Silicon sensors in Medical Physics

Simona Giordanengo

INFN Torino

INFN
Istituto Nazionale di Fisica Nucleare

Outline

- Radiation detectors in medical physics:
  - where and why?
- Silicon sensors for:
  - beam monitoring in particle therapy,
  - timing applications,
  - Flash radiotherapy (FLASH RT),
  - proton/ion imaging.

Introduction

Radiation detectors in medical physics: where and why?

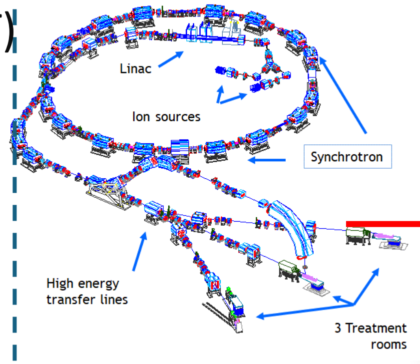
Medical Imaging techniques

- ✓ X-ray Imaging
- ✓ Computed Tomography (CT)
- ✓ Positron Emission Tomography (PET)
- ✓ Single Photon Emission Computed Tomography (SPECT)
- ✓ Image fusion PET-CT

Benefits from new technologies
→ improve image resolution and sensitivity

Radiotherapy with external beams

Cyclotron for protons and
Synchrotron for protons&light ions



- Protons (60-250 MeV/u)
- Carbon ions (115-400 MeV/u)

LINAC for radiotherapy

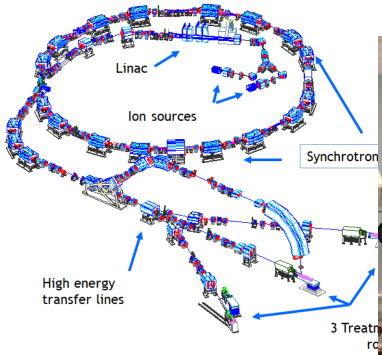
- Photons (6 - 18 MV)
- Electrons (6 - 18 MeV)

Radiation detectors for radiotherapy

- **Beam commissioning**
  - Before facility startup
- **Beam monitoring**
  - Online to guide and control the beam delivery
- **Quality Assurance**
  - daily/weekly/monthly
- **Dosimetry**
  - daily
- **Microdosimetry**
- **Radiobiology**

Radiotherapy with external beams

Cyclotron for protons and
Synchrotron for protons&light ions



- Protons (60-250 MeV/u)
- Carbon ions (115-400 MeV/u)

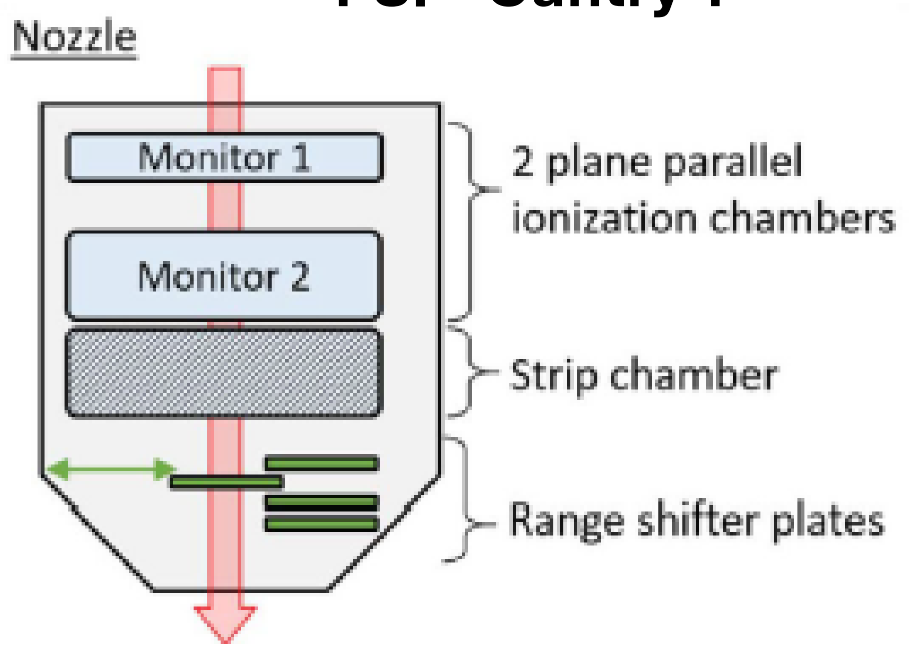
LINAC for radiotherapy

- Photons (6 - 18 MV)
- Electrons (6 - 18 MeV)

The role of beam monitors in the nozzle

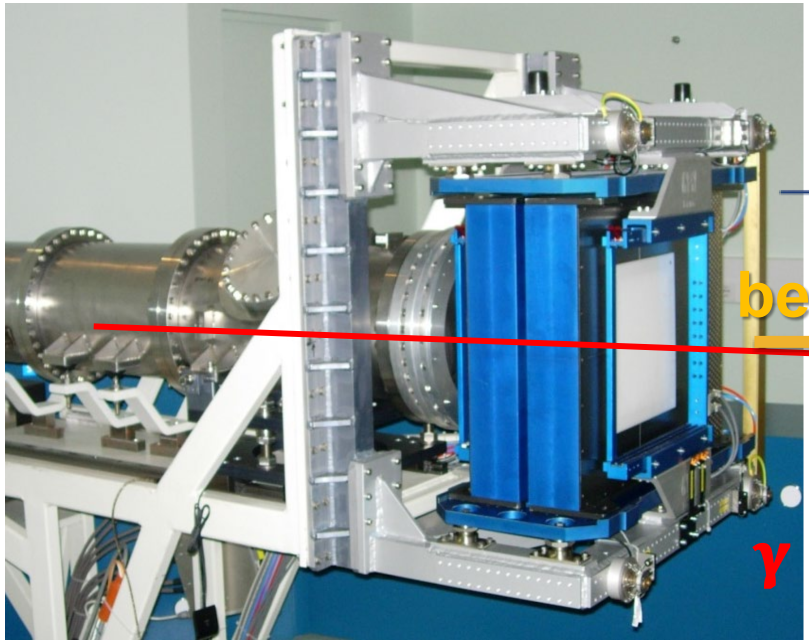
Nozzle equipped with particle detectors integrated with the accelerator control system to **guide and control** the beam in real time.

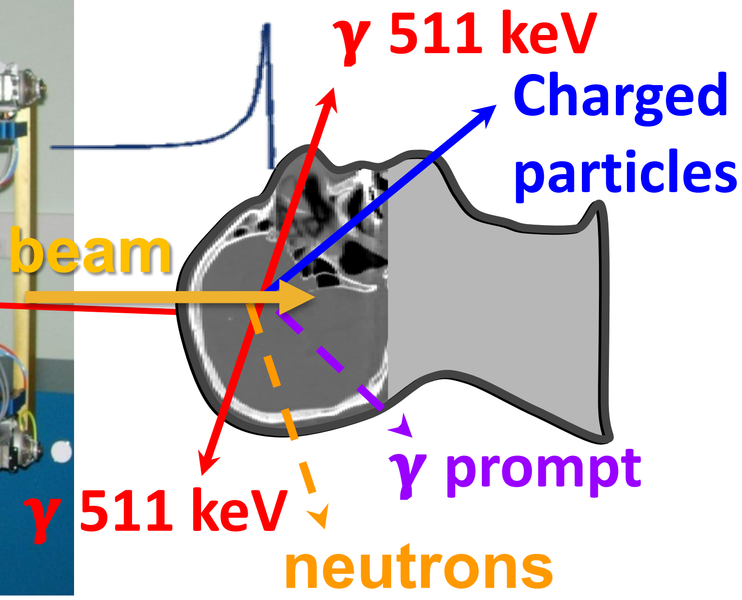
PSI – Gantry 1



Phys. Med. Biol. 68 (2023) 105013

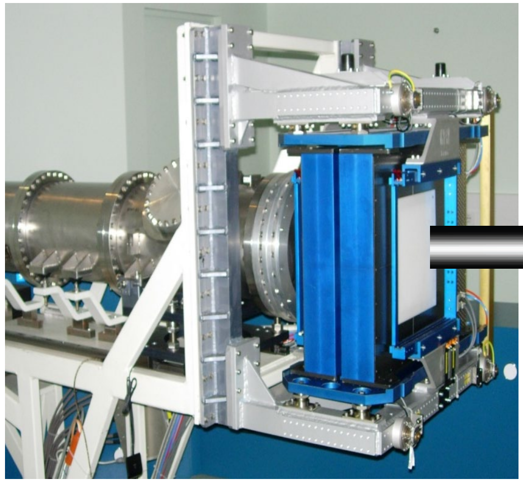
CNAO horizontal beam line



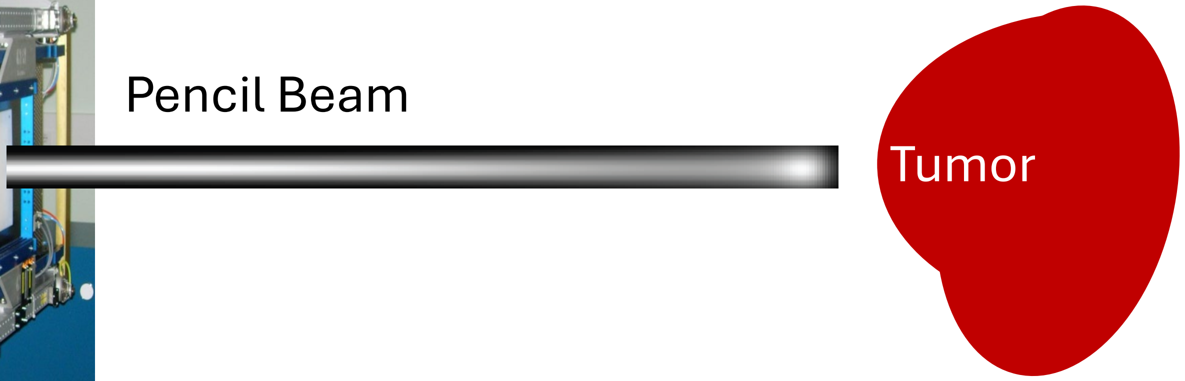


Nucl. Instr. Met. A 698 (2013) 202

Beam characteristics for particle therapy



Target dimension: 1 ÷ 40 cm

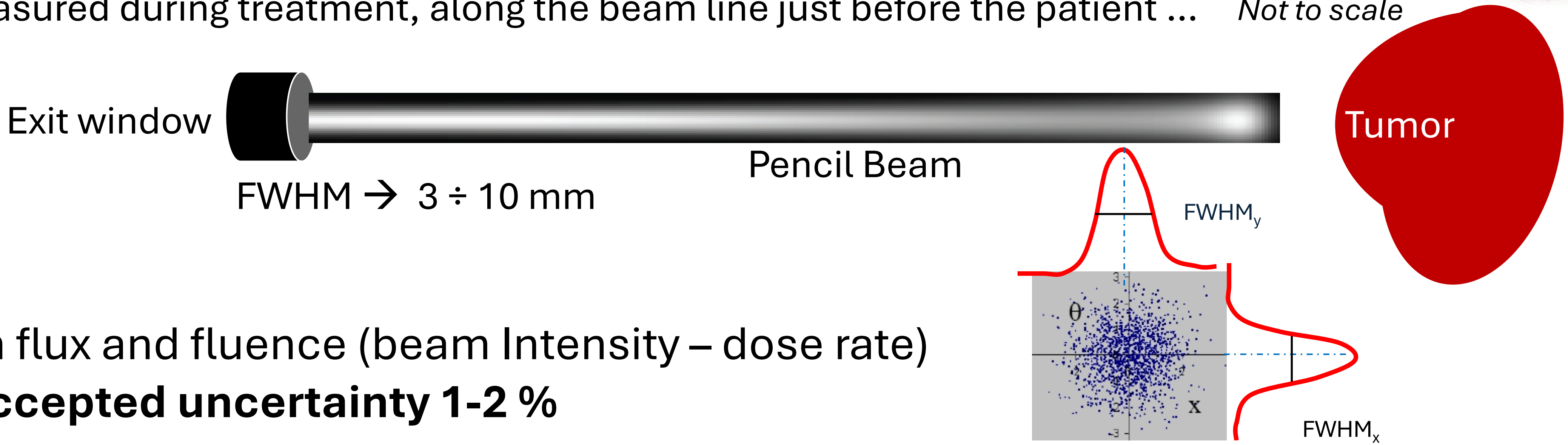


Not to scale

Beam **range** in water for protons&ions →	**3÷30 cm**
Beam **energy range** (protons) [MeV, β, MIP]	**60÷250 MeV, β 0.34-0.59 , 5-2 MIP**
Beam **energy range (C ions)**	**120÷400 MeV/u (β 0.46-0.71)**
Beam **intensity (particles/s)**	**10^8÷10^{10} p/s 4×10^7÷4×10^8 Cions/s**
Spot size (FWHM in air at the isocenter)	**FWHM 7÷20 protons /4÷8 mm Cions (highest÷lowest) Energy**
Field size at the isocenter	**20x20/40×40 cm^2 (min-max)**

Beam parameters measured in the nozzle

To be measured during treatment, along the beam line just before the patient … *Not to scale*



Beam flux and fluence (beam Intensity – dose rate)
→ **Accepted uncertainty 1-2 %**

Transversal Beam positions
→ **Accepted uncertainty ±0.5 mm**

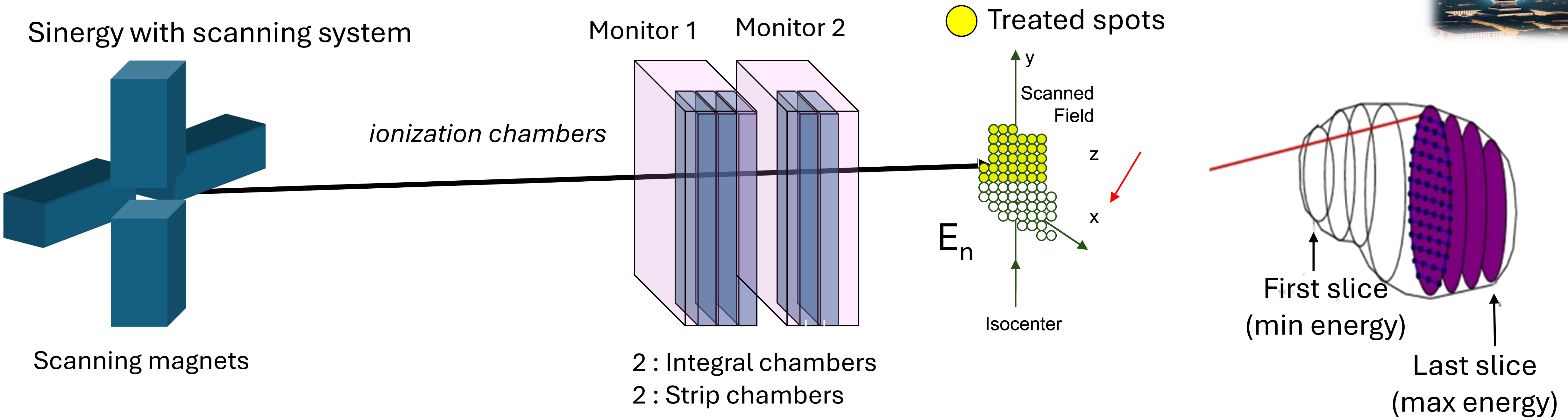
Transversal Beam shape (FWHMs)
→ **Accepted uncertainty ±1 mm**

Beam range or energy
→ ***Accepted uncertainty 1 mm (0.5 - 1 MeV)***

Currently not online!!

Pencil beams are driven by beam monitors

Sinergy with scanning system



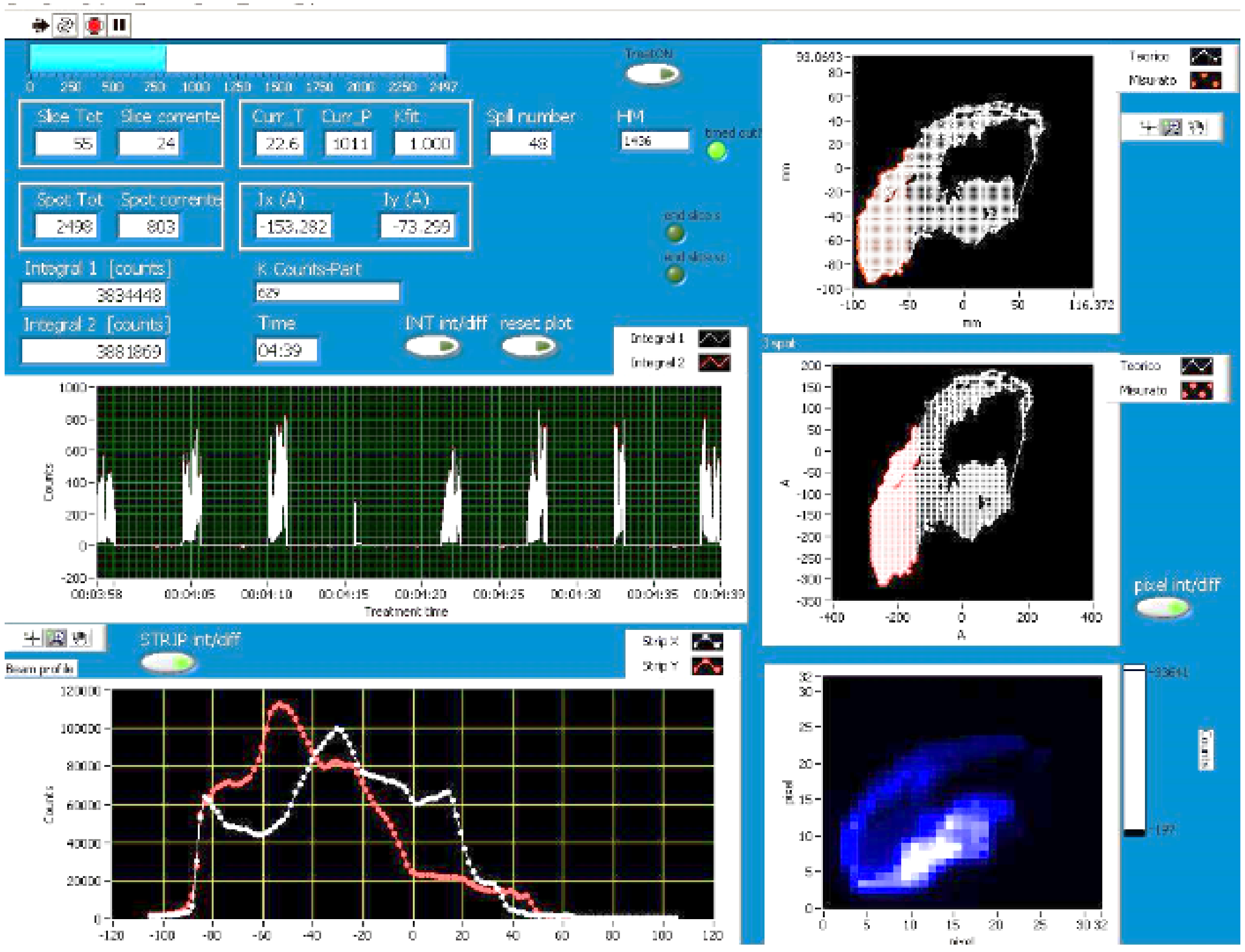
Monitor on-line the beam fluence and position (mandatory), FWHM (optional)

Set the beam position spot by spot through the scanning magnets power supplies

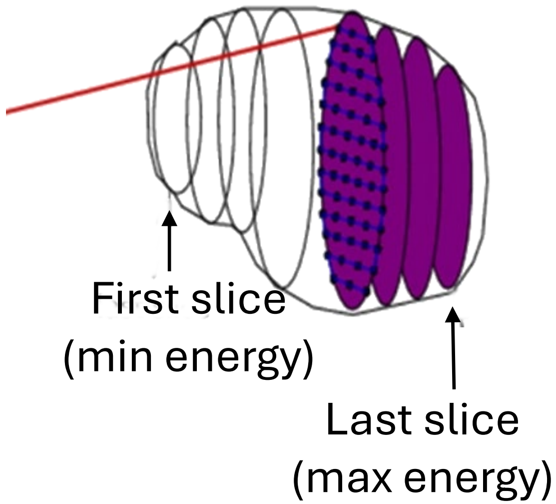
Correct on-line the beam position (feed-back operations)

Stop the beam when something is wrong (beam parameters out of range)

Online beam delivery progress



Dose Delivery System GUI in the CNAO Local Control Room



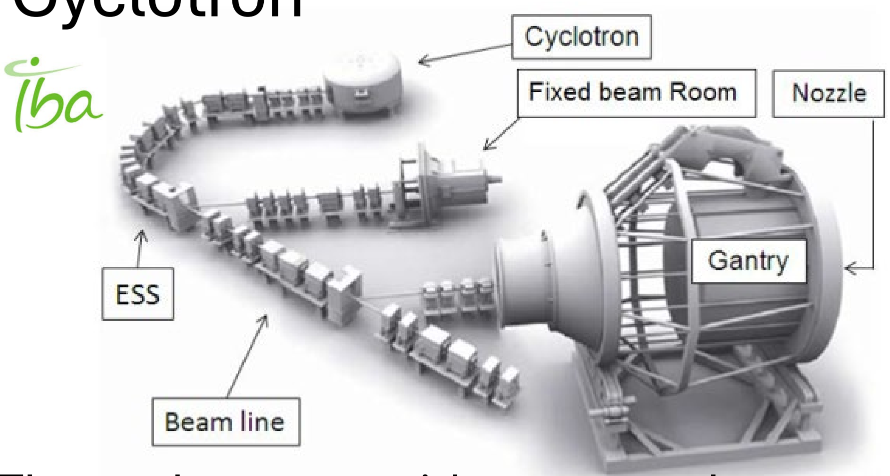
Robustness vs Performances in medical applications

Performances and accuracy

Robustness

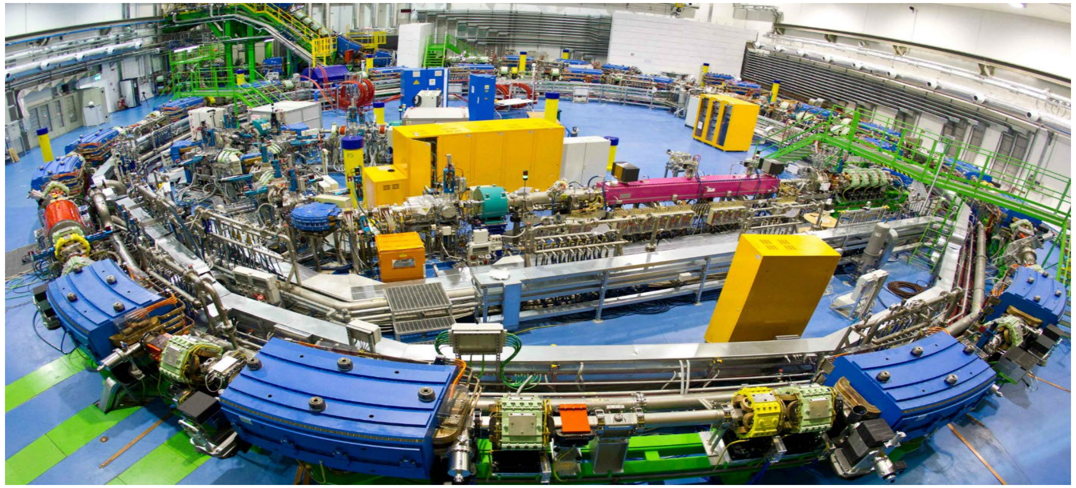
Beam monitor must deal with different beam temporal structures

Cyclotron



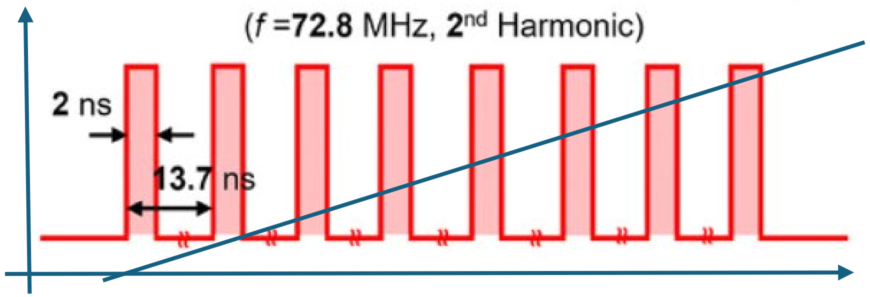
The cyclotron provides proton therapy reliably and at low cost (main vendors on the market: IBA, Varian, Mevion, Hitachi).
Energy modulation with degraders.

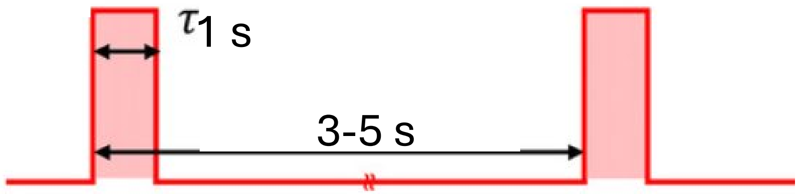
Synchrotron



Multi-ion accelerator (more flexible than cyclotrons).
Beam delivered in spills

Beam monitor integrated charge





State-of-the-art
→ large area gas ionization chambers

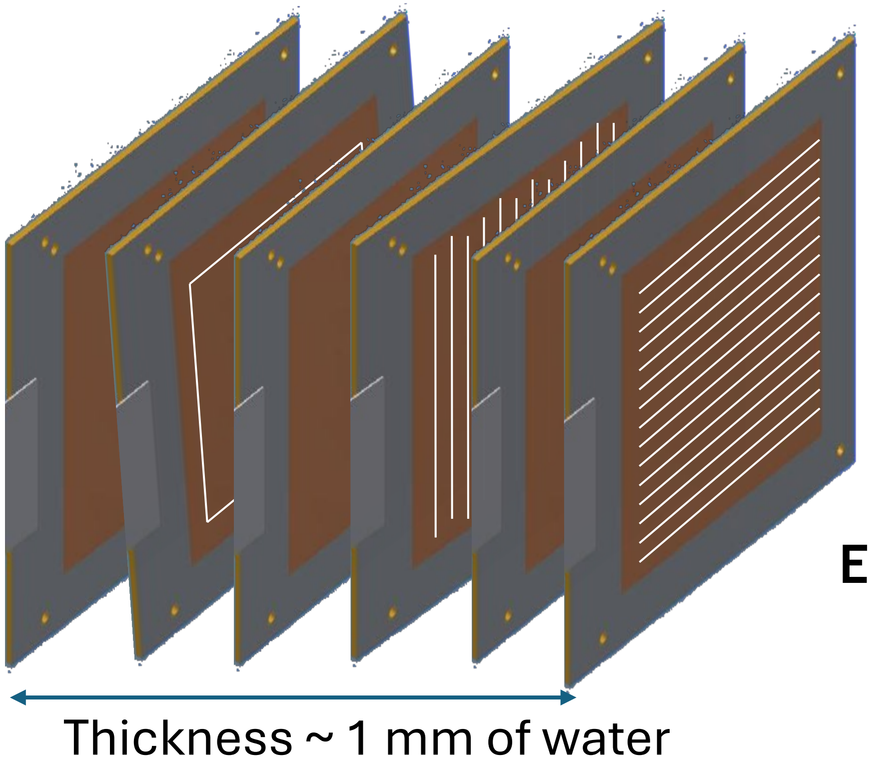
ADVANTAGES

- ✓ Reliability & long term (years) stability
- ✓ Large (up to 40x40 cm^2) sensitive area
- ✓ Simple to use
- ✓ Deeply studied manufacture
- ✓ A few mm water equivalent thickness
- ✓ Radiation resistant

Roadmap: proton therapy physics and biology
Paganetti et al. Phys. Med. Biol. 66 (2021) 05RM01

"Currently ionization chambers(IC) are predominately used (in fact they ***are legally required in most countries).*** *"*

Sequence of Parallel Plate ICs:
→ single **large** electrode for **FLUENCE**
→ electrodes segmented in strips for **BEAM POSITION and SHAPE**



Gas used:
- Air
- N_2,
- Ar-CO_2

E = 1 kV/cm

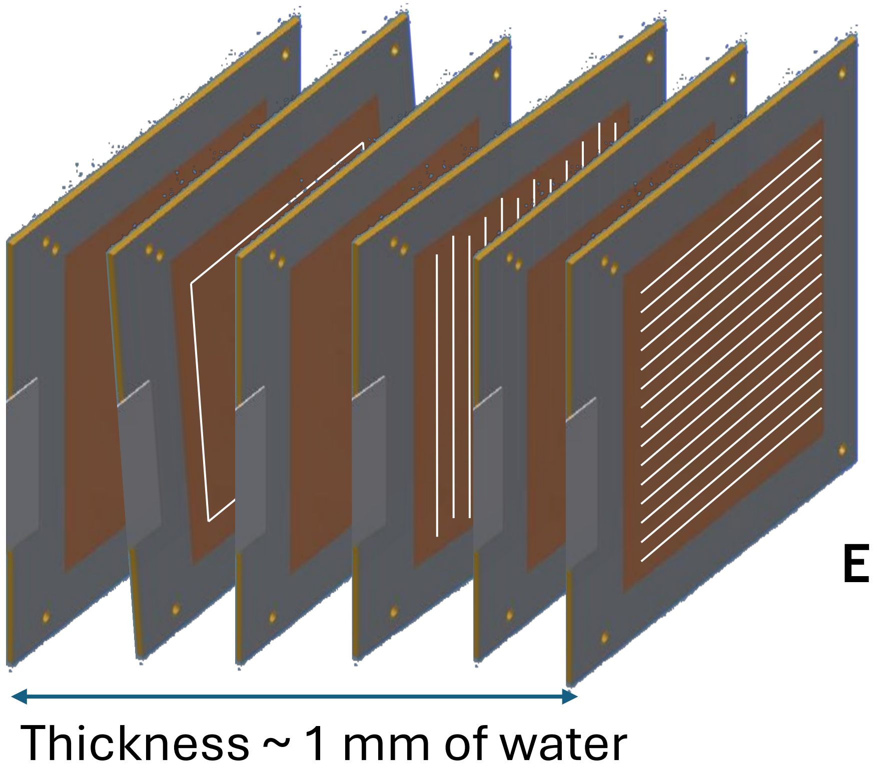
State-of-the-art
→ large area gas ionization chambers

LIMITATIONS

- ✓ **Long collection times ~ 100 μs**
- ✓ **Low Sensitivity ~ 10^4 protons**
- ✓ **Poor time resolution ~ no/poor**
- ✓ **Deviation from linearity @ high dose rates**

Not suitable for
- fast scanning modalities
- timing applications
- high dose rates (FLASH)

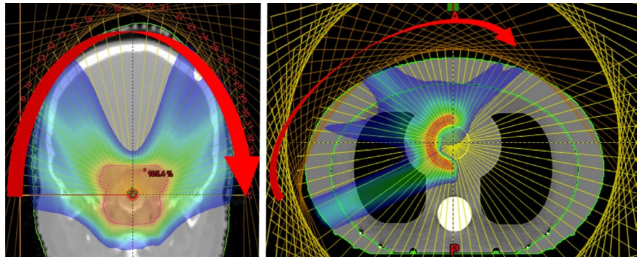
Sequence of Parallel Plate ICs:
→ single **large** electrode for **FLUENCE**
→ electrodes segmented in strips for **BEAM POSITION and SHAPE**

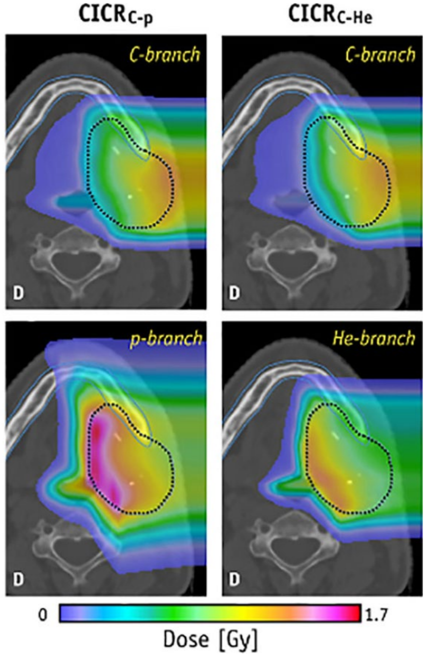


Gas used:
- Air
- N_2,
- Ar-CO_2

E = 1 kV/cm

New challenges for beam monitoring





- New accelerators (different timing structures and treatment procedures)
- Advanced treatment modalities (multiple rescanning, online image-guided, …)
- Fast pencil beam scanning
- Hipofractionation up to FLASH
- Proton Computed Tomography

Future Developments in Charged Particle Therapy: Improving Beam Delivery for Efficiency and Efficacy

Jacinta Yap[1], Andrea De Franco[2] and Suzie Sheehy[1]*

[1] School of Physics, University of Melbourne, Melbourne, VIC, Australia, [2] IFMIF Accelerator Development Group, Rokkasho Fusion Institute, National Institutes for Quantum Science and Technology, Aomori, Japan

Review > Phys Med Biol. 2021 Feb 26;66(5):10.1088/1361-6560/abcd16.
doi: 10.1088/1361-6560/abcd16.

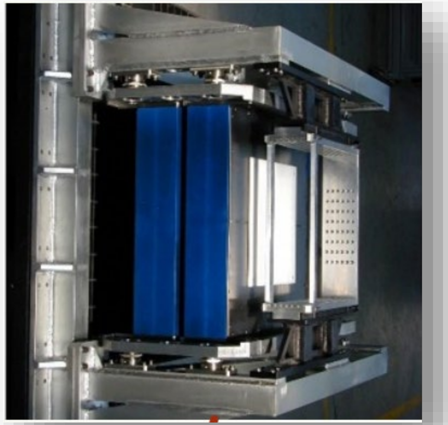
Roadmap: proton therapy physics and biology

Harald Paganetti [1 2], Chris Beltran [3], Stefan Both [4], Lei Dong [5], Jacob Flanz [1 2], Keith Furutani [3], Clemens Grassberger [1 2], David R Grosshans [6], Antje-Christin Knopf [4], Johannes A Langendijk [4], Hakan Nystrom [7 8], Katia Parodi [9], Bas W Raaymakers [10], Christian Richter [11 12 13], Gabriel O Sawakuchi [14], Marco Schippers [15], Simona F Shaitelman [6], B K Kevin Teo [5], Jan Unkelbach [16], Patrick Wohlfahrt [1], Tony Lomax [15]

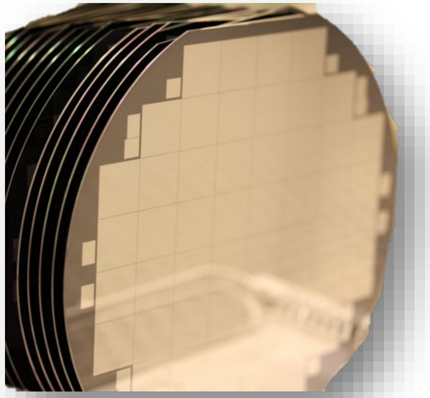
INFN MoveIT project (2017-2021)

Solid state detectors for p-beam monitoring

IONIZATION CHAMBERS



SOLID STATE SENSORS: LGAD 45-60 μm thickness
int. gain ~ 10



Collection times **~ 100 μs** → **~ ns**

Sensitivity **~ 10^4 protons** → **single protons**

Time resolution **~ no/poor** → **<< 100 ps**

Not suitable for
- fast scanning modalities
- timing applications

- direct counting # protons
- timing applications

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

- **Signal pile-up**
  → fast sensors & readout
  → segmentation
- **Radiation tolerance**
  → manufacturing strategies
  → damage compensation
- **Large sensitive area**
  → technological challenge

Increased complexity

Thin Low Gain Avalanche Detectors

- 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

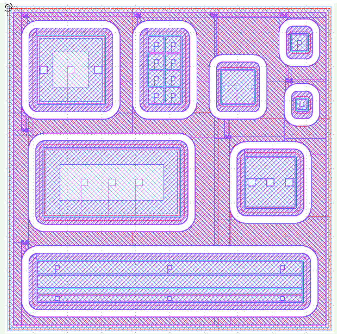
- Large area (2.7×2,7 cm²)
- 144 strips

Detectors for timing applications

- Smaller size, 11 strips
- Strip area 2.2mm^2, active thickness 45 μm, total thickness 615 μm)
- Si- substrate removed to reduce total thickness to 70 μm

Pads for large ionization rate studies

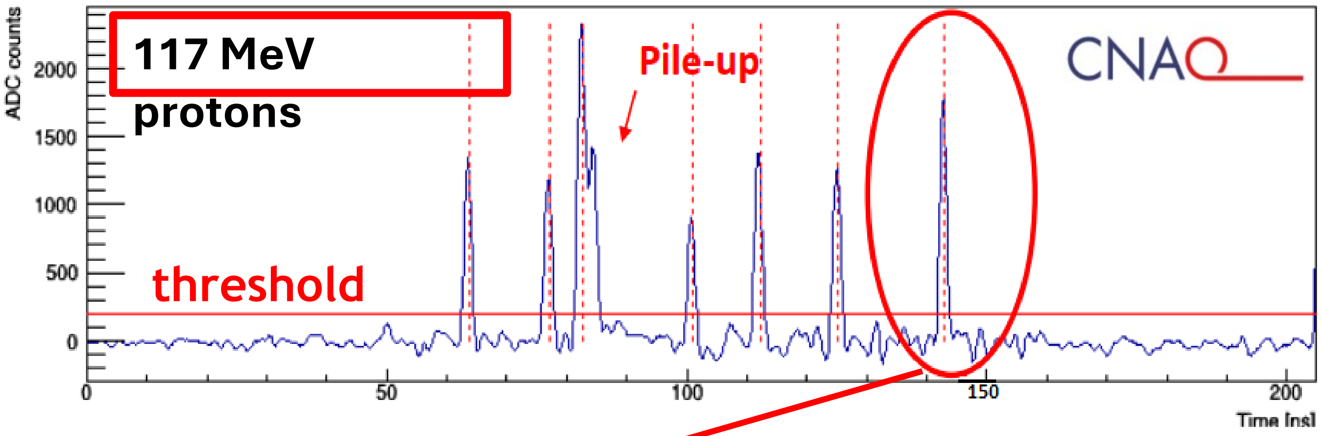
- 4 active thicknesses (15/20/30/45 μm)
- 5 pad sizes (0,125/0,25/0,56/1/2 mm²)

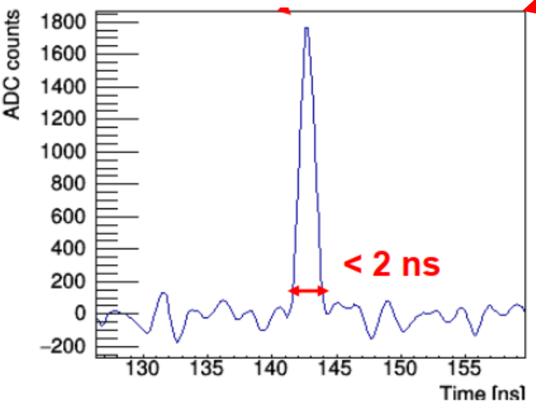


Internal gain	
yes	no
✓	✓
✓	✓
✗	✓
Use: Protons	Use: C-ions FLASH

Proton counting

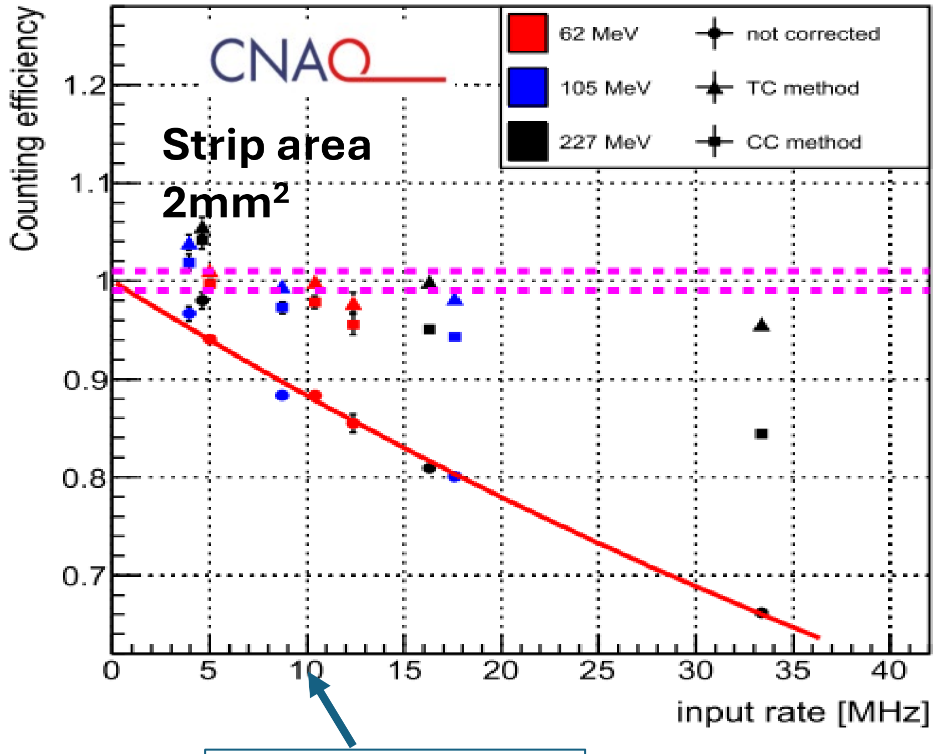
Data collected with strip sensors + digitizer





- Short peak duration
- Large Landau fluctuations
- Single particle discrimination
- Signal pile-up

Pile-up correction studies



CNAO beam flux
5×10^8 p/cm^{2}s

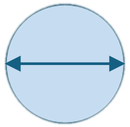
Mohammadian-Behbahani M, et. al., *NIM A 1040 (2022) 167195*
Monaco V, et. al., *Phys. Med. Biol.* 68 (2023) 235009

Technologies for multi-channels silicon detectors

Custom ASIC

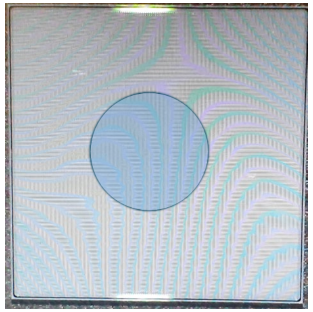
Custom Frontend board

Proton pencil beam ❯ LGAD strips ❯ ABACUS ❯ ESA-ABACUS ❯ 3 FPGA ❯ LabVIEW interface

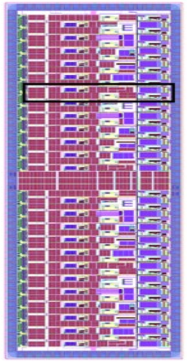


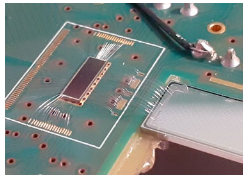
1 cm FWHM

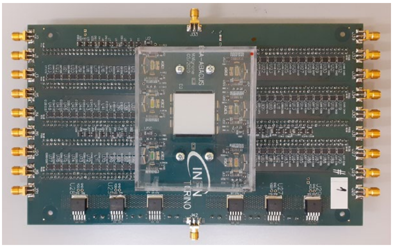
10^8 p/s*cm^2



146 strips

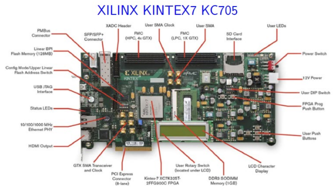




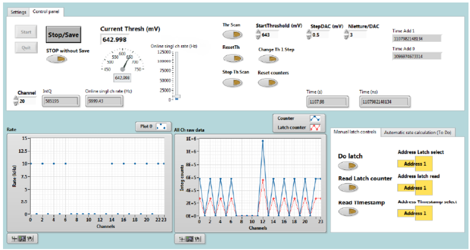


6 ABACUS
24x6 channels

Kintex-7

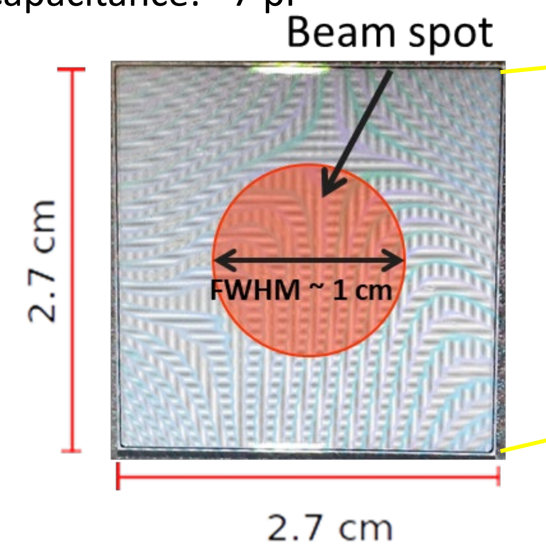


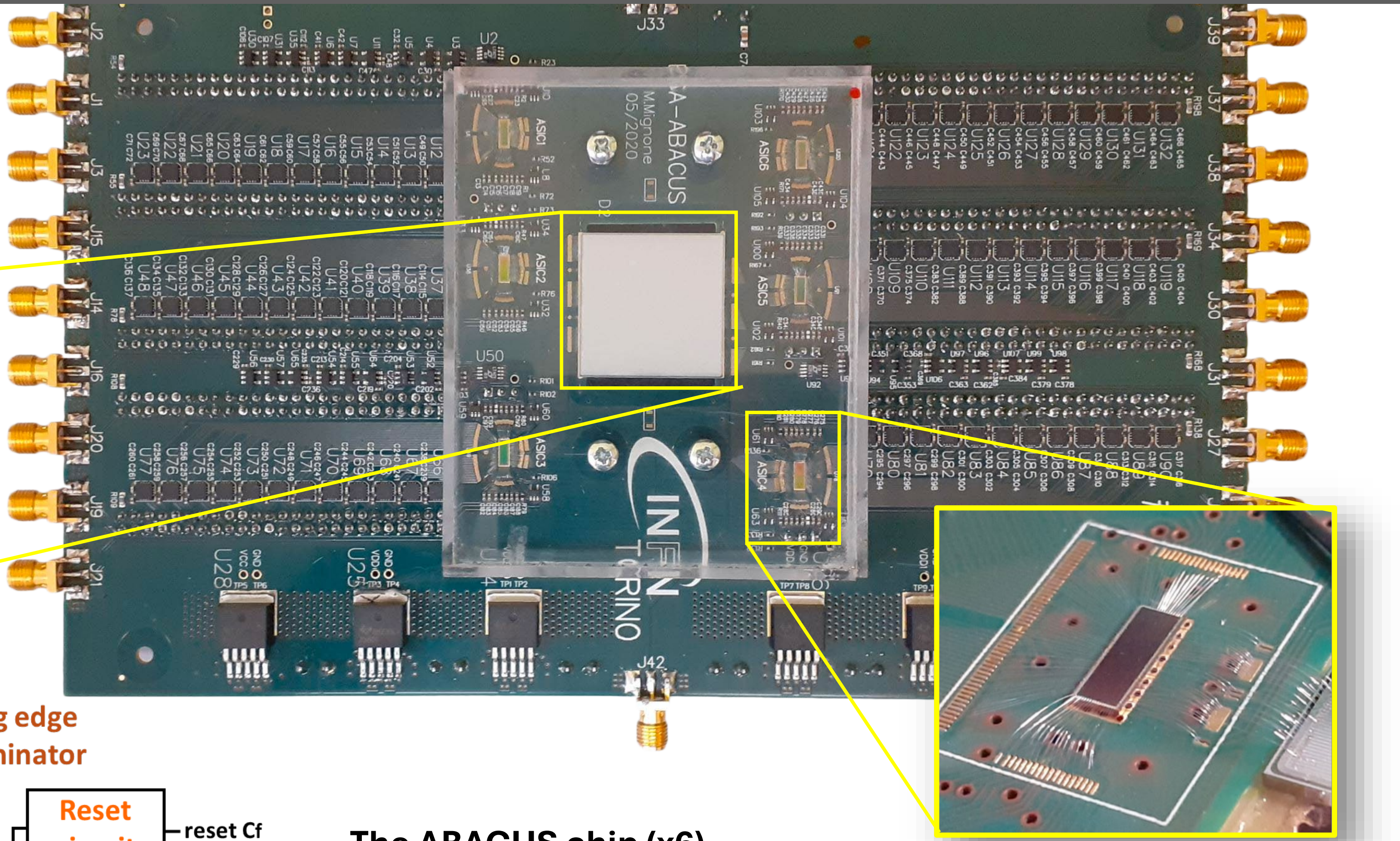
Gbit ethernet interface

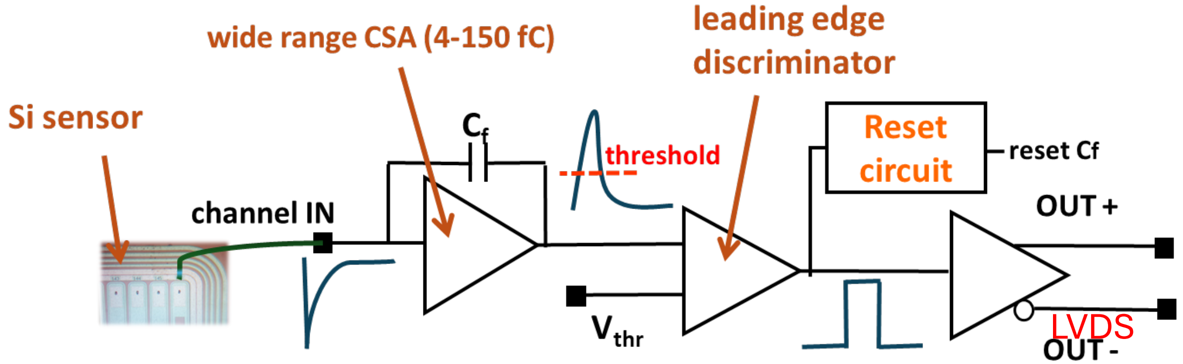


2.7×2.7 cm² particle counter (ESA ABACUS)

Silicon strip sensor
Strips width: 114 µm
Pitch: 180 µm
Active thickness: ~50 µm
Capacitance: ~7 pF



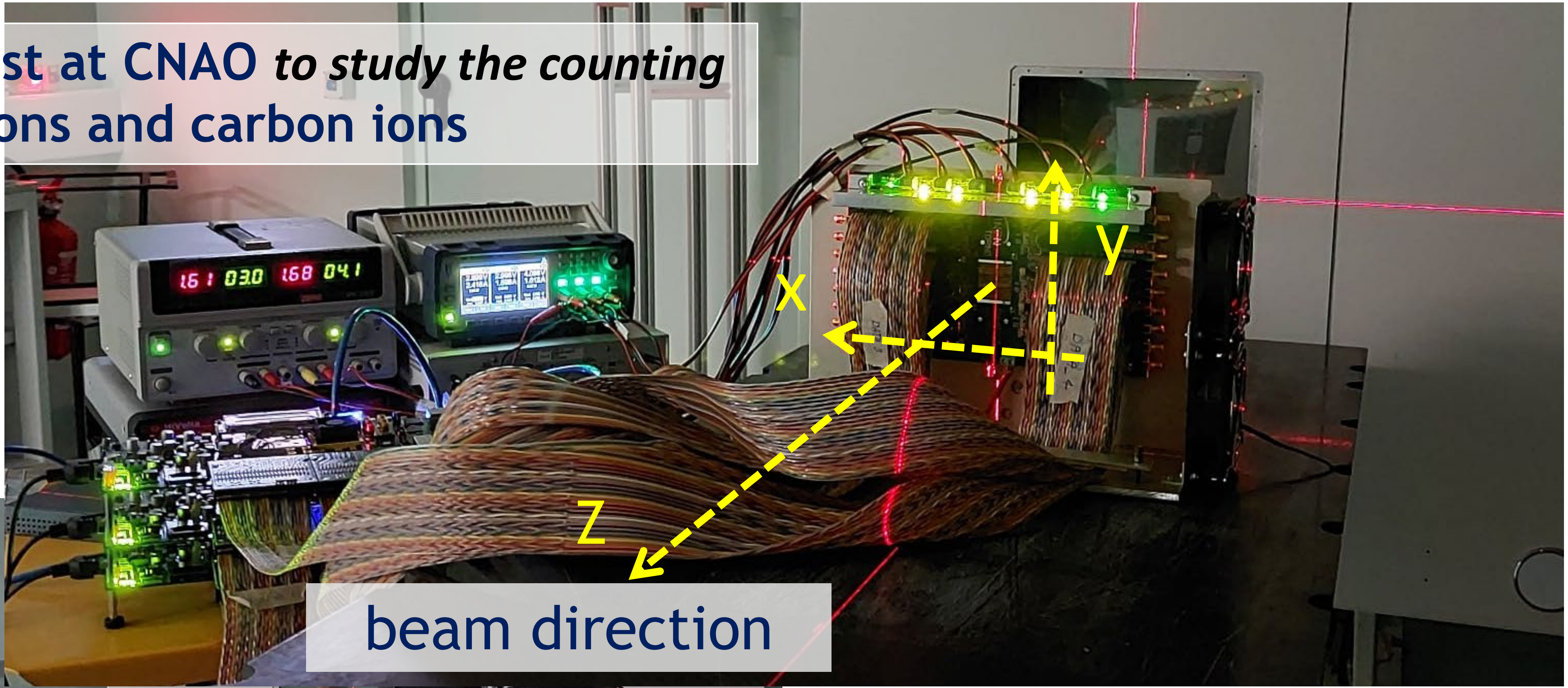




The ABACUS chip (x6)

- 110 nm CMOS technology, chip area = 2 × 5 mm², 24 channels, 144 in total. CSA dynamic range: 4 fC – 150 fC. Dead time : < 10 ns.

Particle counter test at CNAO *to study the counting efficiency* with protons and carbon ions



Runs with different energies in the clinical energy range

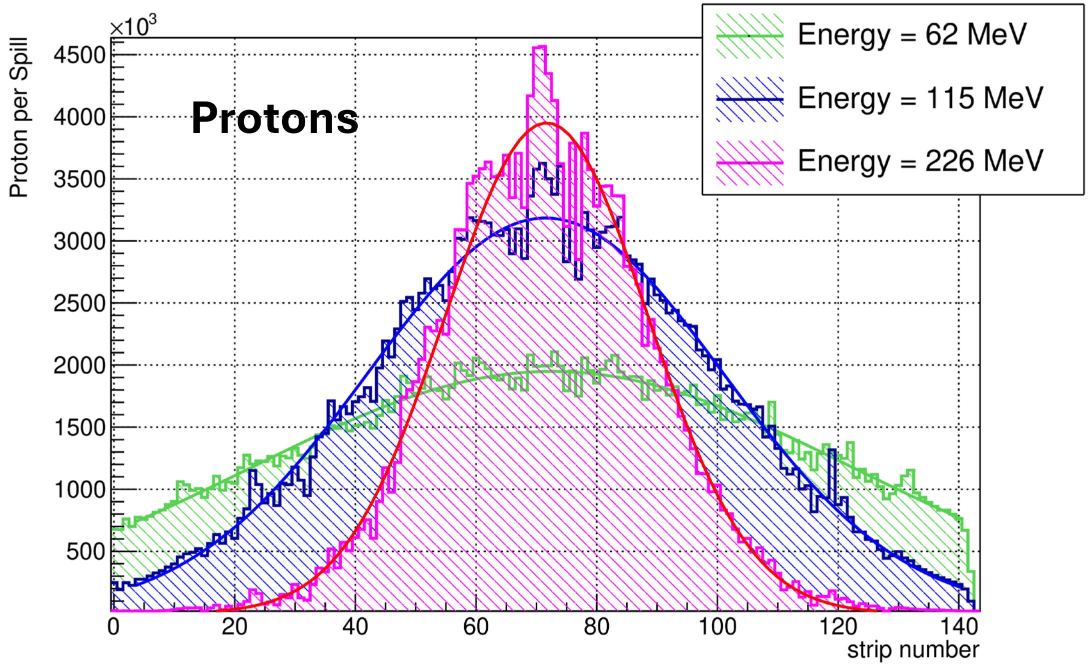
- 60 - 230 MeV (protons)
- 115 - 400 MeV/u (carbon ions)

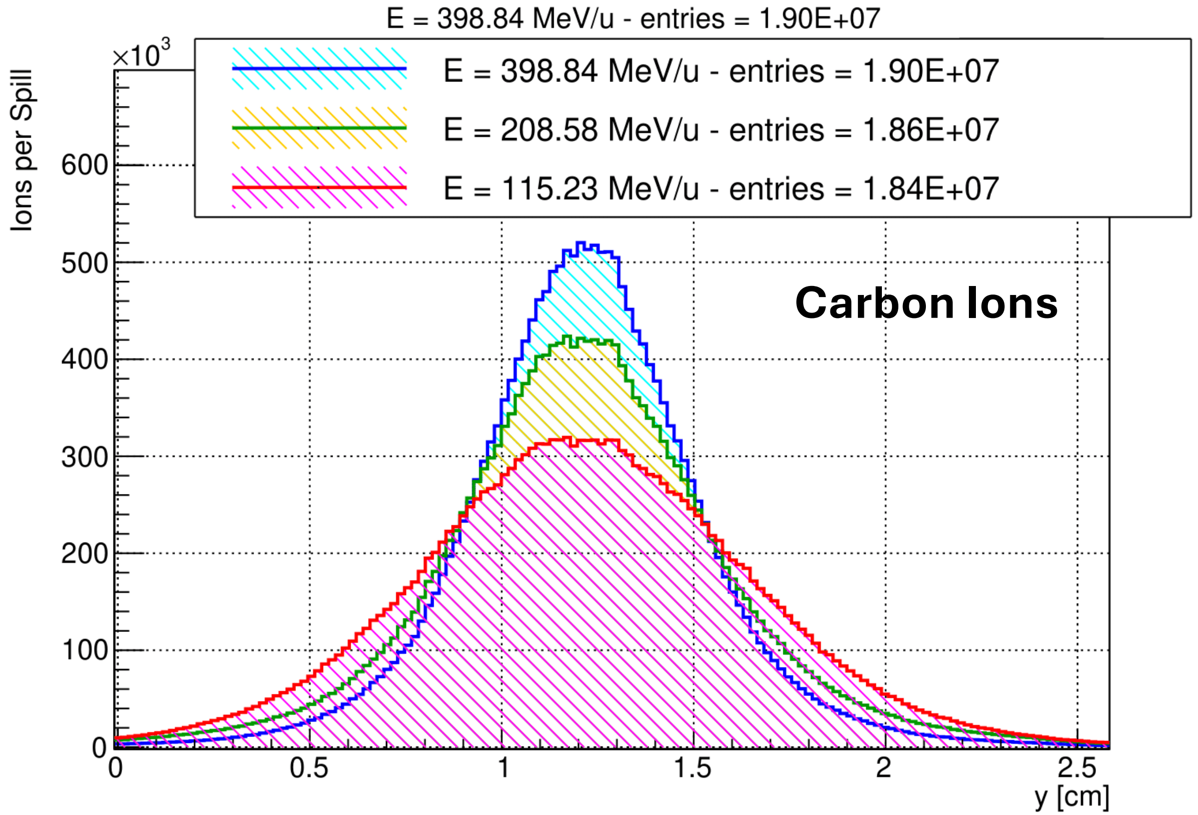
Different beam fluence rate:

- 20, 50, 100 % of maximum fluence rate

Measured beam profiles and fluence at CNAO

Protons per spill





Three different energies, 60 - 230 MeV (protons), 115 - 400 MeV/u (carbon ions)

Three different beam fluence: 20, 50, 100 % of the maximum fluence rate.

Counting efficiency: 50% protons, > 90 % Carbon ions

Perspectives about *online* beam fluence and position control

Technology ready for fix pencil beam characterization.

→ Improved front-end readout will overcome noise issues encountered with protons.

→ Current LGAD radiation tolerance will guarantee 1 year of safe operation

✓The challenge

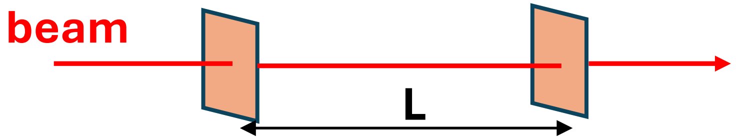
→ Increase the sensitive area (> 24x24 cm^2)

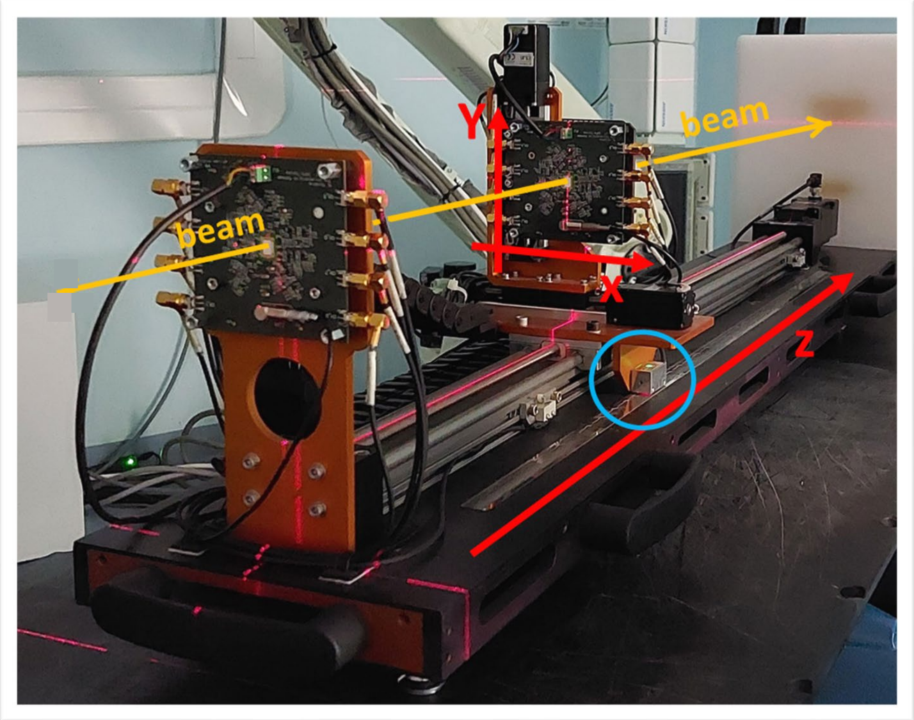
- Pixel segmentation needed

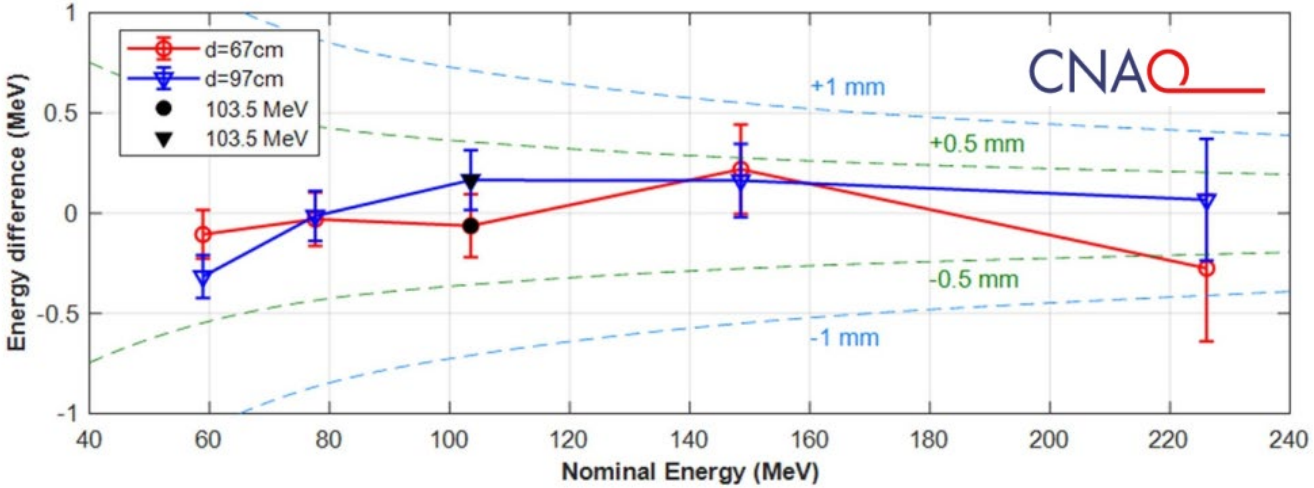
Exploiting timing performances of fast silicon detectors

Timing application (i): beam energy detector

Beam energy/range from time-of-flight



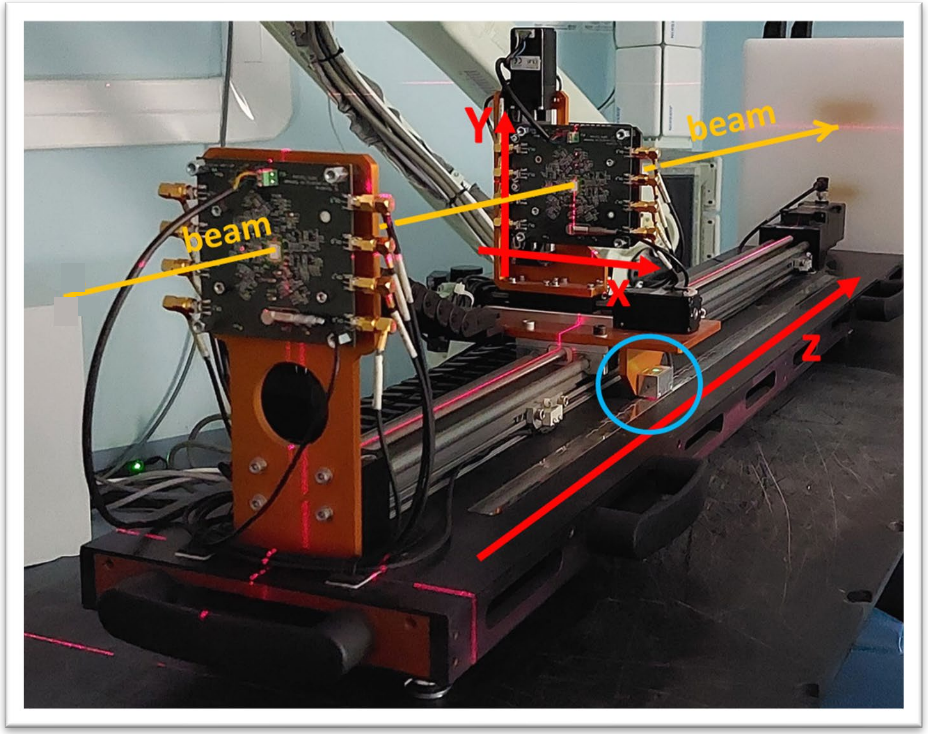




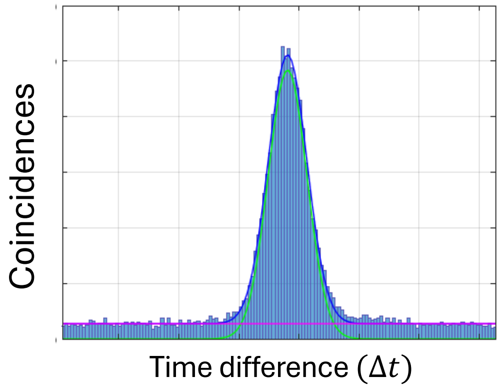
- ➢ range can be measured with ±1 mm uncertainty;
- ➢ need few ms of active acquisition time;
- ➢ requires precise calibration of the system.

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

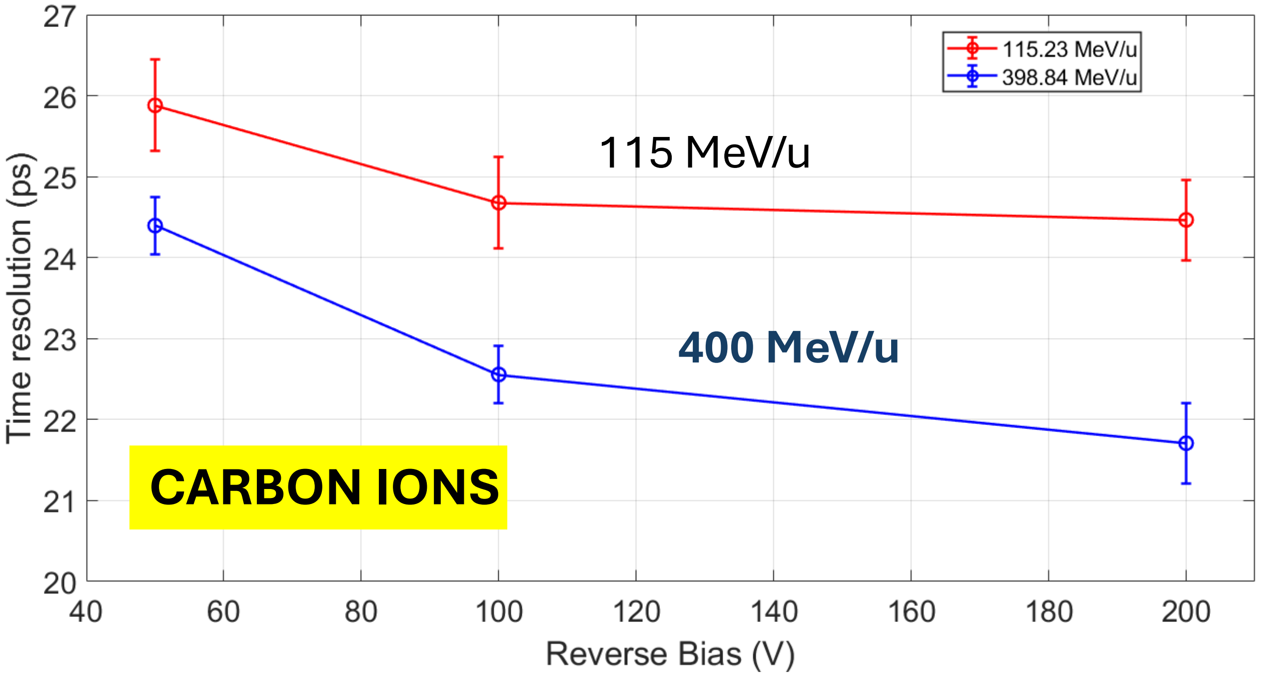
Time resolution for ion crossing with thin silicon sensor



- Two Si sensors with the same characteristics placed in a telescope configuration 30 cm apart.
- Beam energies (MeV/u): 115.2 and 398.8.
- Bias voltage: 50V, 100V, and 200 V.



$$\sigma_t \text{ (ps)} = \sigma(\Delta t) / \sqrt{2}$$



Time resolution values for single ion crossing were **less than 26 ps**

(relative error < 2%)

Perspectives about *online* beam energy control

Today

Current treatments do not need online beam energy control

→ the beam energy is guaranteed by the accelerators control system

Future

→ Clinical treatments with LINAC accelerator will provide fast energy modulation with online beam energy control.

The challenge

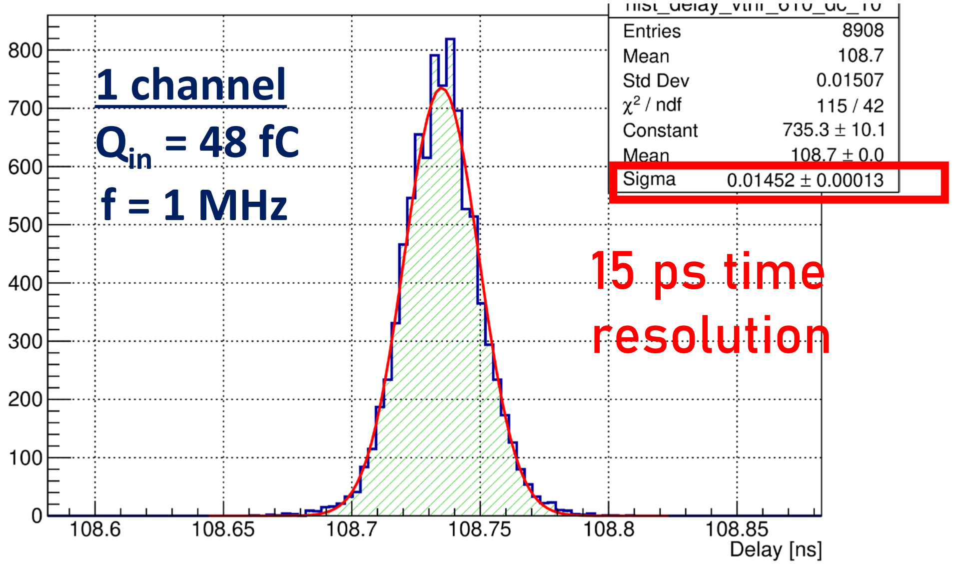
→ Energy measurement in the limited space and time constrained by clinical requirements.

Particle crossing time measurements
CERN picoTDC evaluation board (64 input channels)

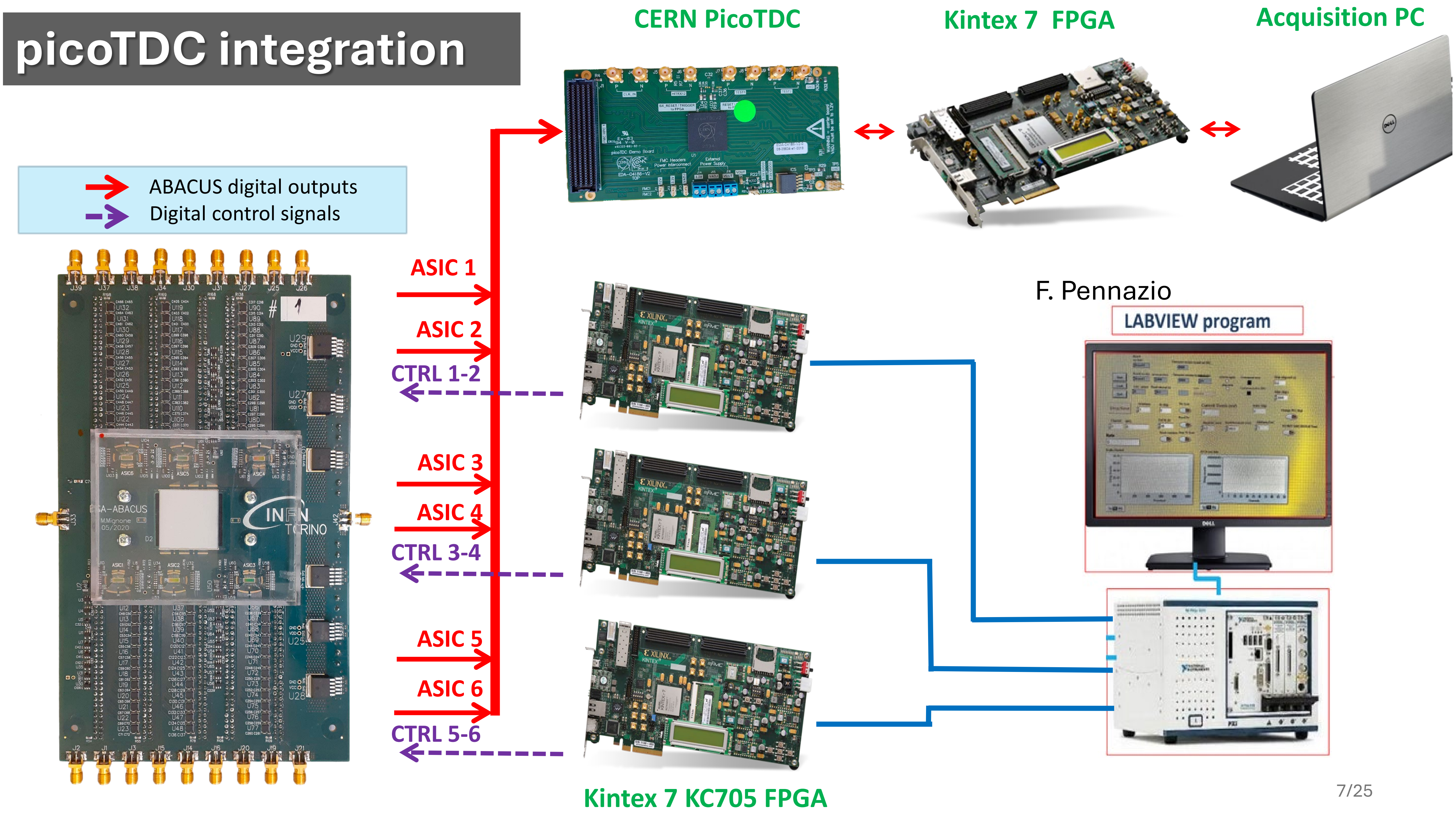
- 3ps or 12ps binning
- very low jitter (<1ps)
- High rate capability
- Readout through FPGA

Successfully integrated with 8 channels of ESA-ABACUS

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



picoTDC integration

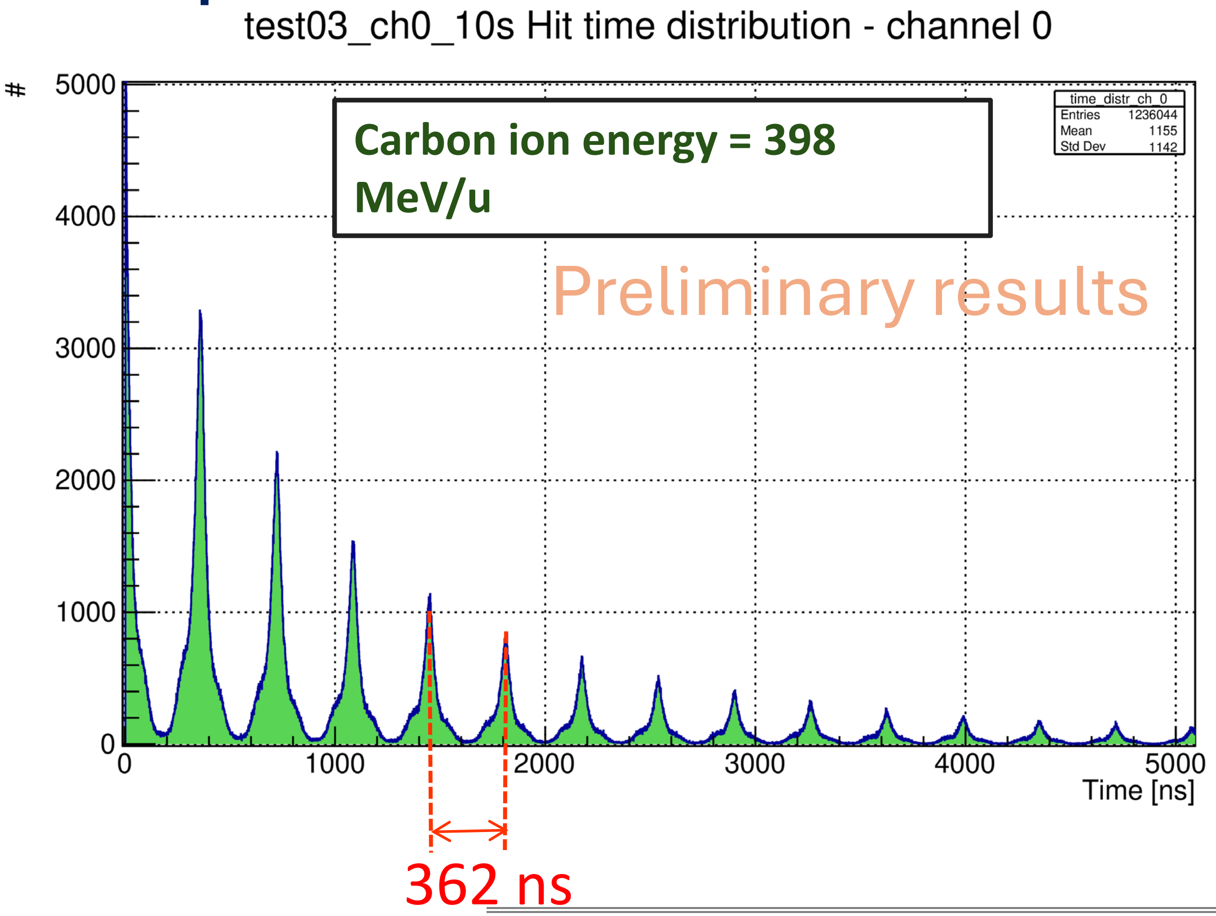


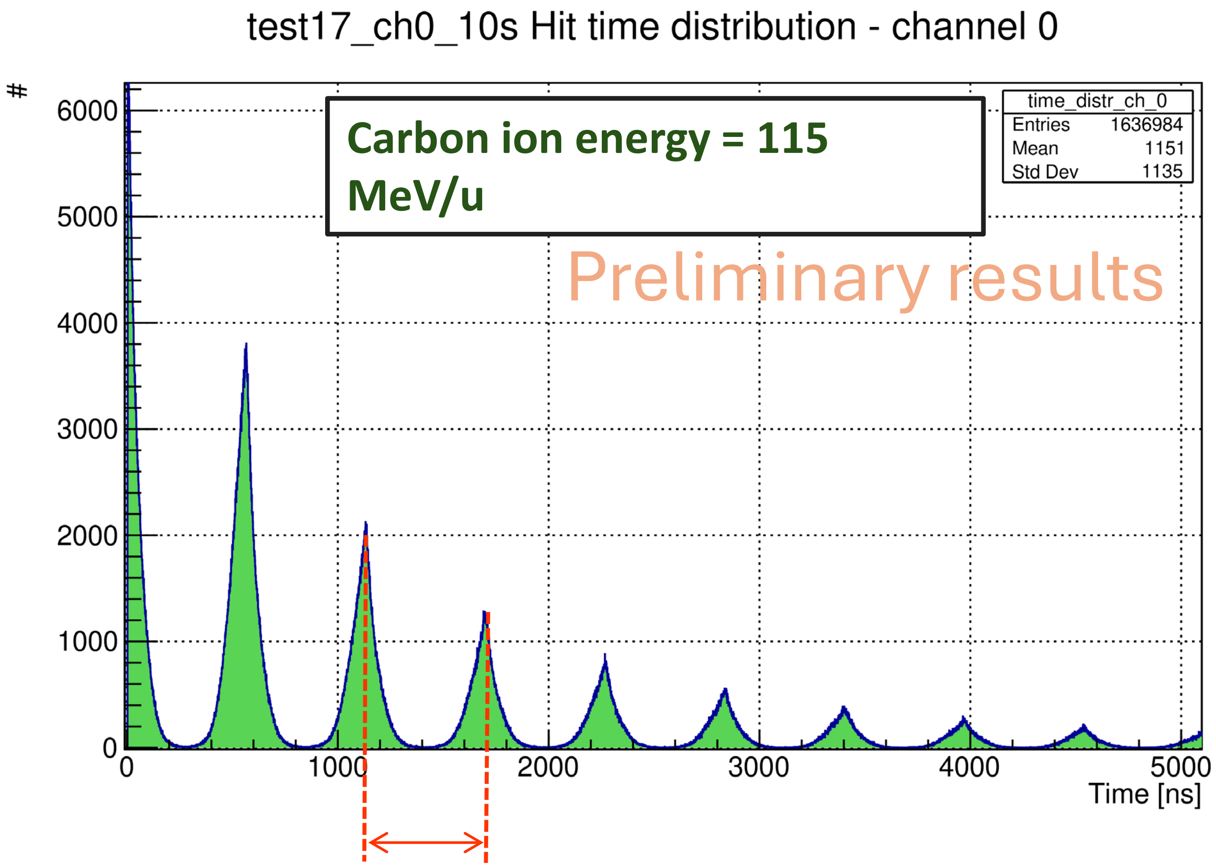
Timing application (ii): beam time microstructure with picoTDC

Time difference between 2 c-ions

- **3 ps bin size**
- **20 μs time window**

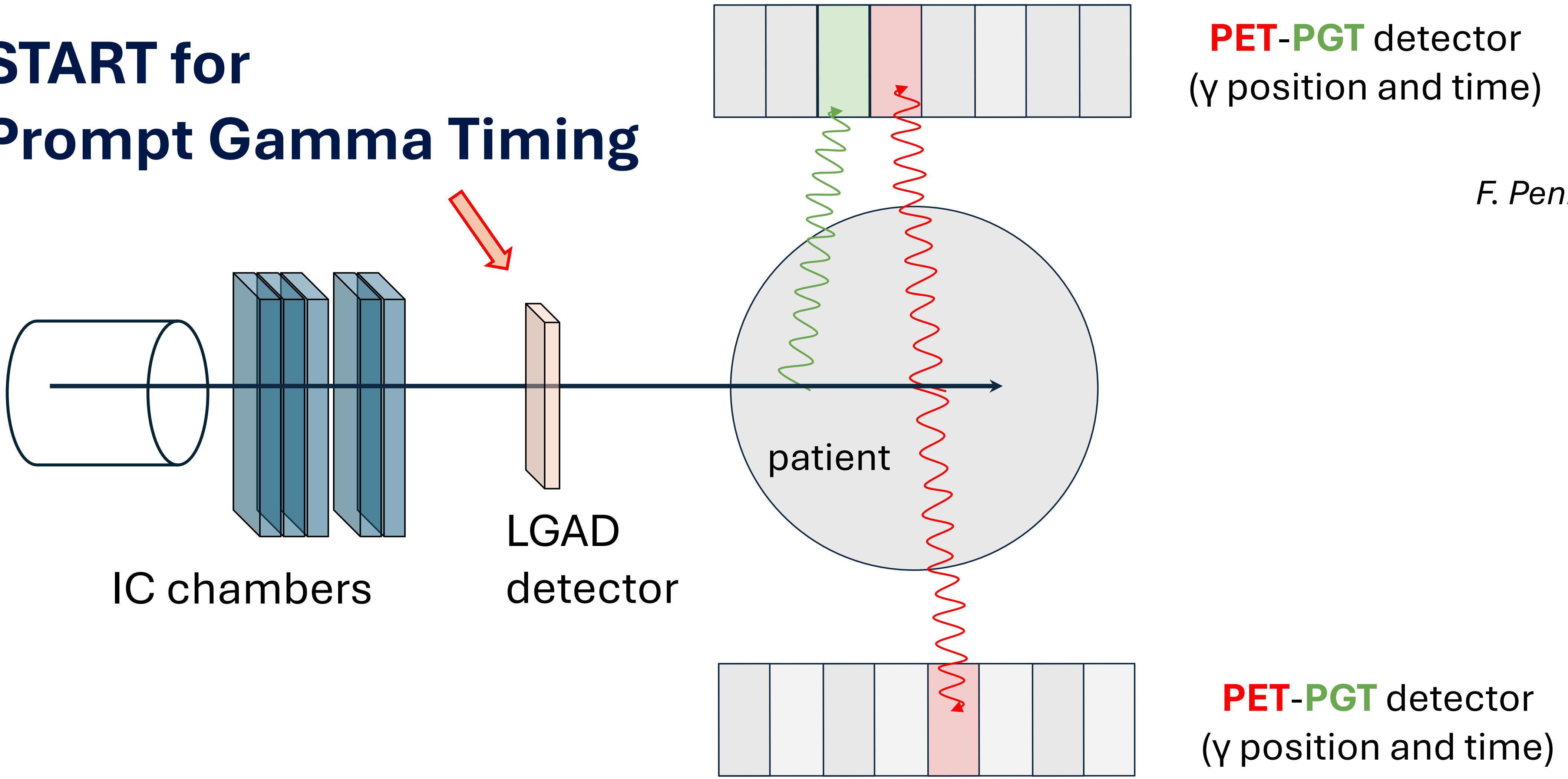
The bunch structure and the accelerator radiofrequency were observed for all the energies.





Timing application (iii): Start time for Prompt Gamma Timing

START for
Prompt Gamma Timing



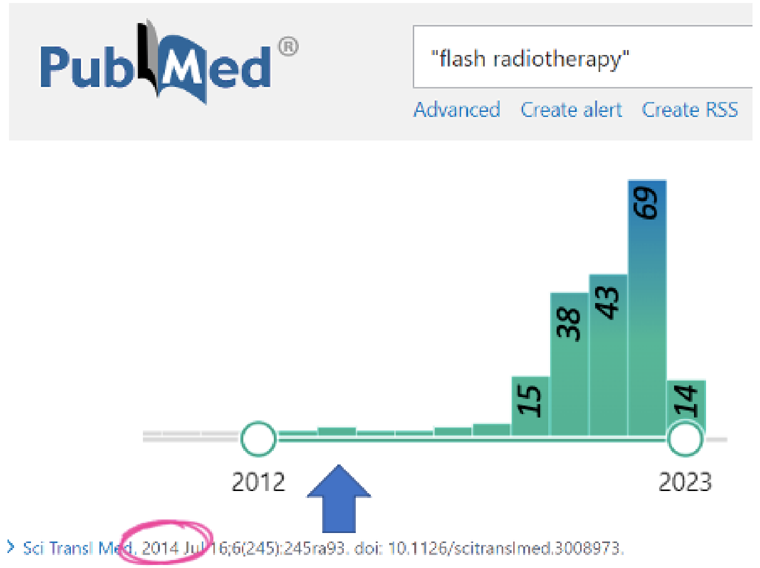
F. Pennazio's talk

Exploiting thin silicon sensors for FLASH RT

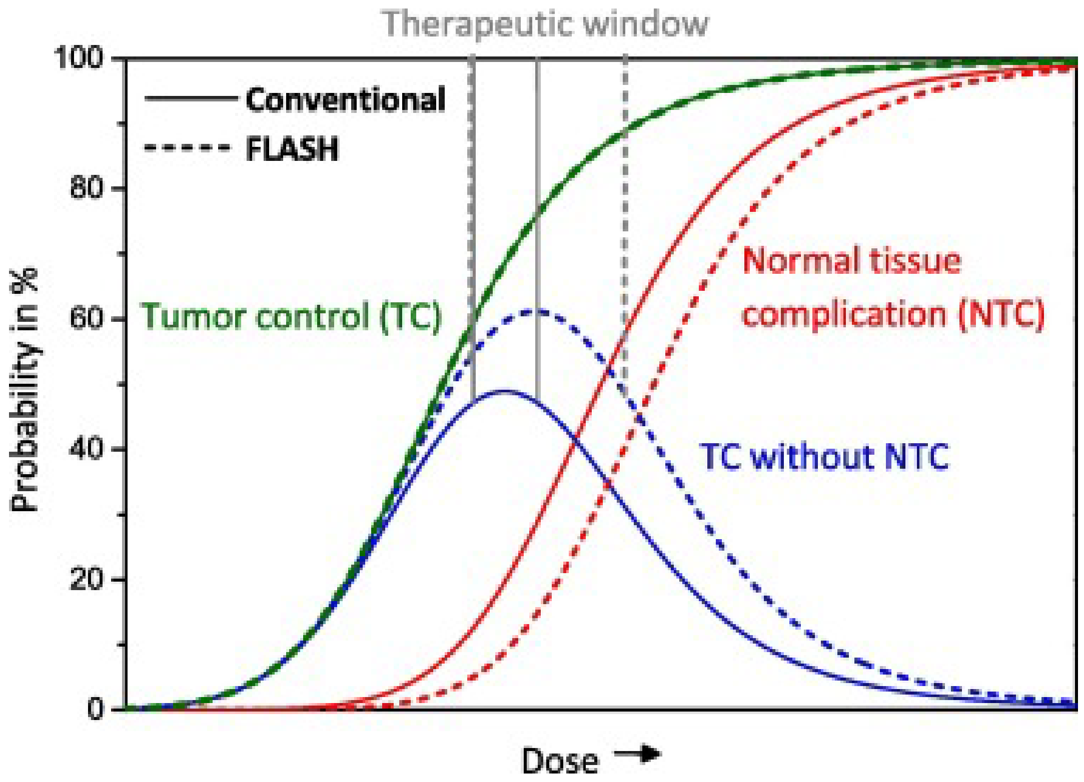
FLASH radiotherapy

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

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



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



FLASH radiotherapy

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

- 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)

New field for BM: FLASH RT

*Interrupting a FLASH treatment quickly enough to avoid a misadministration is clearly a non-trivial task and **no publicly available testing data exist showing a commercial system is able to stop delivery of a FLASH dose quickly enough** to address this need. [Taylor et al. Med Phys. 2022]*

Main Challenges

- *Ultra High Dose Rate and high dose deliveries --> Reproducibility and interlock activation*

*Only the dependence on the average dose rate and on the duration of the entire irradiation has been clearly observed so far, but **the roles of…***
- ***Dose per pulse***
- ***Instantaneous dose per pulse***
- ***Pulse duration and frequency***

***.. still remain to be understood**.*
[Di Martino 2020 frontiers]

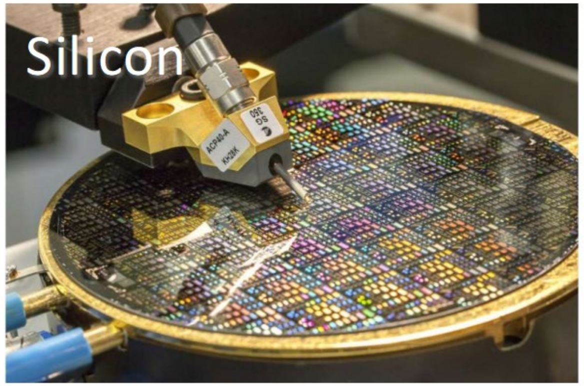
Main Requirements

- *Linearity and no saturation*
- *Radiation hardness*

Possible solutions

- *Introduction of correction factors*
- *Optimization of the existing technologies*
- *Investigation of novel detection methods*

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

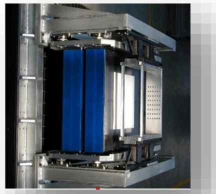
- High electrical stiffness, speed of charges, melting T, thermal diffusivity, industrual maturity
- Preliminary sim: dose-rate linearity up to 10^{11} Gy/s on X-ray beams for SiC membrames (2 μm thick)

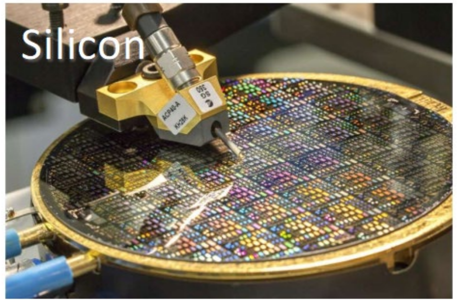
STLAB

Silicon sensors for FLASH RT beam monitoring

Conventional IC used in LINACs

Ionization chambers





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

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 • high dose rates (FLASH)	New applications • Monitoring high intensity and pulsed beams (high dose rates needed for FLASH RT)

Main issues

High dose rates (FLASH)
→ 10^3 × dose rates
→ plasma effects in silicon

Radiation tolerance
→ manufacturing strategies
→ damage compensation

Monitoring of FLASH UHDR electron beams

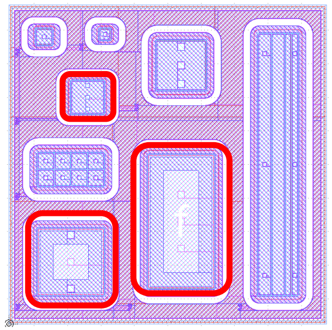
INFN-FRIDA project
2021-2024

UNIVERSITÀ DI TORINO — INFN Istituto Nazionale di Fisica Nucleare

ElectronFlash accelerator (CFR - Pisa)

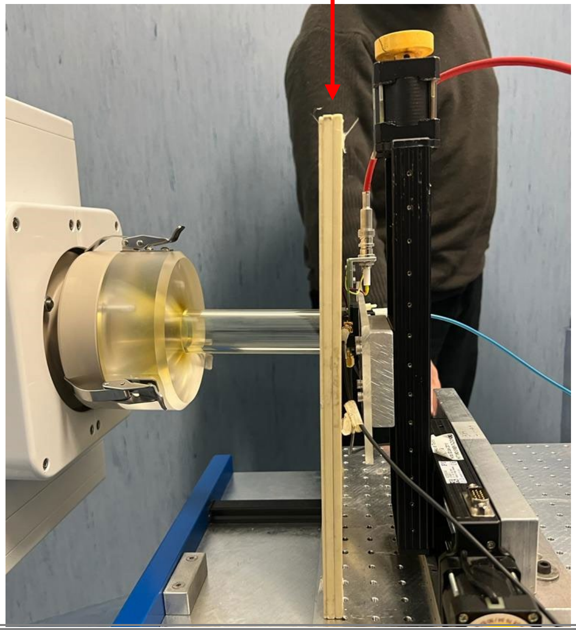
- **9 MeV** electrons pulsed beam
- Beam current: **1-100 mA**
- Pulse duration: **4 μs**
- Pulse frequency: **5 Hz**
- Uniform fields using 3 cm PMMA plastic applicator

Sensors tested

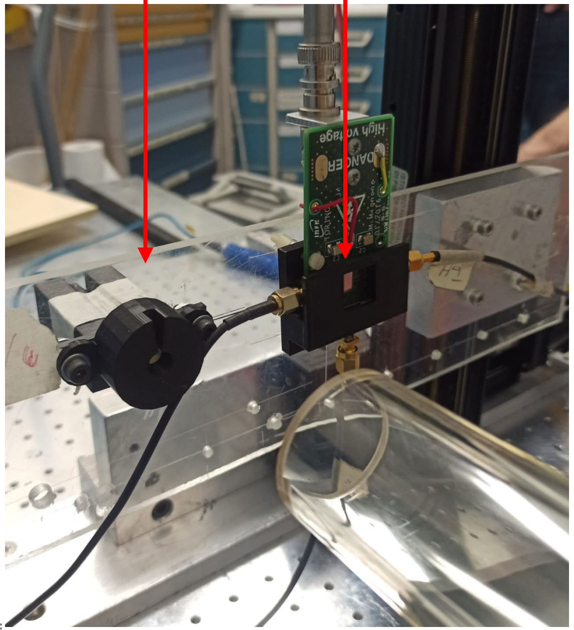


- **45/ 30μm** thickness
- **2/1/0.25 mm^2** area
- Bias voltage: **10V ÷ 200V**
- Dose/Pulse **0 ÷ 10Gy**

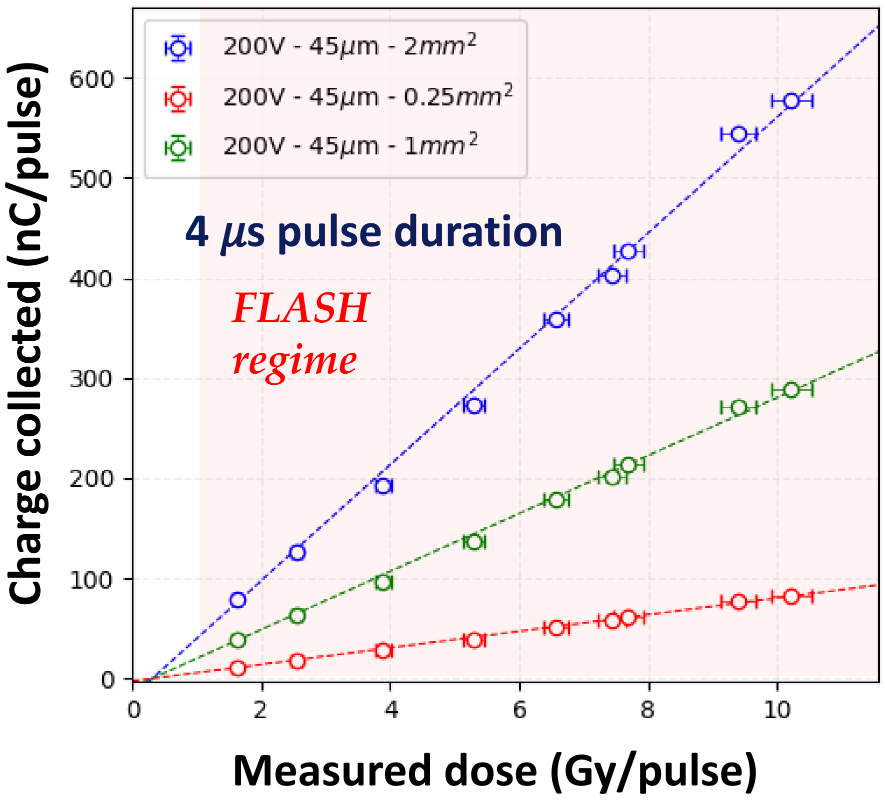
13mm solid water slab

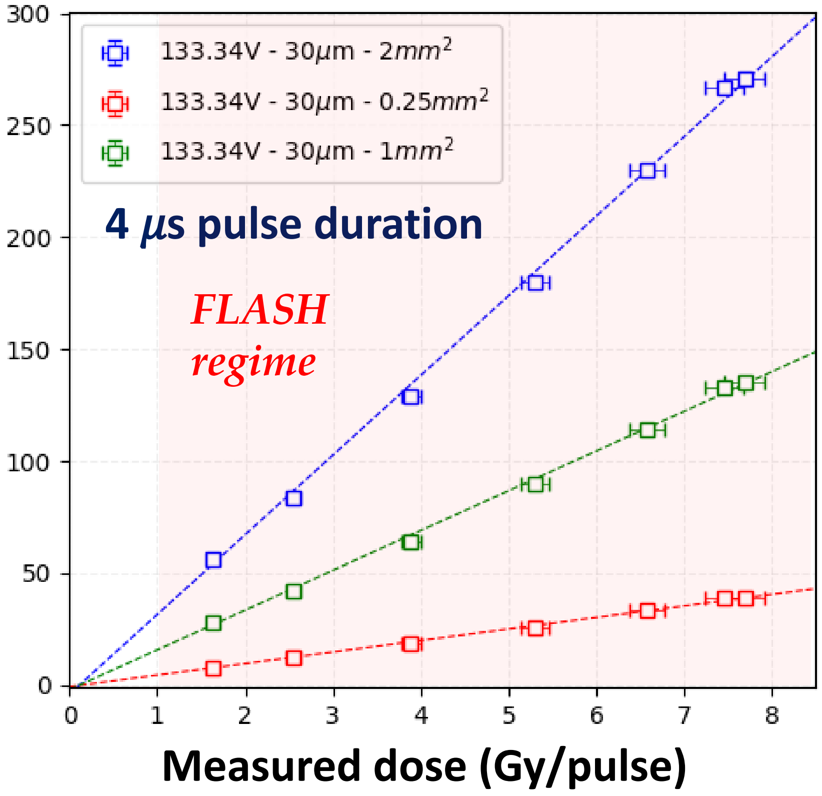


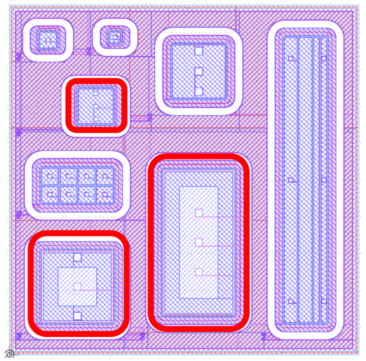
Flash diamond and silicon sensor in same conditions



Monitoring of FLASH UHDR electron beams



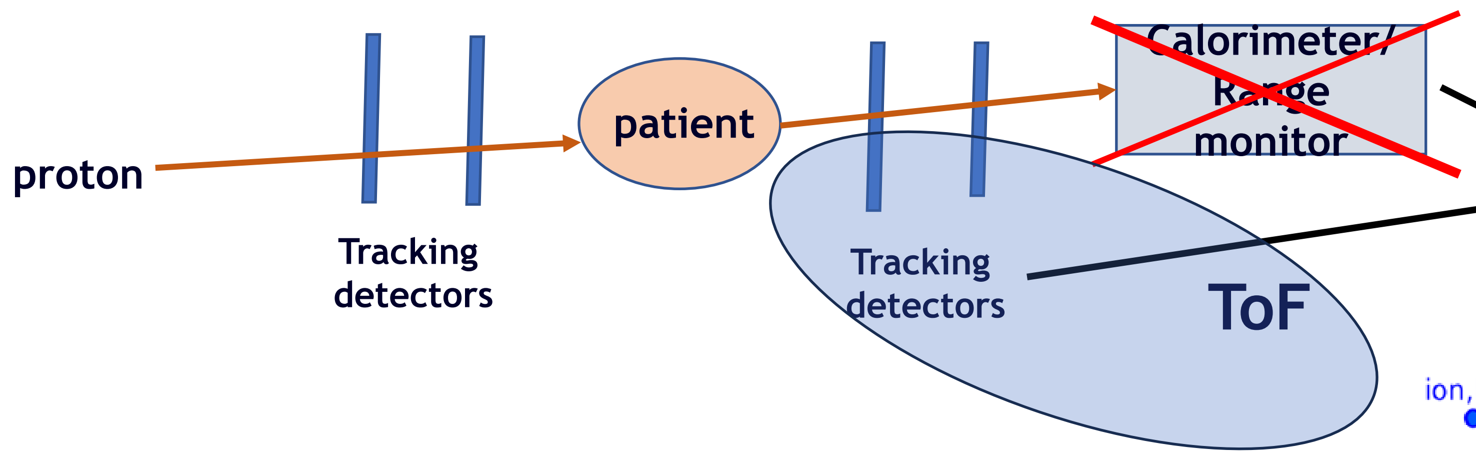




- Collected charge/pulse **scales** with **pad area** and **sensor thickness**
- **Ratios** between different area/thickness **independent from dose/pulse**

4D-tracking with LGADs for proton Radiography&CT

Measurement of residual proton energy from ToF in pCT applications

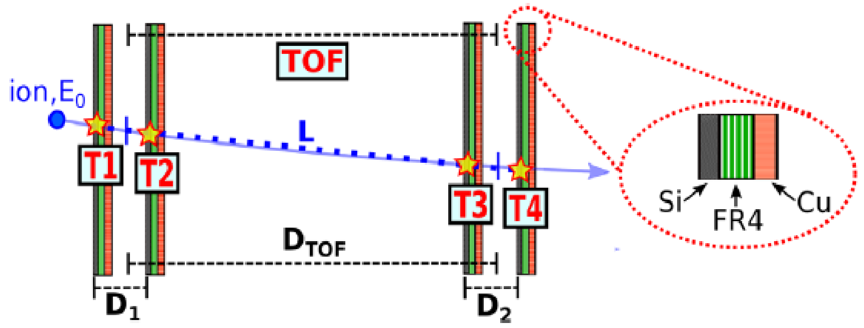


Feasibility study of a proton CT system based on 4D-tracking and residual energy determination via time-of-flight

Felix Ulrich-Pur[1], Thomas Bergauer[1], Alexander Burker[2], Albert Hirtl[2], Christian Irmler[1], Stefanie Kaser[1], Florian Pitters[1] and Simon Rit[3]

[1] Austrian Academy of Sciences, Institute of High Energy Physics (HEPHY), Nikolsdorfer Gasse 18, A-1050 Wien, Austria
[2] TU Wien, Atominstitut, Stadionallee 2, A-1020 Wien, Austria
[3] Lyon University, INSA-Lyon, University Lyon1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR5220, U1206, France

Phys. Med. Biol. 67 (2022) 095005



Schematic of a TOF calorimeter based on LGAD detectors. The TOF is measured between two timing stations (T1/T2 and T3/T4), each consisting of two generic LGAD planes

Summary and Conclusions

Specific optimization of
sensors,
frontend readout,
high performance DAQ,

tailored on specific
applications
(counting, timing, imaging,
dosimetry, radiobiology, ...)

> 24x24 cm^2 Si-based beam monitor in clinical nozzle

Conclusions

- Silicon detectors offer interesting features for new developments in radiation therapy
- For 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

Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI TORINO

Spare slide

Hybrid microdosimeter exploits silicon sensors tracking capability

A Novel Hybrid Microdosimeter for Radiation Field Characterization Based on the Tissue Equivalent Proportional Counter Detector and Low Gain Avalanche Detectors Tracker: A Feasibility Study

https://doi.org/10.3389/fphy.2020.578444

Front. Phys., 11 February 2021
Sec. Radiation Detectors and Imaging

Figure 2

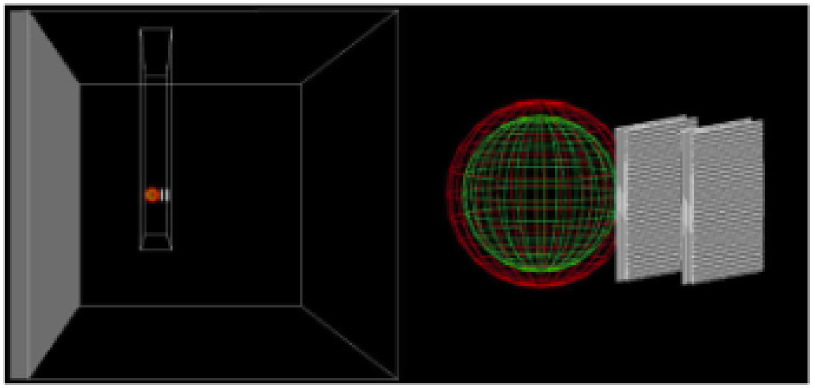


FIGURE 2. 3D scheme of the geometry used for all Geant4 simulations. Both the TEPC and the four 24-strips LGADs are contained in PMMA box filled with air. The box is placed inside a water phantom, whose walls are made of PMMA. A broader view is show in left panel, while a zoom on HDM is illustrated in right panel.

Imaging with protons and ions →

proton/ion radiography
proton/ion Computed Tomography

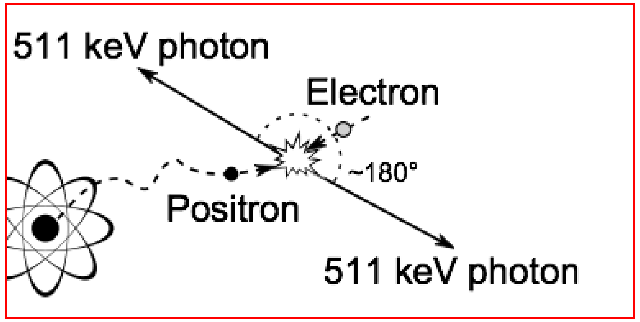
→ needed to reduce uncertainty in the water equivalent path, density

→ measure the residual proton energy
→ measure directly the Stopping Power 3D distribution

will take advantage from 4D particle tracking through silicon sensors

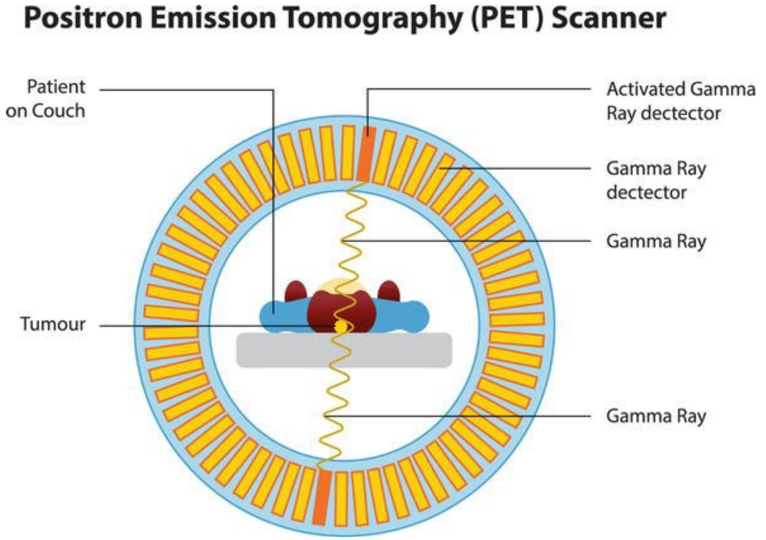
Imaging with e+

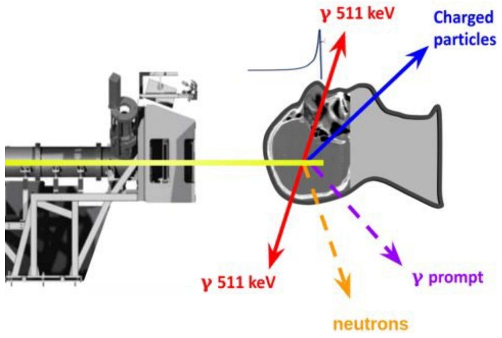
Arrays of photon detectors around the patient to detect the 2 γ opposite directions

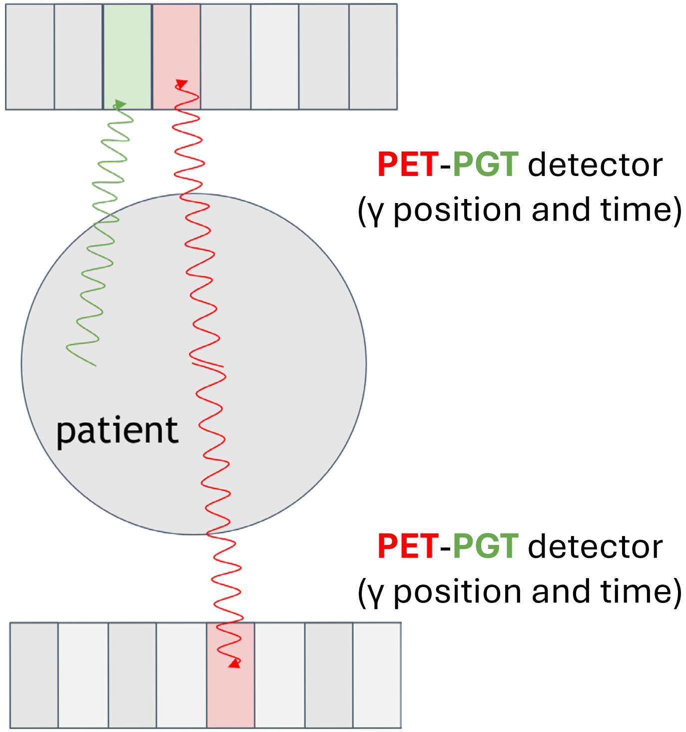


- Therapeutic hadron beams produce β^+ emitters in the body
- Offline and in-beam PET provide the range of particles and the dose distribution

For diagnostic purpose







Advanced Imaging with Phase-Contrast X-ray imaging for medical imaging

If interpreted as waves, X-rays-just like visible light-experience a phase shift in matter, and this-if exploited correctly-can produce a new class of X-ray images, which then depict the wave interactions of X-rays with matter, rather than only the attenuating properties, as done until now.

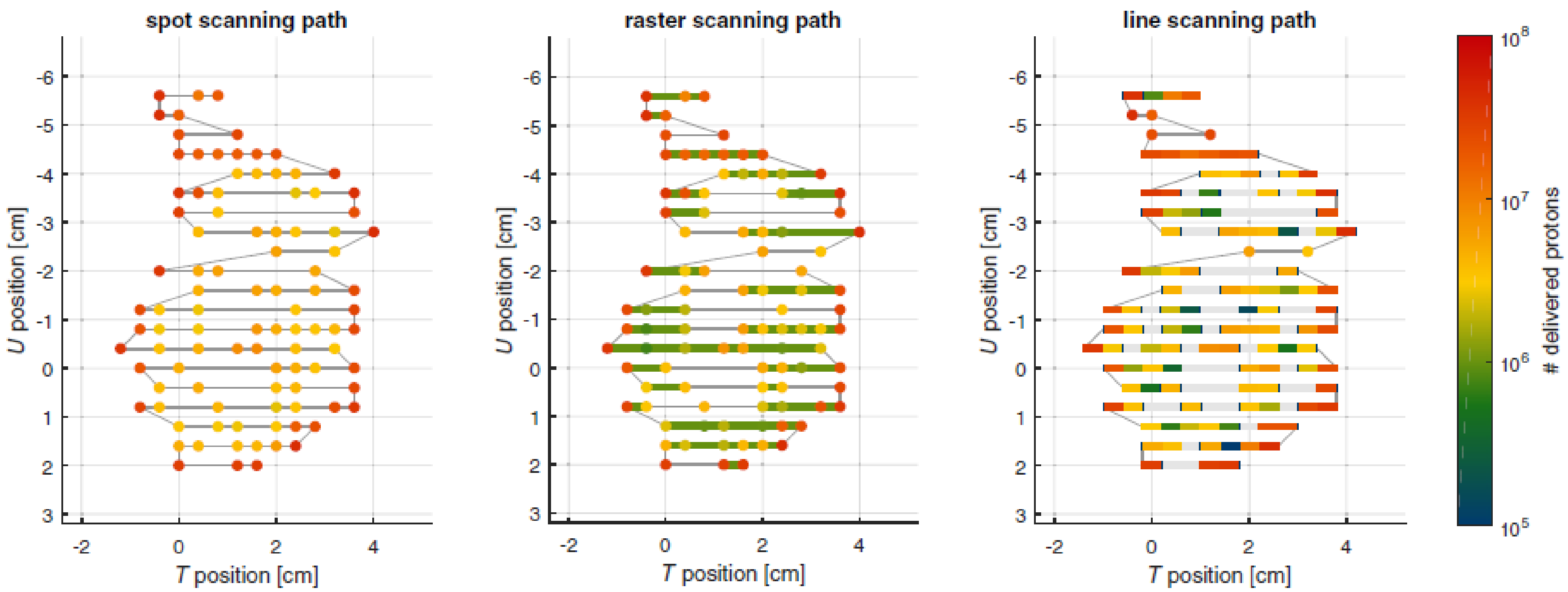
Grating Interferometry
can be performed both at Synchrotron Radiation (SR) facilities and using laboratory X-ray sources.
Until now, GI has been applied in a laboratory setting
mostly with low-brilliance X-ray tubes, by using either long or compact interferometer arrangements [1,3,4]. Liquid-metal-jet sources, combined with a phase and an analyzer grating, improve the resolution and sensitivity of PCI, thanks to a higher photon flux [5]. GI systems at 25 keV [6] and 9.25 keV [7] yield reduced scan times or an improved signal to noise ratio;

The use of a high granularity detector pushes the resolution down to the micron scale.
X-ray sCMOS camera

Future Developments in Charged Particle Therapy: Improving Beam Delivery for Efficiency and Efficacy

Jacinta Yap[1], Andrea De Franco[2] and Suzie Sheehy[1]*

[1] School of Physics, University of Melbourne, Melbourne, VIC, Australia, [2] IFMIF Accelerator Development Group, Rokkasho Fusion Institute, National Institutes for Quantum Science and Technology, Aomori, Japan



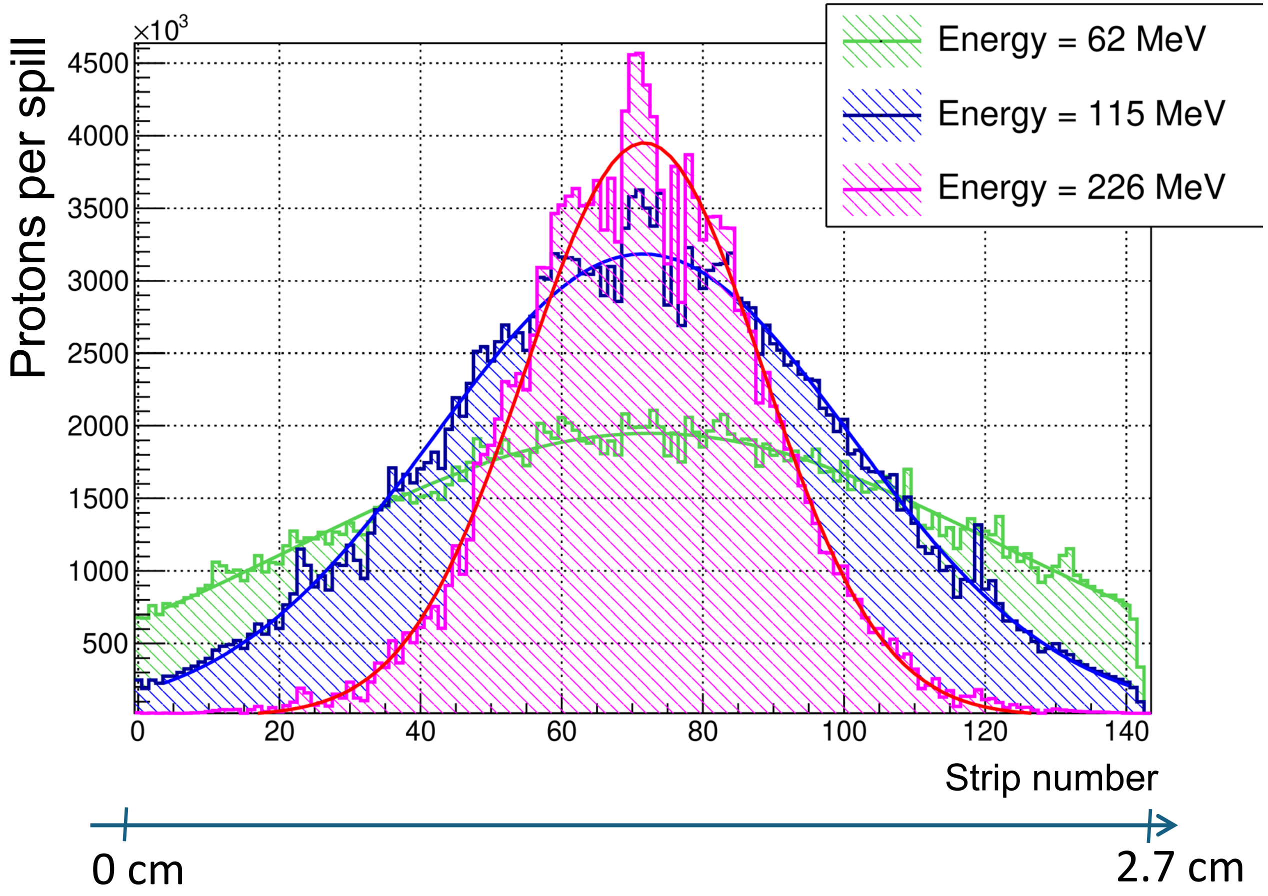
Phys. Med. Biol. **63** (2018) 145006

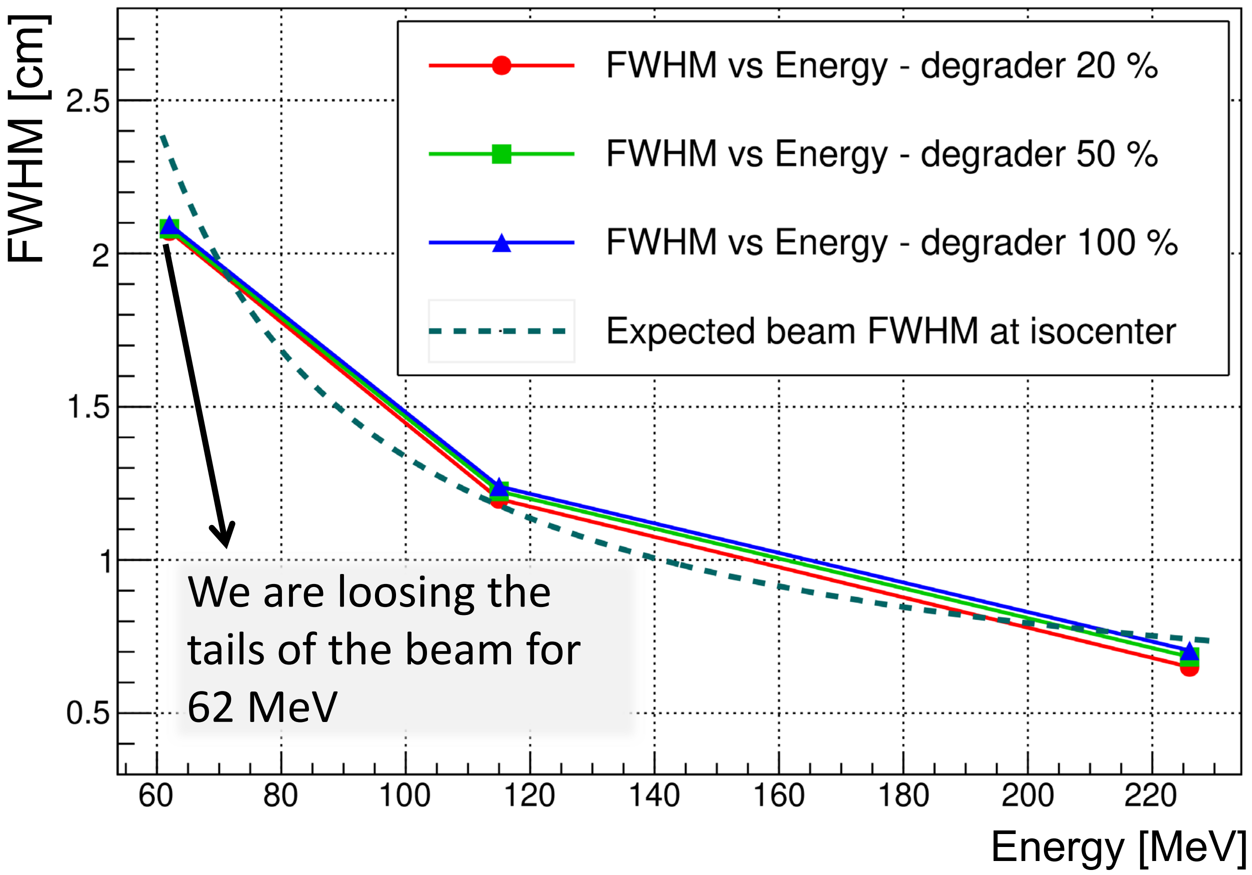
- Scan paths for: spot scanning, raster scanning and line scanning
- Iso-energy slice (E = 151 MeV)
- Beam weights were optimized for a total field dose of 0.606 Gy

REVIEW
Frontiers - 2021
doi: 10.3389/fonc.2021.780025

«The possibility of volumetric rescanning and other advanced techniques require the BDS to be able to deliver efficiently with fast energy modulation.»

Protons - beam projection on y axis





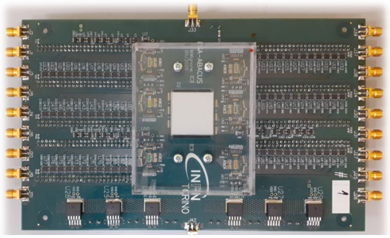
- **The lower the energy** and **the wider the beam** because of multiple scattering of protons with air
- **Curves →** Gaussian fit

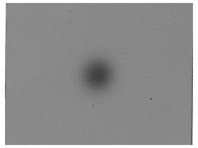
$$FWHM = 2\sqrt{2\ ln(2)}\ \sigma_{Guaussian\ fit}\ .\ p$$

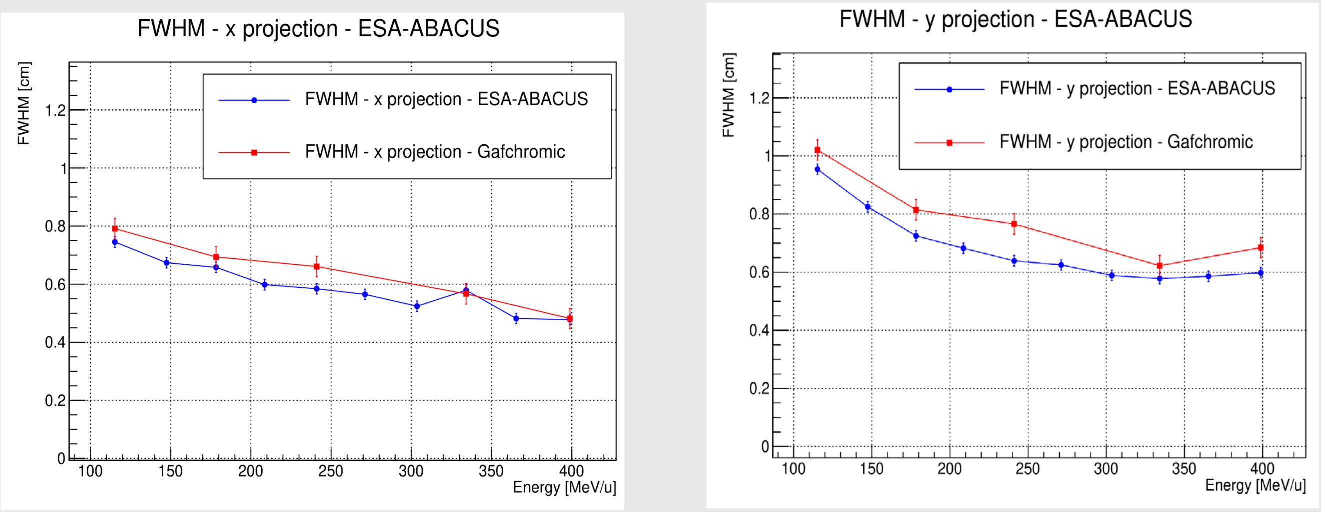
Strip pitch = 180 µm

Expected FWHM at isocenter from
Mirandola et Al 10.1118/1.4928397

C-ions counter

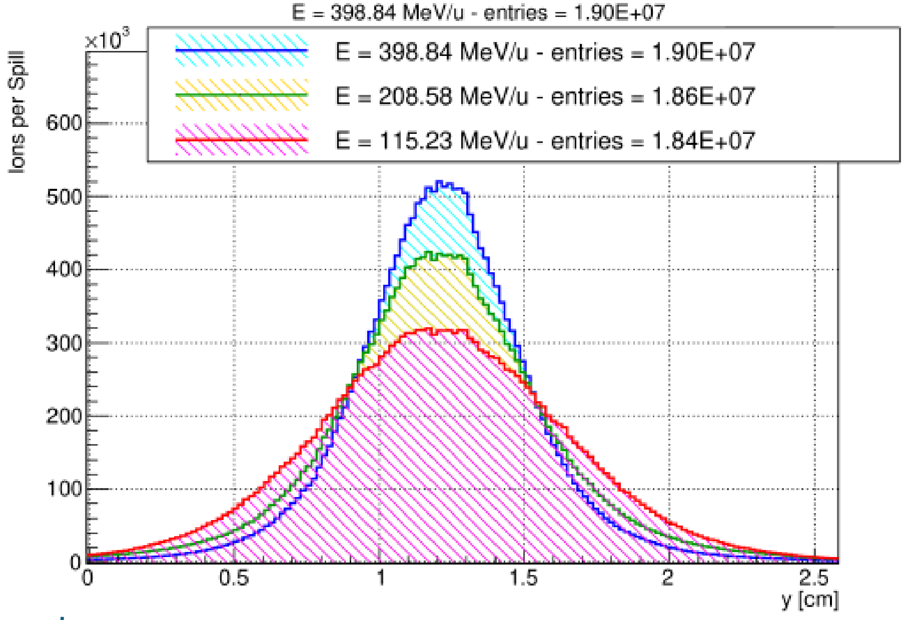






Comparison of beam FWHM with GAFCHROMIC films

Carbon Ions



0 cm

2.7 cm

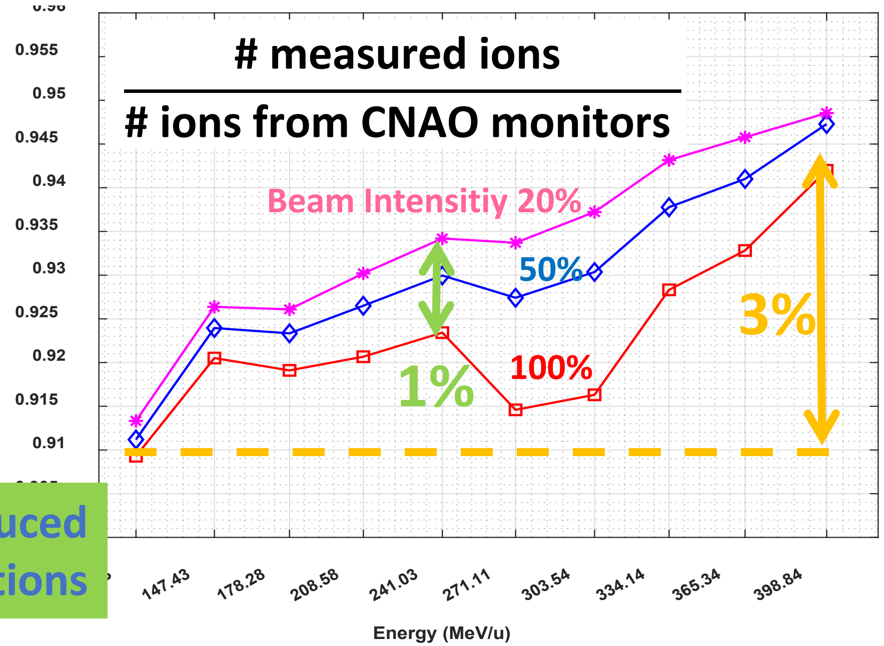
Spots of **5*10^7** C ions

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



Beam monitor systems

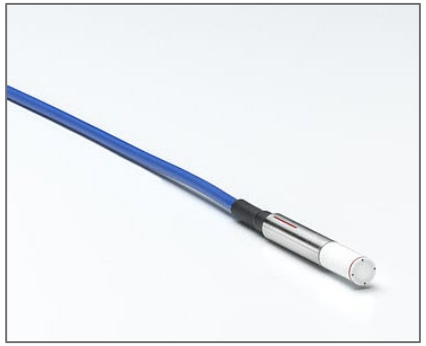
- Continuous check of beam parameters
- **IC CONV**: Gas-filled IC → **IC UHDR** : high rate of recombination, too slow
- Need of **new beam monitoring device** to stop delivery of a FLASH dose **quickly enough**

Conventional IC used in LINACs

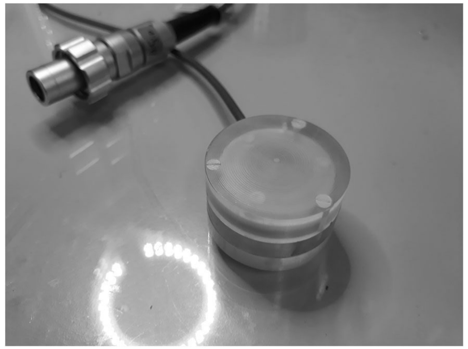
- High temporal resolution
- High spatial resolution
- Beam transparency
- Large response dynamic range
- Large sensitive area
- Radiation hardness

Existing technologies

DOSIMETERS

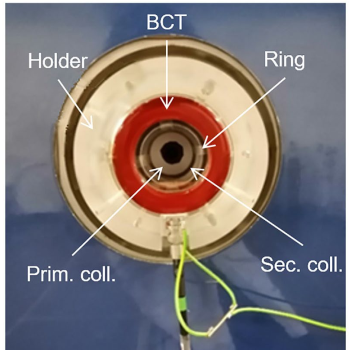


PTW 60019 microDiamond



Ultra-Thin Ionization chamber (UTIC)

BEAM MONITOR



Beam Current Transformers (BCT)

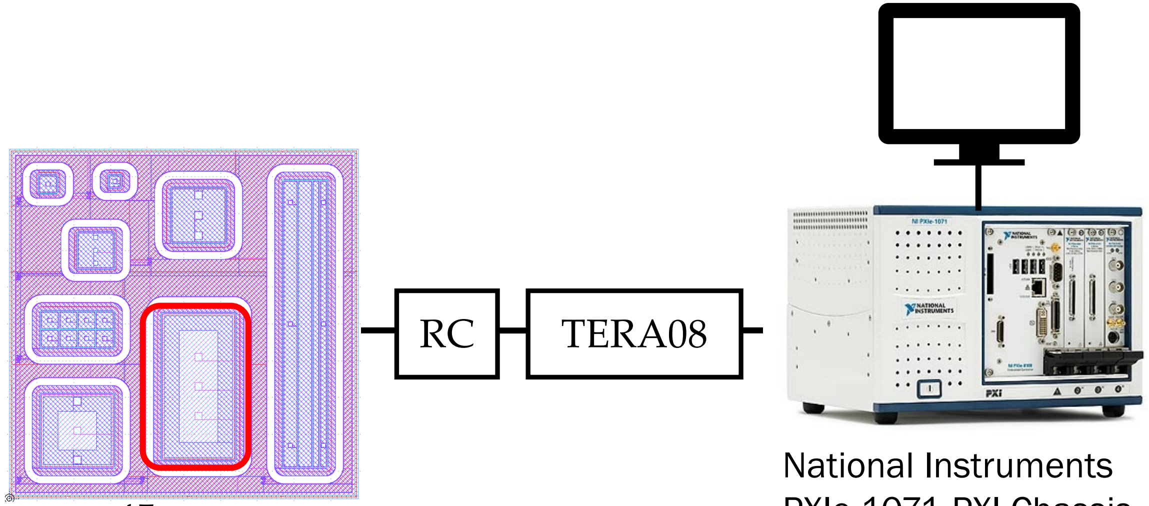
Experimental setup

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

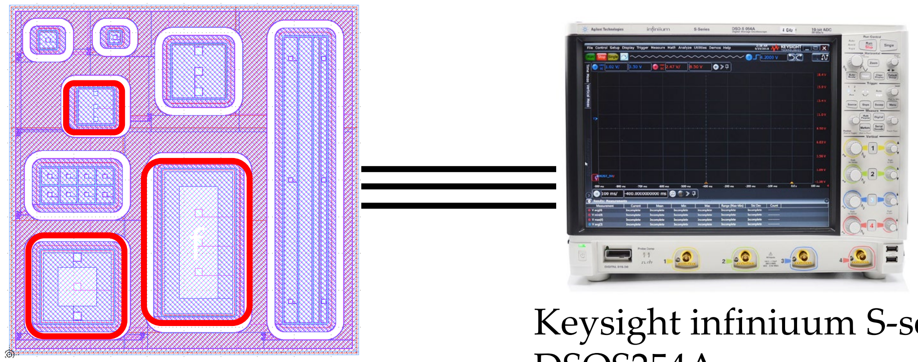
Oscilloscope measurements

- 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

National Instruments PXIe-1071 PXI Chassis

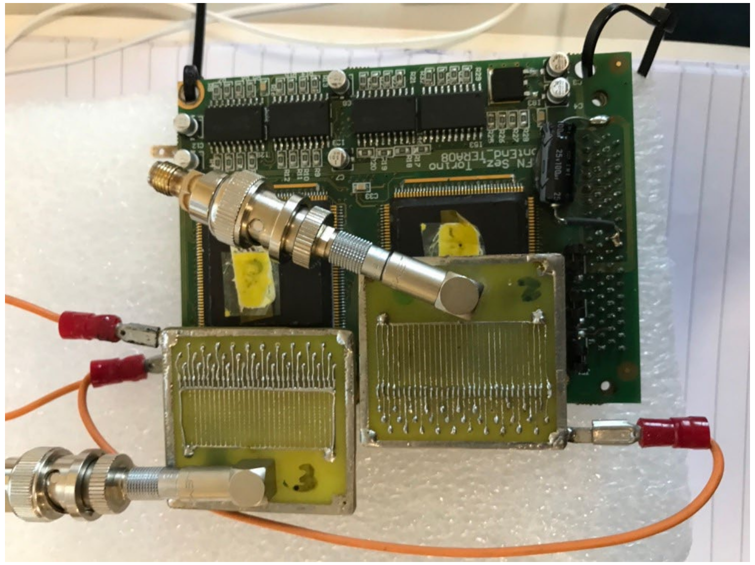


30/45μm

Keysight infiniuum S-series DSOS254A

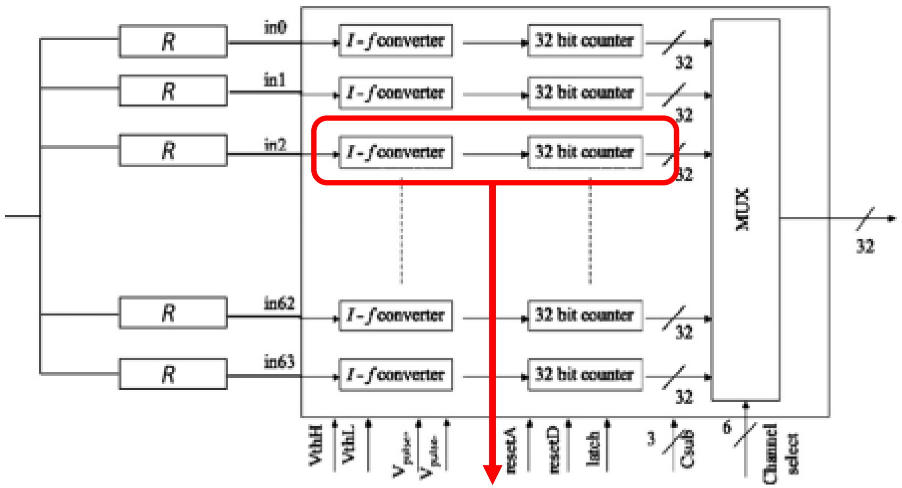
Readout system: TERA08

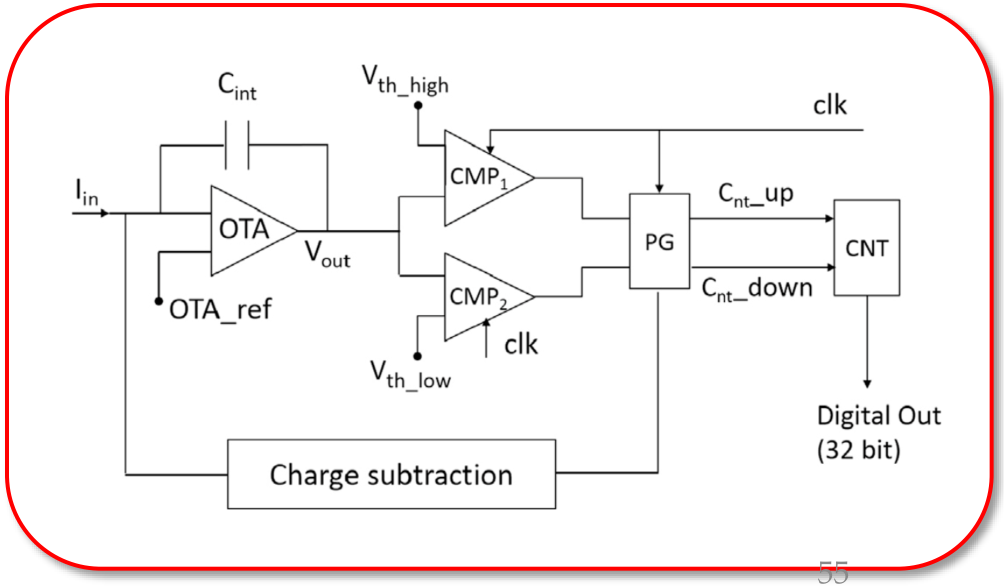
- Readout with **TERA08** (64 equal CHNs)
- In each CHN **current-to-frequency converter** (each digital pulse = fixed input charge quantum)
- Converter based on **recycling integrator architecture**



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

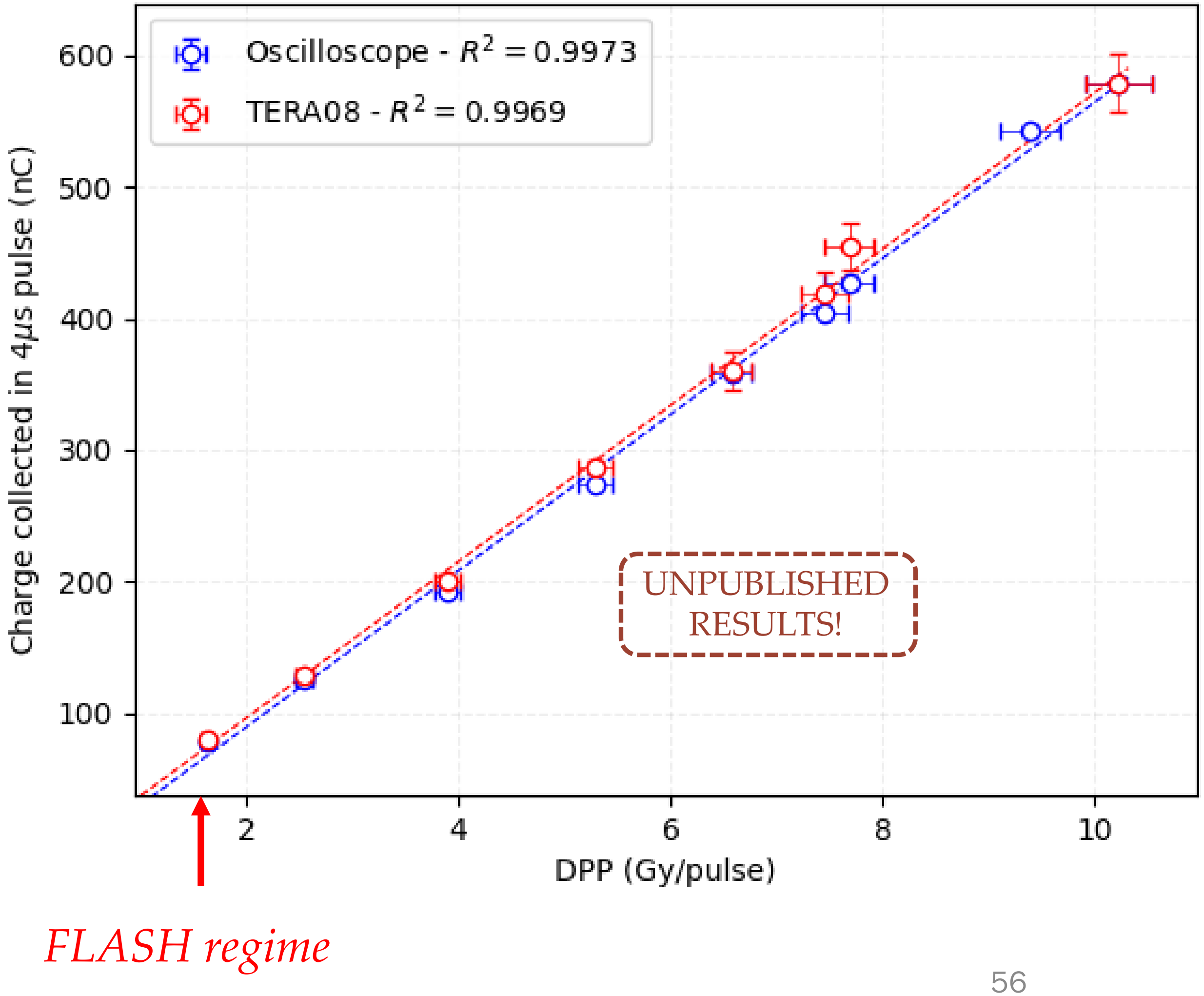
Chip structure





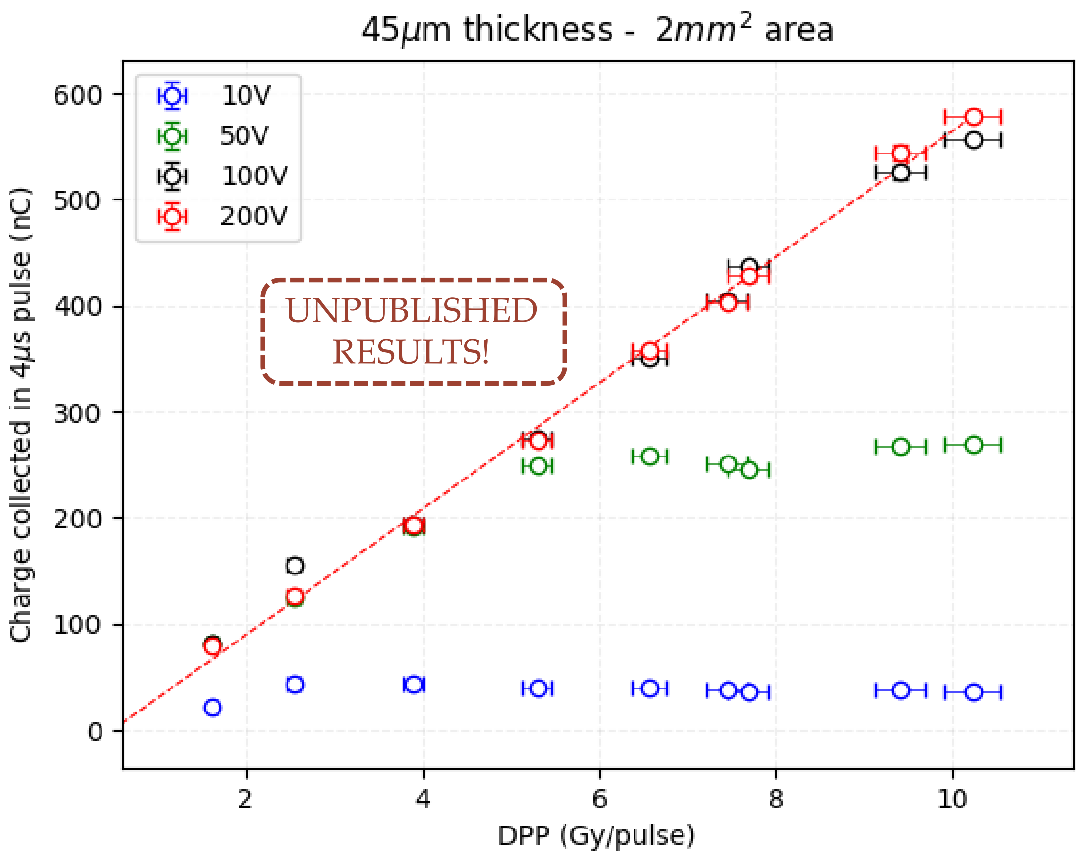
TERA08 and oscilloscope comparison

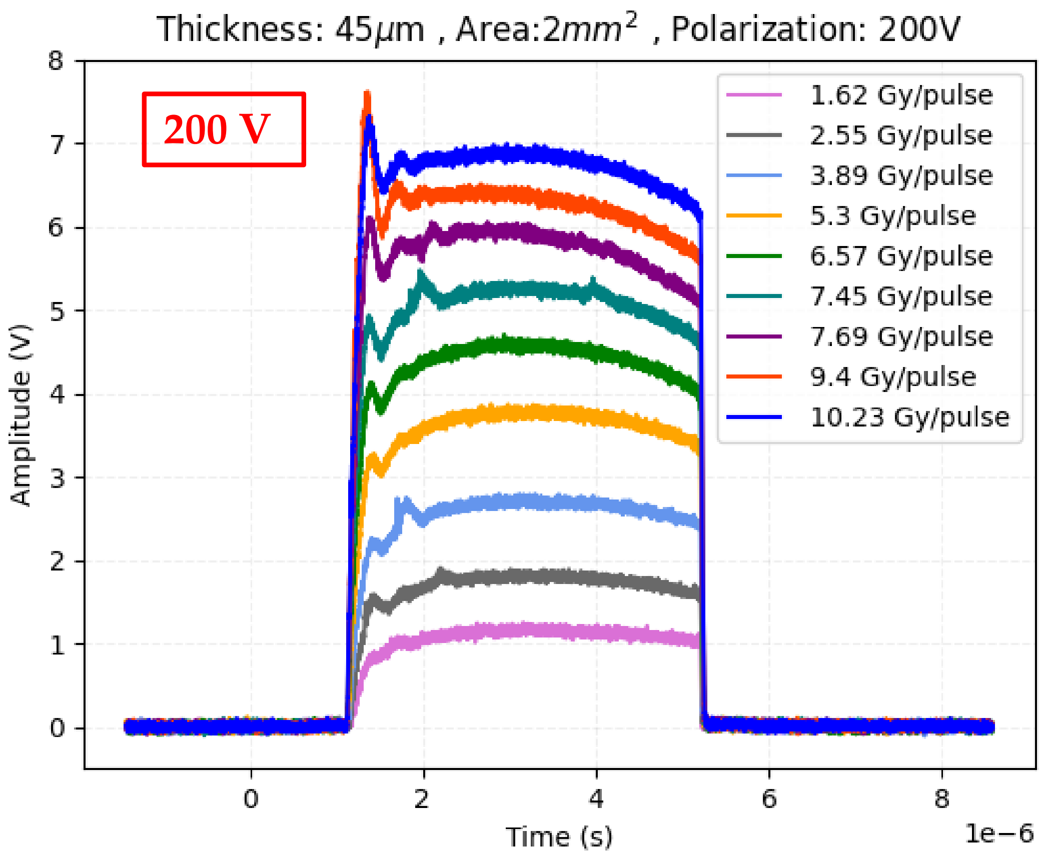
- 45 μm thickness, 2mm^2 area
- 200V bias voltage
- **Good linearity** ($R^2 > 99\%$) up to dose-rates >10Gy/pulse (1Gy/pulse is already FLASH regime)
- **Good correlation** of charge measured with TERA08 and oscilloscope



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

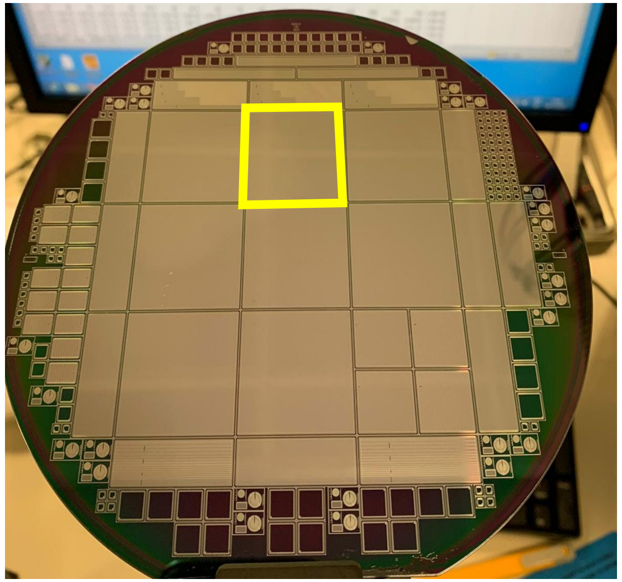




Next steps: TERA09

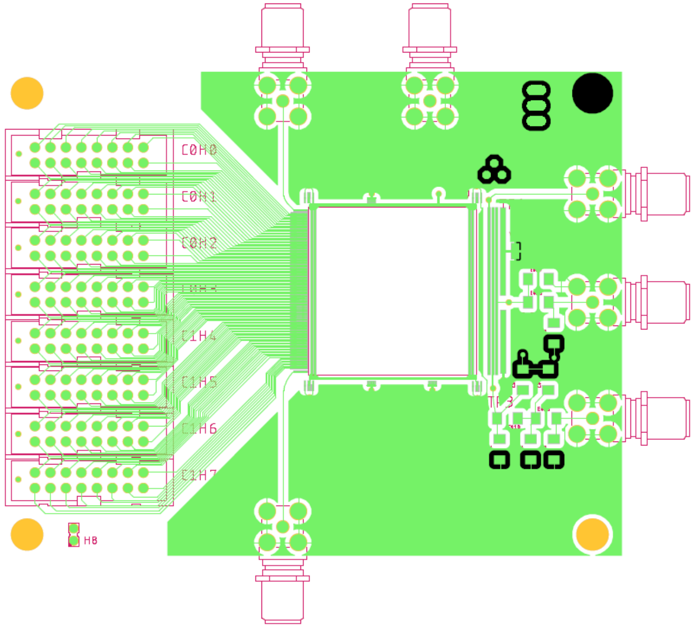
- Frontend chip based on 64 charge recycling CHNs
- **Extended current range** with respect to TERA08 (preliminary design and test phase): 12 μA / chn with 200 fC.
- Larger sensor (Area 2.7×2.7 cm^2 and 146 strips) to cover all beam spot area (~ cm^2)
- Strip based / pad based system: **Online control**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

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