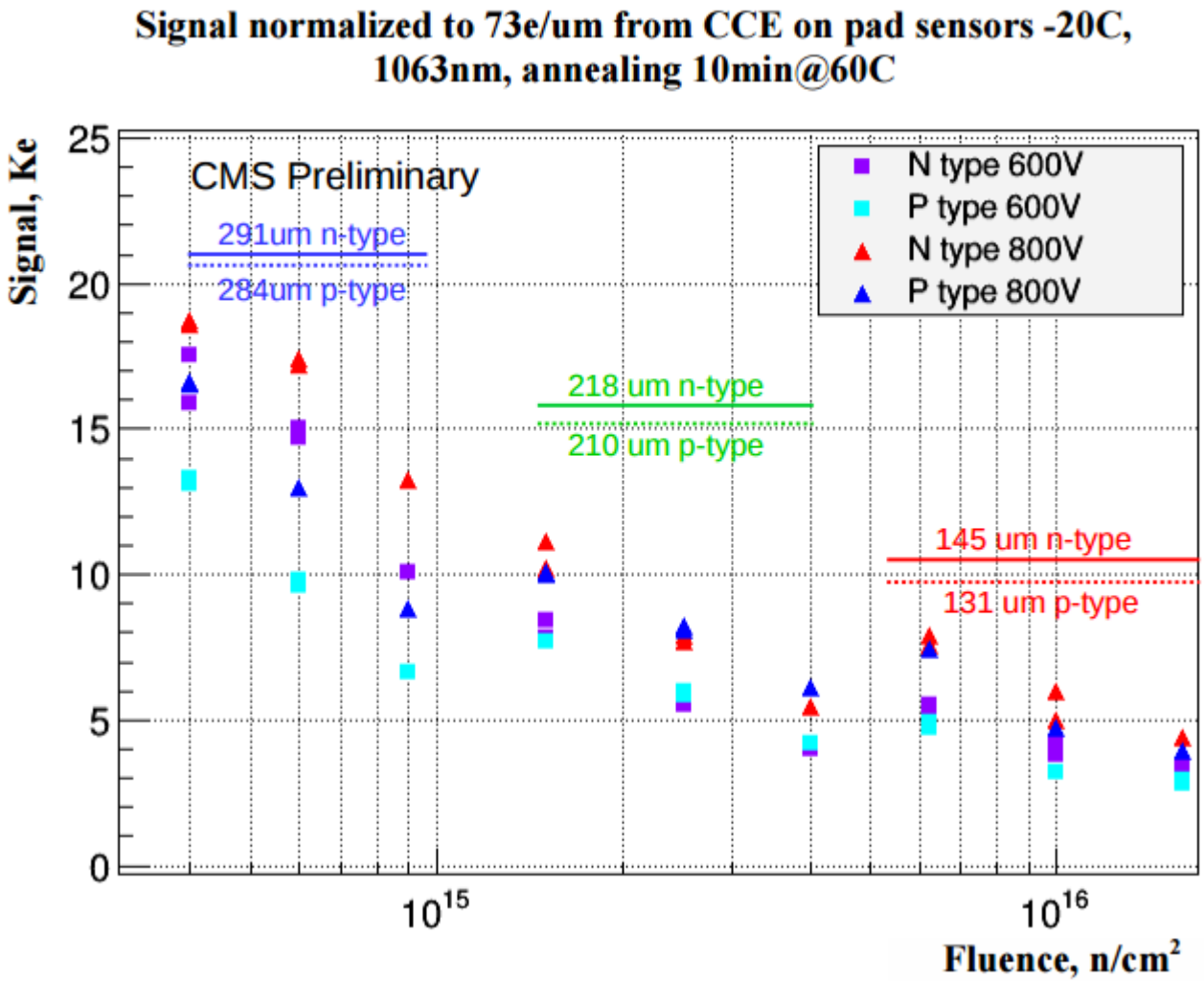
TCT measured at -20^{0}C, IR laser(1060 nm) pulse width: 50 ps, top illumination
FZ 200um N-type





- Shorter pulse and rise time after irradiation --> relevant for timing
- Collection time < 10 ns
- CCE lower after irradiation
- At these high fluences it is hard to estimate the depletion voltage, CCE is increasing with Vbias.

Characterization after neutron irradiation



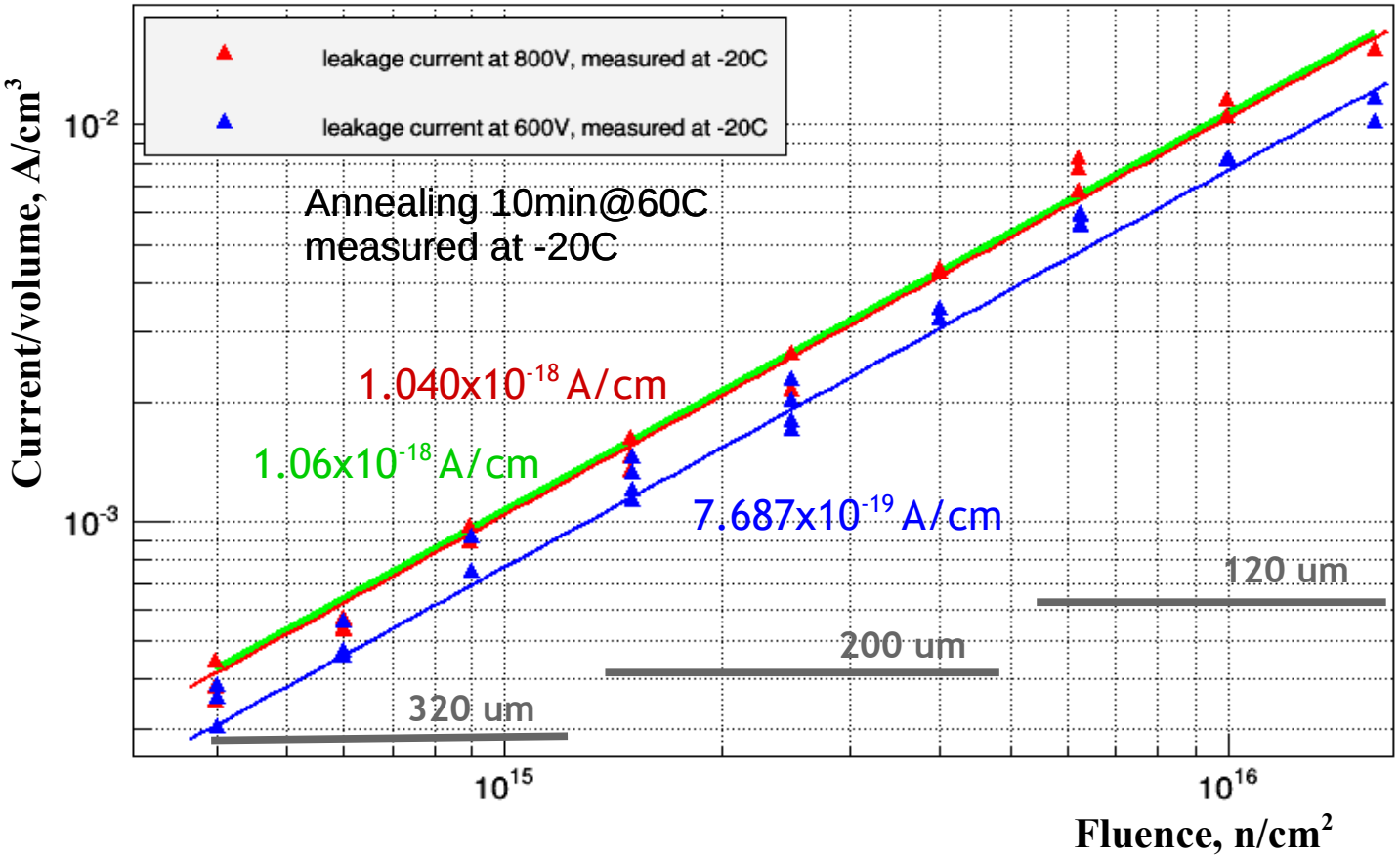
- Charge collection efficiency for ≈ 300 μm (leftmost set of points), ≈ 200 μm (middle set of points), and ≈ 120 μm silicon sensors (rightmost set of points).
- For 300 μm, low fluences, p-type diodes show lower values of CCE. For 200 μm and 120 μm both are closer.
- The lowest value of the charge measured is ~4.0/5.0 ke- for the nominal fluence (120 um). It is ~3.0/4.0 Ke- for ×1.5 the nominal. Worst case is enough for the MIP calibration (SN > 1.5/2.0)

Characterization after neutron irradiation

M. Moll's Thesis alpha value scaled to -20C: ~1.06×10^{-18} A/cm

$$\Delta I = \alpha \, \Phi_{eq} \, V$$

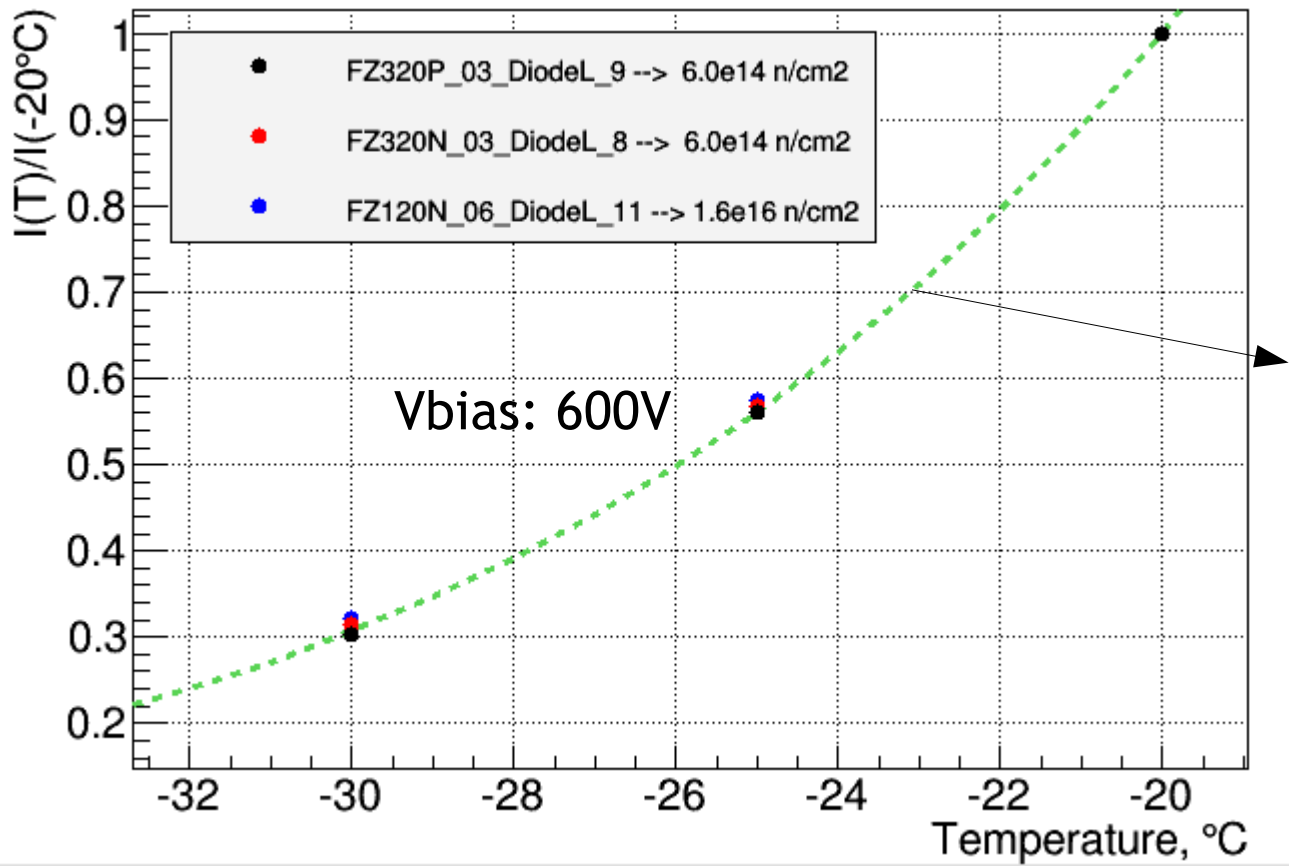
Leakage current comparison



- Leakage current normalized by the volume of the diode (for all thicknesses and two type of bulk doping) increases proportional to the fluence
- The value measured at 800V is equal the alpha value given in the bibliography.
- At very high fluences the current still continue to scale linearly with the volume and the fluence.

Characterization after neutron irradiation

Measurement of bulk current vs bias voltage (IV) as a function of the temperature (-20ºC,-25ºC,-30ºC)



Scaling factor

$$\frac{I_1}{I_2} = exp(\frac{-Ea}{2 * Kb} * (\frac{1}{T_1} - \frac{1}{T_2}))$$

- Ea (activation energy) = 1.21 ev
- Kb = 8.6173e-5 ev/K^{-1}

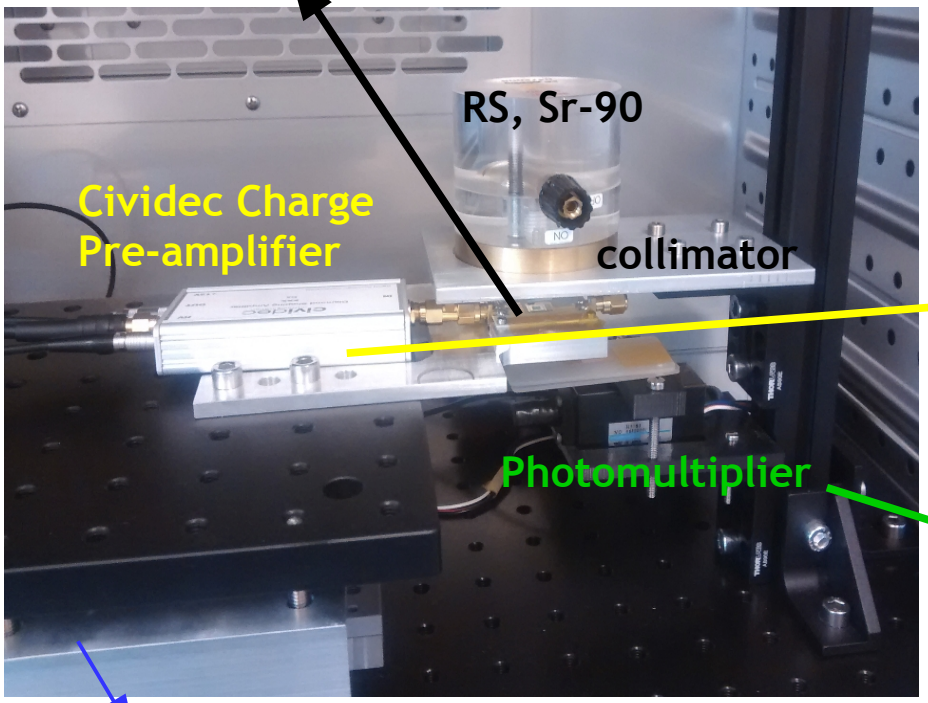
- Normalized to value of the current at -20^{0}C
- Results are compatible between p-type and n-type
- Also compatible between different active thickness and different irradiation fluences
- The scale factor for the alpha value from -20ºC to -30ºC is in agreement with our measurements. Green curve shows the formula used to scale from -20 to -30ºC.

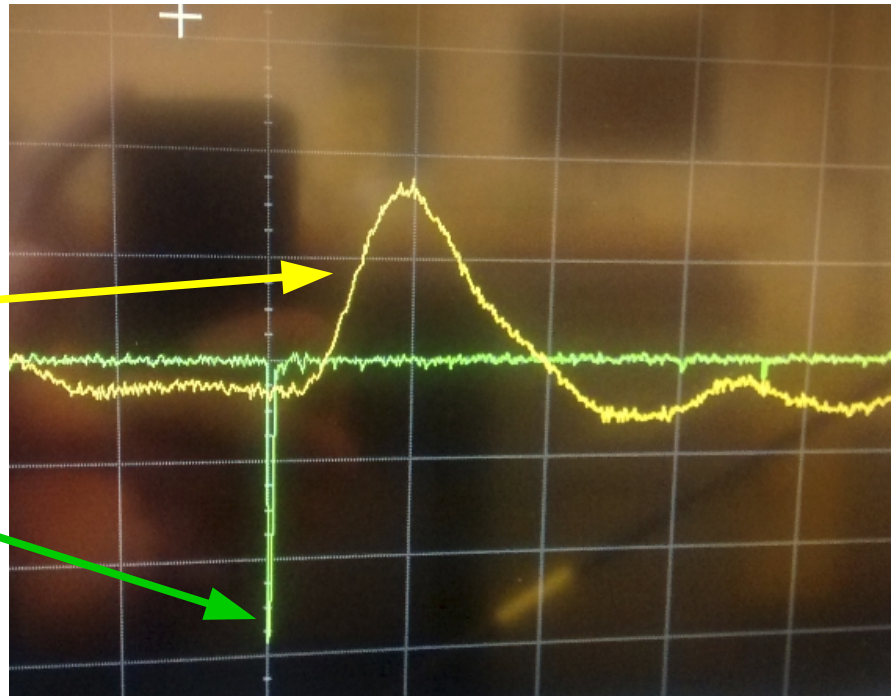
Characterization after neutron irradiation

MIP studies set-up

- MIP should be resolved for calibration proposes, but during operation higher signals are expected
- Characterization of the landau parameters distribution

Sensor (FZ120P) mounted on a pcb



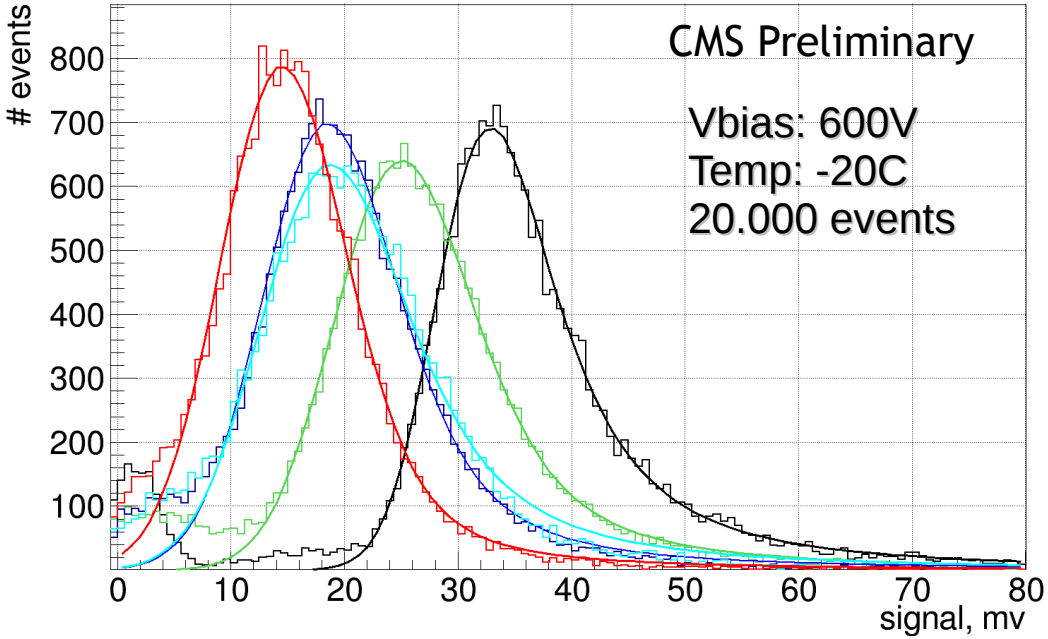


XY stages --> allow the external positioning of the sensors inside the beam

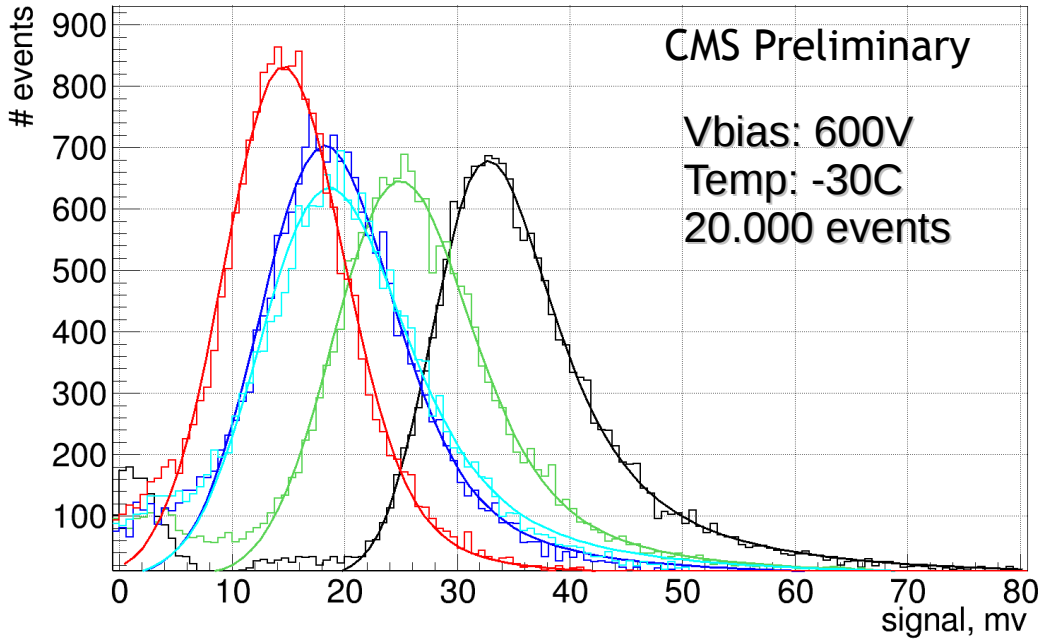
- Set-up inside a climatic chamber:
  - Operation temperature between -70^{0}C and 180^{0}C
  - Humidity below 10% RH

Characterization after neutron irradiation

Sr-90 charge collection: first results FZ320P



Fluence	MPV	Width
unirradiated	31.45 mV	2.73 mV
4e14 n/cm^2	23.23 mV	2.23 mV
6e14 n/cm^2	16.42 mV	1.72 mV
6e14 n/cm^2	16.69 mV	1.97 mV
9e14 n/cm^2	12.48 mV	1.36 mV

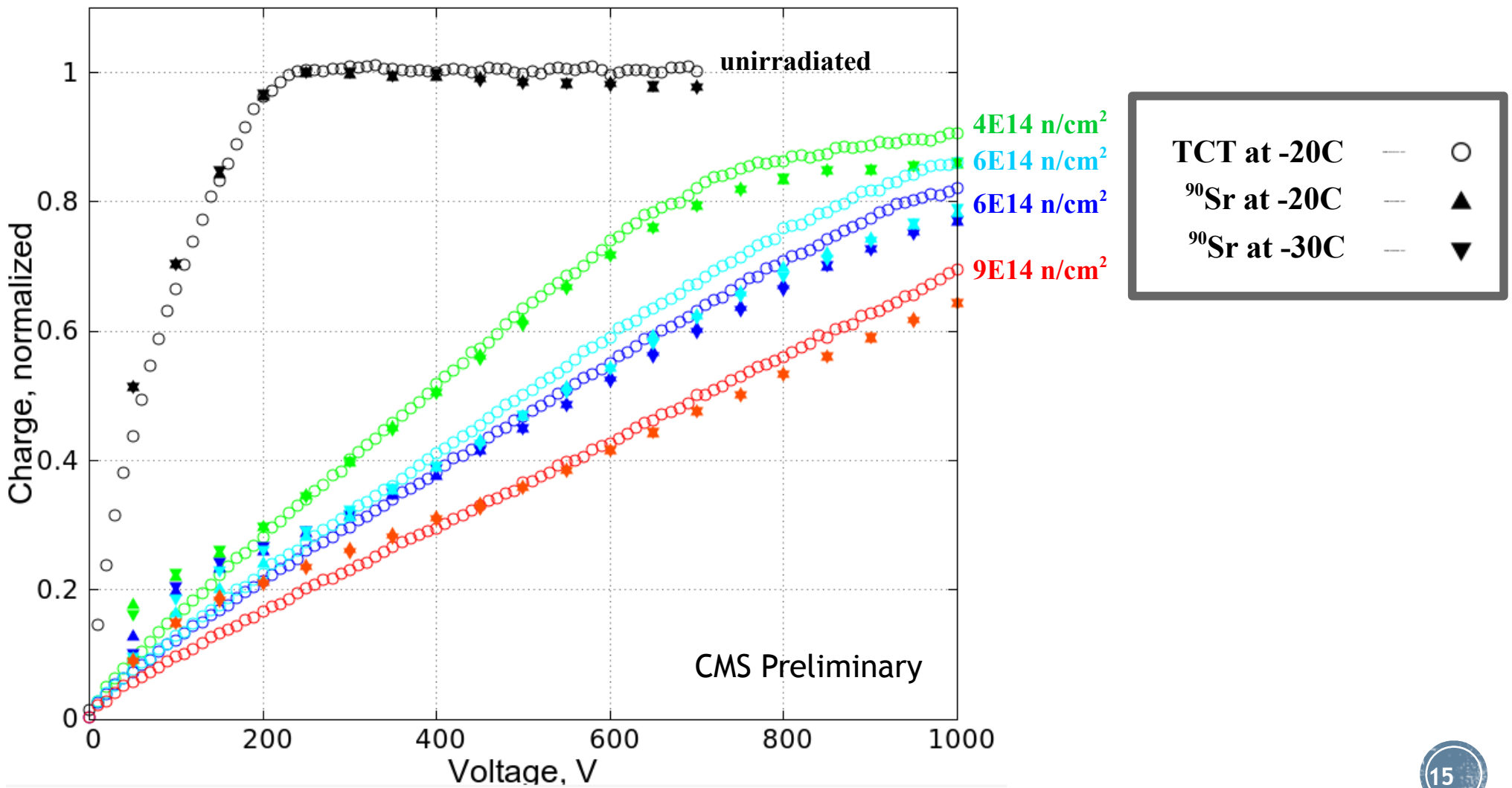


Fluence	MPV	Width
unirradiated	31.33 mV	2.77 mV
4e14 n/cm^2	22.75 mV	2.14 mV
6e14 n/cm^2	16.11 mV	1.75 mV
6e14 n/cm^2	16.52 mV	1.91 mV
9e14 n/cm^2	12.63 mV	1.18 mV

Characterization after neutron irradiation

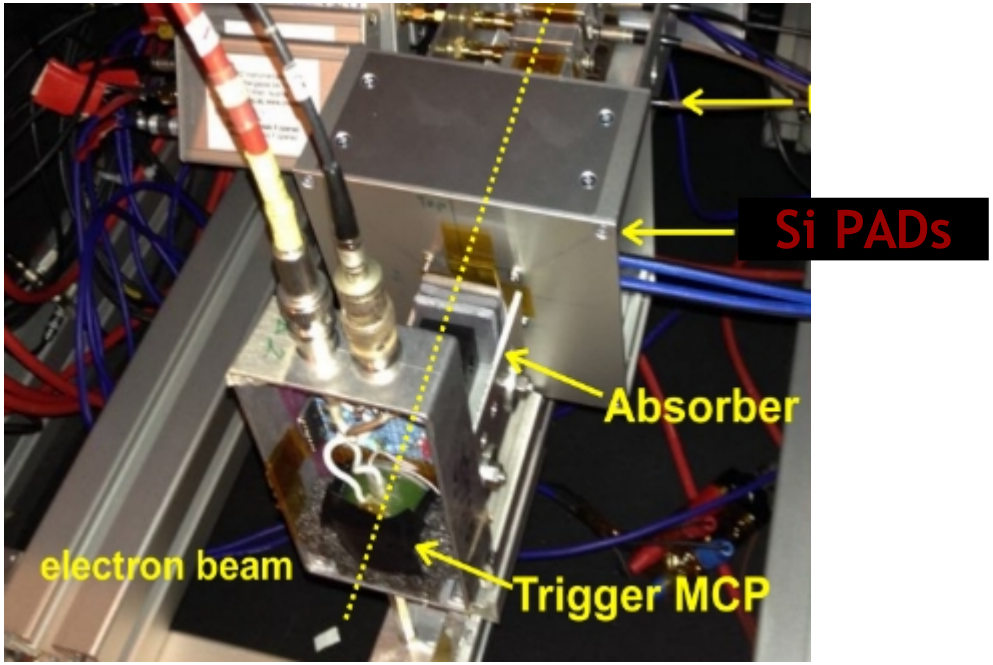
Sr-90 vs TCT IR laser measurements

FZ320P



Precision timing and test beam

Test of time response with Si PAD (Jul 2015)

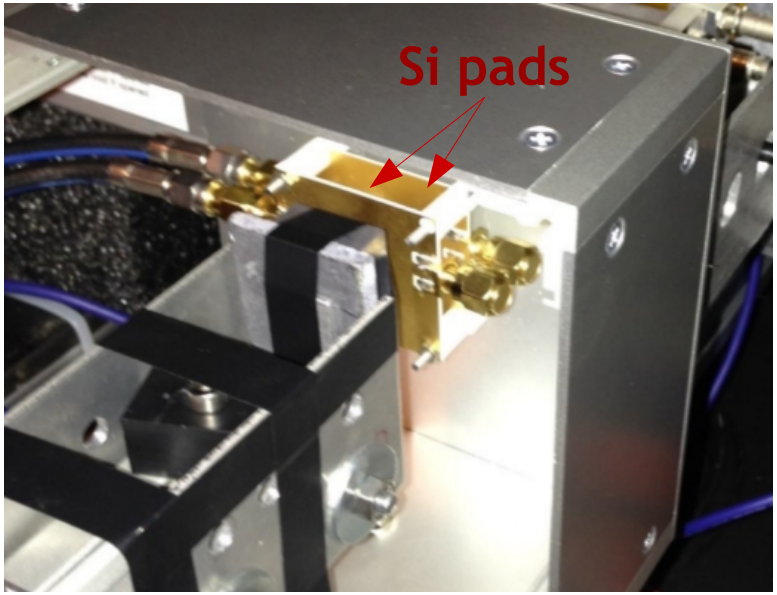


- **Goal: measure intrinsic time capabilities for EM shower and MIPs for Si pads**
  - MCP: used as trigger and time reference, also studied in previous test beams
  - Thin Si pads: understand intrinsic timing capabilities of HGCAL sensors

- **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, ~700MHz bandwidth, up to 32 channels

Precision timing and test beam

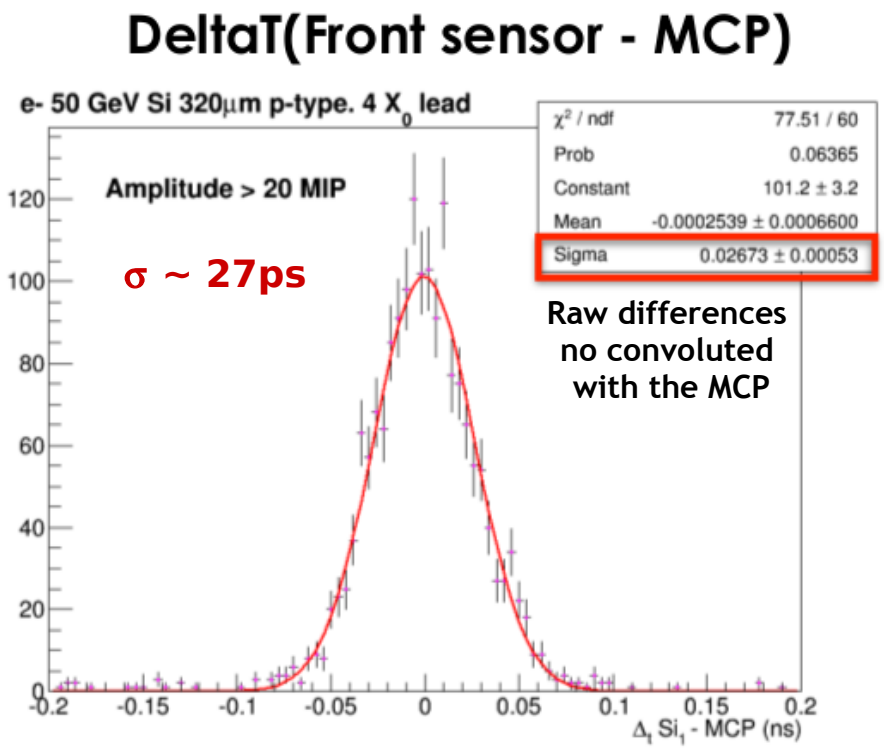
Test of time response with Si PAD (Jul 2015)

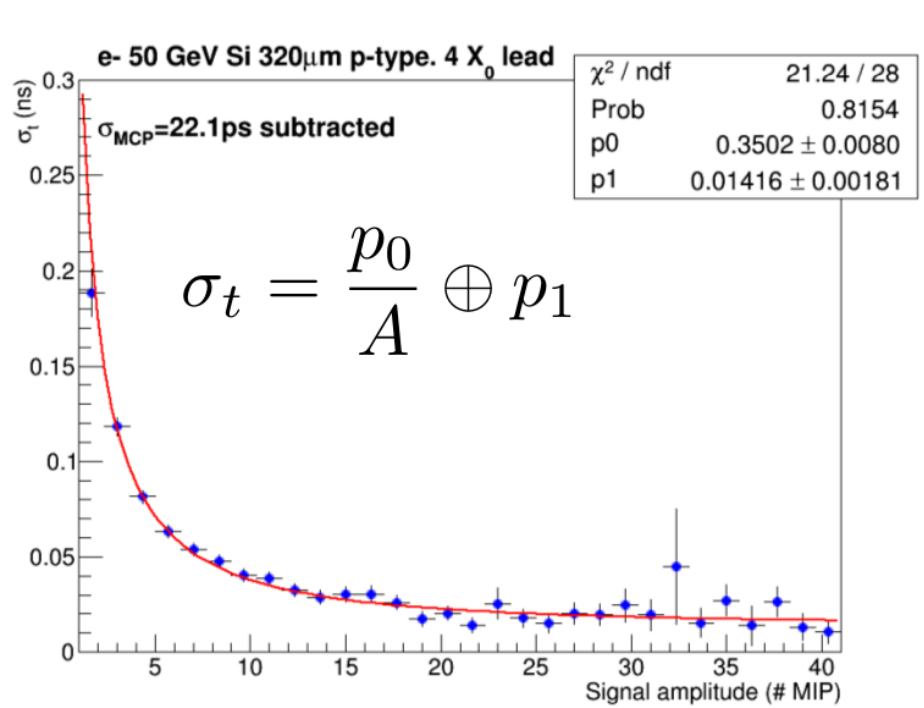


Test beam plan:

- 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**.
- Tested at different bias voltage: 400V, 600V and 700V
- Run with absorbers (e^- + absorbers → 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>)
  - There is enough precision in the electronics/DAQ to verify intrinsic jitters at the level of 10-20 ps.

Precision timing and test beam





- Very similar resolution comparing sensors of different thickness for signals >20 MIP
  - EM photons p_T showers of more than a few GeV for the energy of 1MIP to ~100 MIPs are expected
- 1 MIP time resolution from the fit:
  - ~350 ps for the 320 um
  - ~430 ps for the 200 um
  - ~600 ps for the 120 um
- Intrinsic time capabilities of thin Si sensors time for multiple MIP signals are demonstrated using full information from waveform digitised at 5 Gs/s and broadband low noise amplifiers (2Ghz)
  - **Resolution ~15ps for signal amplitude>20 MIP for unirradiated 120,200,320mu sensors**

Summary and future activities

- Measurements after neutron irradiation of IV, CV and CCE completed for the FZ diodes after the first step of annealing.
- CCE values measured are in agreement with the expected values.
- Leakage current scales linearly with the fluence.
- MIP studies setup is working and we are measuring on it, we will have measurements for all the diodes soon.
- A successful test beam program was carried out in July 2015 to show intrinsic time performance of thin Si sensors as expected for HGCAL

- Complete measurements after irradiation for the Epi diodes
- Continue with the MIPs studies.
- Perform 80min at 60C additional annealing → repeat measurements
- Measure irradiated sensors in a new test beam to study the time performance after irradiation.