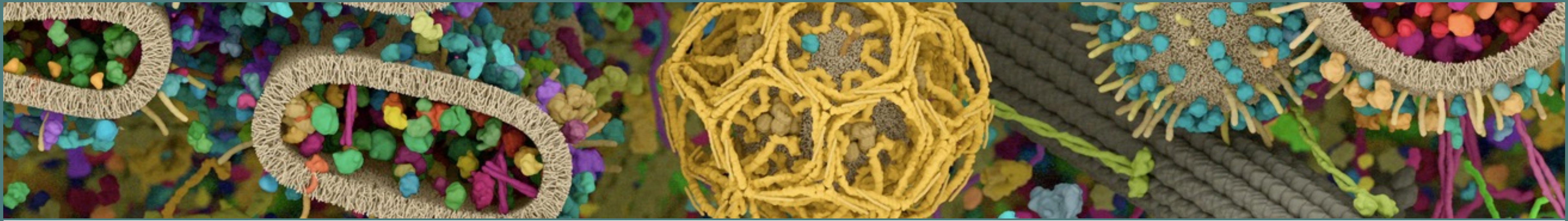

Silicon sensors for beam monitoring: first characterization with Ultra-High Dose Rate (UHDR) electron beams

Elisabetta Medina, elisabetta.medina@unito.it

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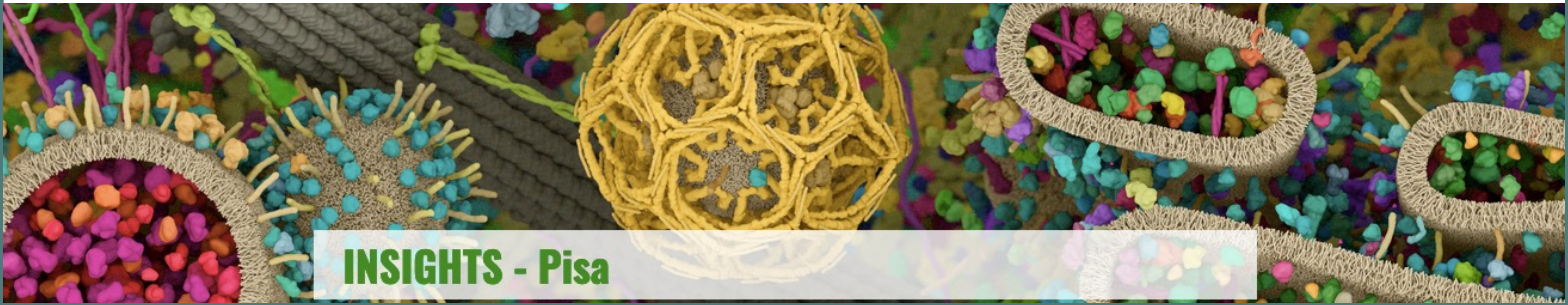
INFN Istituto Nazionale di Fisica Nucleare

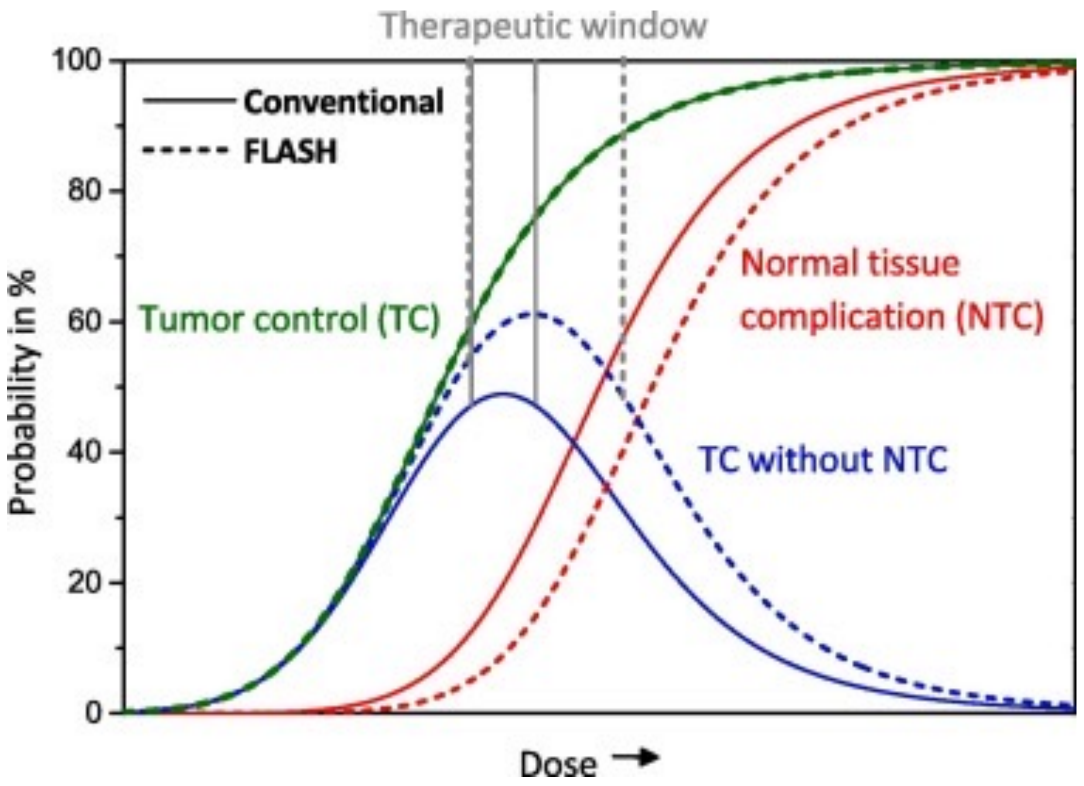


FLASH radiotherapy

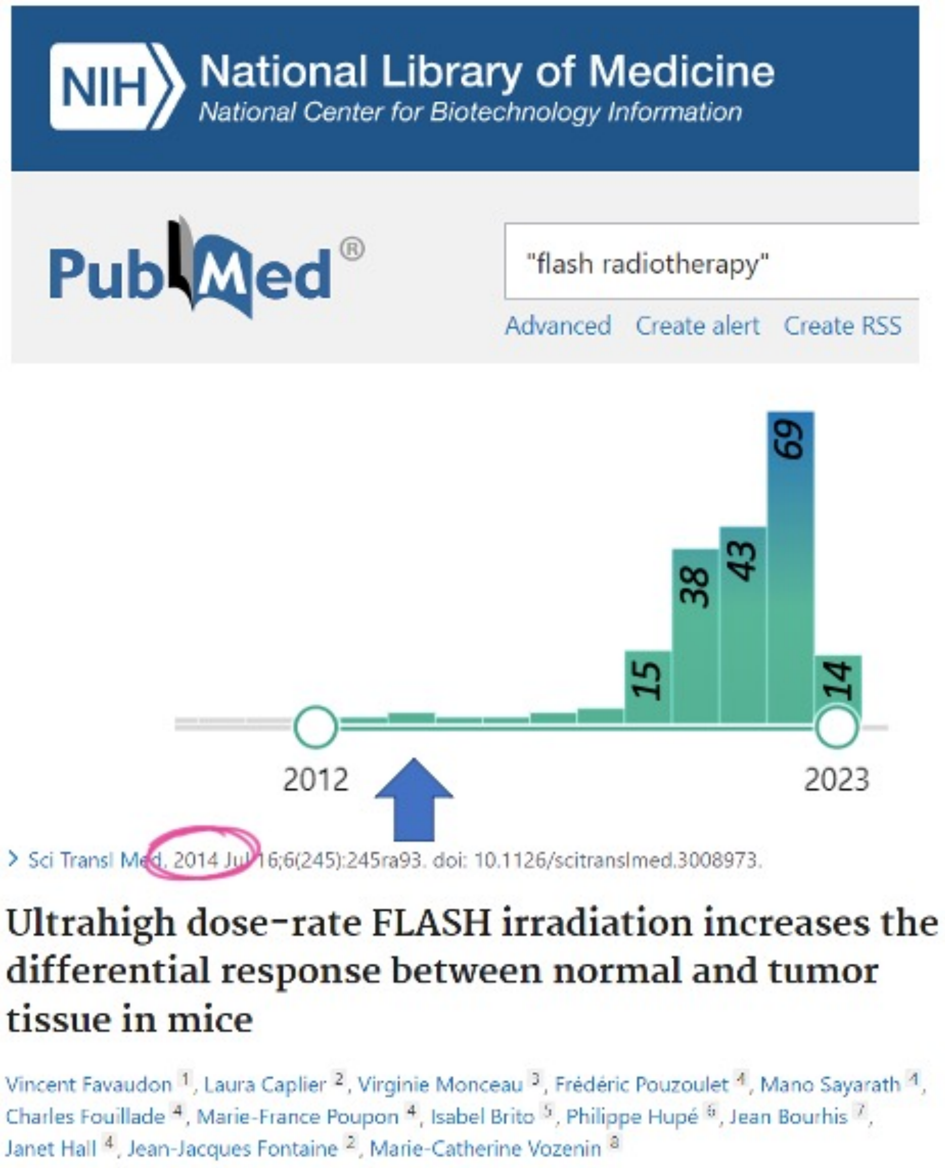
FLASH RT delivers radiation (electrons, photons, particles) at ultra-high dose rate (UHDR, average dose rate > 40 Gy/s) in < 200 ms.

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

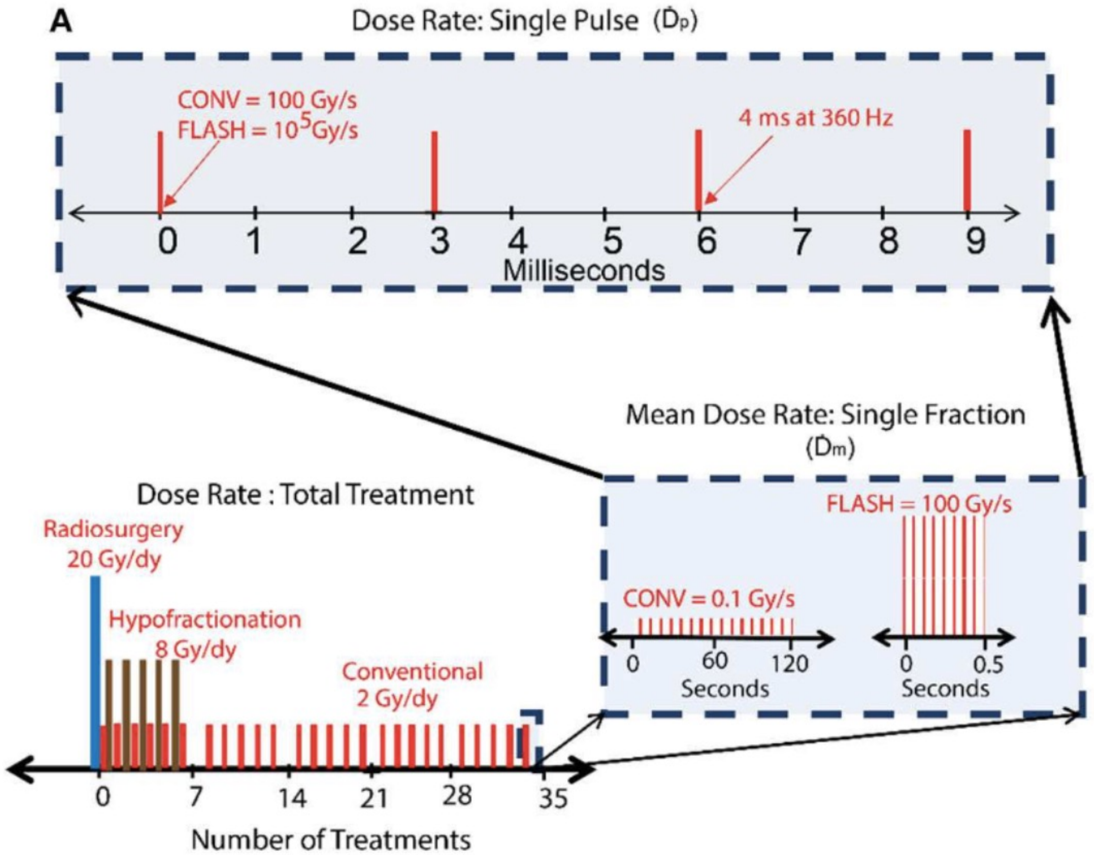
FLASH EFFECT:
Does not induce classical radiation induced toxicity in normal tissues. Retains antitumor efficacy compared to standard RT



FLASH radiotherapy



- 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)



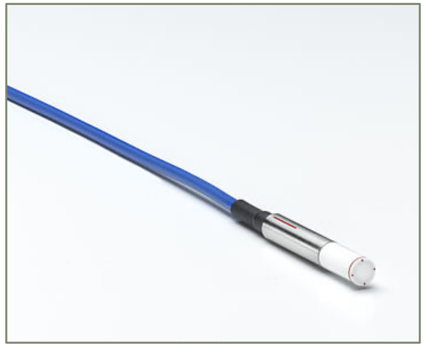
Beam monitor systems

- 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**

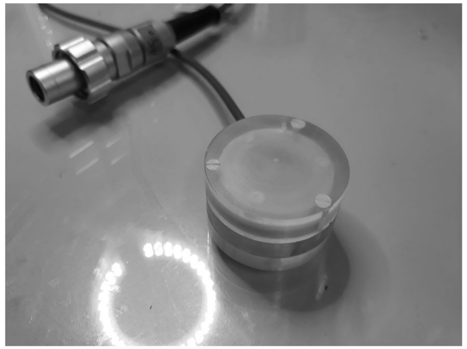
Conventional IC used in LINACs

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

DOSIMETERS

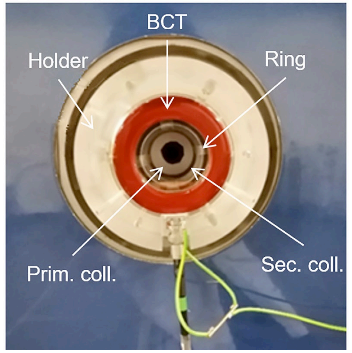


PTW 60019 microDiamond



Ultra-Thin Ionization chamber (UTIC)

BEAM MONITOR



Beam Current Transformers (BCT)

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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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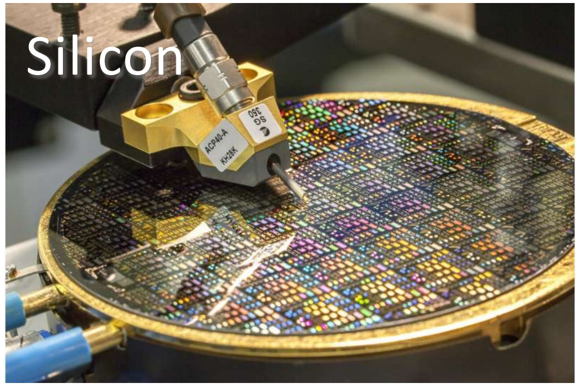
Solid State Devices for Beam Monitoring



- **Ultra-thin** ~10µm
- Well-developed manufacturing **technology**
- High **sensitivity** (tens of thousand times > than ICs)
- **Fast** response

Unkown factors: linearity with DR, recombination, radiation resistance

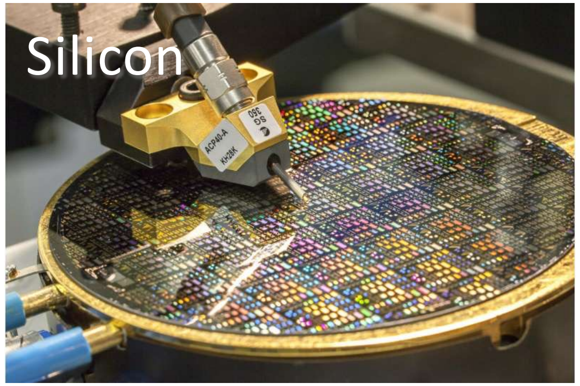
- **Radiation hardness**
- High **resistivity** of intrinsic diamond
- Large saturated **carrier velocity**

Challenging issues: dose-rate linearity, possibility of straddle areas several cm^2

- **Compromise** between industrial maturity of Si and the robustness of diamond
- High electrical stiffness, speed of charges, melting T, thermal diffusivity, industrual maturity

STLAB

Solid State Devices for Beam Monitoring



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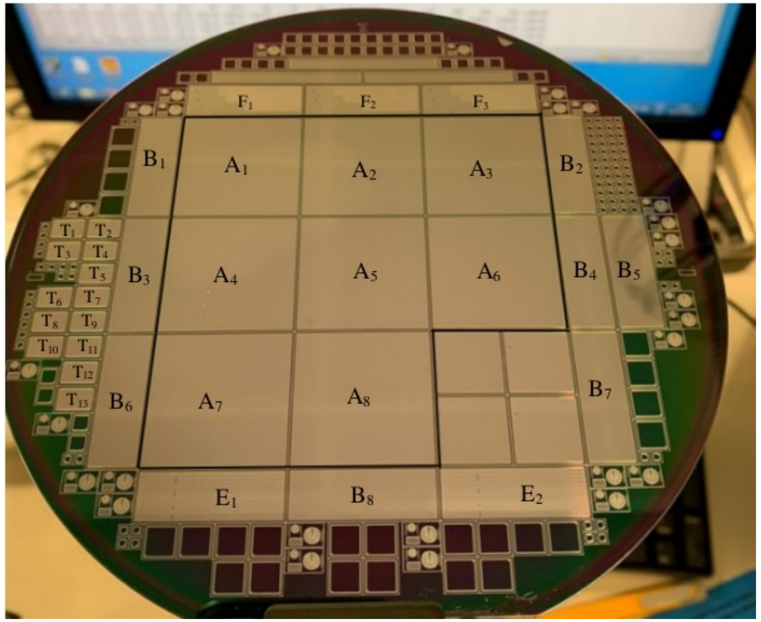
STLAB

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

MoVe IT

FONDAZIONE BRUNO KESSLER



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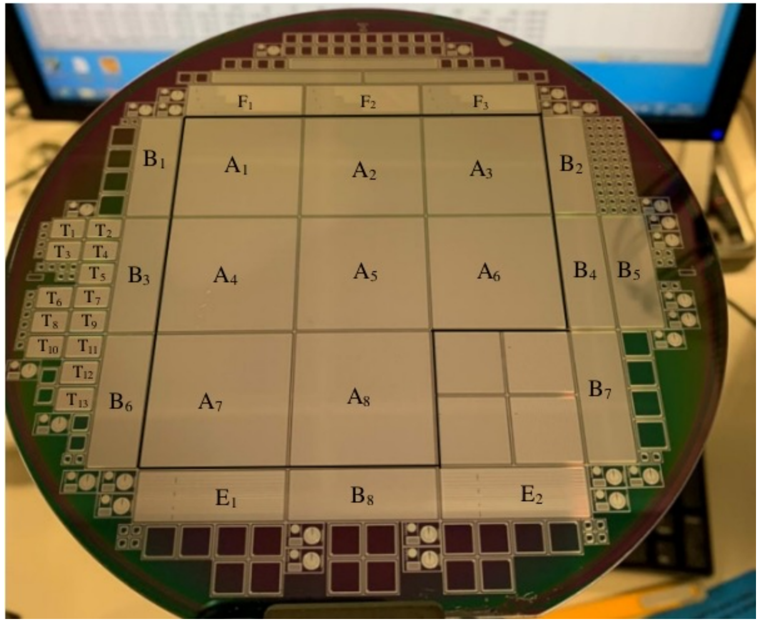
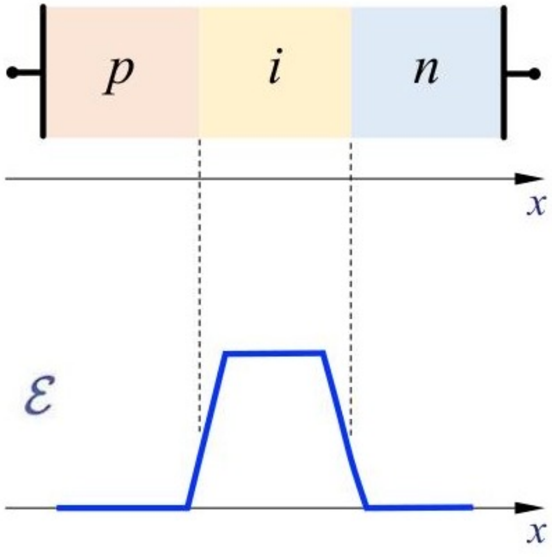


UHDR beams

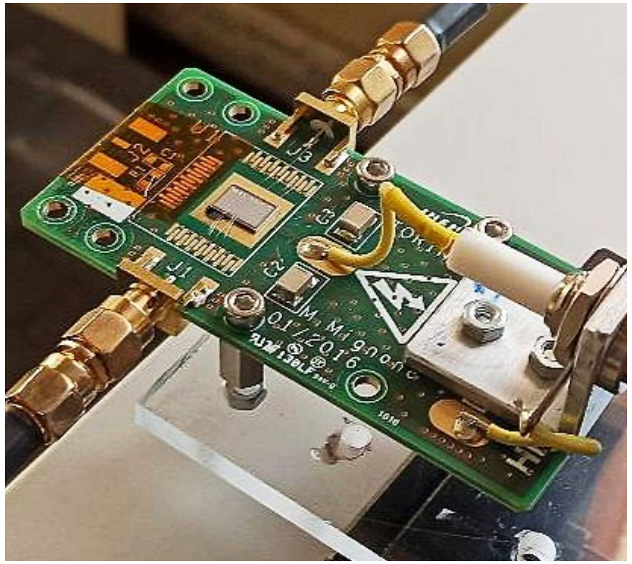
PiN detector used
(Q generated large enought
NO GAING NEEDED)



Thin silicon detectors

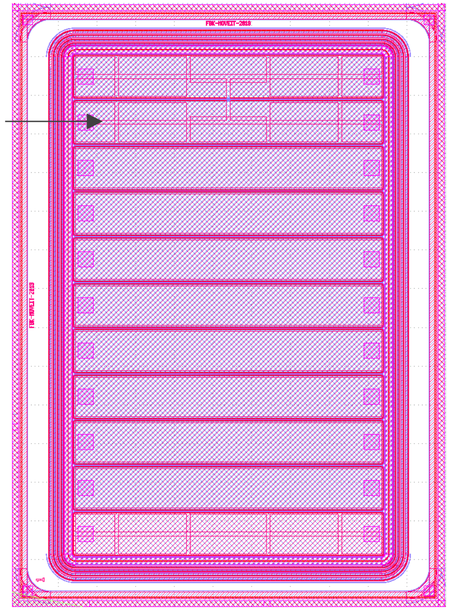
Silicon devices in Turin: used so far for *single particle counting* → With **TERA08** signal can be integrated

FONDAZIONE BRUNO KESSLER



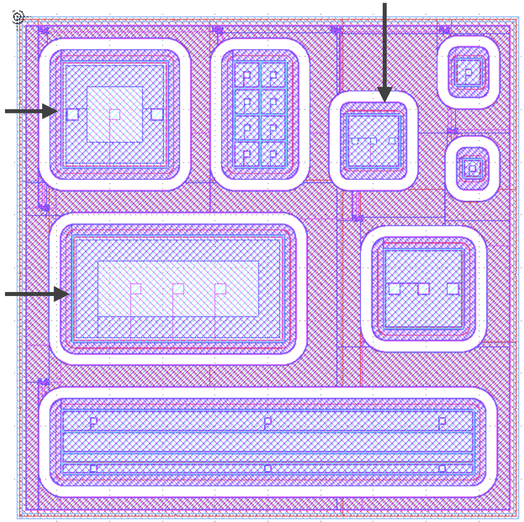
Mounted on HV distribution board

- **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

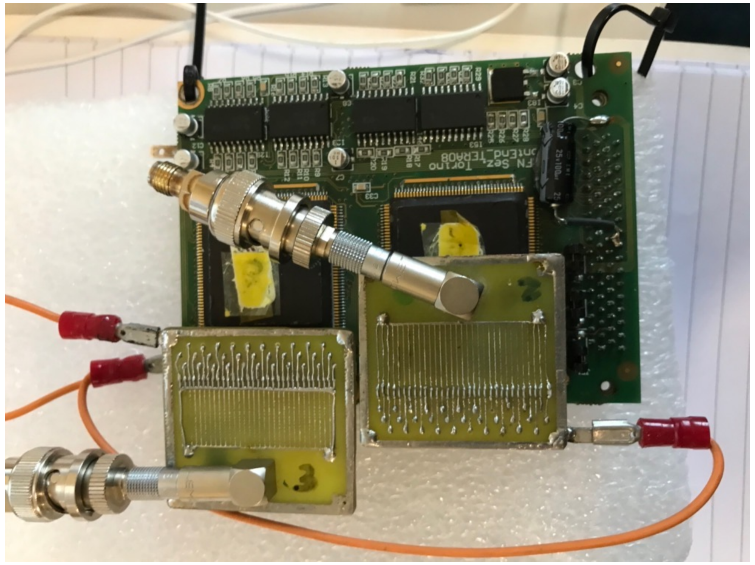
- **3 pad sensors (pin)** **[eXFlu]**
- Areas 2/1/0.25 mm^2, active thickness **45/30 μm**, total thickness 615 μm)
- (Thanks to **Valentina Sola**)



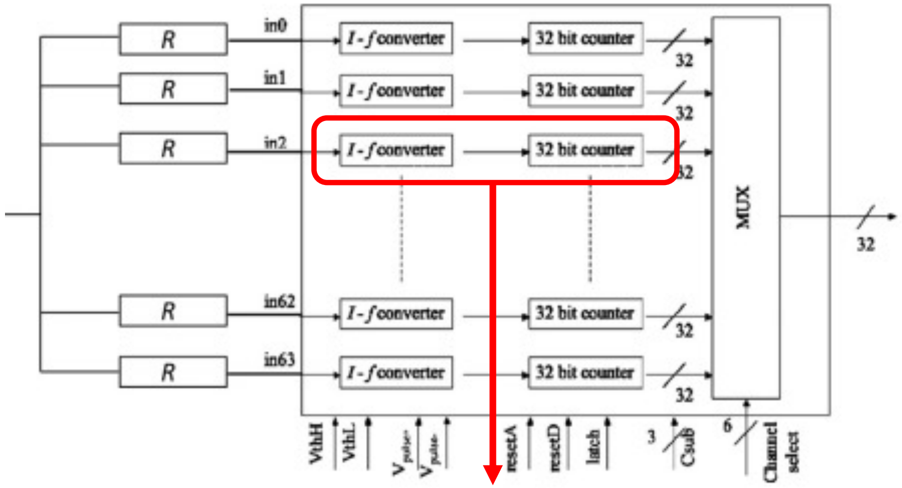
To compare **different areas and thickness** on UHDR beams

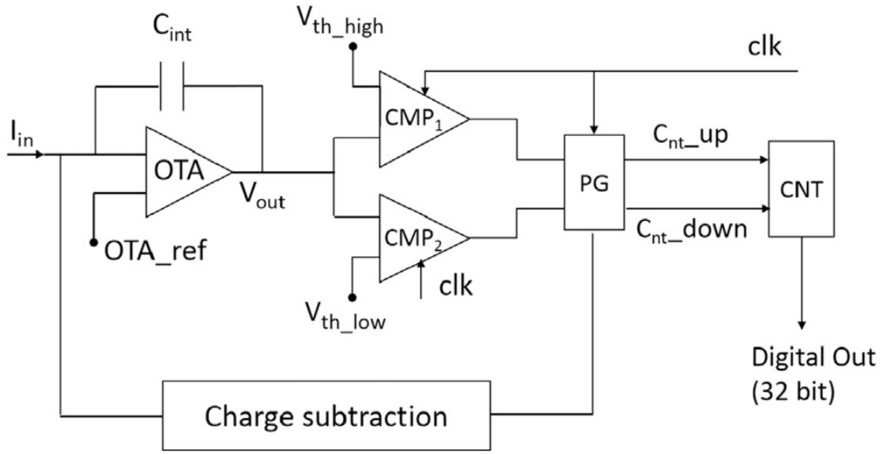
Readout system: TERA08

- 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



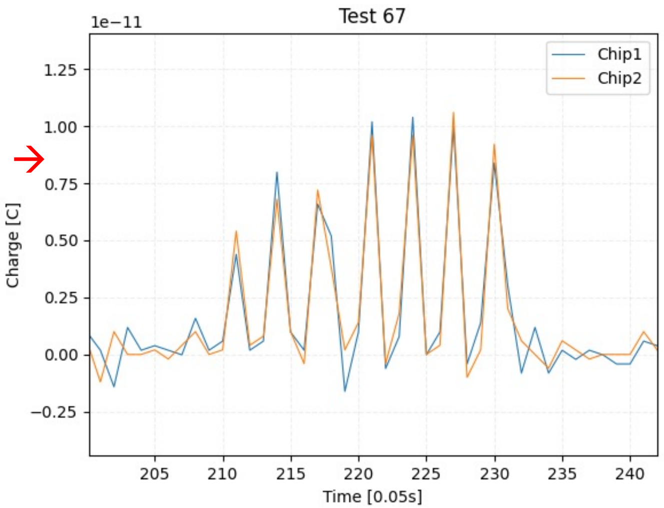


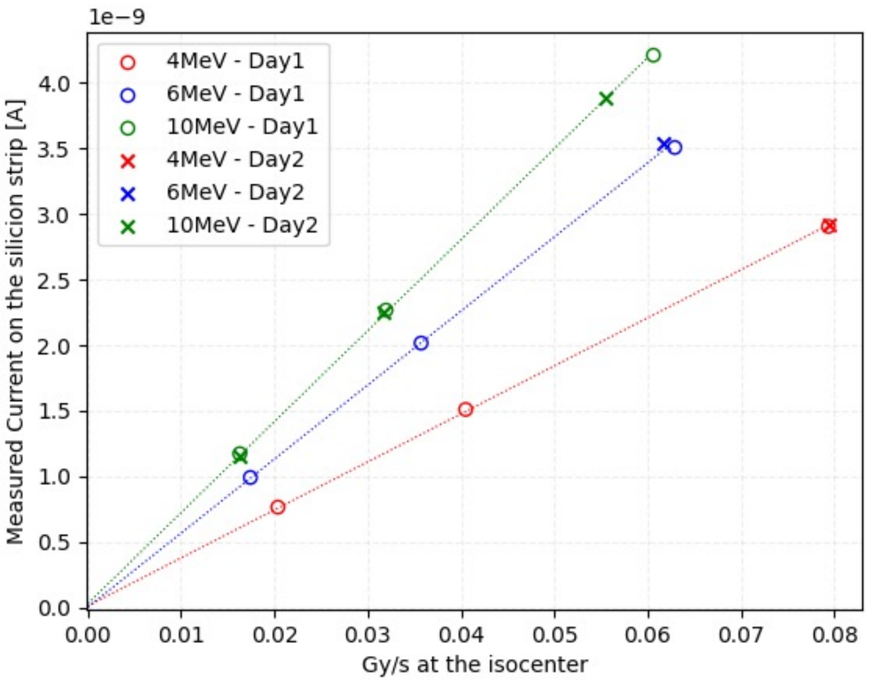
DAQ Period (μs)	Q_c(fC)	Max conversion freq per chn	Max conversion (total)	Max current (for 64 CHNs)
1e4 (0.01 s)	200 fC	20 MHz	1280 MHz	± 256 μA

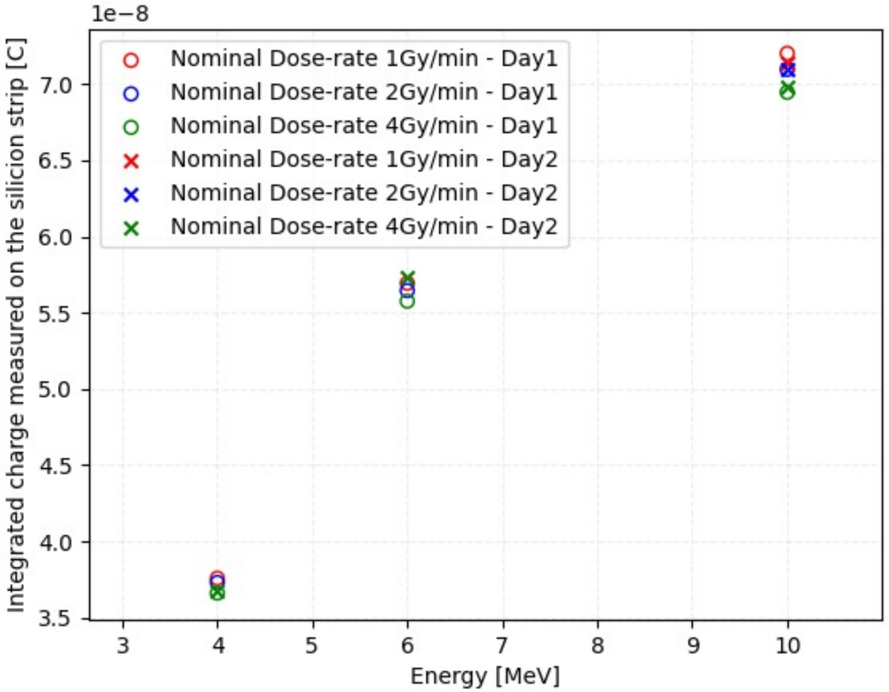
First tests with conventional electrons beams

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

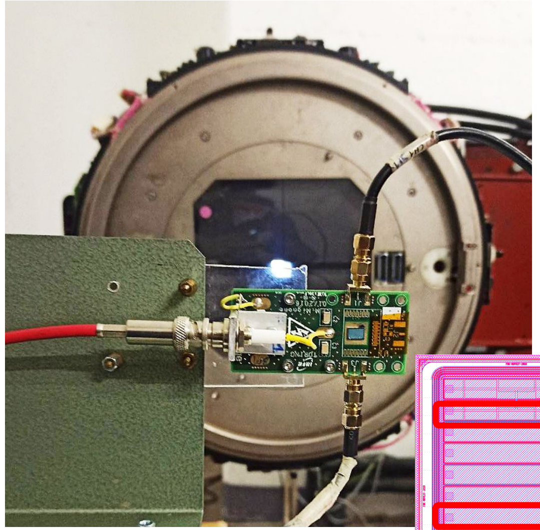
Example of data acquisition (7 pulses clearly distinguishable) →

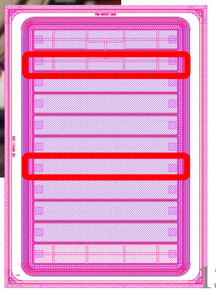






Elekta





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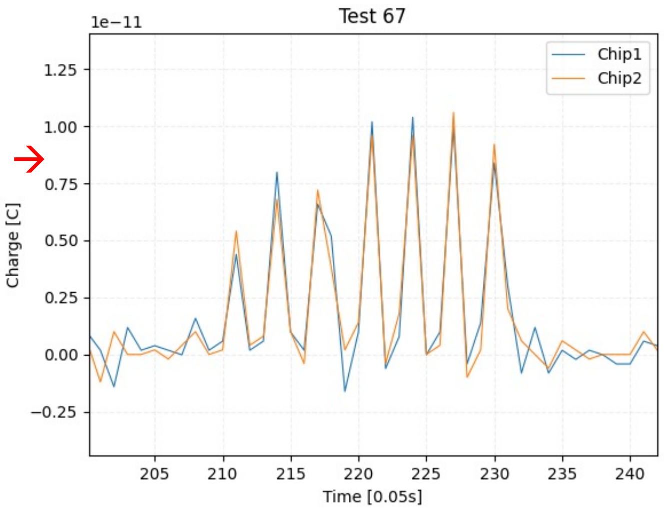
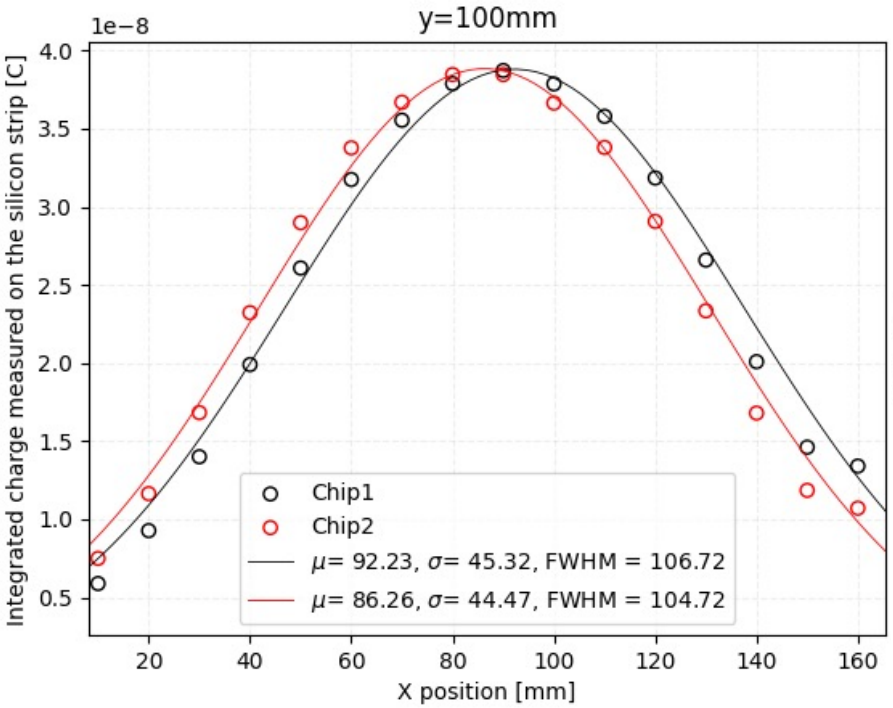
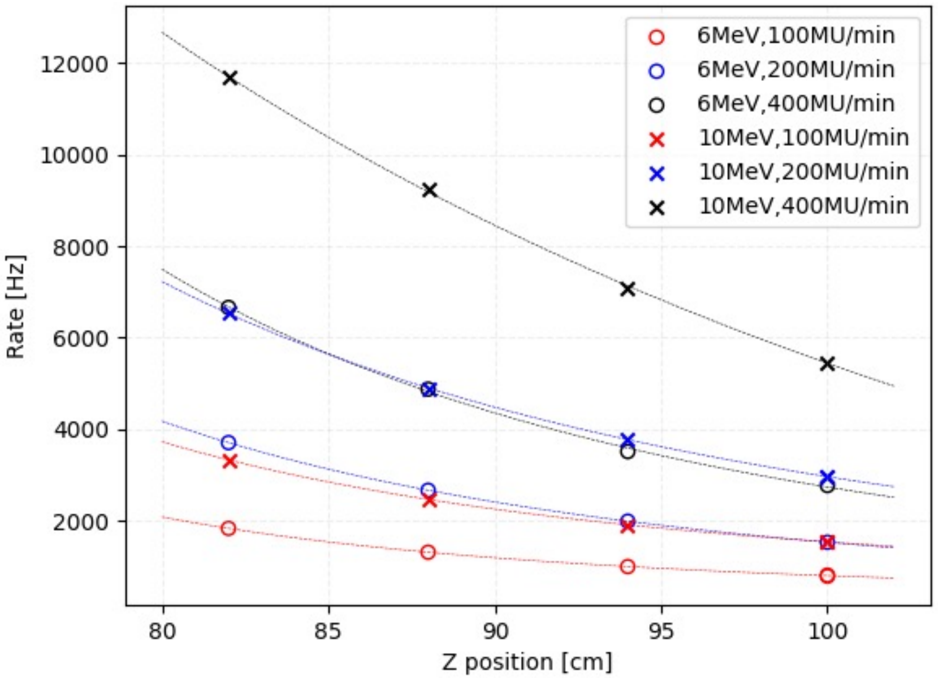
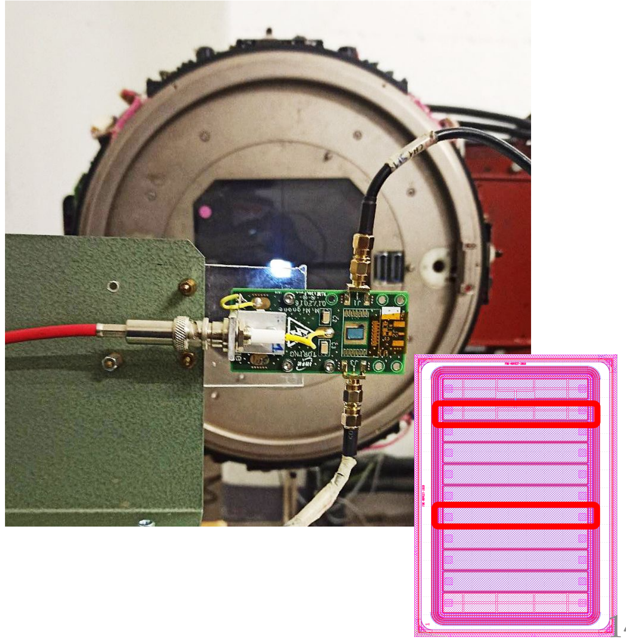




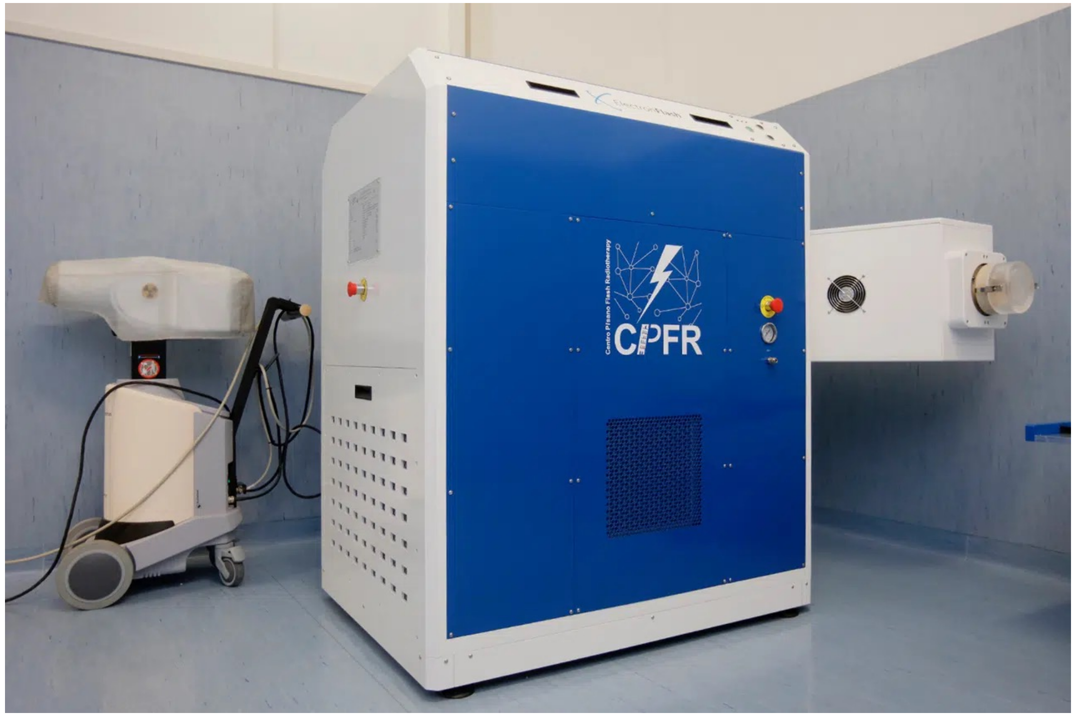
6MeV, 200 MU/min, 50 MU tot, FS 10X1 cm
FWHM compatible with field size



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

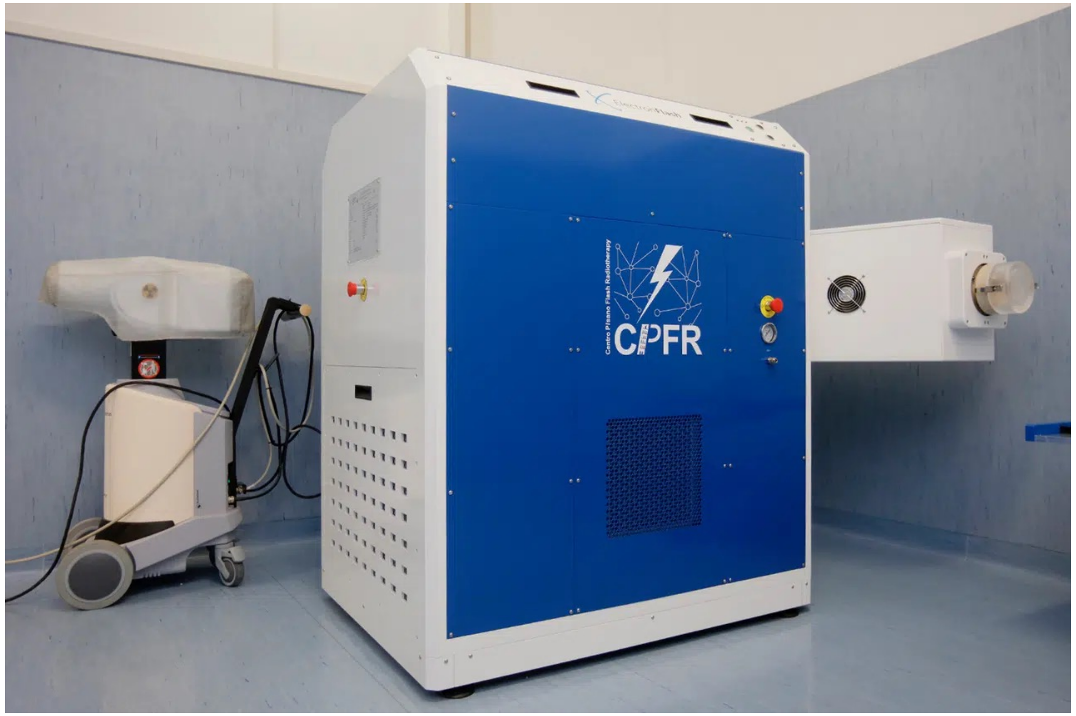


- **ElectronFlash accelerator** (Centro Pisano Multidisciplinare sulla Ricerca e Implementazione Clinica della Flash Radiotherpy)
- Sordina IORT Technologies S.p.A (**S.I.T**)
- 7 MeV and 9 MeV
  Beam current: 1-100 mA
  Pulse duration: 0.5-4 μs
  Pulse frequency: 1-249 Hz
- **Indipendent variation of 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

Centro PIsano Flash Radiotherapy
CPFR

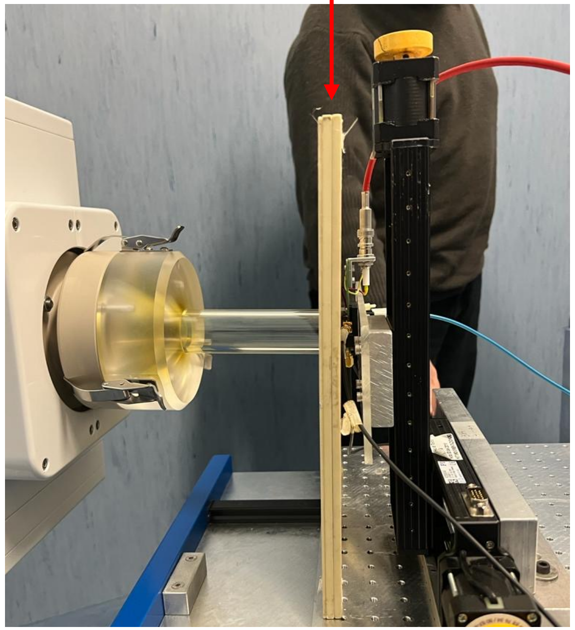
SIT

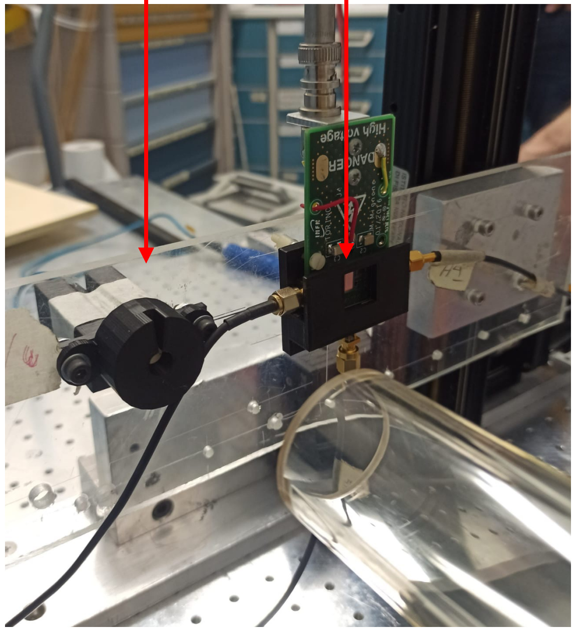


- **9 MeV**, **3 cm** diameter PMMA applicator (up to **~ 10 Gy/pulse**), **4μs** pulse duration
- 13 mm solid water slab (reduced air gap between slab-sensor)

13mm solid water slab

FlashDiamond and silicon sensor in same conditions

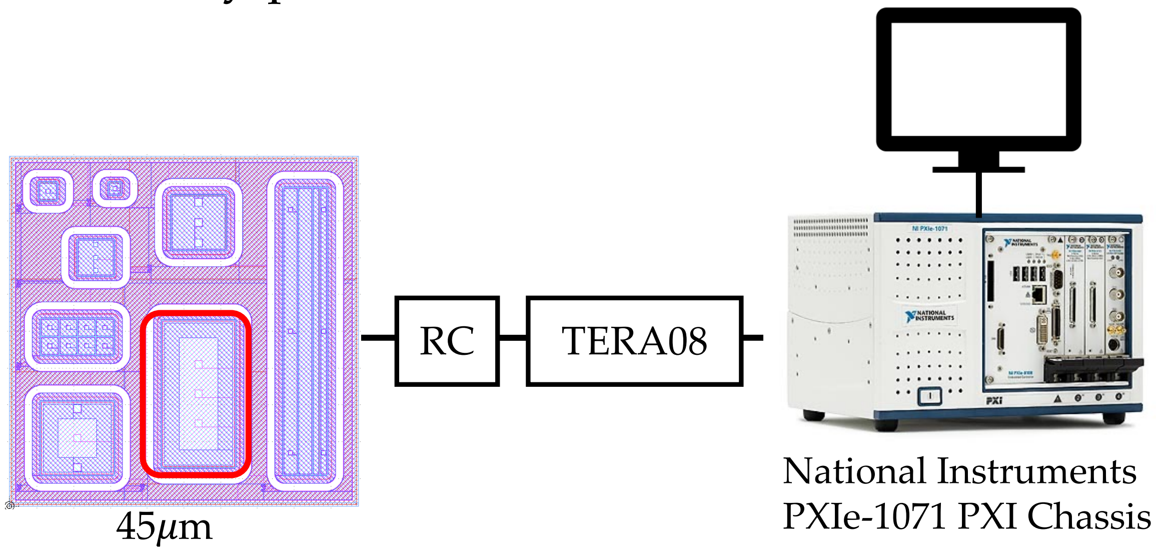




Experimental setup

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



National Instruments
PXIe-1071 PXI Chassis

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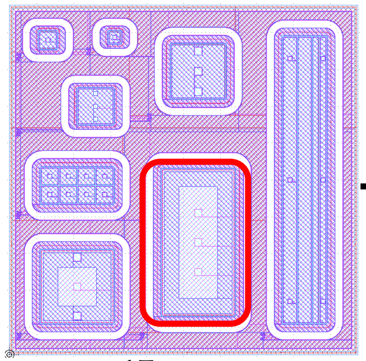
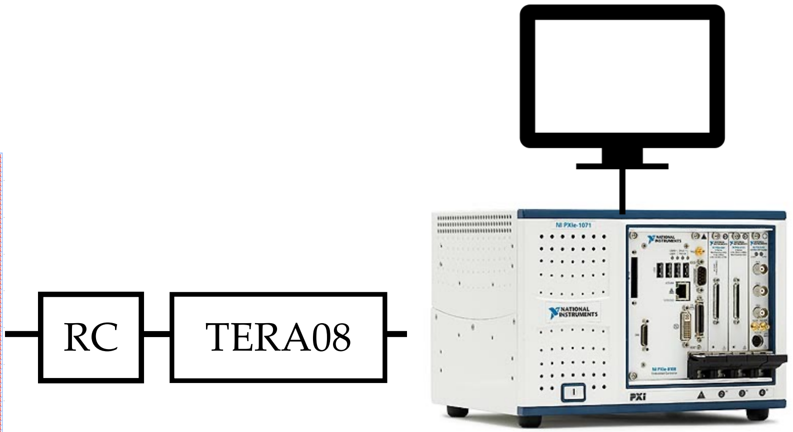
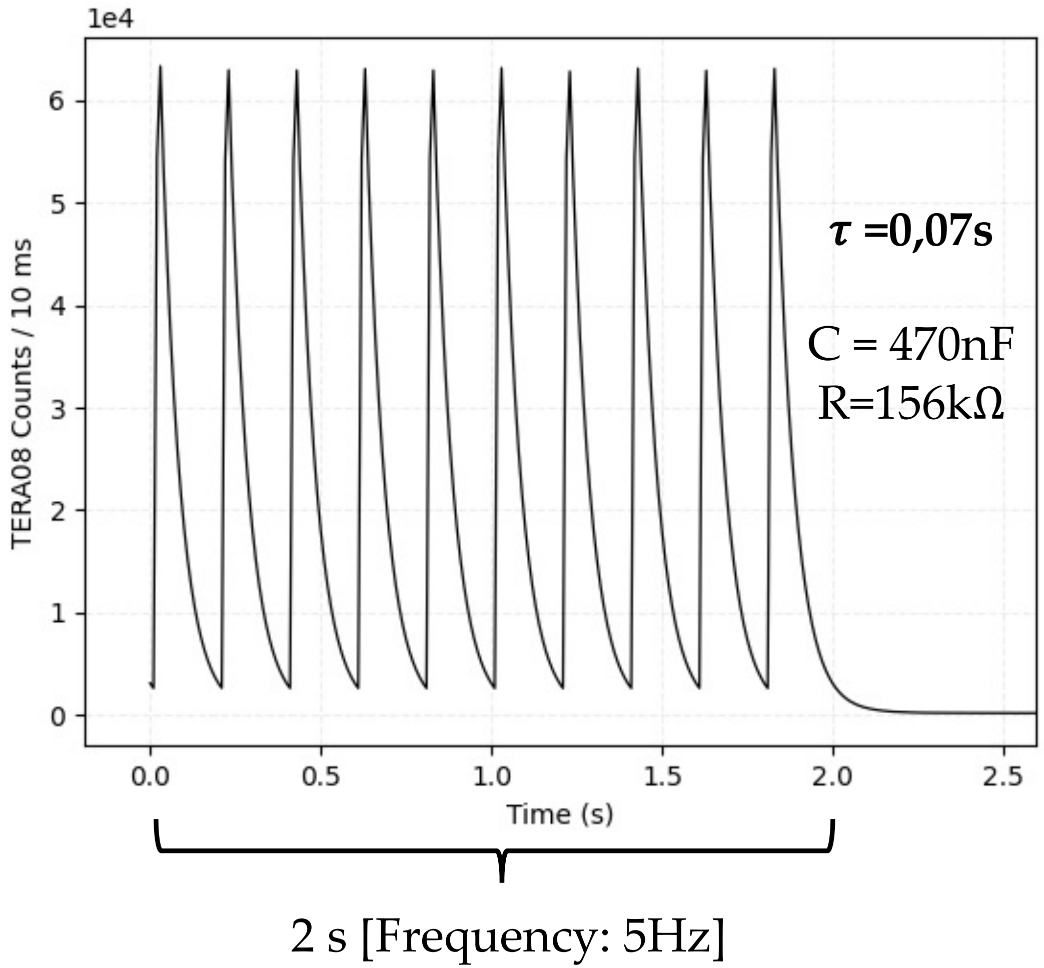


45μm



National Instruments PXIe-1071 PXI Chassis



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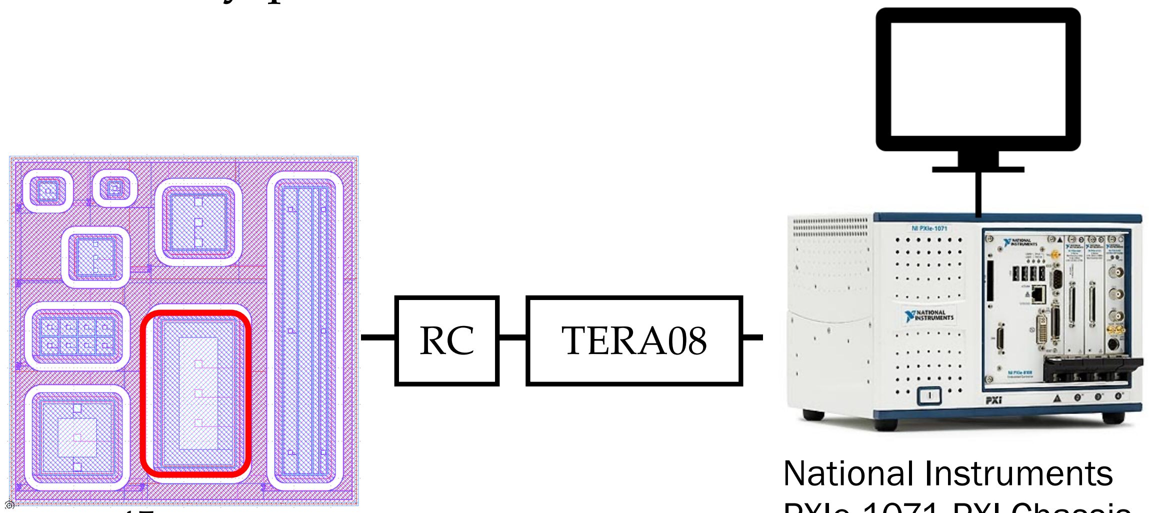
Oscilloscope measurements

- 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



45μm

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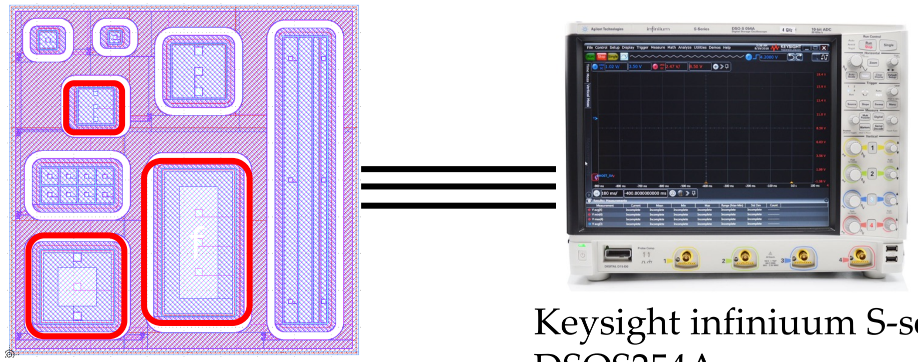
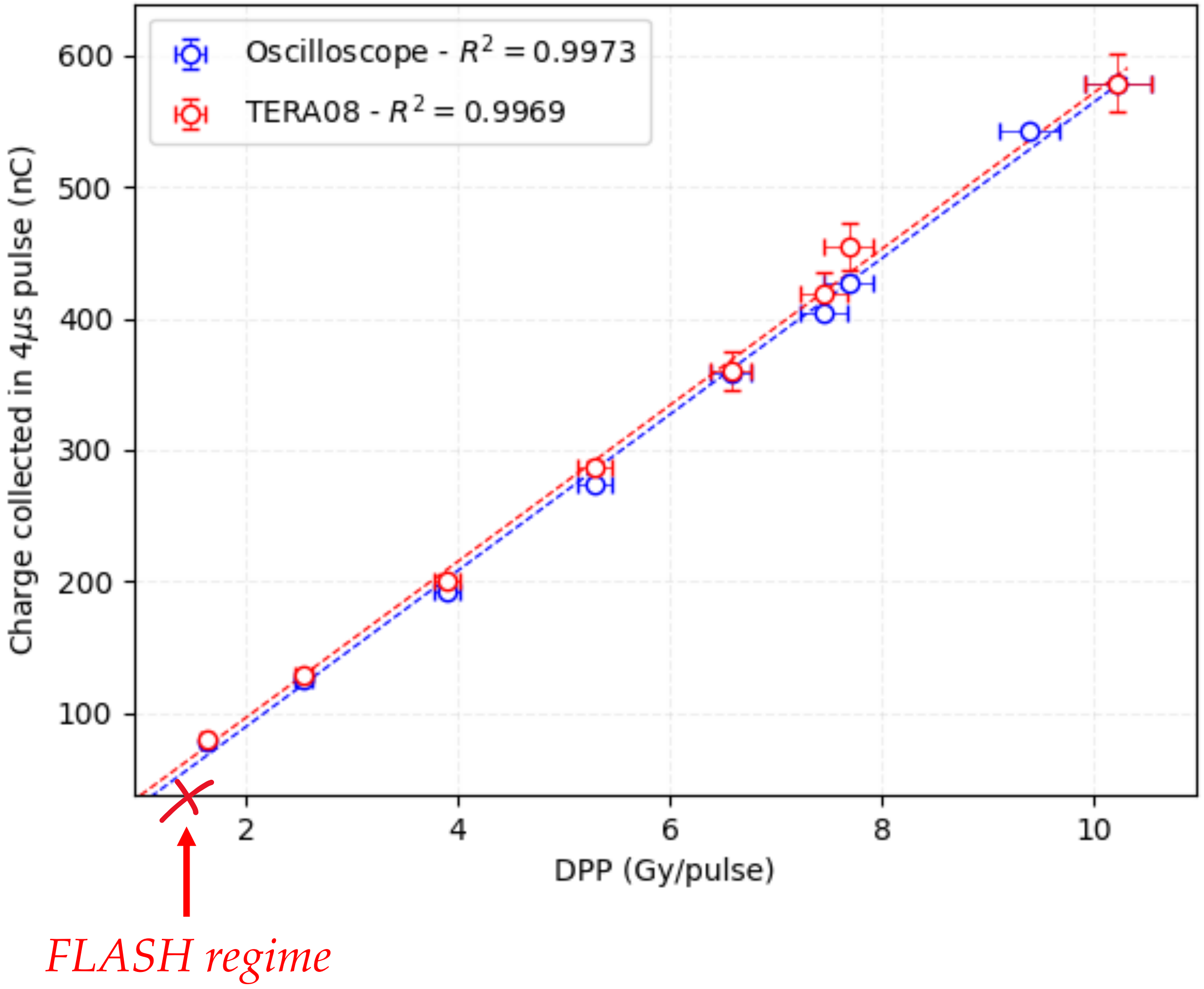


30/45μm

Keysight infiniuum S-series DSOS254A

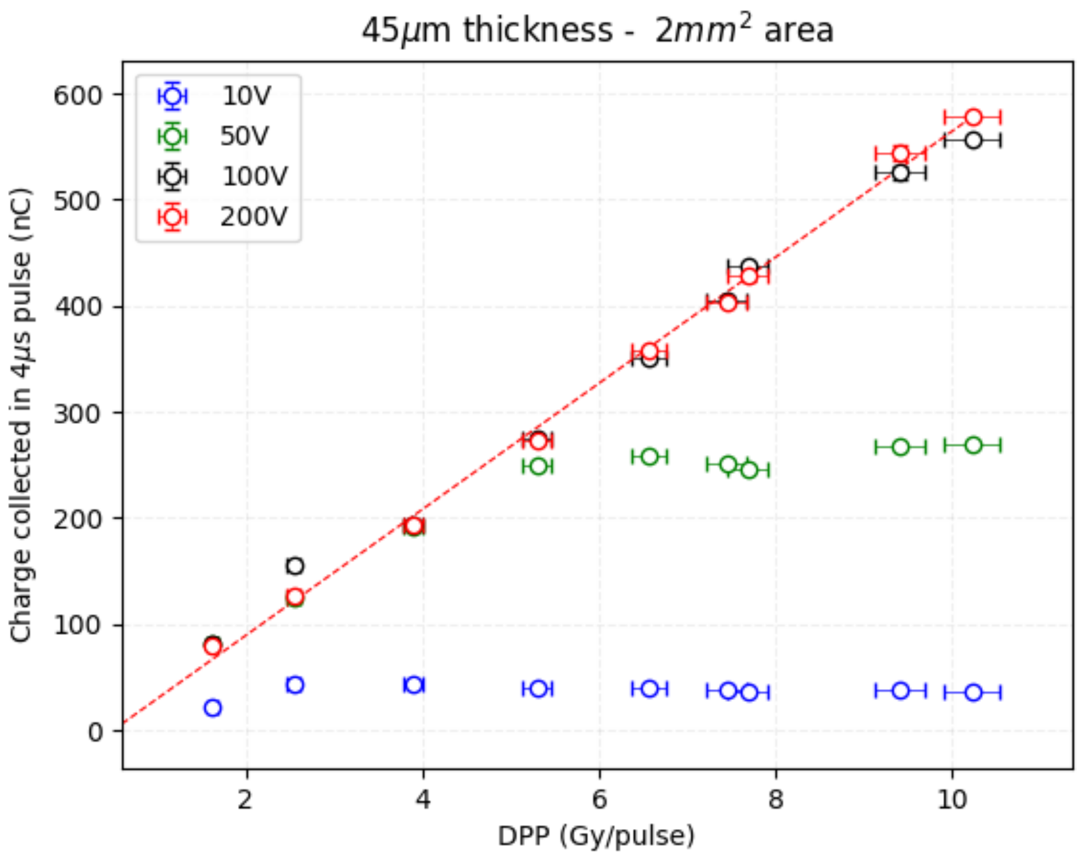
TERA08 and oscilloscope comparison

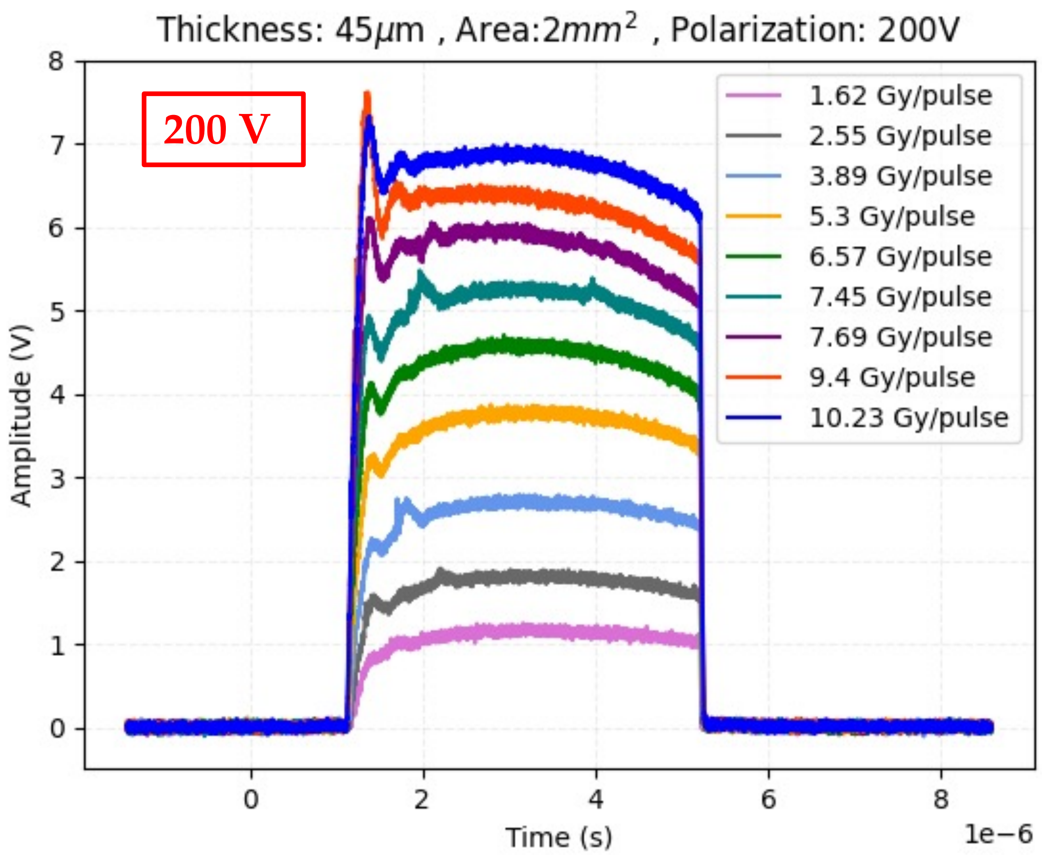
- 45 μm thickness, 2mm^2 area
- 200V bias voltage
- **Good linearity** (R^2 > 99%) up to dose-rates >10Gy/pulse (1Gy/pulse is already FLASH regime)
- **Good correlation** of charge measured with TERA08 and oscilloscope



Electric Field distortion

- 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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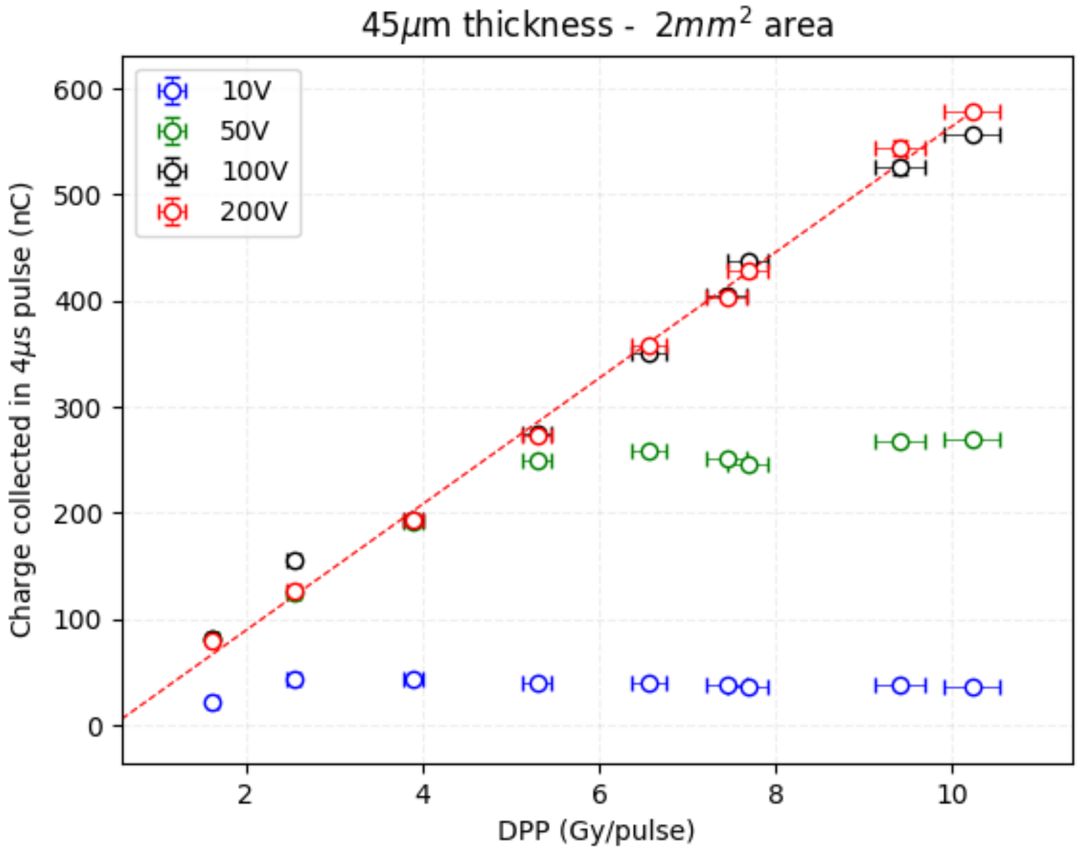
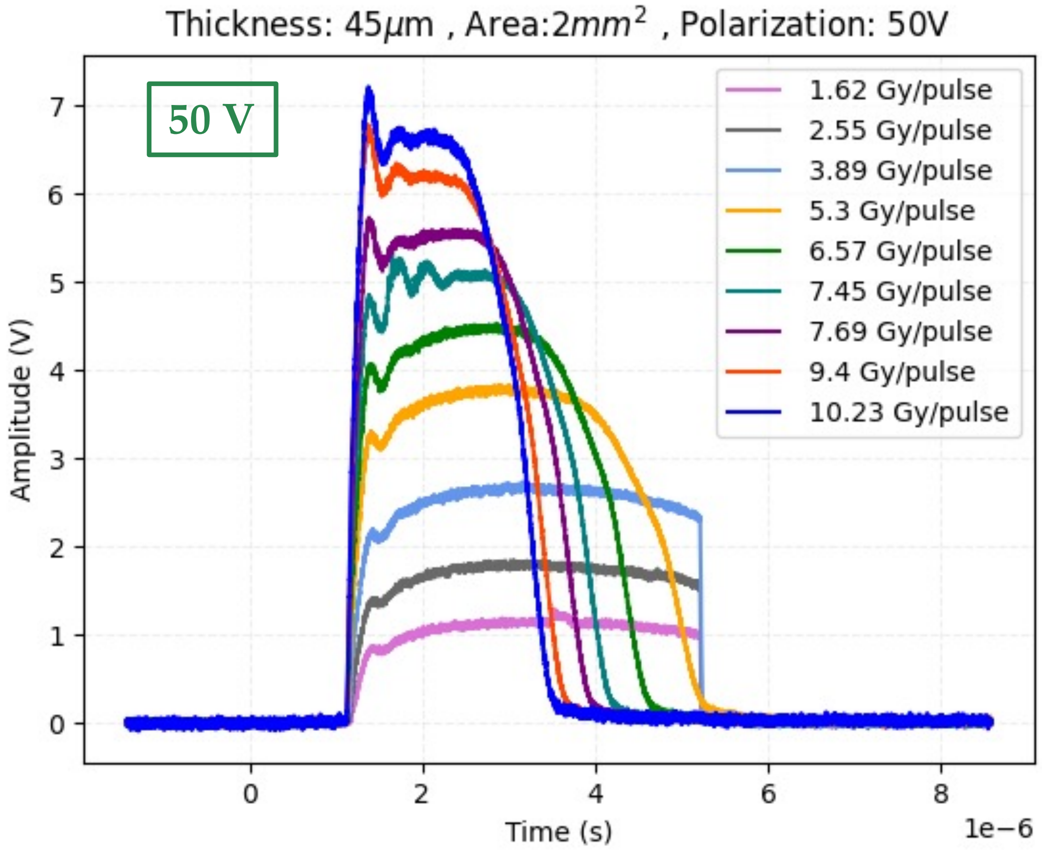
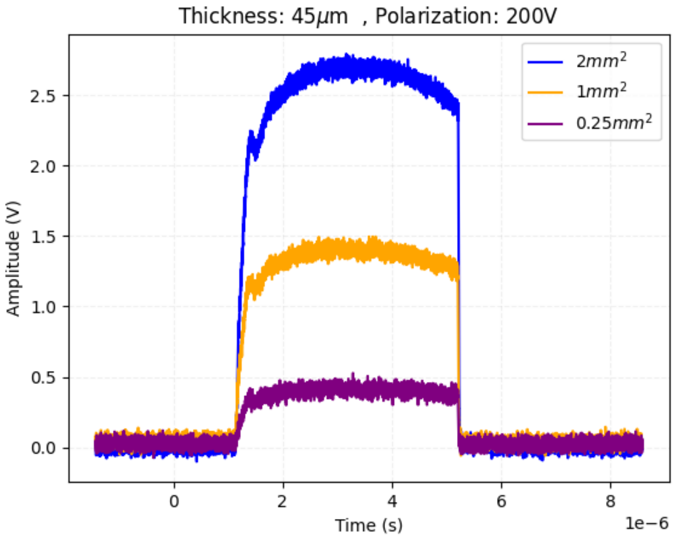
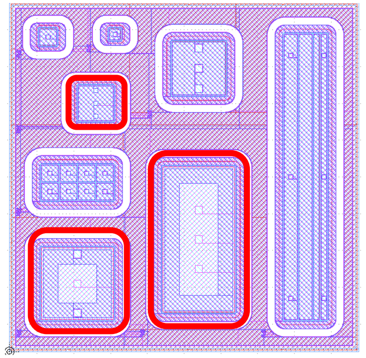


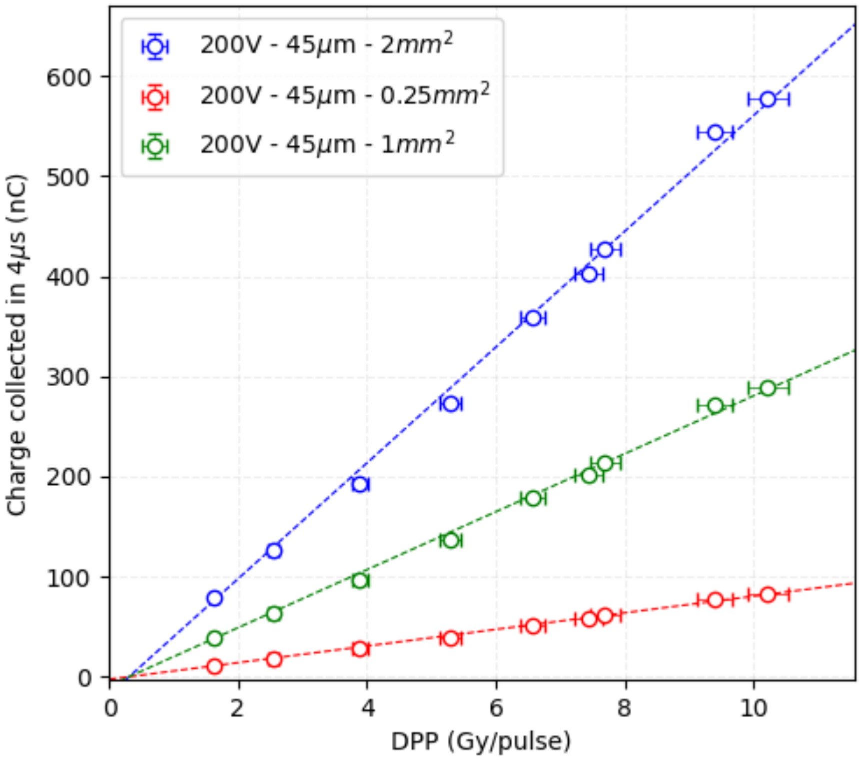


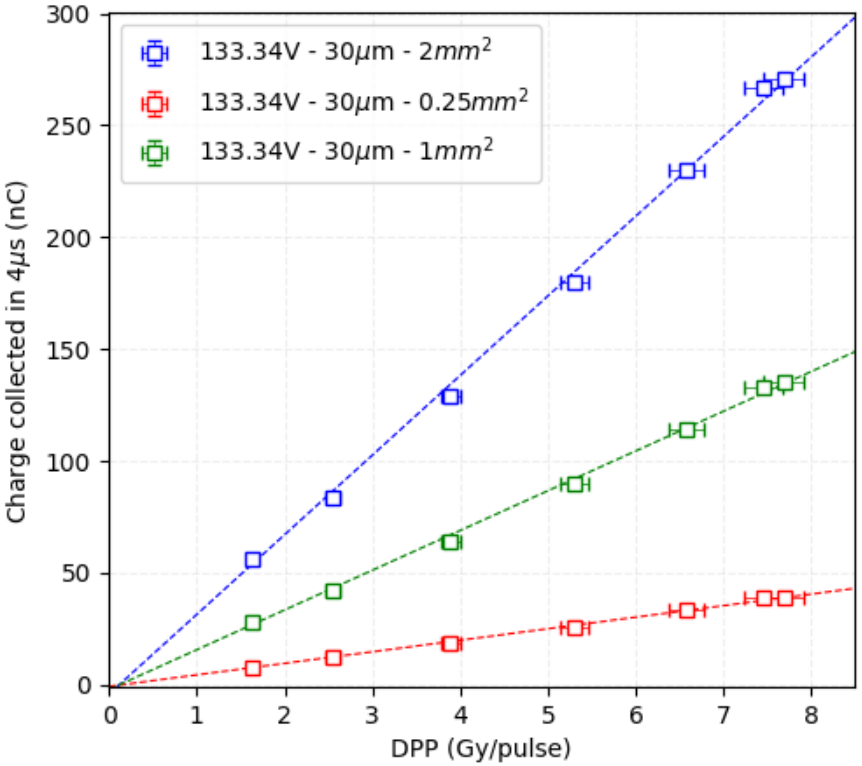
Area and thickness

- 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.





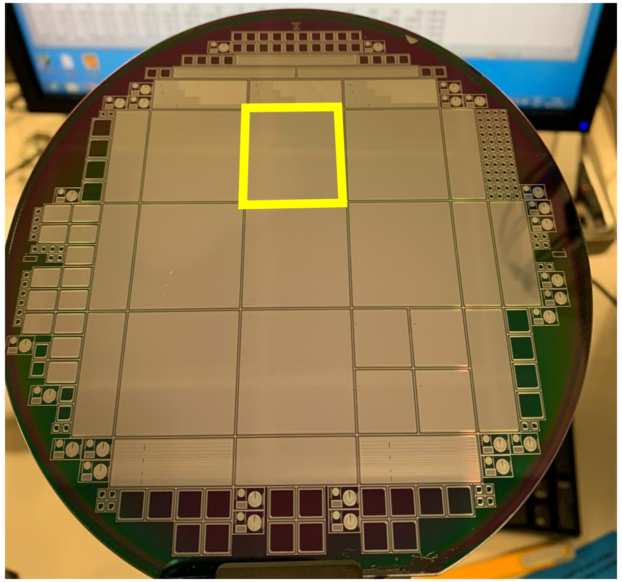




Next steps: TERA09

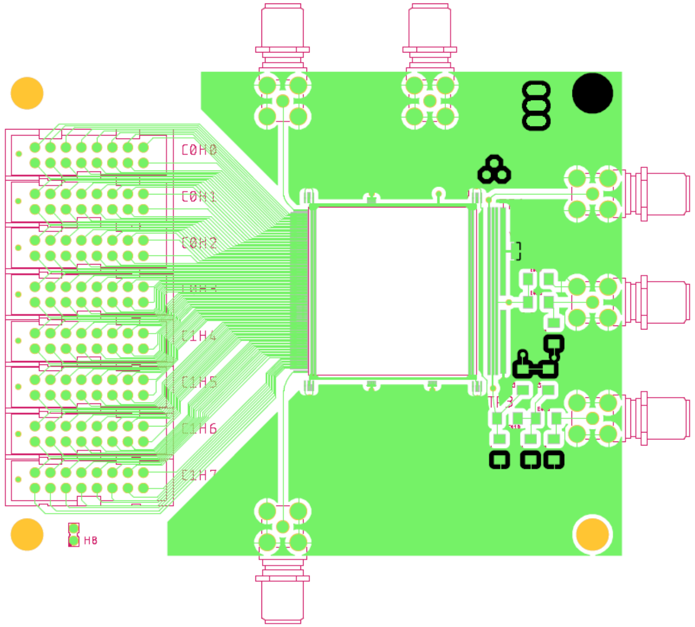
- Frontend chip based on 64 charge recycling CHNs
- **Extended current range** with respect to TERA08 (preliminary design and test phase): 12 µA / chn with 200 fC.
- Larger sensor (Area <u>2.7×2.7 cm^2</u> and 146 strips) to cover all beam spot area (~ cm^2)
- Strip based / pad based system: **Online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

Large sensor



[Designed to cover proton beam spot]

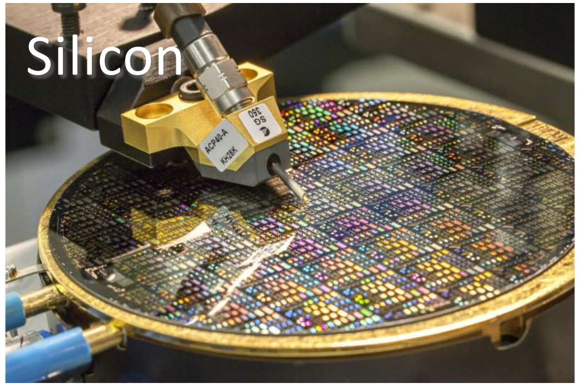
Detector board



TERA09

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

Solid State Devices for Beam Monitoring



- **Ultra-thin** ~10μm
- Well-developed manufacturing **technology**
- High **sensitivity** (tens of thousand times > than ICs)
- **Fast** response

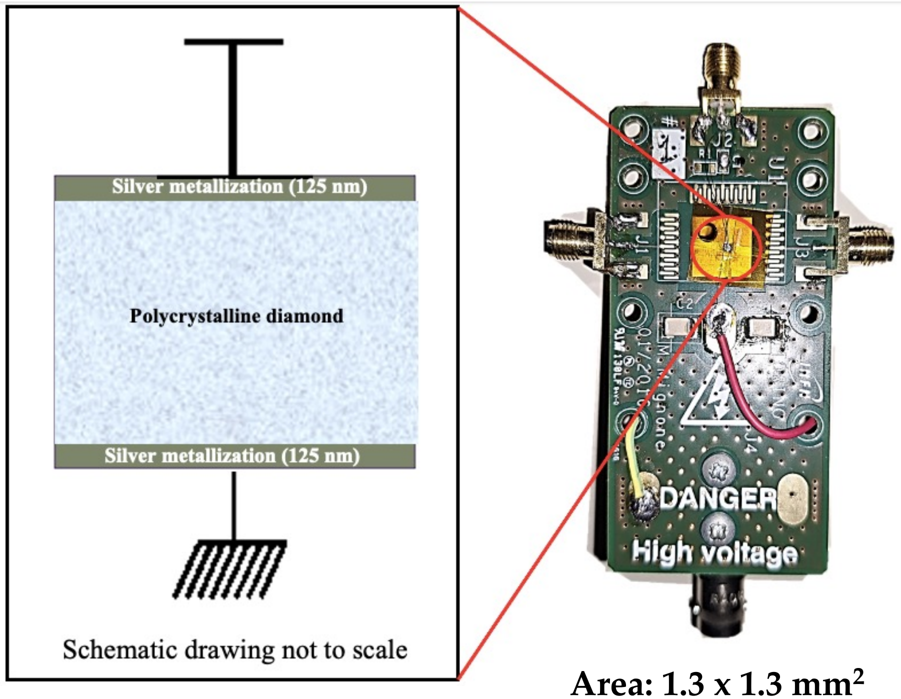
Unkown factors: linearity with DR, recombination, radiation resistance

- **Radiation hardness**
- High **resistivity** of intrinsic diamond
- Large saturated **carrier velocity**

Challenging issues: dose-rate linearity, possibility of straddle areas several cm^2

- **Compromise** between industrial maturity of Si and the robustness of diamond
- High electrical stiffness, speed of charges, melting T, thermal diffusivity, industrual maturity

Diamond detector

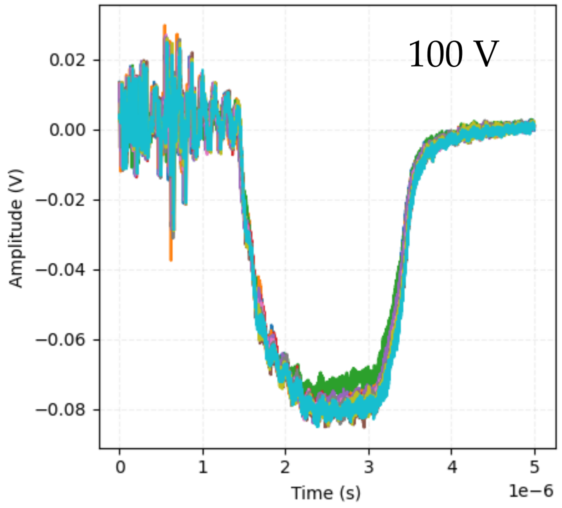


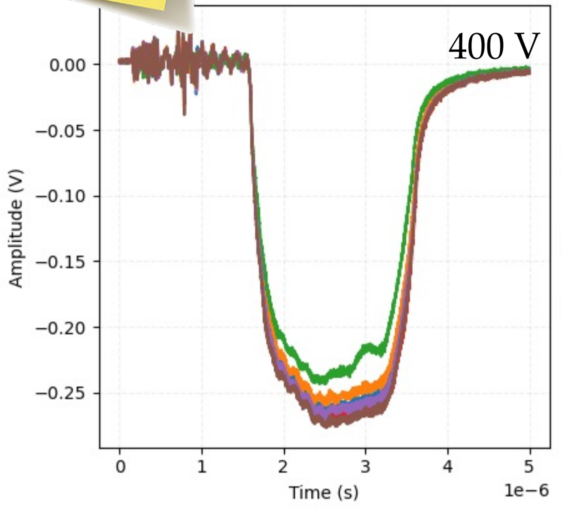
Area: 1.3 x 1.3 mm^2
Thickness: 100 μm

- **CVD Polycrystalline diamond**
- Metallised the diamond on both sides with aluminium layers
- Both positive and negative voltages.

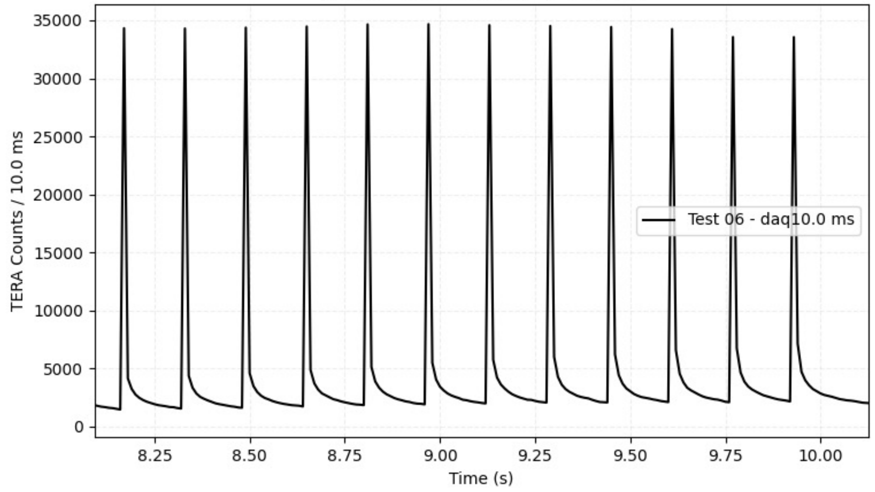
- LINAC Elekta SL18
- *FLASH MODE and CONV MODE*
- In-house developed sample
- Metallization vs Implantation

Oscilloscope



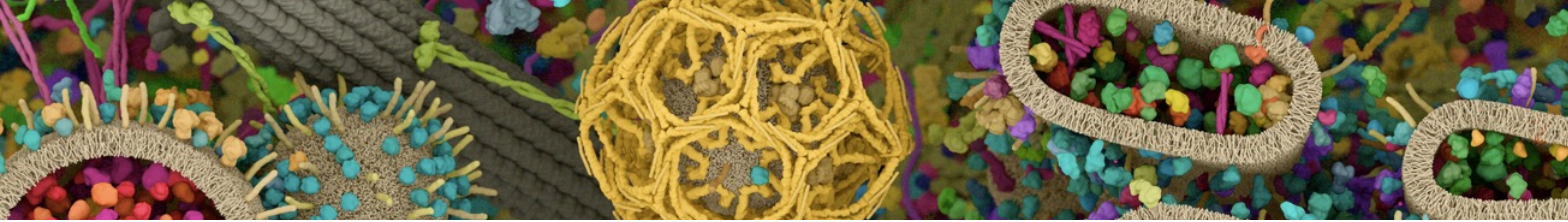


TERA08



Summary

- Different geometries of silicon sensor (pad/strip) were tested
- **Good linearity ($R^2 > 0.99$) up to more than 10 Gy/pulse**
- 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



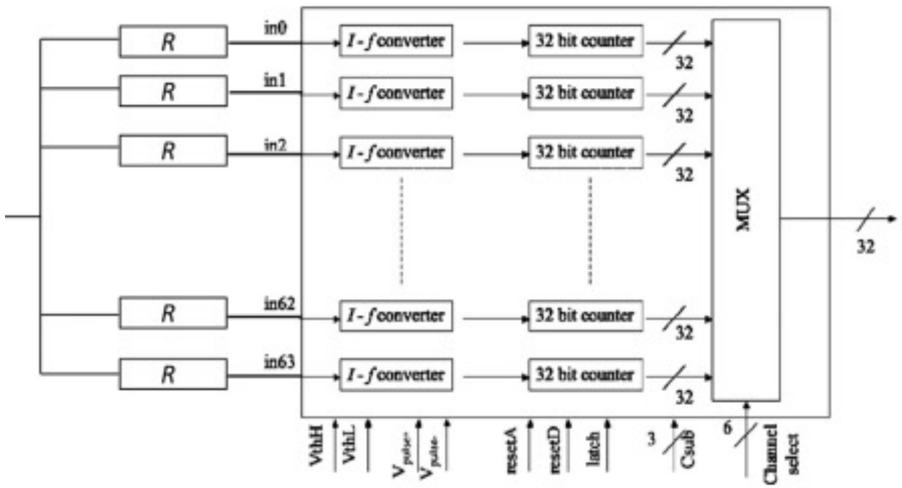
Thanks for the attention!

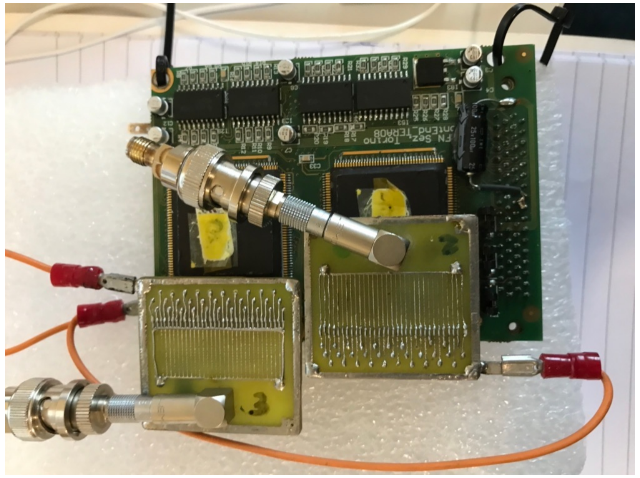
Backup slides

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



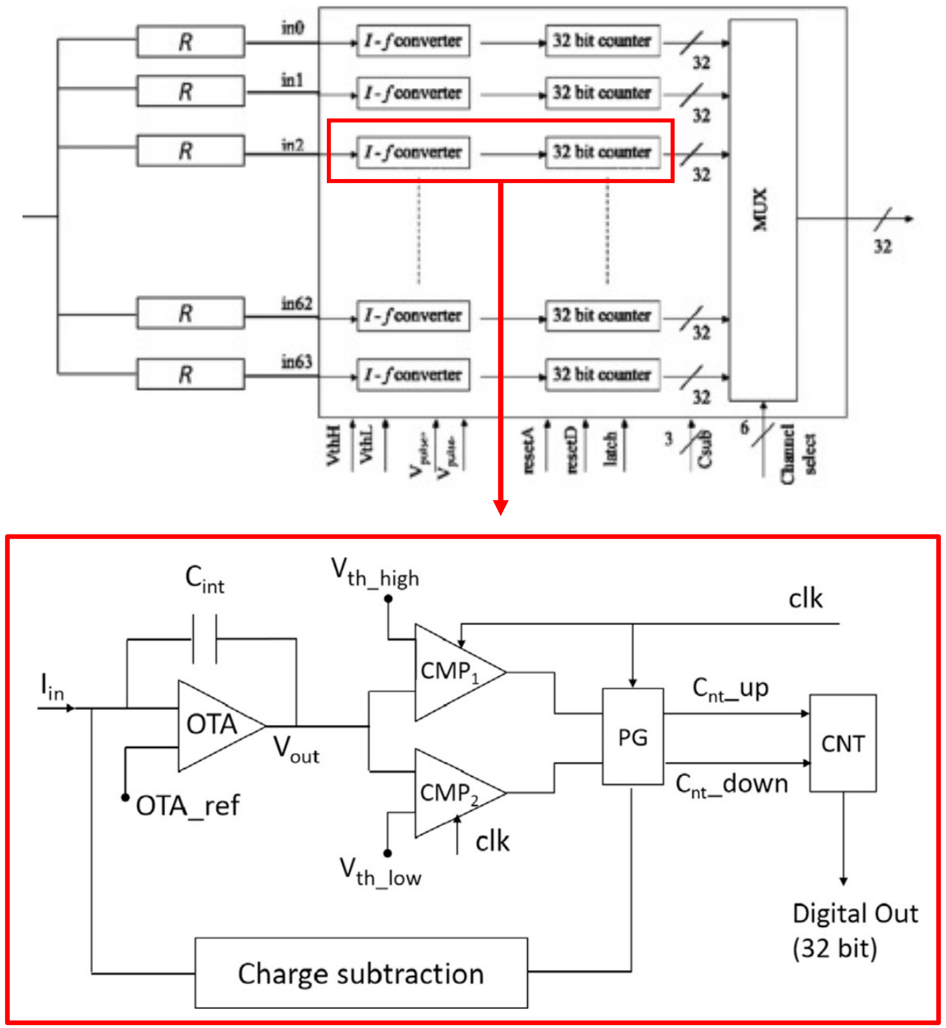


TERA08

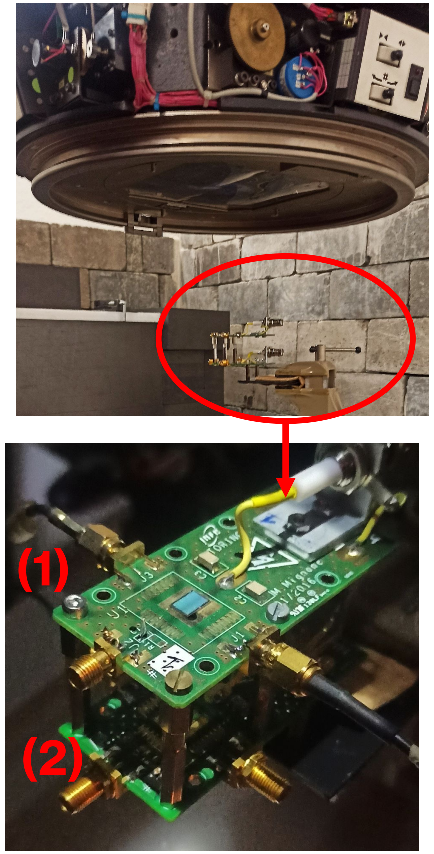
- I_{in} integrated over 600fF capacitor $\mathbf{C_{int}}$ (via Operational Transcoddutance Amplifier **OTA**)
- $\mathbf{V_{out}}$ compared to +/-thr (by 2 synchronous comparators $\mathbf{CMP_1}$ $\mathbf{CMP_2}$)
- Pulse Generator **PG**: pulse to increment/decrement counte **CNT**
- In parallel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

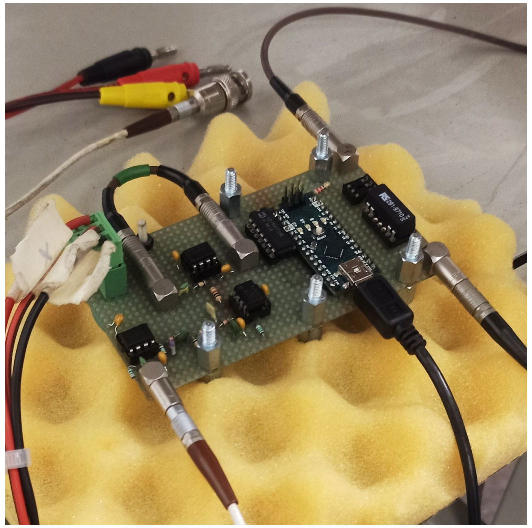


LINAC upgrade



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

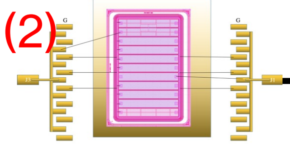
1. Signal to a **in-house built electrical circuit**: transimpedance amplifier converts photocurrent into small V with subsequent amplification
2. Gain chosen to have suitable input to a Schmitt-Trigger
3. Signal of ~5V as input to ARDUINO to count pulses
4. When amount of pulses reached: logical signal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



In-house built electrical circuit

Silicon sensor

(2)



I_{IN} → Transimpedance amplifier+OP Amp → Schmitt-Trigger → ARDUINO UNO (As pulse counter) → Optocoupler circuit → **Thyratron**

Diamond sensor: first test