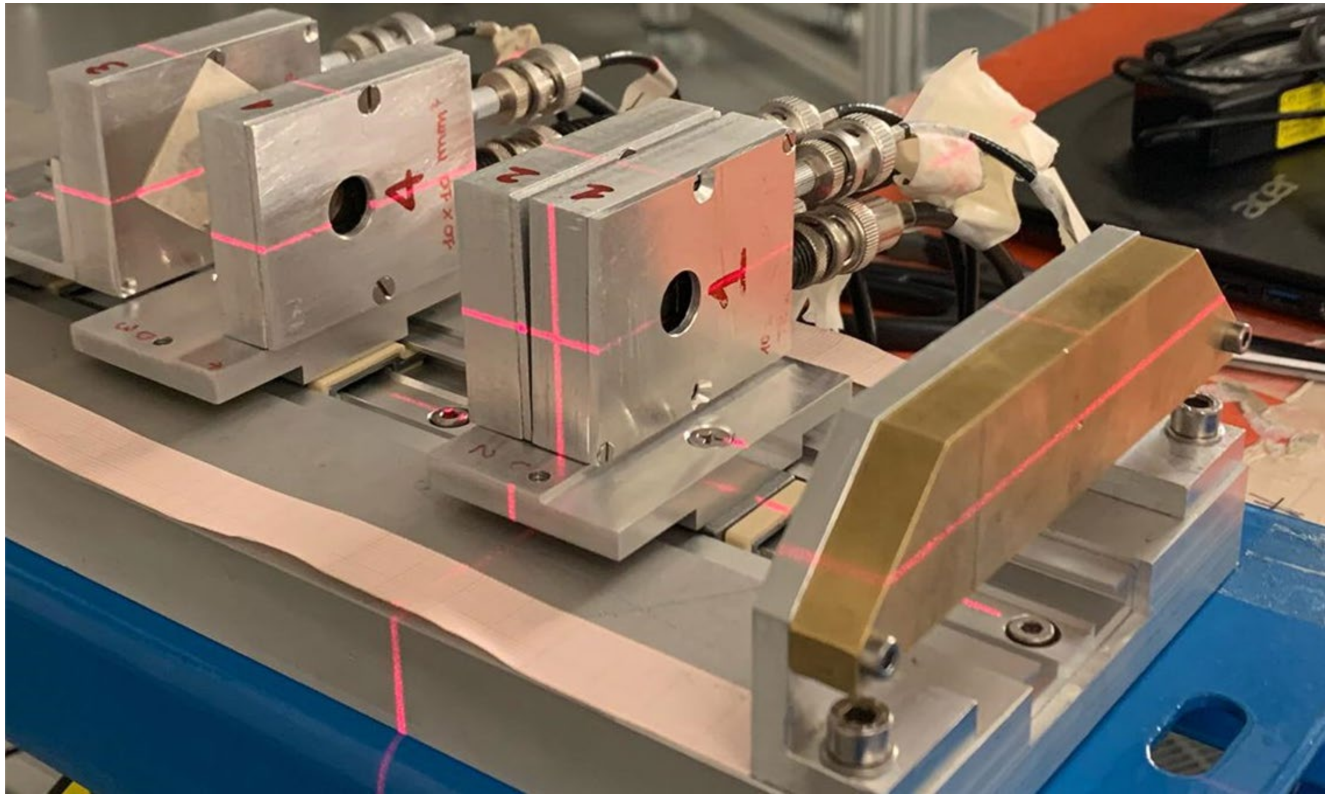
IMPULSE has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161.



PRAGUE

Proton RAnGe measure Using silicon carbidE

Experimental tests and future developments

M. Guarrera[1, 2], G. Petringa[2, 3], A. Amato[2], R. Catalano[2], A. Kurmanova[2], D. Margarone[3], S. Tudisco[2], C. Verona[4], G. A. P. Cirrone[2]

[1]Department of Physics and Astronomy "Ettore Majorana", University of Catania - Catania, Italy
[2]INFN-Laboratori Nazionali del Sud - Via S. Sofia, Catania, Italy
[3]ELI-Beamlines, Institute of Physics (FZU), Czech Academy of Sciences, Prague, Czechia
[4]Dip. di Ing. Meccanica, Università di Roma "Tor Vergata," Roma, Italy

Outline

- The project
- Detector prototype
- Final configuration

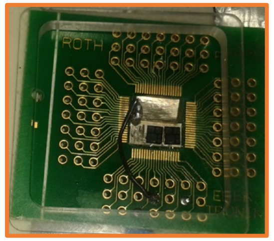
The project

PRAGUE (Proton RAnGe measure Using silicon carbidE) detector

Main goal:

- ❑ Online dosimeter;
- ❑ PDD distribution of proton beams;
- ❑ $10^5 - 10^{10}$ pps intensity beams;
- ❑ High longitudinal spatial resolution;
- ❑ Dose on biological samples.

- ➢ Dose rate independent;
- ➢ LET independent;
- ➢ High radiation hardness.

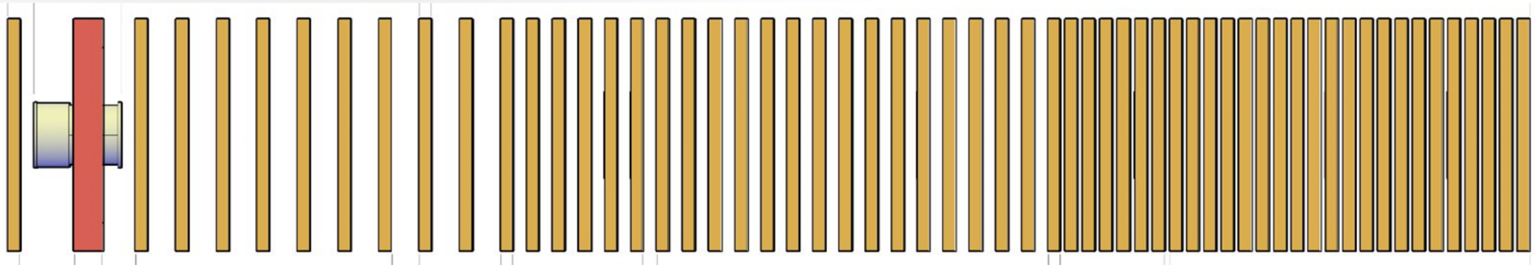


Old generation:
- 2 x 2 mm^2
- 43,7 µm

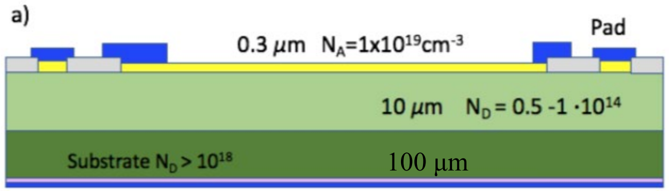
PRELIMINARY CONFIGURATION

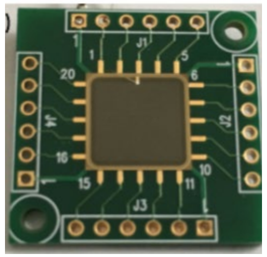
Proton beam

30-150 MeV

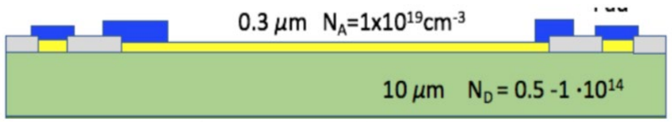


Entrance reconstruction



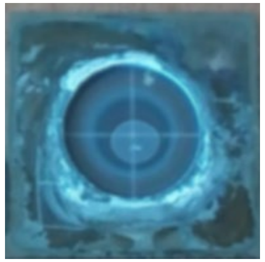


Bragg Peak reconstruction



Hydrofluoric Acid

IMM

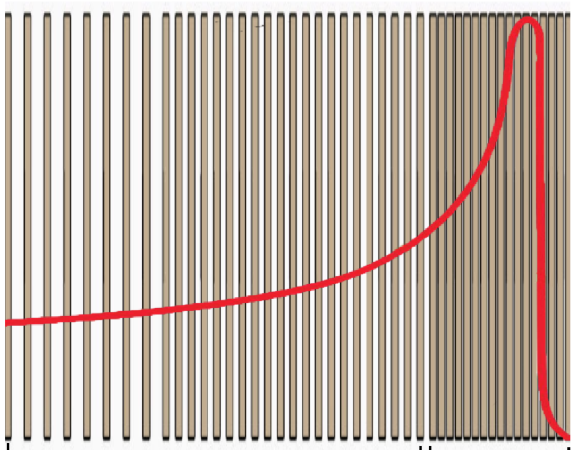


IMPULSE

INFN

eli beamlines

MARIE CURIE ACTIONS



30 standard SiC with 10um of active layer and 100um of passive substrate

30 new SiC w/o passive layer

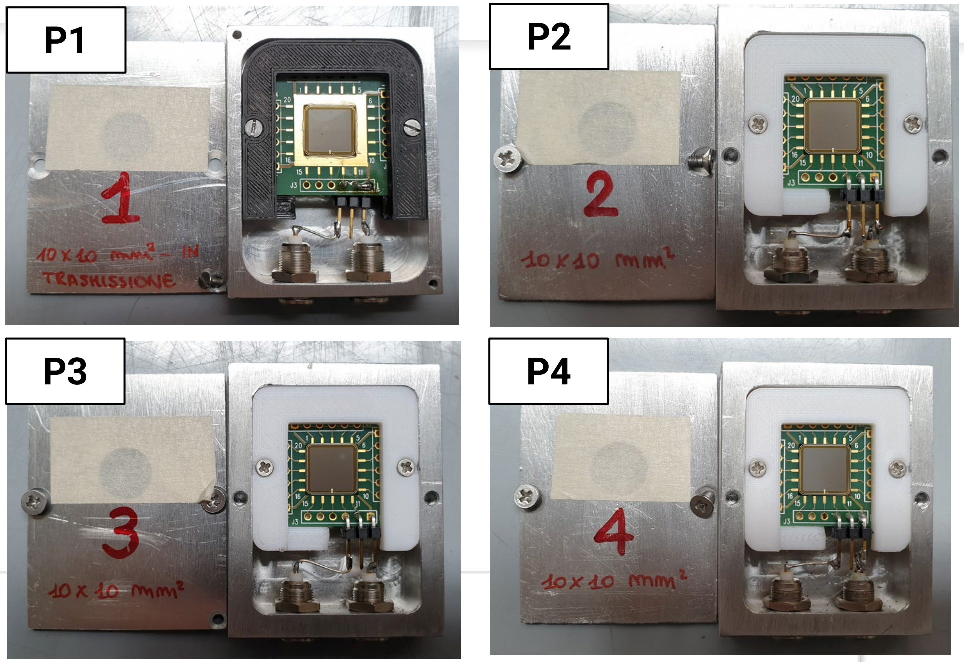
Financial support by both INFN and Horizon 2020 and is currently ongoing

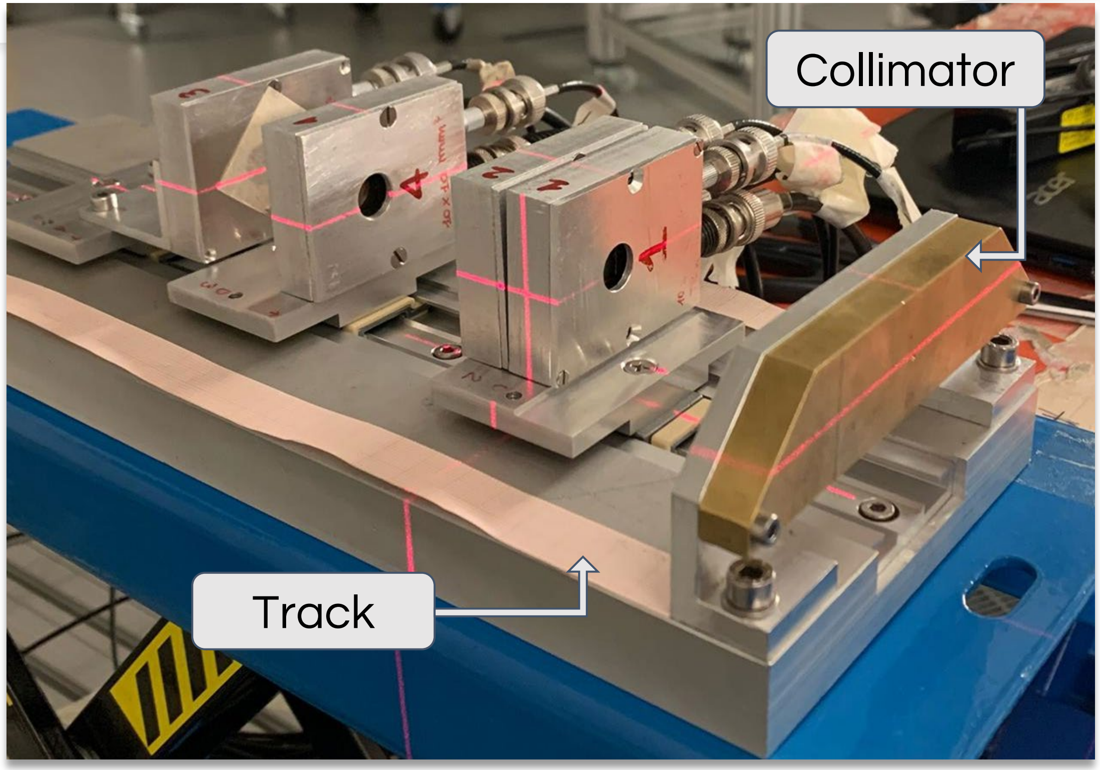
Detector prototype

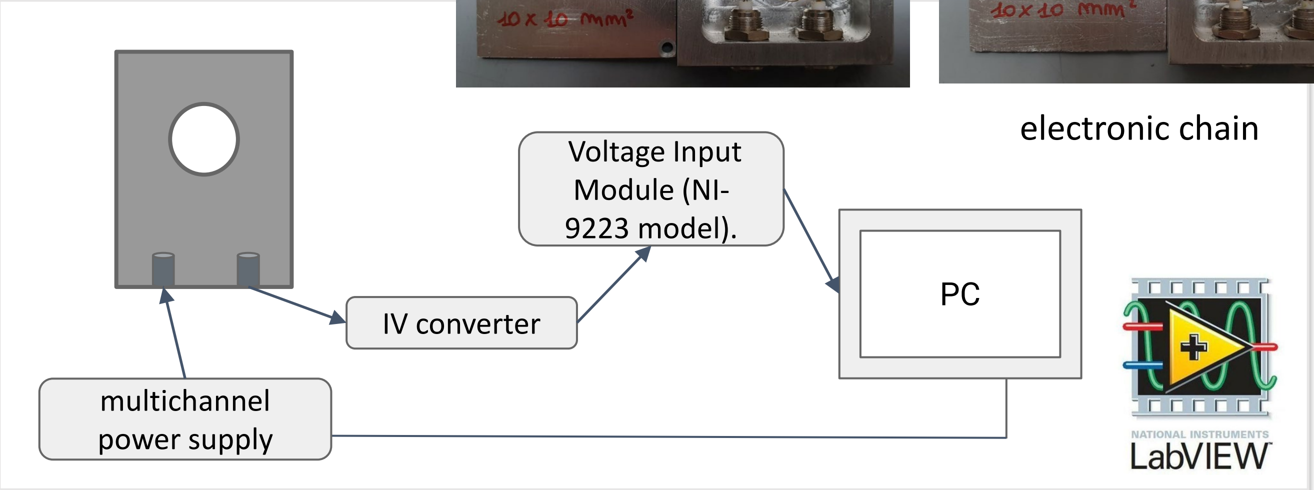
Mariacristina Guarrera, guarrera@lns.infn.it

PRAGUE
The realization of a prototype made of 4 SiC detectors

Perforated PCB





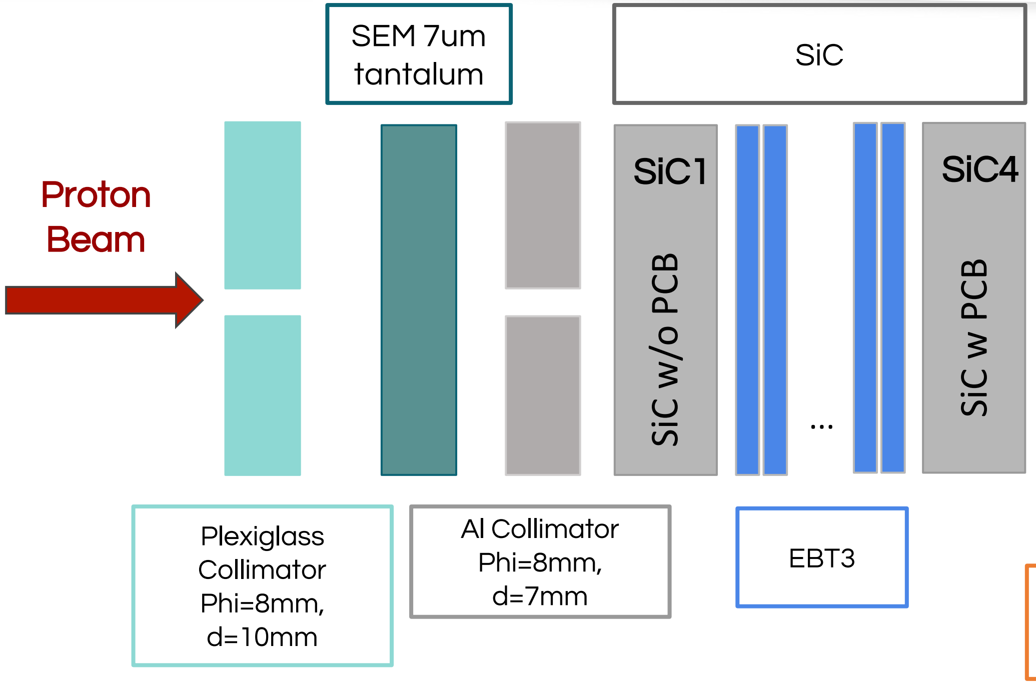


Aluminum boxes contain a 1 x 1 cm^2 detector

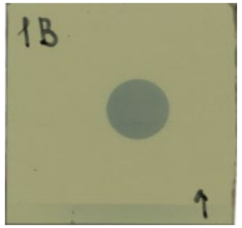
- active layer of **10,3 µm**
- passive layer of **125,67 µm**
- mounted on **PCB**.

PRAGUE prototype - Experimental campain @ Institute of Nuclear Physics Av Čr, Řež

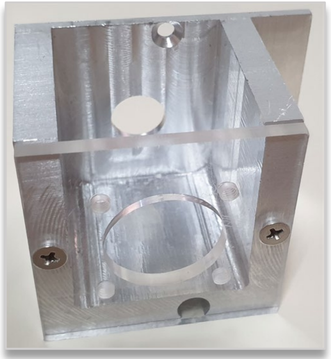
Configuration 1



- ❑ Proton **beam energy**: 35 MeV
- ❑ **Fluence**: 10^8 protons/cm2
- ❑ Irradiation **field**: circular shape; 10 mm in diameter
- ❑ **SEM**: Secondary Emission Monitor



Holder for EBT3 in stack configuration

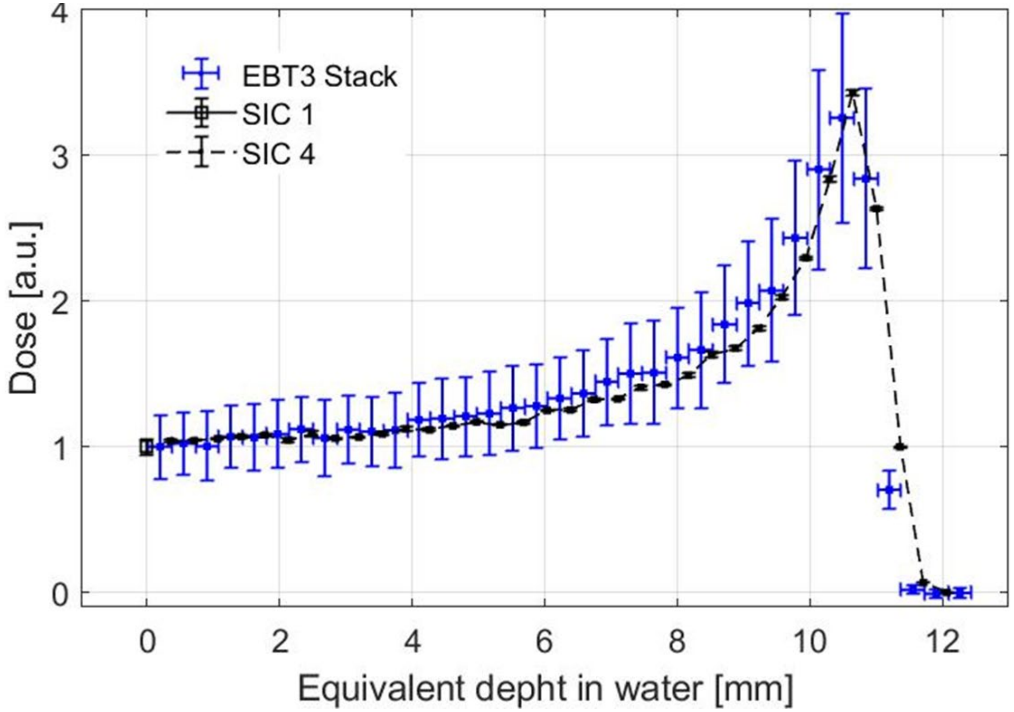


What has been done?

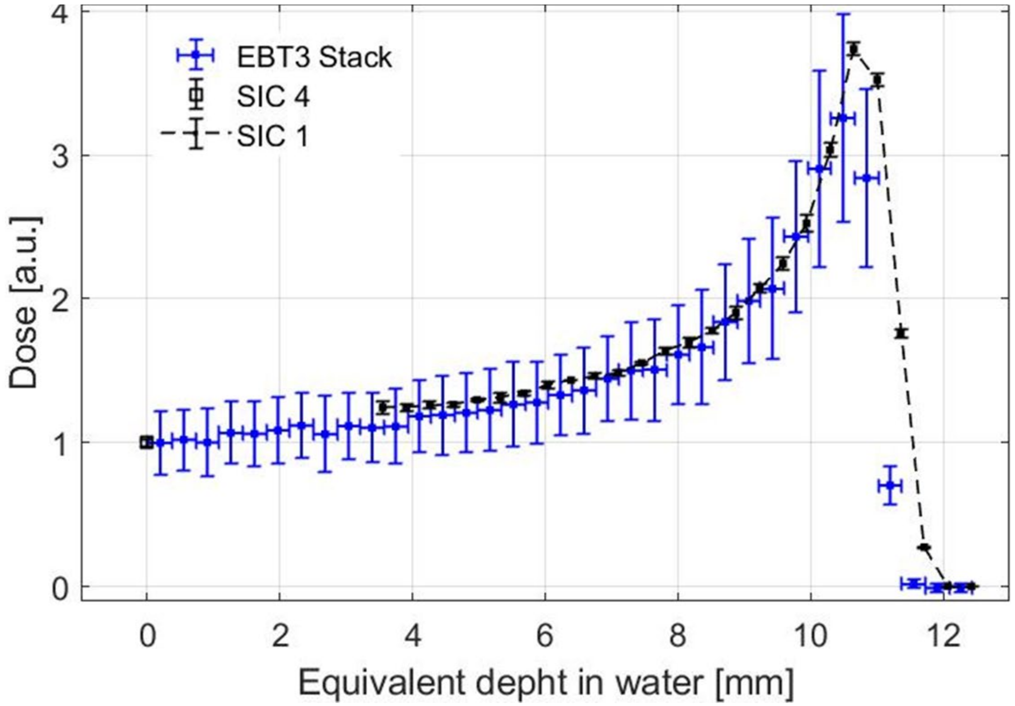
- ➢ Estimation of the WET of the detectors
- ➢ Acquisition of the PDD distribution using a stack of EBT3 gafchromic films
- ➢ Acquisition of the PDD distribution by varying the number of the EBT3 absorbers between the first and second detector

PRAGUE prototype - Experimental campain @Institute of Nuclear Physics Av Čr, Řež

Bragg Peak reconstruction using SIC4 detector (configuration 1)



Bragg Peak reconstruction using SIC1 detector (configuration 2)

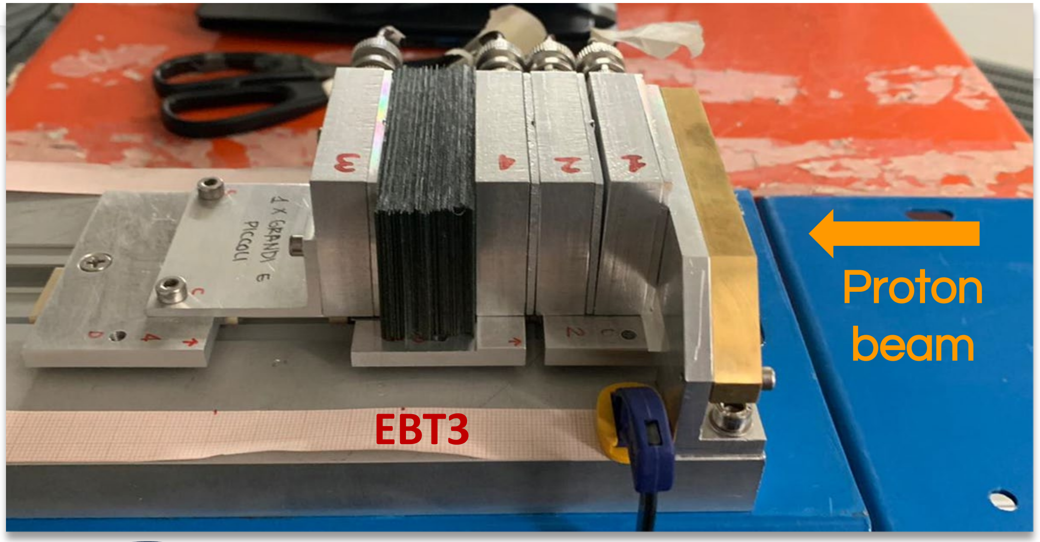


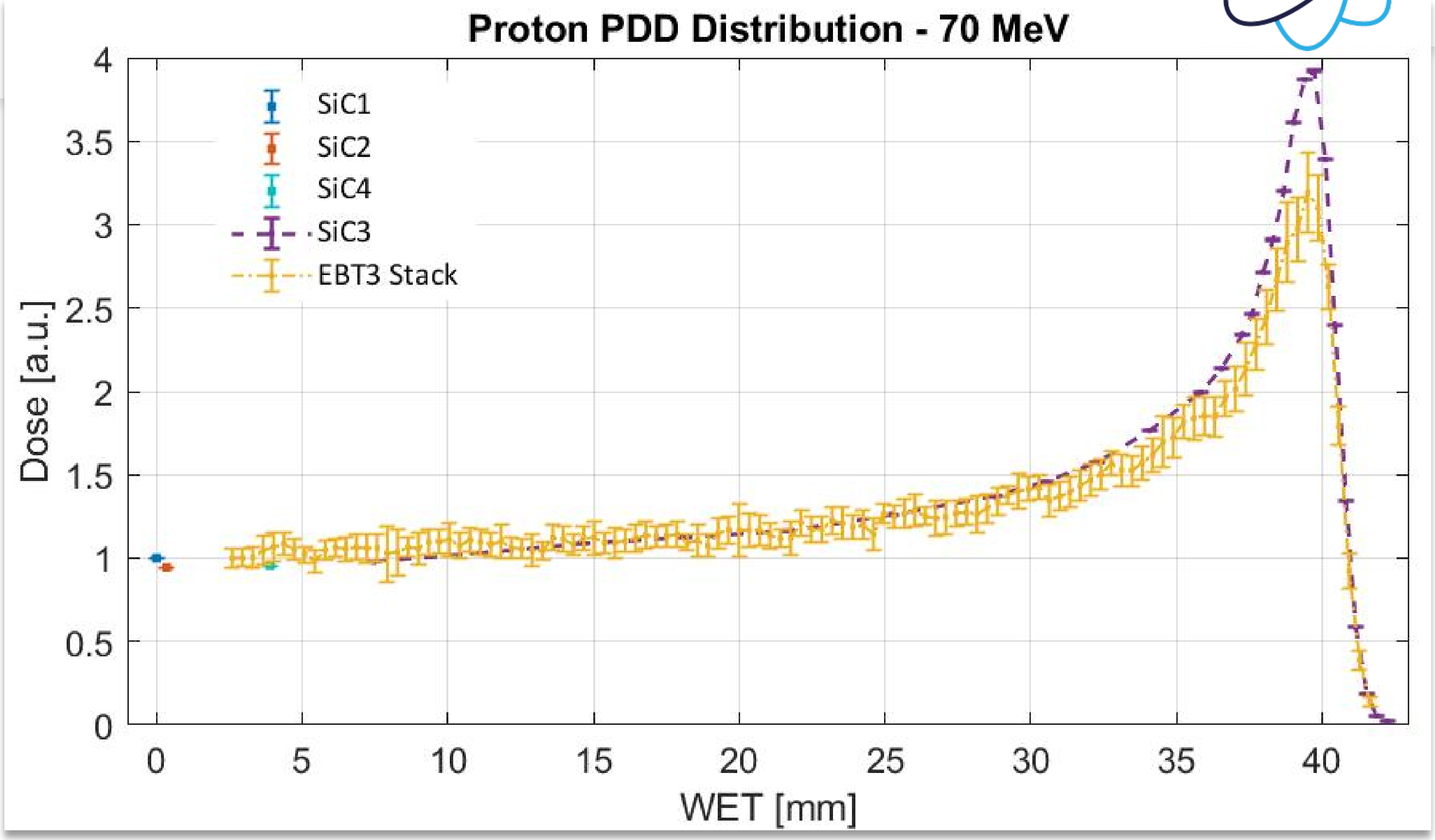
Good agreement within experimental errors!

EBT3 Peak - Plateaux ratio	SiC Peak - Plateaux ratio Conf.1	SiC Peak - Plateaux ratio Conf.2
3.25496	3.43025	3.73533

16th IPRD Conference, 25-29 September 2023
Mariacristina Guarrera, guarrera@lns.infn.it

PRAGUE prototype - Experimental campain @Trento Proton Therapy Centre





Istituto Nazionale di Fisica Nucleare

- Proton beam **energy**: 70 MeV
- **Intensity**: 10^8 protons/s
- Irradiation **field**: circular shape - 10 mm in diameter
- Clinical proton beam **dose-rate**
- **Ionization chamber** provided by the center: it returns the number N of protons incident on the collimator. It is used to monitor the beam current.

GAF PEAK [mm]	SIC PEAK [mm]	EBT3 Peak - Plateaux ratio [a.u.]	SiC Peak - Plateaux ratio [a.u.]
39.6±0.2	39.8±0.2	3.3	3.9

The results are consistent with the previous ones!

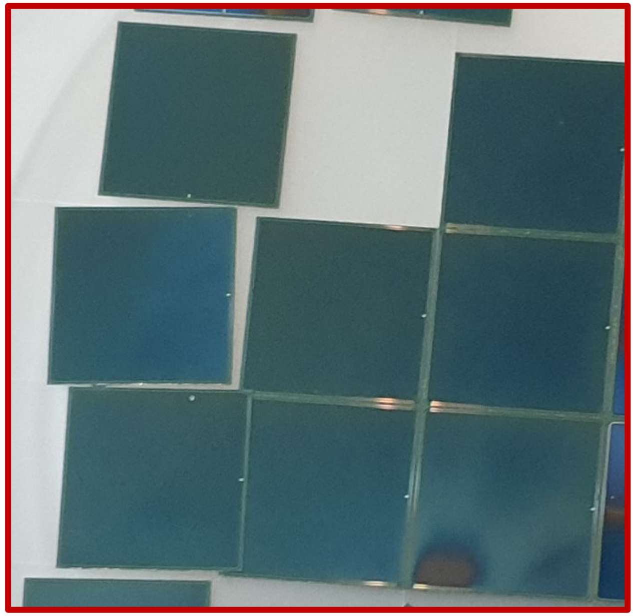
Azienda Provinciale per i Servizi Sanitari
Provincia Autonoma di Trento

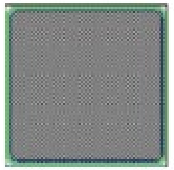
Final configuration

Mariacristina Guarrera, guarrera@lns.infn.it

Final detectors assembly

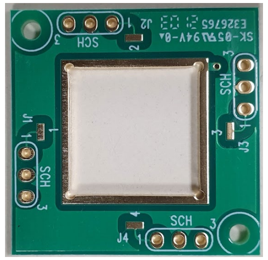
80 SiC devices:

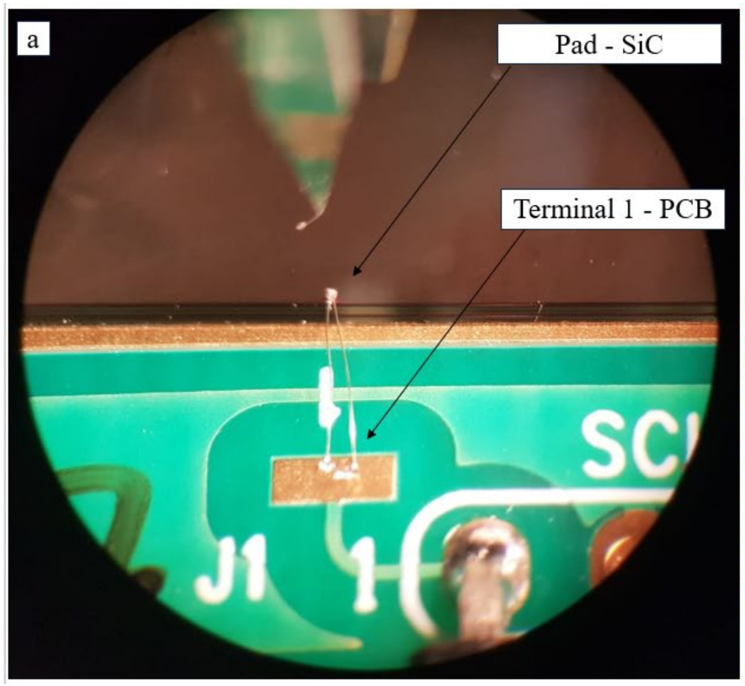


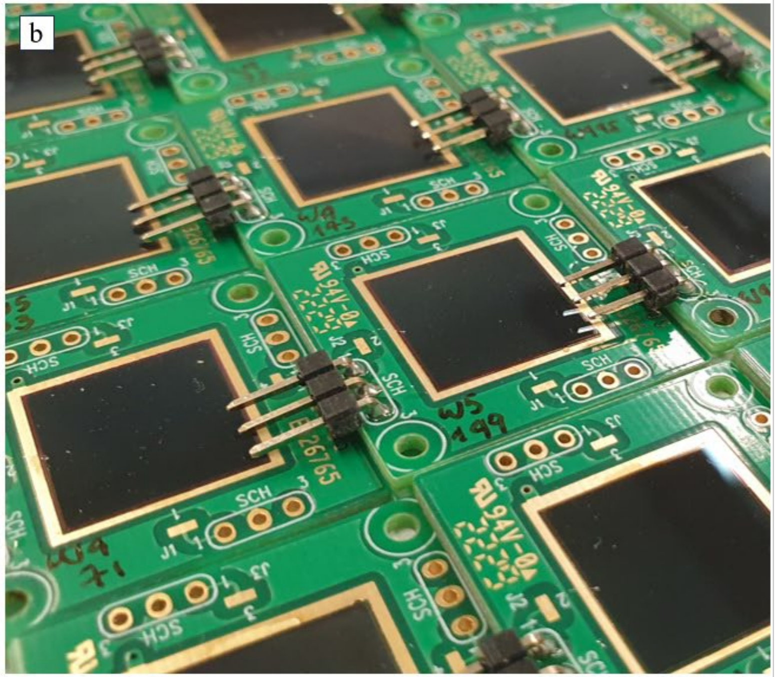


15.4 x 15.4 mm

+





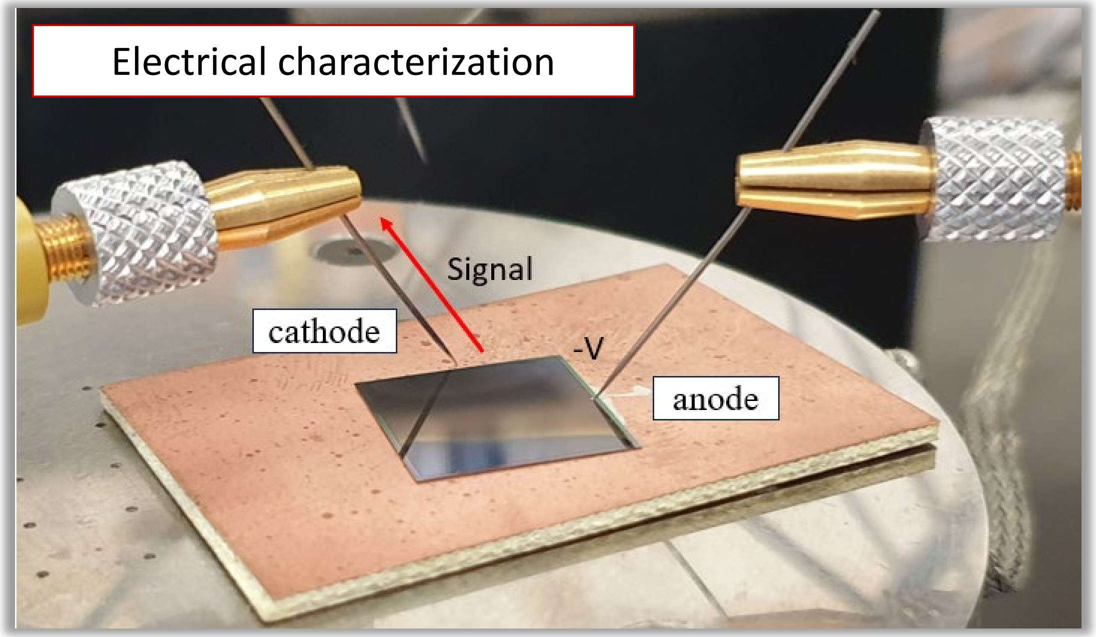


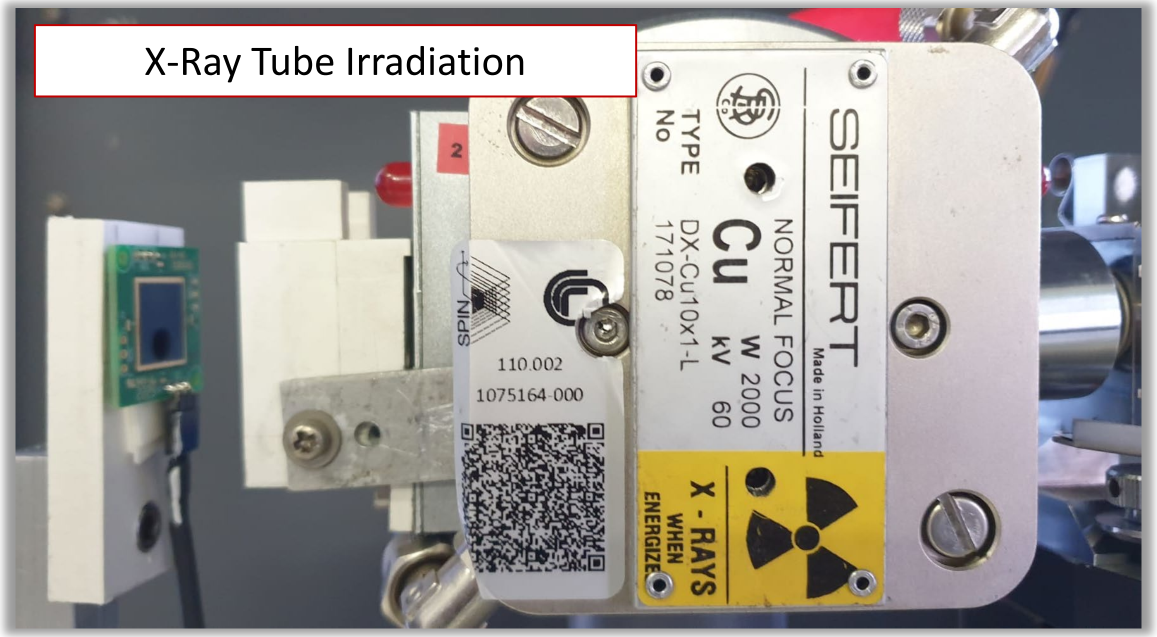
1. SiC were glued to the perforated PCB with silver conductive glue
2. A wire bonding (1-2 mils) was performed between the pad and the PCB at terminal 1
3. Electrical pins have also been welded to the PCB board

- $p^+ \rightarrow$ 0,3 µm - $N_A=1\cdot10^{19}cm^{-3}$
- n $\rightarrow$ 10 µm - $N_D = 8 \cdot 10^{13}$ cm^{-3}
- Substrate $\rightarrow$ N_D = 0.5 - 1 $\cdot$ 10^{14} cm^{-3}

Mariacristina Guarrera, guarrera@lns.infn.it

Final detectors characterization

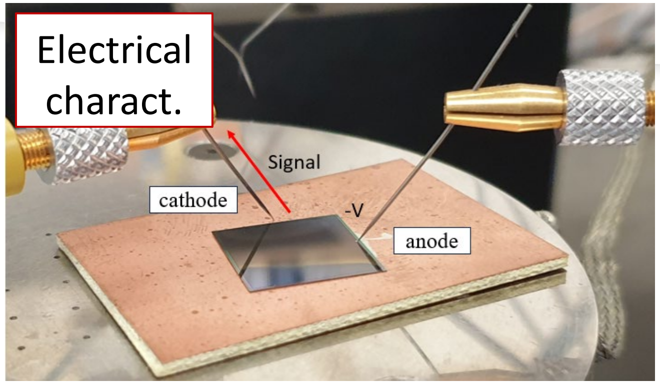




Tests:
- **IV profile** → we selected 50 “good” SiC
- **CV profile**

Tests:
- **Stability**
- **CCE**
- **Linearity**

Final detectors: CV profile



- **Saturation capacitance** → minimum C;
- **Depletion voltage** → intersection method;
- **Depletion region thickness**:

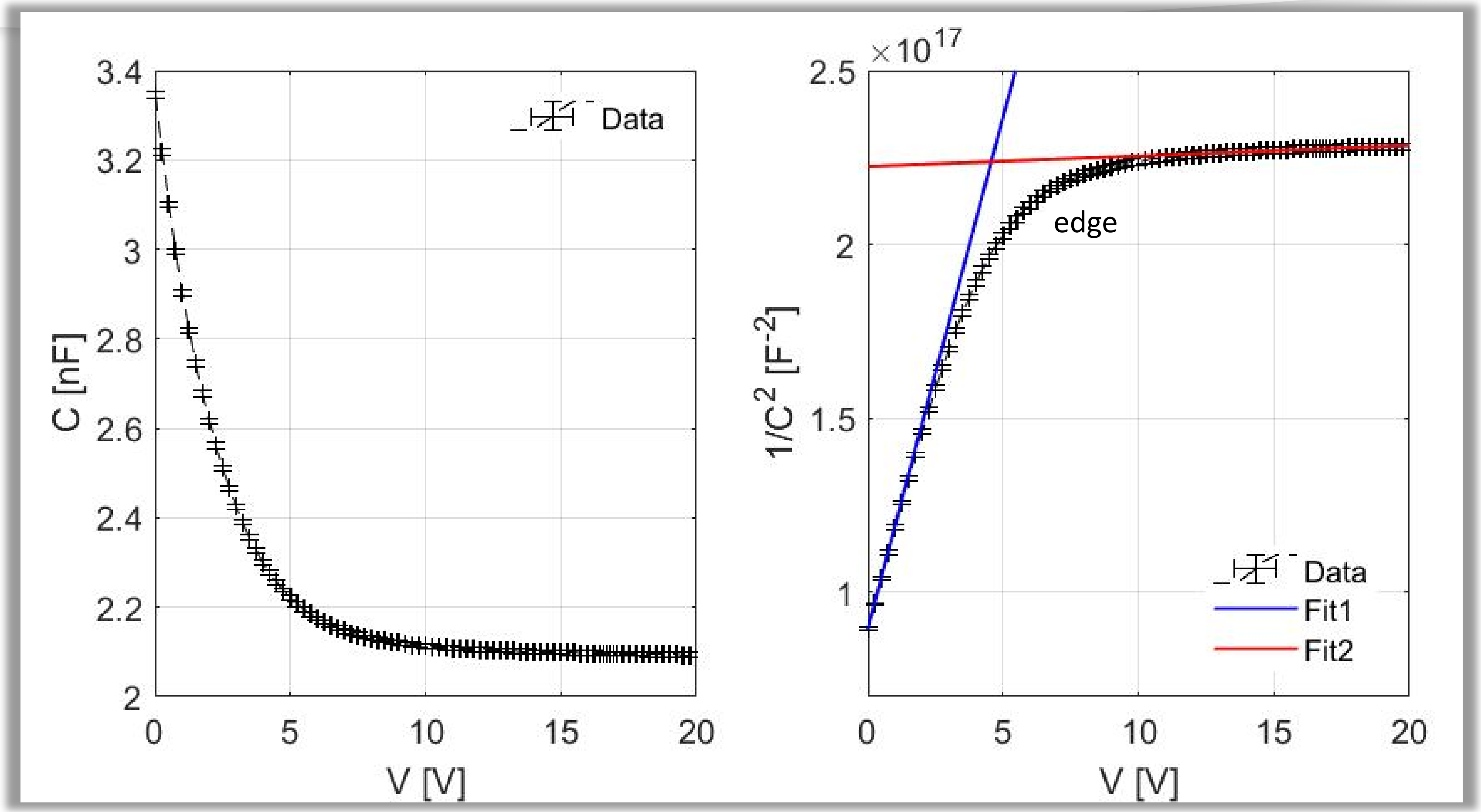
$$W = \frac{A \cdot \varepsilon_s}{C_s}$$

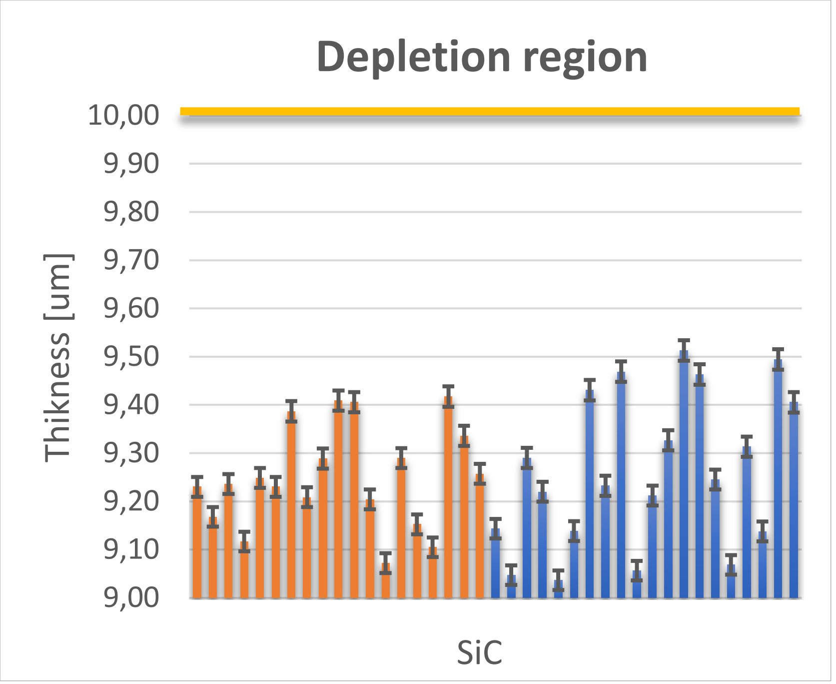
- **Built-in potential** - Fit1 parameters:

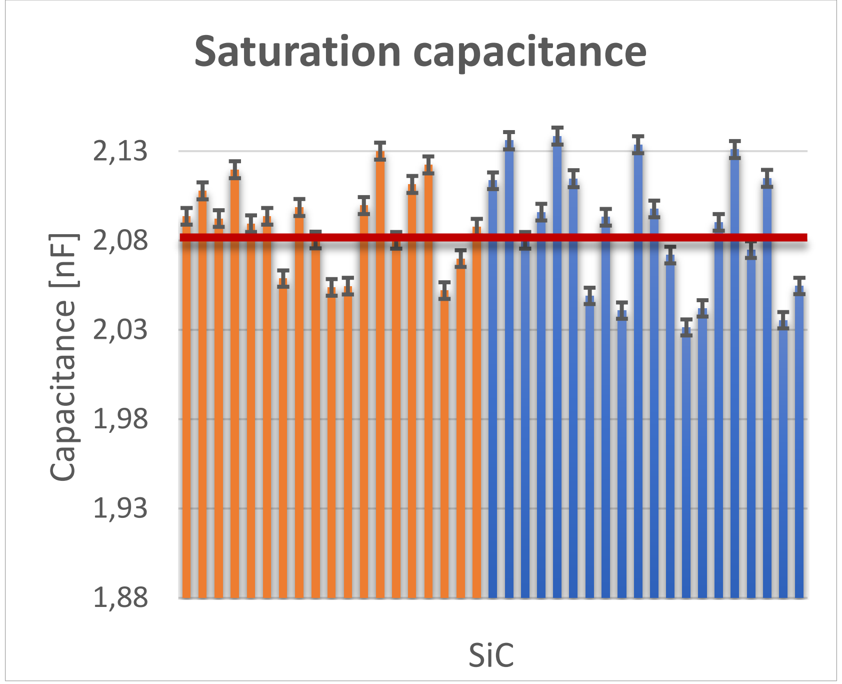
$$V_{bi} = \frac{q_1}{m_1}$$

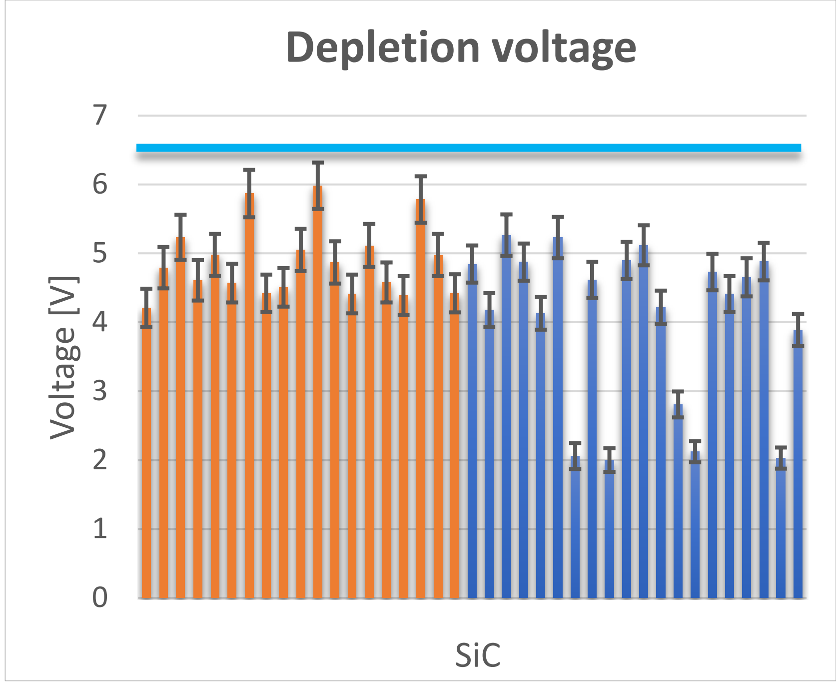
- **Donor concentration** - Fit1 parameters:

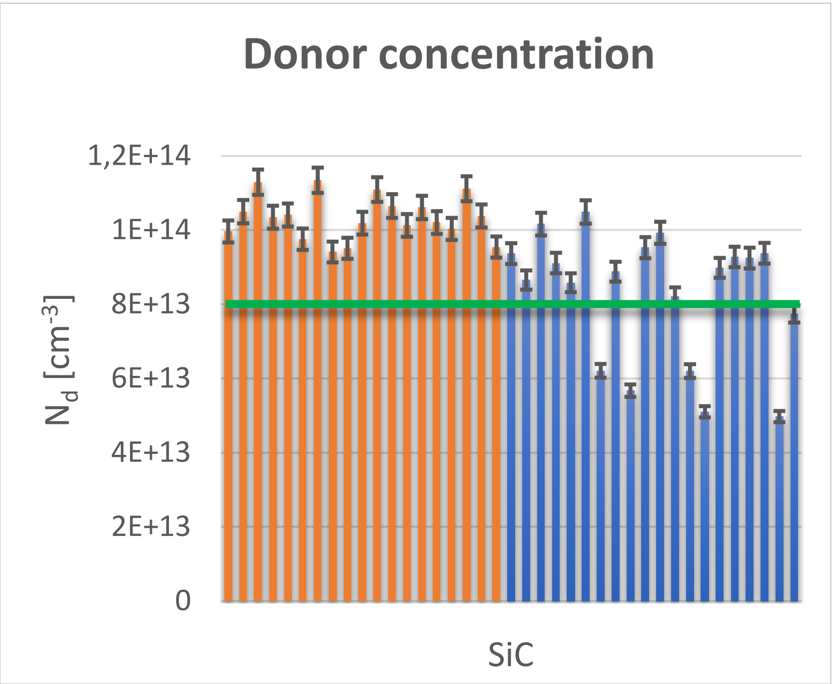
$$N_D = \frac{2}{e \cdot \varepsilon_s \cdot m_1}$$

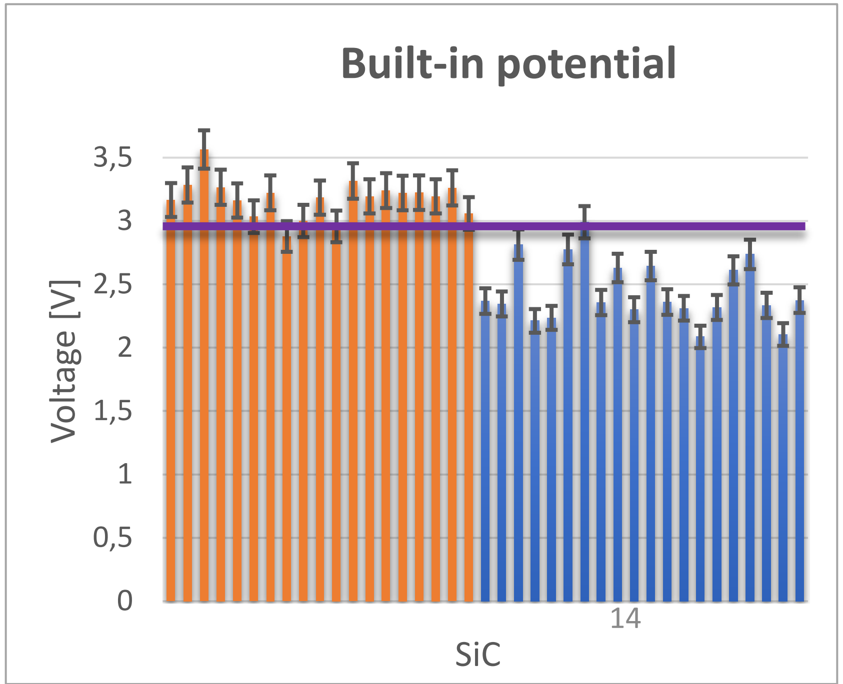












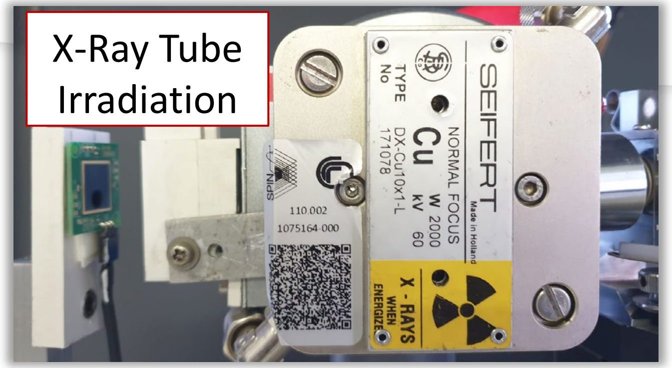
- Nominal W
- $C_s = \frac{A \cdot \varepsilon_s}{W_{exp}} = 2{,}08\text{nF}$
- $V_v = N_D \frac{e \cdot W^2}{\varepsilon_s} = 6{,}5\ V$
- Nominal N_d
- $V_{bi} = 2{,}58 \cdot 10^{-2} \log\left(\frac{N_A N_D}{n_i^2}\right)\ V = 2{,}95\ V$

W4
W5

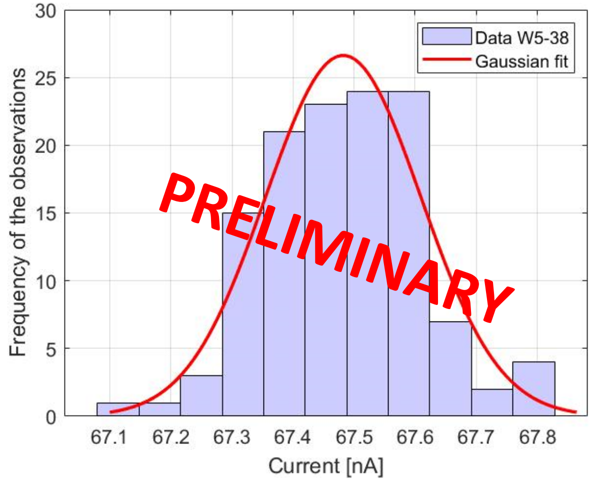
The assumptions used in the derivation of the capacitance include:

- **uniform doping**;
- abrupt junction approximation;
- planar junction.

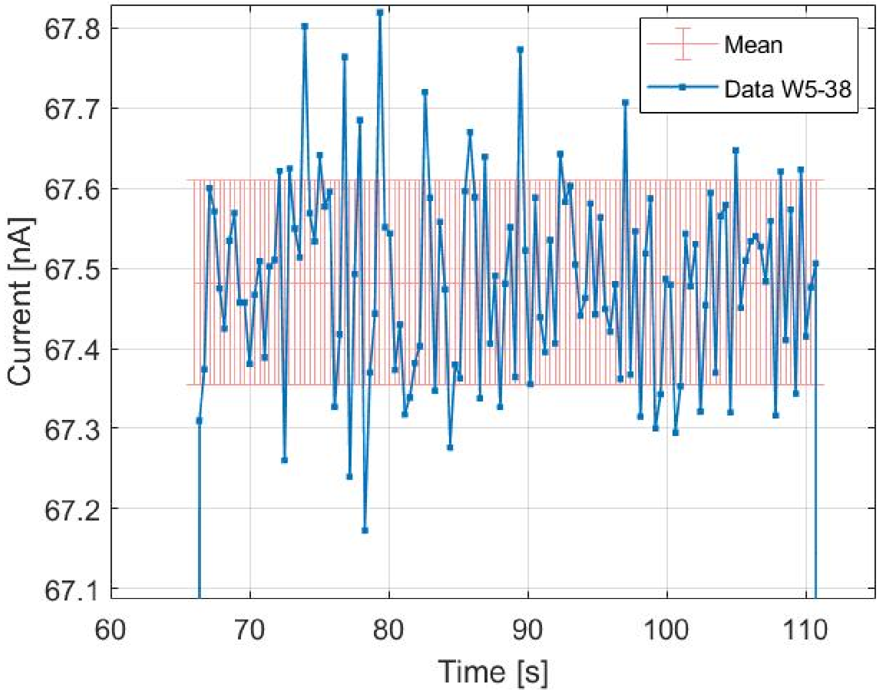
Final detectors: Stability & CCE



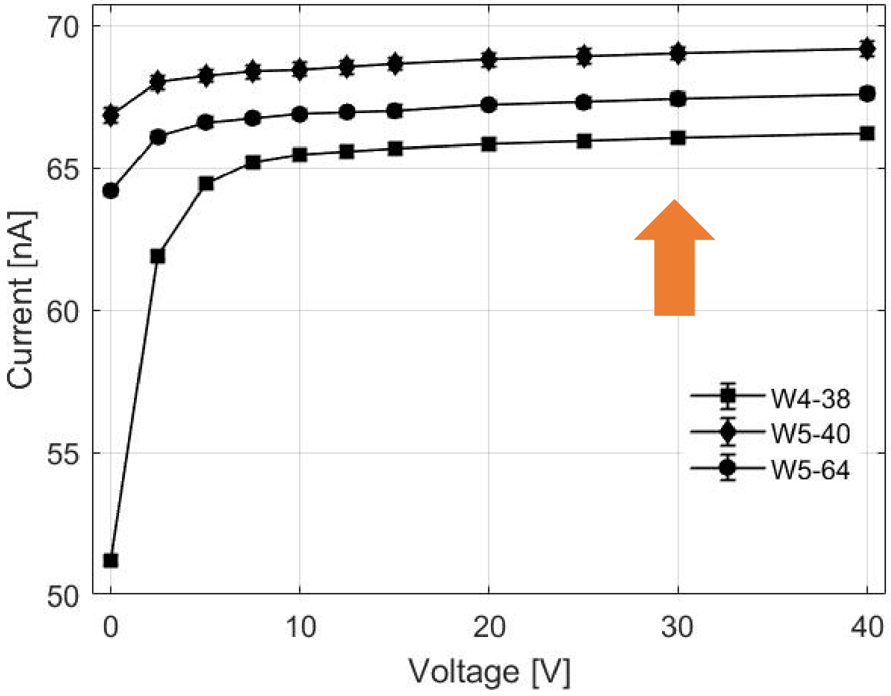
Voltage Tube: 10 kV
Current Tube: 5 mA



χ^2 test
Random fluctuations!

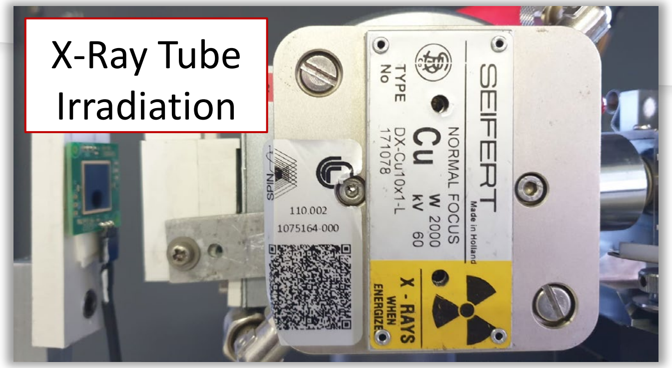


63.8% of fluctuations within 0.5% of the mean value.

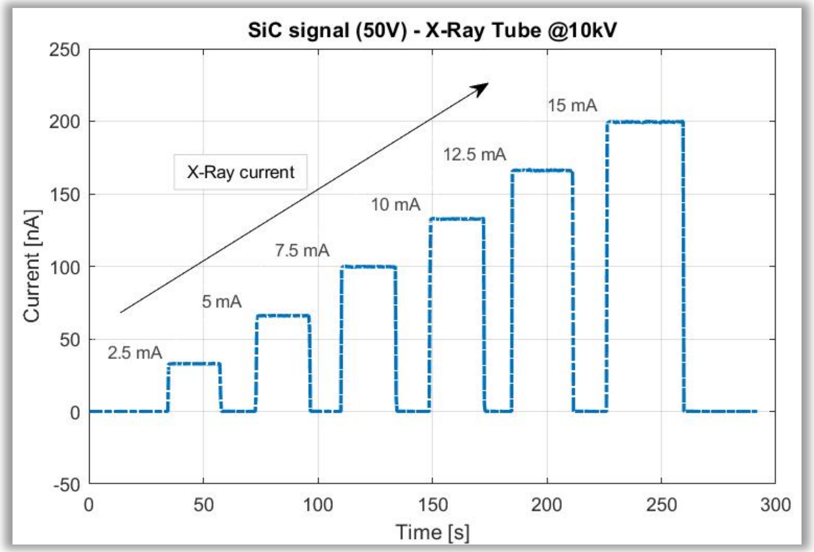


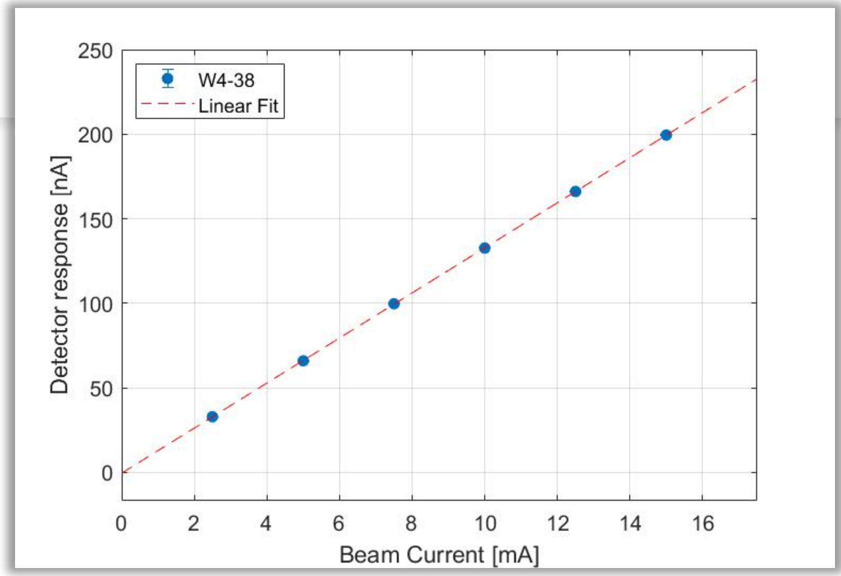
Saturation region @30 V.

Final detectors: linearity

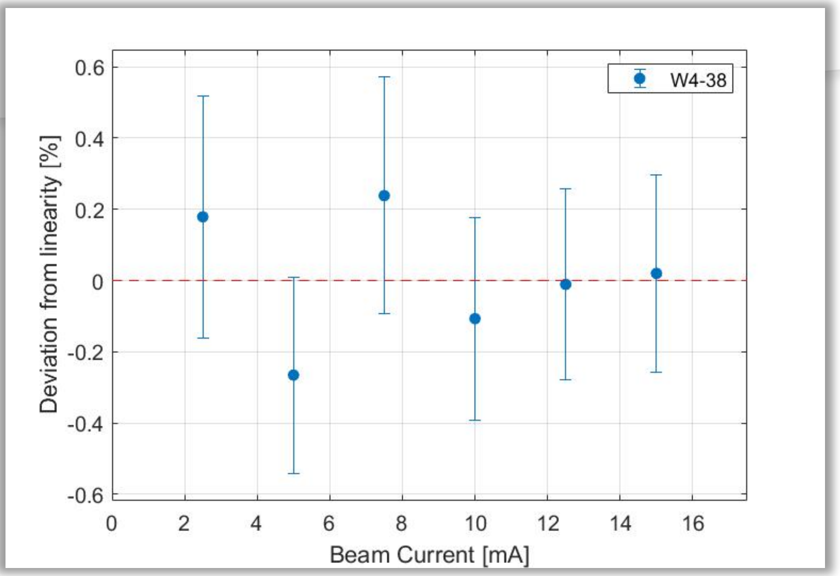


Voltage Tube: 10 kV
Current Tube: 2.5 - 15 mA

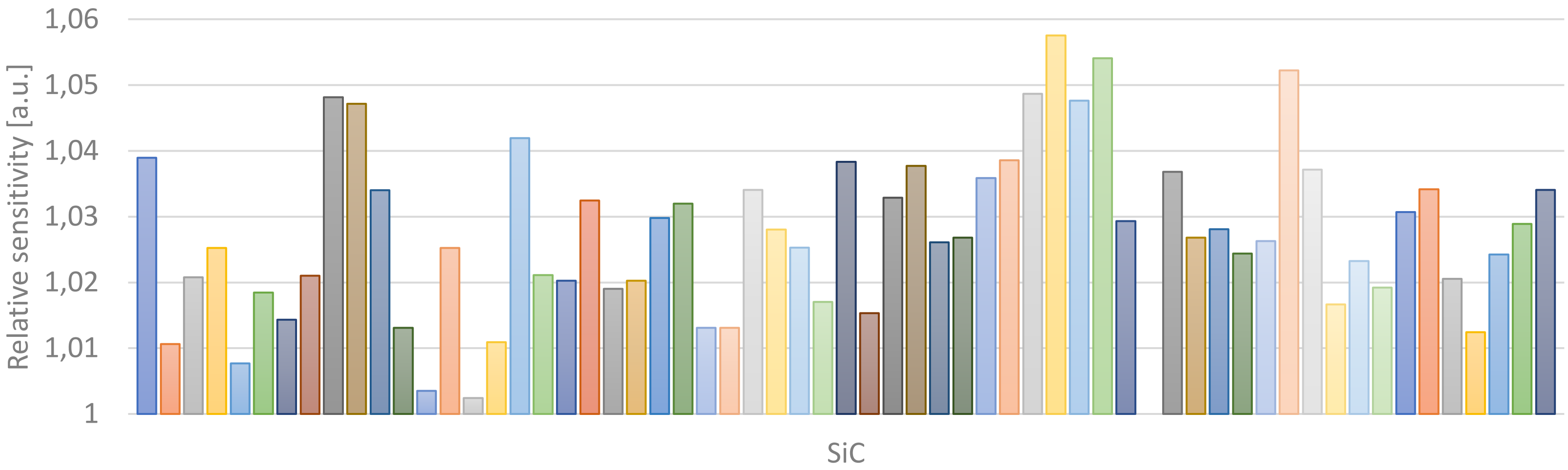




The slopes represent the sensitivity of the detectors.

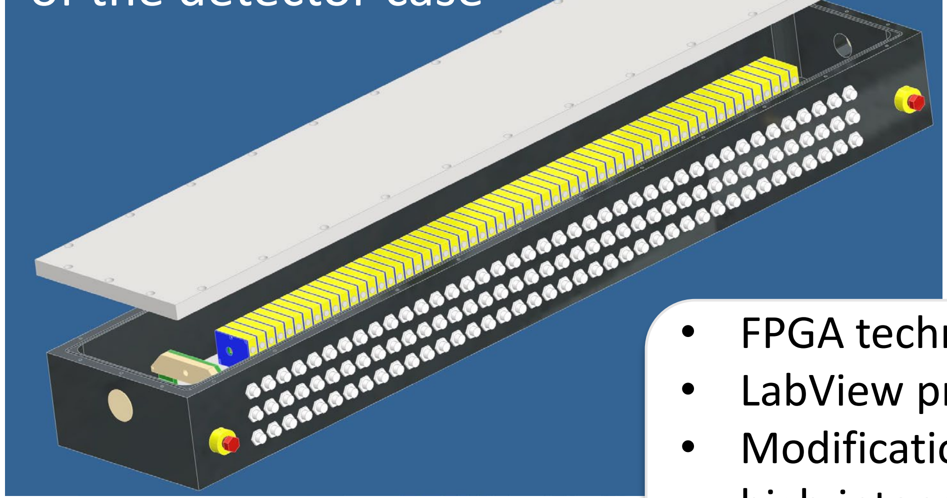


Maximum deviation: 1,5%. in 90% of cases < 1%



Electronic chain & detector case

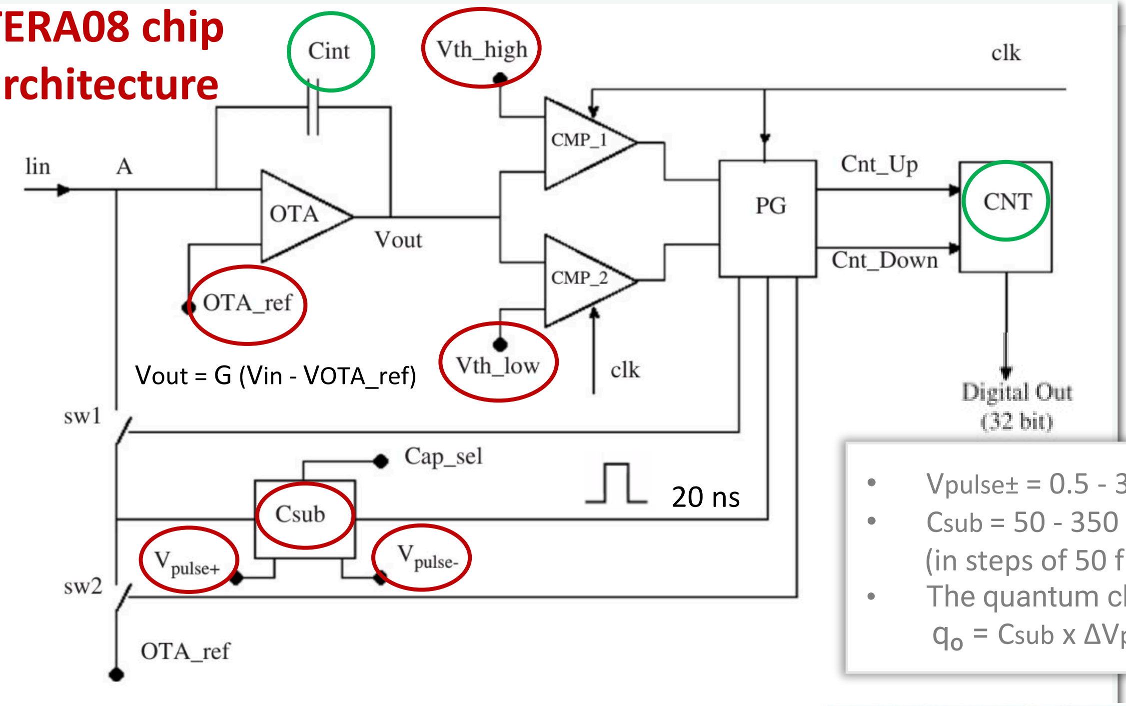
Preliminary technical draw of the detector case



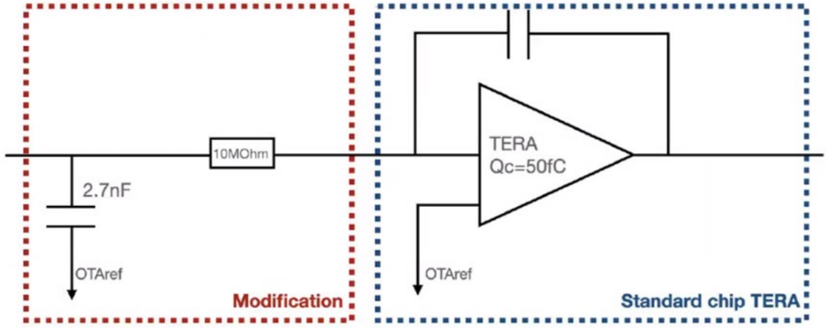
PRAGUE will provide positive signals

- FPGA technology
- LabView program
- Modification for high intensity beams (INFN-LNS)

TERA08 chip architecture



- $V_{pulse\pm}$ = 0.5 - 3.3 V
- Csub = 50 - 350 fF (in steps of 50 fF)
- The quantum charge q_o = Csub x ΔVpulse



- ❑ **Charge-to-count/current-to-frequency converter** (based on the recycling integration principle)
- ❑ **64 independent channels**
- ❑ Maximum conversion frequency ν_{max} **= 20 MHz**
- ❑ Quantum charge set q_o**= 25 fC - 1.155 pC**
- ❑ Maximum input current $I_{max} = q_o \times \nu_{max} = \pm 22\ \mu A$

Conclusion

Electrical characterization

- IV [0-200V/0-4V] → **50 "good" SiC devices 20-50 pA @10-50V revers bias**
- CV [0-20V] → **Mean W: 9,25 um; Saturation capacitance: 2nF; Depletion voltage: 4V; Built-in potential: 2-3 V**

X-Ray Tube Irradiation

- Stability → **Maximum oscillation found: 0.4%**
- Linearity → **Maximum deviation from linearity: 1,5%**
- CCE → → **≅ 100% @ 30V**

Next steps

- **Detectors**
  - Spectroscopic measurements - **in progress**
  - Proton beam irradiation – **scheduled**
- **Electrical readout**
  - realization of the new interface board - **in progress**
  - software acquisition - **in progress**
  - New board characterization– **scheduled**
- **Case detector**
  - design of the detector case - **in progress**
  - realization of the detector case - **scheduled**

Thanks for the attention

This work was supported by the National Institute for Nuclear Physics (INFN) that funded the PRAGUE (Proton Range Measure using Silicon Carbide) project. It was also supported by European Structural and Investment Fund and the Czech Ministry of Education, Youth and Sports (Project International mobility MSCA-IF IV FZU-CZ.02.2.69/0.0/0.0/20-079/0017754).

eli | beamlines

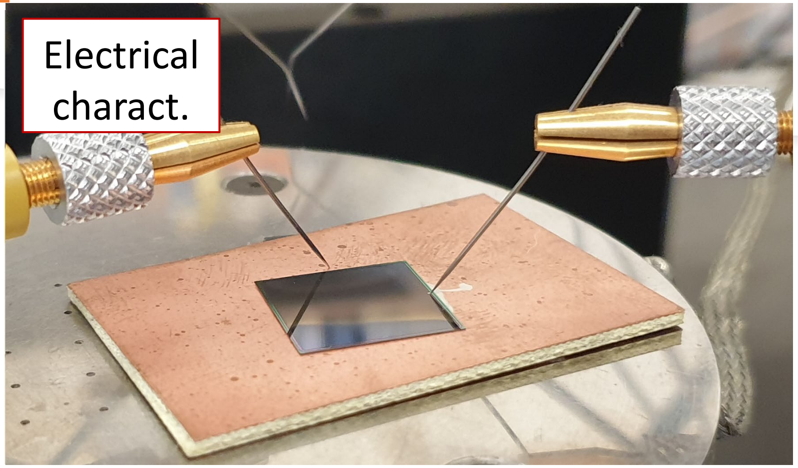
IMPULSE

IMPULSE has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161.

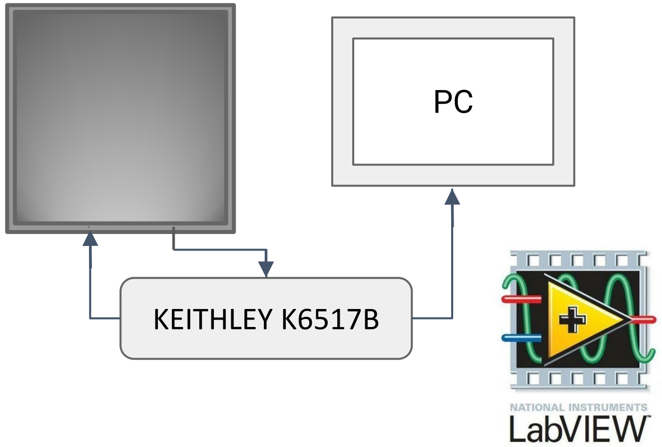
INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

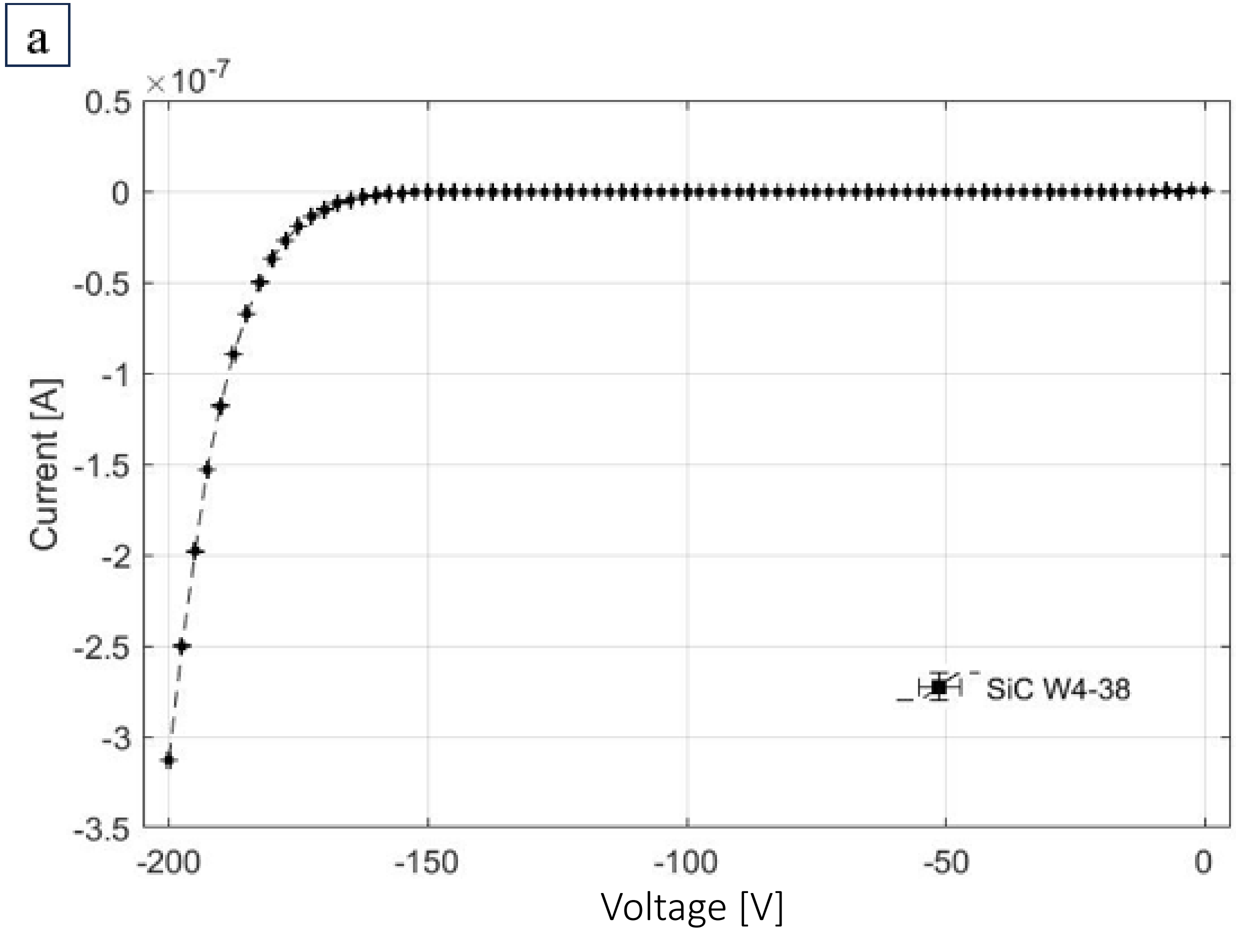
Backup slides

PRAGUE – final detectors



Tests:
- IV

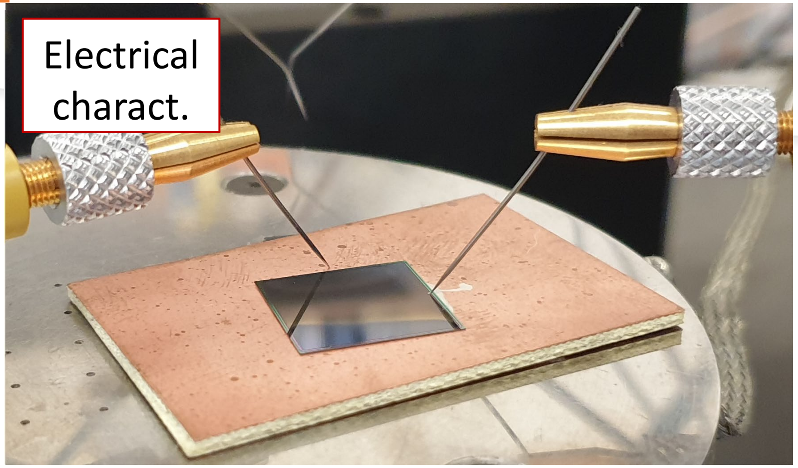




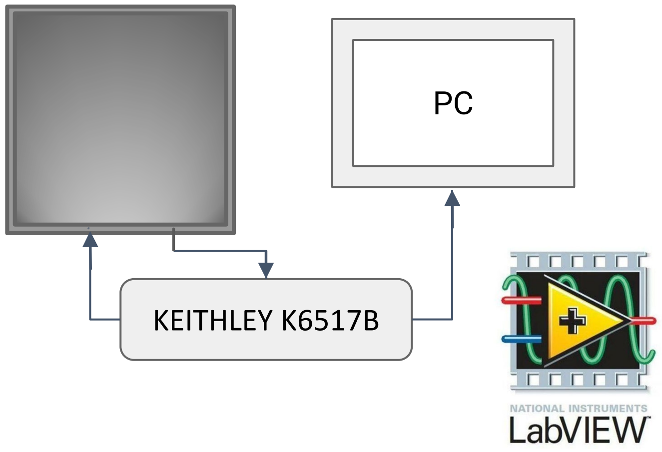
PRAGUE – final detectors

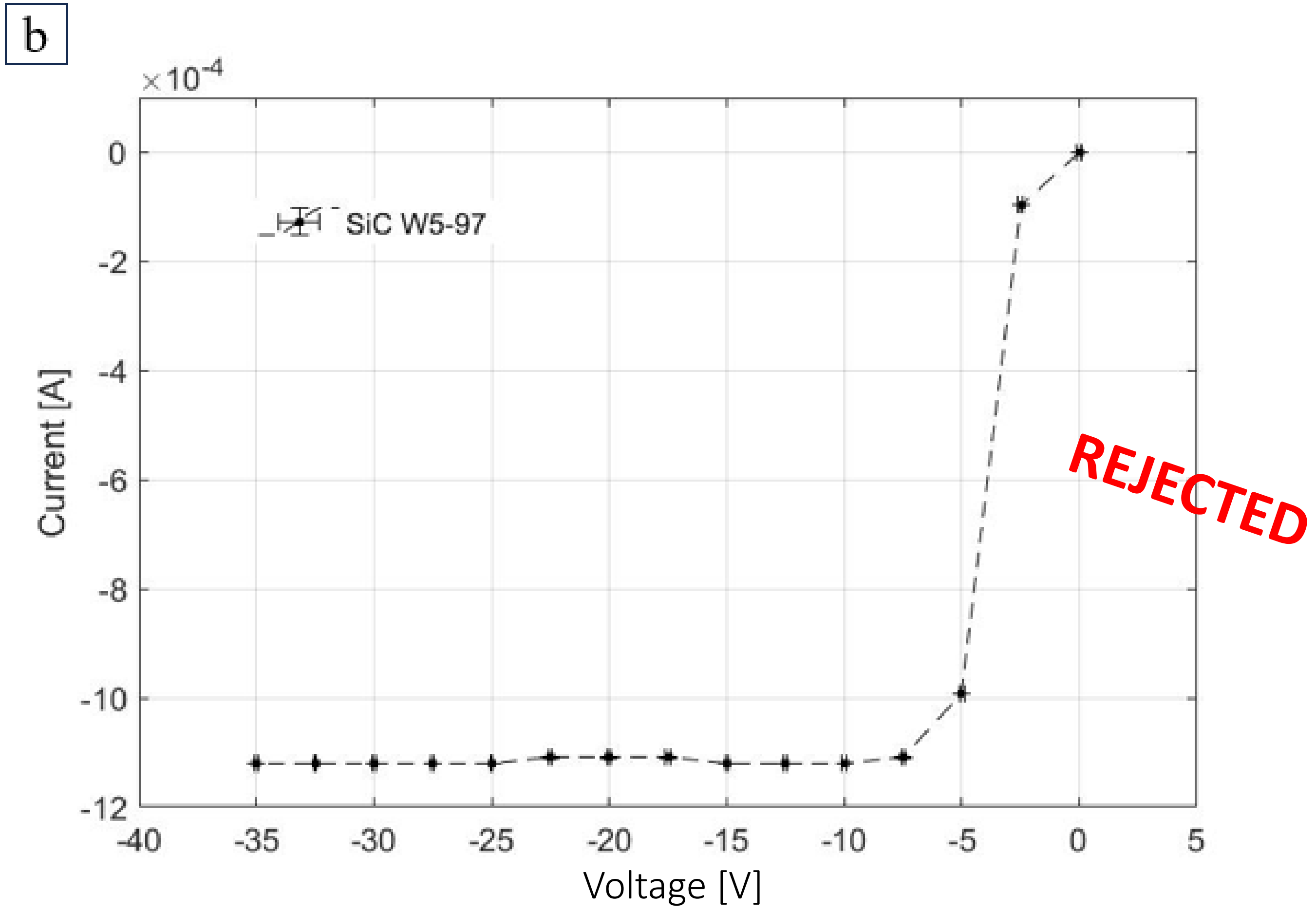
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Electrical charact.

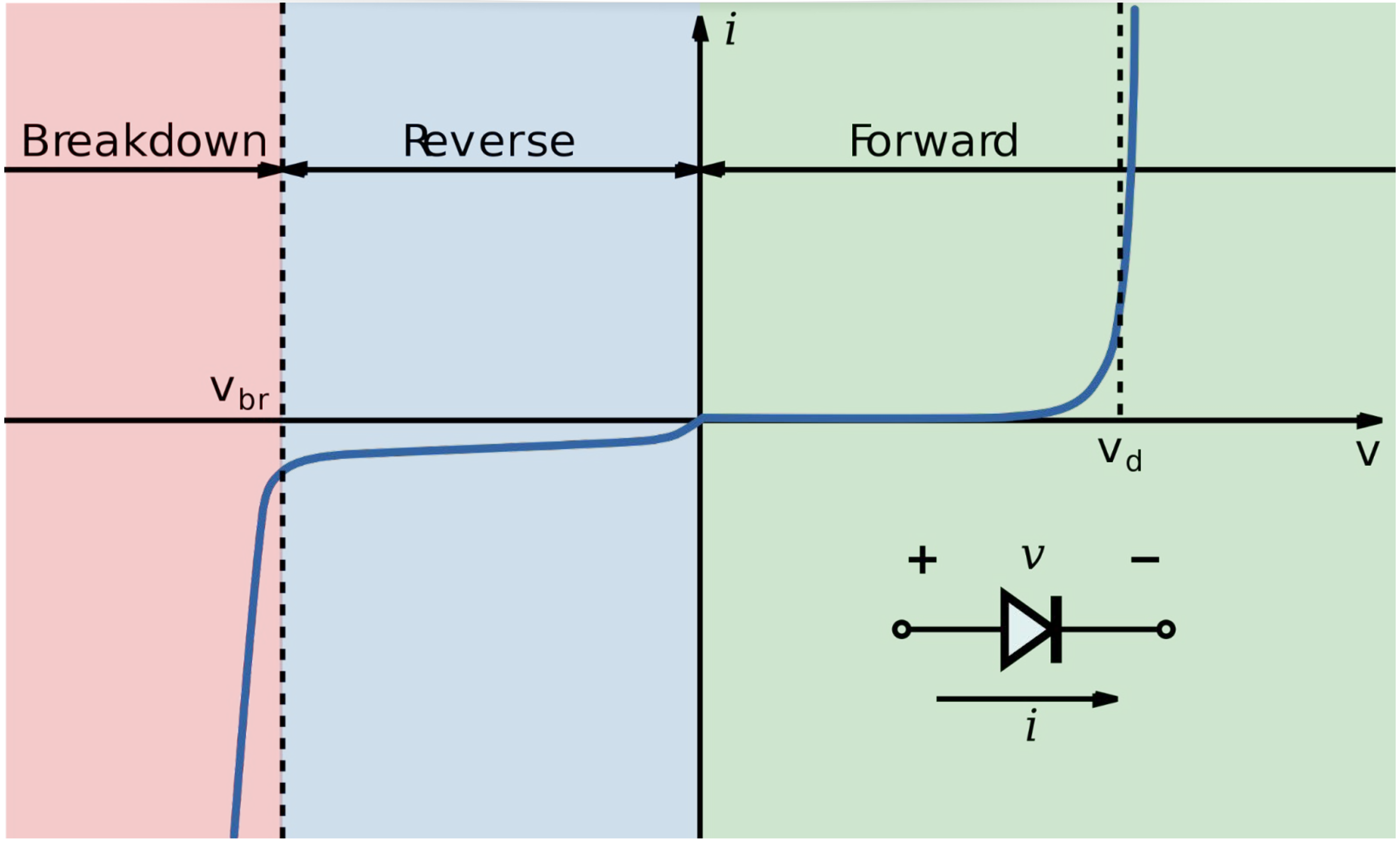


Tests:
- IV → we selected 50 "good" SiC

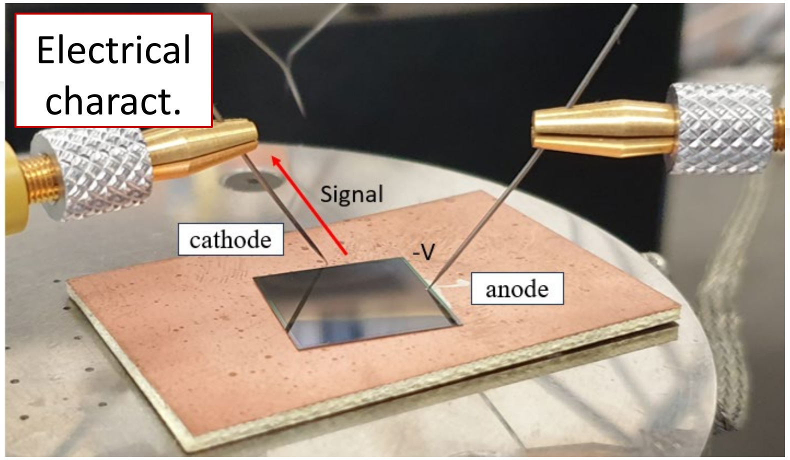


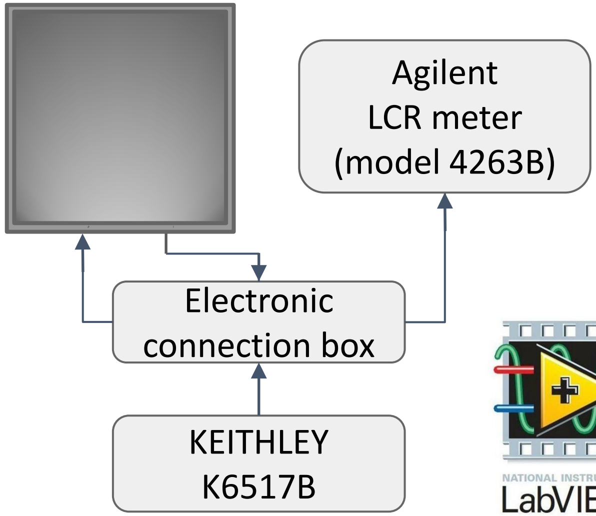


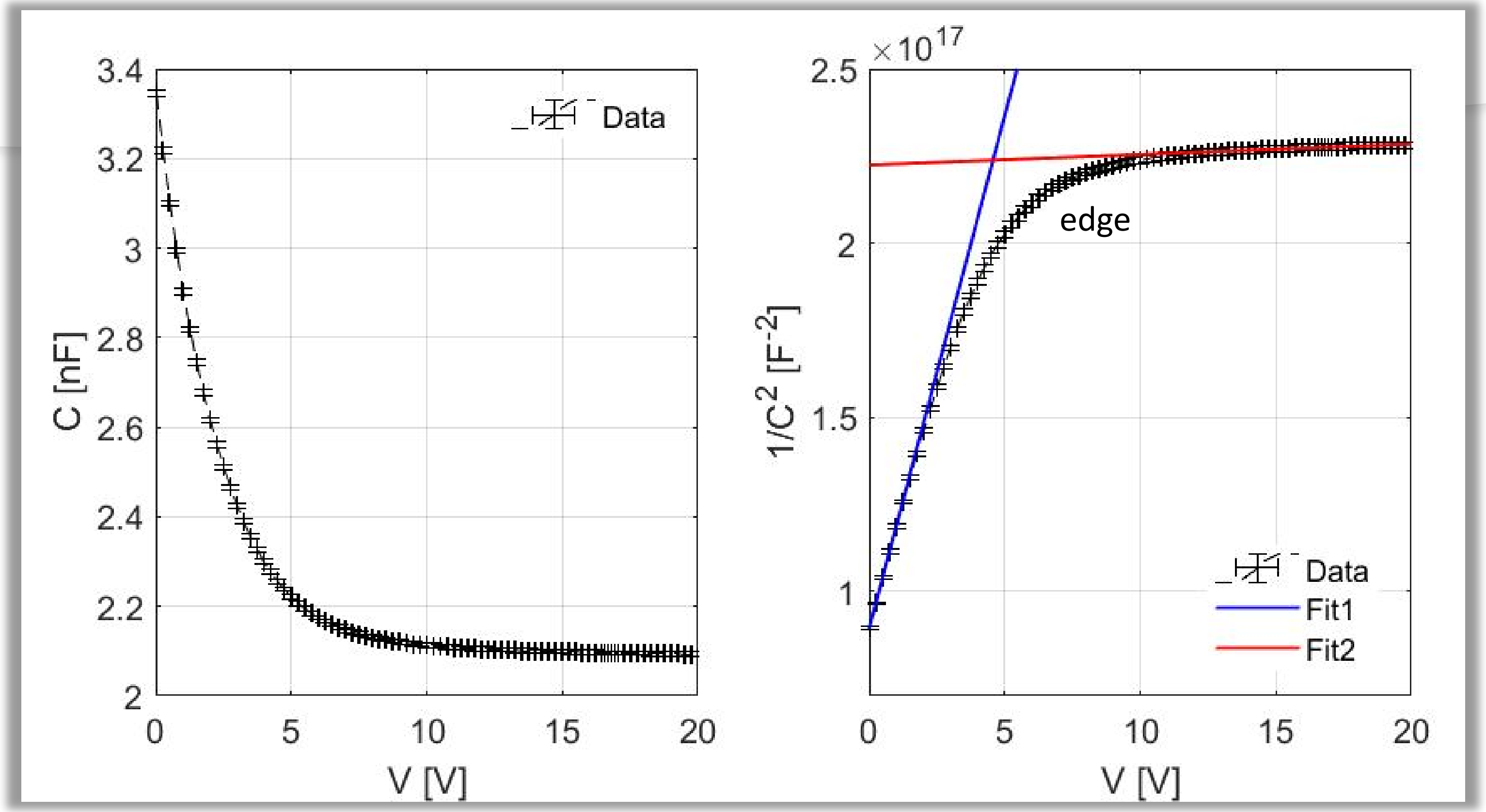
IV profile



Final detectors: CV profile







- **Saturation capacitance** → minimum C;
- **Depletion voltage** → intersection method;
- **Depletion region thickness**:

$$W = \frac{A \cdot \varepsilon_s}{C_s}$$

- **Built-in potential** - Fit1 parameters:

$$V_{bi} = \frac{q_1}{m_1}$$

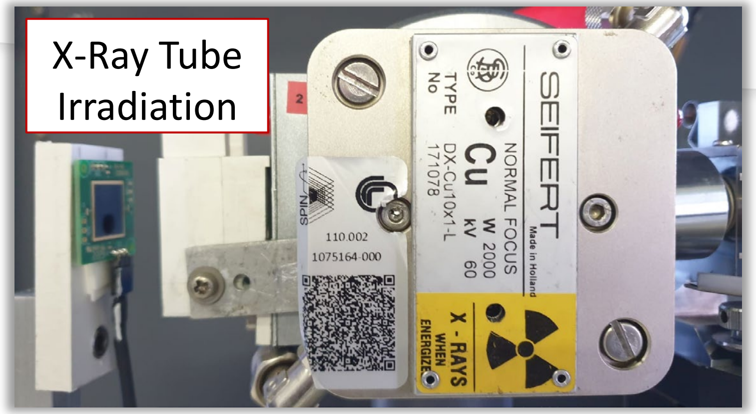
- **Donor concentration** - Fit1 parameters:

$$N_D = \frac{2}{e \cdot \varepsilon_s \cdot m_1}$$

Mariacristina Guarrera, guarrera@lns.infn.it

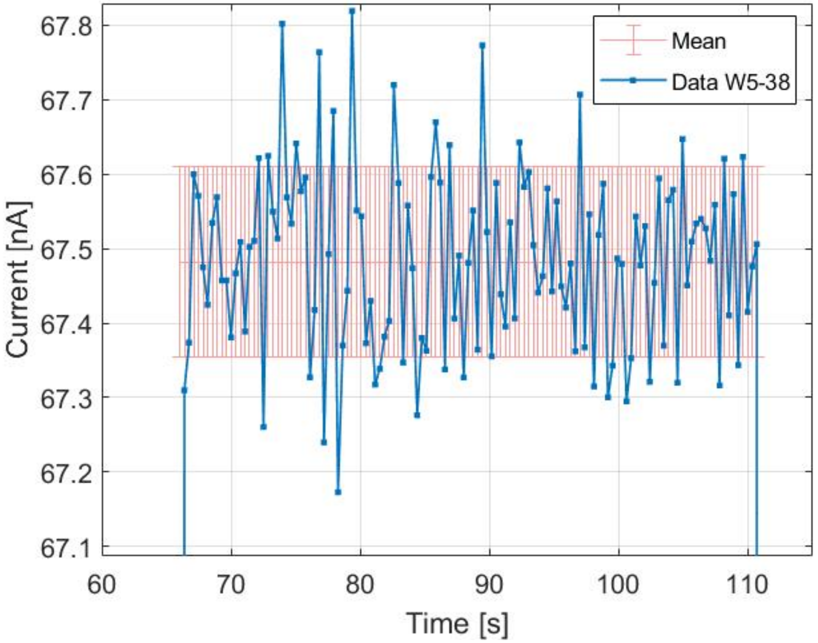
PRAGUE – final detectors

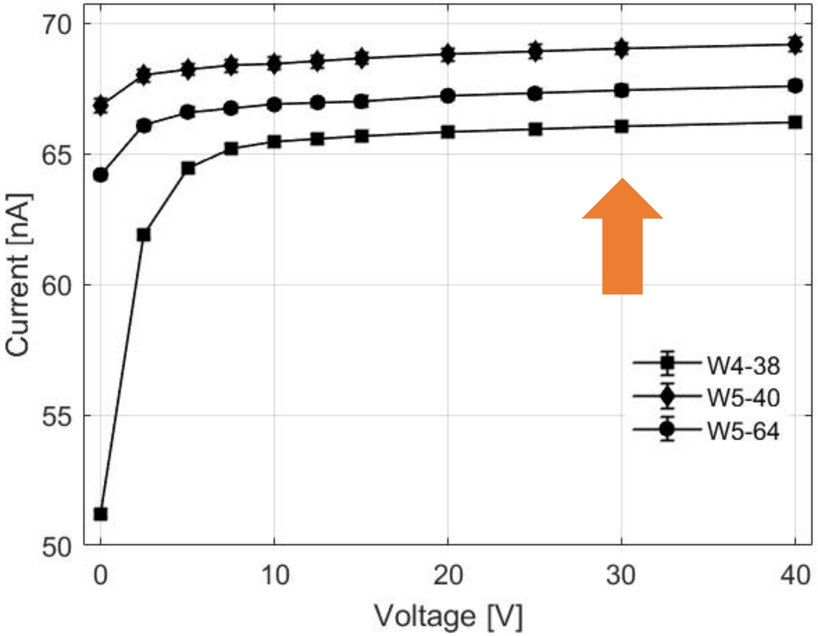
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

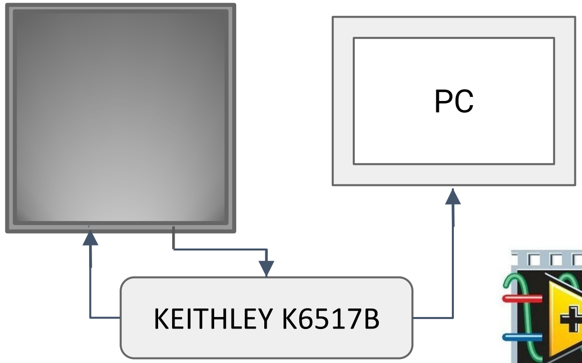


Tests:

- Stability
- CCE

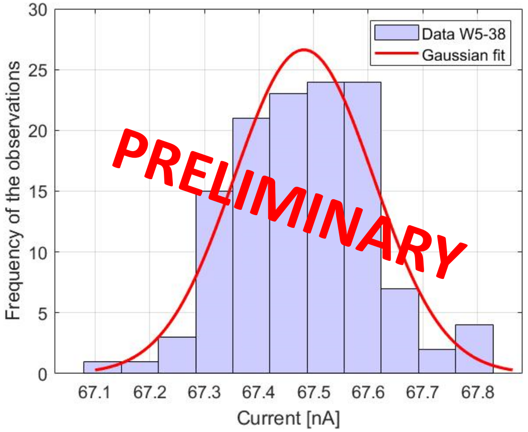






LabVIEW

Sampling rate: 3Hz
Full scale: 200 nA
Reverse voltage: 30V
Voltage Tube: 10 kV
Current Tube: 5 mA



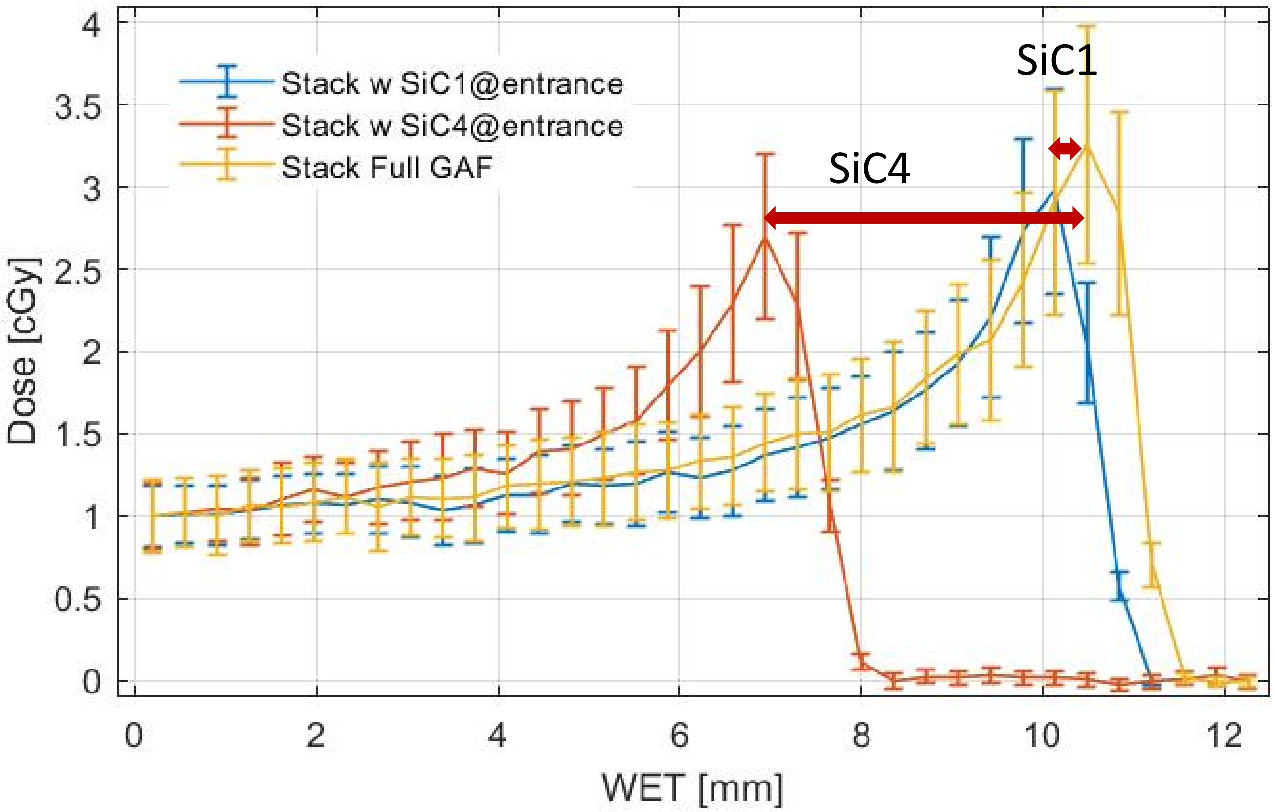
63.8% of fluctuations within 0.5% of the mean value.

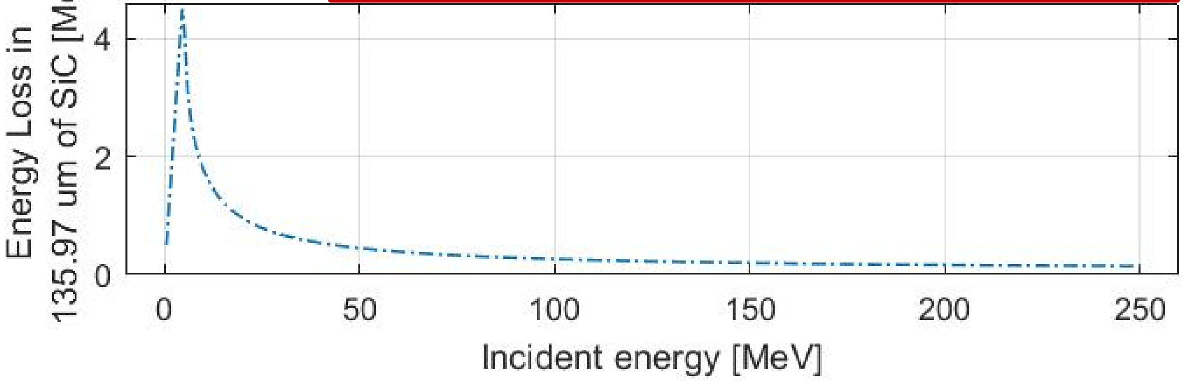
χ^2 test:
Random fluctuations!

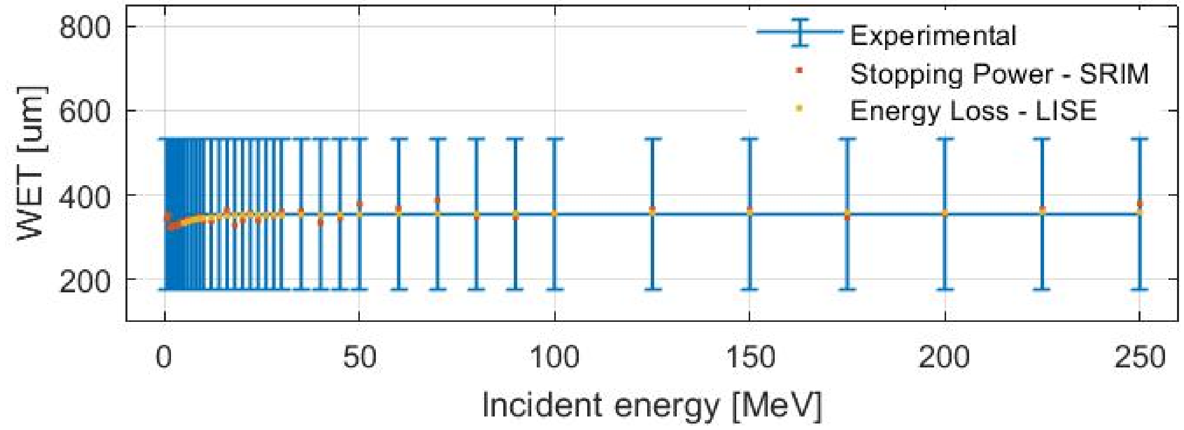
16th IPRD Conference, 25-29 September 2023
Mariacristina Guarrera, guarrera@lns.infn.it

PRAGUE prototype - Experimental campain @ Institute of Nuclear Physics Av Čr, Řež

Validation: 5 – 250 MeV for SiC1 → 135,97 µm







SiC1 = 0,355±0,177 mm → 1 EBT3 EQUIVALENT
SiC4 = 3,55±0,177 mm → 10 EBT3 EQUIVALENT

$$t_w = t_m \frac{\rho_m}{\rho_w} \frac{S_m(E_i)}{S_w(E_i)}$$

Thin-target approach
Stopping power ratio (SPR) approximation

Phys Med Biol. 2009 March 21; 54(6): 1383–1395.

16th IPRD Conference, 25-29 September 2023
Mariacristina Guarrera, guarrera@lns.infn.it

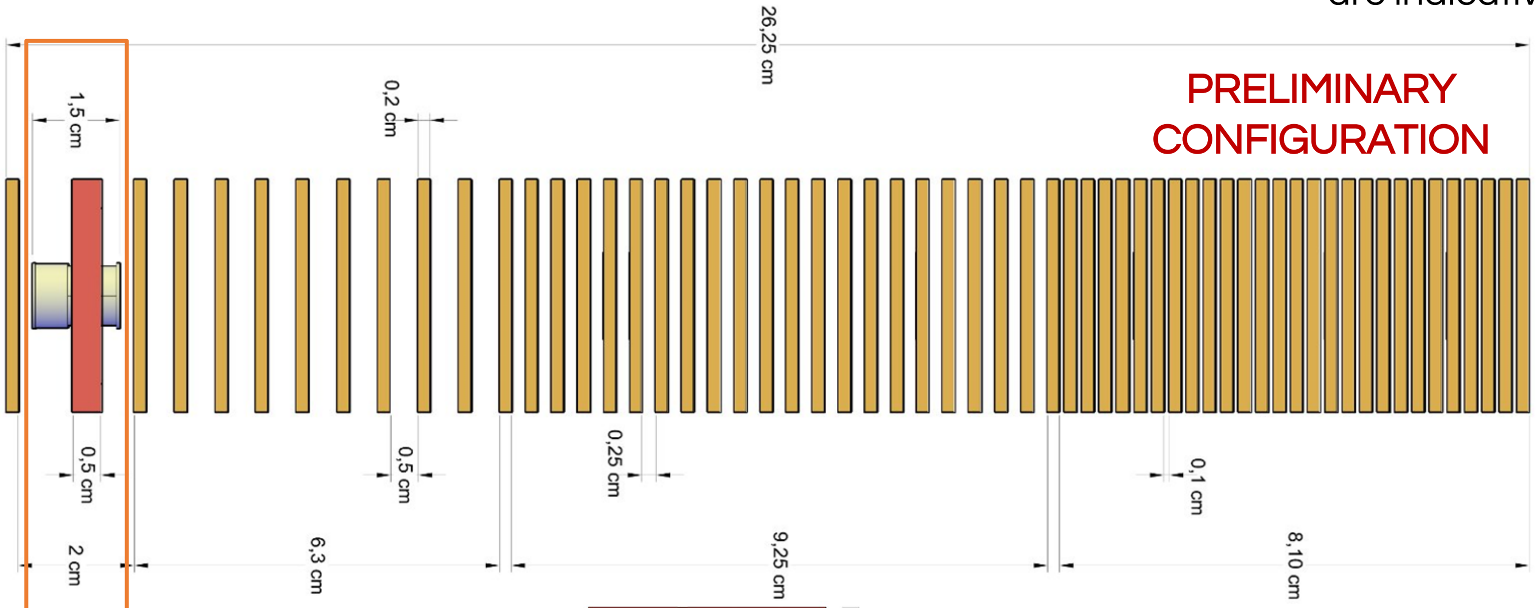
PRAGUE
(Proton RAnGe measure Using silicon carbidE) detector

Main goal! First **dosimeter** able to reconstruct online the PDD (Percentage Depth-Dose) distribution of a proton beam (30 MeV and 150 MeV) with both conventional and high- intensity.

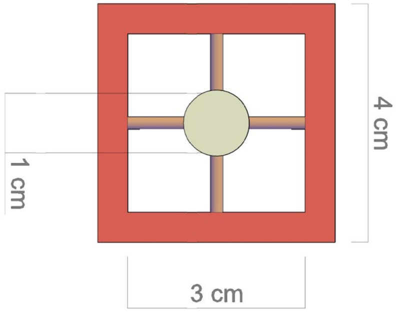
Distances are indicative

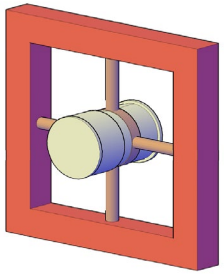
PRELIMINARY CONFIGURATION

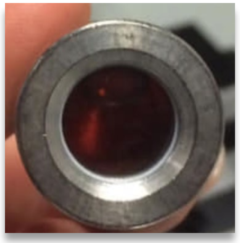
Proton beam

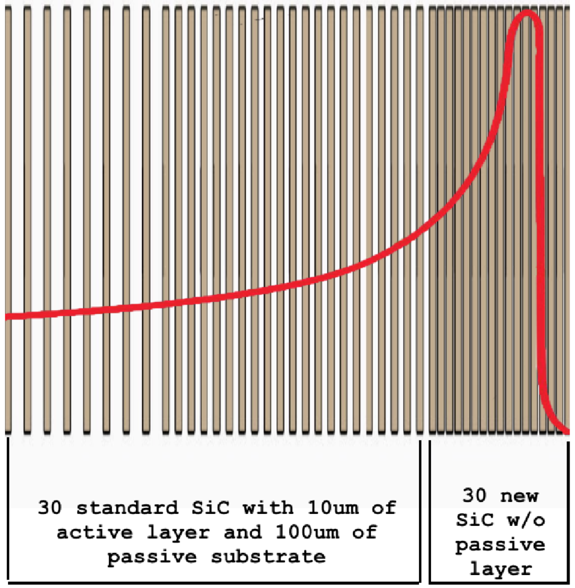


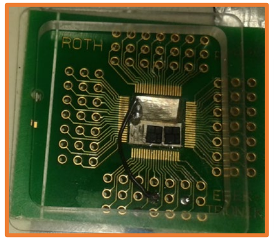
Holder for Biological Sample











Old generation:
- 2 x 2 mm^2
- 43,7 µm

60 **new generation** SiC (sensitive area of **15 × 15 mm^2** and active thickness of **10.3 µm**) in a stack configuration.

Silicon Carbide

Principal properties at room temperature of 4H-SiC compared to Silicon and Diamond

Properties	Diamond	Silicon	4H-Silicon Carbide
Energy Gap [eV]	5.45	1.12	3.26
Hole lifetime τ_p	10^{-9}	$2.5*10^{-3}$	$6*10^{-7}$
Relative dielectric constant ε_r	5.7	11.9	9.7
e-h pair energy (eV)	13	3.62	7.78
Density (gr/cm^3)	3.52	2.33	3.21
Thermal conductivity (W/cm °C)	20	1.5	3-5
Electron mobility [cm^2/Vs]	1800-2200	1400-1500	800-1000
Hole mobility [cm^2/Vs]	1200-1600	450-600	100-115
Breakdown electric field (MV/cm)	10	0.2-0.3	2.2-4.0
Max working temperature (°C)	1100	300	1240
Displacement [eV]	43	13-20	25

Wide bandgap
lower leakage current than silicon

High signal
Diamond 16 e/um
SiC 51 e/um
Si 89 e/um

=> more charge than diamond

Fast responce time

High Radiation hardness

Disadvantages diamond production:

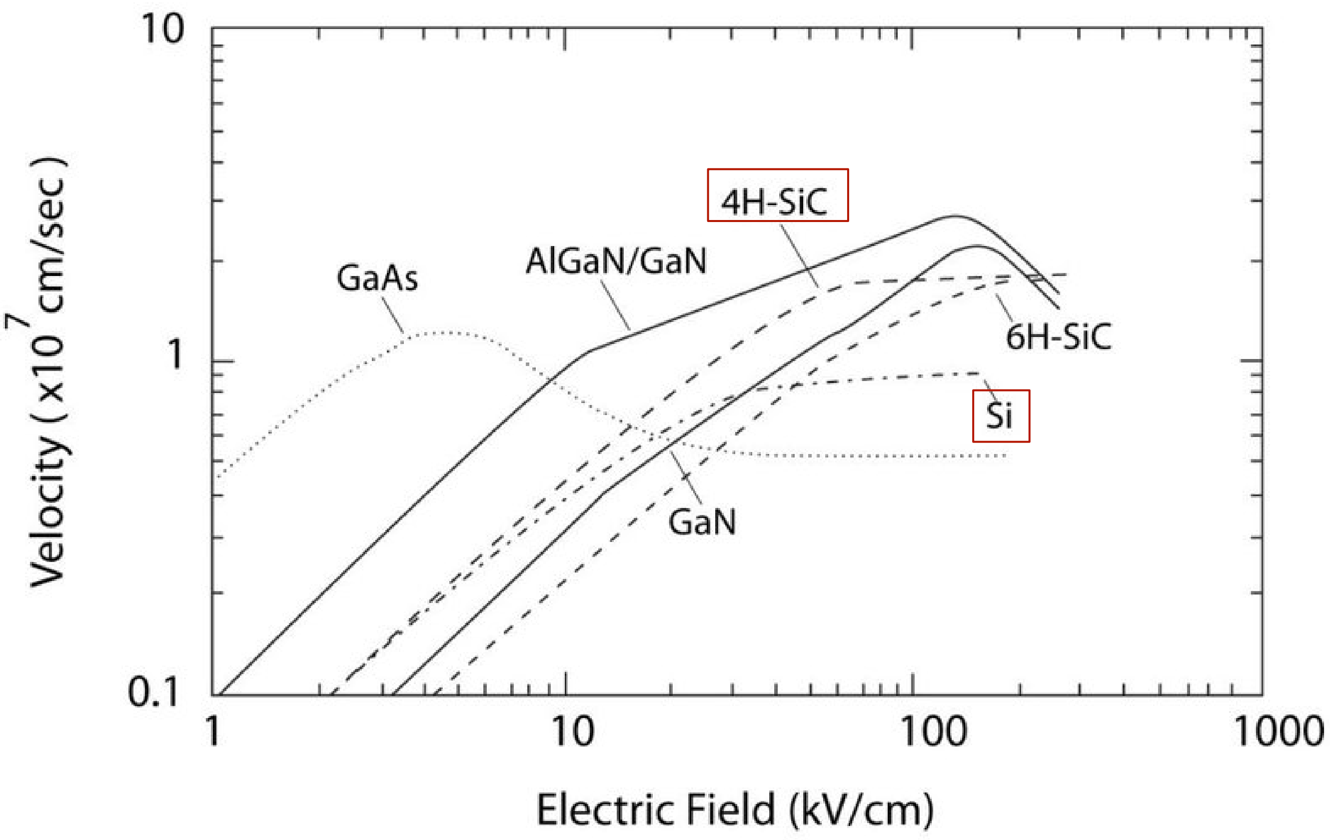
- higher costs;
- limited size while maintaining a high level of purity.

Main SiC Detectors features:

- dose rate independent
- LET independent
- linear response with absorbed dose
- high radiation hardness
- fast response

Principal properties at room temperature of 4H-SiC compared to Silicon and Diamond

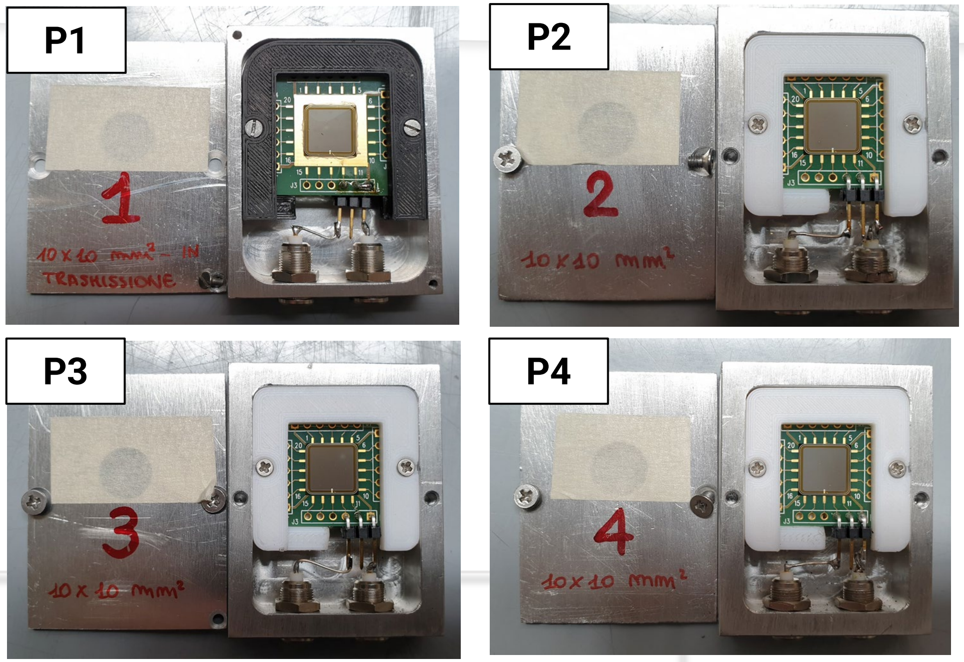
Saturated electron velocity [cm/s]	
Si	H4-SiC
1×10^7	2×10^7

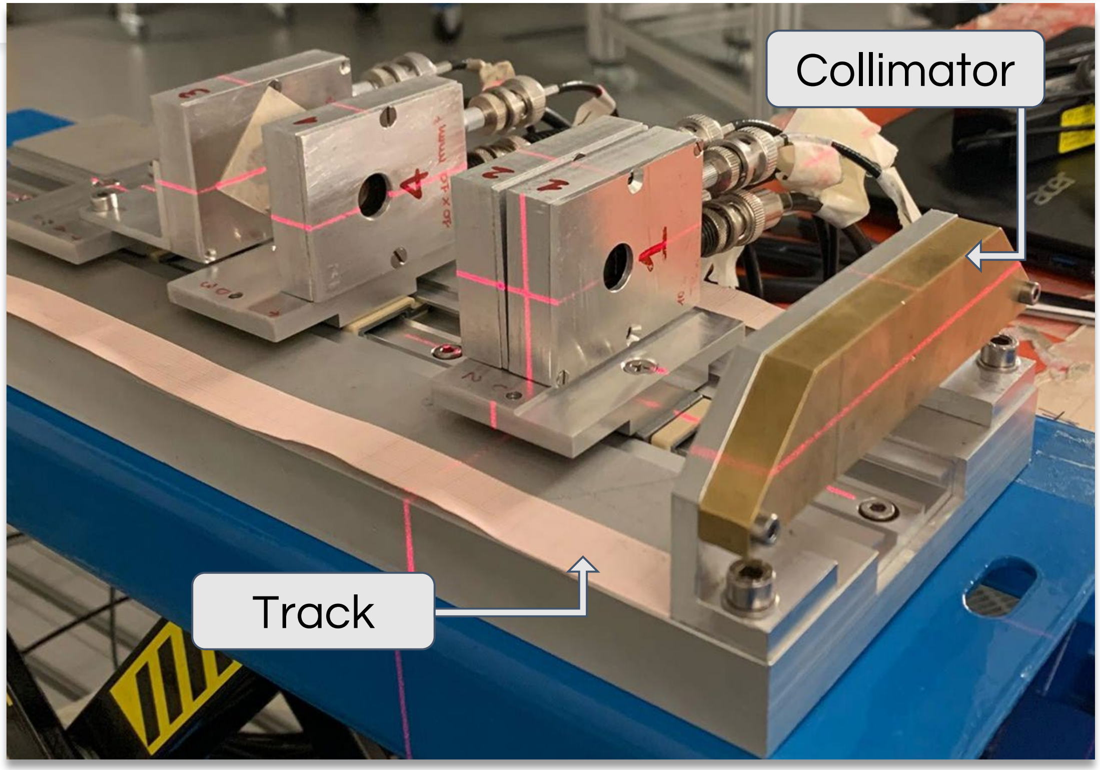


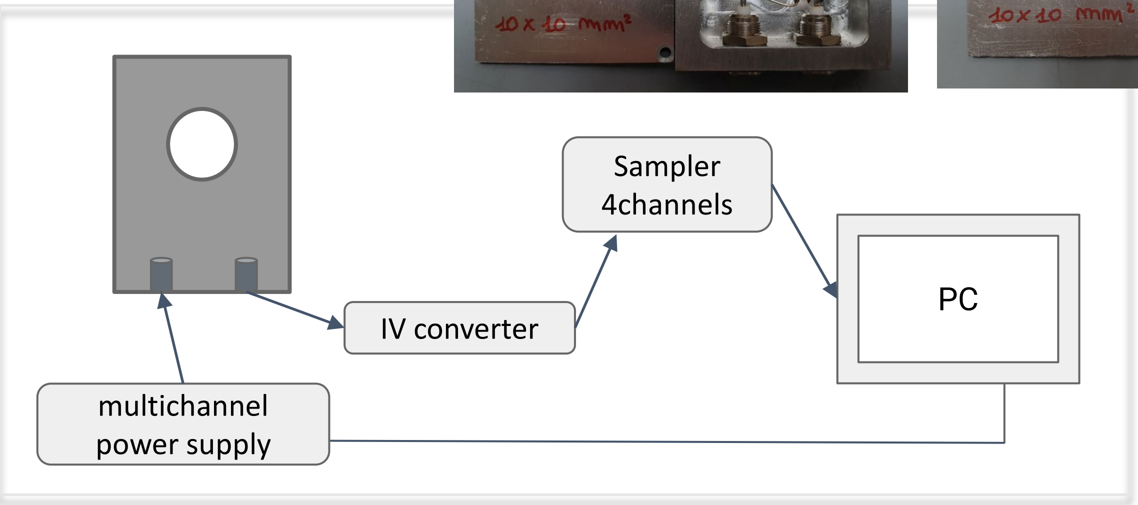
PRAGUE prototype characterization

PRAGUE
The realization of a prototype made of 4 SiC detectors

Perforated PCB



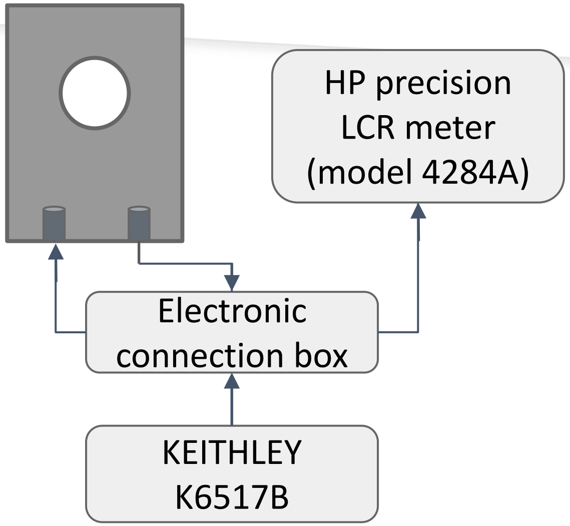




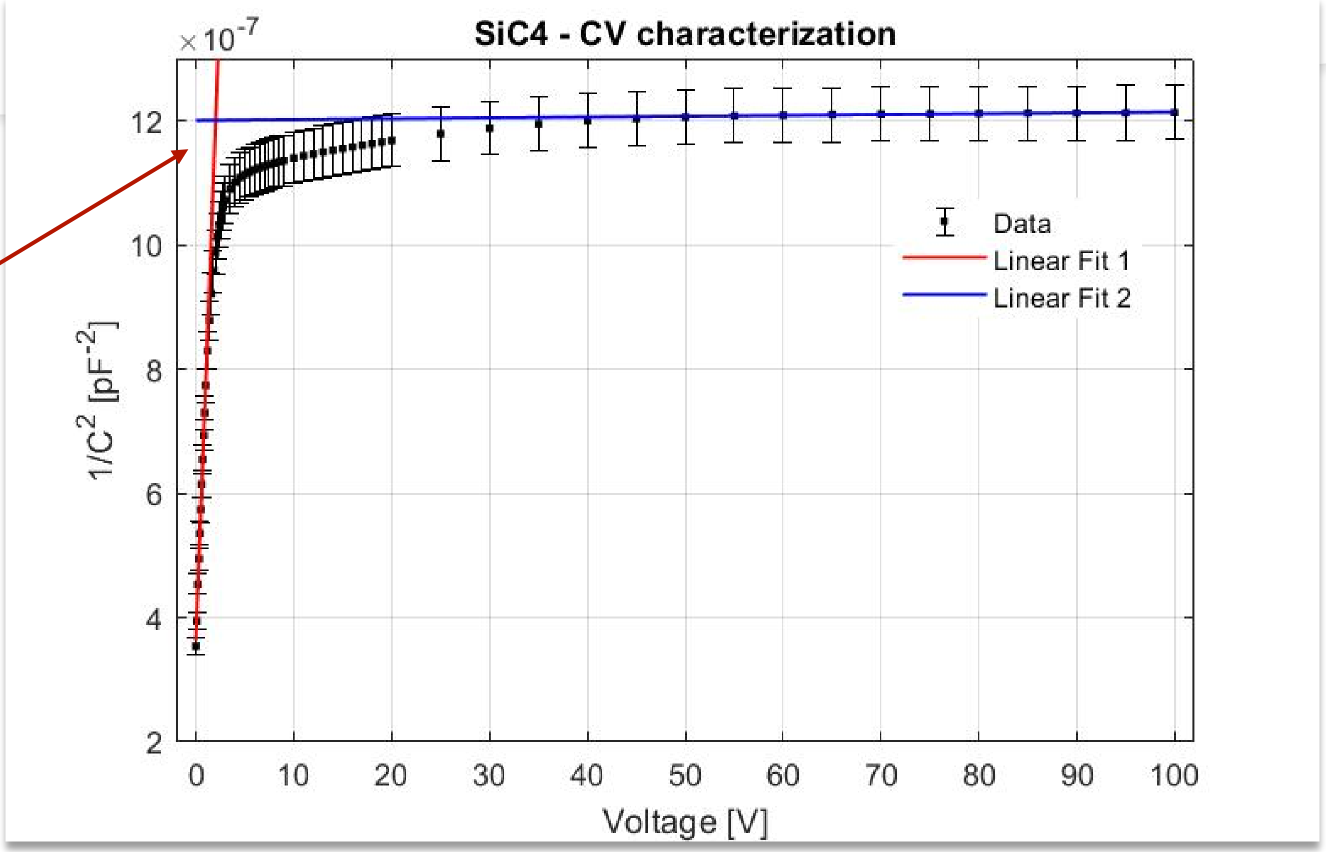
Aluminum boxes contain a 1 x 1 cm^2 detector

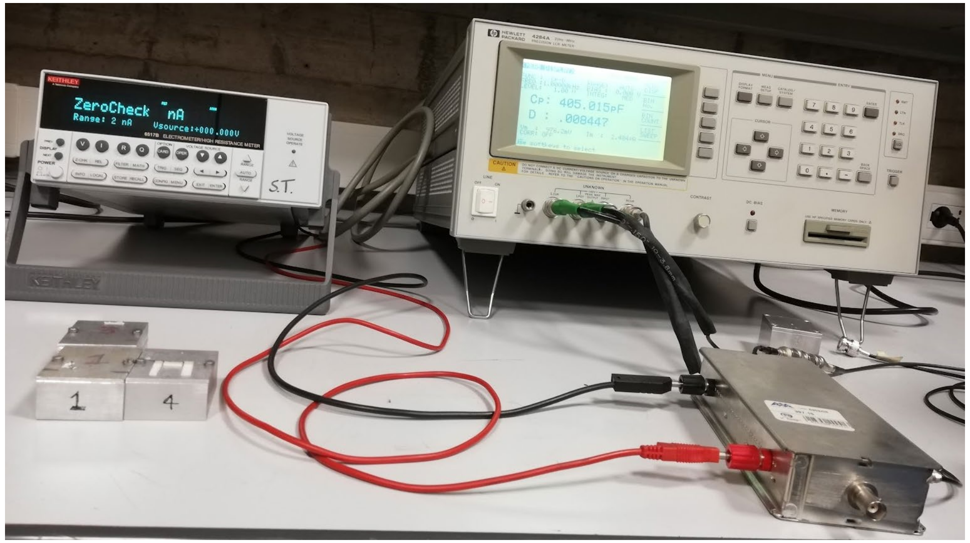
- active layer of **10 µm**
- passive layer of **110 µm**
- mounted on **PCB**.

PRAGUE prototype – CV characterization



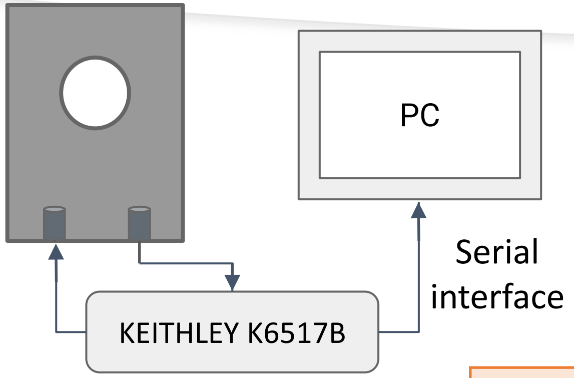
the point where the slope suddenly changes

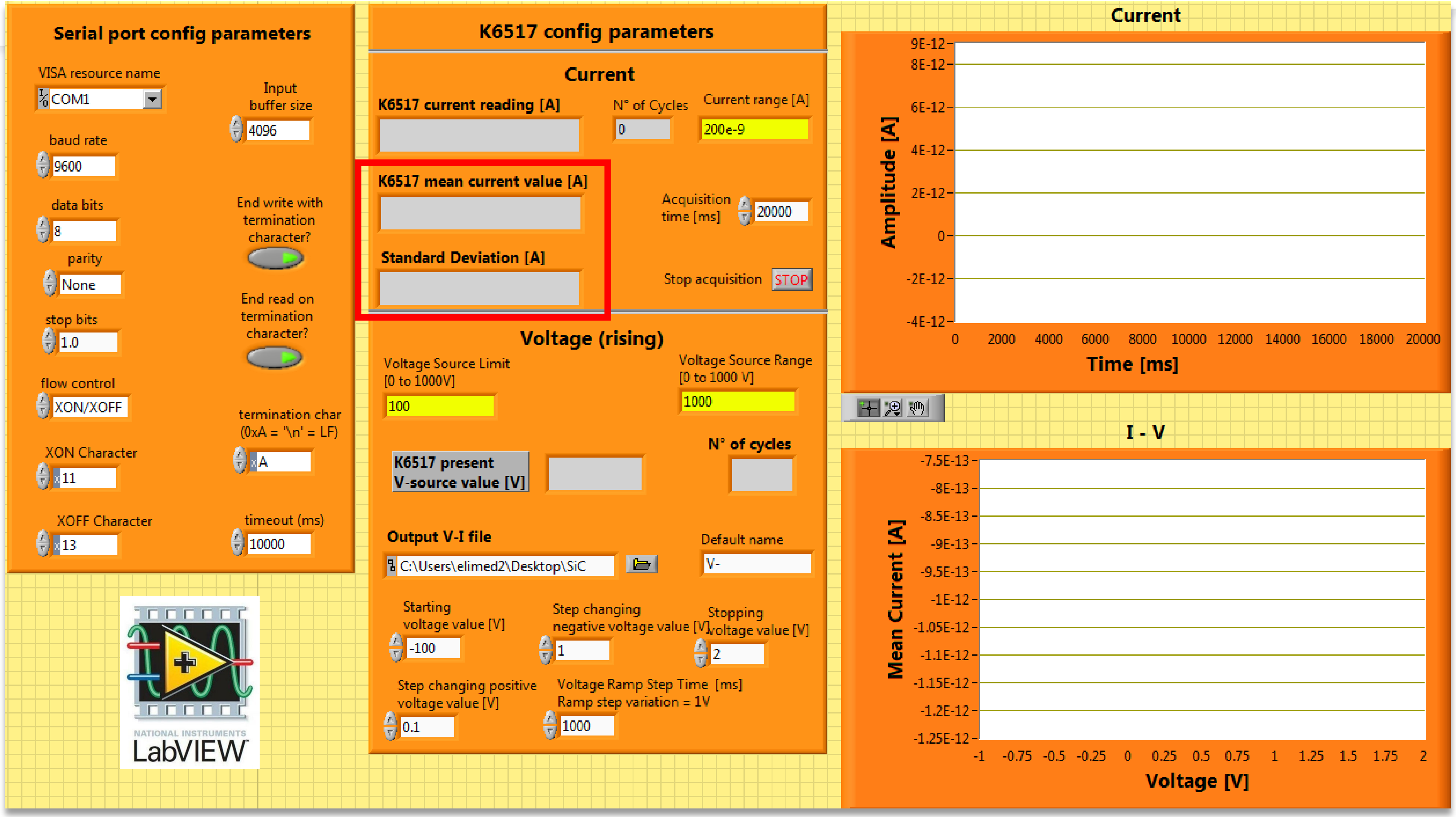




	SiC1	SiC2	SiC3	SiC4
Depletion Voltage	1.8±0.5 V	2.1±0.5 V	1.9±0.5 V	2.0±0.5 V
Saturation Capacitance	923±16 pF	895±16 pF	896±16 pF	908±16 pF

PRAGUE prototype – IV characterization

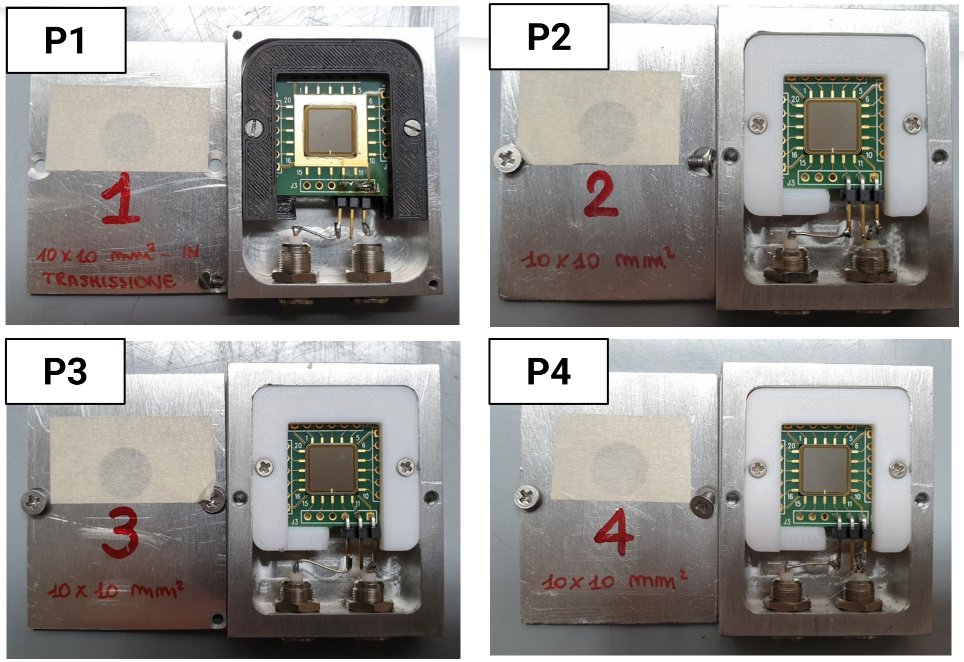


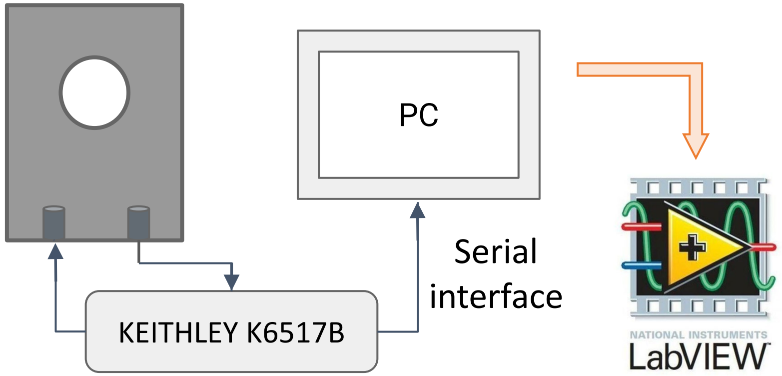


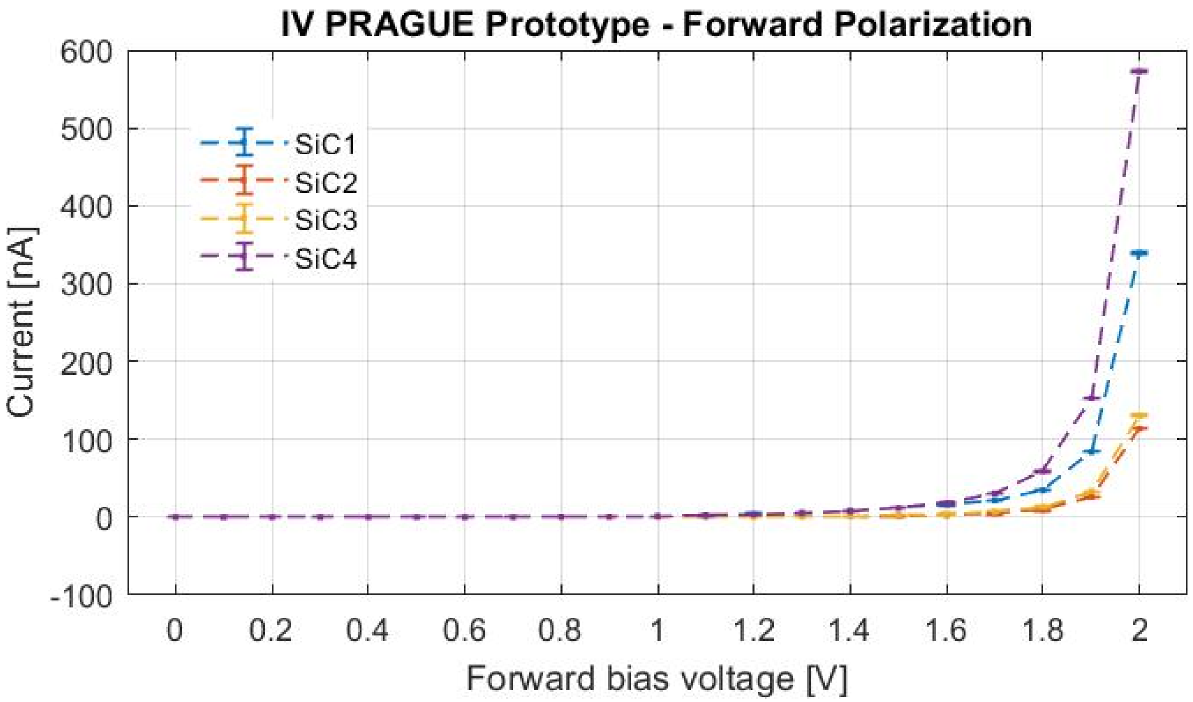
It is possible to set:

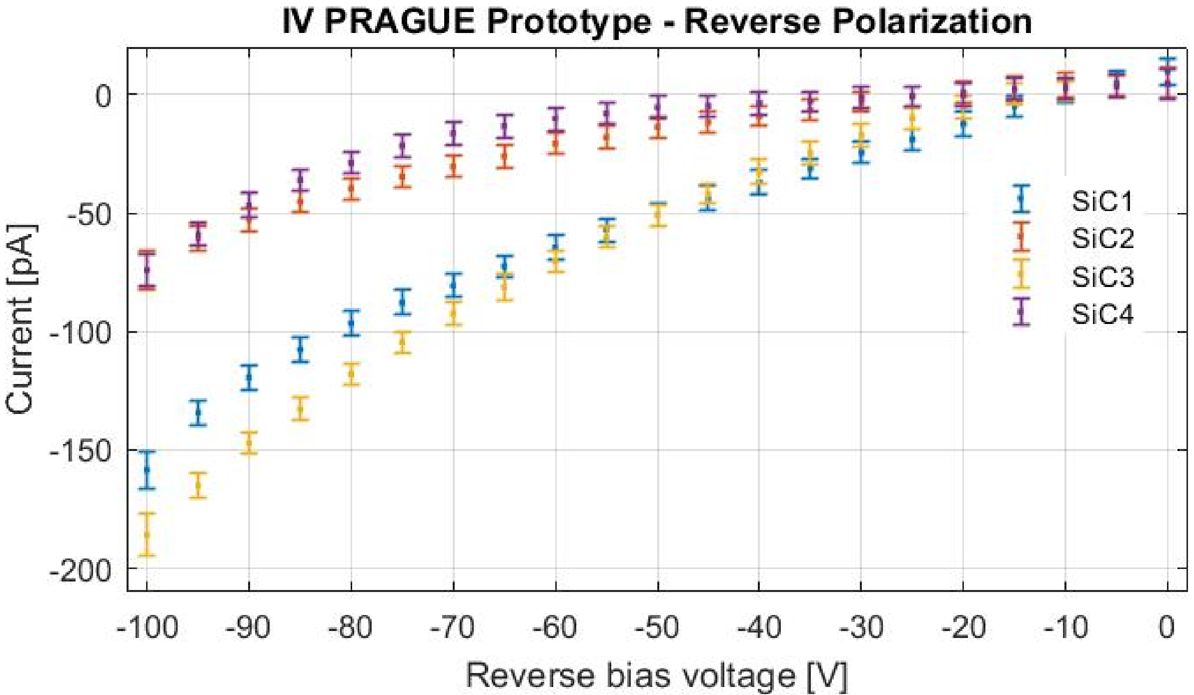
- **acquisition time** for current measurements;
- **current full scale**;
- **voltage ramp** (start and stop value, step voltage value, step voltage time);
- **voltage full scale**;
- **voltage limit**.

PRAGUE prototype – IV characterization



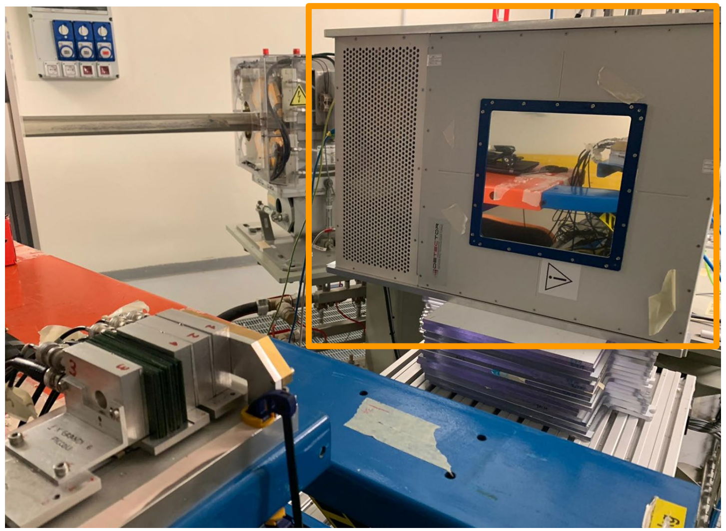


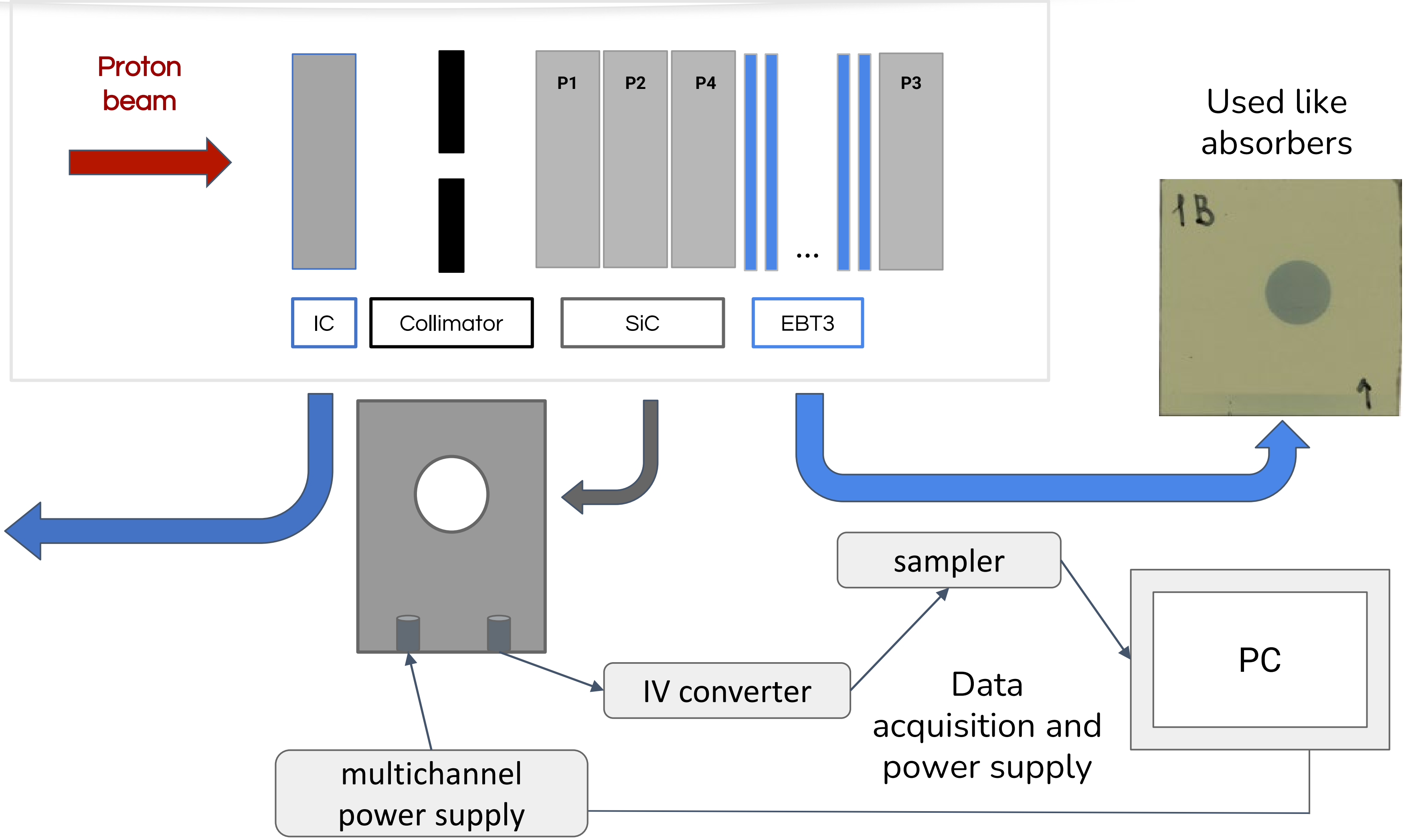




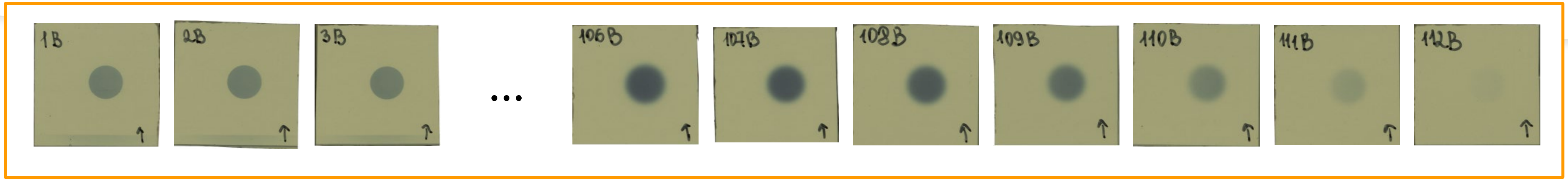
PRAGUE prototype - Experimental campain @Trento Proton Therapy Centre

Ionization chamber provided by the center: it returns the number ***N*** of protons incident on the collimator and the dose ***D*** released at the isocenter.

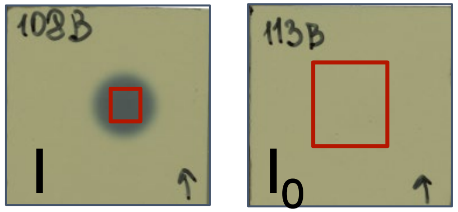




PRAGUE Prototype
A preliminary study @PTC of Trento - EBT3 data analysis



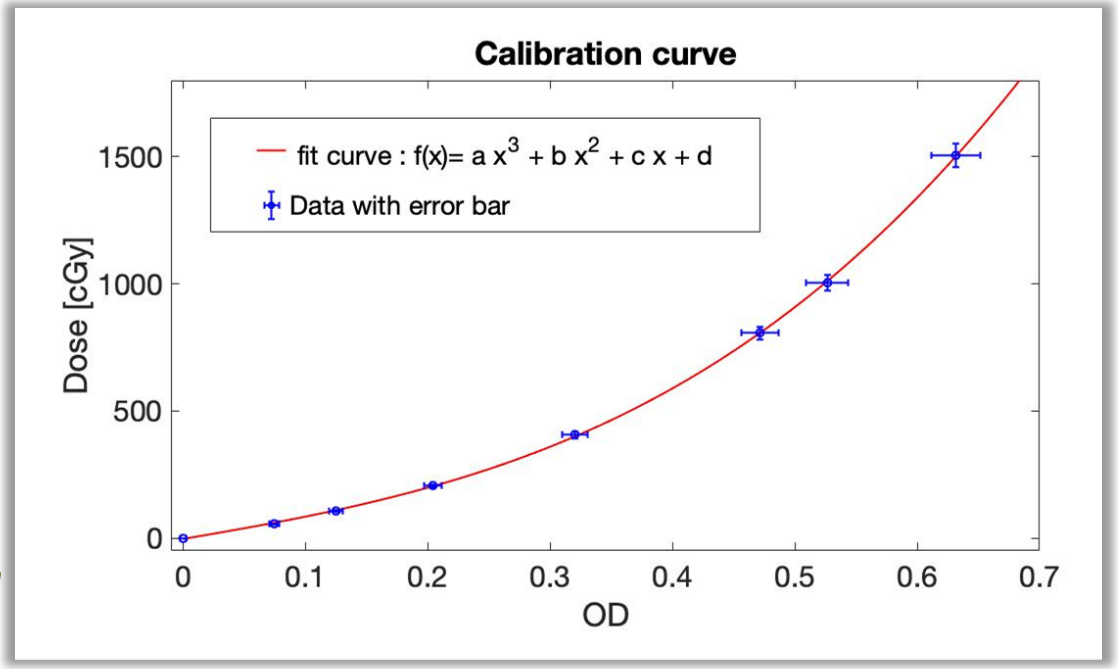
EBT3 stack irradiated with 70 MeV proton beam.



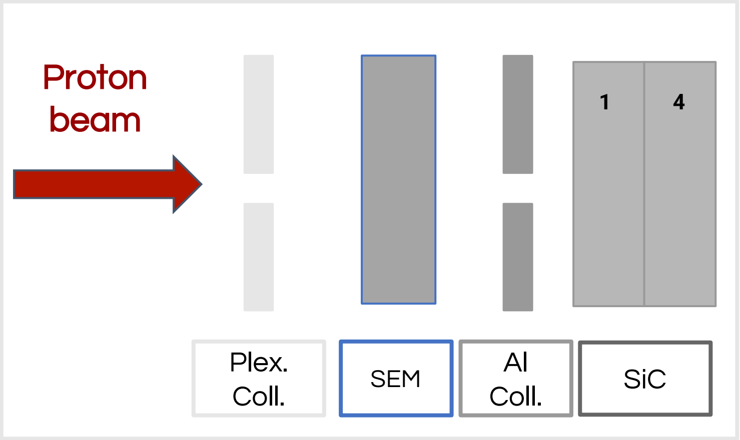
$$OD = -\log \frac{I}{I_0}$$

Property	EBT3	EBT3-U	HD-V2
Active layer thickness [μm]	28	28	12
Passive layer thickness [μm]	125	125	97
Number of passive layer	2	1	1
Dynamic dose range [Gy]	0.1-20	0.1-20	10-1000
Spatial resolution [μm]	< 25	< 25	< 5
Water Equivalent Thickness [μm]	355±20	195±10	150±10

To convert the OD film response in dose, the RCFs were firstly calibrated in terms of absorbed dose in water:



PRAGUE Prototype @ Institute of Nuclear Physics Av Čr (CZ) - results



We acquired 10 shots of 10 s. Then we repeated the acquisition by inverting the detectors.

By comparing the answer of the detectors, I found that SIC1 and SIC4 at entrance read a mean current value of:

Detector	Mean current [nA]	Error [nA]
SIC 1	19,975	0,002
SIC 4	28,271	0,003

SIC4 reads more than SIC1 → we can find a factor k such that:

$$k = SIC4/SIC1$$

in other words:

SIC4 = k SIC1 or SICI=SIC4/k

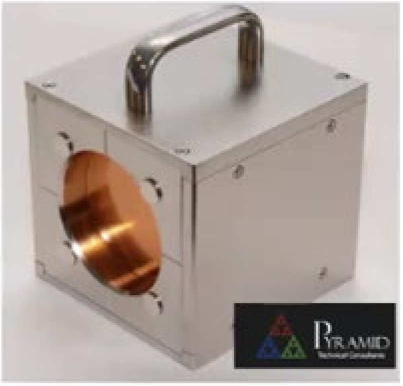
k [a.u.]	Error [a.u.]
1,415	0,005

PDD distribution measurement: state of art

State of art on PDD measurement in protontherapy

Water tank with a motorized system

Multi-layer Ionization Chambers

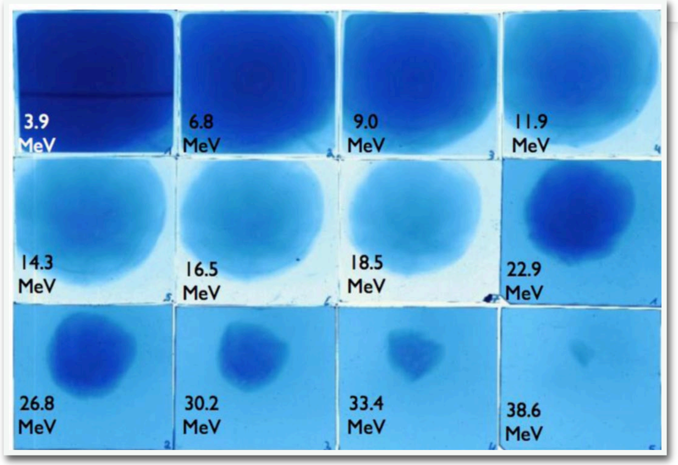


Multi Faraday Cups

Scintillator stack

Detector	Advantage	Disadvantage	Spatial resolution
Water Tank and ionization chamber	Linear response, LET and energy independent	dose rate dependent, high time consuming	~ 0.20 mm
MultiLayer Ionization Chamber	Linear response, LET and energy independent	dose rate dependent, low spatial resolution (order of mm)	~ 1 mm
Multi Layer Faradaycup	Linear response, LET and energy independent, dose rate independent	low spatial resolution (order of mm), high activation amount	~ 1 mm
Scintillator stack	High spatial resolution, linear response	LET and energy-dependent, low radiation hardness	~ 0.25 mm

State of art on PDD measurement – laser driven beam



Radiochromic films

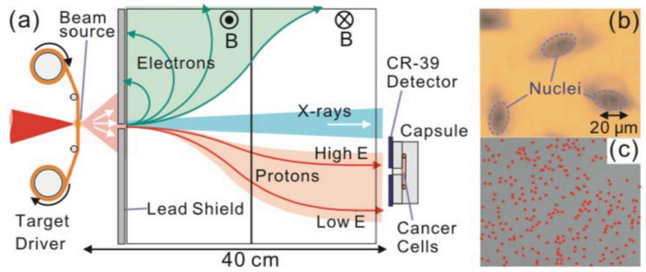
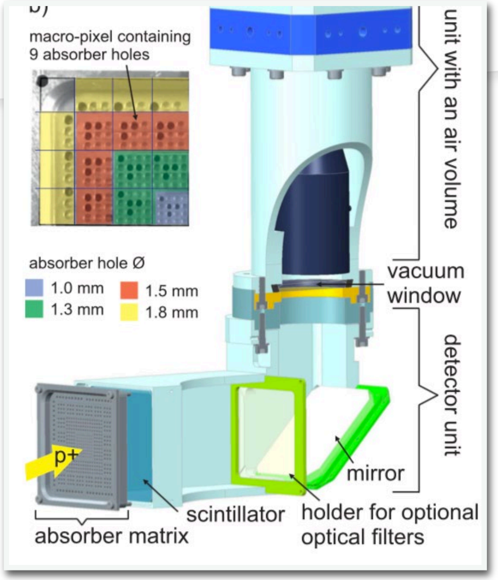


FIG. 1. (Color) (a) A schematic drawing of experimental setup. (b) An image of cancer cells taken by a microscope. (c) A spatial distribution of protons detected by CR-39 in a single laser shot. Each red point represents a single proton bombardment. The screen size is set to be same as that in the frame (b).

CR39 detector



Scintillator stack/grid

Detector	Advantage	Disadvantage
Radiochromic films	Linear response, dose rate independent	LET and energy-dependent, passive detector, high time consuming
CR39 detector	Linear response, dose rate independent	Saturation in fluency and incident energy, high time consuming
Scintillator systems	High spatial resolution, linear response	LET and energy-dependent, low radiation hardness

What do we expect?

Proton LASER Beam					
	Energy [MeV]	**N° of particles**	**Charge [nC]**	**Shot time [ns]**	**Current**
Maximum	1	10^7	191,5	100	1,91 A
Minimum	60	10^4	0,006	100	57583,5 nA

Proton Continuous Beam					
	Energy [MeV]	**N° of particles**	**Charge [nC]**	**Shot time [s]**	**Current**
Maximum	1	10^9	19146,5	60	319,1 nA
Minimum	250	10^4	0,002	1	0,002 nA