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

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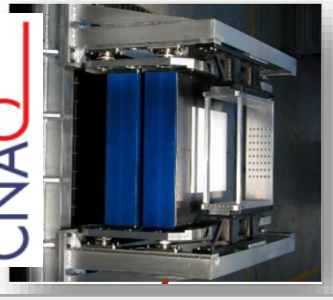
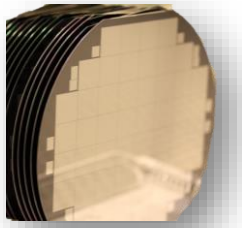
Motivation for Solid State sensors

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

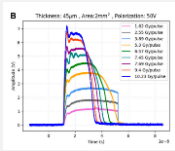
→ difficult above **10^{10} p/cm²s**

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)

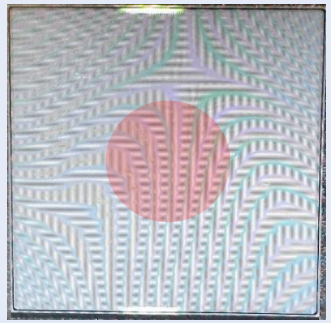
- thickness of sensitive volume **< 50 µm**
- internal charge multiplication **~ 10**

➡ **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



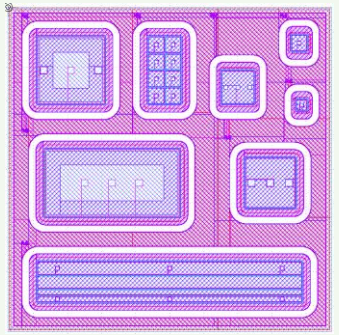
Beam spot
1 cm FWHM

Detectors for timing applications

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

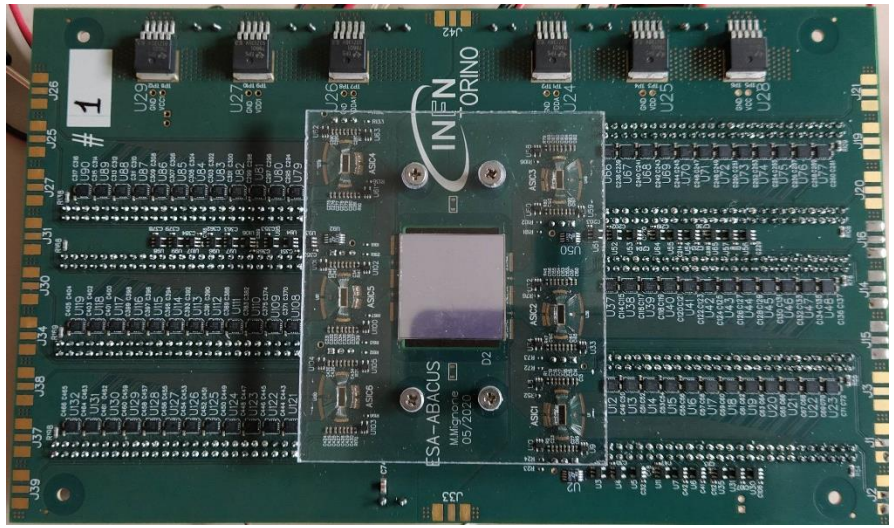
Pads for large ionization rate studies (ExFLU)

- 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)



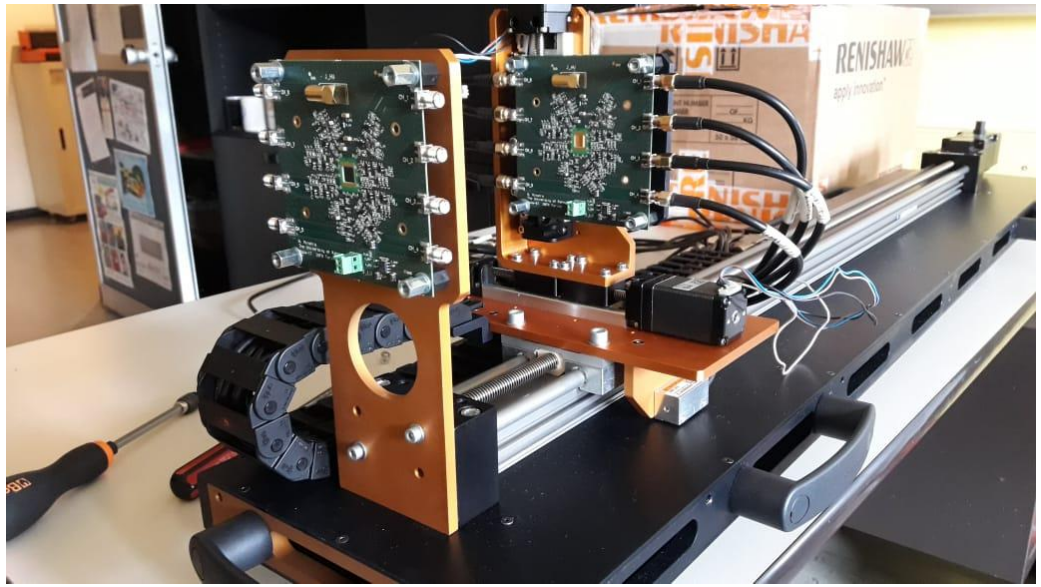
Proton beam particle counter (ESA ABACUS)

- 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*



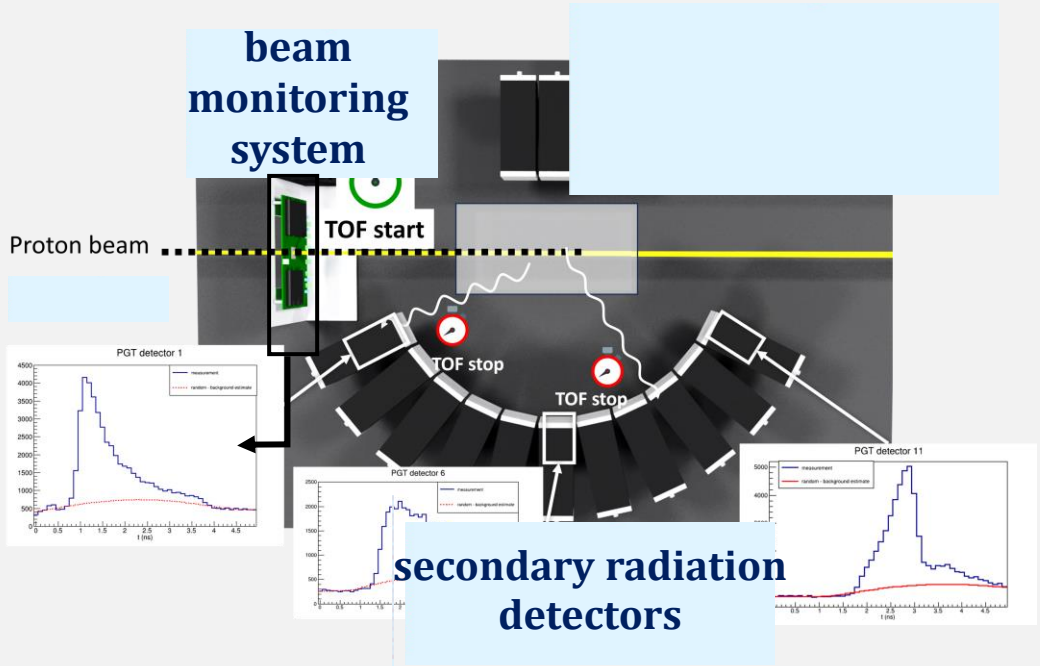
INFN SIG project (2022-2025)

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**

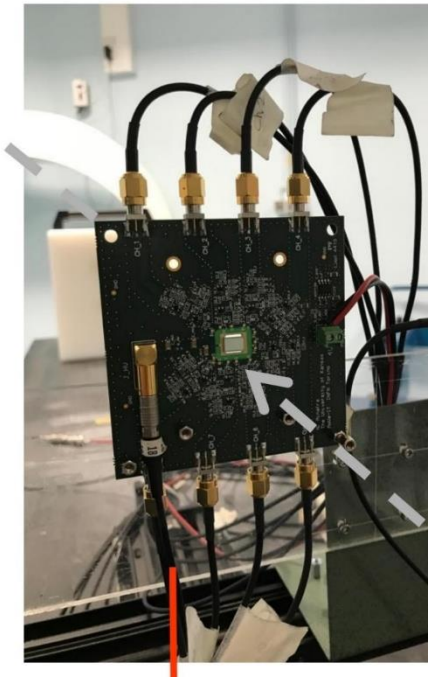
Prompt Gamma Timing (PGT)

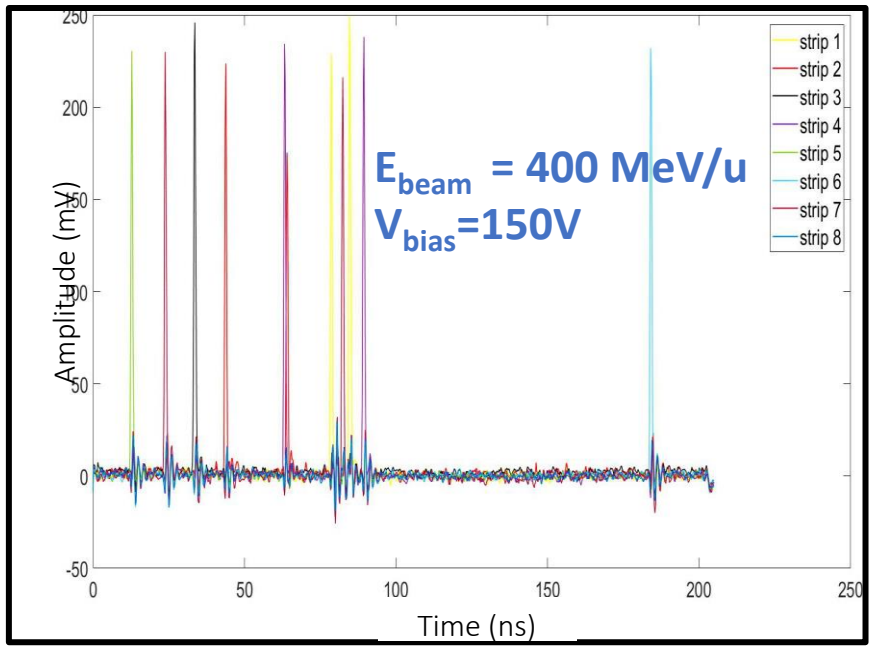
measurement of prompt gamma emission time to get insights into the range of ions



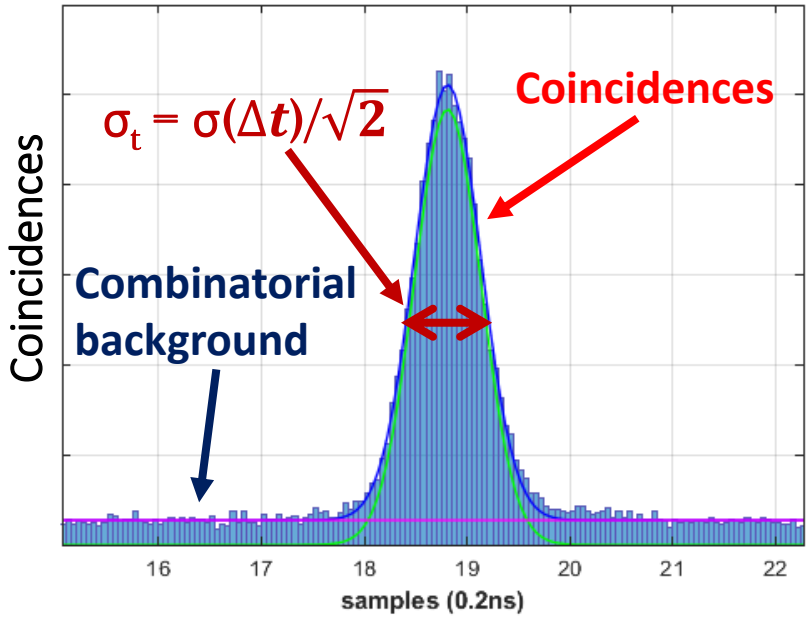
- **Integration with beam monitoring for time synchronization**
- **PGT distributions measured @ CNAO with protons and C-ions (Merlino INFN project)**
  - **Non-optimized acquisition system**
  - **Low efficiency (large deadtimes)**
  - **Sub-clinical beam intensities**
- **Develop new acq. system based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

C-ions signal in thin sensors



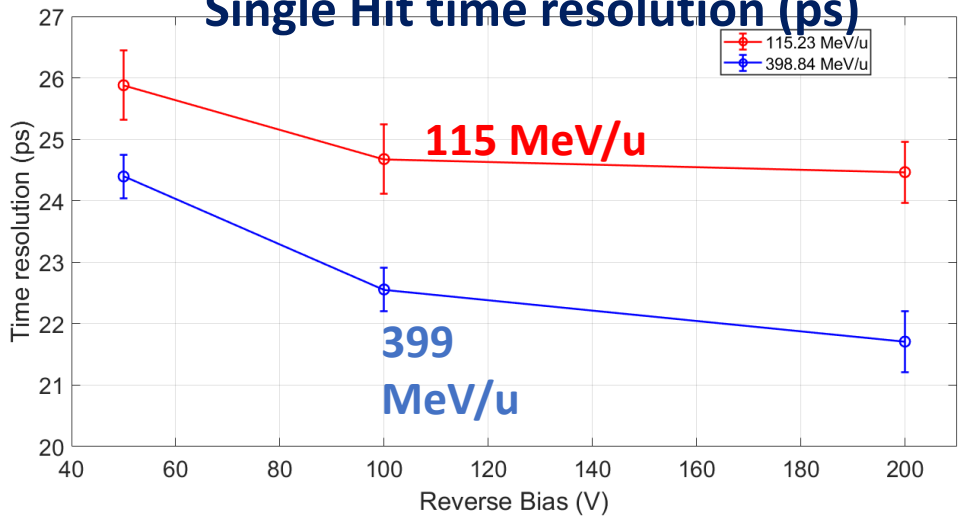


Histogram of arrival time difference



- 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

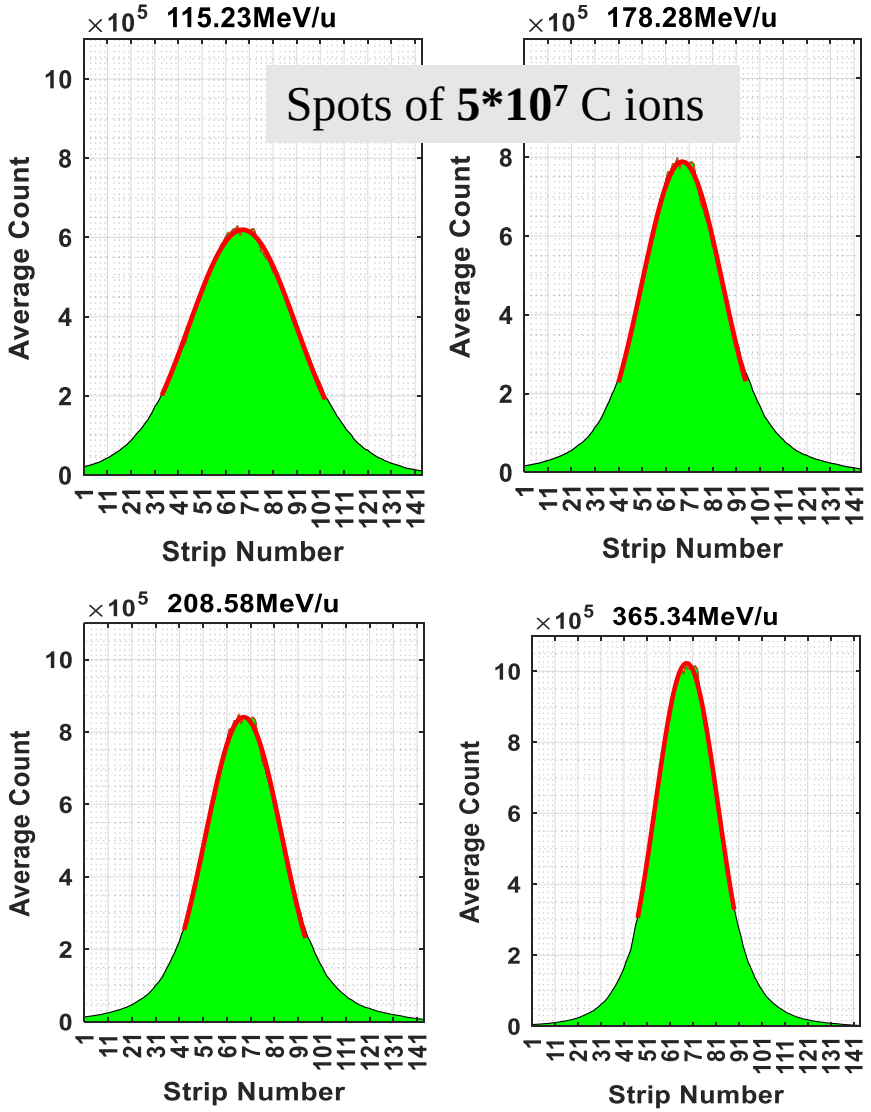
Single Hit time resolution (ps)

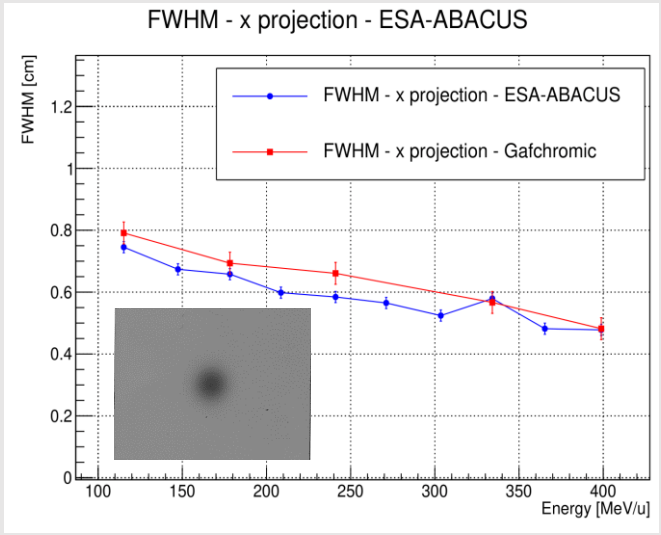


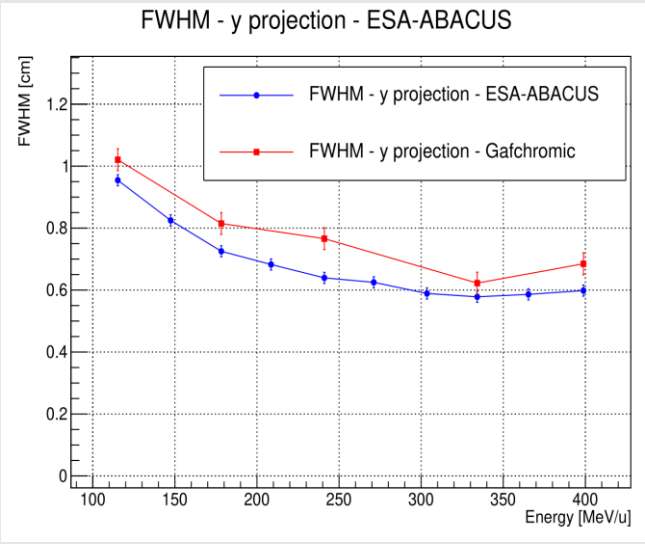
C-ion beam counter

Beam Profile

Spots of $5*10^7$ C ions







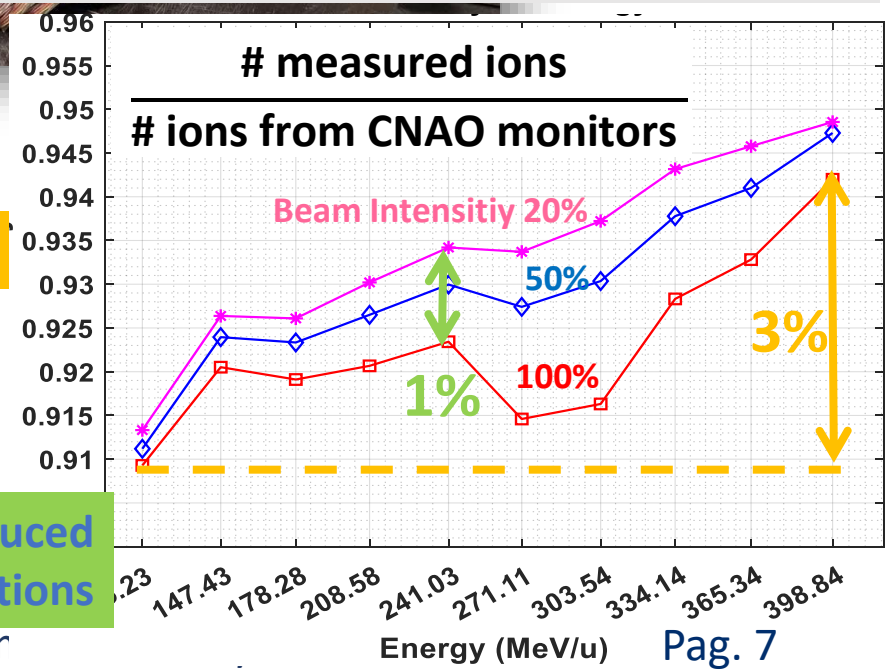
Comparison of beam FWHM with GAFCHROMIC films

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



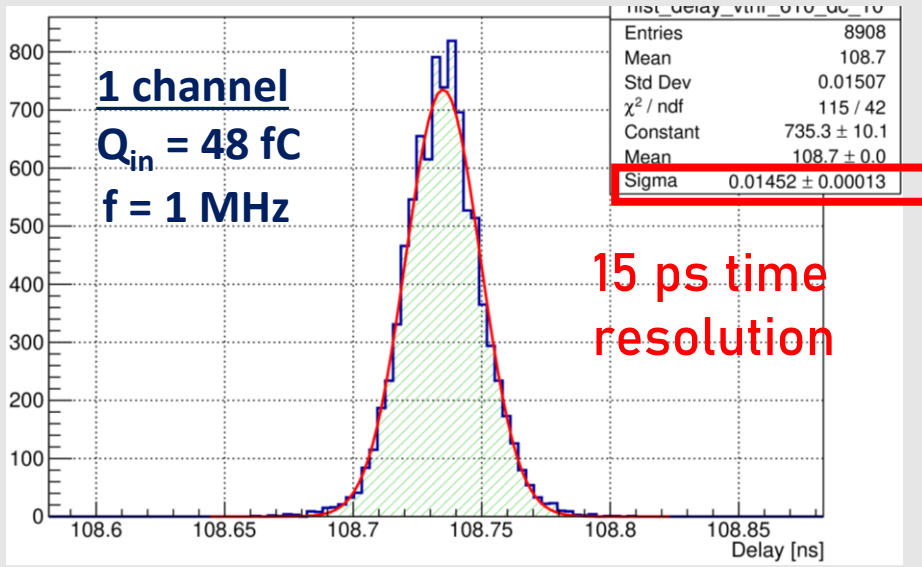
Time measurements with CERN picoTDC

CERN picoTDC evaluation board (64 input channels)

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

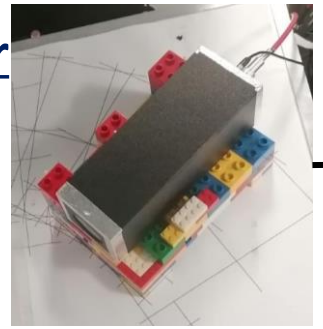
Successfully integrated with 1 channel of ESA-ABACUS board

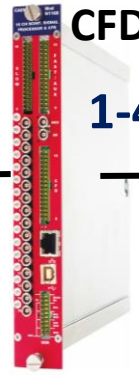
- ➢ **Conversion efficiency 100%**
- ➢ **Tested up to 150 MHz freq.**



December 2023 integration test @ CNAO

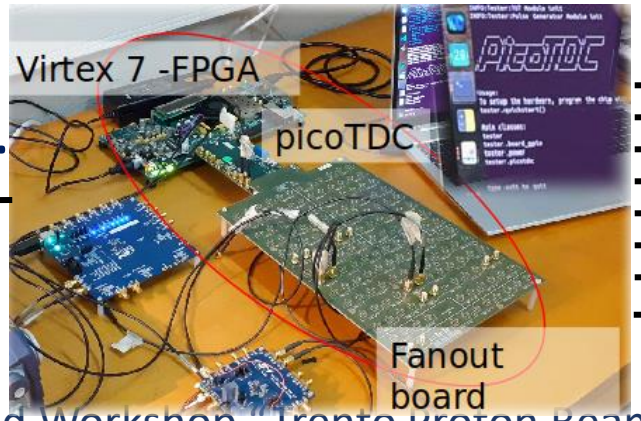
PG detector
LaBr3
+
PMT/SIPM



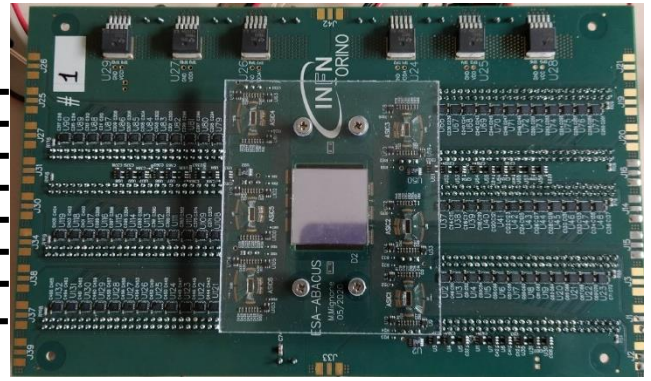


CFD

1-4 chn.



8 chn.

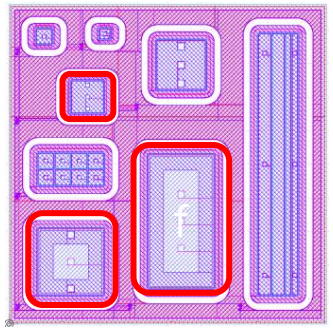


Monitoring of FLASH UHDR electron beams

ElectronFlash accelerator (CFR - Pisa)

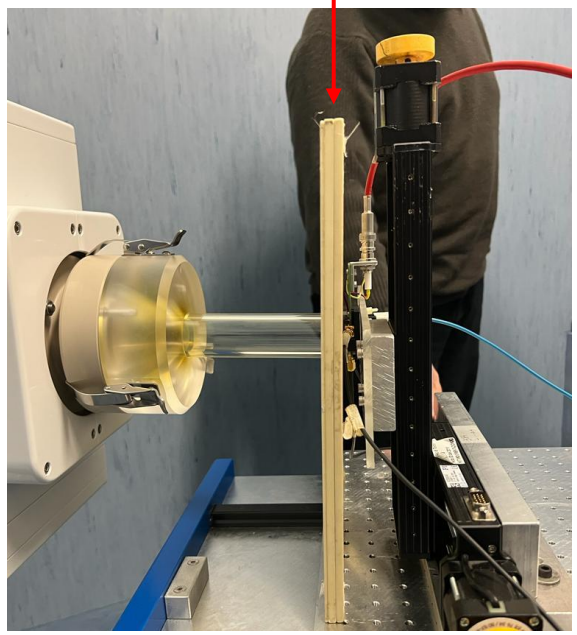
- **9 MeV** electrons pulsed beam
- Beam current: **1-100 mA**
- Pulse duration: **4 μs**
- Pulse frequency: **5 Hz**
- Uniform fields using 3 cm PMMA plastic applicator

Sensors tested

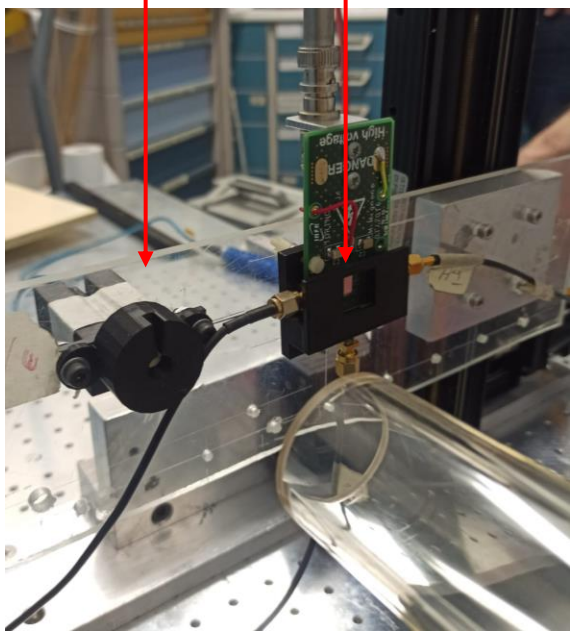


- **45/ 30μm** thickness
- **2/1/0.25 mm²** area
- Bias voltage: **10V ÷ 200V**
- Dose/Pulse **0 ÷ 10Gy**

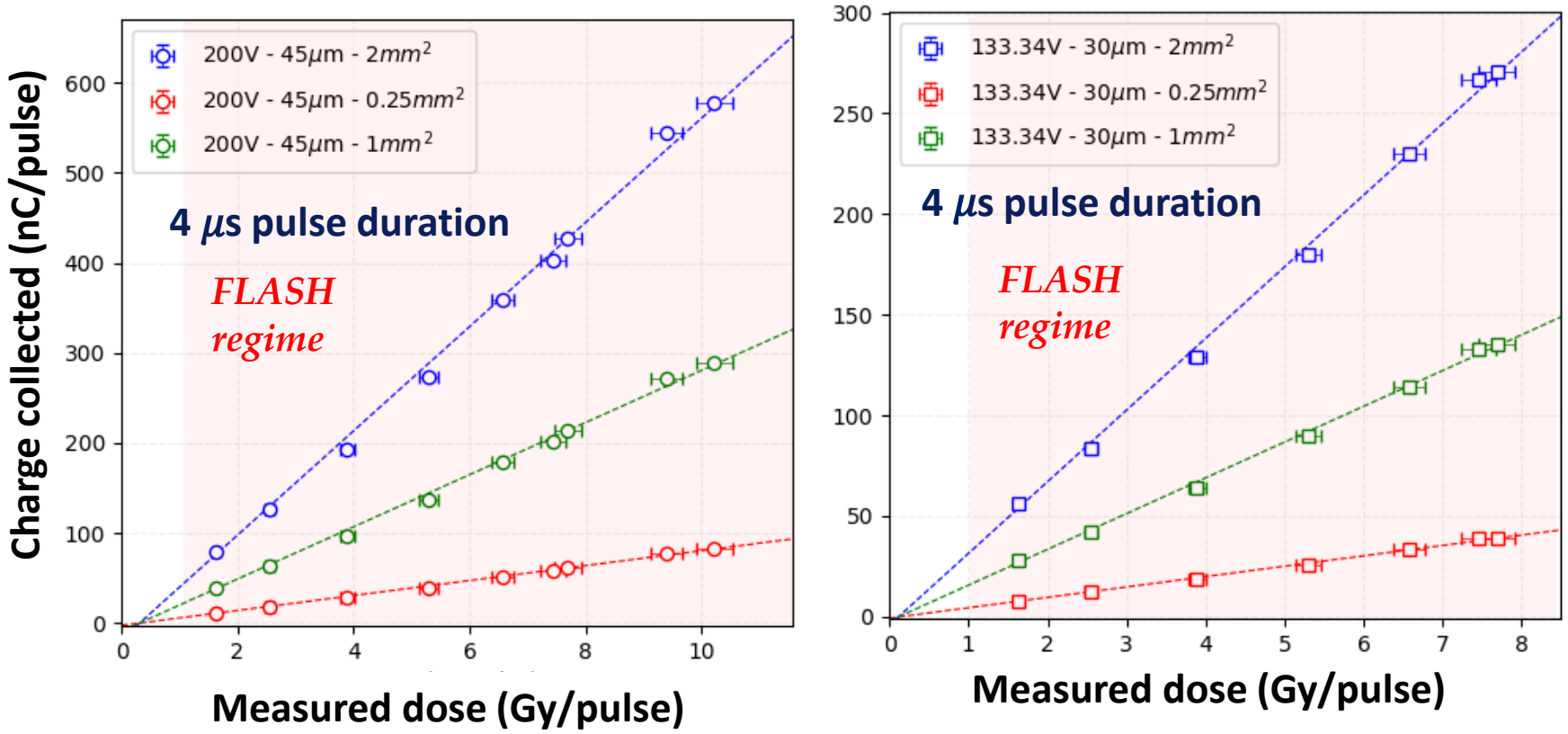
13mm solid water slab



FlashDiamond and silicon sensor in same conditions



Monitoring of FLASH UHDR electron beams



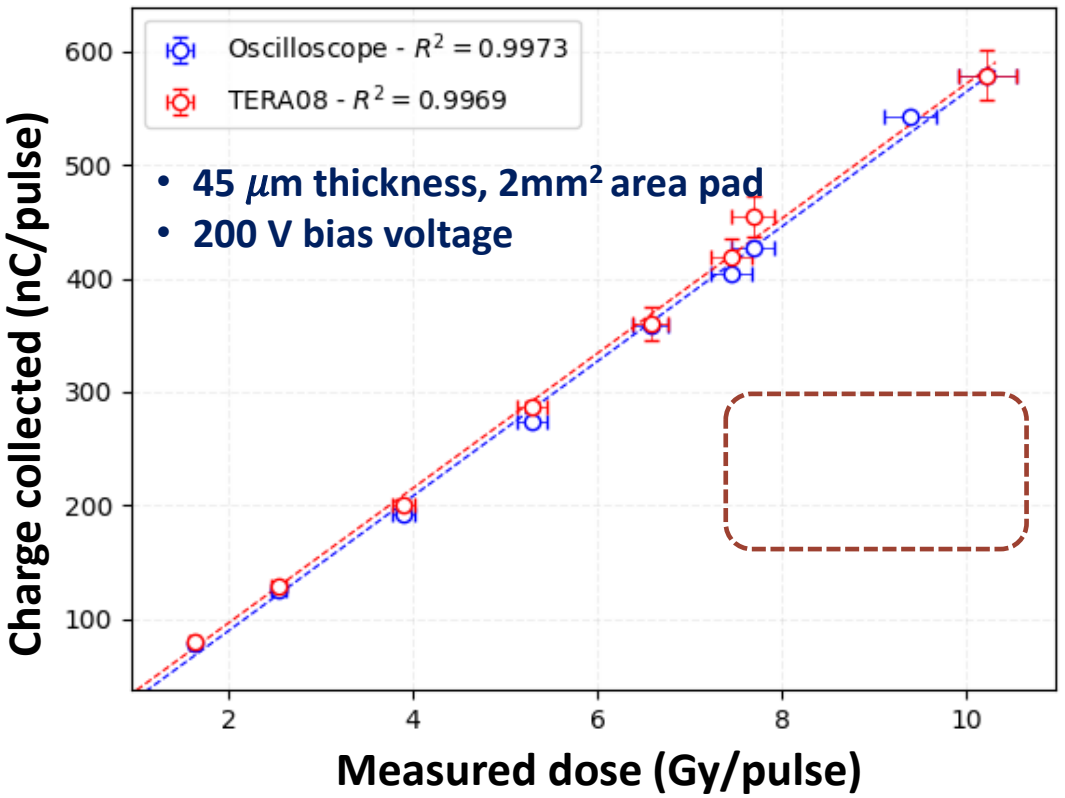
- Collected charge/pulse **scales** with **pad area** and **sensor thickness**
- **Ratios** between different area/thickness **independent from dose/pulse**

Medina et al. 10.3389/fphy.2024.1258832

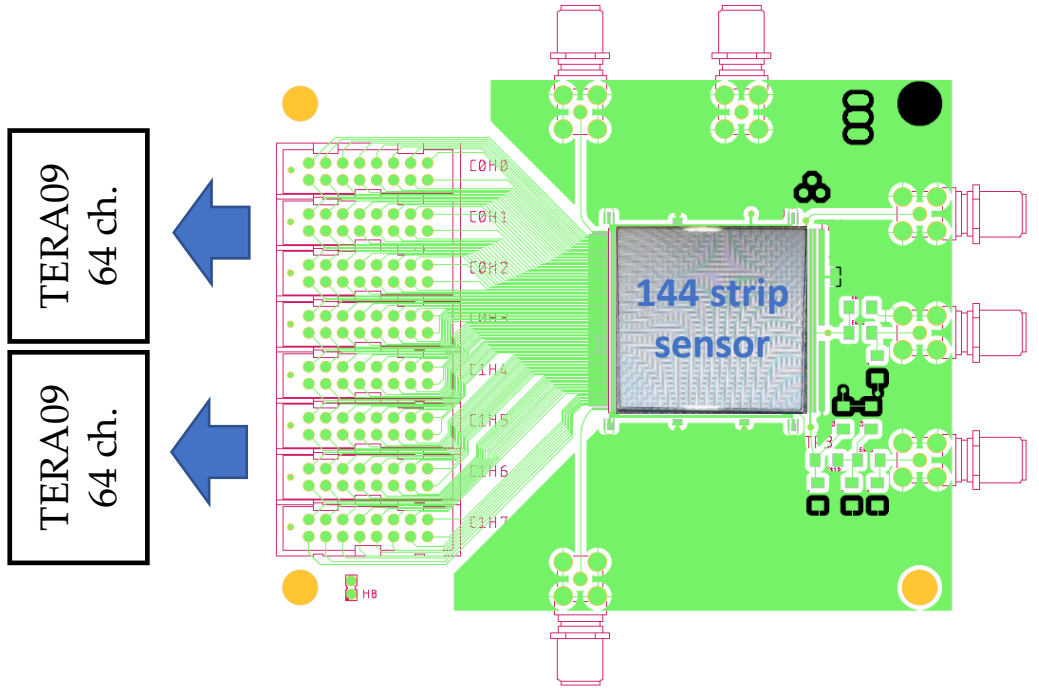
Monitoring of FLASH UHDR: front-end readout

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

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