Update on radiation hardness of Silicon Diodes for the future CMS High Granularity Calorimeter (HGCAL)

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26th RD50 workshop
Santander, June 22-24, 2015

Outline

- High Granularity Calorimeter (HGCAL)
- HGCAL silicon sensors
- Results of the characterization after neutron irradiation:
  - IV, CV
  - CCE
  - MIP sensitivity
- Precision timing and test beam
- Summary and future activities

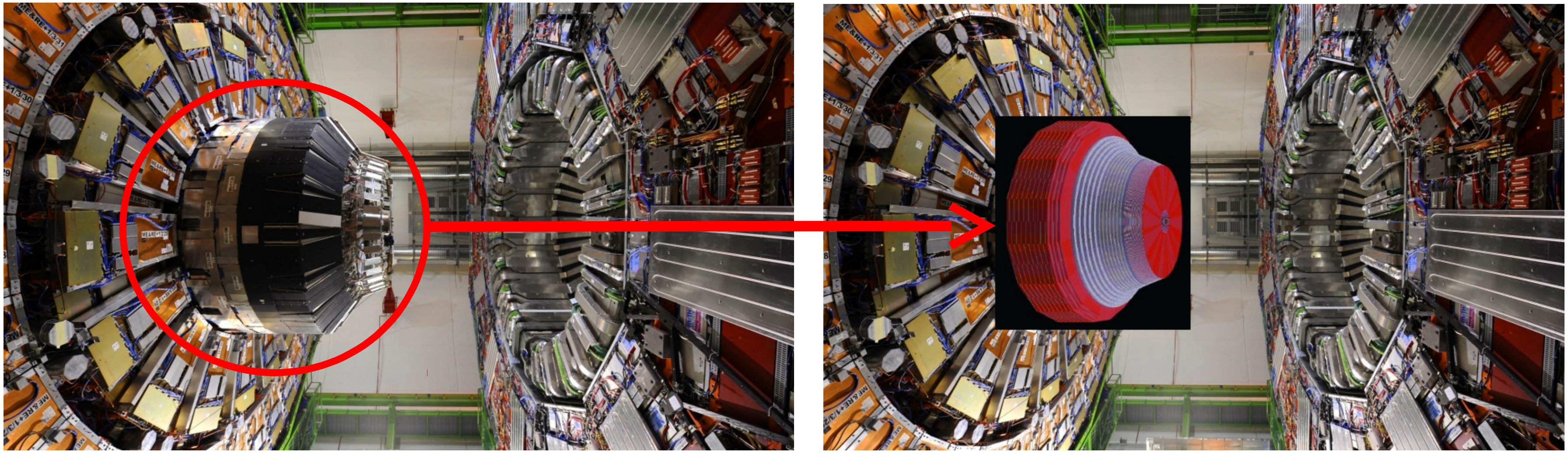
High Granularity Calorimeter (HGCAL)

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.

Current detector **An Si Based HGC CMS at the HL-LHC**



High Granularity Calorimeter (HGCAL)

Major Engineering Challenges

~600 m2 of Silicon in a high radiation environment.

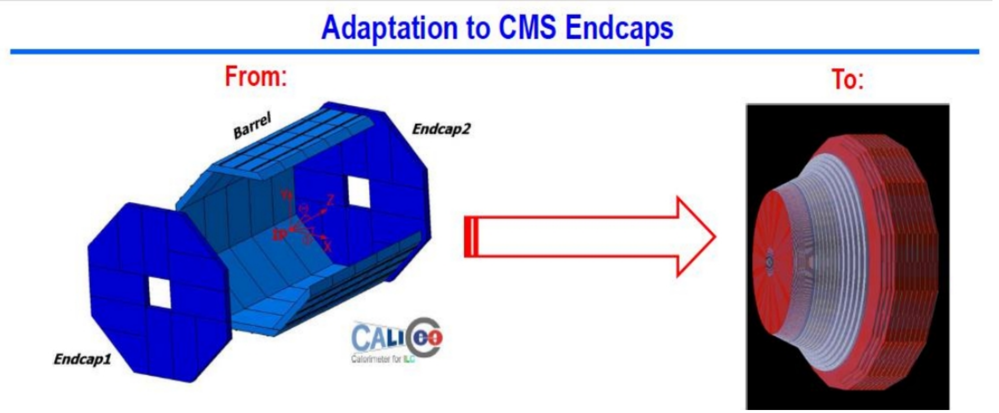
- Cost.
- Very high radiation levels – need to plan for $1.5x10^{16}$ neutrons/cm^2

Cooling.

- We need a compact calorimeter with small gaps between absorber plates.
- We need to operate at – 30^oC
- Total power is ~ 100 kW.

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.



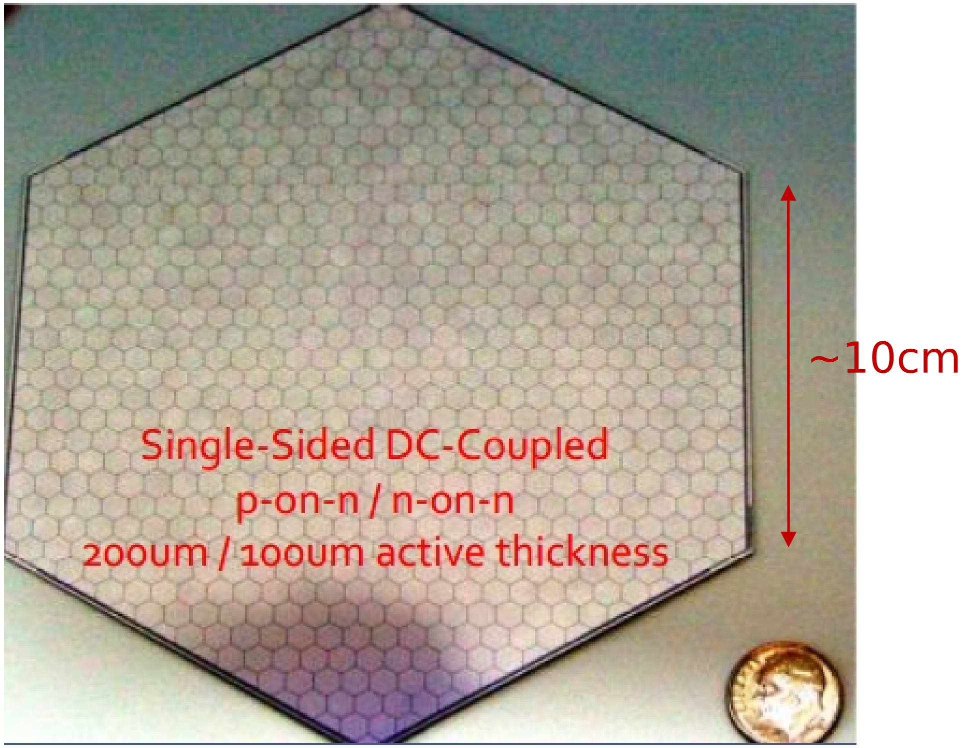
HGCAL Silicon sensors

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 $1.5 \cdot 10^{16} n/cm^2$

Sensors under investigation:

- Silicon growth technique (Epi: epitaxial layer, FZ: floating zone)
- 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



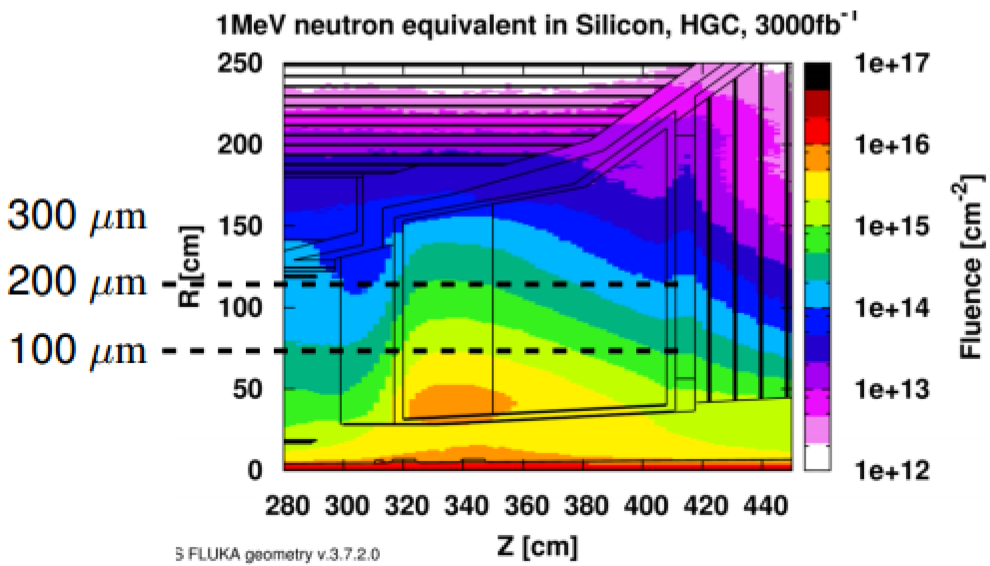
HGCAL operating conditions:

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

HGCAL Silicon sensors

Available sensors

- Sensors irradiated in Ljubljana
- Sensors initially measured at Hamburg and then shipped to CERN
- P: bulk P (n-on-p)
- N: bulk N (p-on-n)



List of sensors, only Floating Zone:

Status during Hamburg 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

Current status at CERN

	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

→

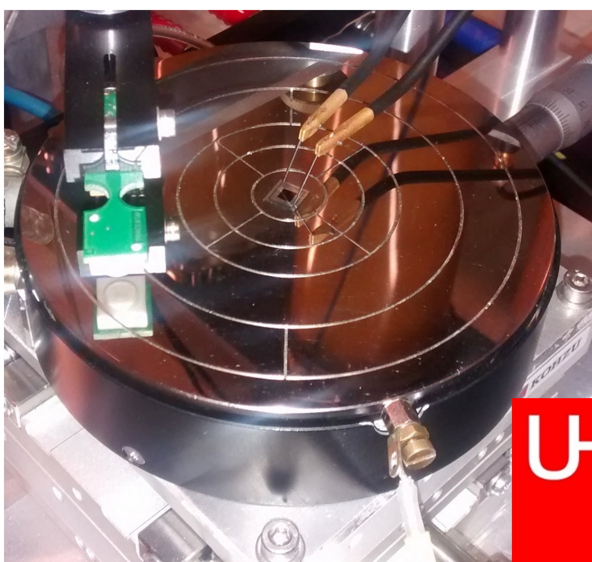
re-irradiation

Characterization after neutron irradiation

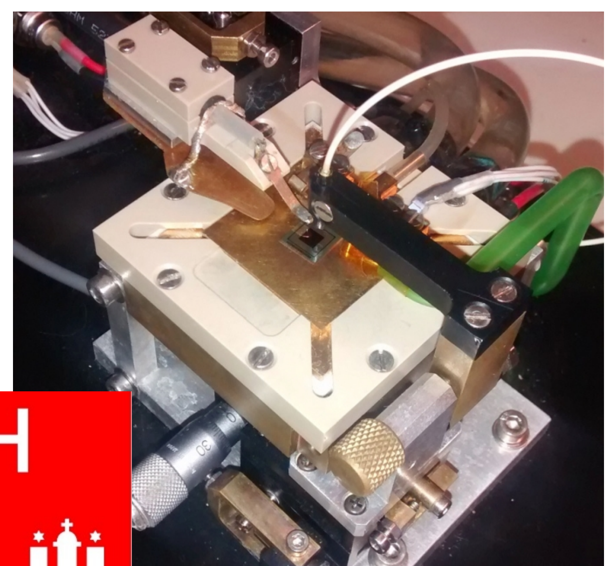
Properties to be measured:

- Bulk current I(U, Φ, h) → power consumption, noise
- Capacitance (1 MHz signal): C(U, Φ, h) → capacitance seen by electronics (below ~50pF)
- Charge collection efficiency CCE(U, Φ, thickness) → signal
- MIP sensitivity with beta source → for calibration purpose and S/N
- Effect of annealing on the properties (up to 3 months at room temperature)

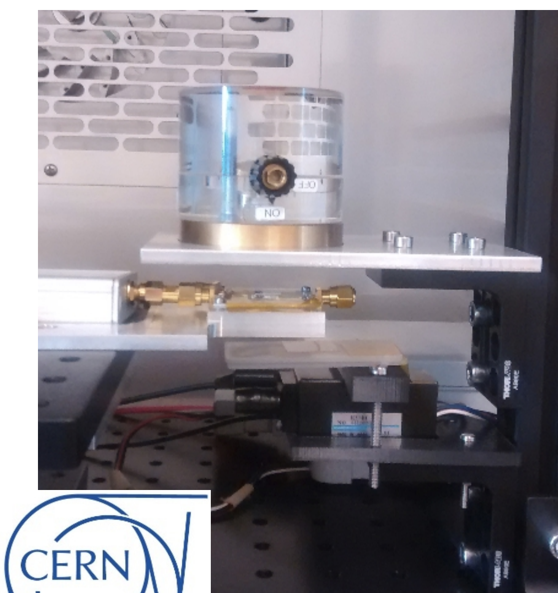
IV/CV set-up



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

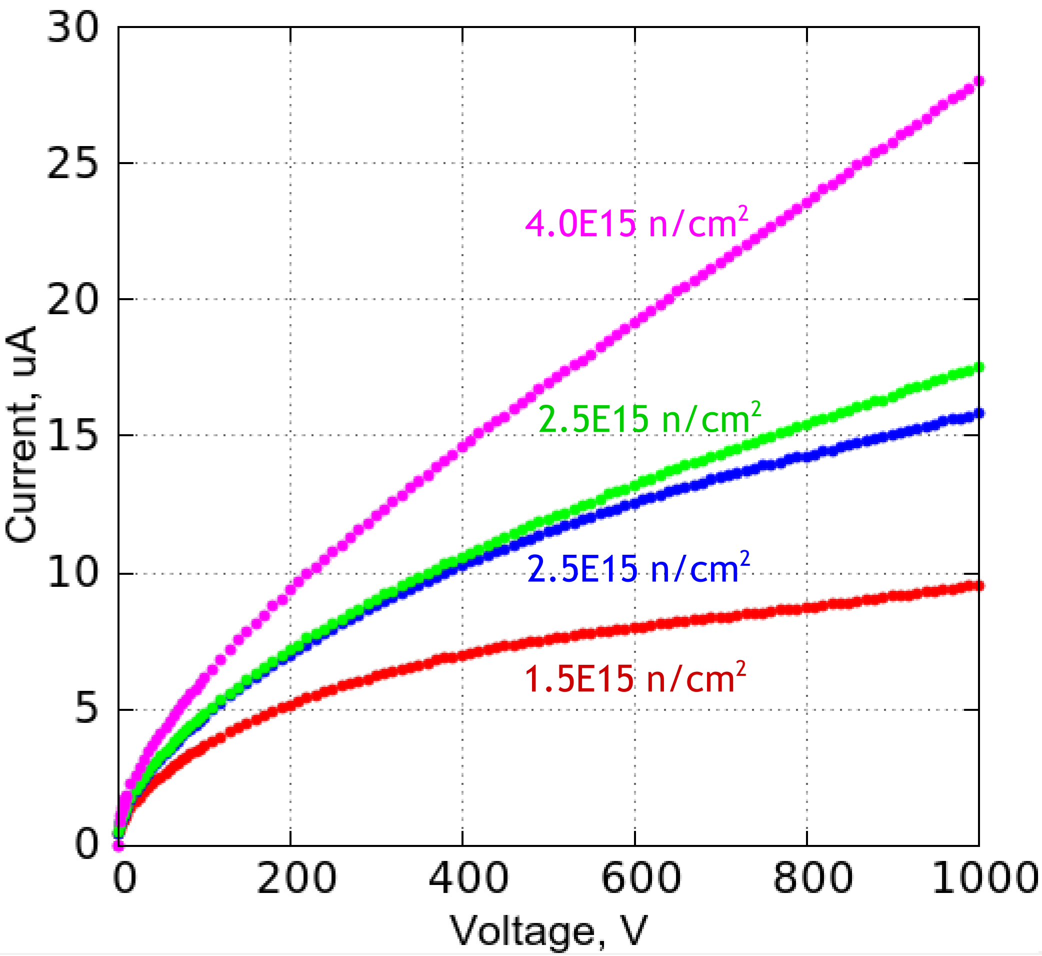


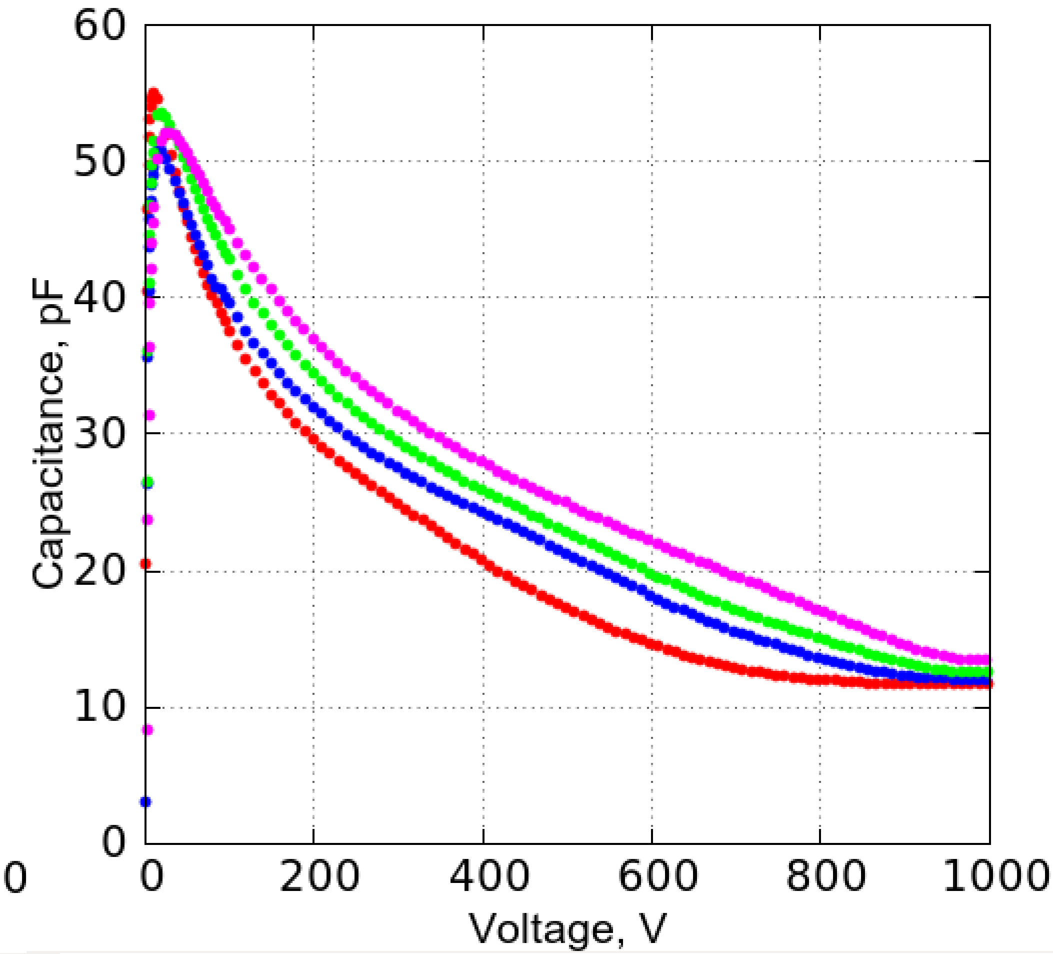
MIP sensitivity with RS



Characterization after neutron irradiation

Examples of IV and CV measurements: FZ 200um N-type, at -20^{0}C (455Hz for CV)

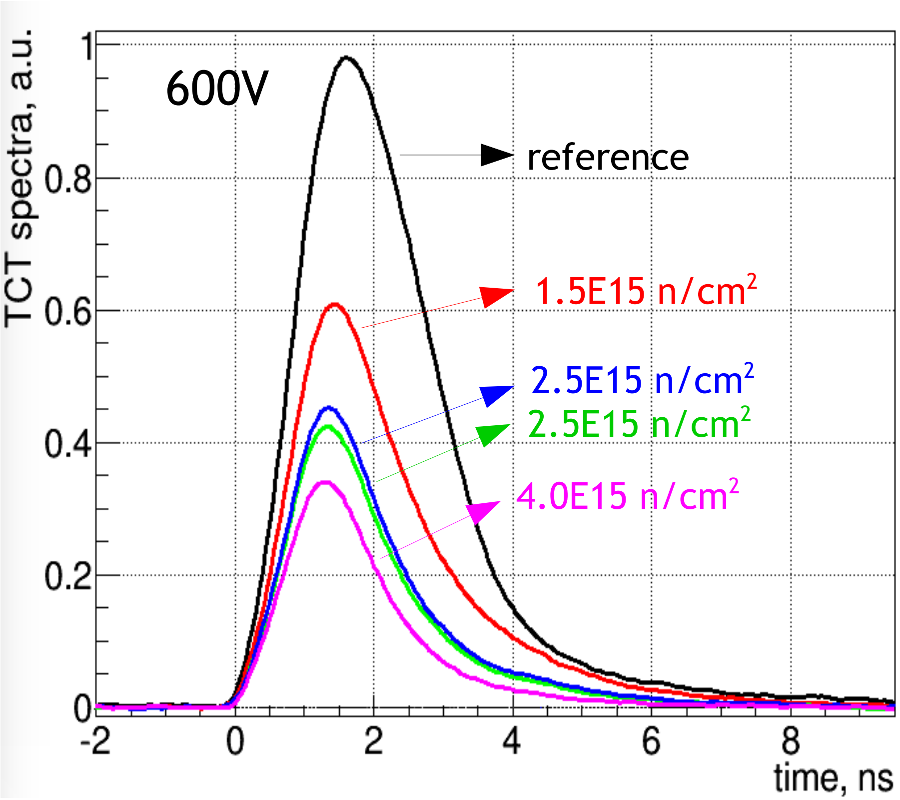


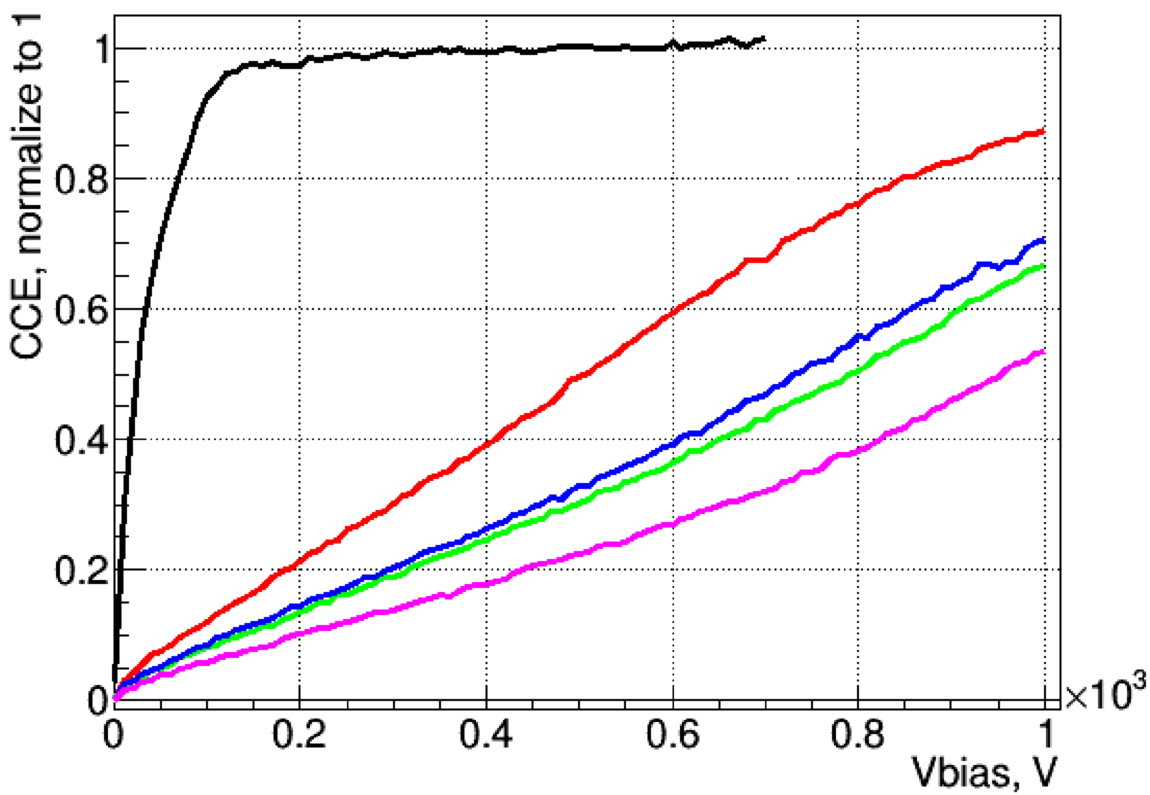


- The higher the fluence, the higher is the leakage current
- Higher is the fluence higher is the capacitance, depletion voltage increases with fluence --> capacitance increase.

Characterization after neutron irradiation

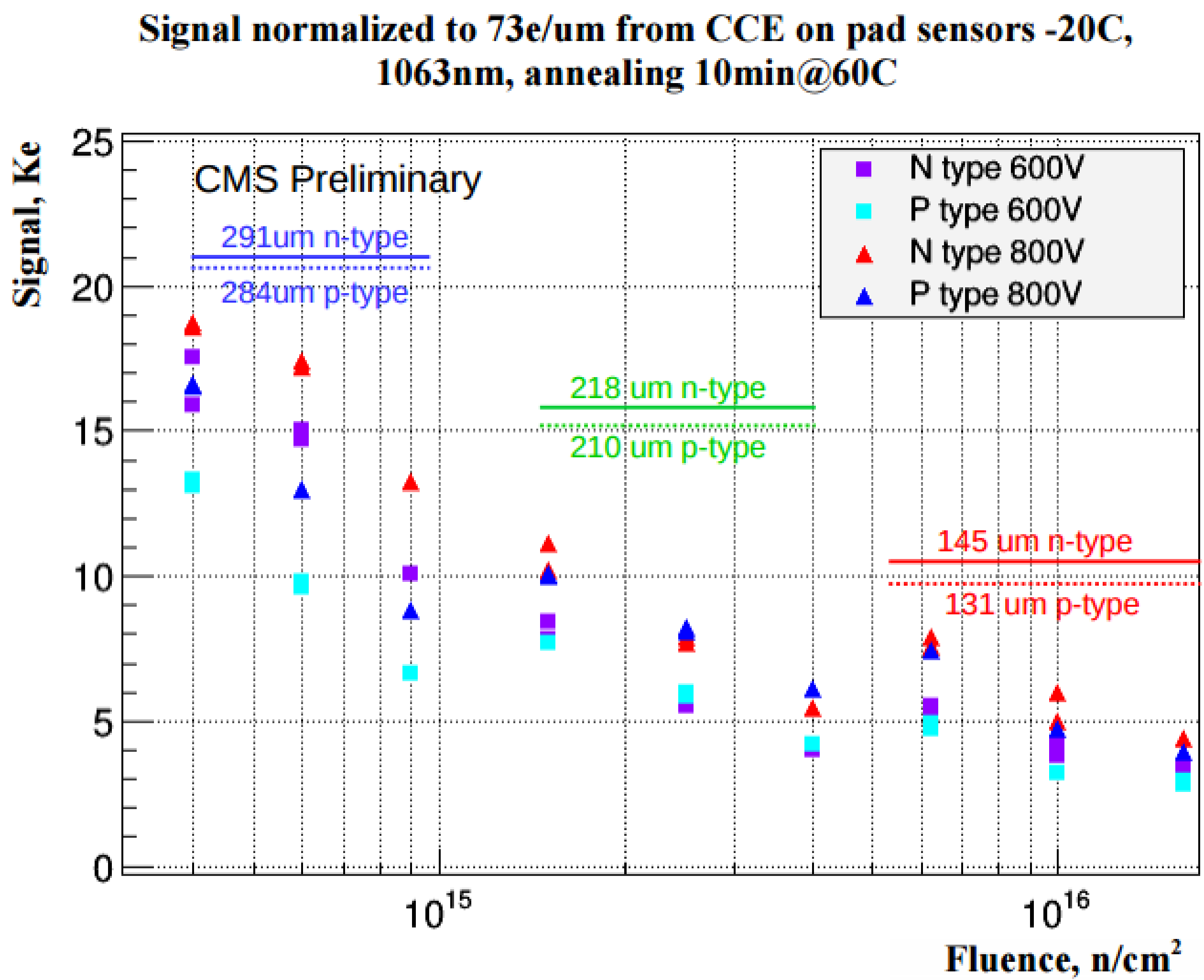
TCT measured at -20^{0}C, IR laser(1060 nm) pulse width: 50 ps, top illumination
FZ 200um N-type





- 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

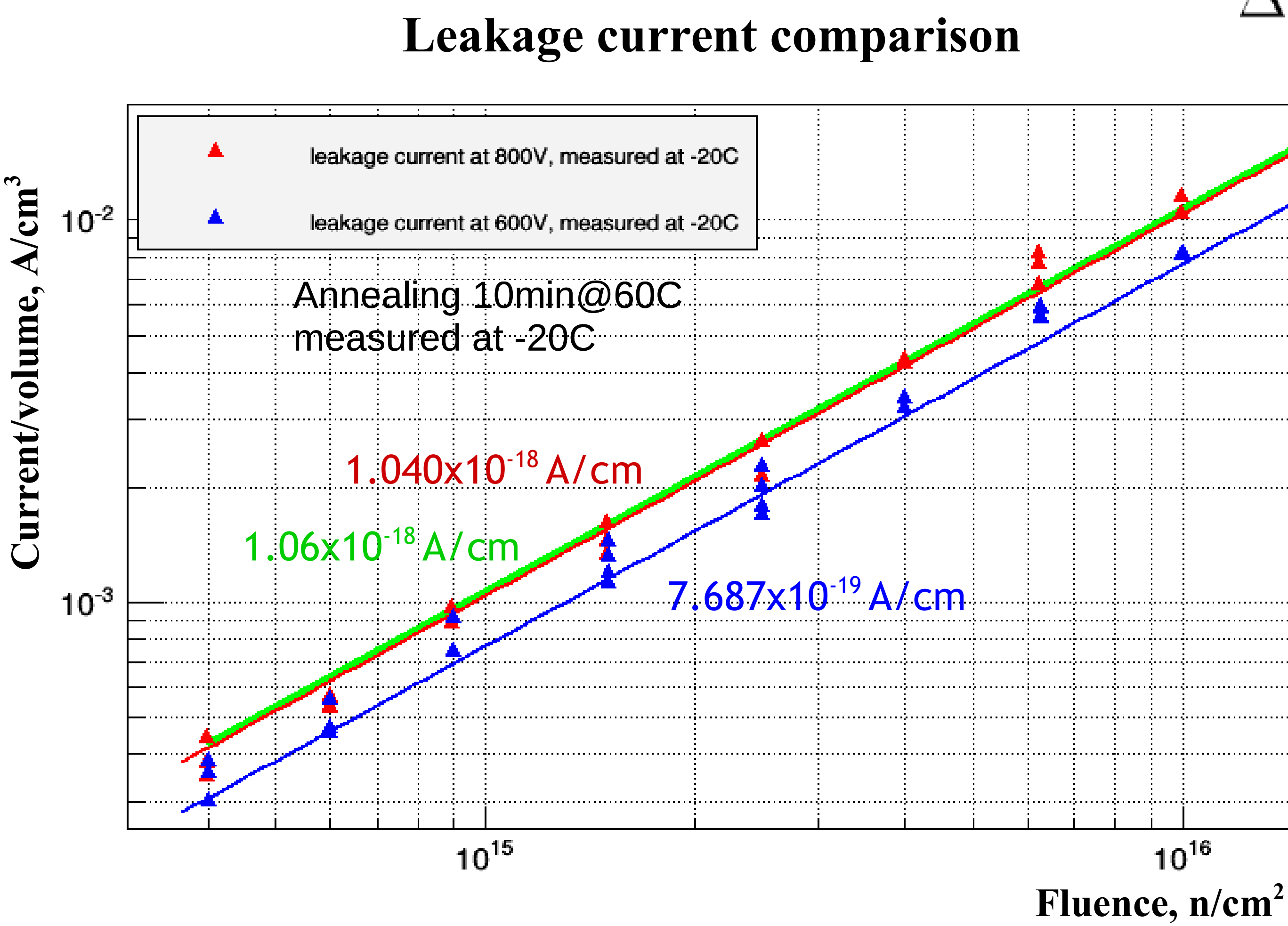


- Charge collection efficiency for ≈ 300 μm (leftmost set of points), ≈ 200 μm (middle set of points), and ≈ 120 μm silicon sensors (rightmost set of points).
- For 300 μm, low fluences, p-type diodes show lower values of CCE. For 200 μm and 120 μm both are closer.
- The lowest value of the charge measured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

Characterization after neutron irradiation

M. Moll's Thesis alpha value scaled to -20C: ~1.06x10^{-18} A/cm

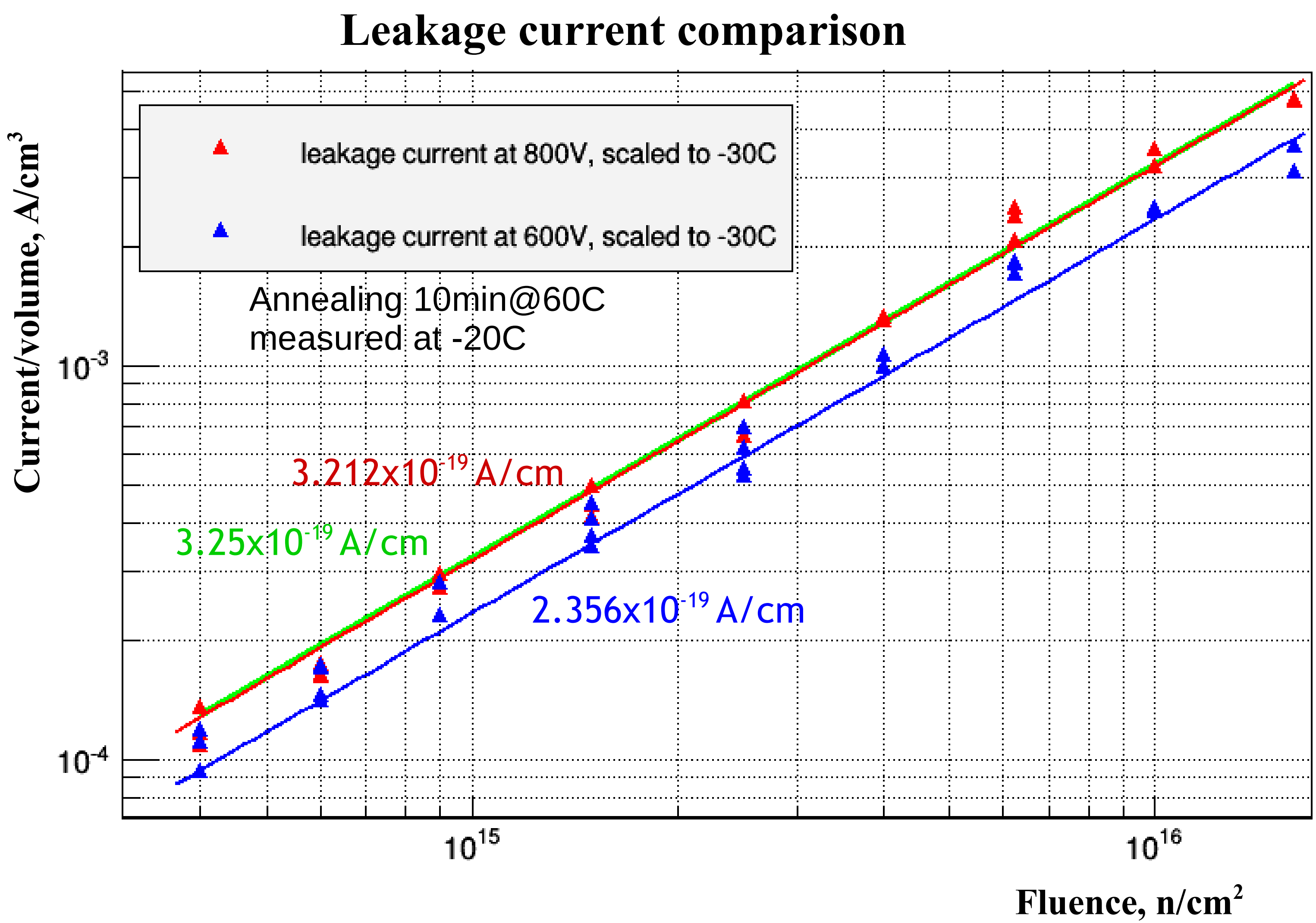
$$\Delta I = \alpha\, \Phi_{eq}\, V$$



- 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.
- Value at 600V a bit lower than expected.

Characterization after neutron irradiation

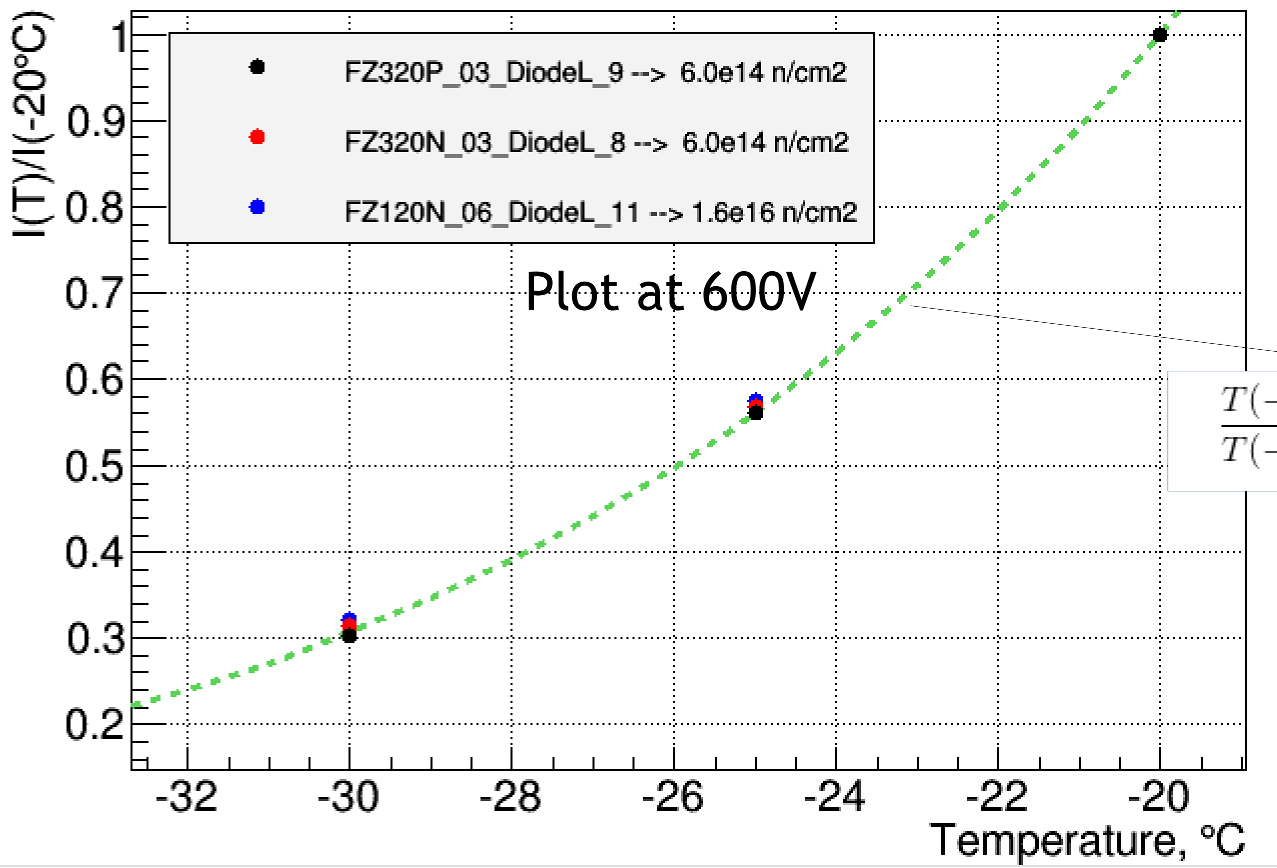
M. Moll's Thesis alpha value scaled to -30^{0}C: ~3.25x10^{-19} A/cm



- Same plot, but now scaled to -30^{0}C, closer to the operation temperature of the HGCAL.
- Same agreement, lower temperature --> lower values of the leakage current

Characterization after neutron irradiation

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



Scaling factor

$$\frac{T(-30)}{T(-20)} * exp(\frac{-Ea}{2*Kb} * \frac{1}{T(-30)} - \frac{1}{T(-20)})$$

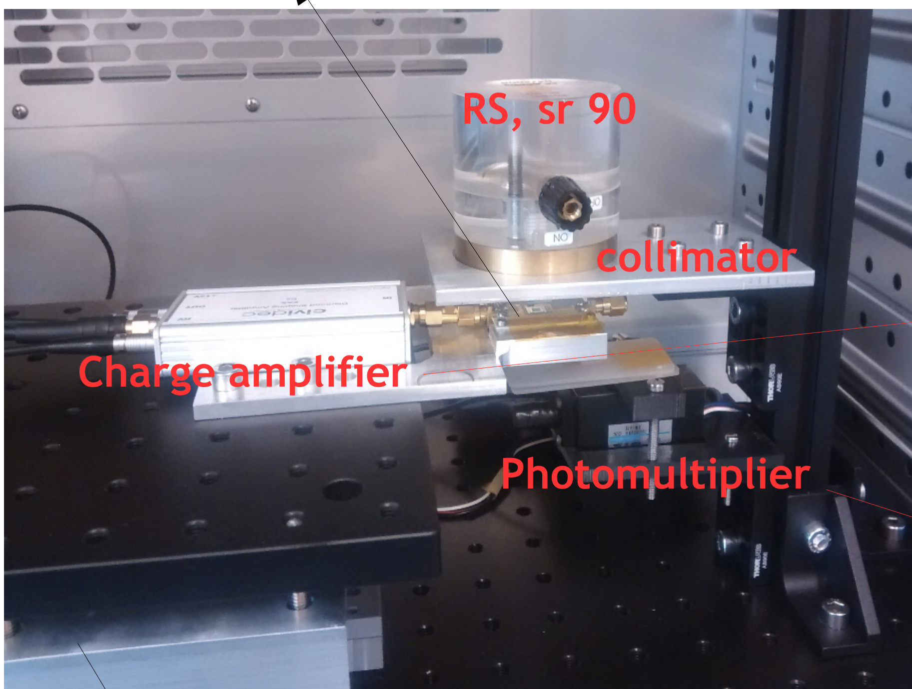
- Ea (activation energy) = 1.21 ev
- Kb = 8.6173e-5 ev/K^{-1}

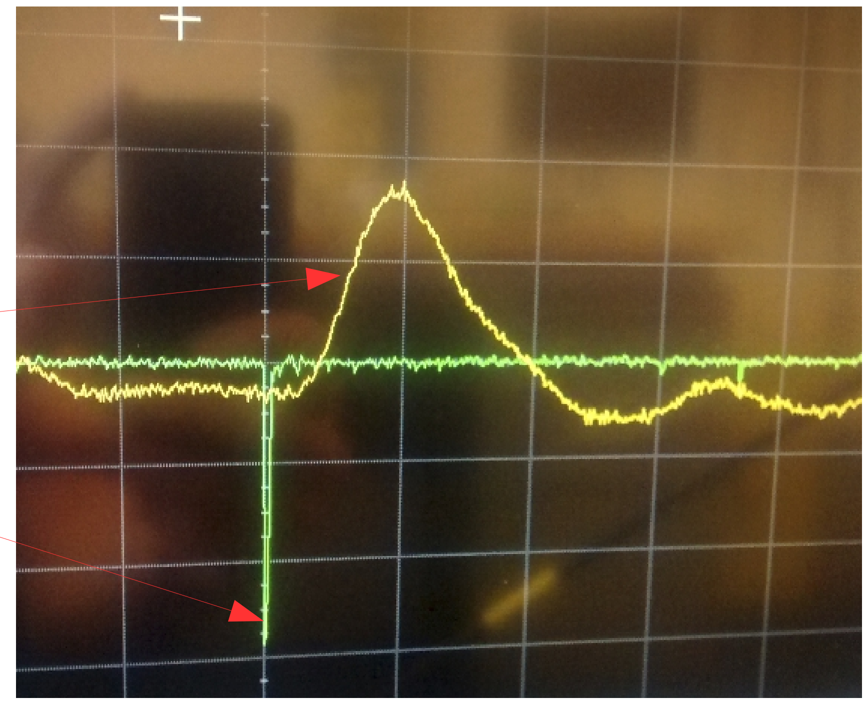
- Normalized to value of the current at -20^{0}C
- Results are compatible between p-type and n-type
- Also compatible between different active thickness and different irradiation fluences
- The scale factor for the alpha value from -20ºC to -30ºC is in agreement with our measurements. Green curve shows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

Characterization after neutron irradiation

MIP sensitivity set-up → is ongoing, but it still needs extra work in order to get the first good measurements

Sensor (FZ120P) mounted on a pcb





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

- Example of one single signal given by the charge amplifier in yellow. The amplitude of this signal is proportional to the charge collected from the sensor after one MIP.
- Set-up inside a climatic chamber:
  - Operation temperature between -70^{0}C and 180^{0}C
  - Humidity below 10% RH

Precision timing and test beam

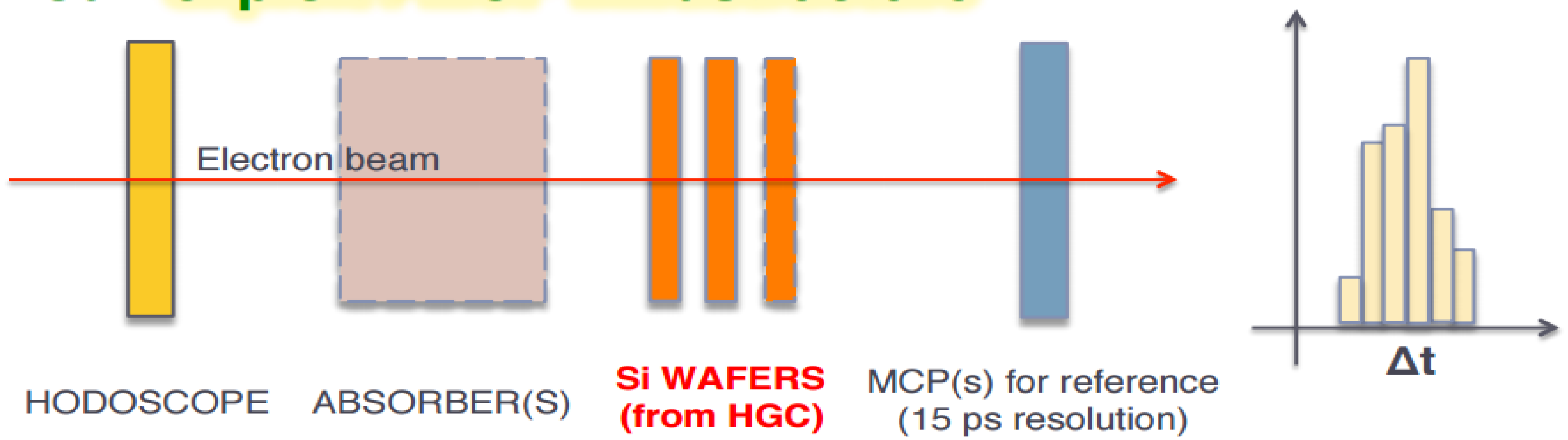
Test of time response with Si PAD

- **General timing studies in CMS**
  - Vertex location to better than 1 cm in diphoton events from photon timing with 30 ps precision – proven
  - Event and object cleaning with 30 ps timing of vertices (from hits associated to charged tracks) and of showers – studies ongoing
- **Simulation studies with HGCAL**
  - Single cell timing to O(100) ps possible with ToT electronics for deposits above about 30 MIPs
    - Photon and (high-energy) hadron shower timing to <30 ps from combined cells information
- **Proposed test of time response of Si PADs with beam**
  - Digitize pulses, emulate pulse discrimination offline, verify that the intrinsic detector jitter does not exceed few 10 ps.
- **Implementation**
  - Measure spread of the time difference between different wafers aligned along the beamline
  - Repeat measurements with variable absorbers in front to study the dependence on the number of MIPs

Precision timing and test beam

Test of time response with Si PAD

- **Can exploit i-MCP infrastructure**



Test beam plan:

- Run w/o absorber or muons to calibrate response to MIPs
- Run with absorbers (available from zero to $7X_0$):
  - 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.

Summary and future activities

- ✓ Measurements after neutron irradiations of IV, CV and CCE done at Hamburg and crosschecked at CERN also with higher fluences and after the first step of annealing 10min@60^0C

- ✓ CCE values and leakage current measured are in agreement with the expected values

- ✓ To do:
  - ✓ Perform 80 min at 60°C additional annealing on the diodes (two weeks at room temperature) → repeat measurements
  - ✓ Workshop for comparison of results with HPK campaign (and other data, lower fluence neutrons, but also protons...)
  - ✓ First results with beta source coming soon → for MIP sensitivity
  - ✓ Precision timing test → ongoing