A novel approach for beam characterization and online monitoring in particle therapy

***O. A. Marti Villarreal*[1,2]**, A. Vignati[1,2], S. Giordanengo[2], M. Abujami[1,2], D. Bersani[1], E. Data[1,2], C. Galeone[1,3], F. Mas Milian[1,2,4], E. Medina[1,2], D. M. Montalvan Olivares[1,2], R. Cirio[1,2], V. Monaco[1,2], R. Sacchi[1,2]

[1]Dipartimento di Fisica, Università degli Studi di Torino, Italy
[2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino - Torino, Italy
[3]GSI: Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[4]Universidade Estadual de Santa Cruz, Ilhéus, Brazil

Istituto Nazionale di Fisica Nucleare

FONDAZIONE BRUNO KESSLER

Outline

- Beam monitors for particle therapy: MoVeIT, FRIDA and SIG INFN projects
- Sensors production by FBK (Trento, Italy)
- Italian facilities dedicated to particle therapy
- Direct energy measurements of particle beams using ToF
- Particle Counting
- Thin silicon sensors for carbon ions tracking: preliminary tests at CNAO
- Silicon Devices for Monitoring Electron/Proton FLASH Beams
- Remarks and Conclusions

Beam monitors for particle therapy

:Modeling and Verification for Ion beam Treatment planning (INFN)

Implementation of advanced radiobiological models in ion TPS, experimental verification in-vitro and in-vivo

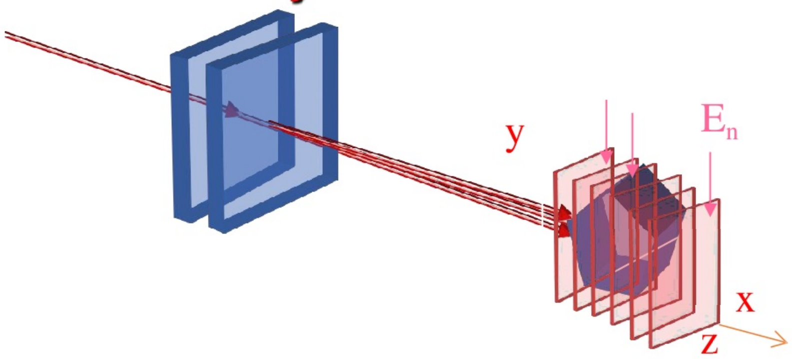
Two devices were developed based on Low Gain Avalanche Detectors (LGAD):

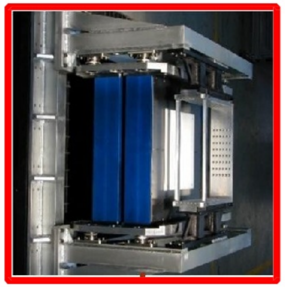
1. to **directly count** individual protons
   area 3*x*3 cm^2;
   up to fluence rate of 10^8 p/s*cm^2 (with error < 2% : clinical requirement); segmented in strips (beam projections in two orthogonal directions);

2. to **measure the beam energy** with Time-of-Flight (ToF) techniques error < 1 mm range in water.

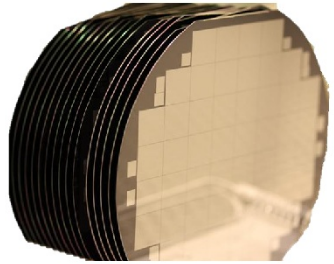
For additional details [http:// www.tifpa.infn.it/projects/move-it/](http://www.tifpa.infn.it/projects/move-it/)

Monitor System





vs.



IONIZATION CHAMBER

- Robust
- Simple construction and readout
- Large sensitive area
- Radiation resistance

- Slow collection time (~100 μs)
- Low sensitivity (10^4 protons/s)
- Dependance on beam energy and environmental parameters

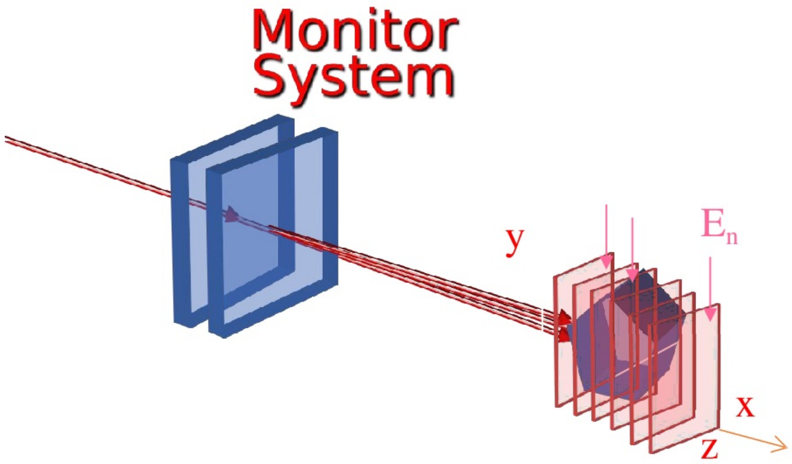
Not appropriate for fast scanning modalities and timing applications

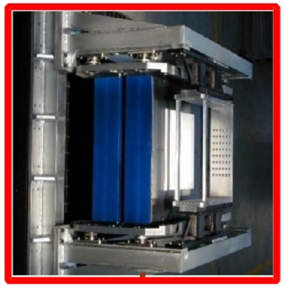
SOLID STATE DETECTORS

- Fast collection time (~ns)
- Excellent time resolution (<100 ps)
- Good sensitivity (single protons)

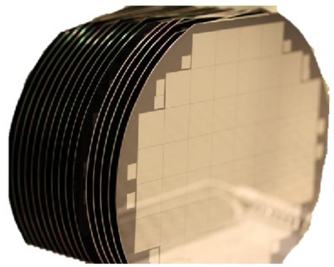
Main issues at $10^{10}\ p/cm^2 s$

- **Radiation resistance**
  -> maufacturing strategies
  -> damage compensation
- **Pile-up effects**
  -> Fast sensors and readout
  -> Segmentation





vs.



IONIZATION CHAMBER

- Robust
- Simple construction and readout
- Large sensitive area
- Radiation resistance

- Slow collection time (~100 μs)
- Low sensitivity (10^4 protons/s)
- Dependance on beam energy and environmental parameters

Not appropriate for fast scanning modalities and timing applications

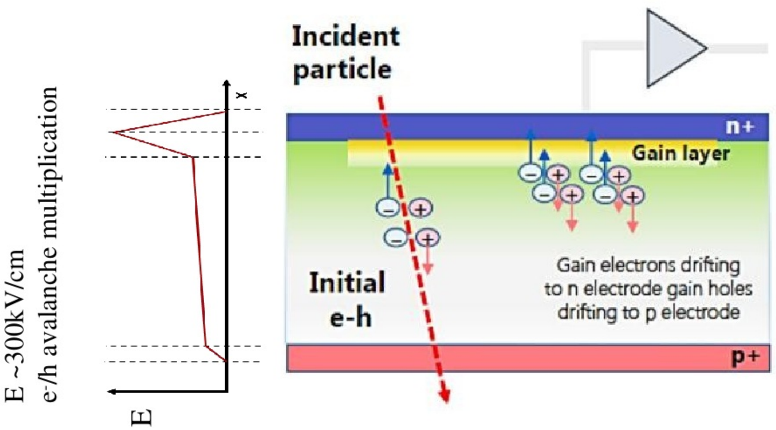
SOLID STATE DETECTORS

- Fast collection time (~ns)
- Excellent time resolution (<100 ps)
- Good sensitivity (single protons)

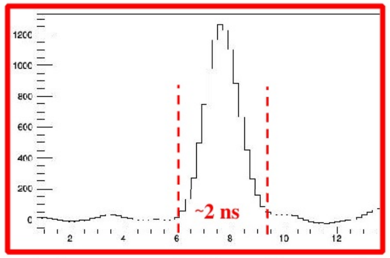
Main issues at $10^{10}\ p/cm^2s$

- **Radiation resistance**
  -> maufacturing strategies
  -> damage compensation
- **Pile-up effects**
  -> Fast sensors and readout
  -> Segmentation

LGAD



- **fast signal duration (1-2 ns)**
  Single particle detection capability

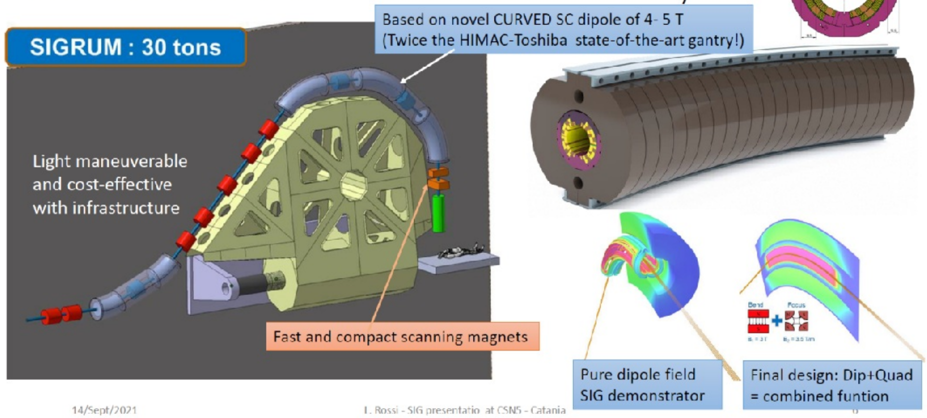


- **Excellent time resolution (tens of ps)**
  Optimal for Energy measurement using ToF techniques

SIG
Superconducting Ion Gantry

INFN project (2022-2025)

International collaboration: CERN-CNAO-INFN-MedAustron for an advanced ion SC Gantry



Goal: develop a **compact Ion Gantry** based on **NOVEL CURVED SUPERCONDUCTING magnet**

TORINO Medical Physics Group

New technologies for Dose Delivery System

→ New beam monitor able to track the single carbon ion using segmented **thin silicon sensors** with advanced front-end readout and DAQ system to **provide the time of crossing information**

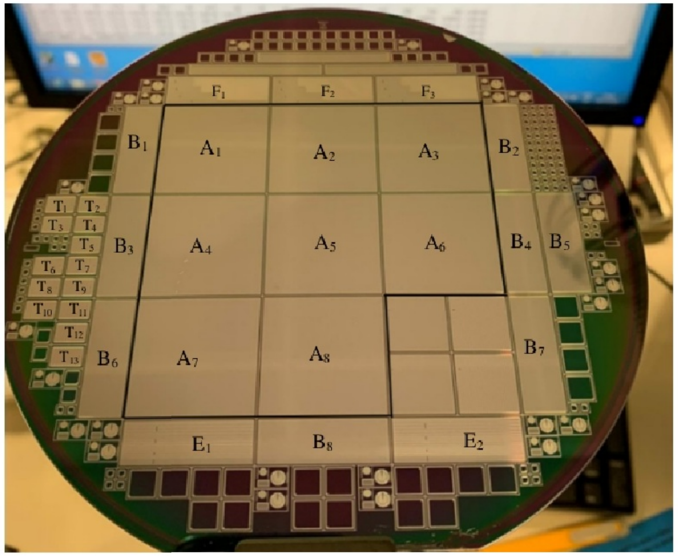
FRIDA
FLASH Radiotherapy with hIgh Dose-rate particle beAms

INFN project (2022-2024)

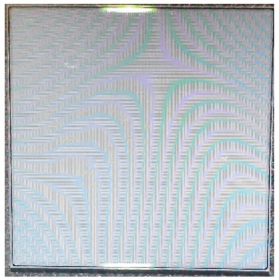
Current monitoring solutions **lack the necessary precision** to give robust estimates of the instantaneous and average dose rate (**needed to characterise the FLASH effect**) and to provide a reliable feedback on the radiation delivery during the treatment.

Within the FRIDA INFN project, we are studying **thin silicon sensors** and **associated readout electronics** for **electron/proton** beam monitoring in high dose-rate regimes.

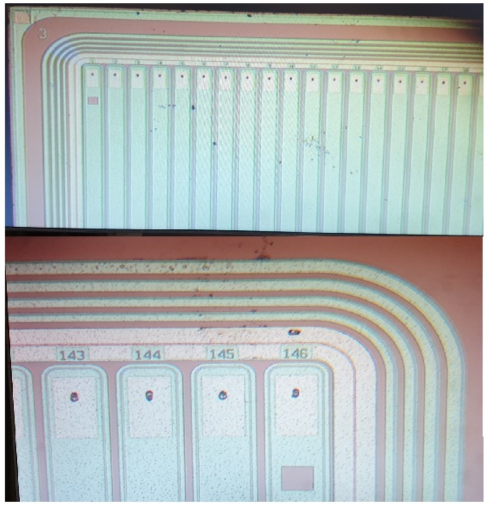
Sensor production by FBK (Trento, Italy)



Group	Wafer n.	Substrate	Dose P_{gain} (a.u)	Active thickness (µm)	Total thickness (µm)
I	1,2, 14	Epi	0.96	45	615
II	3,4,5,6,7	Si-Si	0.96	60	630
III	8,9,10,11,12,13	Si-Si	0.98	60	630



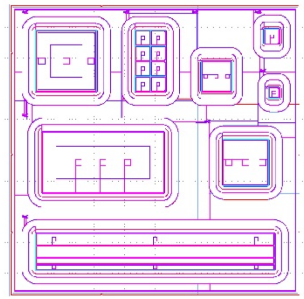
Type A
-> Large area: 2.6 x 2.6 cm²
-> 146 strips



Type T
11 strips of 2.2 mm² (3993 µm x 550 µm)
Pitch = 591 µm

Thin sensor production is ongoing for monitoring FLASH beam(EXFLU Project Valentina Sola)

- 4 different substrate thicknesses: 15, 20, 30, and 45 μm
- Very small sensitive areas: from 2 mm² up to 0.03 mm²



*Under review:
O. A. Marti Villarreal, et al. Characterization of large LGAD sensors for proton counting in particle therapy. Journal of Instrumentation (2021). **Conference proceeding.**
O. A. Marti Villarreal, et al. Characterization of thin LGAD sensors designed for beam monitoring in proton therapy. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2022). **Full paper.**

Italian facilities dedicated to particle therapy

PROTONTERAPIA TRENTO

Trento proton therapy facility **Cyclotron**

Max Flux: ~10^{10} p/s
Energy: 70- 228 MeV
Spot size: 1.6- 0.6 cm FWHM
At the End of 2022 for 228 MeV
Flux: ~10^{12} p/s

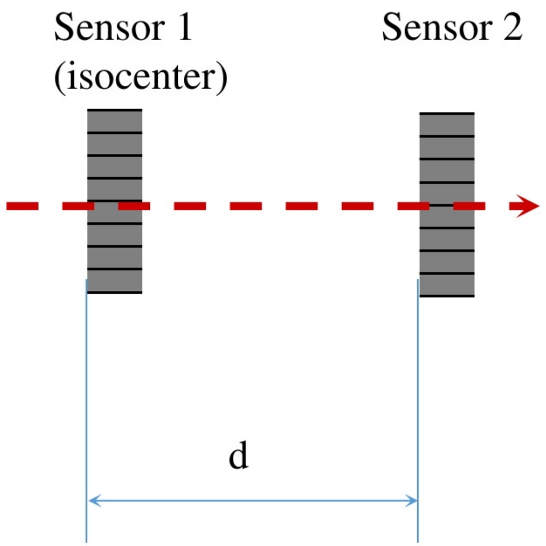
CNAO

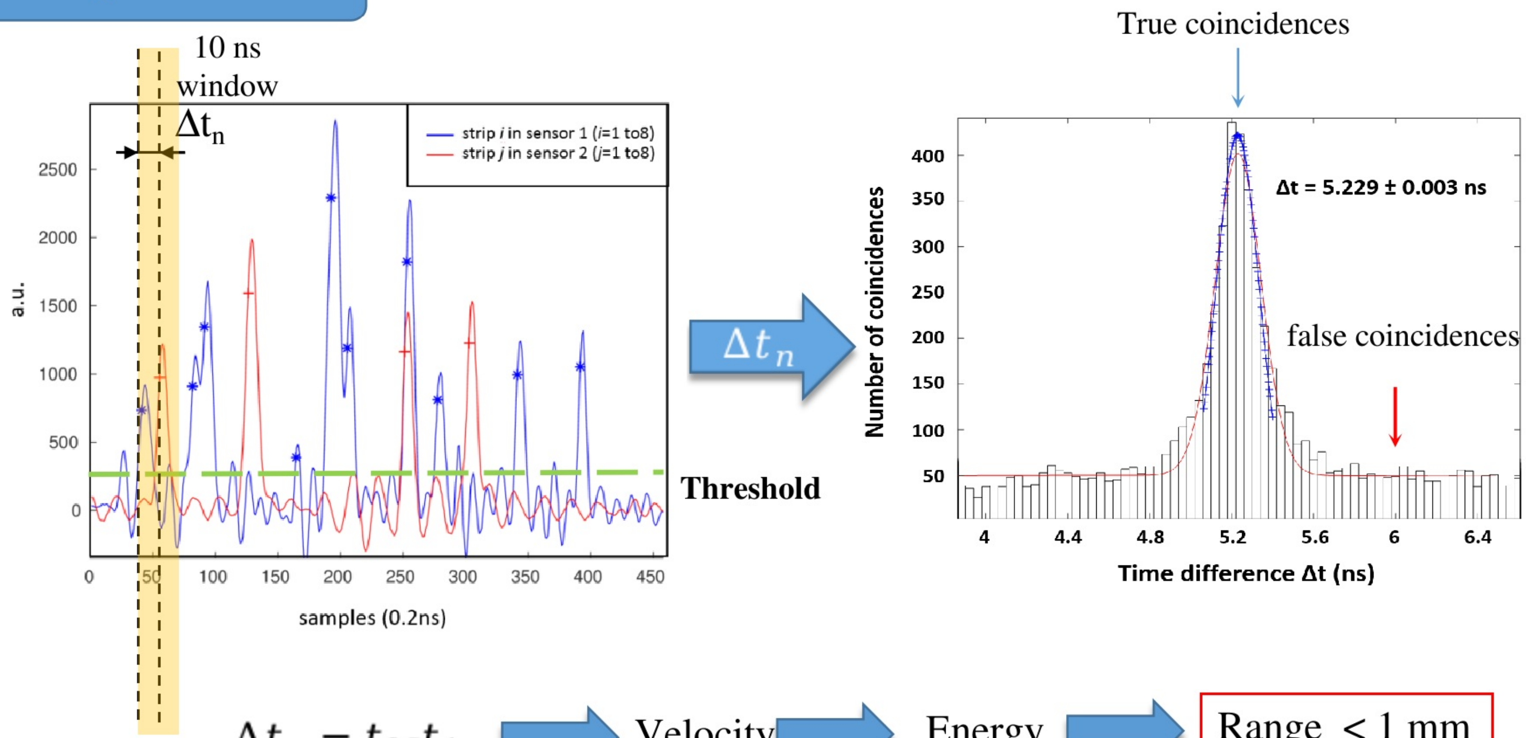
National Center for Oncological Hadrontherapy **Synchrotron**

Protons
Max Flux: ~10^{9} p/s
Energy: 60- 230 MeV
Spot size: 2.2- 0.7 cm FWHM
Carbon ions
Max Flux: ~10^{7} C/s
Energy 120- 400 MeV/u
Spot size: 1.1- 0.4 cm FWHM

Direct energy measurements of particle beams using ToF

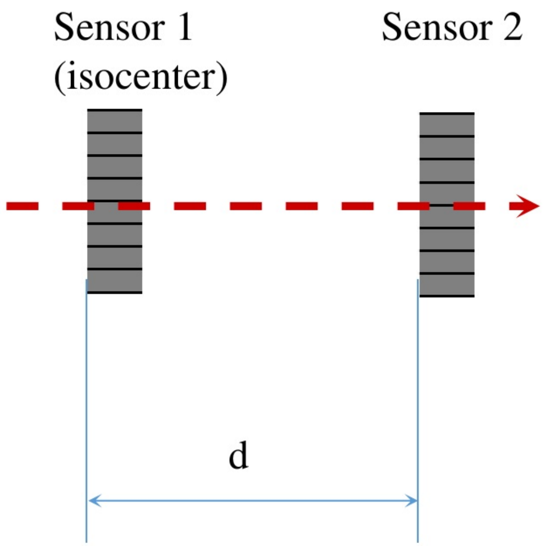
Energy measurement using ToF

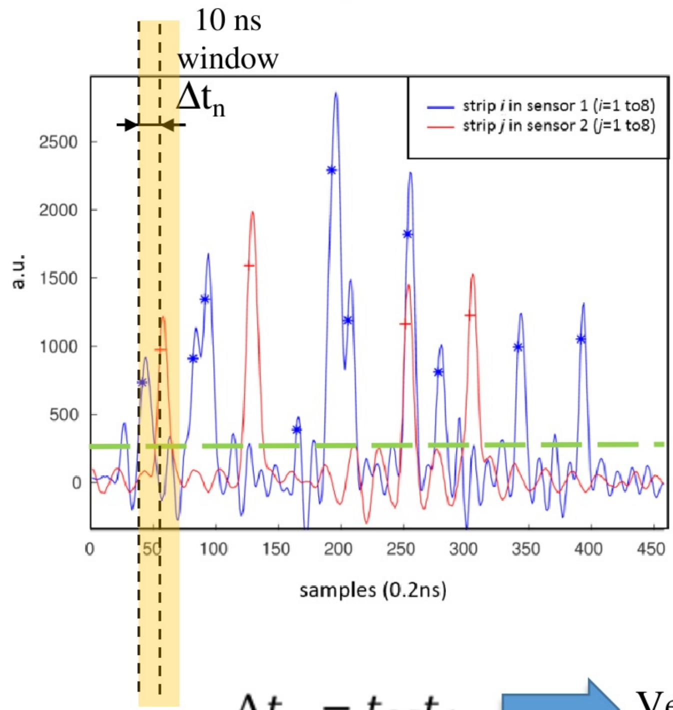




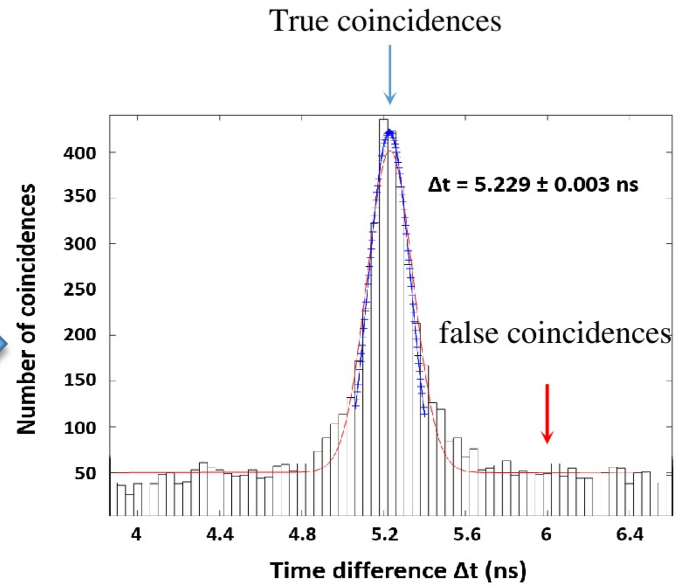
$\Delta t_n = t_2$-t_1 → Velocity → Energy → Range < 1 mm

Energy measurement using ToF





Δt_n



$\Delta t_n = t_2\text{-}t_1$ → Velocity → Energy → Range < 1 mm

Relative calibration

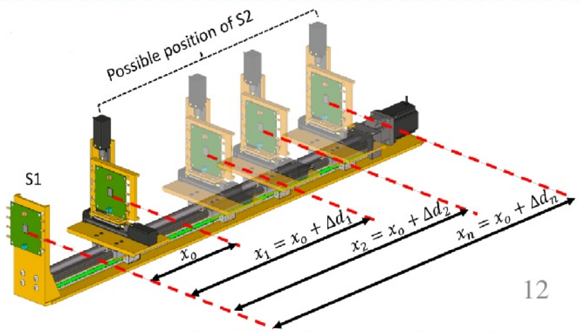
$$\chi^2(offset, d_j) = \sum_{i,j}\left(\frac{(\Delta t_{ij} - offset) - ToF(K_i, d_j)}{\sigma_{ToF_{ij}}}\right)^2$$

For additional details

Vignati, A., et al. "A new detector for the beam energy measurement in proton therapy: a feasibility study ," Physics in Medicine and Biology Journal July 2020 DOI: 10.1088/1361-6560/abab58.

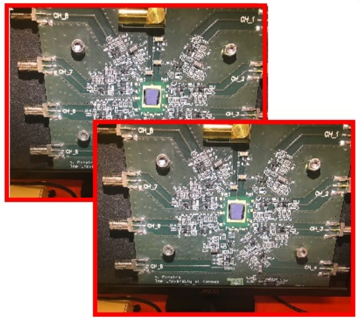
Self-calibration

(Patent pending)



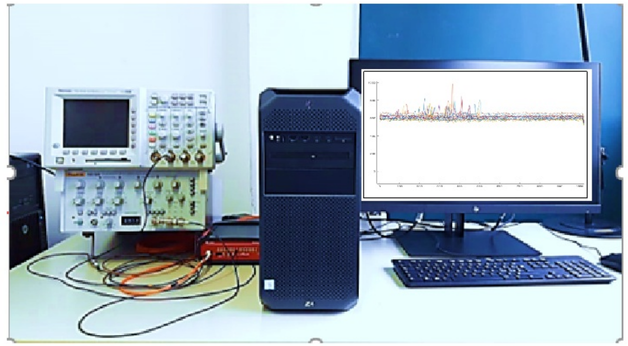
Experimental setup

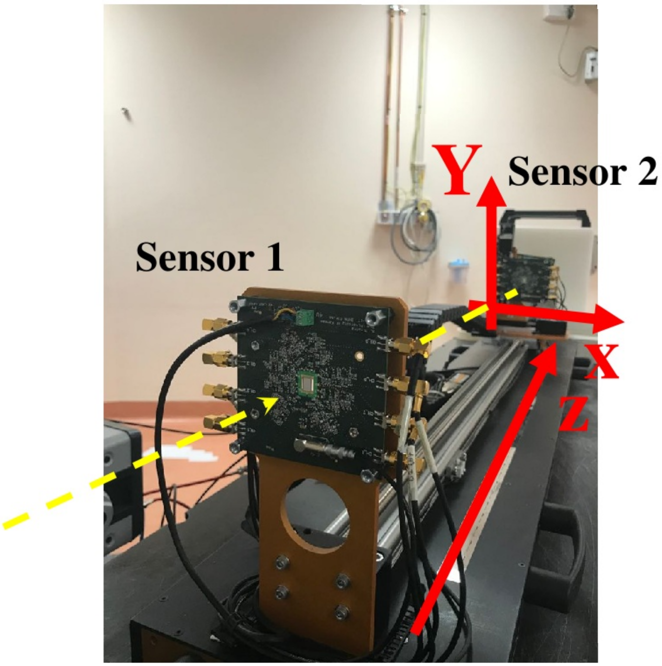
16 signals configuration

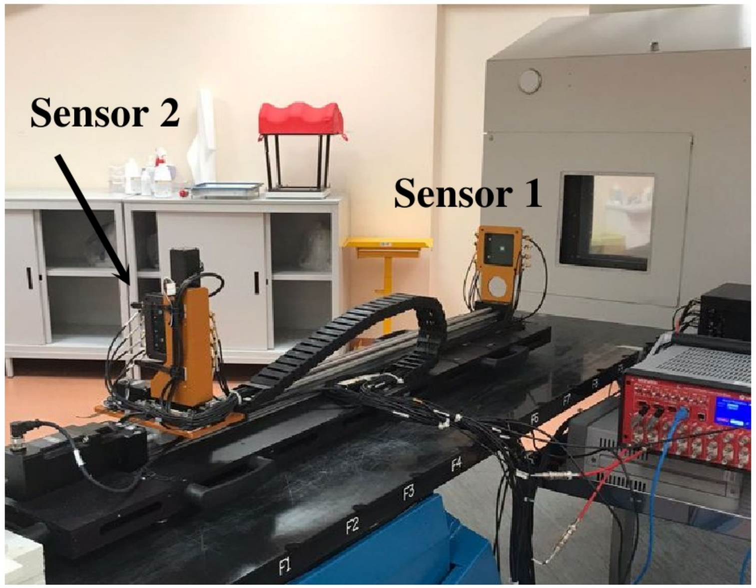


CAEN DT5742 (5 GS/s)

Optical link
(80 MB/s)

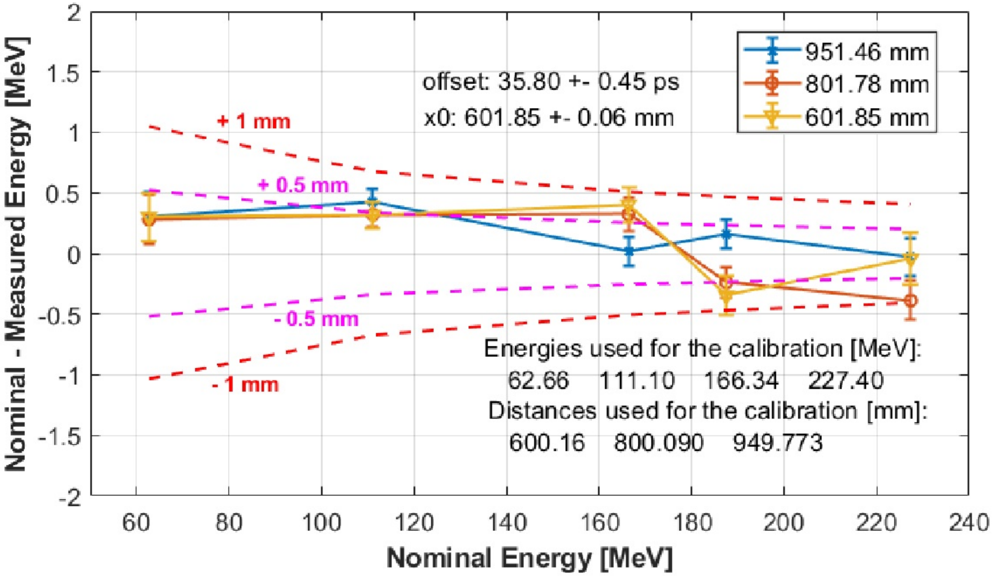




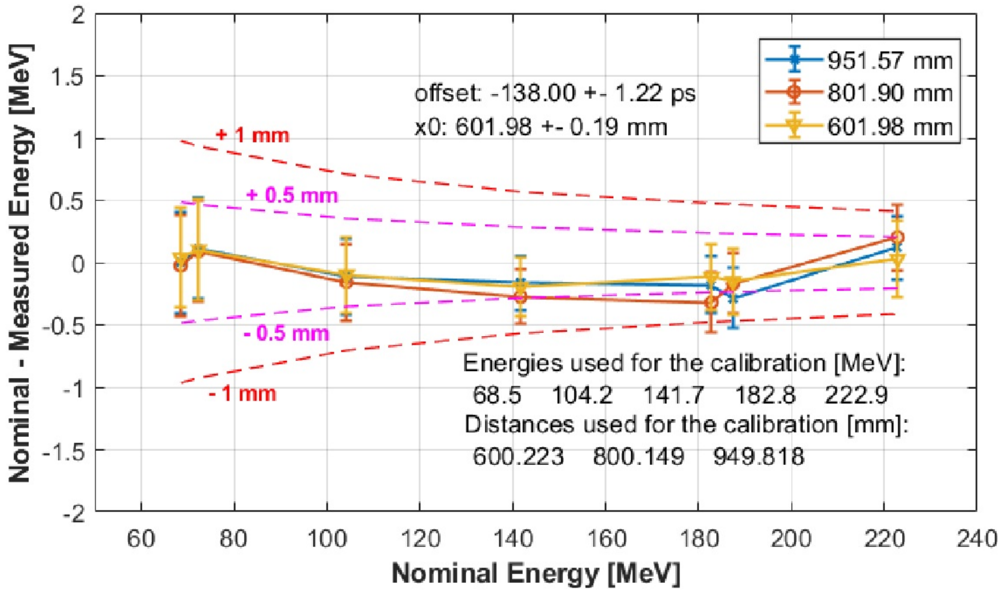


Main results of the ToF in two differents facilities

CNAO



PROTONTERAPIA TRENTO



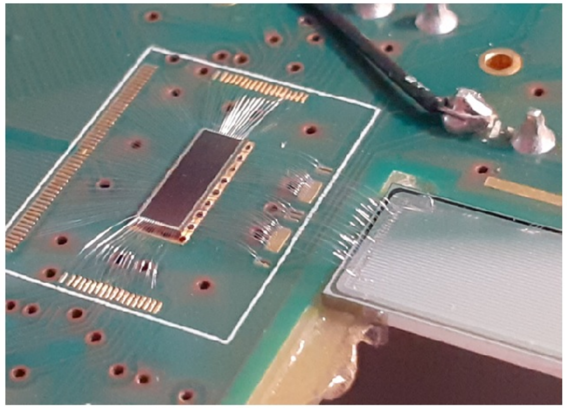
Clinical application

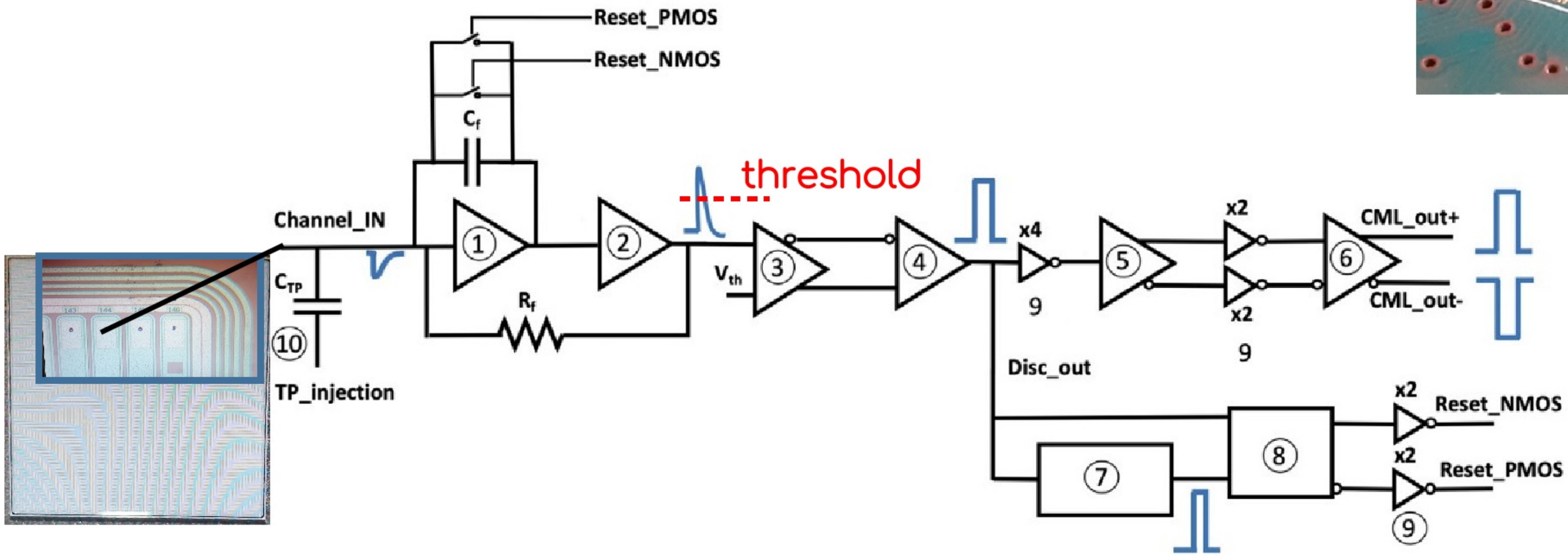
- Beam Commissioning
- Fast QA procedures

Particle Counting

Readout electronics: ABACUS* chip

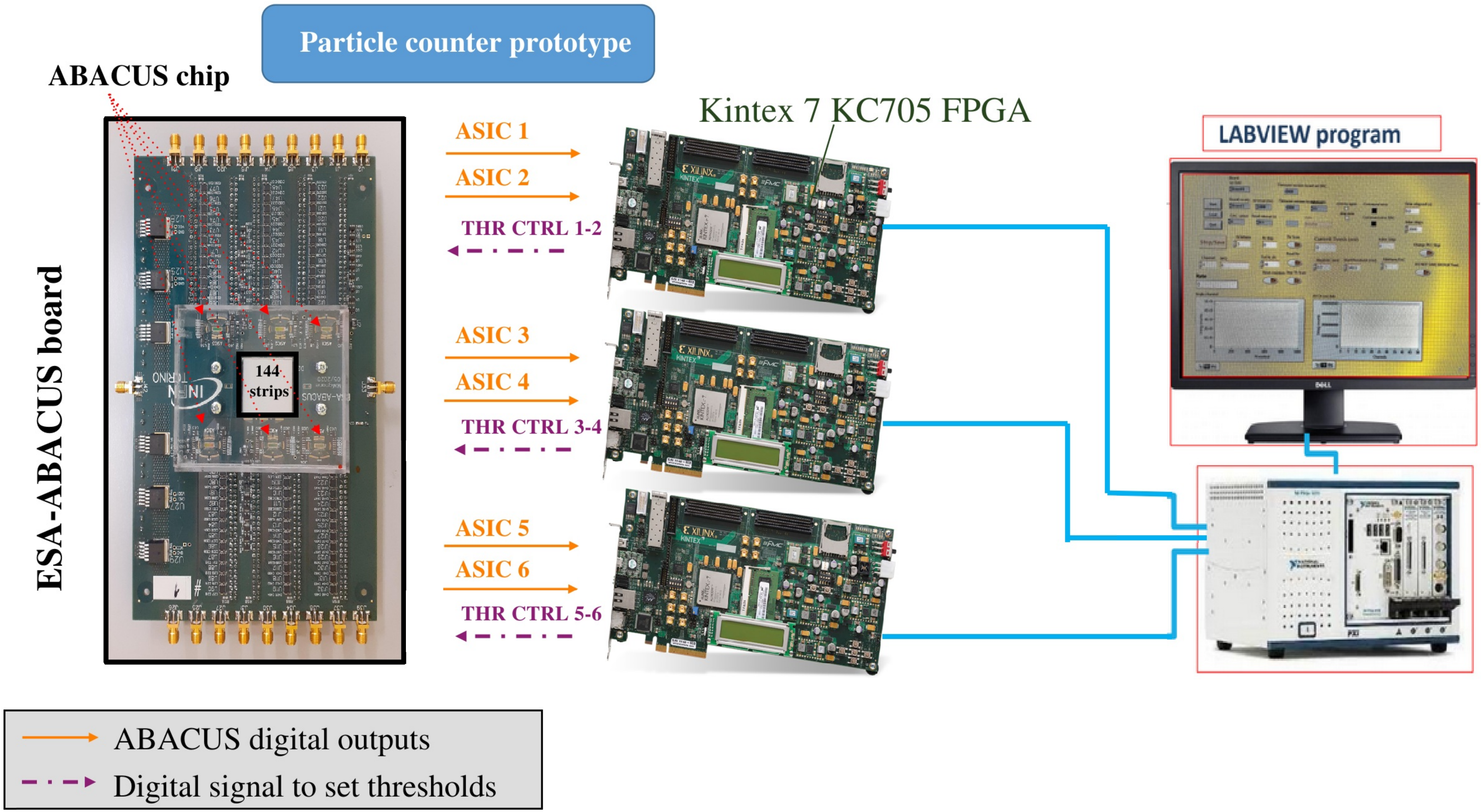
- 110 nm CMOS technology,
- chip area 2 x 5 mm² having 24 identical channels
- Dead time: ~10 ns
- CSA dynamic range: 4fC-150 fC



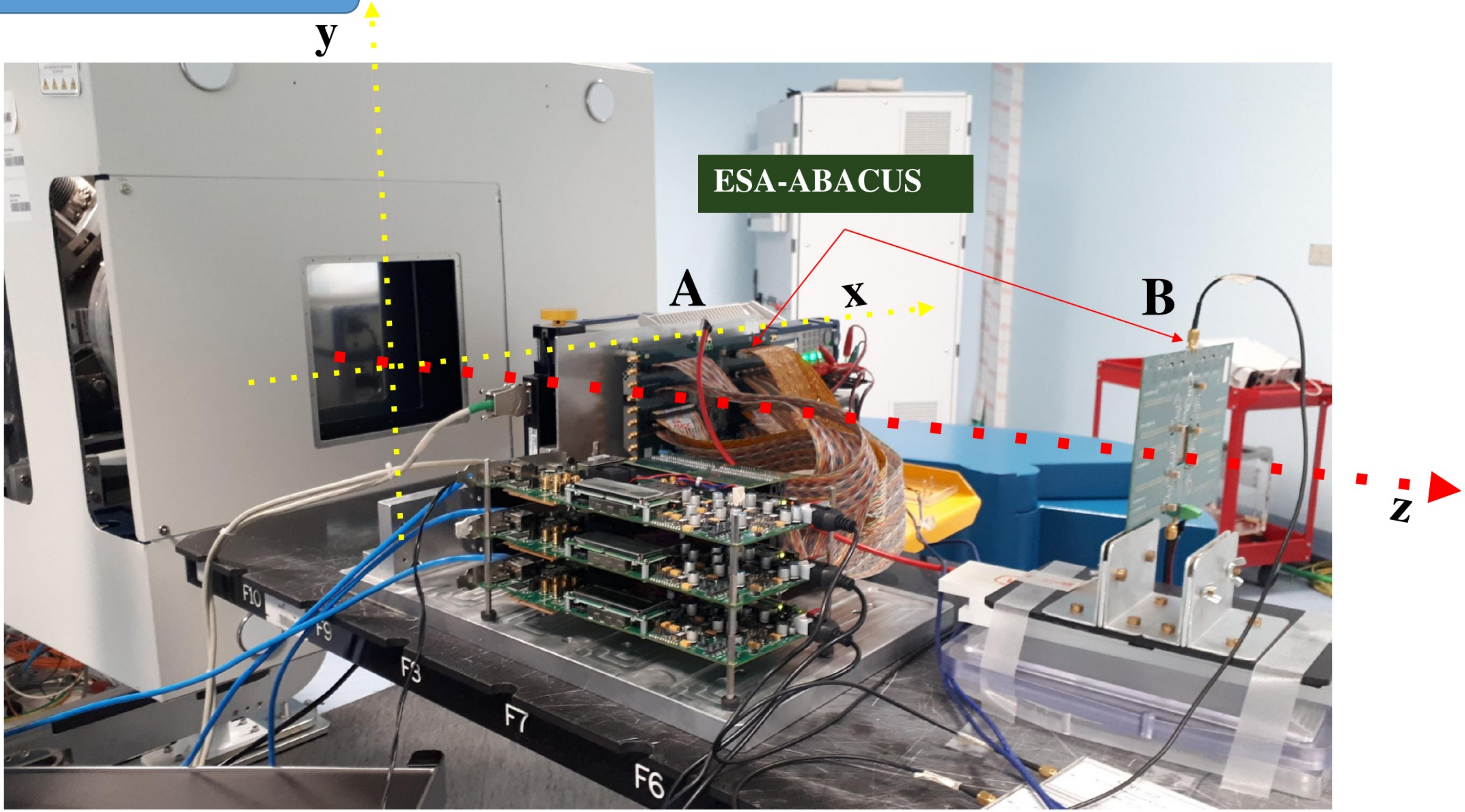


- Discriminator driven by:
- Ext 16-bit DAC, global V_{th}
- Int 6-bit DAC, single channel V_{th} tunning

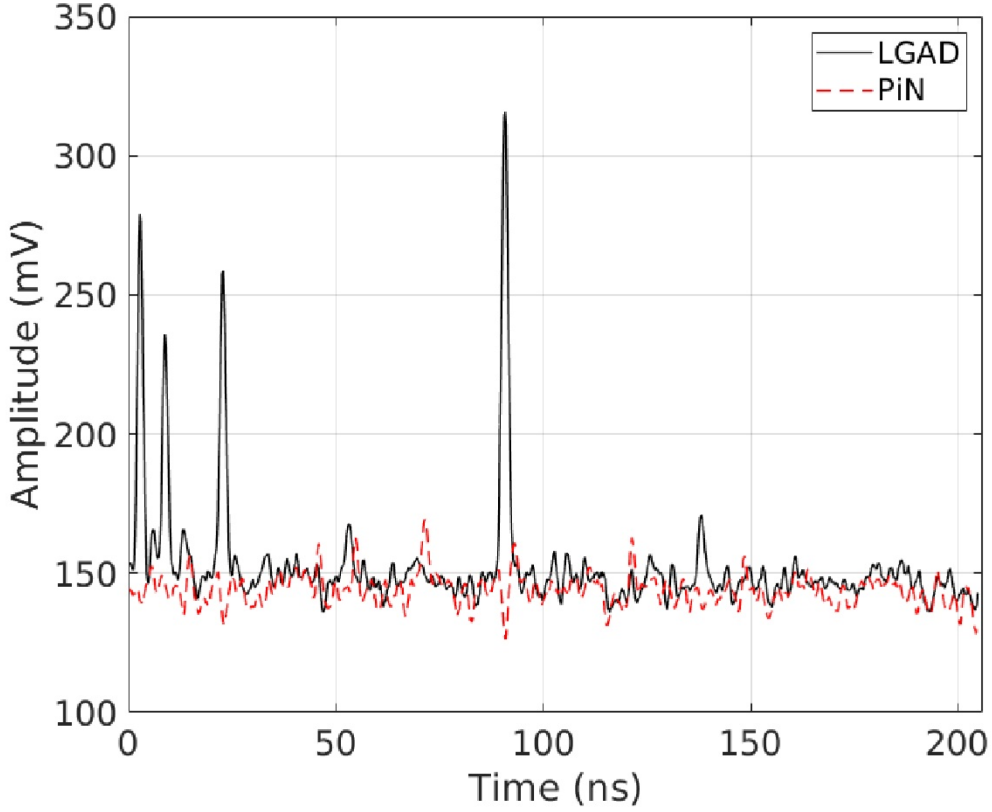
*Fausti, F., et al. "A single ion discriminator ASIC prototype for particle therapy applications." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 985 (2021): 164666.


Particle counter prototype
ABACUS chip
ESA-ABACUS board
144 strips
ASIC 1
ASIC 2
THR CTRL 1-2
ASIC 3
ASIC 4
THR CTRL 3-4
ASIC 5
ASIC 6
THR CTRL 5-6
Kintex 7 KC705 FPGA
LABVIEW program
ABACUS digital outputs
Digital signal to set thresholds

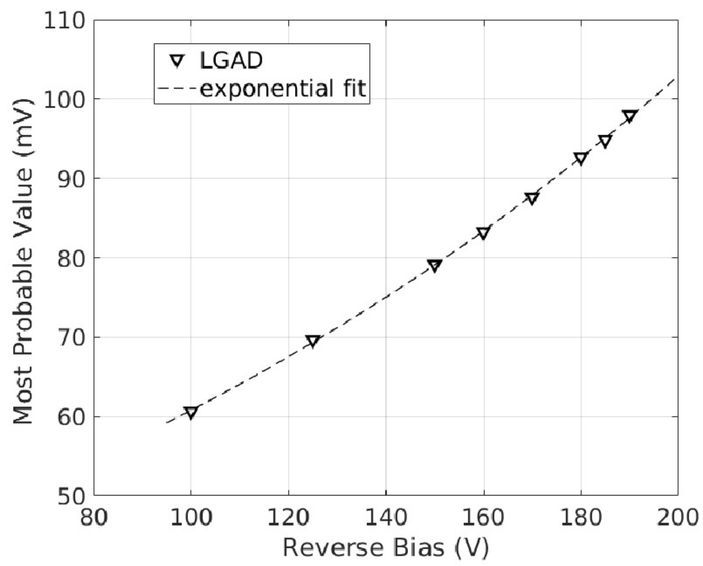
Experimental setup (Cont.)

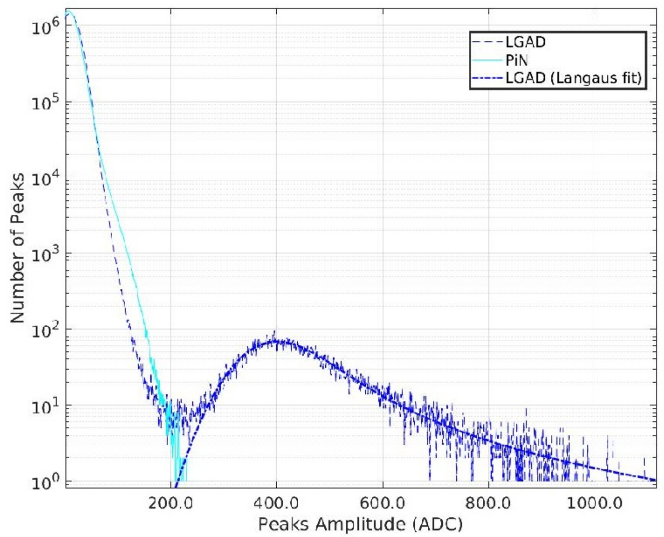


Main results from board "B" using the analog channels



Energy: 62.28 MeV
Bias Voltage: 190 V

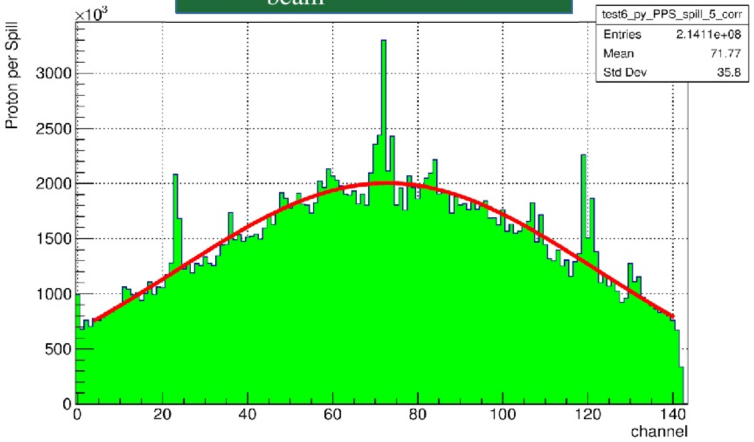




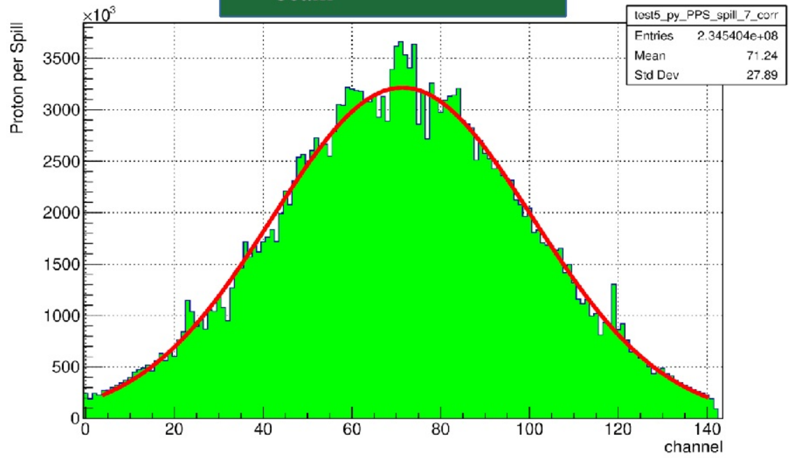
Main results from board “A” using the digital channels

5×10^{8} ***protons per spill***

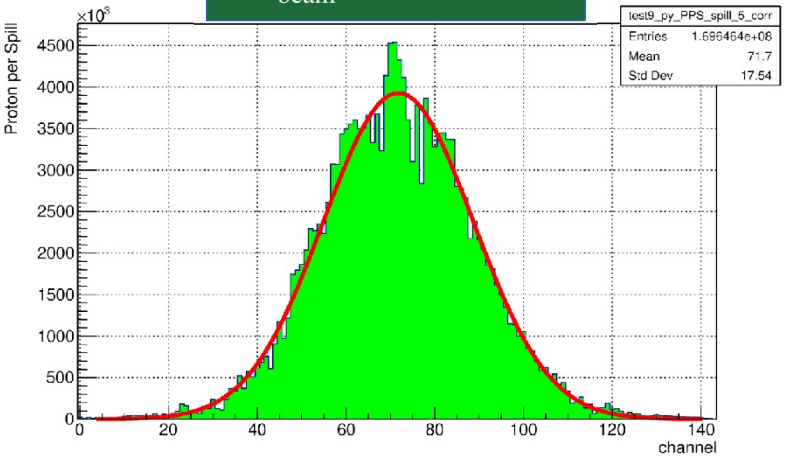
E_{beam} = 62 MeV

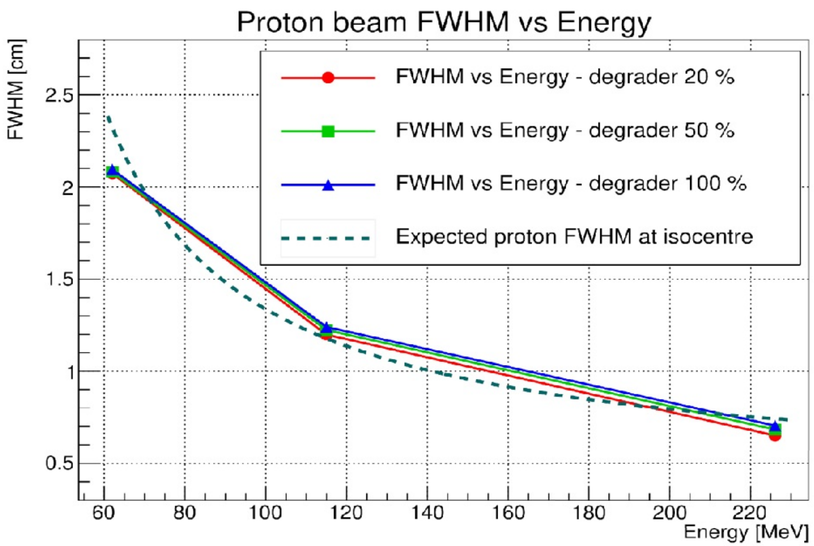


E_{beam} = 115 MeV



E_{beam} = 226 MeV



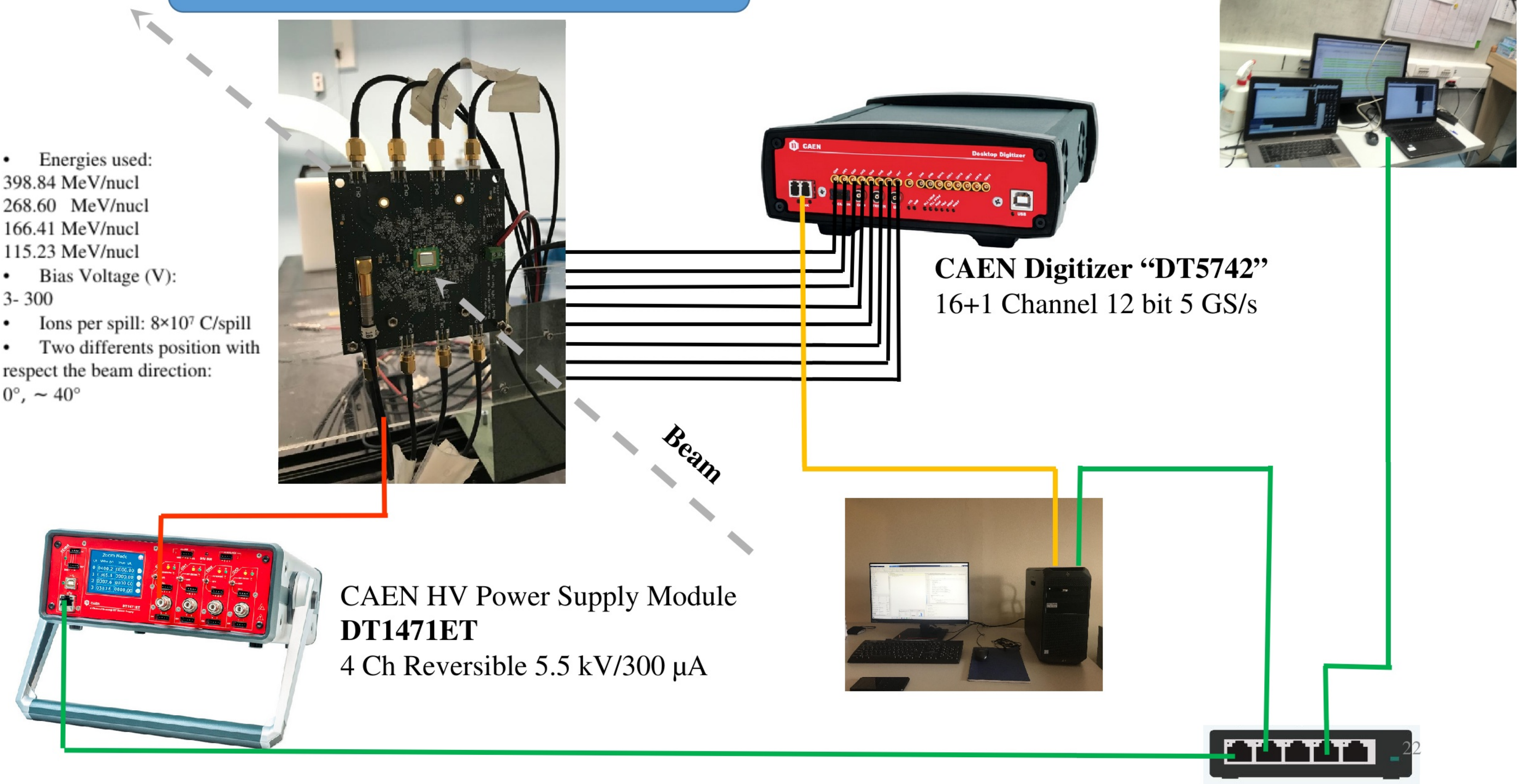


work in progress

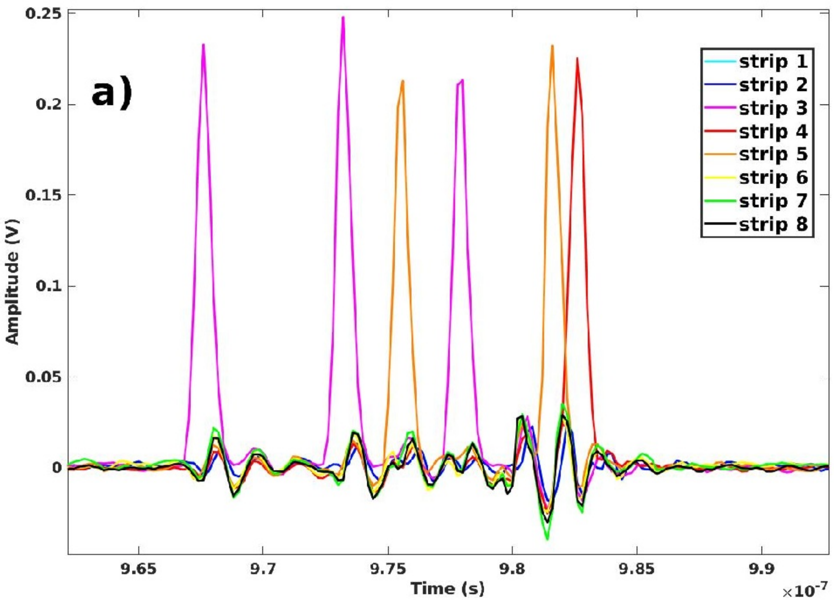
Thin silicon sensors for carbon ions tracking: preliminary tests at CNAO

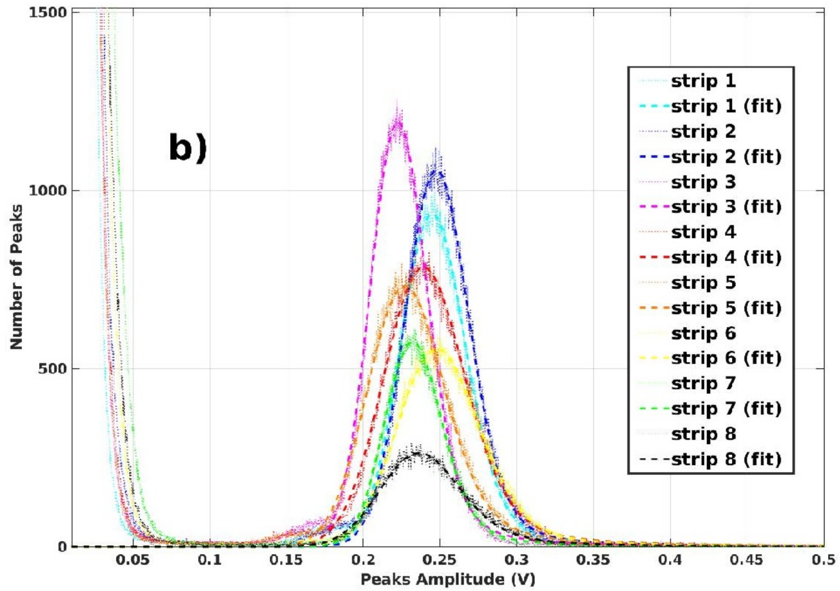
Experimental Setup used at CNAO

- Energies used:
398.84 MeV/nucl
268.60 MeV/nucl
166.41 MeV/nucl
115.23 MeV/nucl
- Bias Voltage (V):
3- 300
- Ions per spill: 8×10^{7} C/spill
- Two differents position with respect the beam direction:
0°, ~ 40°

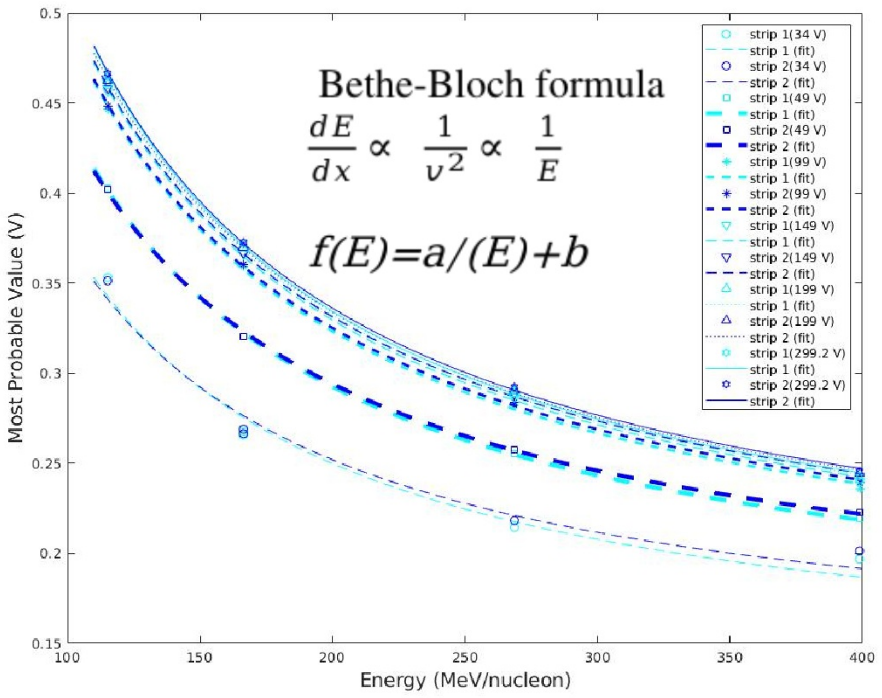


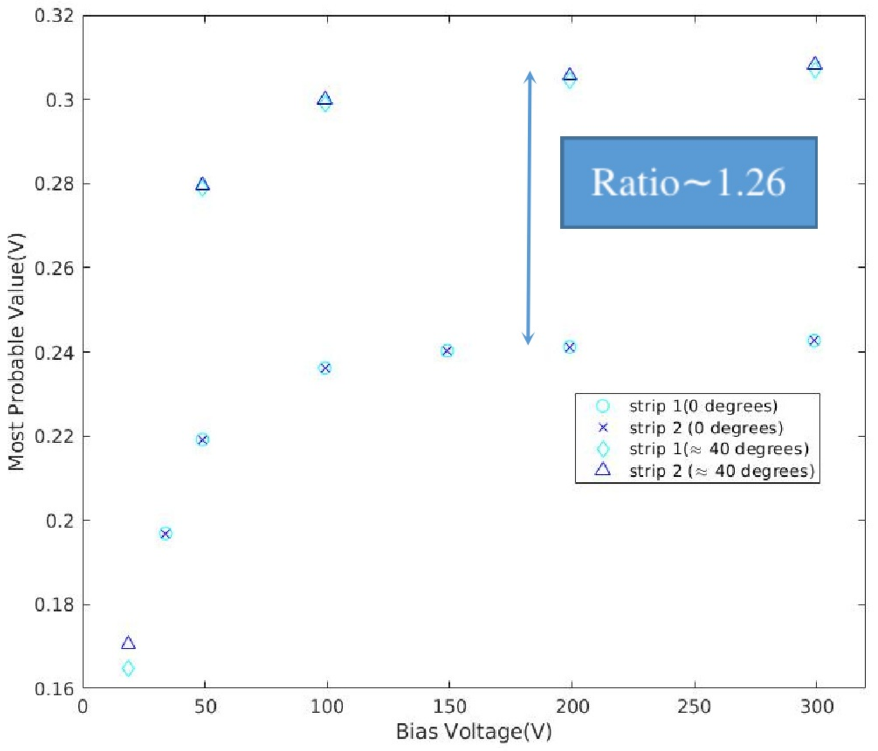
Bias Voltage: 149 V
Energy: 398.84 MeV/nucleon





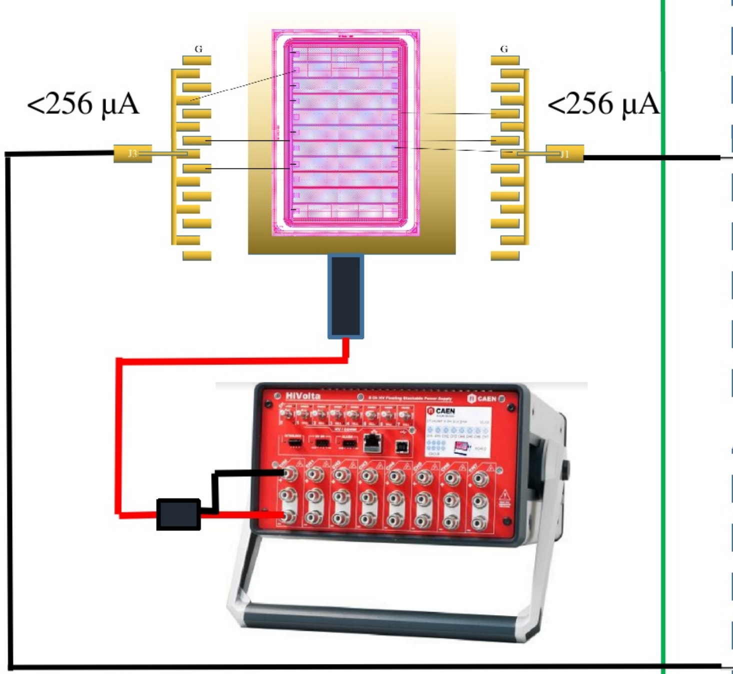
MPV *vs*. Energy (MeV/u) using several bias voltages and MPV *vs*. bias voltage with the sensor positioned at two different angles with respect the beam direction (0 and 40 degrees) for 398.84 MeV/u

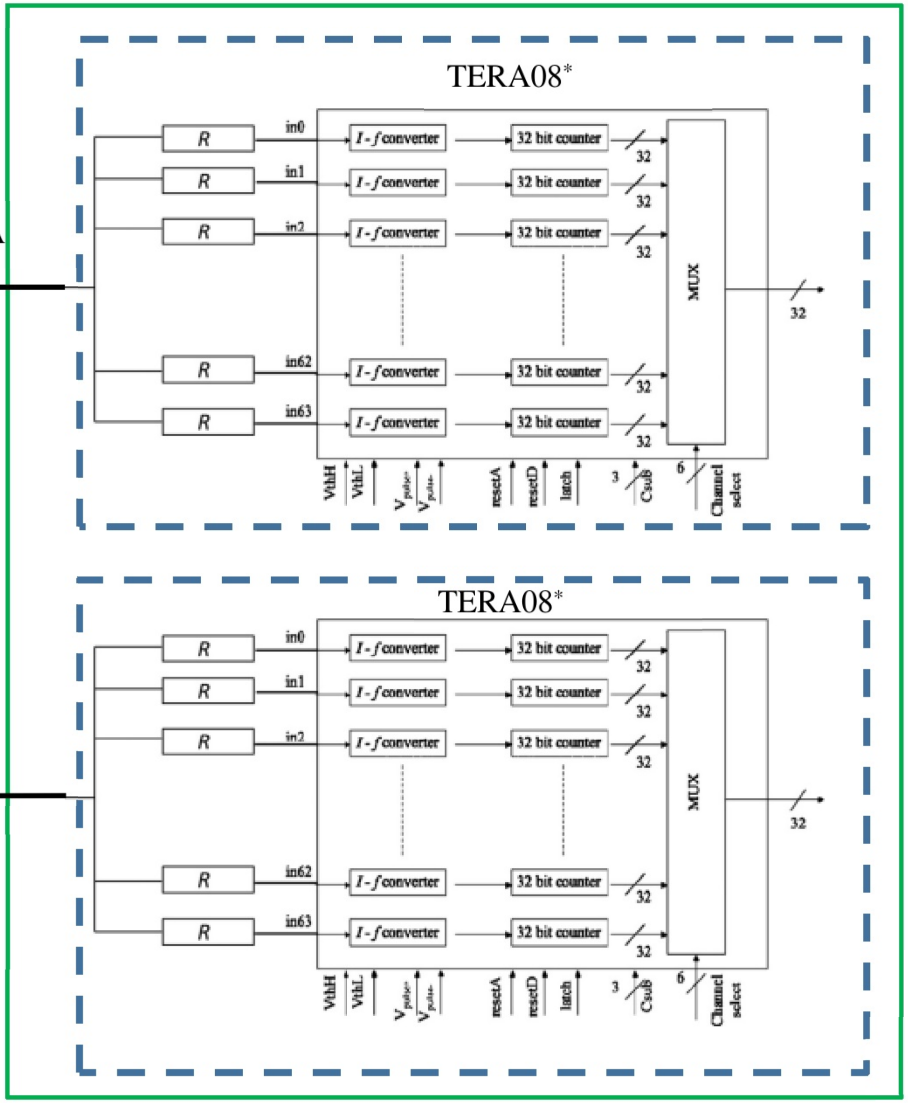


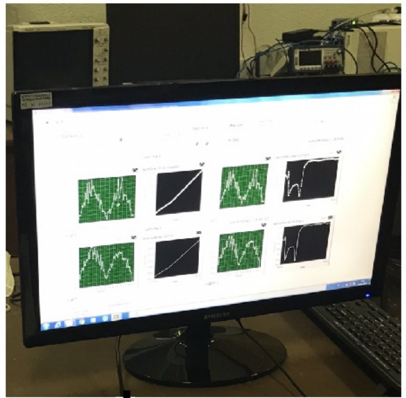


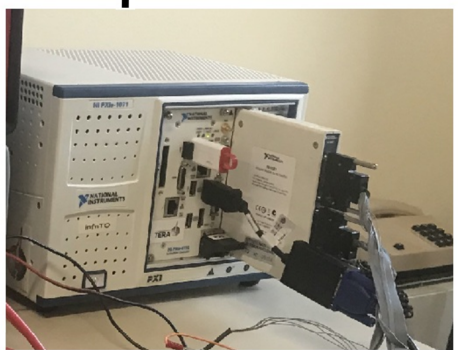
Silicon Devices for Monitoring Electron/Proton FLASH Beams

Experimental setup







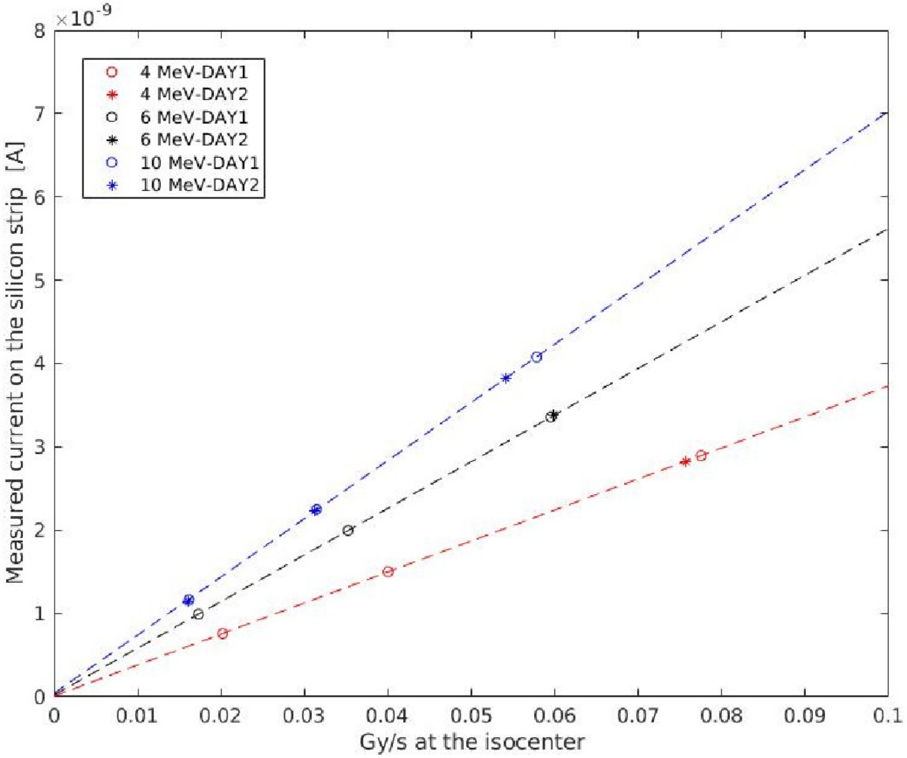


National Instruments PXIe-1071
PXI Chassis

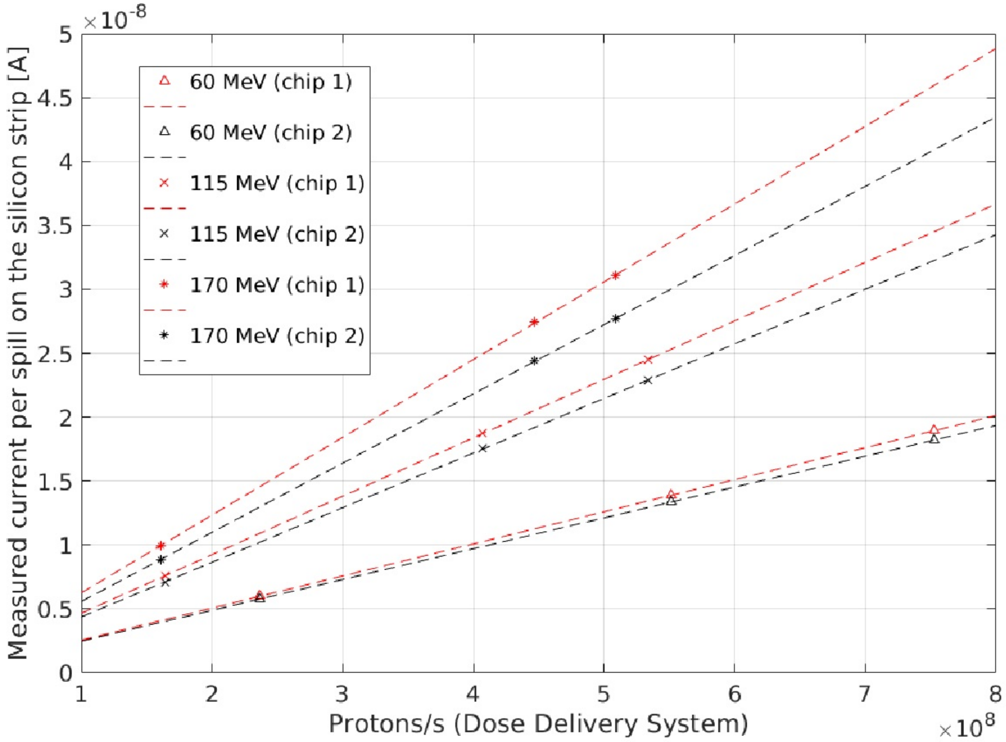
*Cirio, Roberto, et al. "A simple method to increase the current range of the TERA chip in charged particle therapy applications." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 798 (2015): 107-110

Linearity

Electrons measurements at Elekta SL18 LINAC



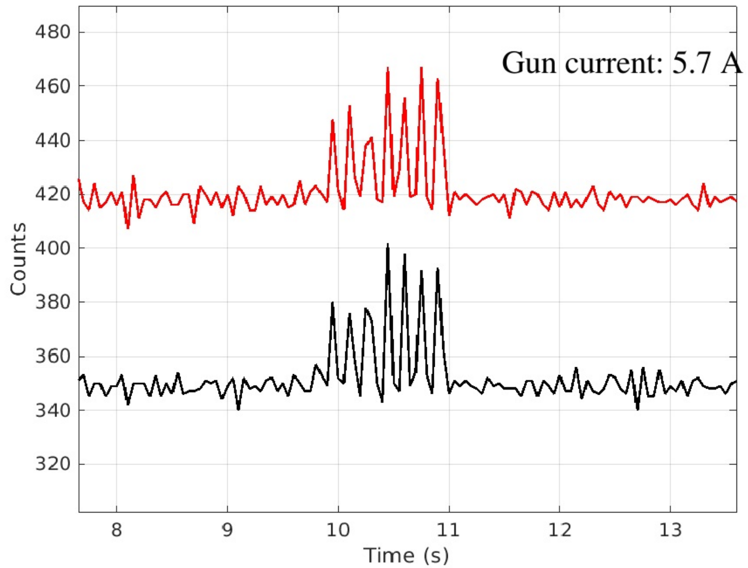
Protons measurements at CNAO

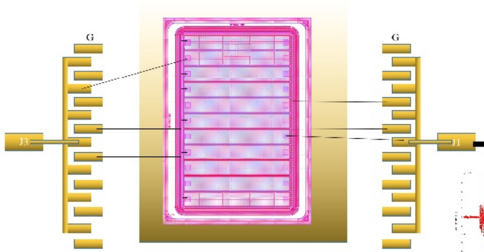


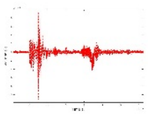
Preliminary result on a modyfied Elekta SL18 LINAC (work ongoing)

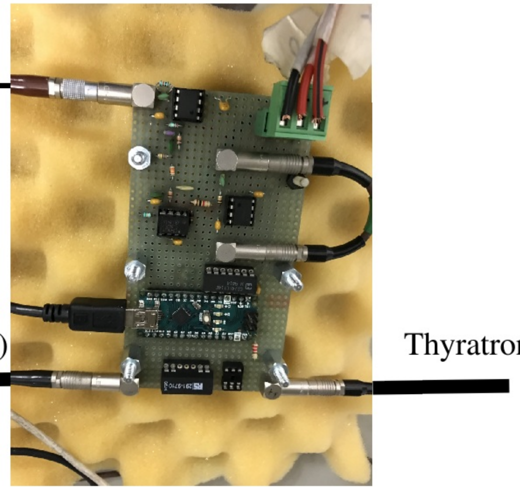
Standard silicon sensor
strip area: 2.2 mm^2
active thickness: 60 μm
total thickness: 630 μm
No detector bias needed
Energy: 10 MeV

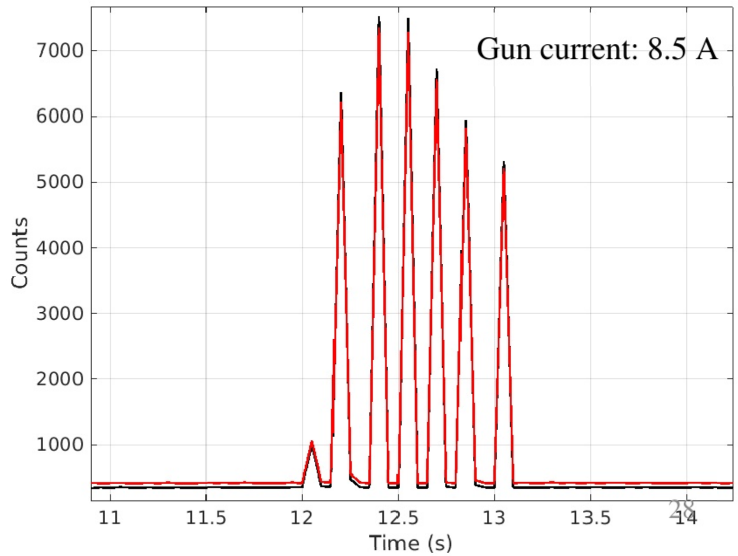
As example: 7 pulses were requested











An increase factor of the measured current of about 100 was observed

[1]Lempart, M., Blad, B., Adrian, G., Bäck, S., Knöös, T., Ceberg, C., & Petersson, K. (2019). Modifying a clinical linear accelerator for delivery of ultra-high dose rate irradiation. Radiotherapy and Oncology, 139, 40-45.

Remarks and Conclusions

- The LGAD technology can be used for beam characterization and online monitoring of proton beam.
- The measured energies using ToF were independent with the beam time structures and only a few milliseconds were necessary to achieve 1mm range precision;
- For the first time, LGAD sensors with a large sensitive area able to cover the entire beam spot (FWHM) at the isocenter were tested with clinical proton beams at CNAO. The results showed good separation between signal and noise in the LGAD strip, a feature not seen on the PiN;
- Using a 2.6×2.6 cm^2 LGAD sensor, the proton counter was able to replicate the beam profile to at least 115 MeV;
- Preliminary tests of thin silicon sensors for single carbon ions detection on clinical beams were performed at CNAO, showing very promising results and preparing the groundwork for future development of a counter and beam energy detector specifically developed for clinical carbon ions;
- Preliminary tests with electrons and protons using conventional dose-rates and intensities respectively confirmed the linearity and reproducibility of the system. In addition, an upgrade of a modyfied Elekta SL18 LINAC is ongoing. Finally, a measured current per pulse increased by around a factor of 100 on the first upgrade attempt.

Thank you!!!