Silicon & Diamond Sensors:
Characterization under UHDR beams

Medical Physics group
Physics Department,
University of Turin & INFN (Turin)

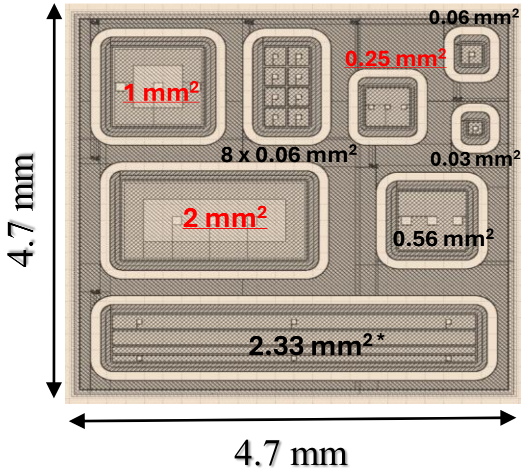
The Competence of our Group in Silicon sensors...

Development & research of Silicon detectors and Custom electronic readout devices for clinical applications in Conventional and FLASH particle therapy.

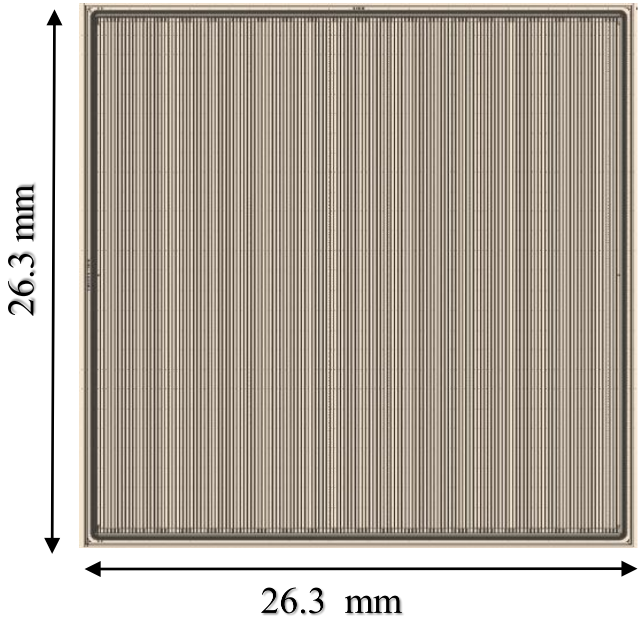
Silicon sensors with different geometries:

FONDAZIONE BRUNO KESSLER

eXFlu



MoVe IT



Parameters	**Multipad sensor**	**Strip-segmented sensor**
Total Area (mm^2)	22.6	690
Active thickness (µm)	15/20/30/45	45
Total thickness (µm)	570/655	630
Number of strips/pads	8	146
Strip/Pads Area (mm^2)	0.03 - 2.33	4.72
Breakdown voltage (V)	**> 350**	**~ 300**

*: It consists of four strips: two 200-µm wide and two 100-µm wide.

Experimental Measurement Campaigns

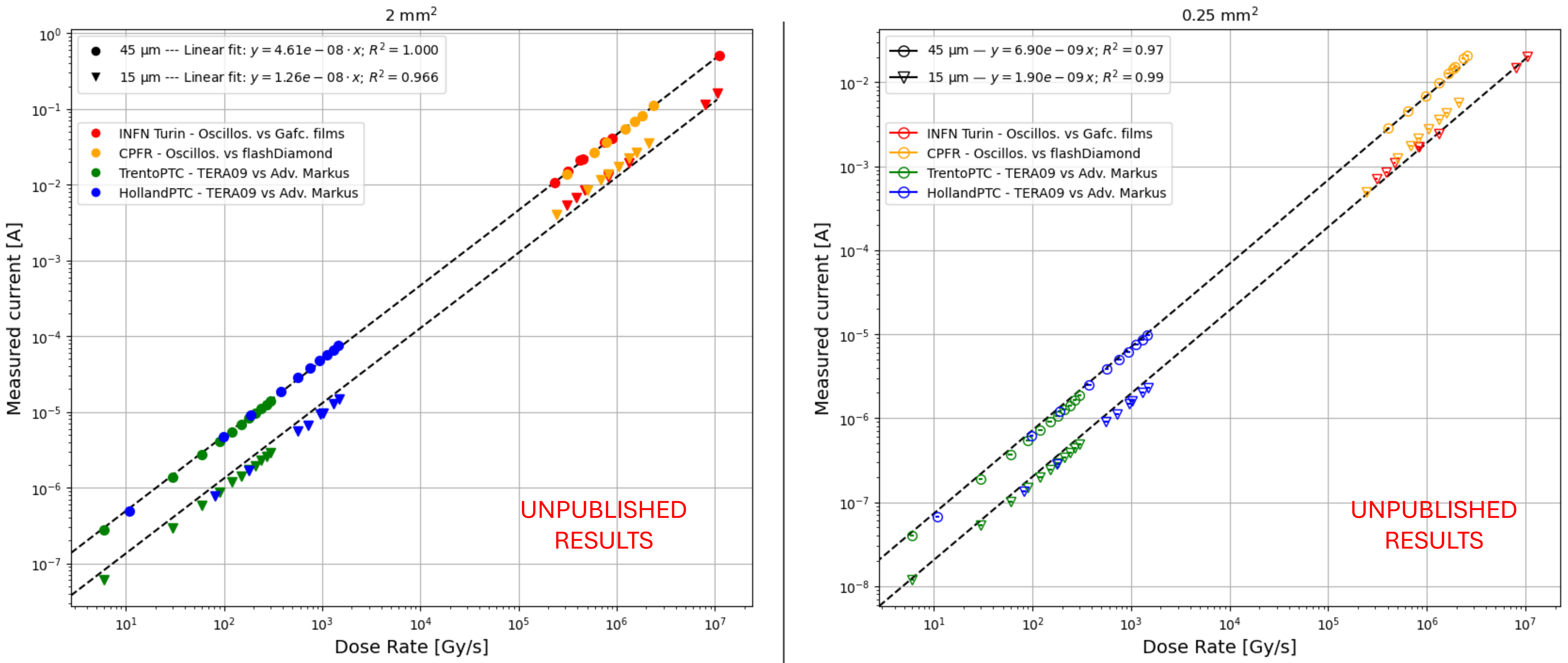
- Sensor performance characterized under electron & proton UHDR beams at four facilities:

Facility	Accelerator	Beam	Nominal current [nA]	I-DR range [Gy s^{-1}]
TrentoPTC (Trento-Italy)	Isochronous Cyclotron (IBA Proteus 235)	Proton: ***228 MeV***	*1-500*	*6-300* NEW 2025
HollandPTC (Delft-The Netherlands)	Isochronous Cyclotron (Varian ProBeam)	Proton: ***250 MeV***	*1-800*	*10-1480* NEW 2025
CPFR (Pisa-Italy)	LINAC Electron Flash (S.I.T)	Electrons: ***9 MeV***	10^3 - 10^5	$(4\text{-}25) \times 10^5$
INFN-UniTO (Turin-Italy)	LINAC (Elekta SL18 MV)	Electrons: ***10 MeV***	*n.d.*	$(3\text{-}105) \times 10^5$

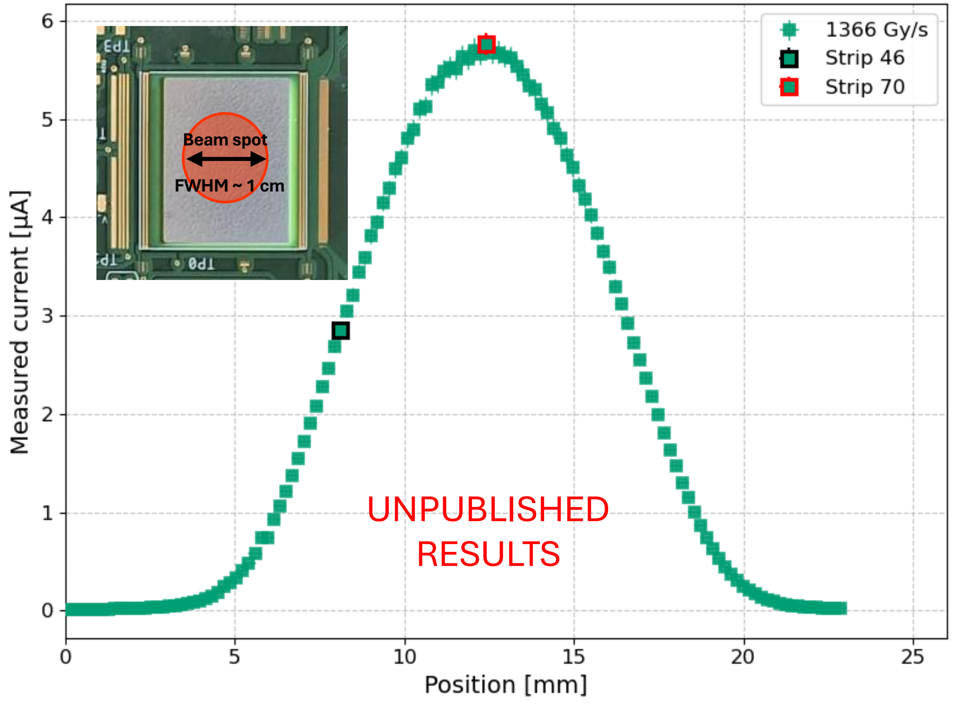
- Readout electronics:
  - Keysight Oscilloscope (*2.5GHz, 20GSa* s^{-1})
  - TERA 09 ASIC (*64 channels, quantum charge: 600 fC, max current: 12 μA*)

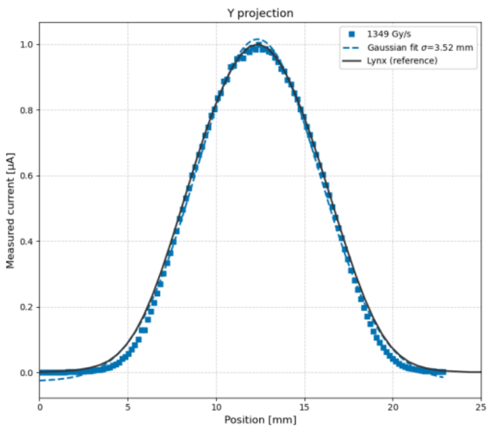
- Measurements performed under dosimetric reference conditions, except for one conducted inside the LINAC head (wedge position: SSD = 18.6 cm).

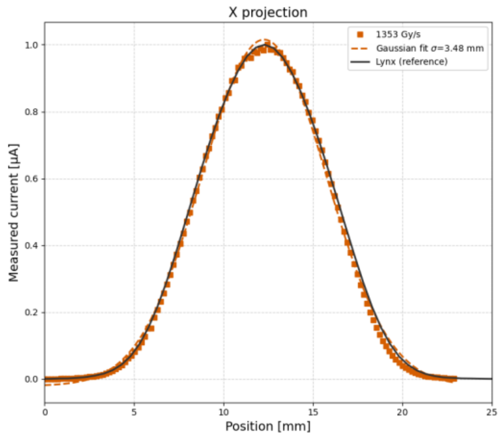
Linear response performance: Multipad sensors

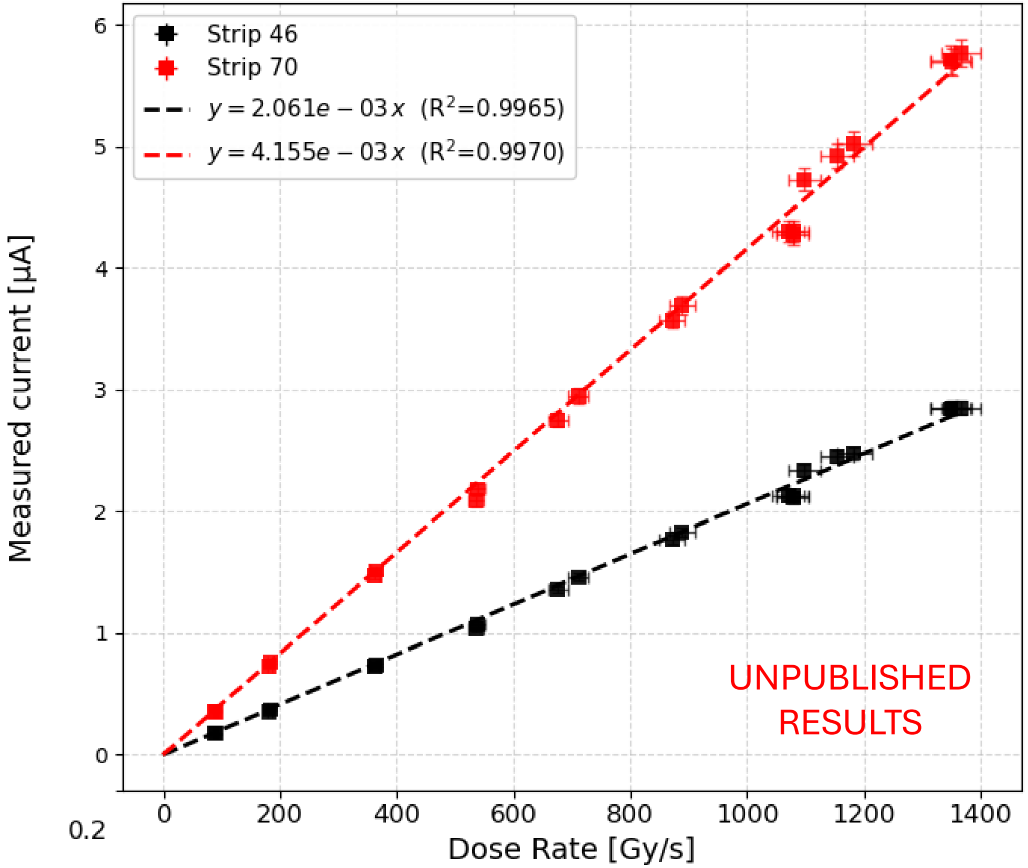


1D Proton UHDR Beam Profile Measurements: Strip sensor







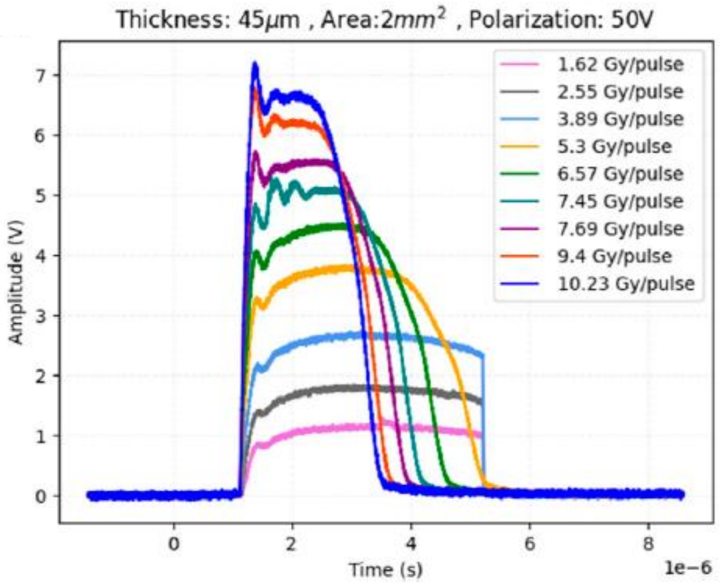


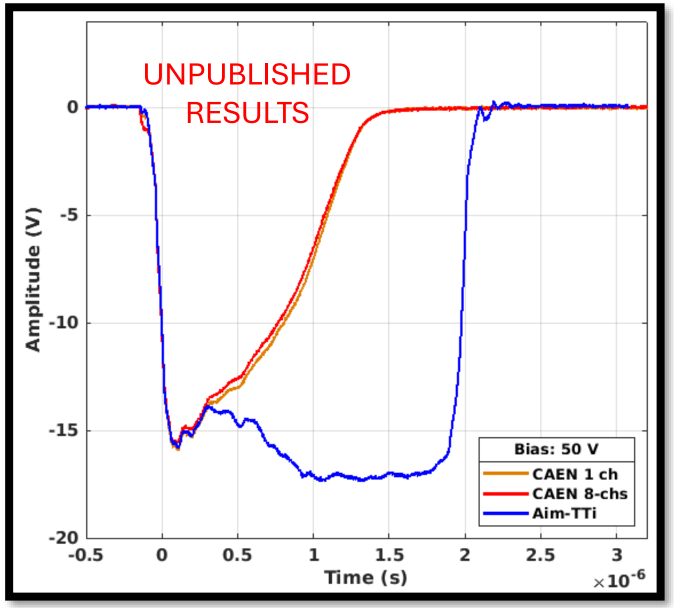
Projection	σ (silicon sensor) [mm]	σ (Lynx) [mm]
Y	3.52 ± 0.18	3.5 ± 0.5
X	3.48 ± 0.18	3.5 ± 0.5

Key problems & Solutions: Signal Distortion

At low bias voltages, waveform distortion occurred for DPP >3.89 Gy.

- Signal duration was shorter than the LINAC pulse duration.
- Integrated signal plateaued at a constant value.



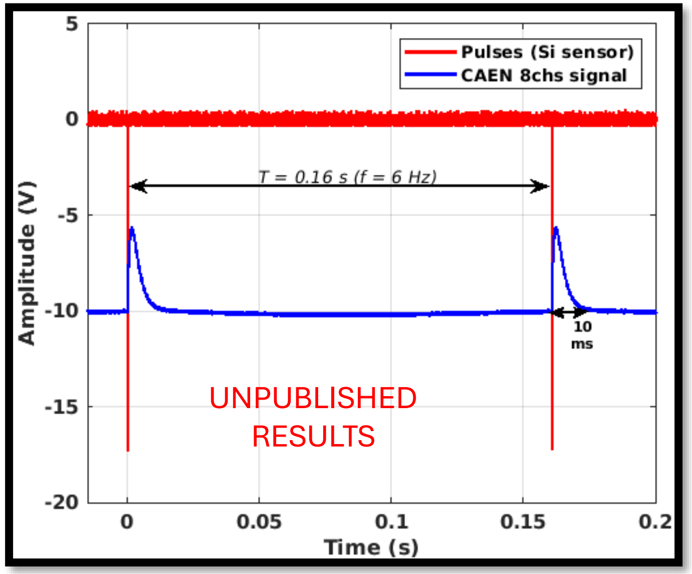


CAEN (DT5471)

Aim-TTi (PLH250P)

CAEN (DT1415ET)

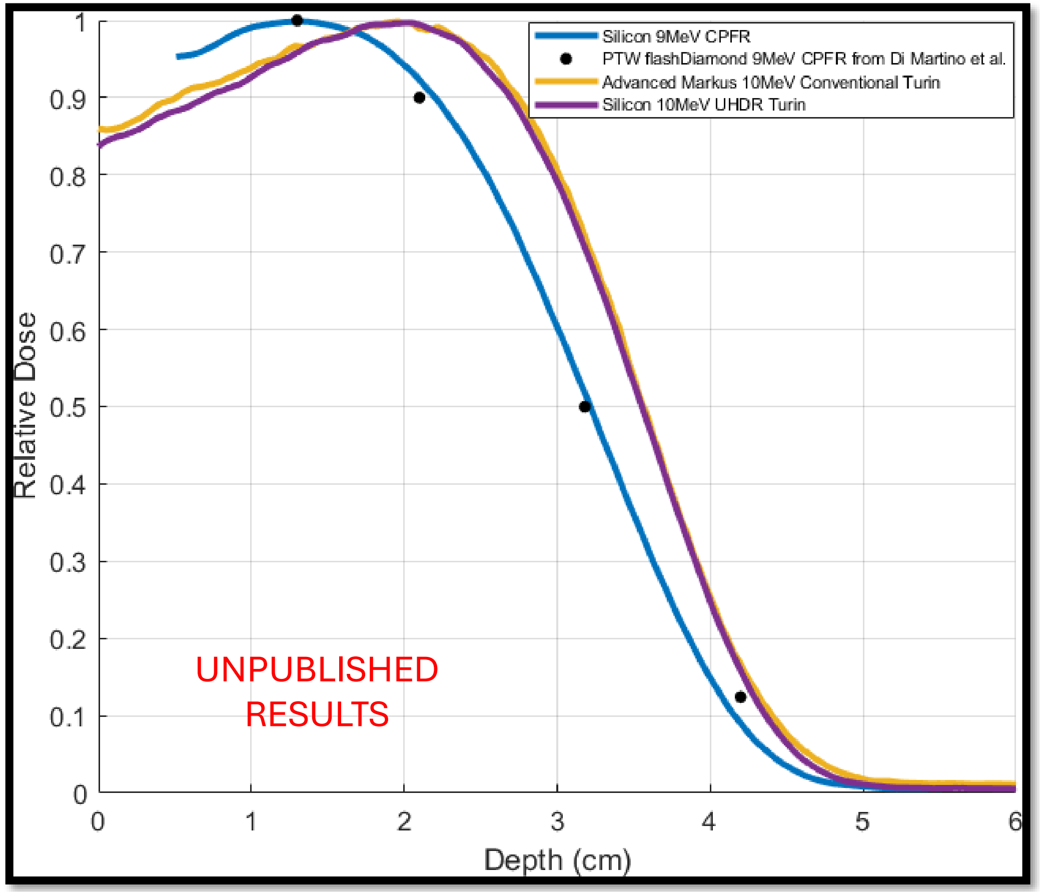
- Signal distortion at low bias and high DPP was caused by HV power supply behavior:
  - A voltage drop (~40 – 50 V) occurred synchronously with each radiation pulse, associated with the digital feedback regulation of the CAEN HV power supplies.
- Signal degradation is not intrinsic to the detector (not due to charge recombination effects in the sensor volume)

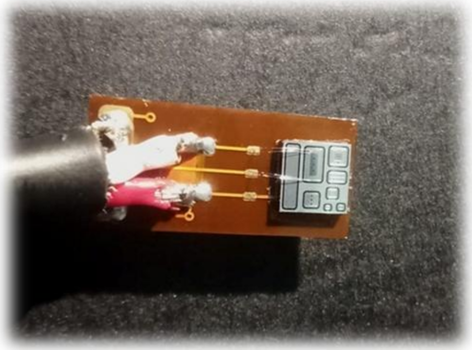


*** Blue signal scaled by a factor of 10 for visualization purposes**

Encapsulated waterproof prototype:

- Multipad sensor (*A:2 mm²*, *t: 45 μm*) on a Kapton PCB
- Housed in a PMMA holder (15×25 mm²)
- Overall Water-Equivalent Thickness: ~ 3.7 mm





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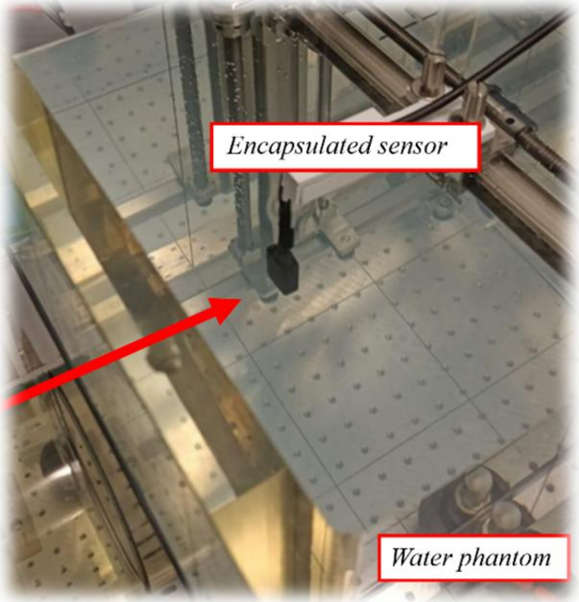


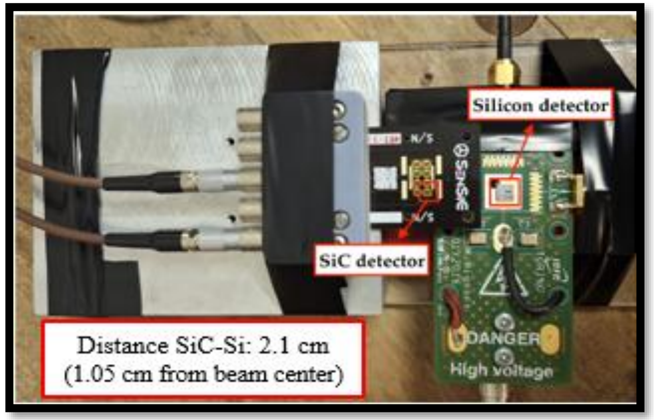
Parameter [mm]	CPFR facility – 9 MeV		
	Silicon	flashDiamond	Discrepancy [%]
R_{100}	13.1	13.0	0.7
R_{90}	22.1	21.0	5.1
R_{50}	32.2	31.8	1.2
R_p	42.4	42.0	0.9

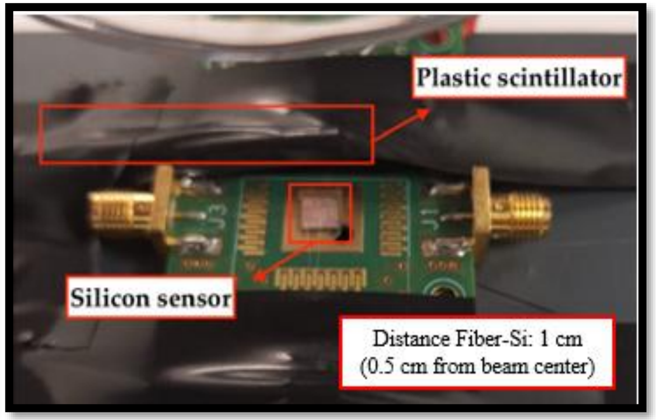
The comparison of the different detector technologies was performed at the Turin LINAC facility.

- Two detectors were irradiated simultaneously under identical conditions.

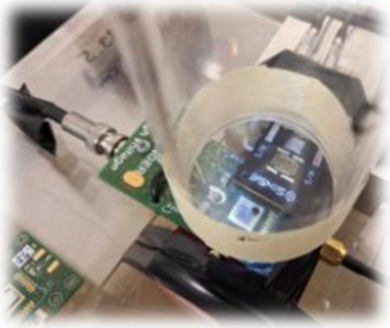
SiC sensor:
- Area: 4.5 mm^2
- Thickness: 10 µm

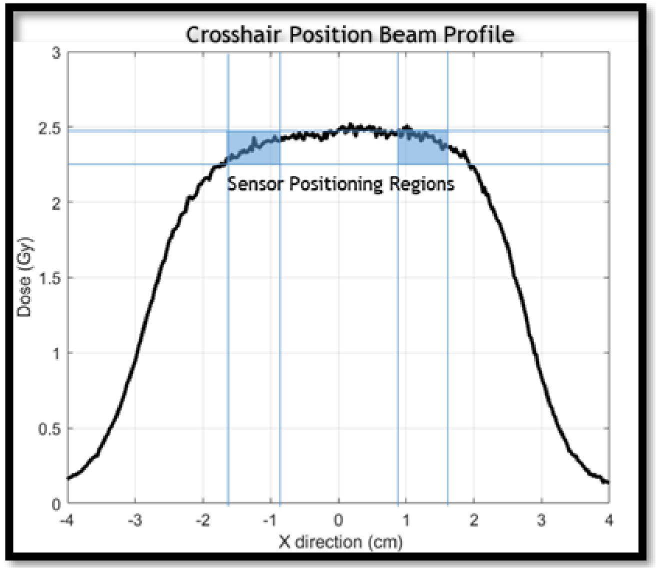
Si sensor:
- Area: 2 mm^2
- Thickness: 45 µm





EJ-212 plastic scintillation fiber:
- Diameter: 1 mm
- Thickness: 1.2 mm



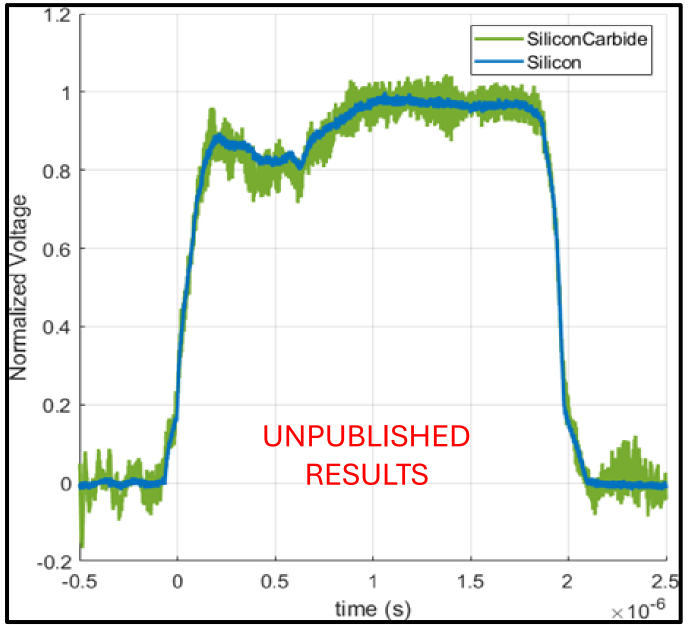


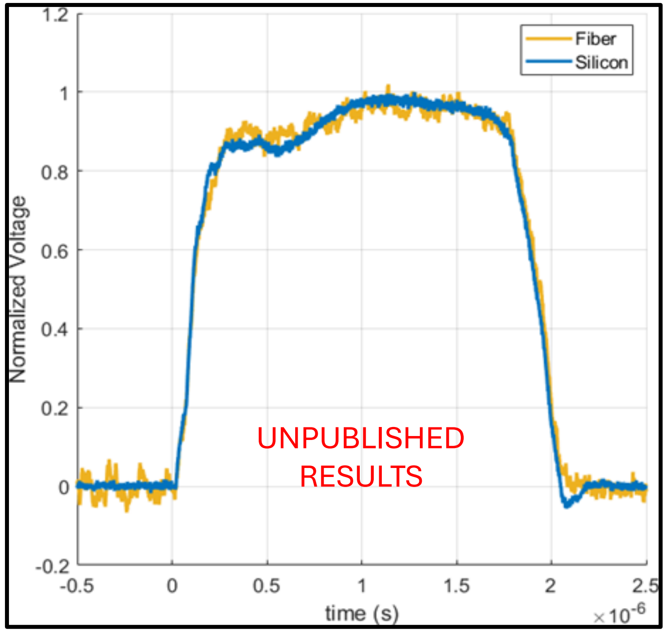
- LINAC Setup Parameters:
  - 10 MeV electrons
  - Field size: 25 × 25 cm (at isocenter)
  - Pulse duration: 2 µs
  - PRF: 6 Hz
  - Instantaneous Dose Rate: 1.3×10^5 - 2.1×10^6 Gy s^{-1}

    (Varying SSD, using 50-mm diamater applicator & changing beam current)

- Pulse temporal profiles

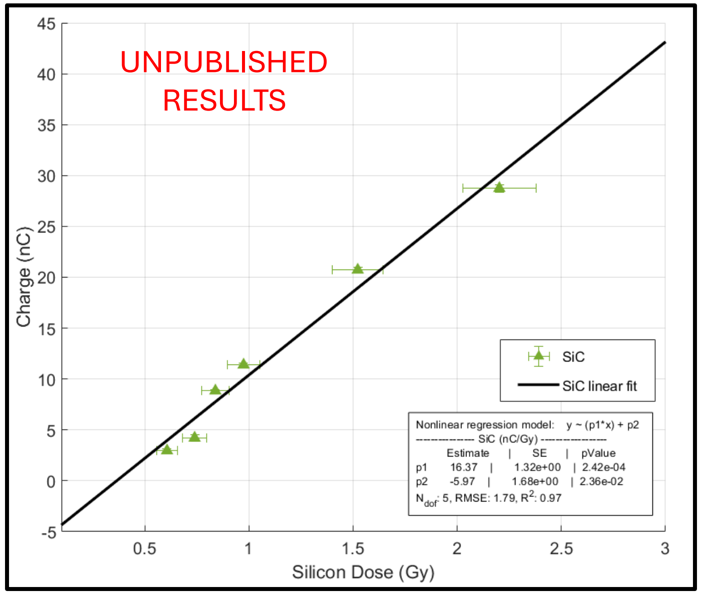
- All three sensors showed:
  - ✓ Comparable signal duration.
  - ✓ Fast rise times.
  - ✓ Rapid transient behaviors.



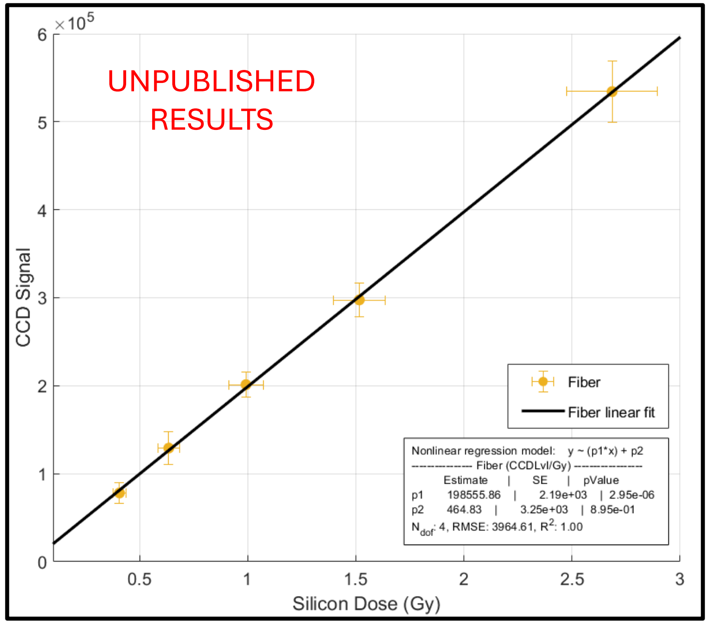


- Results confirm the capability to reproduce the temporal structure of µs-scale pulses.

- Linearity



- Silicon sensor used as reference.
- Strong linear correlation observed in both cases ($R^2 > 0.97$).



- Results confirm the good linear response of these sensors.

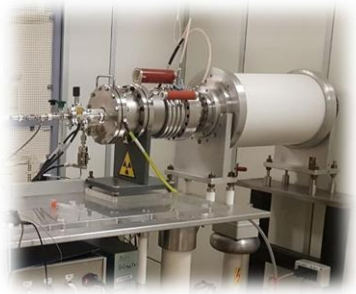
Polycrystalline CVD Diamond-based Sensors

The Reasons:

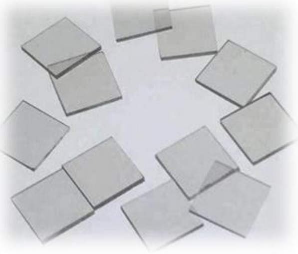
- Near tissue-equivalence response.
- Exceptional radiation hardness.
- Cost-effective candidates for UHDR clinical applications.

AN2000 accelerator – INFN Legnaro

Multi element Ion implanter– UniTO



Vacuum metallization Chamber – UniTO



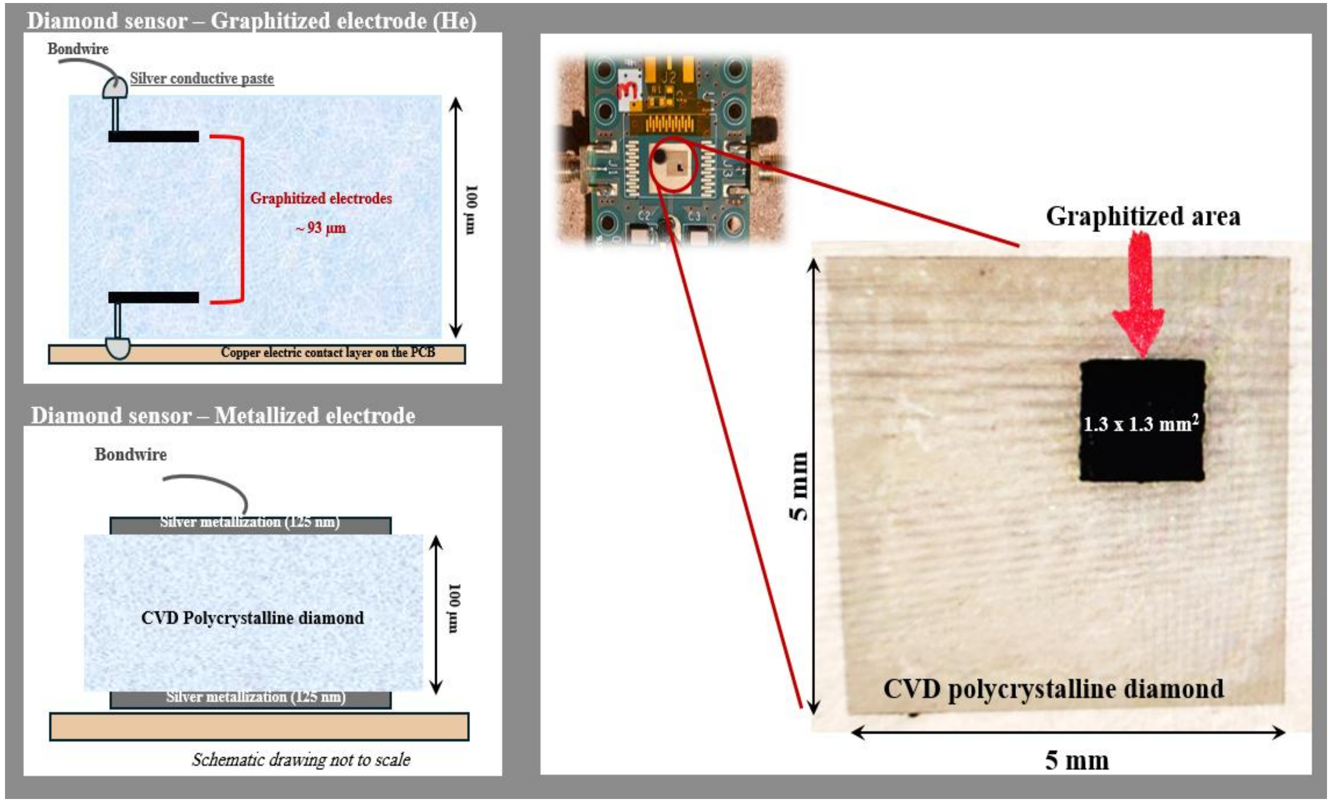
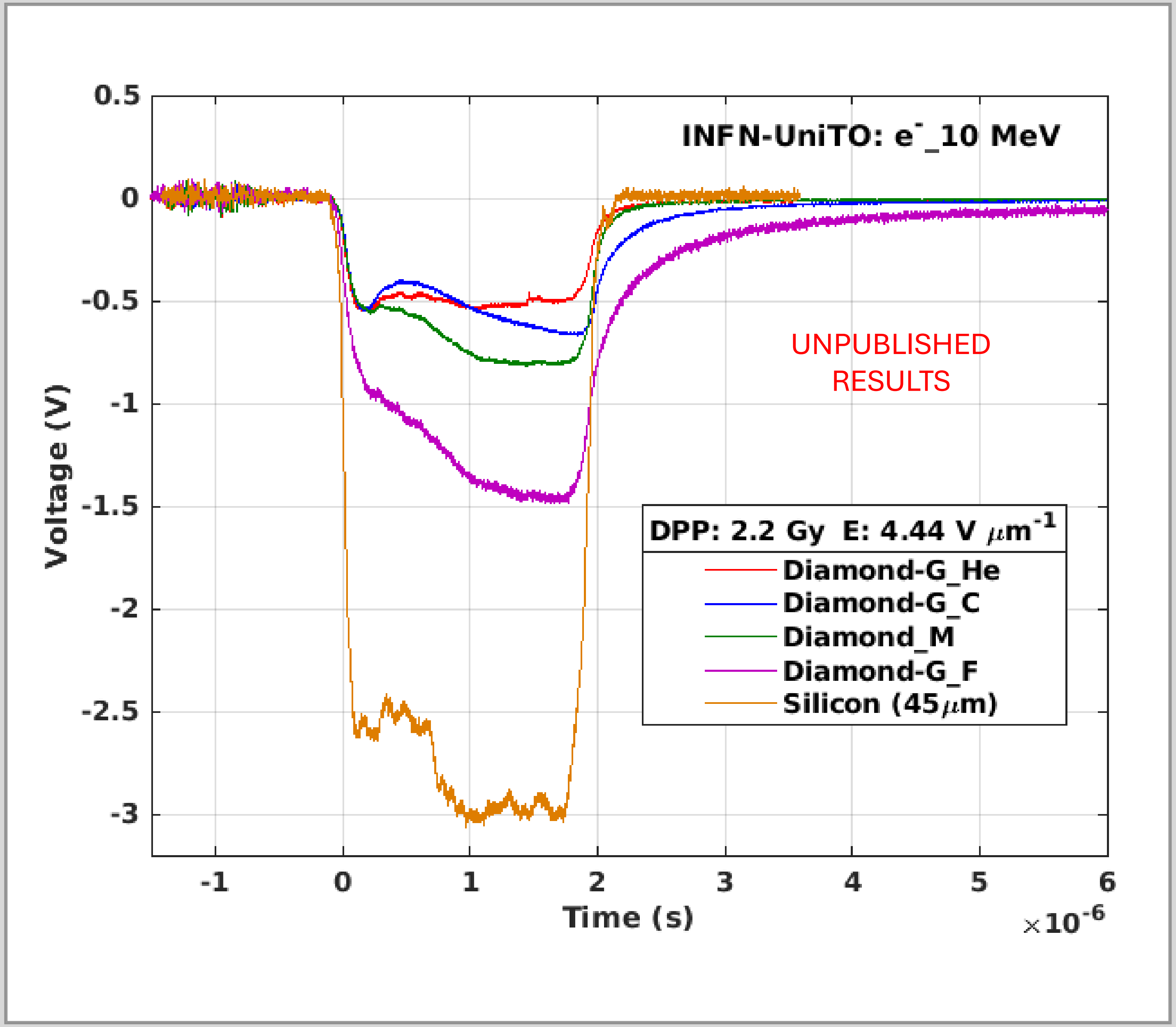
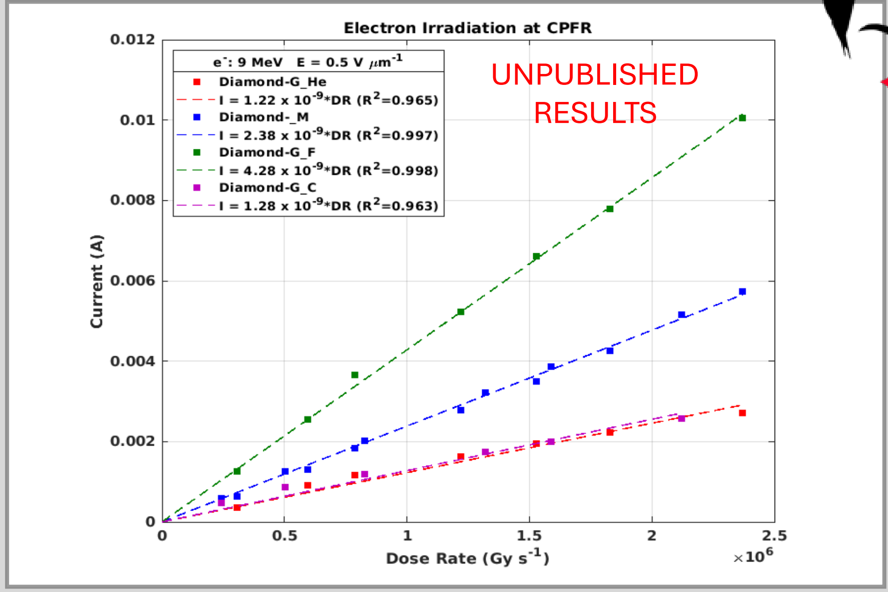


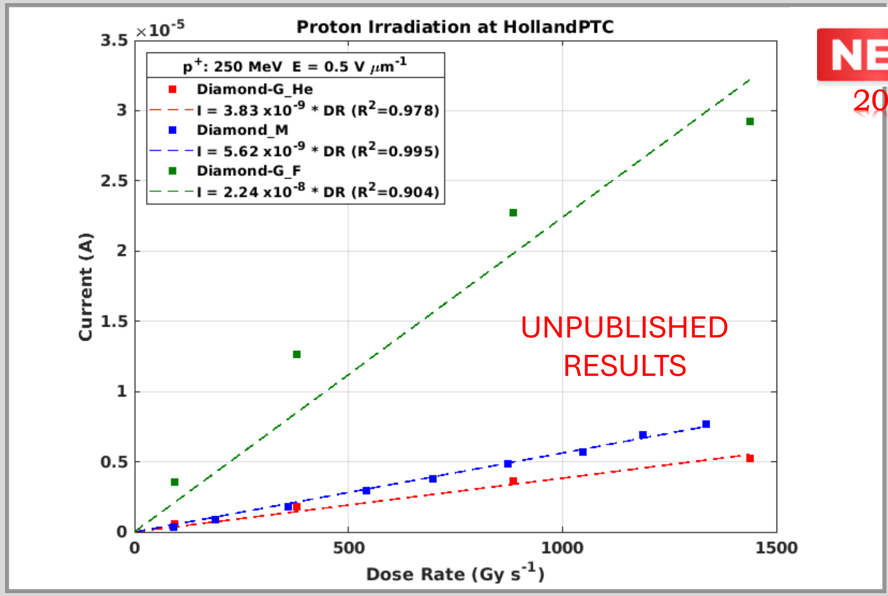
Table 1: Summary of main characteristics of the diamond-based sensor prototypes

Prototype ID	Fabrication Method	Electrode Depth	Active Thickness	Active Volume
Diamond-G_He	He^+ ion implantation + annealing	~ 3.5 µm (subsurface)	~ 93 µm	~ 0.16 mm^3
Diamond-G_C	C^+ ion implantation + annealing	≤ 50 nm (surface)	~ 100 µm	~ 0.17 mm^3
Diamond-G_F	F^- ion implantation + annealing	≤ 50 nm (surface)	~ 100 µm	~ 0.17 mm^3
Diamond_M	PVD of Ag film + annealing	Surface	~ 100 µm	~ 0.17 mm^3

Linear response performance: pCVD Diamond sensors







NEW
2025

Final Remarks

- The thin segmented Silicon Sensors exhibited:
  - High temporal resolution ($\sim ns$).
  - Linear response over a wide dose-rate range (10^1 *to* 10^7 $Gy\ s^{-1}$).
  - Good sensitivity (*suitable for UHDR applications*).
  - High-resolution beam profiling capability ($180\ \mu m$).
  - Reliable online relative dosimetry capability ($< 5\%$ uncertainty).
- The pCVD diamond sensors exhibited:
  - Consistent response across different bias voltage and dose-rate conditions.
  - Fast response time ($< 1\ \mu s$).
  - Linear response (*even at low bias voltages*).
- Silicon sensors capable of reconstructing the radiation pulse temporal structure, enabling accurate beam parameters for radiobiological investigations.
- The intercomparison demonstrated consistent behavior across sensor technologies, confirming their reliability for UHDR measurements.

Next Steps

- Radiation hardness and beam perturbation studies for full validation in beam monitoring applications.

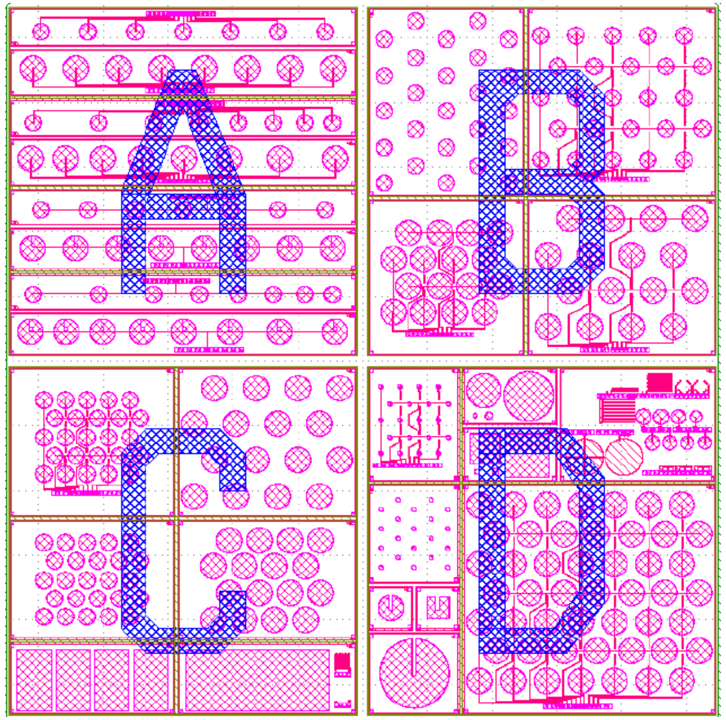
- Optimization of Si sensor active volume isolation to supress lateral charge diffusion (*Trench technology*)

- Performance assessment under VHEE beams.

- Improvement of charge collection efficiency in pCVD diamond sensors (priming, guard ring structures).

- Comparative performance evaluation of pCVD & monocrystalline diamonds sensor.

New Production (Collaboration with PRIN – MORSE)




NIKE


THANKS FOR YOUR
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