Silicon sensors for beam monitoring: first characterization with Ultra-High Dose Rate (UHDR) electron beams

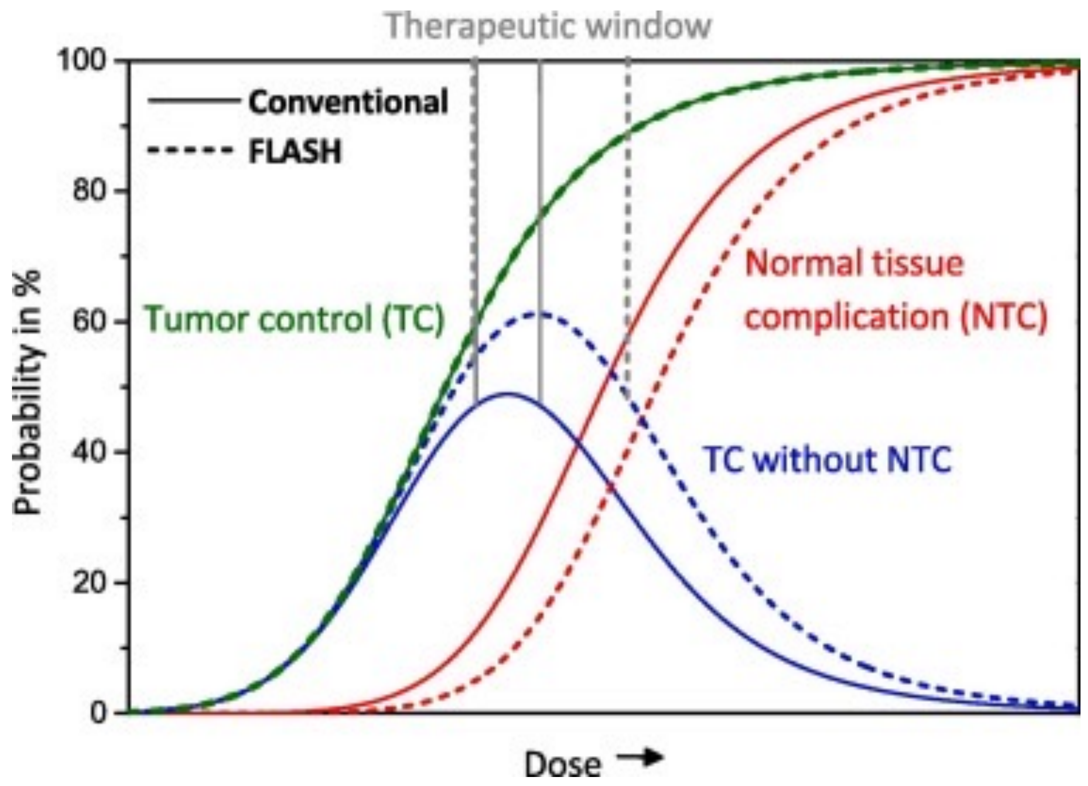
Elisabetta Medina, Aurora Camperi, Matteo Centis Vignali, Umberto Deut, Fabio Di Martino, Veronica Ferrero, Simona Giordanengo, Omar Hammad Ali, Oscar Ariel Martì Villarreal, Felix Mas Milian, Giuliana Milluzzo, Diango Montalvan Olivares, Francesco Romano, Roberto Cirio, Roberto Sacchi , Anna Vignati

FLASH radiotherapy

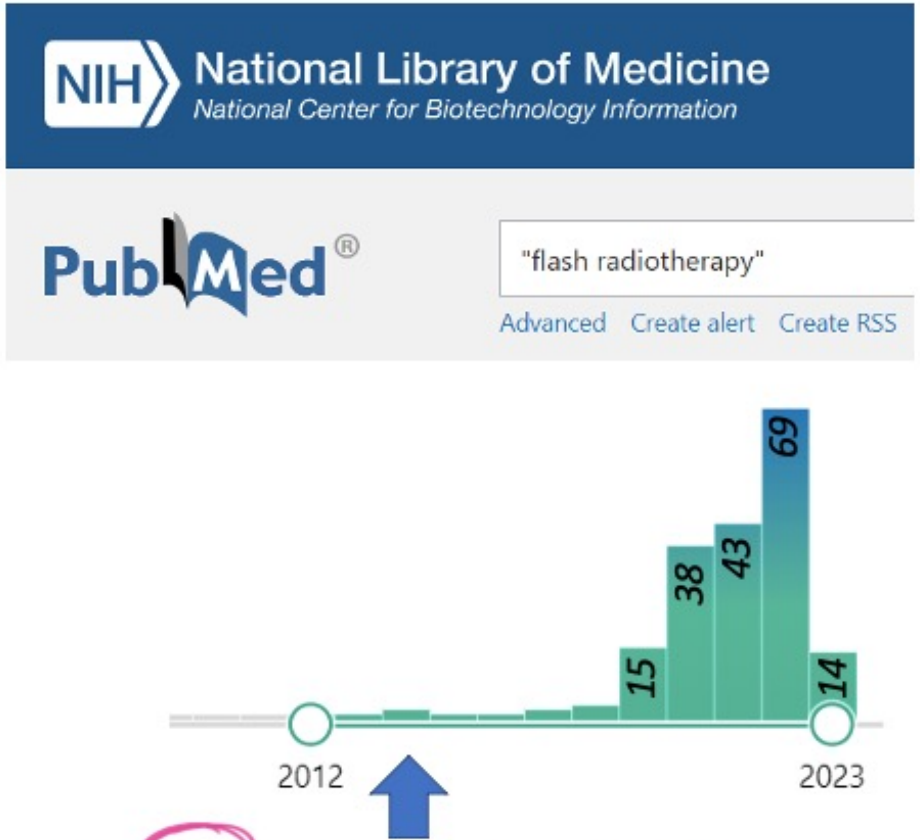
FLASH RT delivers radiation (electrons, photons, particles) at ultra-high dose rate (UHDR, average dose rate > 40 Gy/s) in < 200 ms.

Beam Characteristics	CONV	FLASH
Dose Per Pulse D_p	~0.4 mGy	~1 Gy
Dose Rate: Single Pulse $\dot{D}_p$	~100 Gy/s	~10^5 Gy/s
Mean Dose Rate: Single Fraction $\dot{D}_m$	~0.1 Gy/s	~ 100 Gy/s
Total Treatment Time T	~days/minutes	< 500 ms

FLASH EFFECT:
Does not induce classical radiation induced toxicity in normal tissues. Retains antitumor efficacy compared to standard RT



FLASH radiotherapy

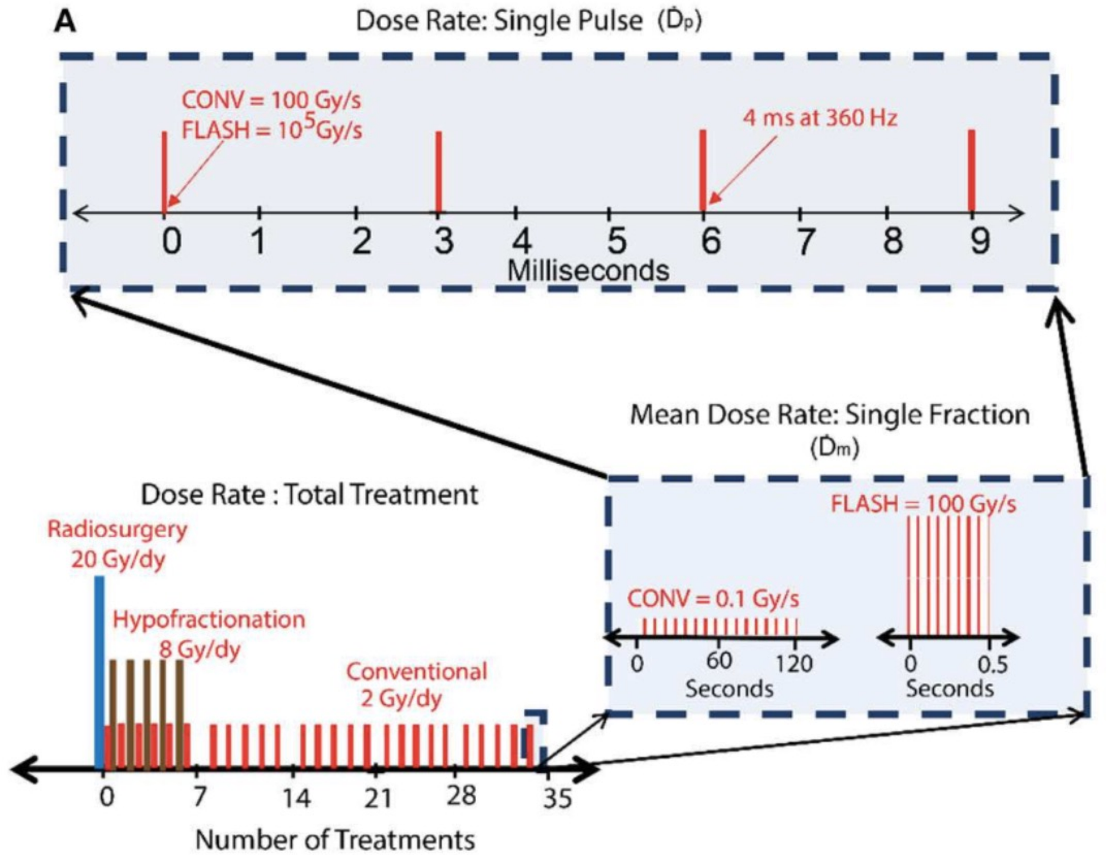


› Sci Transl Med. 2014 Jul 16;6(245):245ra93. doi: 10.1126/scitranslmed.3008973.

Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice

Vincent Favaudon [1], Laura Caplier [2], Virginie Monceau [3], Frédéric Pouzoulet [4], Mano Sayarath [4], Charles Fouillade [4], Marie-France Poupon [4], Isabel Brito [5], Philippe Hupé [6], Jean Bourhis [7], Janet Hall [4], Jean-Jacques Fontaine [2], Marie-Catherine Vozenin [8]

- A crucial role: **dose delivery time structure** (parameters need to be kept under control)
- The most of the pre-clinical studies using **electron** beams (by LINACs with E<20 MeV)



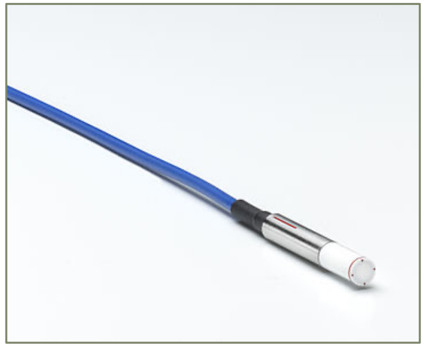
Beam monitor systems

- Continuous check of beam parameters
- **IC CONV**: Gas-filled IC → **IC UHDR** : high rate of recombination, too slow
- Need of **new beam monitoring device** to stop delivery of a FLASH dose **quickly enough**

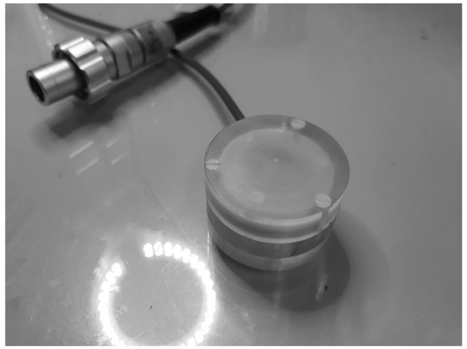
Conventional IC used in LINACs

- High temporal resolution
- High spatial resolution
- Beam transparency
- Large response dynamic range
- Large sensitive area
- Radiation hardness

DOSIMETERS

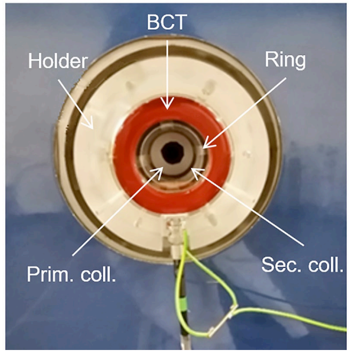


PTW 60019 microDiamond



Ultra-Thin Ionization chamber (UTIC)

BEAM MONITOR



Beam Current Transformers (BCT)

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INFN Istituto Nazionale di Fisica Nucleare

FLASH **R**adiotherapy with h**I**gh **D**ose-rate particle be**A**ms

New beam monitoring technologies:

- ❑ Air-fluorescence based
- ❑ ICT
- ❑ Multi-gaps ion chamber
- ❑ SED
- ❑ **Solid-state detector**

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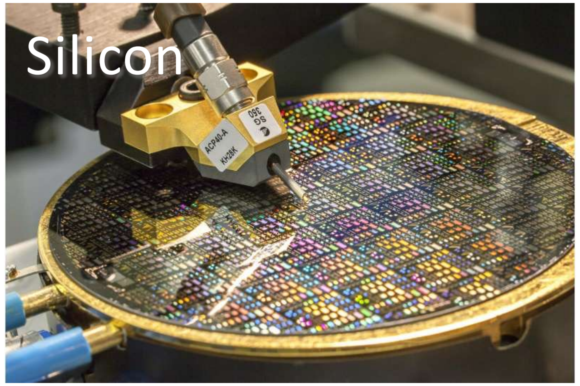
Solid State Devices for Beam Monitoring



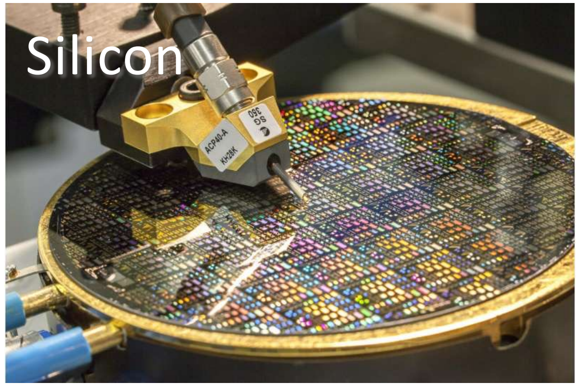
- Ultra-thin ~10µm, segmented, high polarized
- **High sensitivity, spatial res, developed technology**
- Unkown factors: linearity with dose-rate, recombination effect, radiation resistance

- Radiation hardness, high resistivity, large saturated carrier velocity
- Challenging issues: dose-rate linearity, possibility of straddle areas several cm^2

- High electrical stiffness, speed of charges, melting T, thermal diffusivity, industrual maturity
- Preliminary sim: dose-rate linearity up to 10^{11} Gy/s on X-ray beams for SiC membrames (2 μm thick)

STLAB

Solid State Devices for Beam Monitoring



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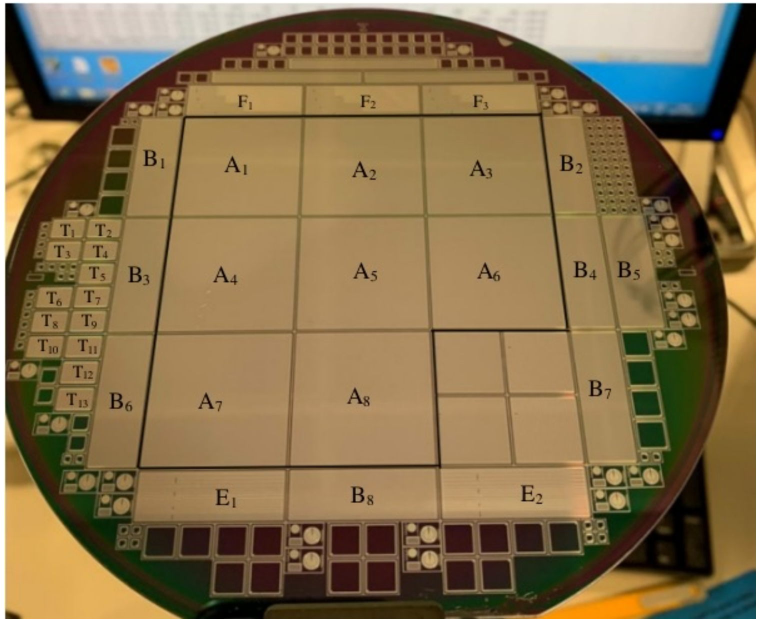
STLAB

Turin Medical Physics group expertise

- Ultra-Fast Silicon Detector (UFSD) based on LGAD technology within INFN **MOveIT** project (FBK production)
- p^{+}gain layer under the n^{++} cathode
- Two prototypes: 1) **Proton counter** for clinical proton beam 2) Device to measure **beam energy using TOF** technique



FONDAZIONE BRUNO KESSLER

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MoVe IT

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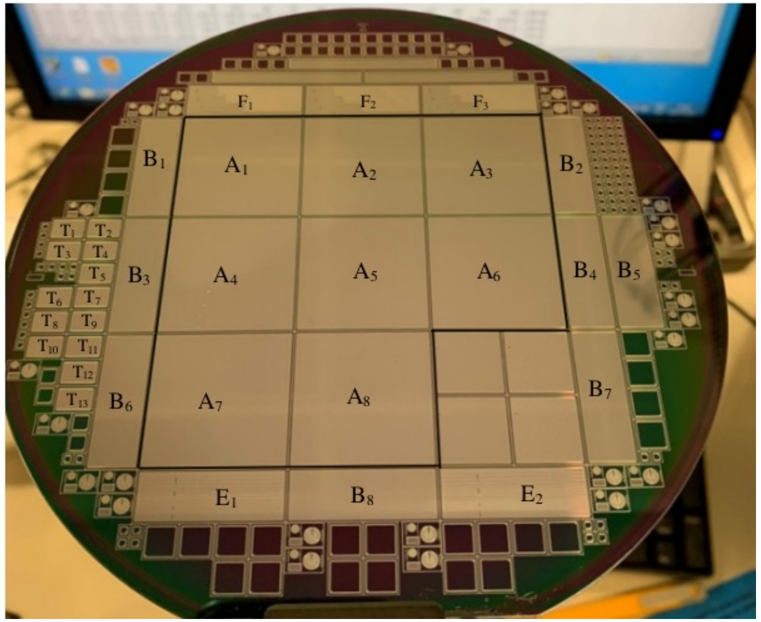
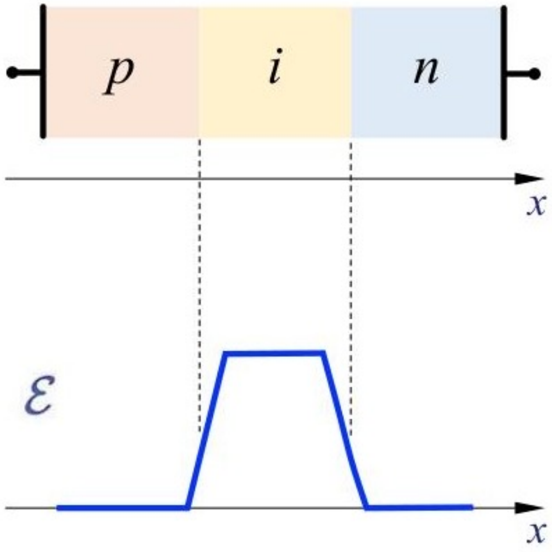


UHDR beams

PiN detector used
(Q generated large enought
NO GAING NEEDED)



Thin silicon detectors

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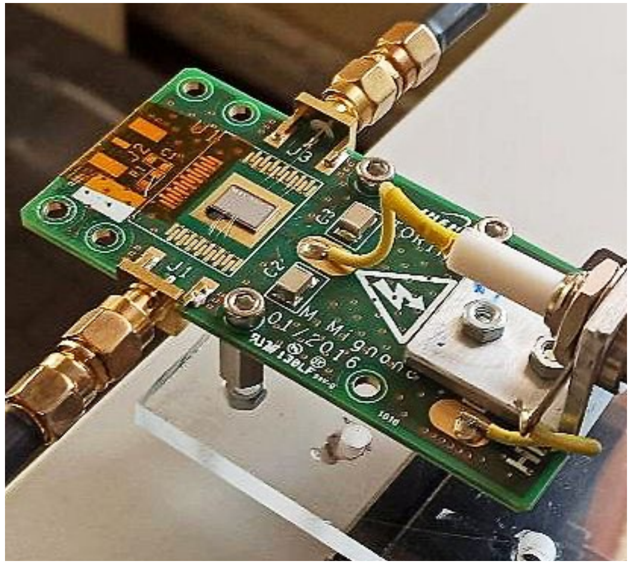
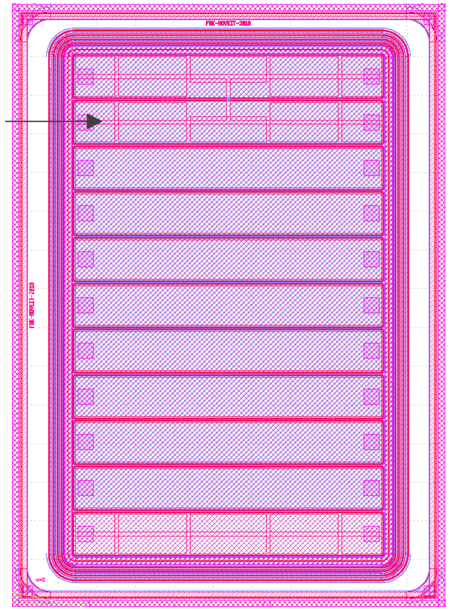
Silicon devices in Turin: used so far for *single particle counting* → With **TERA08** signal can be integrated

FONDAZIONE BRUNO KESSLER



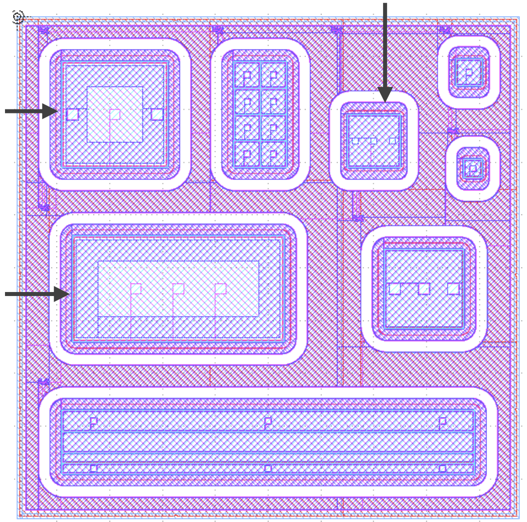
Mounted on HV distribution board

- **11 strips sensor (pin) [MoVeIT]**
- Strip area 2.2mm^2, active thickness 45 μm, total thickness 615 μm)



For **preliminary tests** on conventional e⁻ beams

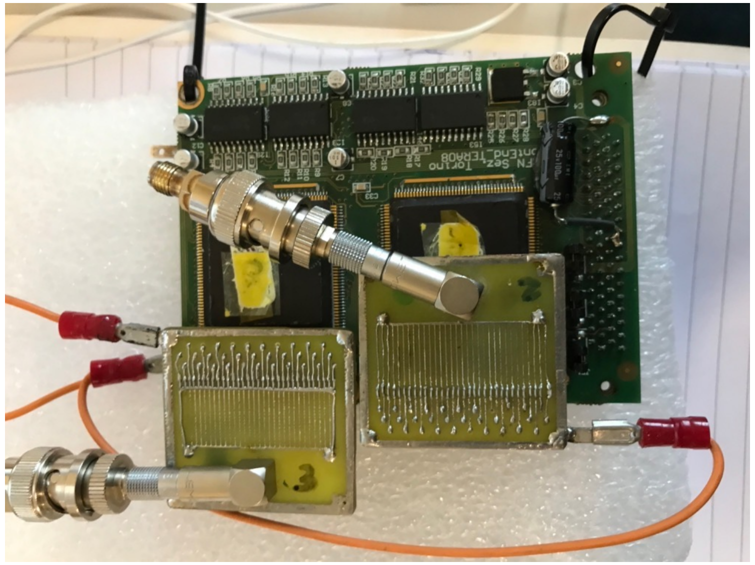
- **3 pad sensors (pin) [eXFlu]**
- Areas 2/1/0.25 mm^2, active thickness **45/30 μm**, total thickness 615 μm)
- (Thanks to **Valentina Sola**)



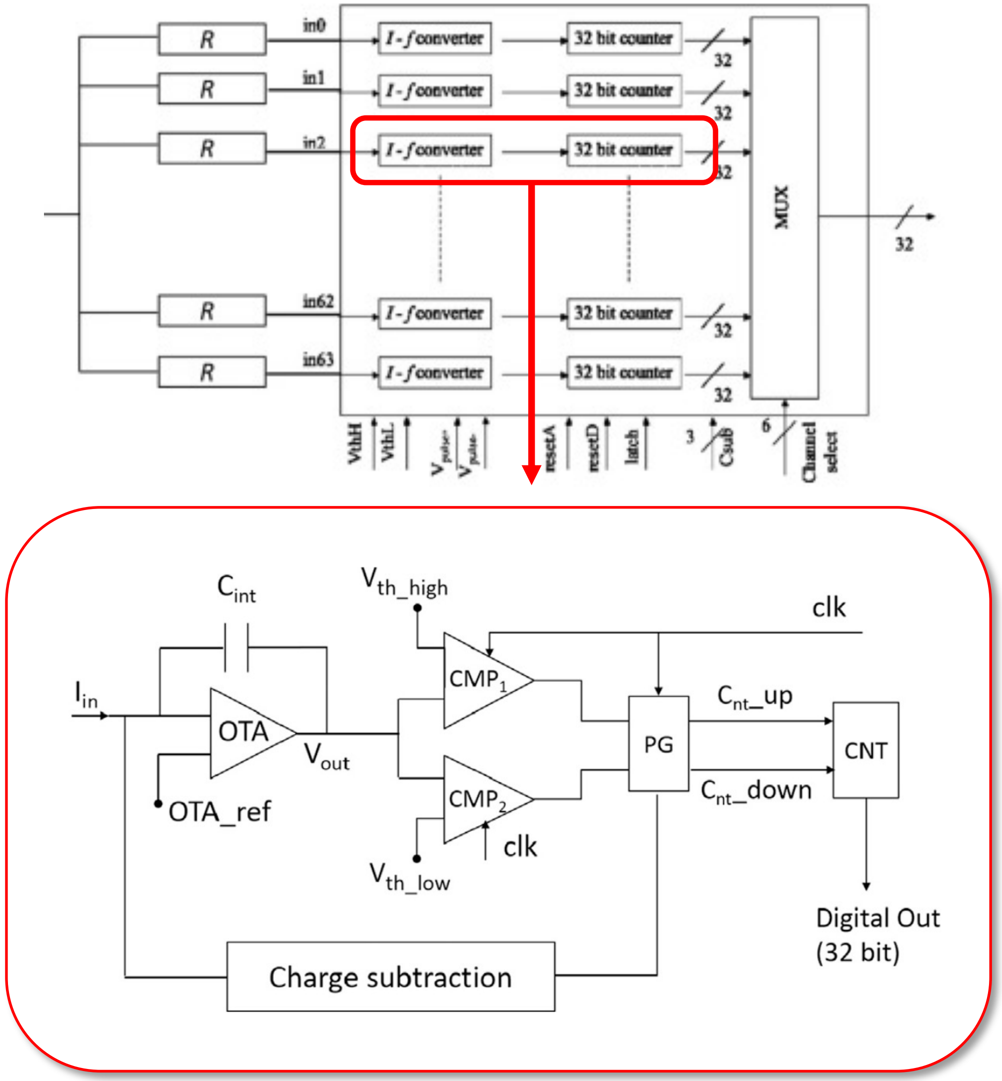
To compare **different areas and thickness** on UHDR beams

Readout system: TERA08

- Readout with **TERA08** (64 equal CHNs)
- In each CHN **current-to-frequency converter** (each digital pulse = fixed input charge quantum)
- Converter based on **recycling integrator architecture**



Chip structure



DAQ Period (µs)	Q_c(fC)	Max conversion freq per chn	Max conversion (total)	Max current (for 64 CHNs)
1e4 (0.01 s)	200 fC	20 MHz	1280 MHz	± 256 μA

First tests with conventional electrons beams

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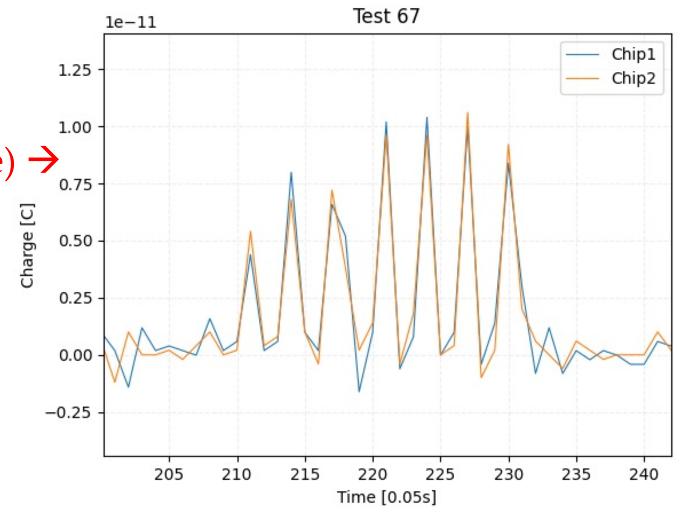
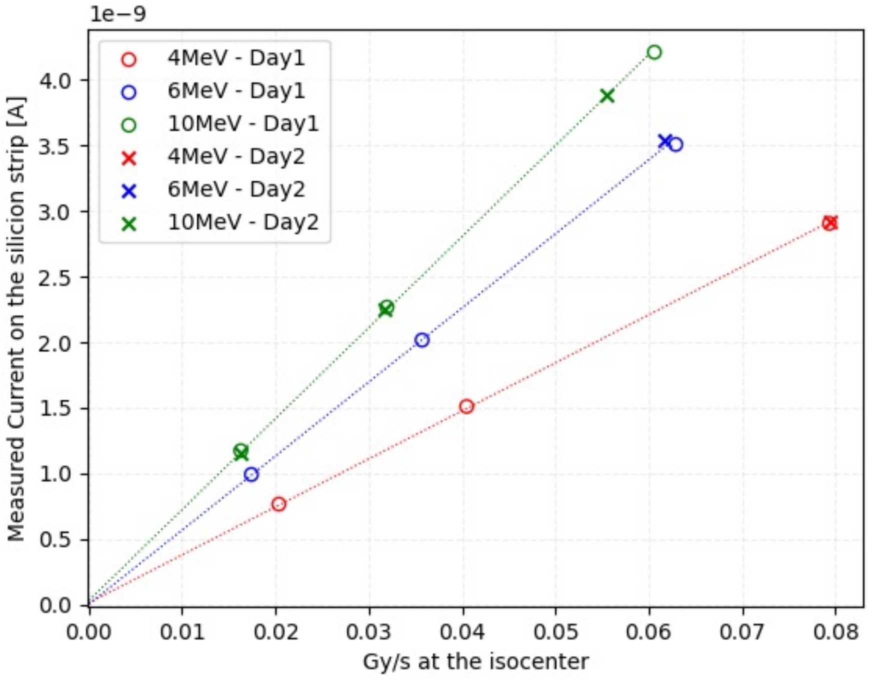
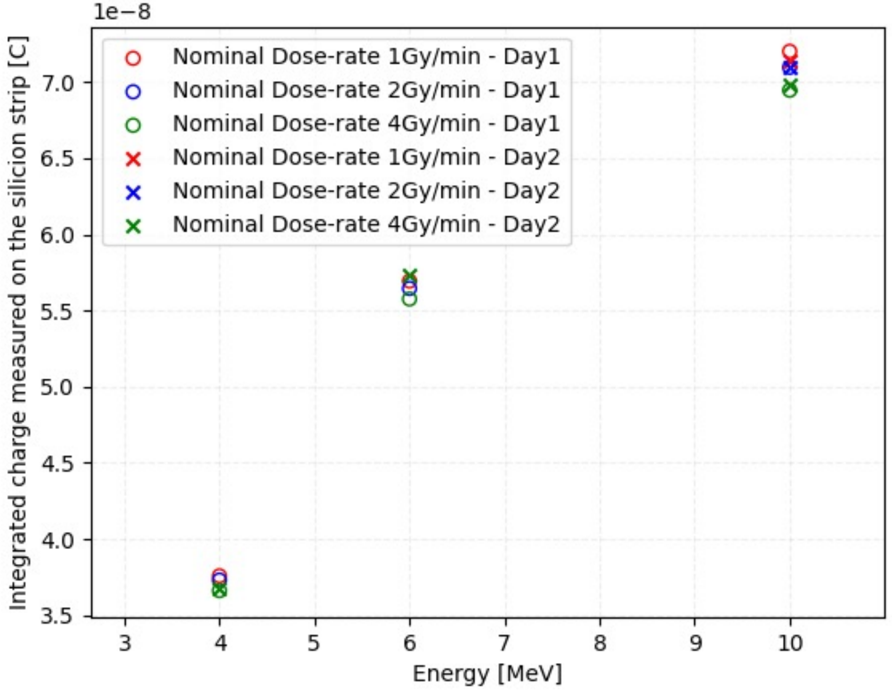
- Conventional beams at **LINAC Elekta SL18**
- 2 strips of 45μm sensor connected to TERA08

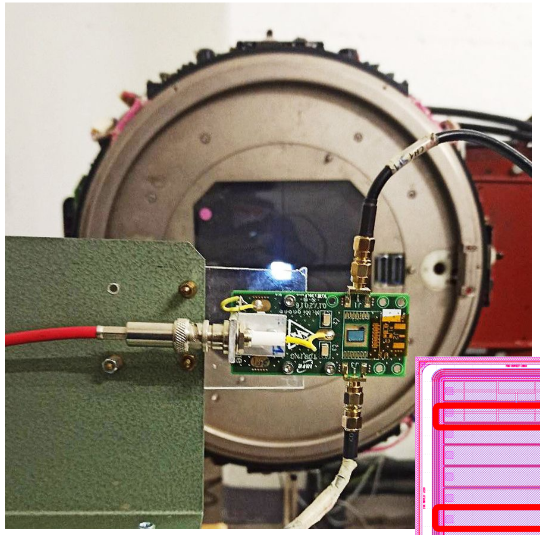
Example of data acquisition (7 pulses clearly distinguishable) →

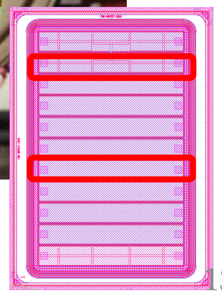






Elekta





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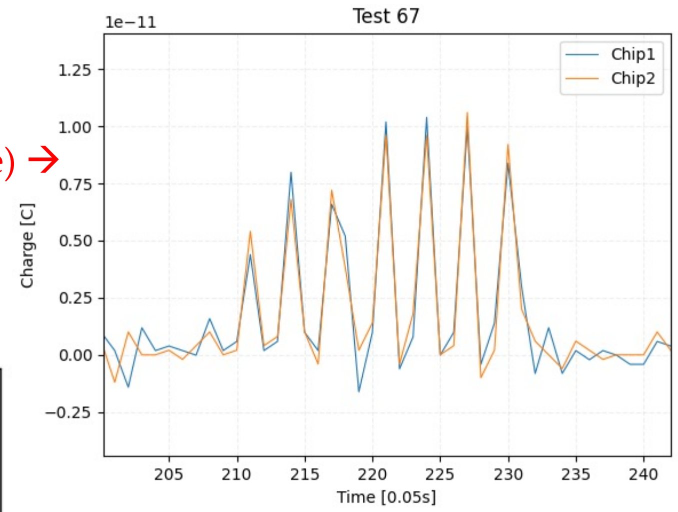
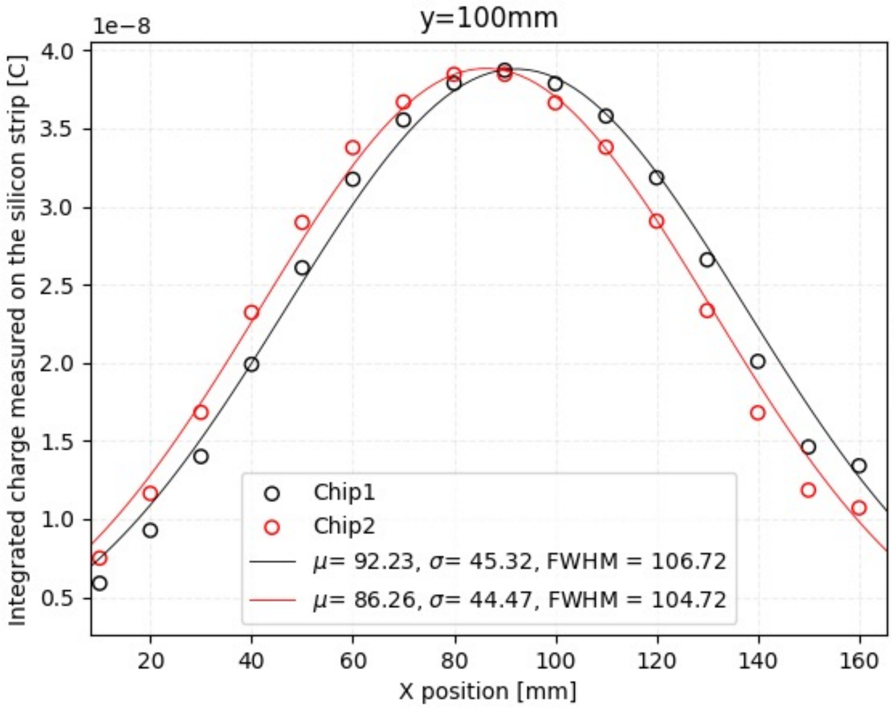
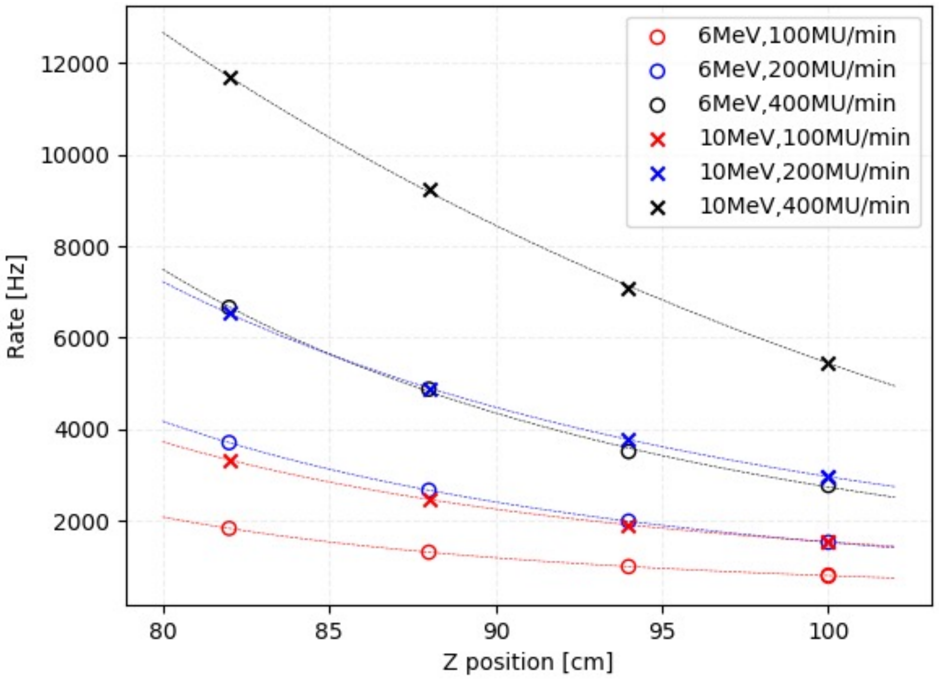
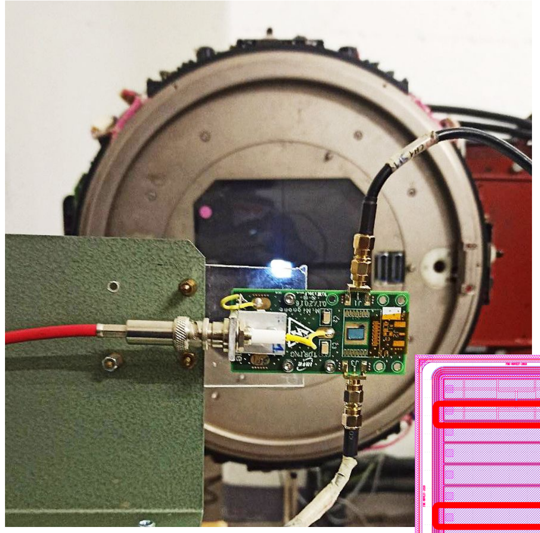


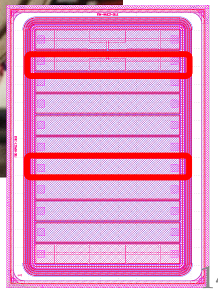


6MeV, 200 MU/min, 50 MU tot, FS 10X1 cm
FWHM compatible with field size

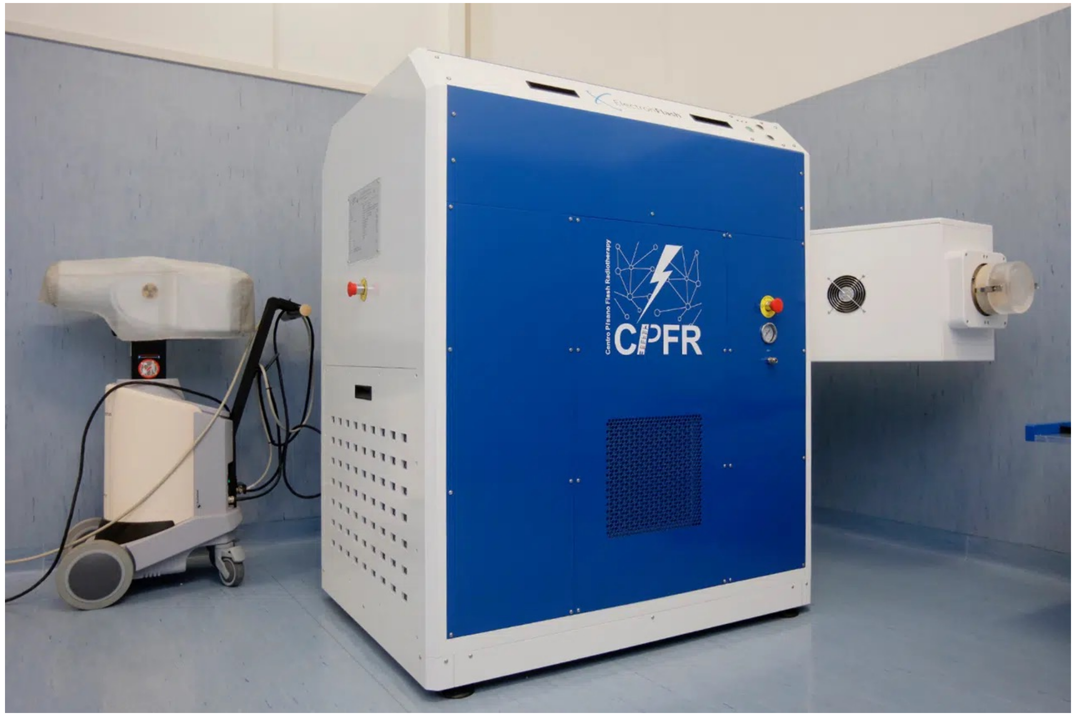


Rate measured as a function of the distance. The data were fitted with the function **y=a+b/(x-c)³**





First characterization with FLASH beams



- **ElectronFlash accelerator** (Centro Pisano Multidisciplinare sulla Ricerca e Implementazione Clinica della Flash Radiotherpy)
- Sordina IORT Technologies S.p.A (**S.I.T**)
- 7 MeV and 9 MeV
  Beam current: 1-100 mA
  Pulse duration: 0.5-4 μs
  Pulse frequency: 1-249 Hz
- **Indipendent variation of parameters** (possible study of the volume effect in FLASH/non-FLASH mode conditions)
- Uniformity of dose profile: PMMA plastic applicator (different max dose-rate)

First characterization with FLASH beams

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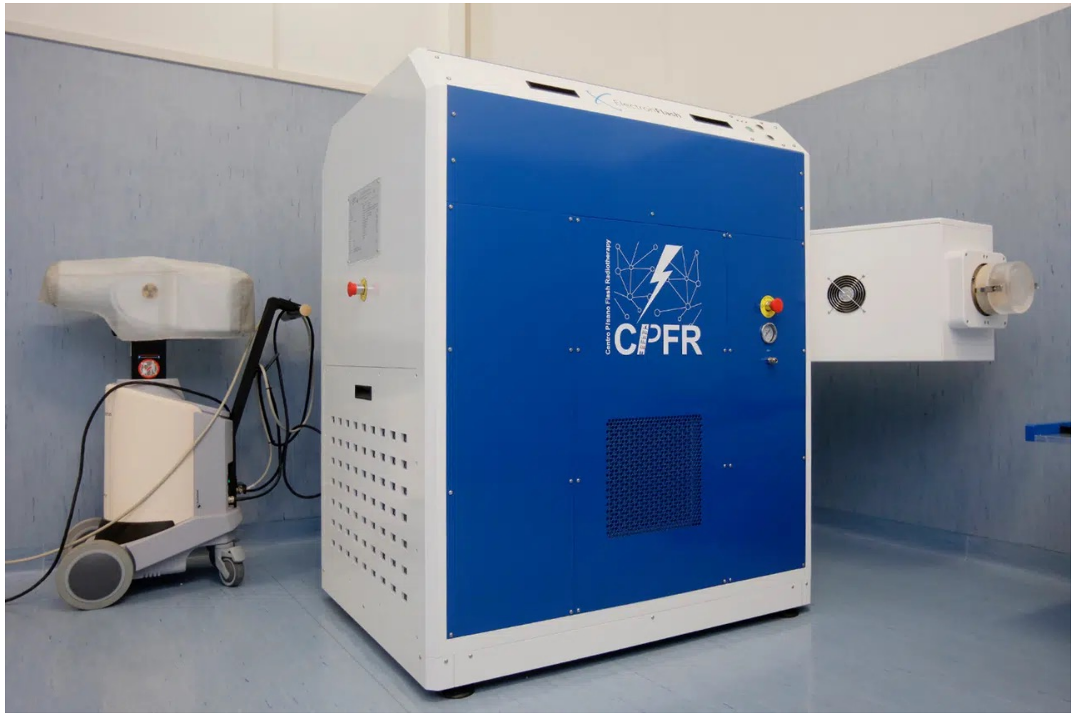
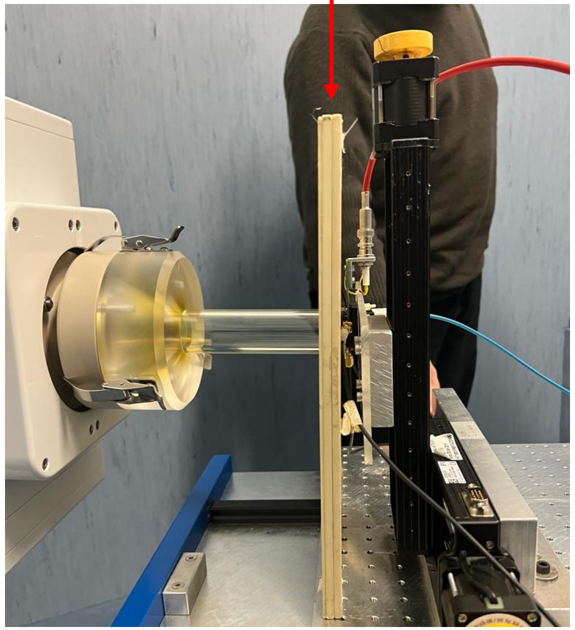
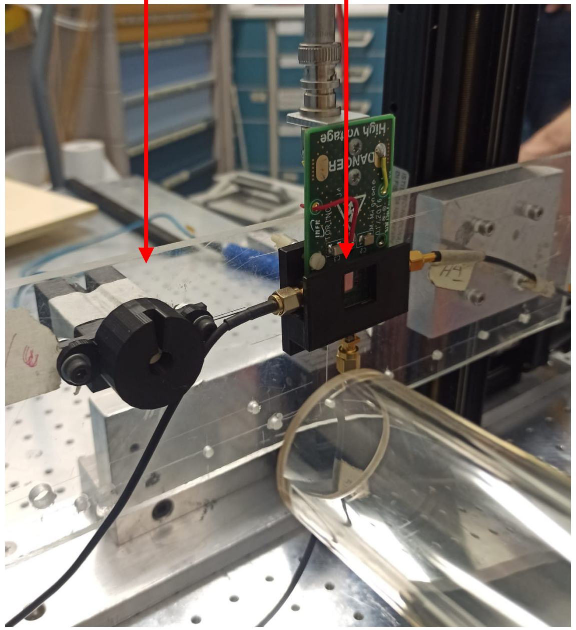
- **9 MeV**, **3 cm** diameter PMMA applicator (up to **~ 10 Gy/pulse**), **4μs** pulse duration
- 13 mm solid water slab (reduced air gap between slab-sensor)



13mm solid water slab



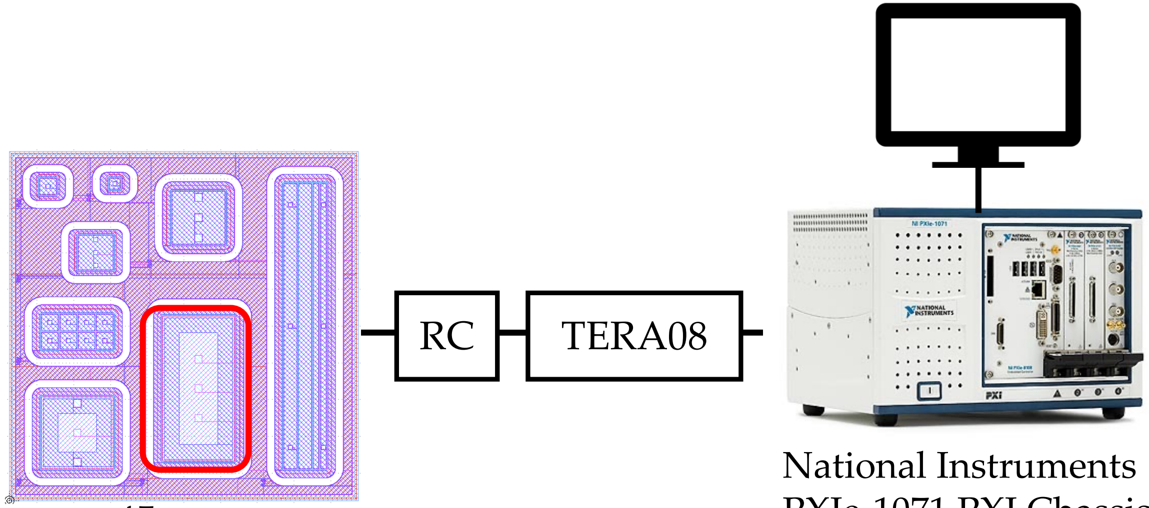
FlashDiamond and silicon sensor in same conditions



Experimental setup

TERA08 measurements

- 45 μm thickness, 2mm^2 area
- RC circuit to extend signal duration and **not exceed 256μA** for 64 chns
- RC connected to TERA08 and NI module
- Bias voltage 200 V
- Increasing dose-per-pulse (DPP) from 0 to ~10Gy/pulse



45μm

National Instruments
PXIe-1071 PXI Chassis

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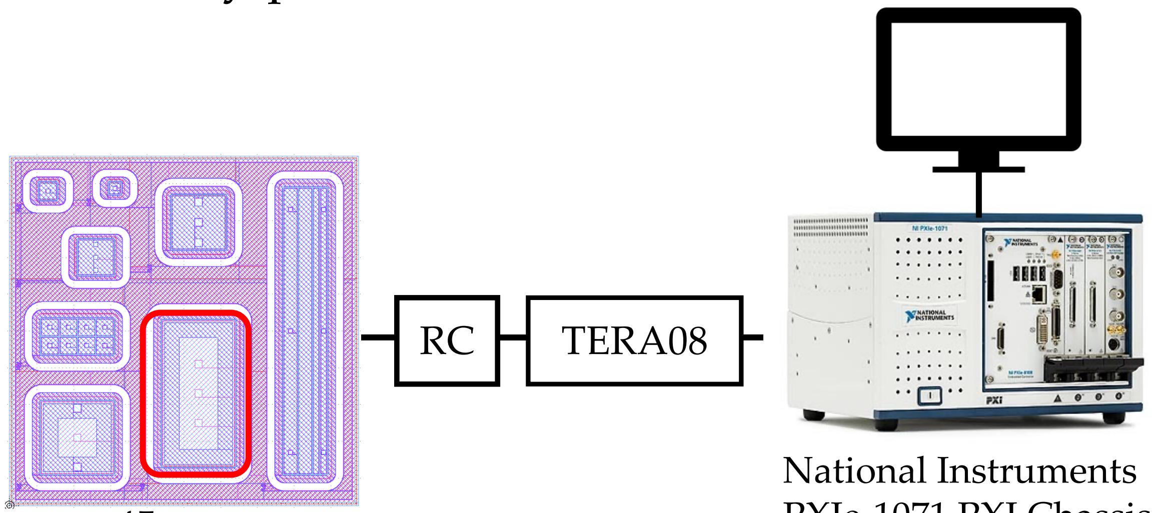

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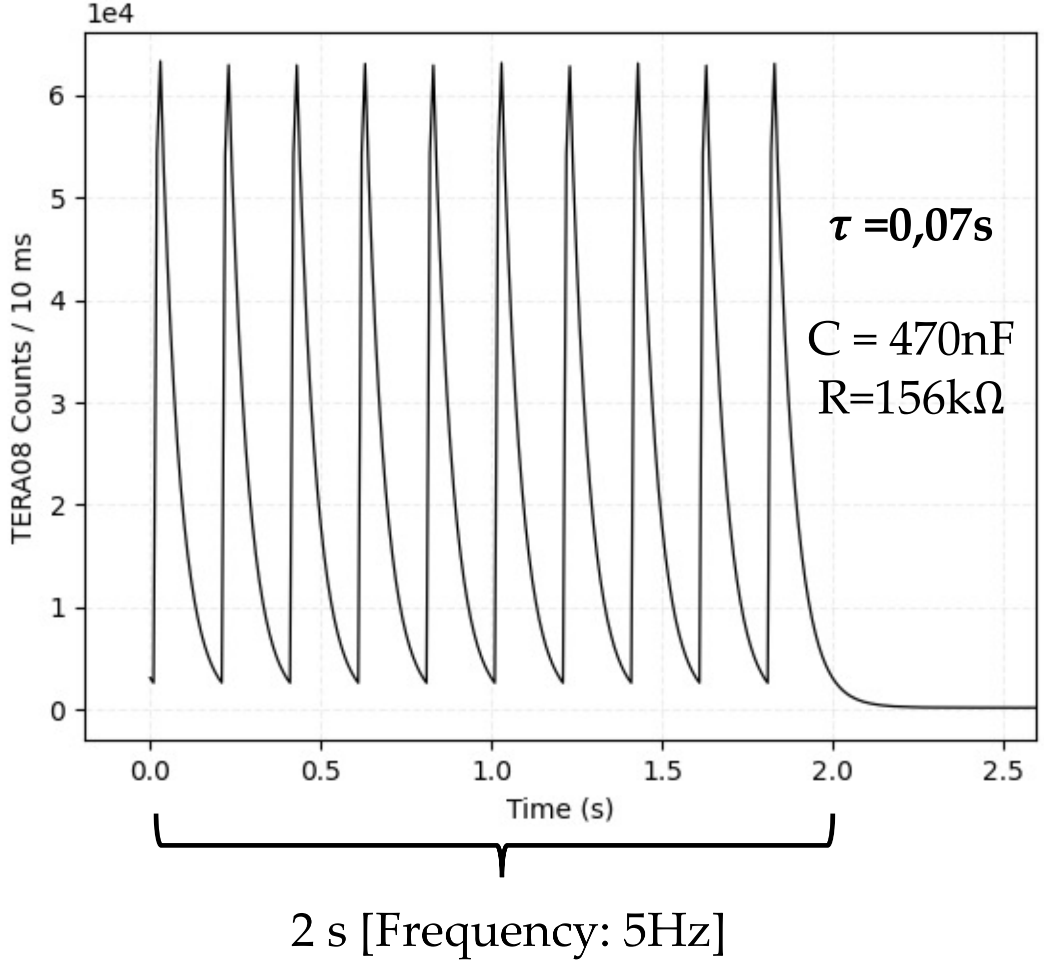

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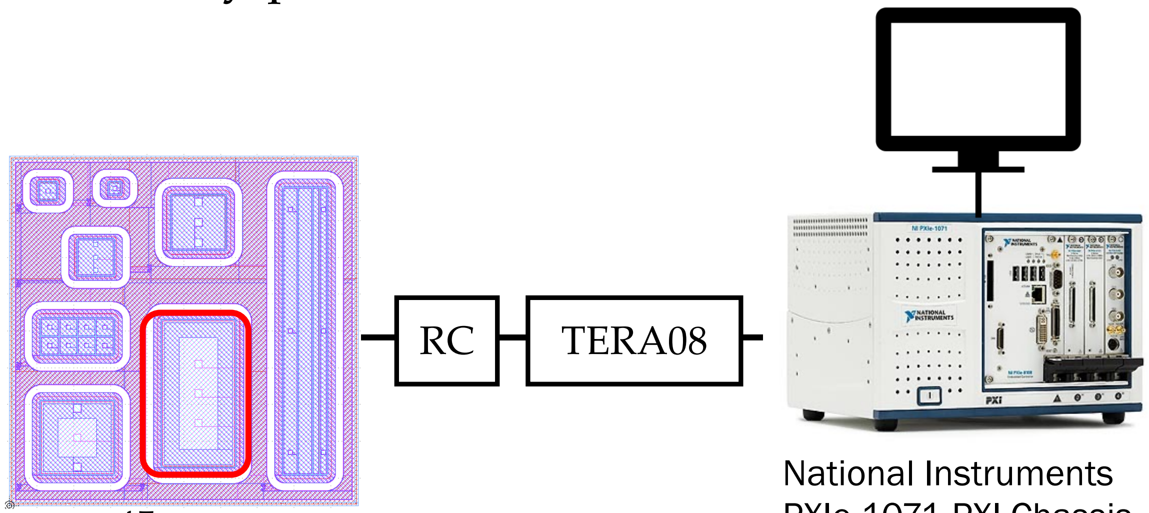
Oscilloscope measurements

- 45μm / 30μm thickness, 2mm^2, 1mm^2 ,0.25 mm^2 area
- 3 pads connect to 3 oscilloscope channels
- Bias voltage: 10V, 50V, 100V, 150V, 200V
- Increasing DPP (from 0 to ~10Gy/pulse)
- Compare **different areas/thickness** charge generation



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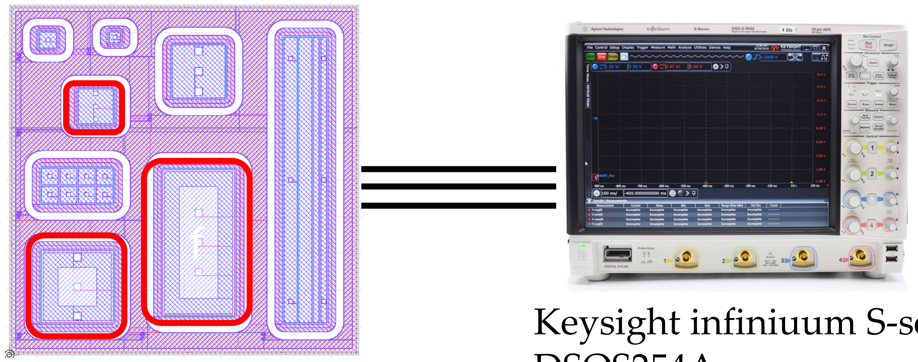

30/45μm

Keysight infiniuum S-series DSOS254A

TERA08 and oscilloscope comparison

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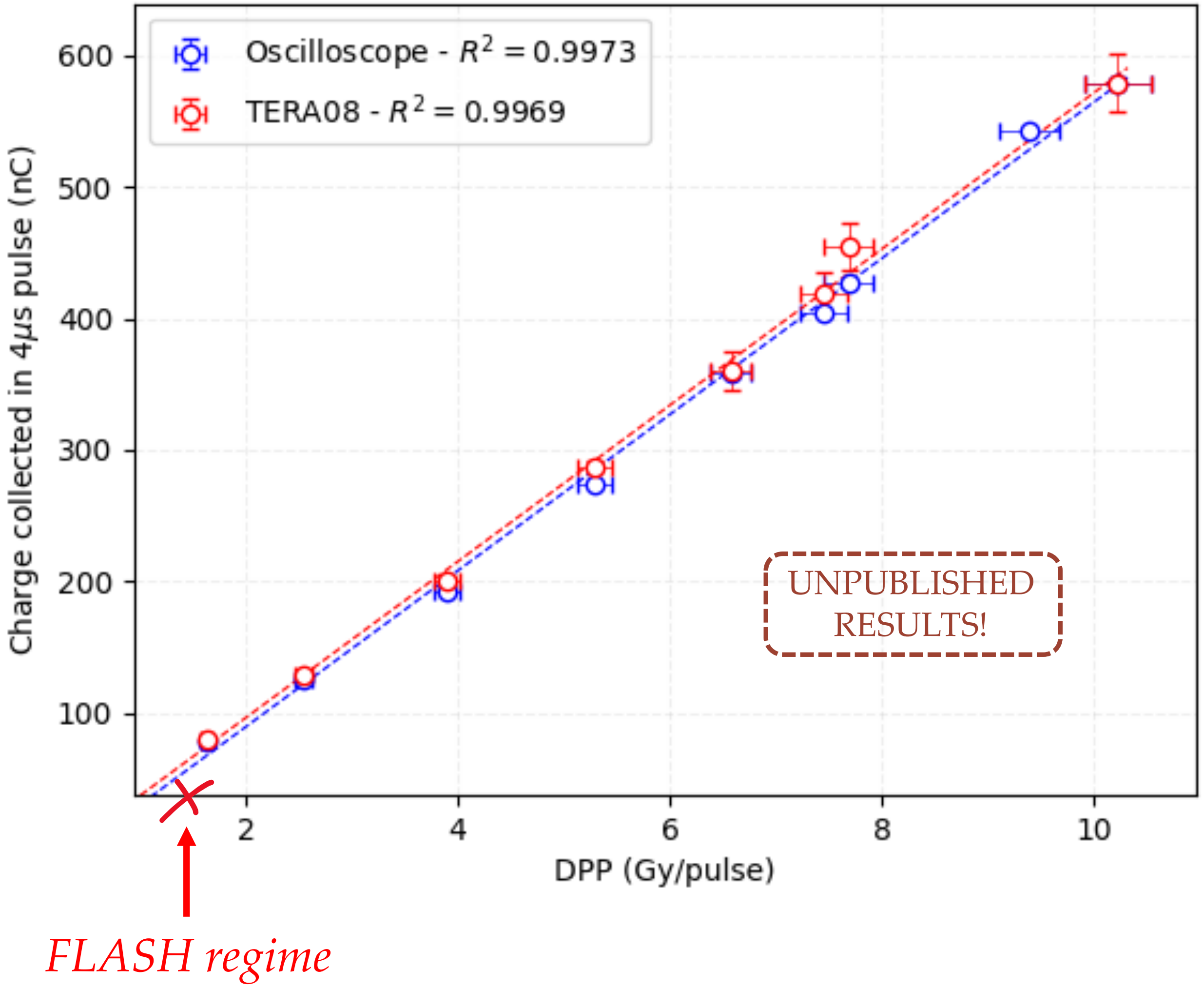
- 45 μm thickness, 2mm^2 area
- 200V bias voltage
- **Good linearity** ($R^2 > 99\%$) up to dose-rates >10Gy/pulse (1Gy/pulse is already FLASH regime)
- **Good correlation** of charge measured with TERA08 and oscilloscope



Electric Field distortion

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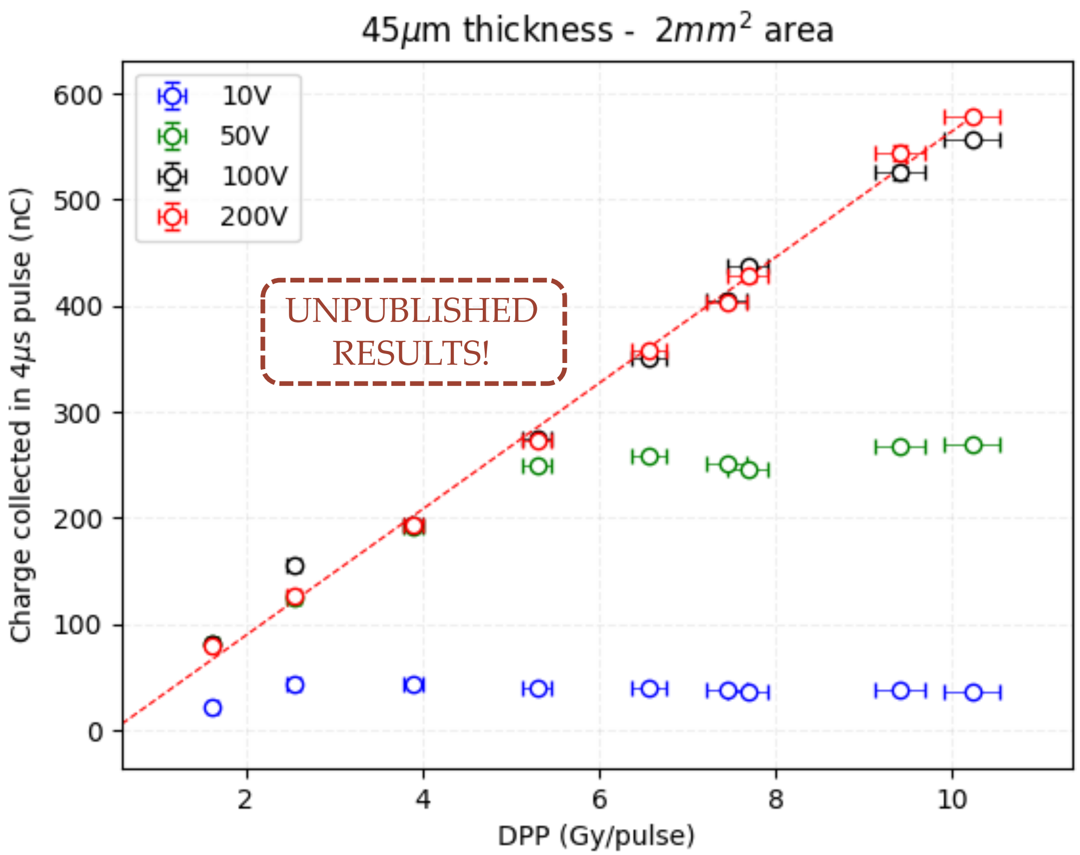
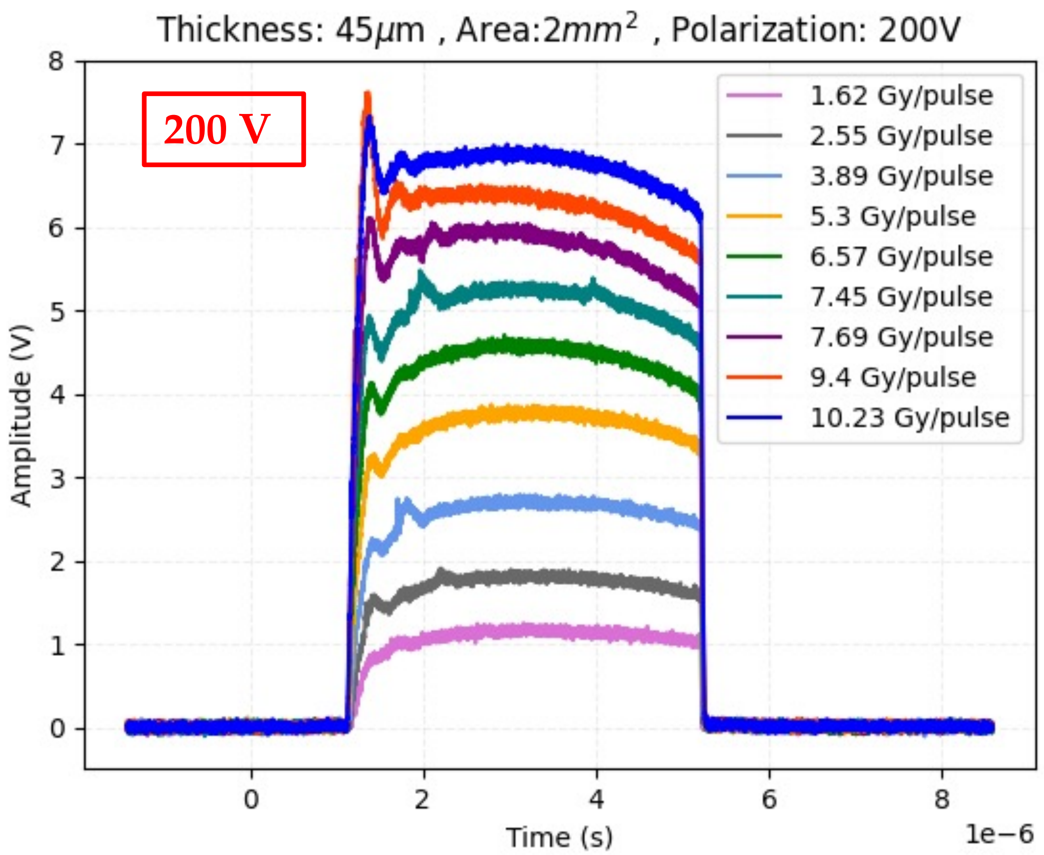
- At bias < 150 V (where the sensor is completely depleted) a shortening of the signal was observed**: electric field distortion** at high dose rates?
- **TCAD Sentaurus simulations** ongoing





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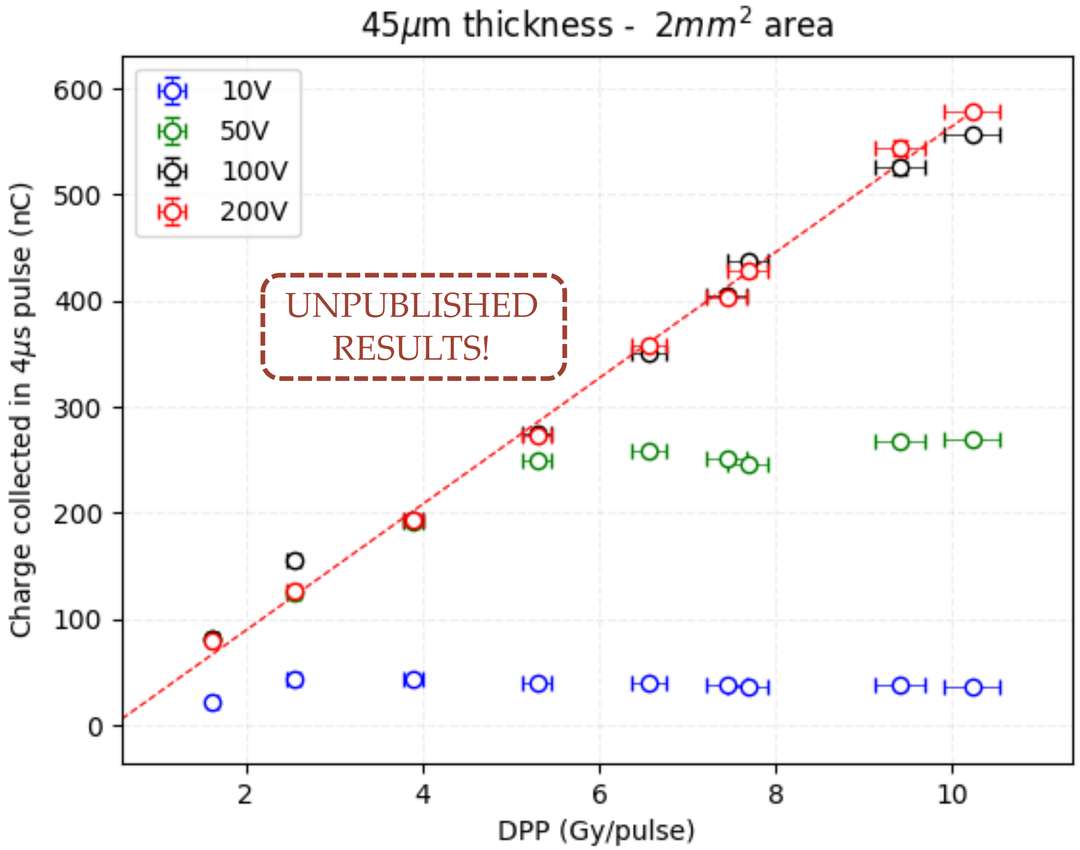
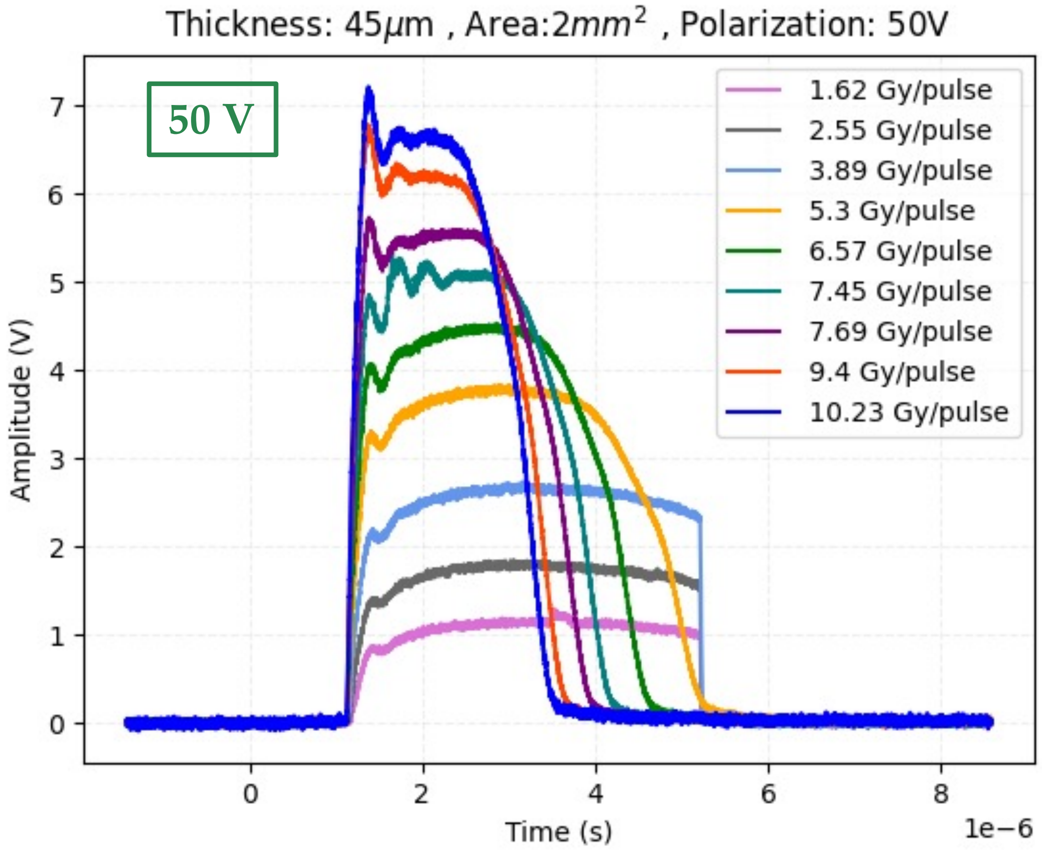
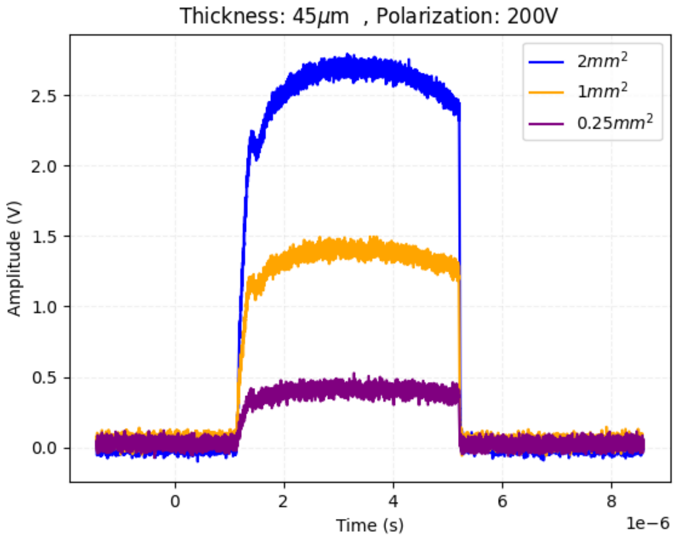
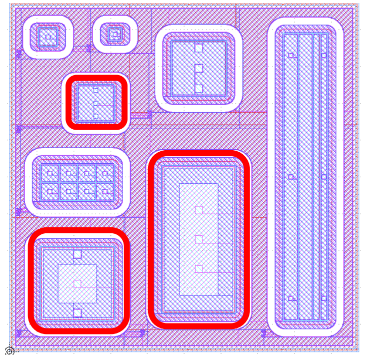


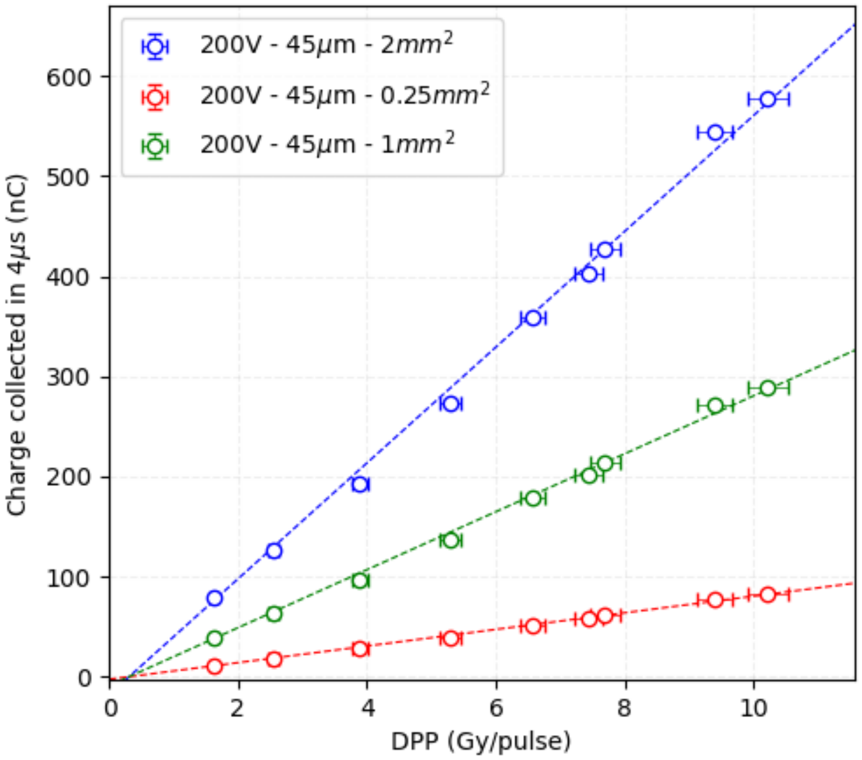


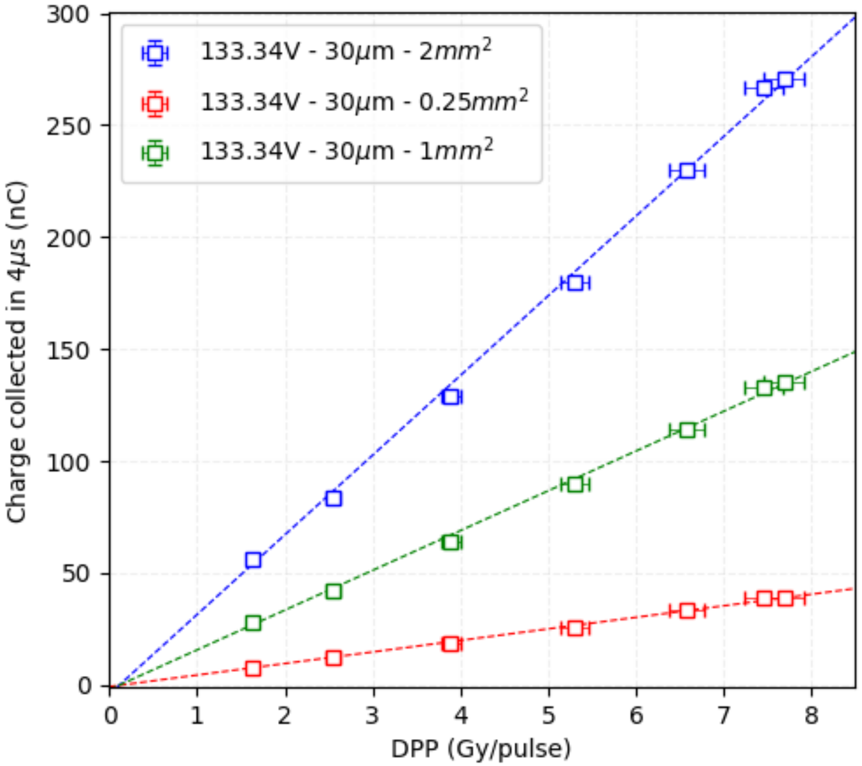
Area and thickness

- Comparison of Q produced in **different thicknesses** and **areas** with the **same electric field** (~ 4.44 V/μm)
- Varies proportionally to the pad area and to the sensor thickness.
- **Ratio** between charges collected in different pads **independent of the DPP**: volume-dependent effects of recombination of charge carriers are playing a negligible effect.









Next steps: TERA09

WORK IN PROGRESS!

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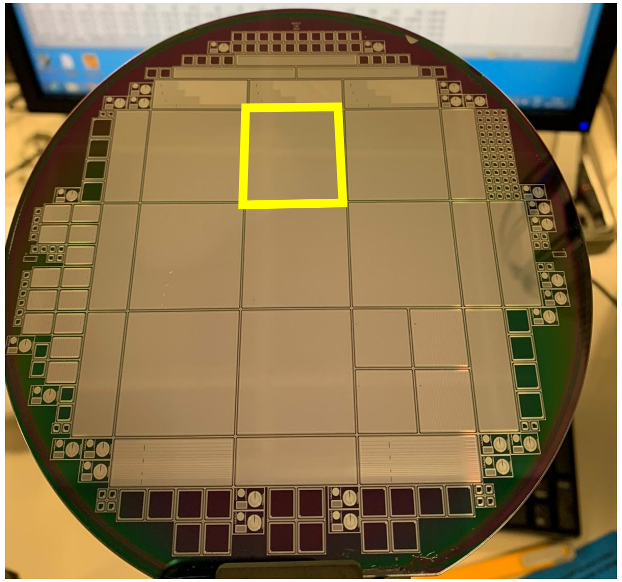
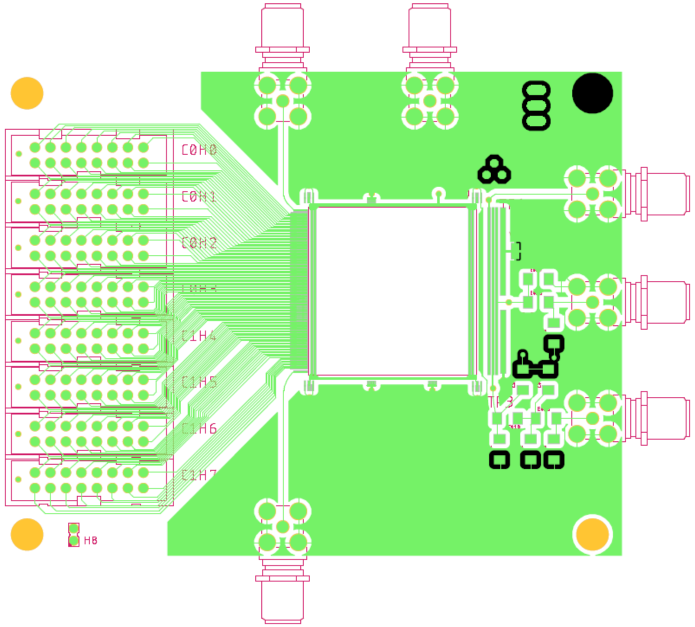
- Frontend chip based on 64 charge recycling CHNs
- **Extended current range** with respect to TERA08 (preliminary design and test phase): 12 μA / chn with 200 fC.
- Larger sensor (Area 2.7×2.7 cm^2 and 146 strips) to cover all beam spot area (~ cm^2)
- Strip based / pad based system: **Online control** of beam shape and dose after **one single shot**

Large sensor



[Designed to cover proton beam spot]

Detector board



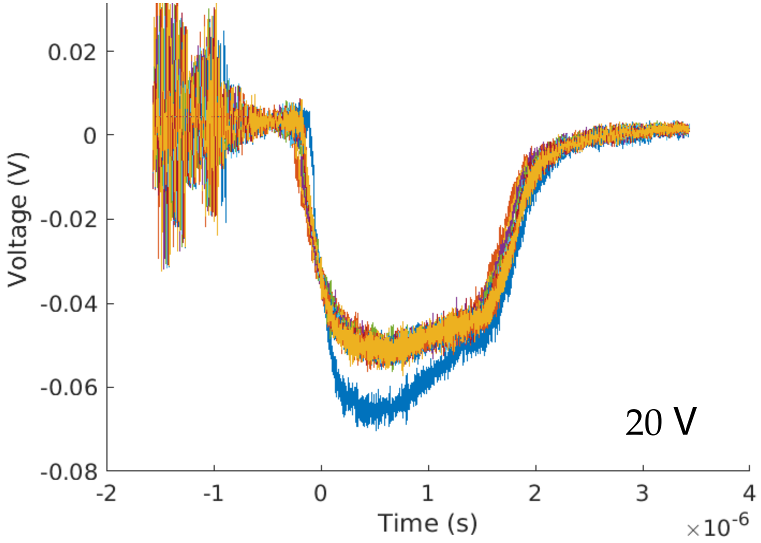
TERA09

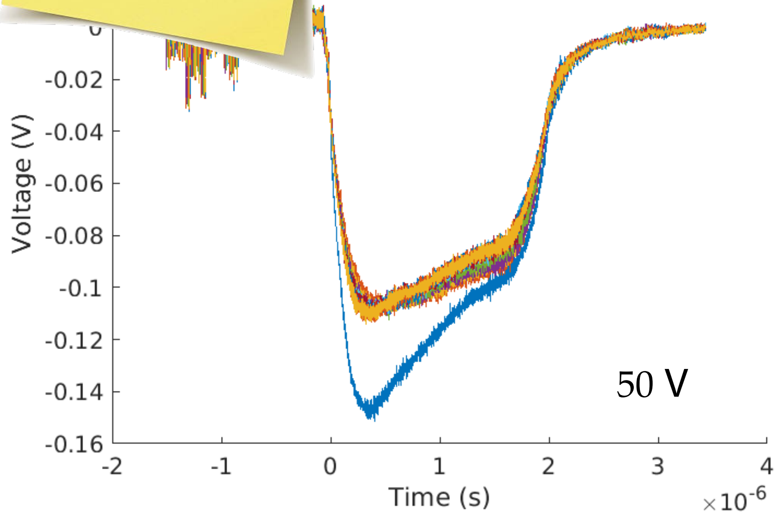
Current range	100 pA-100 μA
Max conv freq	62.5 MHz

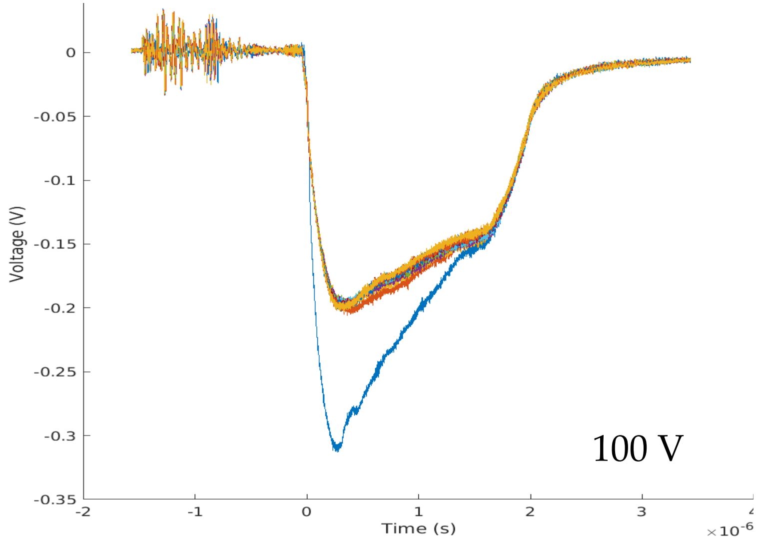
Next steps: Diamond detector

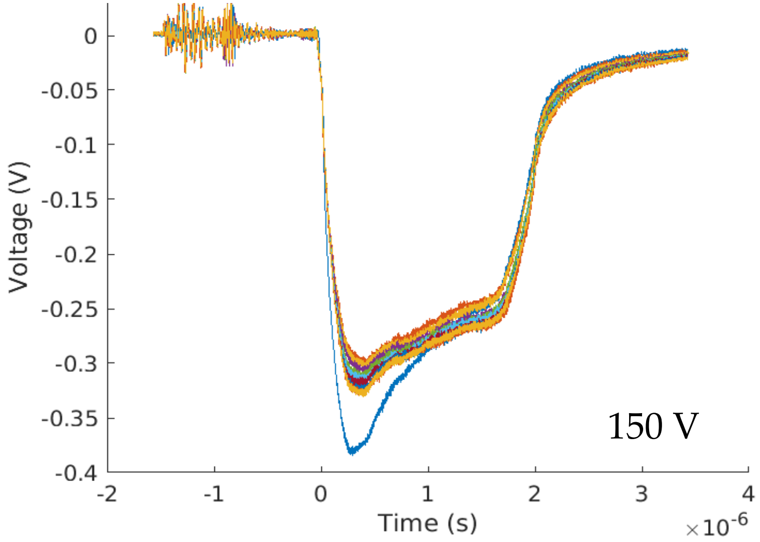
WORK IN PROGRESS!

Diamond Sensor:
Area: 4 mm^2,
Thickness: 100µm









- Polycrystalline diamond.
- Metallised the diamond on both sides with an aluminium layer.
- Both positive and negative voltages.

10 MeV electron beam
(LINAC Elekta SL18 – ***FLASH MODE***).
- Gun current: 7.15 A
- Frequency: 6 Hz
- Number of pulses: 10

Bias: 10 – 150 V
Electric field: 0.1–1.5 V/µm

Summary

- Different geometries of silicon sensor (pad/strip) were tested
- **Good linearity ($R^2 > 0.99$) verified** for both readout systems
- Good matching of integrated charge measured by **TERA08 and oscilloscope**
- **Readout system capable** of supporting the high instantaneous currents generated under FLASH conditions (you can go further!)
- Further studies **and simulations** are ongoing

Thanks for the attention!

Backup slides

Research activity with diamonds

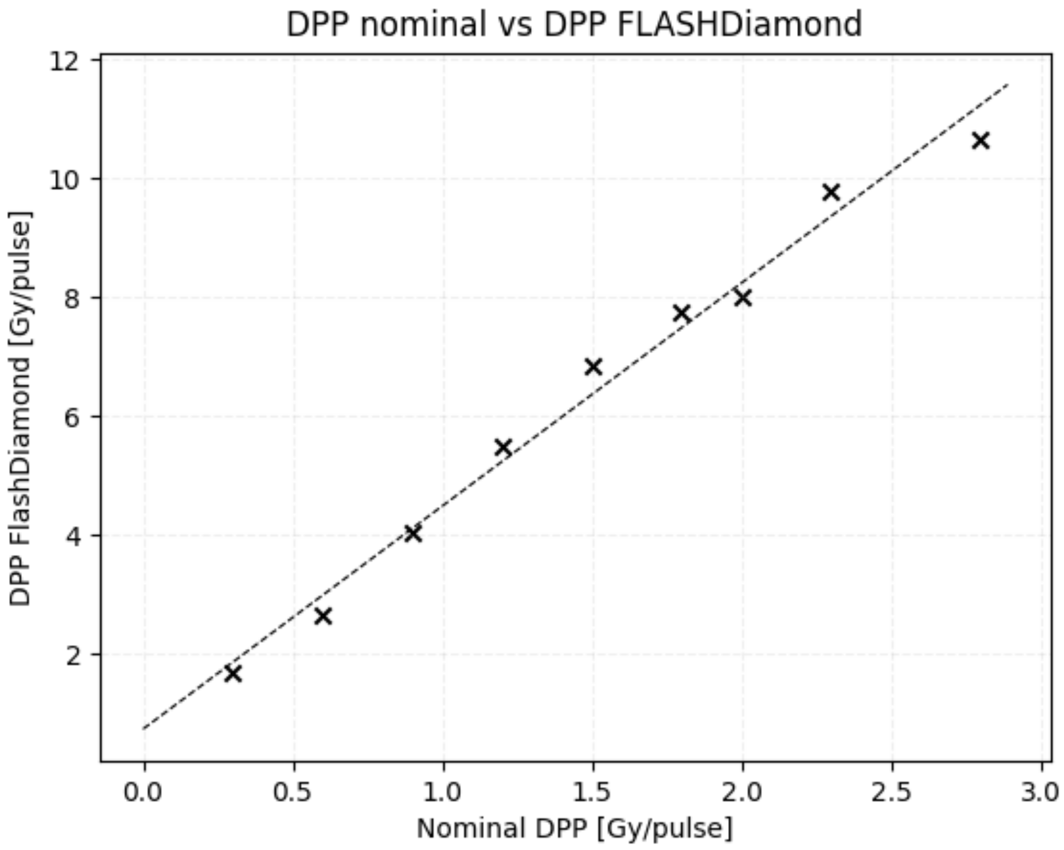
Ref: Marinelli, Marco, et al. "Design, realization, and characterization of a novel diamond detector prototype for FLASH radiotherapy dosimetry." *Medical Physics* 49.3 (2022): 1902-1910.

- FLASH radiotherapy **dosimetry**
- PTW 60019 microDiamond (mD)
- Schottlky diode
- Sensitivity ~1nC/Gy
- Active volume instrinsic diam layer deposited on top of a conductive p-type boron-doped diam layer (used as back contact)
- Built-in voltage ~1V
- Active area few mm2

INFN-TO and University of Turin

- The project started in January and for the moment we have been using silicon devices (from September diamonds)
- Very different principle of use
- We will deposit electrodes at different depths (create different thicknesses on the same sensor)
- Diamond by Rinati and Marinelli is a dosimeter: very small by definition
- We work on beam monitors: we would like to cover a few cmxcm (ok for irradiating cells)

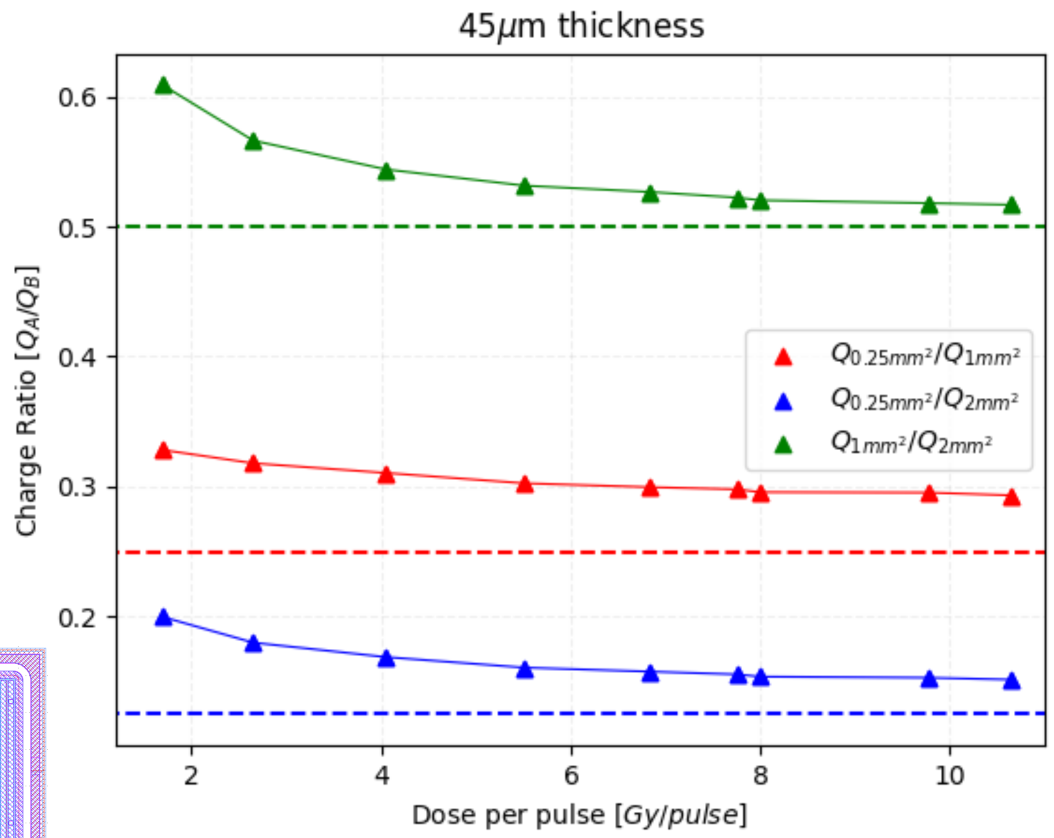
FLASH Diamond reference dose/pulse

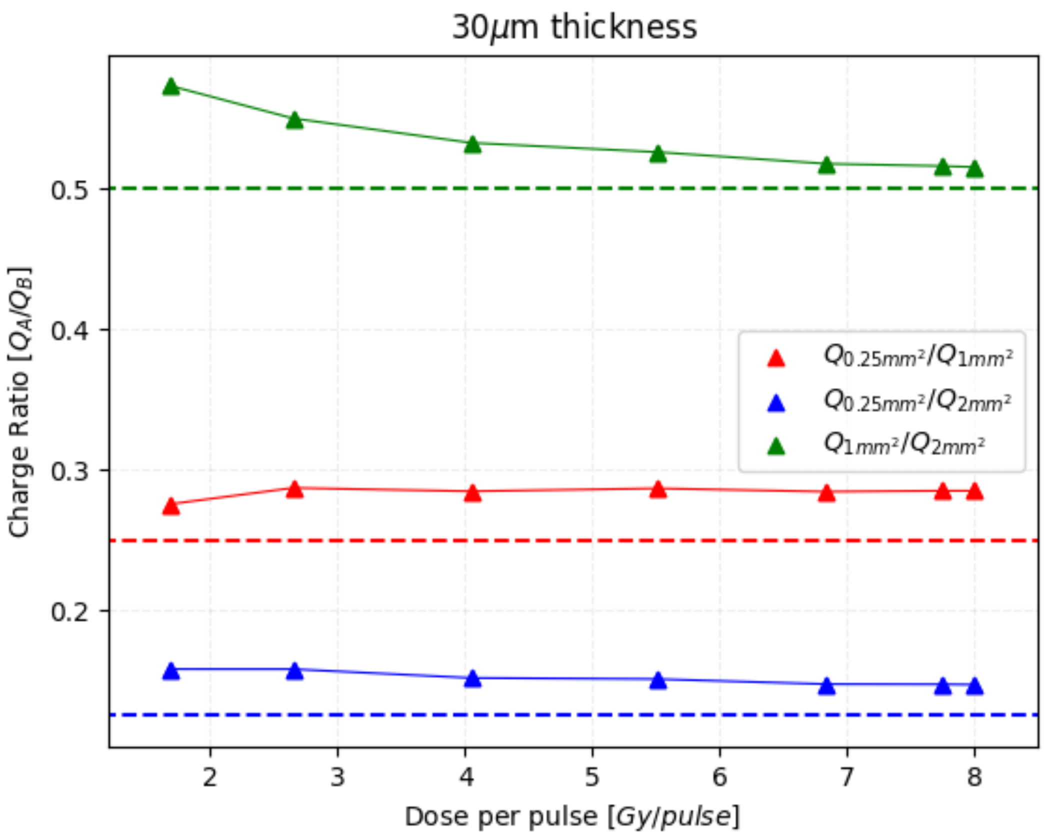


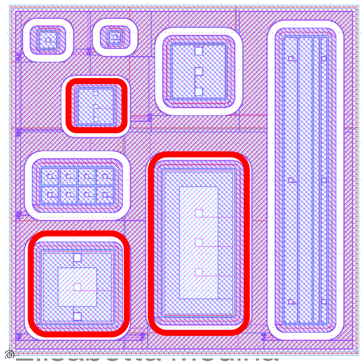
Nominal DPP [Gy/pulse]	Corrected DPP [Gy/pulse]
0.3	1.69
0.6	2.65
0.9	4.05
1.2	5.51
1.5	6.84
1.8	7.75
2.0	8.0
2.3*	9.78*
2.8*	10.64*

Area and thickness

- Comparison of Q produced in different thicknesses and areas with the same electric field (V/μm)
- **Ratio between charge** measured in different pads ~ constant and ~equal to ratio between areas

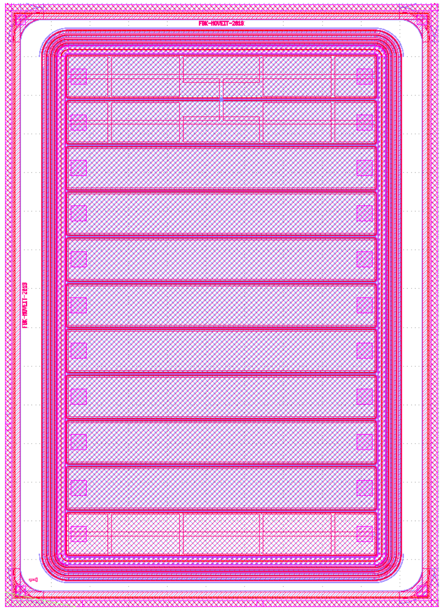


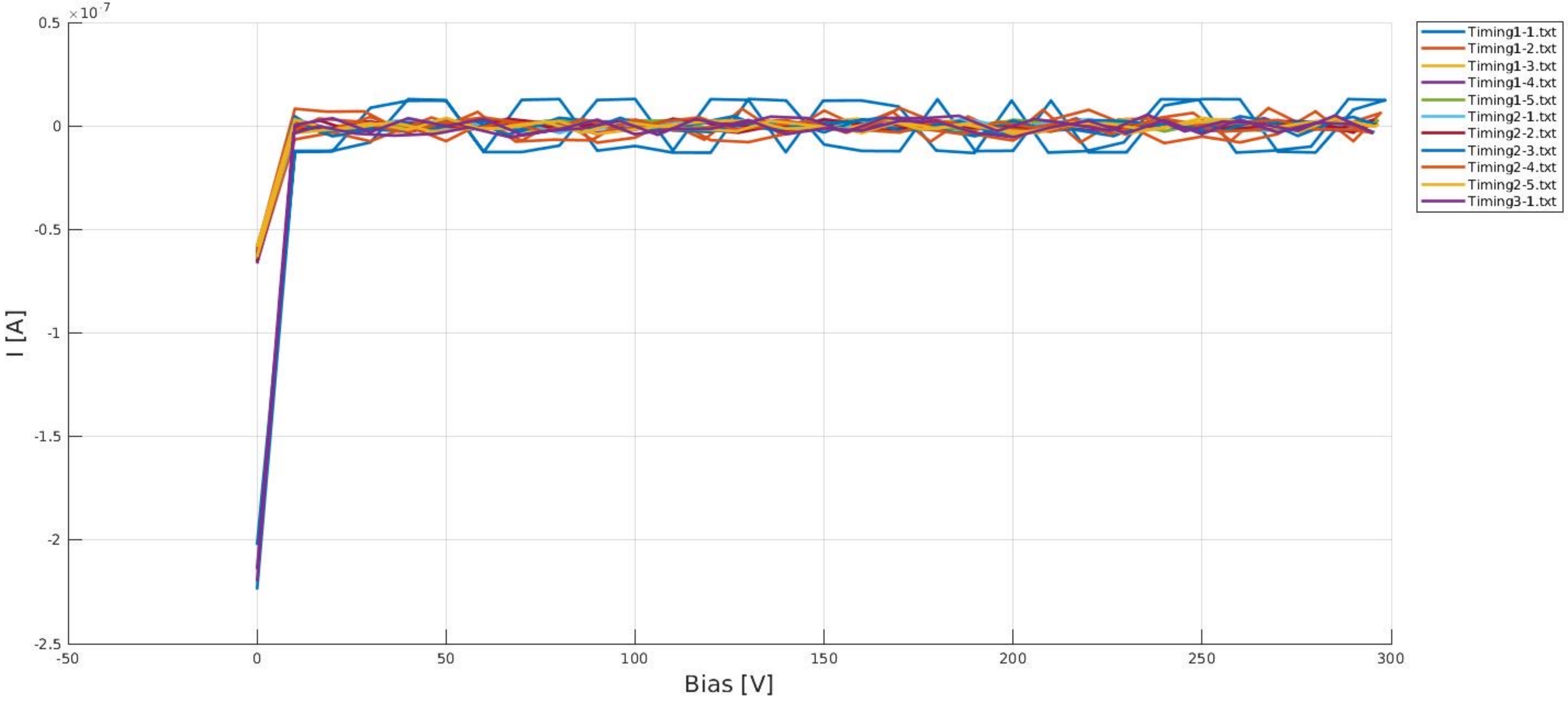




I-V curve 11 strip MoVeIT sensor

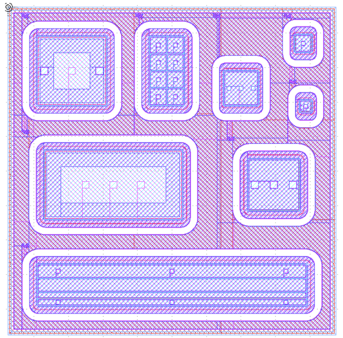
- 11 strips sensor (pin) [MoVeIT]
- Strip area $2.2mm^2$, active thickness 45 μm, total thickness 615 μm)

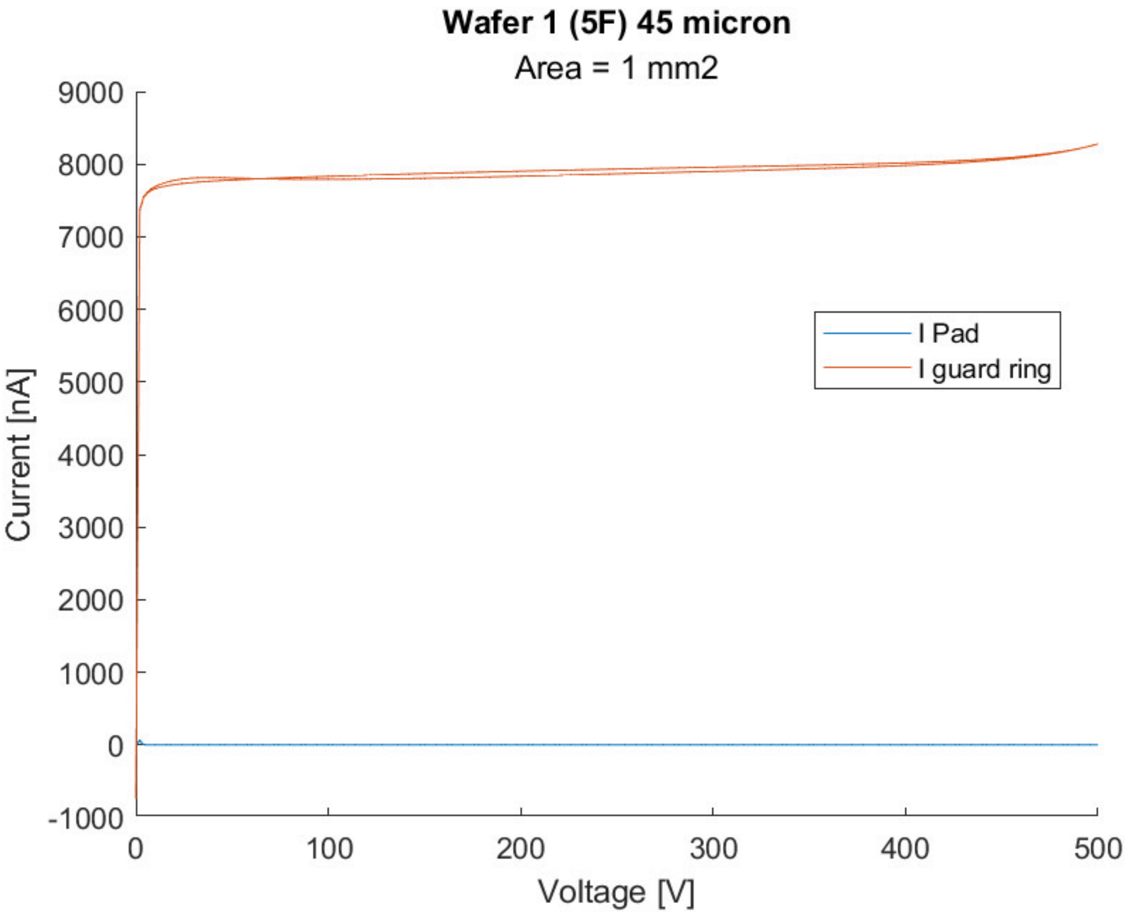


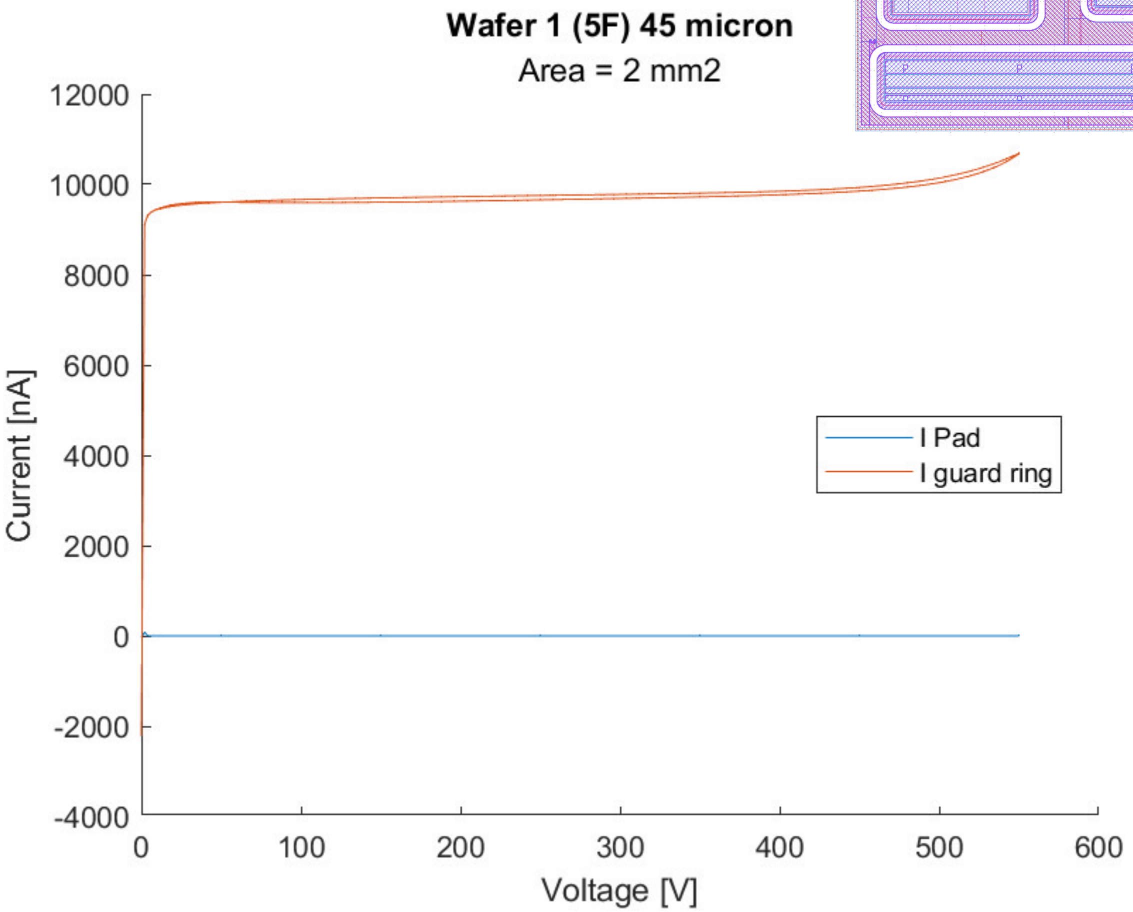


I-V curve pads eXFlu sensor

- **3 pad sensors (pin)** **[eXFlu]**
- Areas 2/1/0.25 mm^2, active thickness **45/30 μm**, total thickness 615 μm) - Thanks to **Valentina Sola**







I-V curve pads eXFlu sensor

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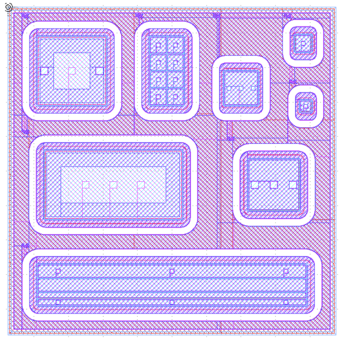
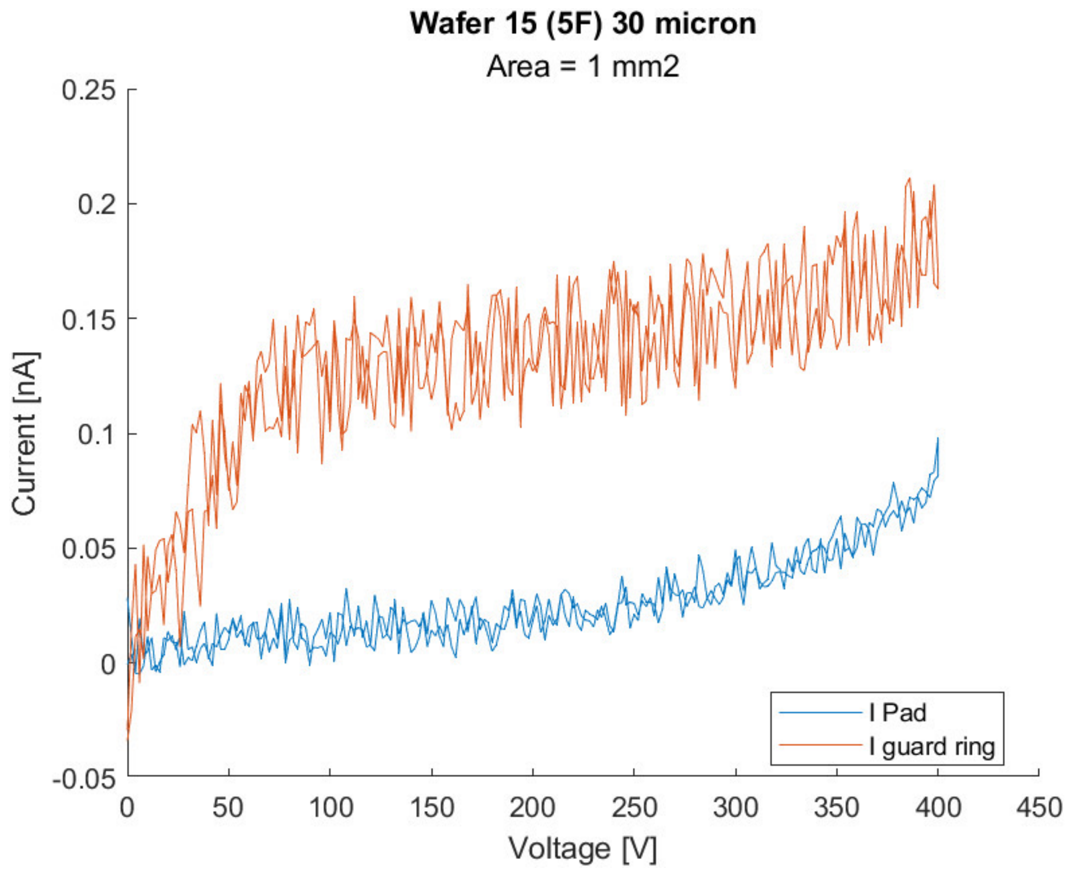
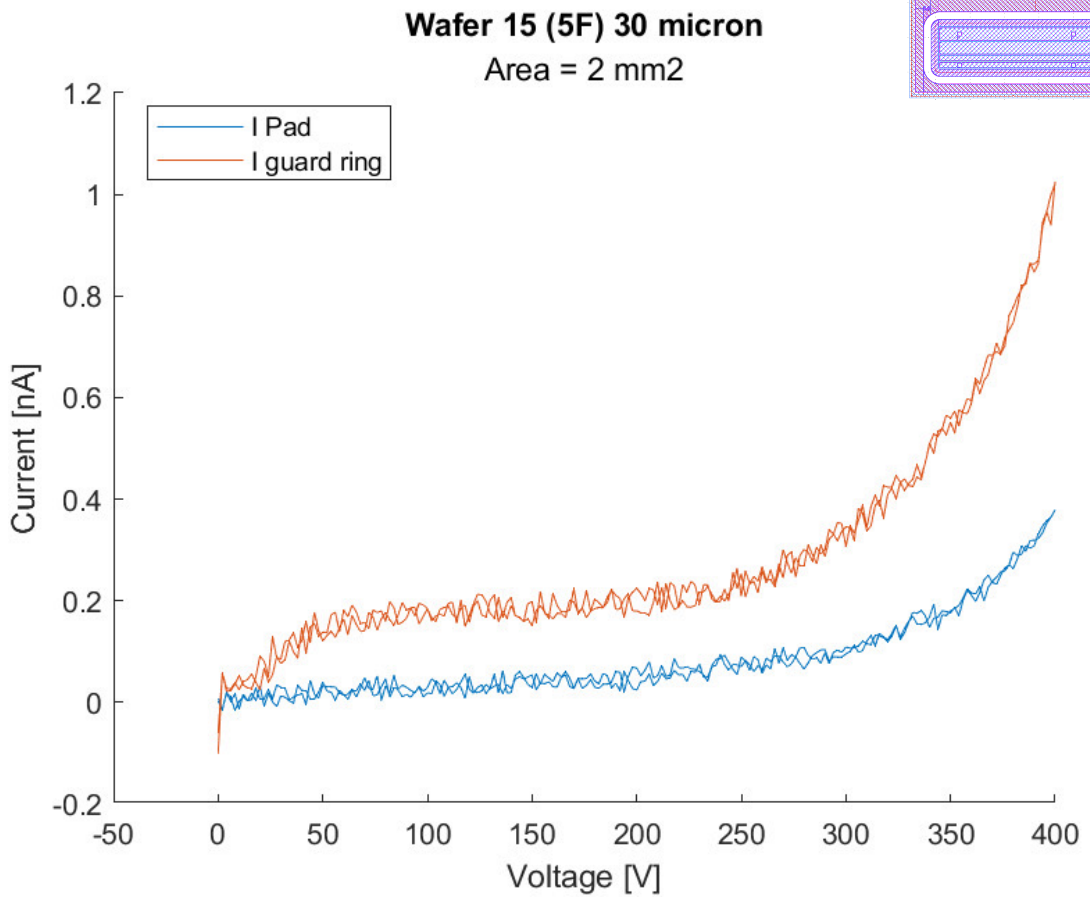


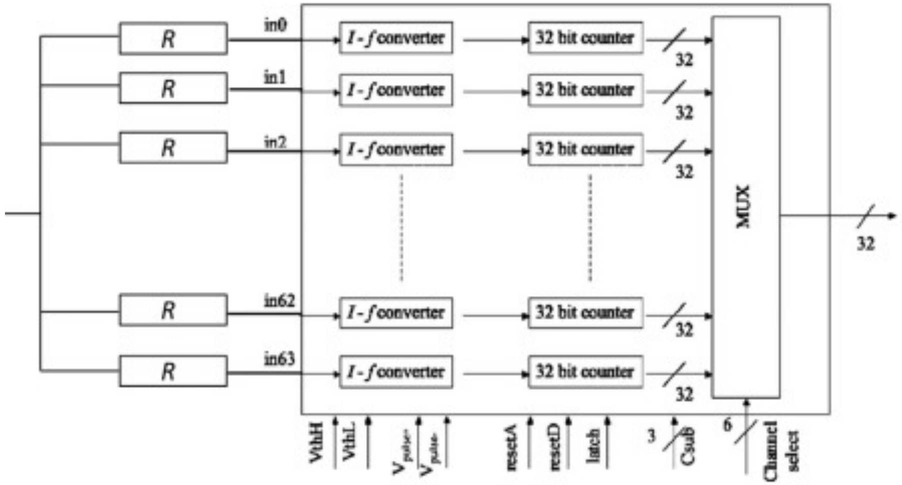


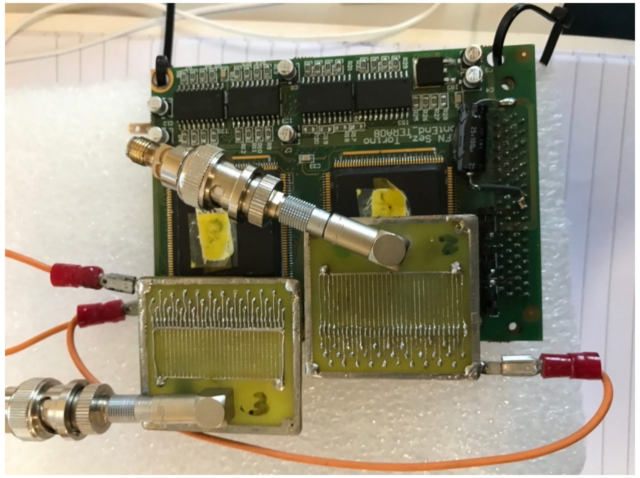


TERA08

- **A**pplication **S**pecific **I**ntegrated **C**ircuit designed by our group and used in several laboratories: **TERA**
- 64 equal CHNs
- In each CHN **Current-to-frequency converter** (each digital pulse = fixed input charge quantum)
- Max conv frequency=20MHz
- Converter accepts both polarities + 32-bit counter (up/down counting capability)
- Converter based on **Recycling integrator architecture**

CHIP1



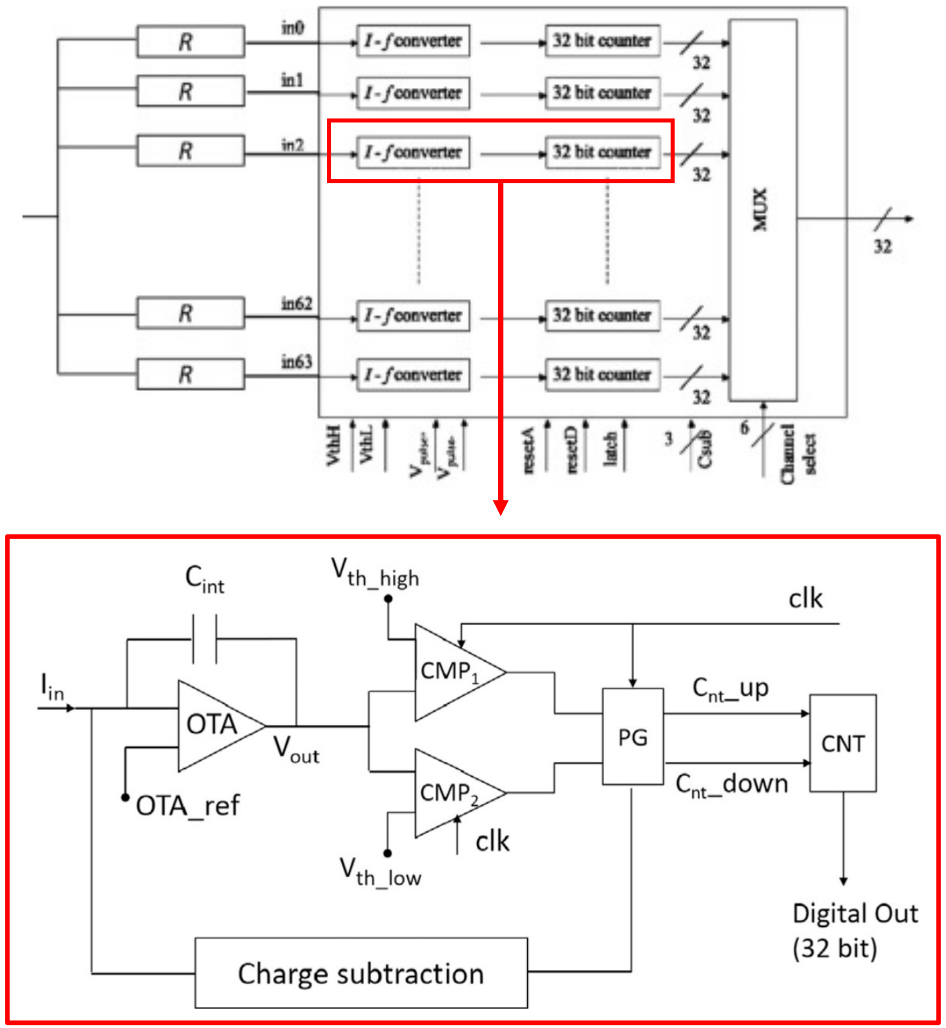


TERA08

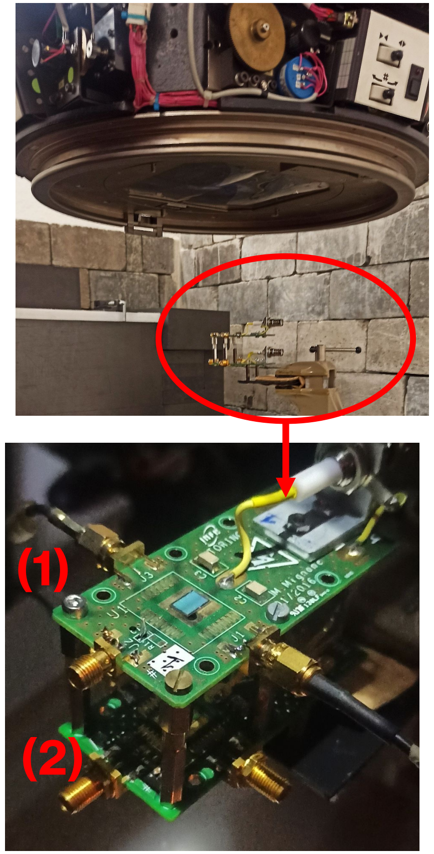
- I_{in} integrated over 600fF capacitor $\mathbf{C_{int}}$ (via Operational Transcoddutance Amplifier **OTA**)
- $\mathbf{V_{out}}$ compared to +/-thr (by 2 synchronous comparators $\mathbf{CMP_1}$ $\mathbf{CMP_2}$)
- Pulse Generator **PG**: pulse to increment/decrement counte **CNT**
- In parallel PG: pulse to **Charge Subtraction Circuit** (subtract +/- charge quantum to C_{int})

DAQ Period (µs)	Q_c(fC)	Max conversion freq per chn	Max conversion (total)	Max current (for 64 CHNs)
1e4 (0.01 s)	200 fC	20 MHz	1280 MHz	± 256 μA

CHIP1

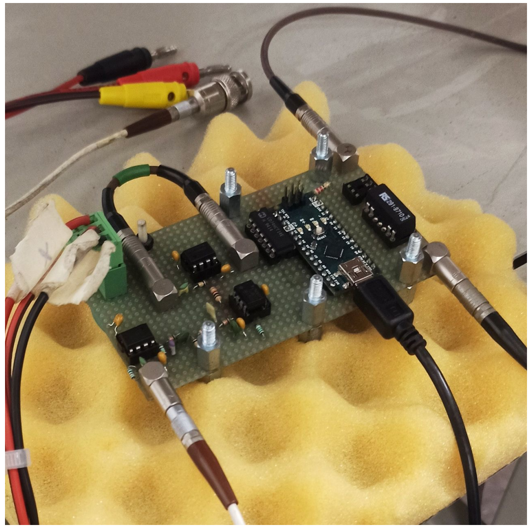


LINAC upgrade

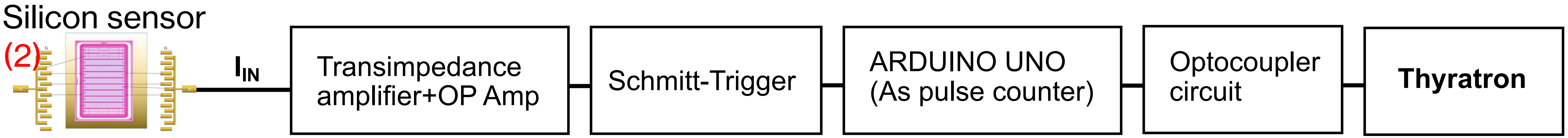


Silicon sensor **(2)** as a beam pulse radiation detector

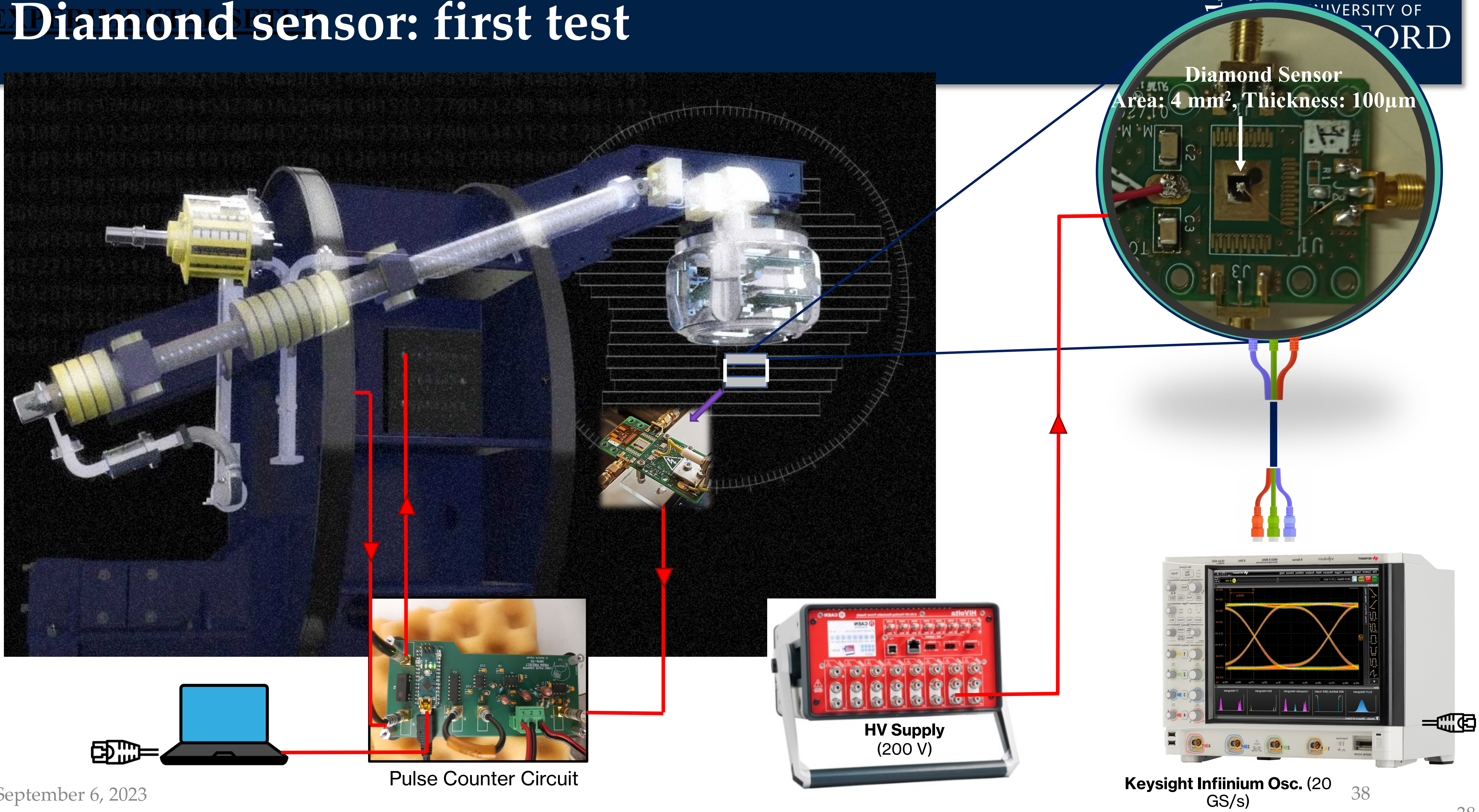
1. Signal to a **in-house built electrical circuit**: transimpedance amplifier converts photocurrent into small V with subsequent amplification
2. Gain chosen to have suitable input to a Schmitt-Trigger
3. Signal of ~5V as input to ARDUINO to count pulses
4. When amount of pulses reached: logical signal to Optocoupler circuit → **Strigger to Thyratron**



In-house built electrical circuit



Diamond sensor: first test



Diamond sensor: first test

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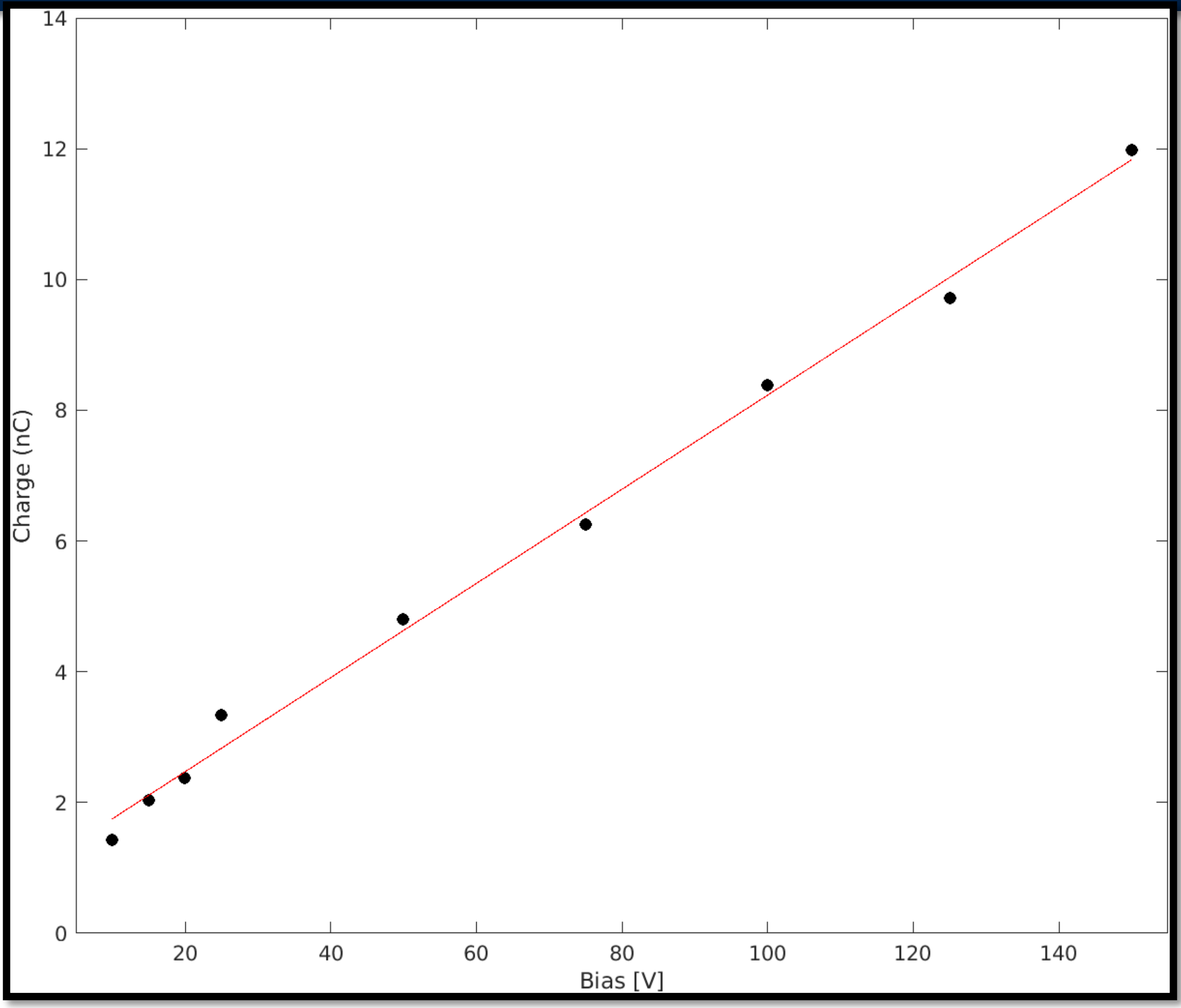

An increase in charge per pulse was observed with increasing bias voltage.

With a bias voltage greater than 175 V, the device was in overcurrent (50 µm), so the measurements were stopped.

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