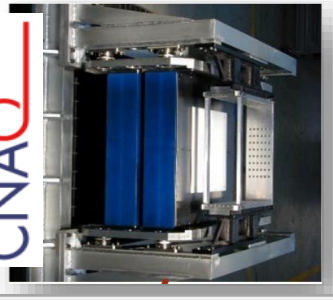
Characterization of thin silicon detectors for applications in conventional and flash irradiations

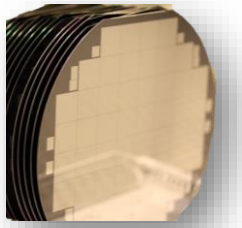
Francesco Pennazio (1) Simona Giordanengo (1) Anna Vignati (1, 2) Mohammed Abujami (1, 2) Davide Bersani (1) Maurizio Boscardin (1) Aurora Camperi (1) Matteo Centis Vignali (3) Piergiorgio Cerello (1) Roberto Cirio (1, 2) Emanuele Maria Data (1, 2) Umberto Deut (1, 2) Marco Donetti (4) Mohammad Fadavi Mazinani (1) Veronica Ferrero (1) Arianna Ferro (1, 2, 5) Elisa Fiorina (1) Cosimo Galeone (1) Felix Mas Milian (1 and 6) Elisabetta Medina (1, 2) Diango Manuel Montalvan Olivares (1, 2) Franco Mostardi (1, 2, 7) Sahar Ranjbar (1, 2) Roberto Sacchi (1)

1 Istituto Nazionale di Fisica Nucleare
2 Università degli studi di Torino
3 Fondazione Bruno Kessler
4 Fondazione CNAO
5 DETECTOR - Devices & Technologies Torino
6 Universidade Estadual de Santa Cruz
7 IBA Dosimetry GmbH, Schwarzenbruck, Germany

Motivation for Solid State sensors

IONIZATION CHAMBERS





SOLID STATE

Collection times	**~ 100 µs**	**~ ns**
Sensitivity	**~ 10^4 protons** **~ 10^3 C ions**	**single particle**
Time resolution	**~ no/poor**	**< 100 ps**
Deviation from linearity @ high dose rates		**Less recombination @ high dose rates** • 10^2 × E field • 10^2 × charge mobility • 10^{-1} × thickness
Not suitable for • fast scanning modalities • timing applications • high dose rates (FLASH)		**New applications** • direct counting # particles • timing applications • high dose rates (FLASH)

Main challenges

Counting particles: signal pile-up

→ fast sensors & readout

→ segmentation

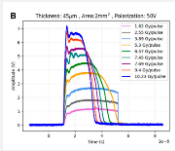
→ difficult above **10^{10} p/cm²s**

High dose rates (FLASH)

→ 10^3 × dose rates

→ plasma effects in silicon

Radiation tolerance



→ manufacturing strategies

→ damage compensation

Increased complexity

Thin Low Gain Avalanche Detectors (LGADs)

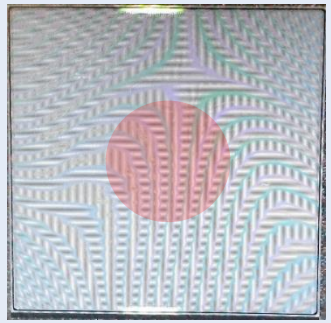
- thickness of sensitive volume **< 50 µm**
- internal charge multiplication **~ 10**

➡ **Enhanced signal of very small duration** + **Time resolution of tens of ps**

Strip detectors (strip area ~ 3 mm², active thickness 45µm)

Detectors for particle counting

- Large area (2.7×2,7 cm²)
- 144 strips



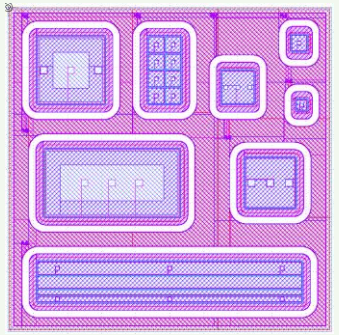
Beam spot
1 cm FWHM

Detectors for timing applications

- Smaller size, 11 strips
- Si- substrate removed to reduce total thickness to 70 µm

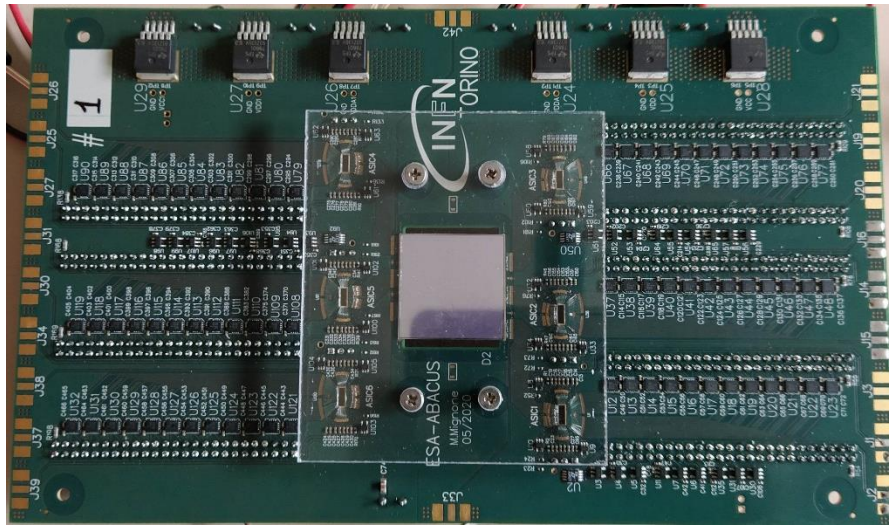
Pads for large ionization rate studies (ExFLU)

- 4 active thicknesses (15/20/**30/45** µm)
- 5 pad sizes (0,125/0,25/0,56/1/2 mm²)



Internal gain	
yes	no
✓	✓
✓	✓
✗	✓
Use: Protons	**Use: C-ions FLASH**

INFN MoveIT project (2017-2021)



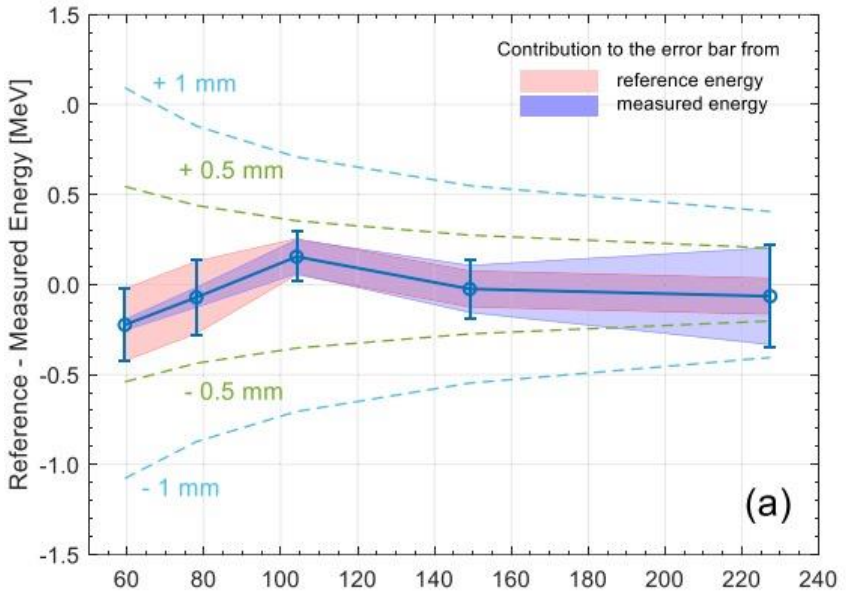
Proton beam particle counter (ESA ABACUS)

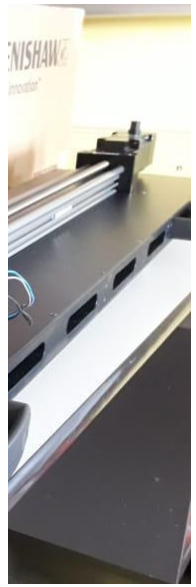
- Six ABACUS front-end discriminators -> 3 FPGA boards
- 2.7×2.7 cm^2 active area (144 strips)
- Counting rate up to 100 MHz with < 2% pileup inefficiency
- For larger rates, inefficiency measurement implemented in FPGA **Mohammadian-Behbahani M, et. al., *NIM A 1040 (2022) 167195***

Beam energy detector

- High precision mechanical system
- XYZ axes remotely controlled
- 8 channel FE board, sensor active area 20 mm^2
- accuracy on ToF measurement < 10 ps
- Self-calibration method developed and tested

A. Vignati, et. al., *Phys. Med. Biol. 65 (2020) 215030*
A. Vignati, et. al., *Med. Phys. 50 (2023) 5817-5827*





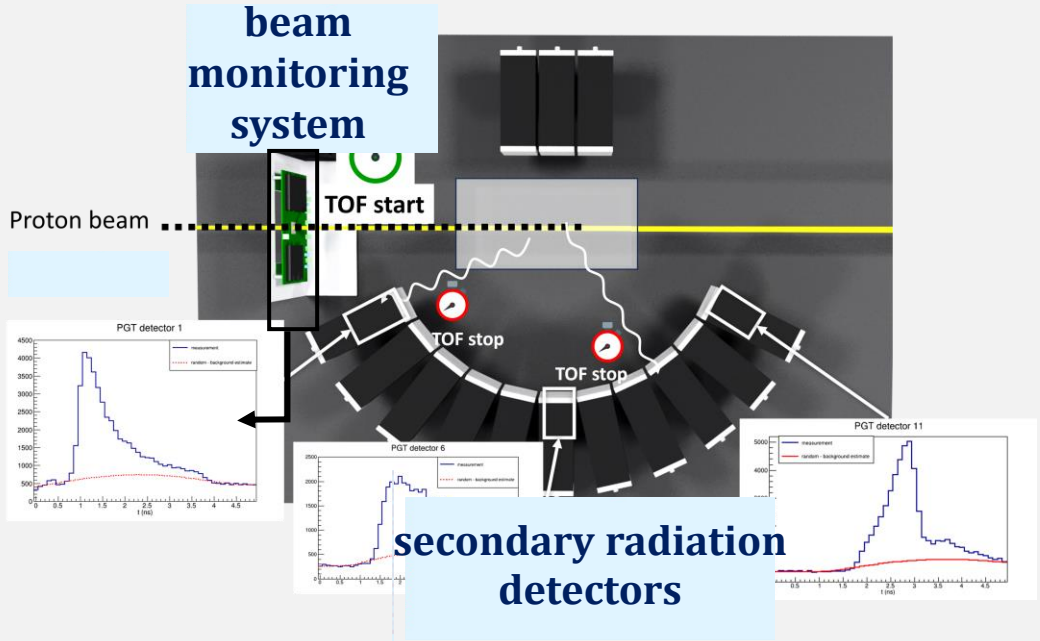
INFN SIG project (2022-2025)

R&D towards an advanced **Superconducting Ion Gantry**

- Multi-ion (He → O)
- Lightweight (based on 4-5 T SC curved dipole)
- Integrated novel **Dose Delivery** and in-vivo **Range Verification Systems for ions**

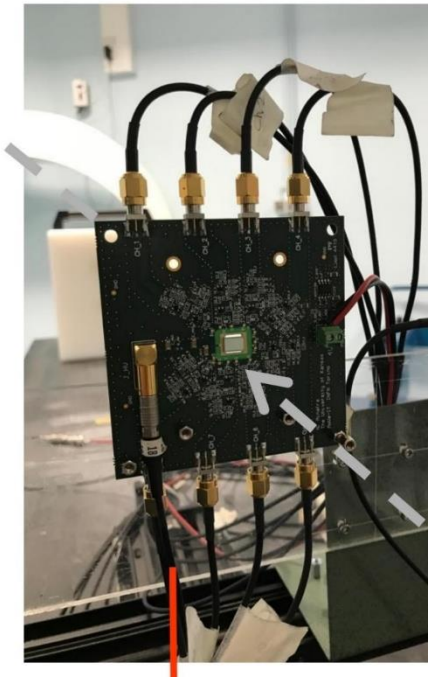
Prompt Gamma Timing (PGT)

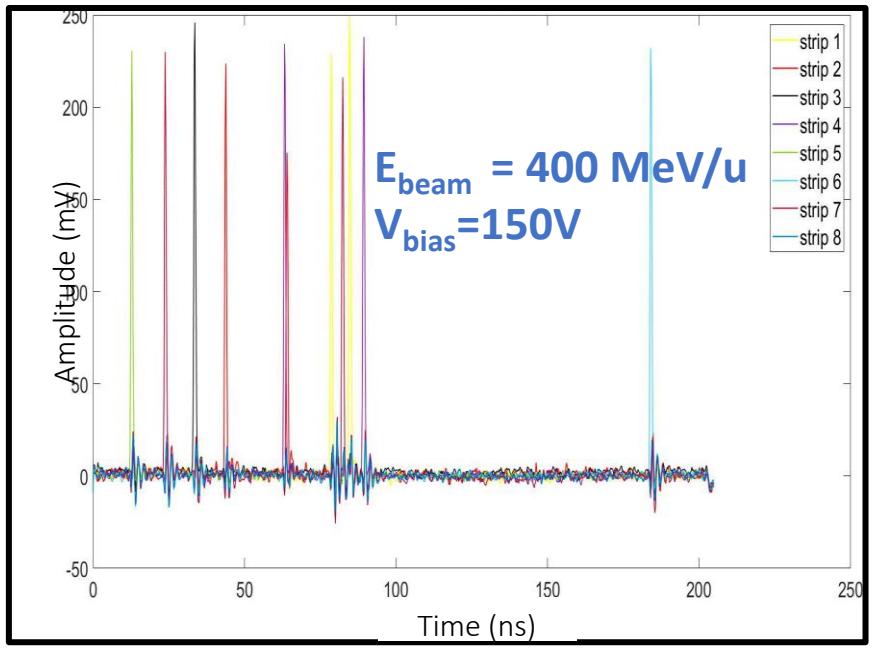
measurement of prompt gamma emission time to get insights into the range of ions



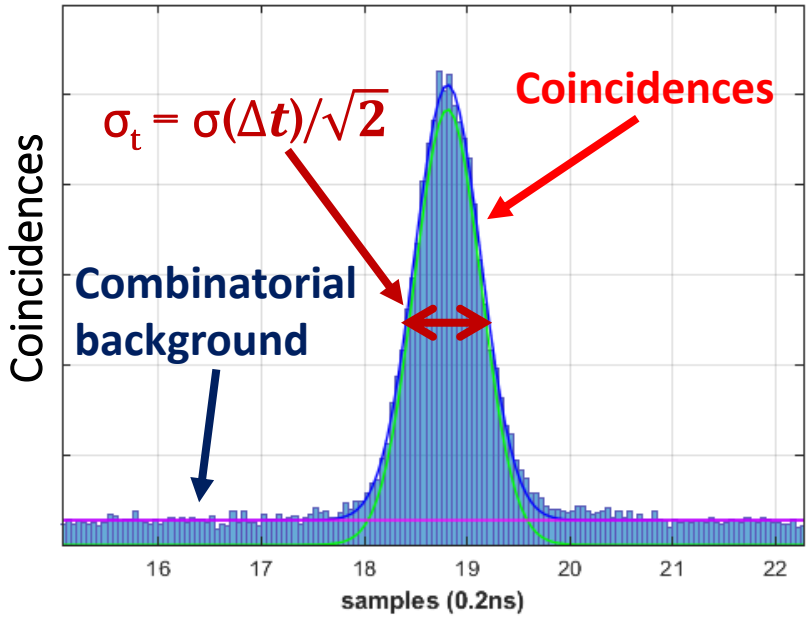
- **Integration with beam monitoring for time synchronization**
- **PGT distributions measured @ CNAO with protons and C-ions (Merlino INFN project)**
  - **Non-optimized acquisition system**
  - **Low efficiency (large deadtimes)**
  - **Sub-clinical beam intensities**
- **Develop new acq. system based on TDC**

C-ions signal in thin sensors



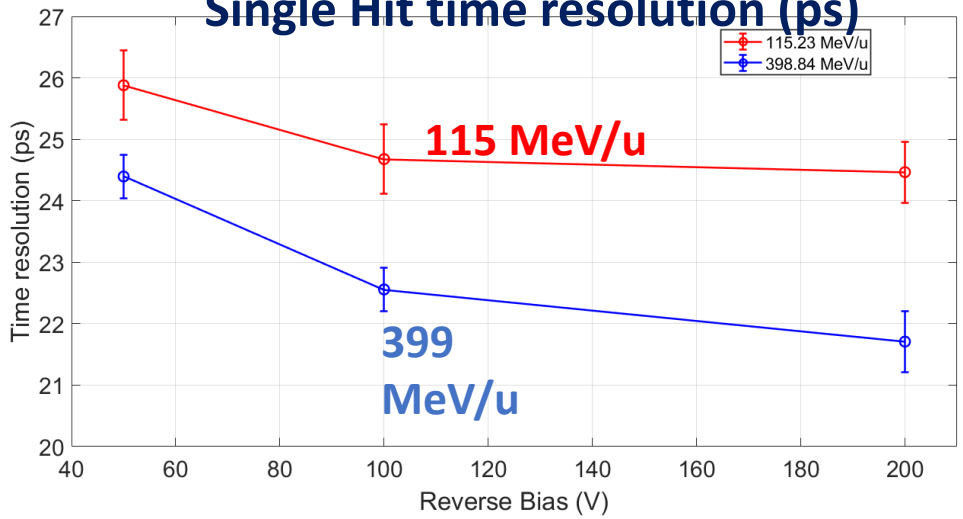


Histogram of arrival time difference



- 11-strips sensor with **gain=1**
- 8-channels amplifier board
- Acquisition with CAEN DT5742 digitizer
  - 16+1 channels, 12 bit ADC
  - 5 GS/s sampling rate

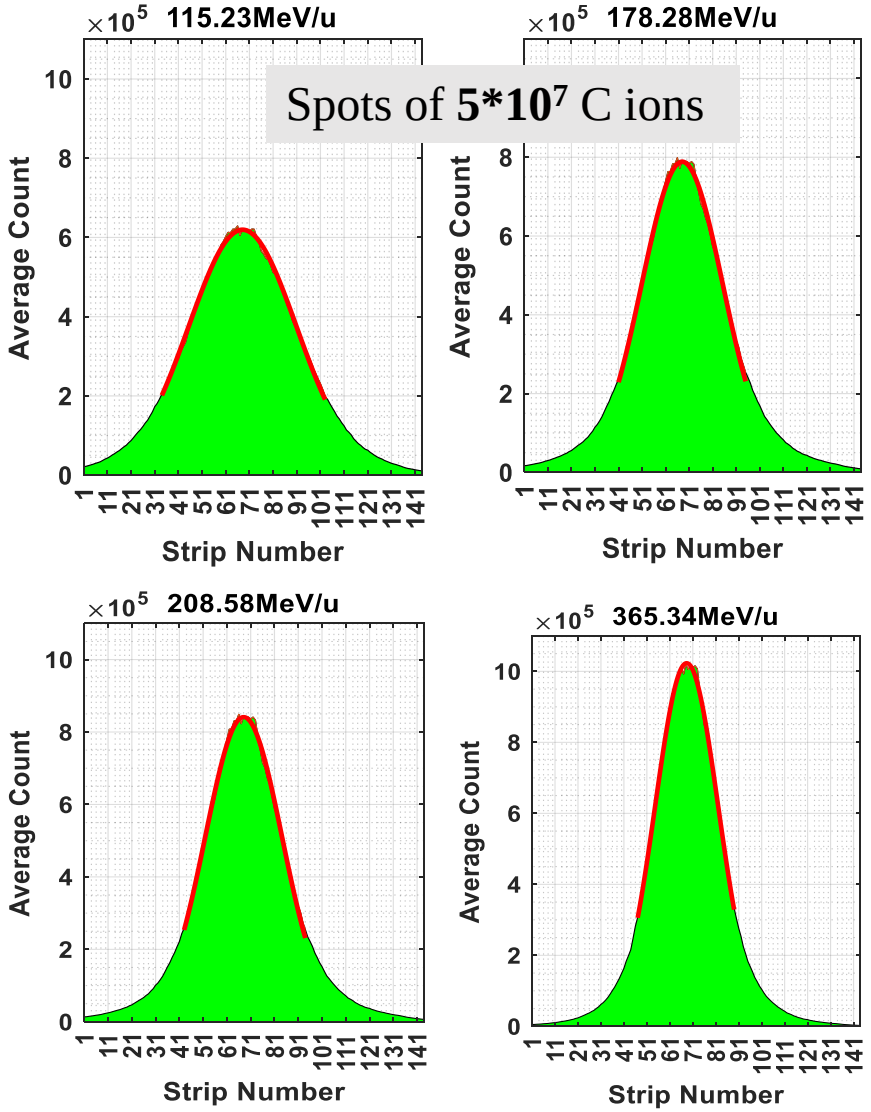
Single Hit time resolution (ps)

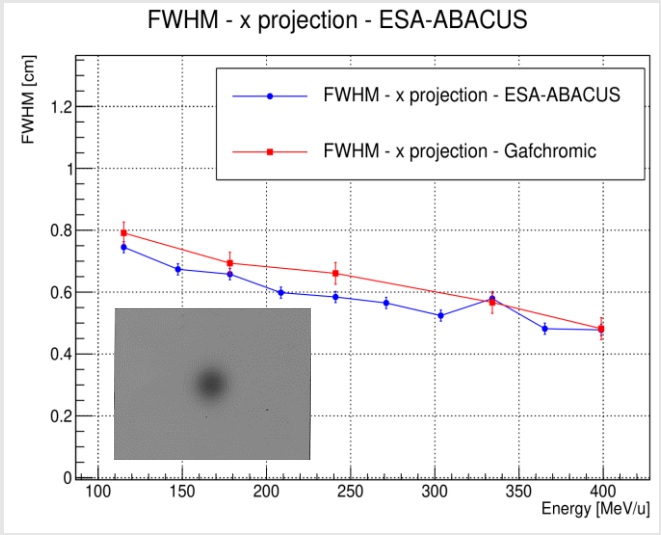


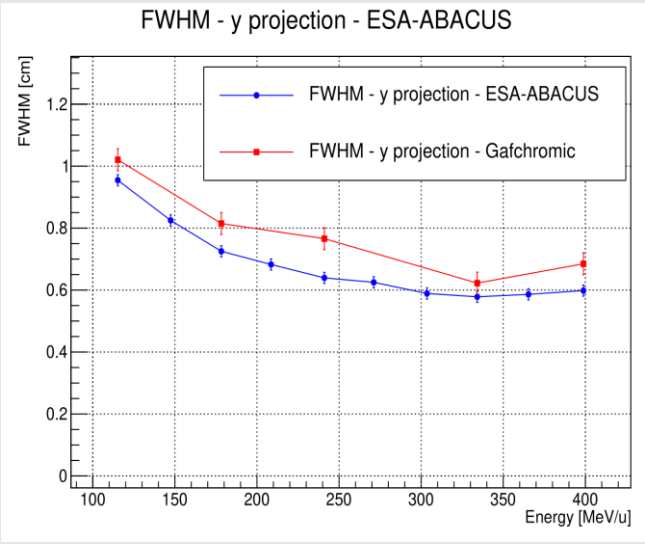
C-ion beam counter

Beam Profile

Spots of $5*10^7$ C ions







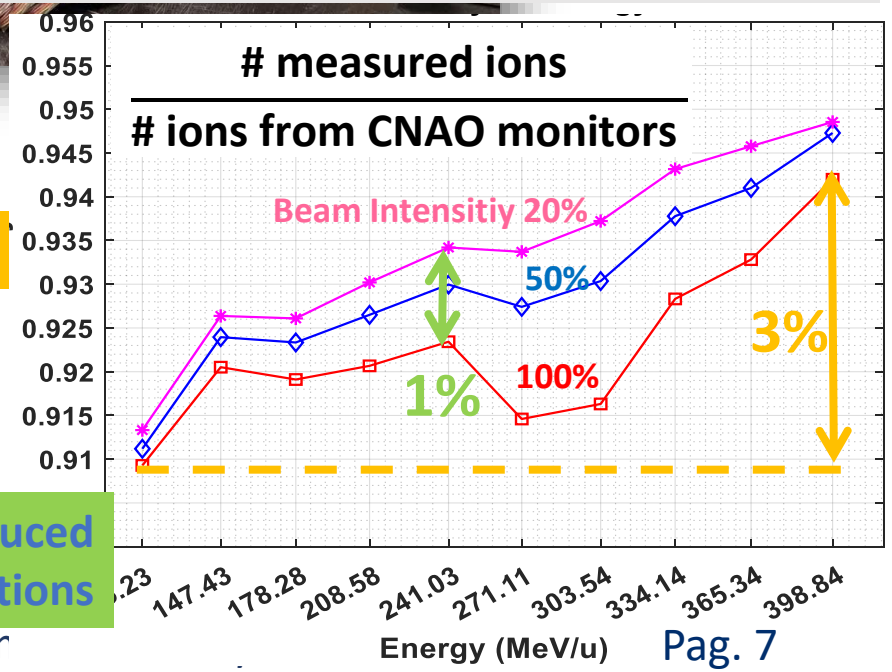
Comparison of beam FWHM with GAFCHROMIC films

3% difference between low-high energy

Tails of beam profile

1% difference between low-high intensity

Pile-up inefficiency reduced to 0.5% after corrections



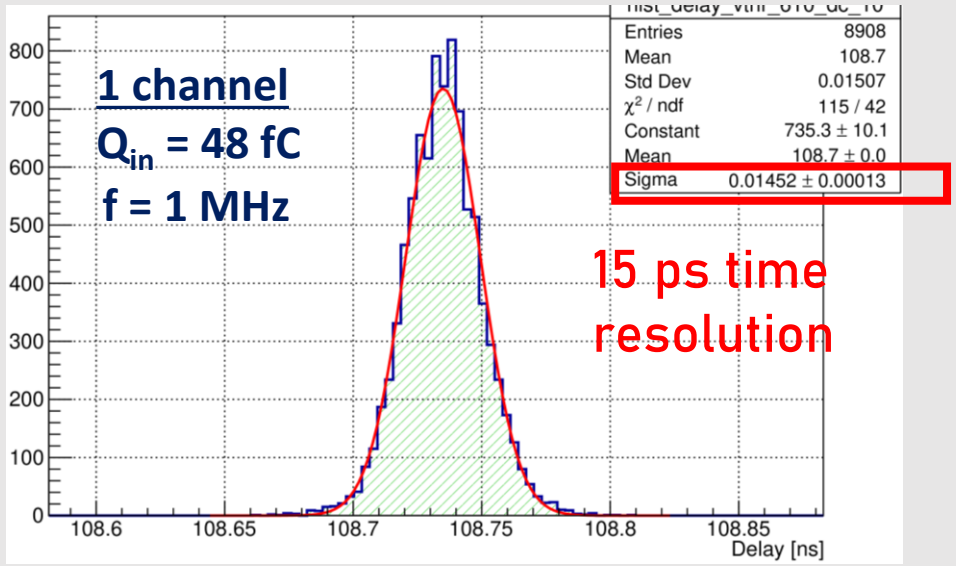
Time measurements with CERN picoTDC

CERN picoTDC evaluation board (64 input channels)

- 3ps or 12ps binning
- very low jitter (<1ps)
- High rate capability
- Readout through FPGA

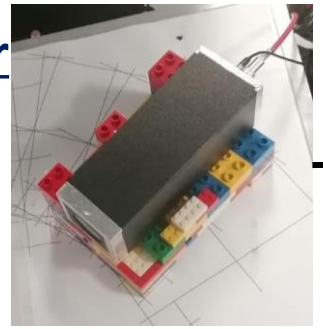
Successfully integrated with 1 channel of ESA-ABACUS board

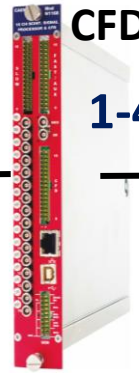
- ➢ **Conversion efficiency 100%**
- ➢ **Tested up to 150 MHz freq.**



December 2023 integration test @ CNAO

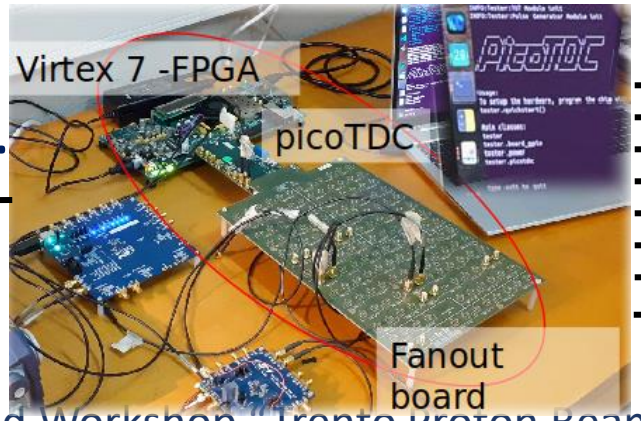
PG detector
LaBr3
+
PMT/SIPM



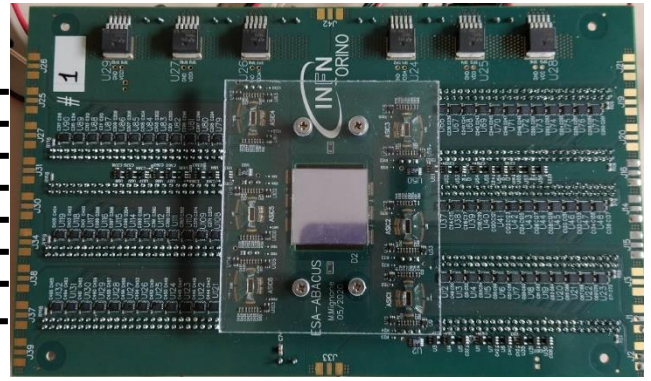


CFD

1-4 chn.



8 chn.

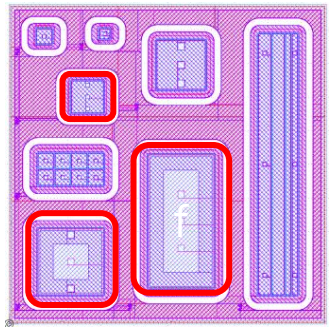


Monitoring of FLASH UHDR electron beams

ElectronFlash accelerator (CFR - Pisa)

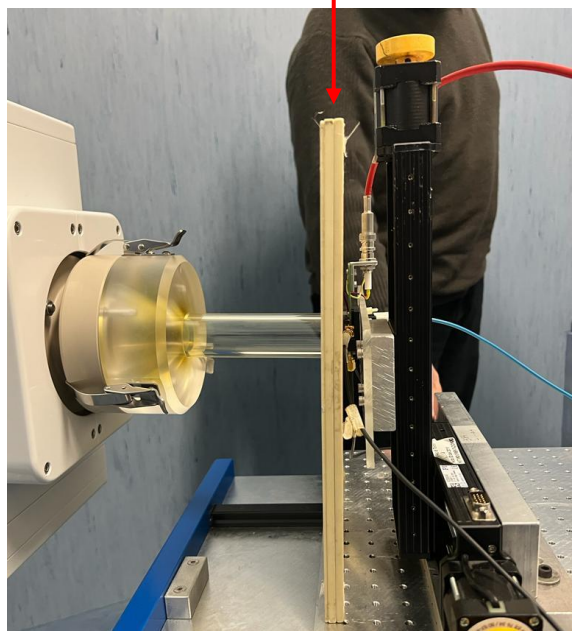
- **9 MeV** electrons pulsed beam
- Beam current: **1-100 mA**
- Pulse duration: **4 μs**
- Pulse frequency: **5 Hz**
- Uniform fields using 3 cm PMMA plastic applicator

Sensors tested

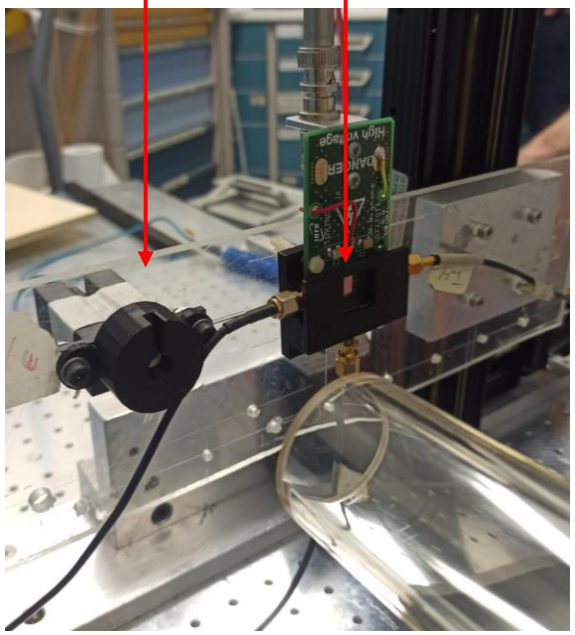


- **45/ 30μm** thickness
- **2/1/0.25 mm²** area
- Bias voltage: **10V ÷ 200V**
- Dose/Pulse **0 ÷ 10Gy**

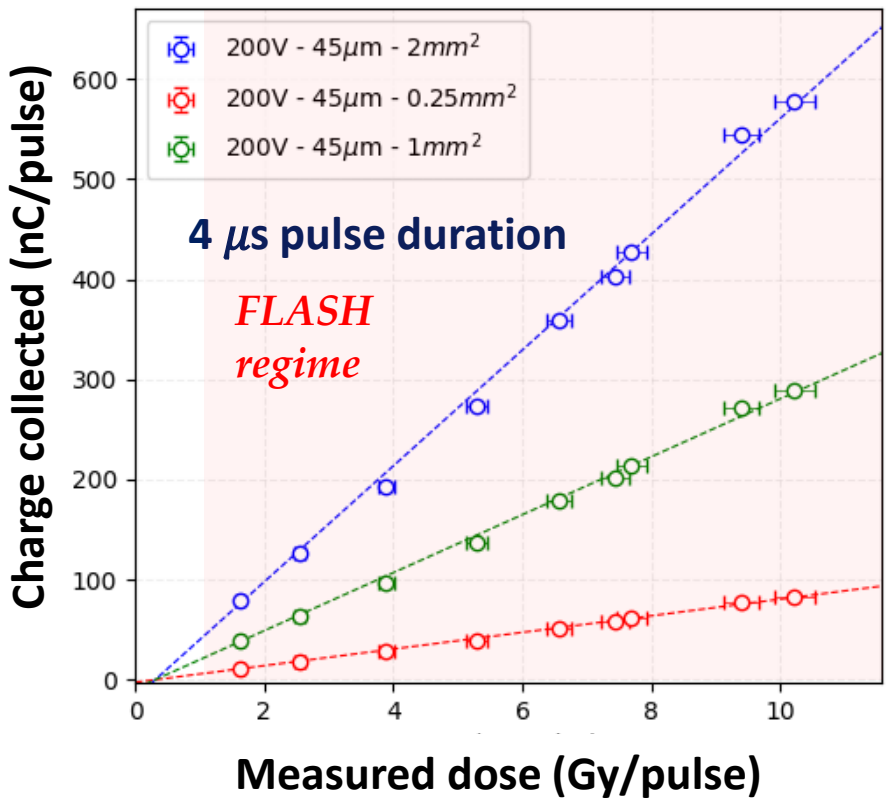
13mm solid water slab

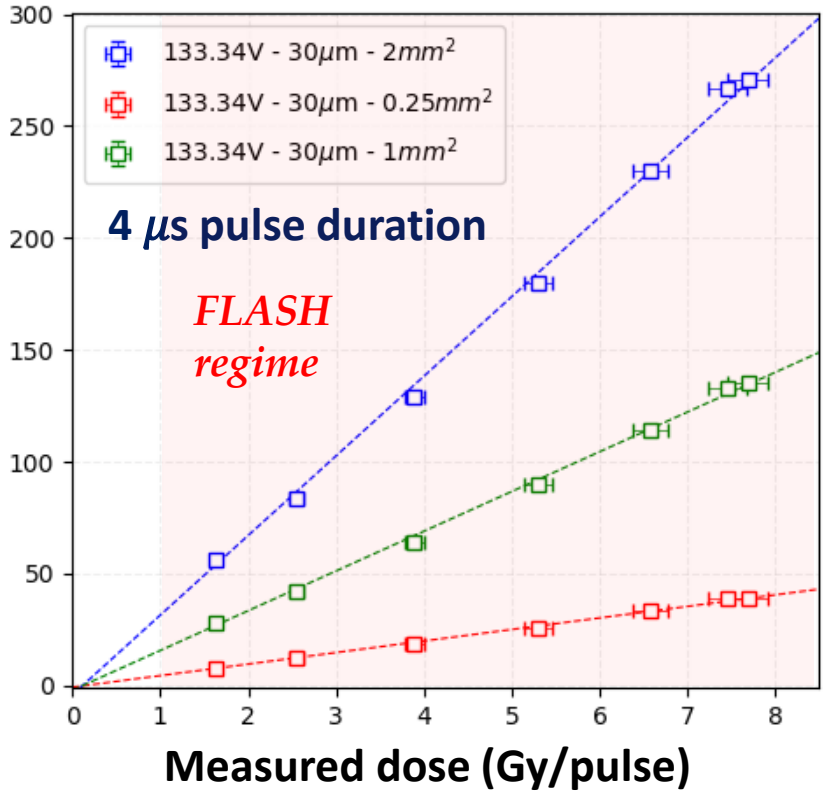


FlashDiamond and silicon sensor in same conditions



Monitoring of FLASH UHDR electron beams





FLASH Radiotherapy with hIgh Dose-rate particle beAms

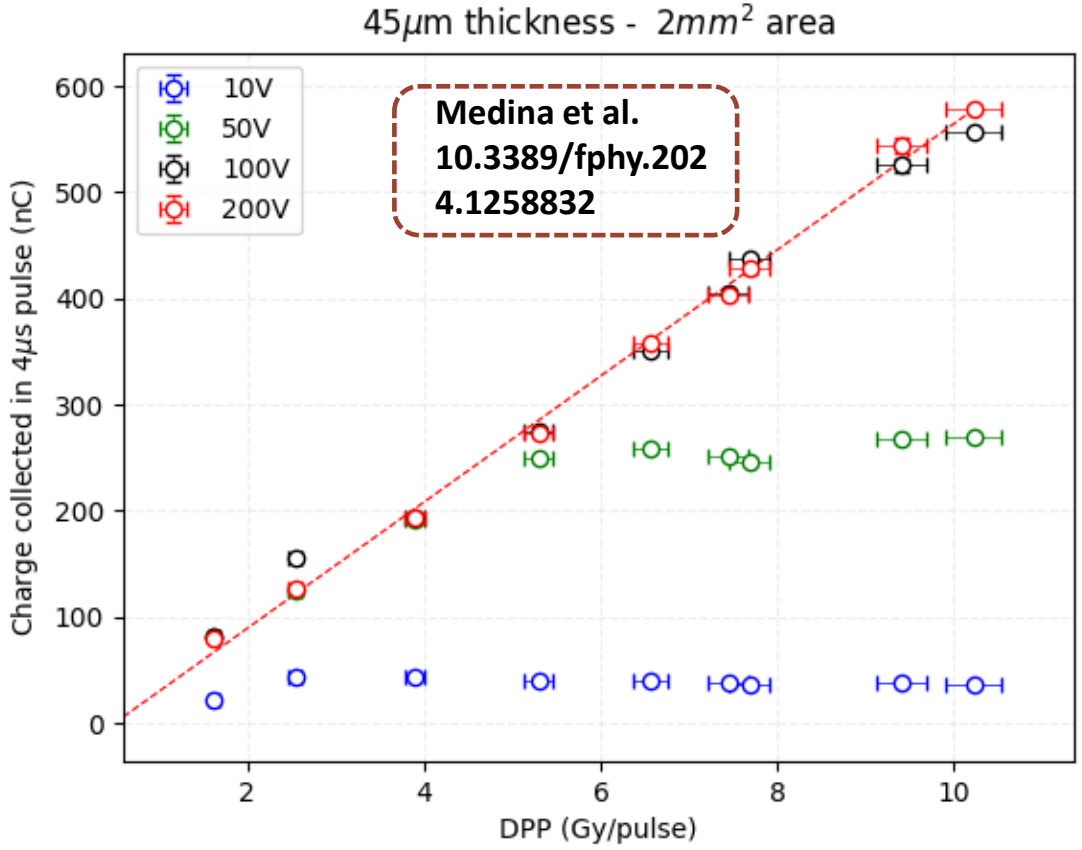
- Collected charge/pulse **scales** with **pad area** and **sensor thickness**
- **Ratios** between different area/thickness **independent from dose/pulse**

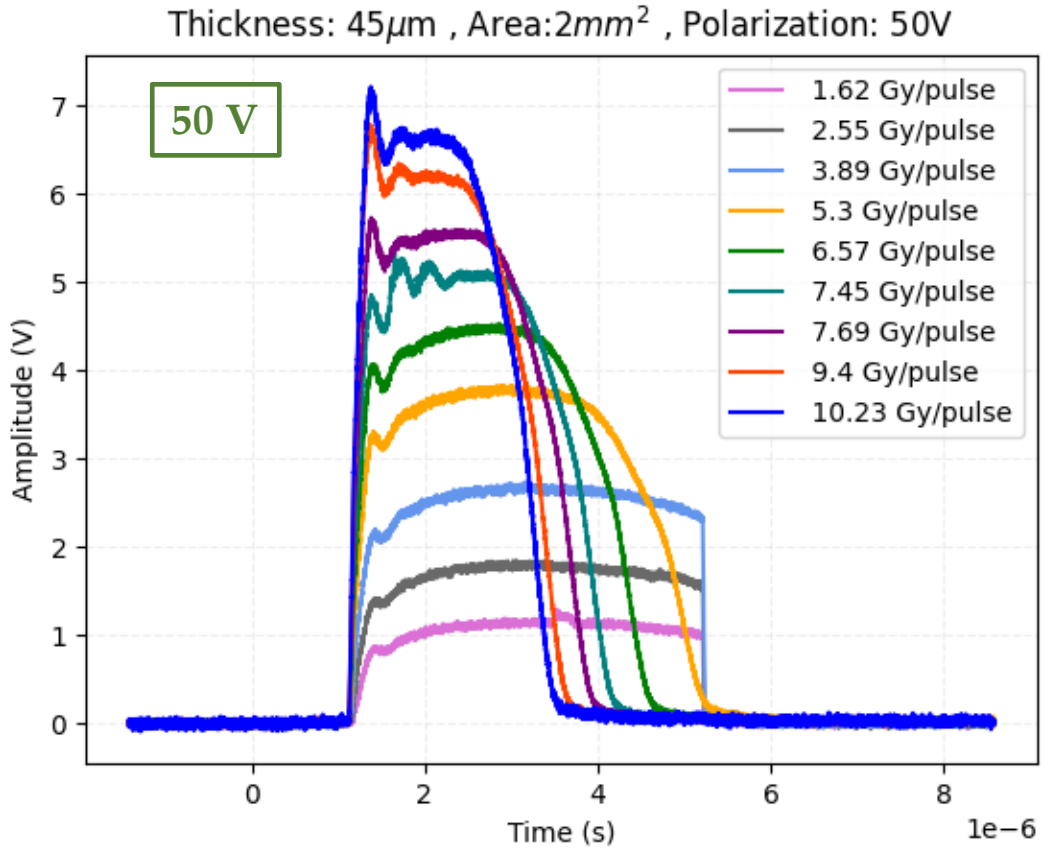
Medina et al. 10.3389/fphy.2024.1258832

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

FLASH Radiotherapy with hIgh Dose-rate particle beAms

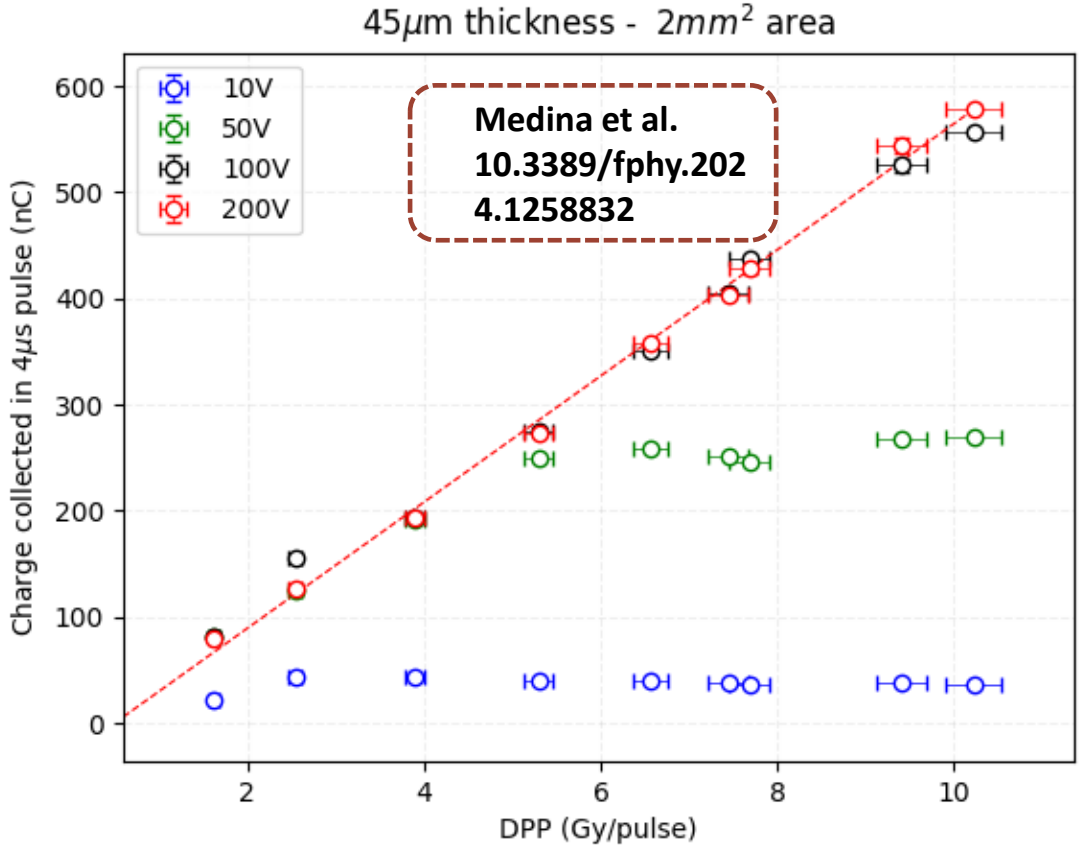


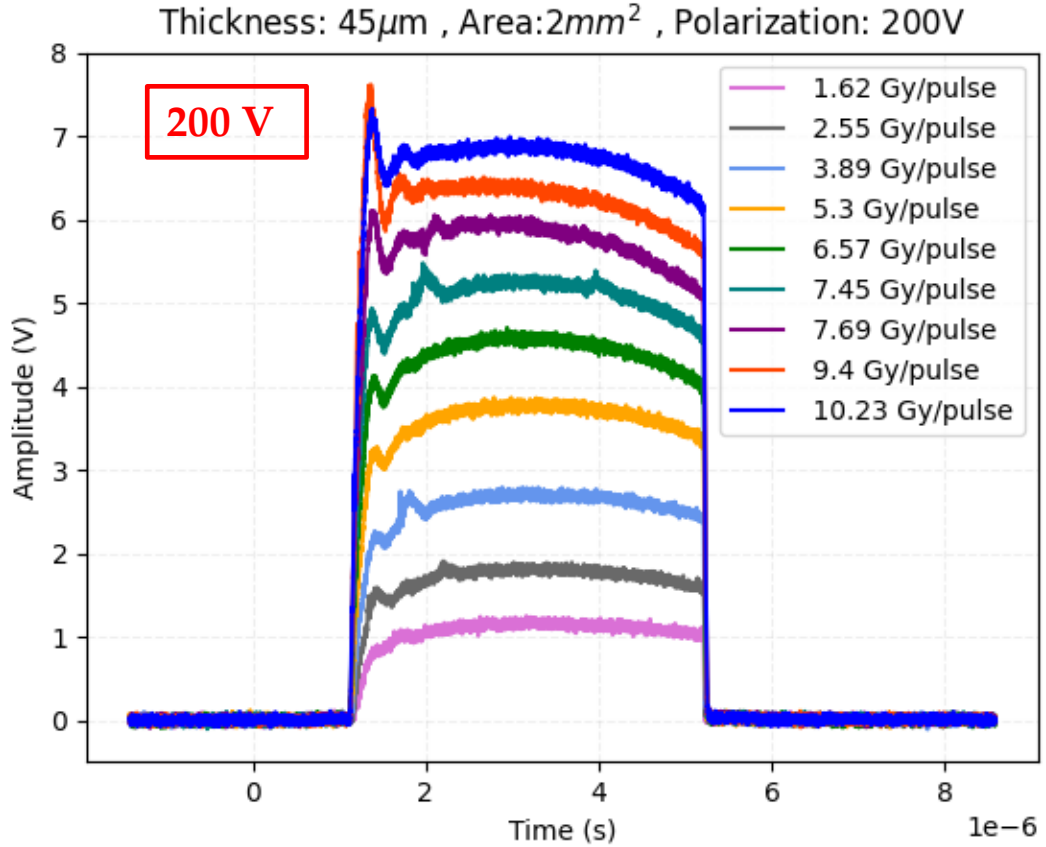


Electric Field distortion

- 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

FLASH Radiotherapy with hIgh Dose-rate particle beAms

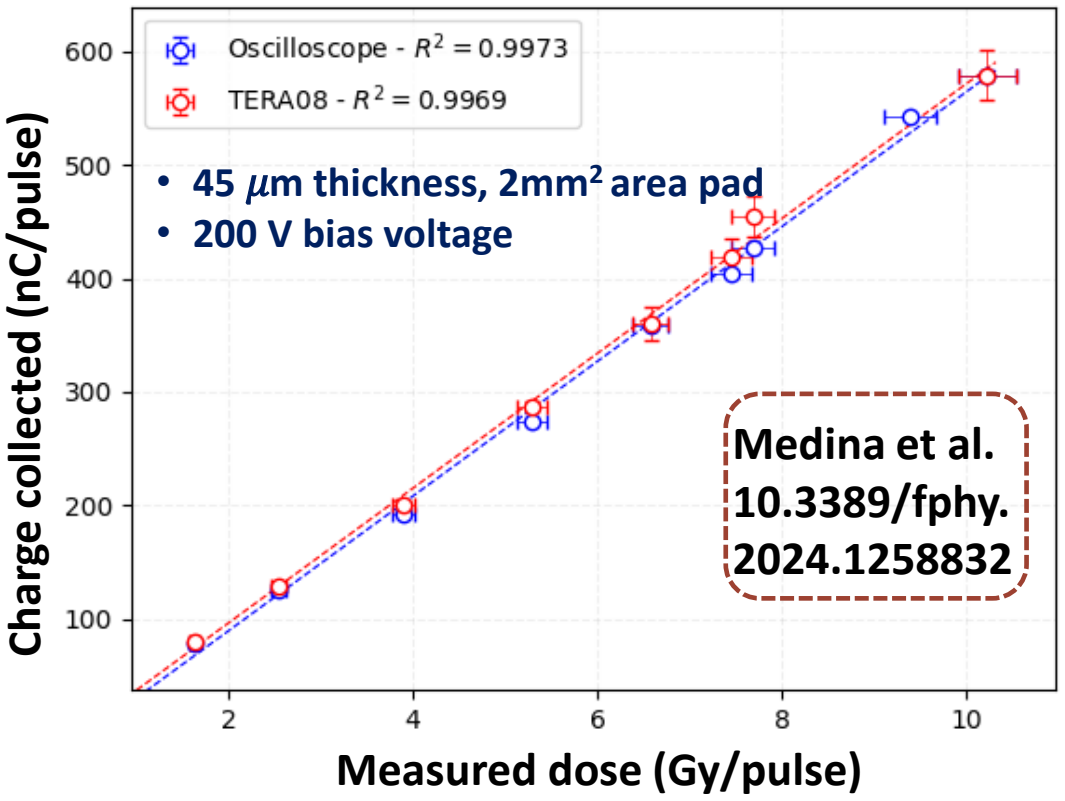




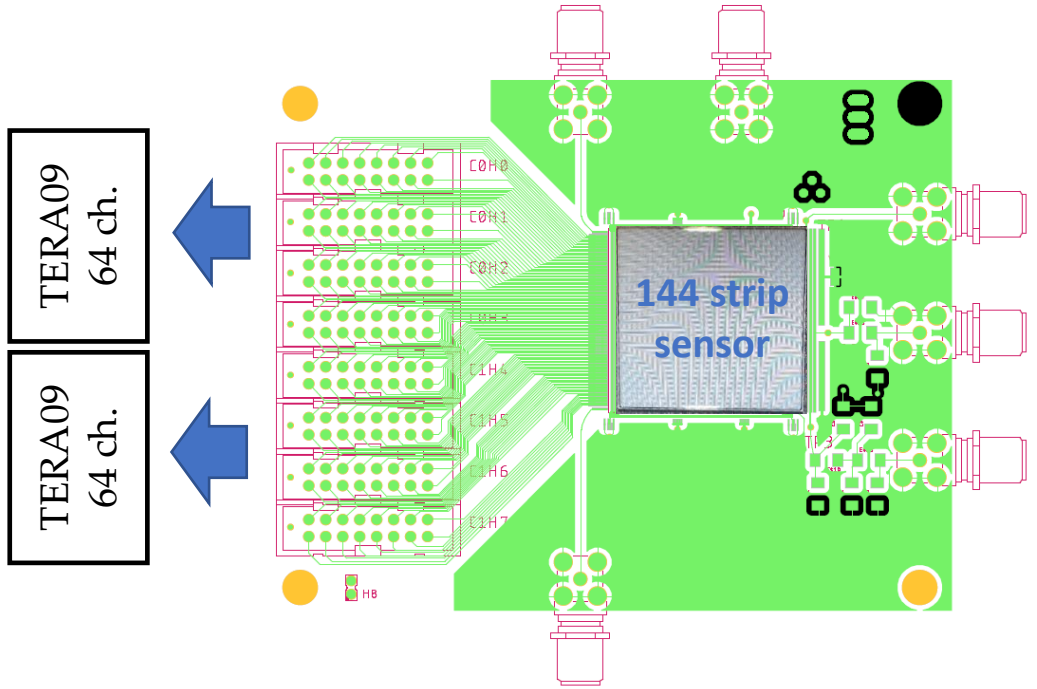
Monitoring of FLASH UHDR: front-end readout

Readout with TERA08 readout ASIC

- 64-channels front-end used @ CNAO
- deadtime free
- **RC input circuit** to prevent from saturation



Detector interface board for TERA09 front-end



- **4 × dynamic range** compared to TERA08
- **Large area** sensor (2.7×2.7 cm^2) to cover **proton** pencil beam cross section

Tested @ CNAO

Tests foreseen at TIFPA

FLASH Radiotherapy with hIgh Dose-rate particle beAms

Summary

- Silicon detectors offer interesting features for new developments in beam monitoring in PT

- Integrating counting and timing in the same device seem possible with state-of-the-art TDCs

- Good linearity with dose per pulse was demonstrated in FLASH e^- beams
  - Interesting for possible combined Si – IC technology
  - Results need to be confirmed with p-beams


Thank you