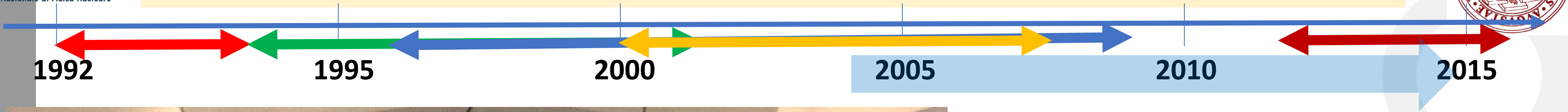
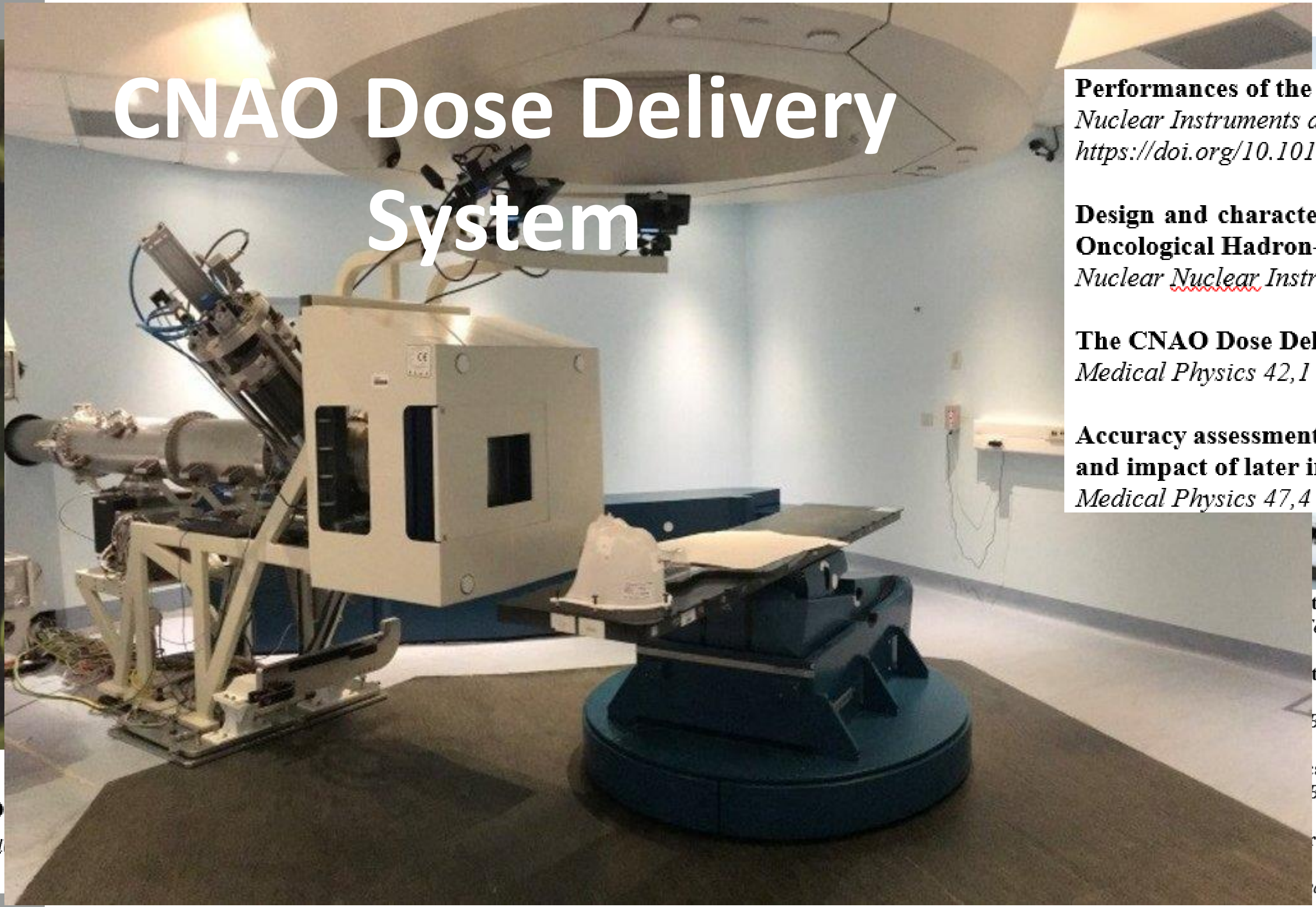
Innovative detectors for beam monitoring in particle therapy

Prof. R. Sacchi – University of Torino and INFN

IN2P3 – CNAO Proposition of collaborative research topics Workshop, 26 November 2021

A quick glance into the past ..... gas detectors





Performances of the scanning system for the CNAO center of oncological hadron therapy
Nuclear Instruments and Methods in Physics Research A 613 (2010) 317-322
https://doi.org/10.1016/j.nima.2009.11.068

Design and characterization of the beam monitor detectors of the Italian National Center of Oncological Hadron-therapy (CNAO)
Nuclear Nuclear Instruments and Methods in Physics Research A698 (2013) 202–207

The CNAO Dose Delivery System for ion pencil beam scanning radiotherapy
Medical Physics 42,1 (2015) 263

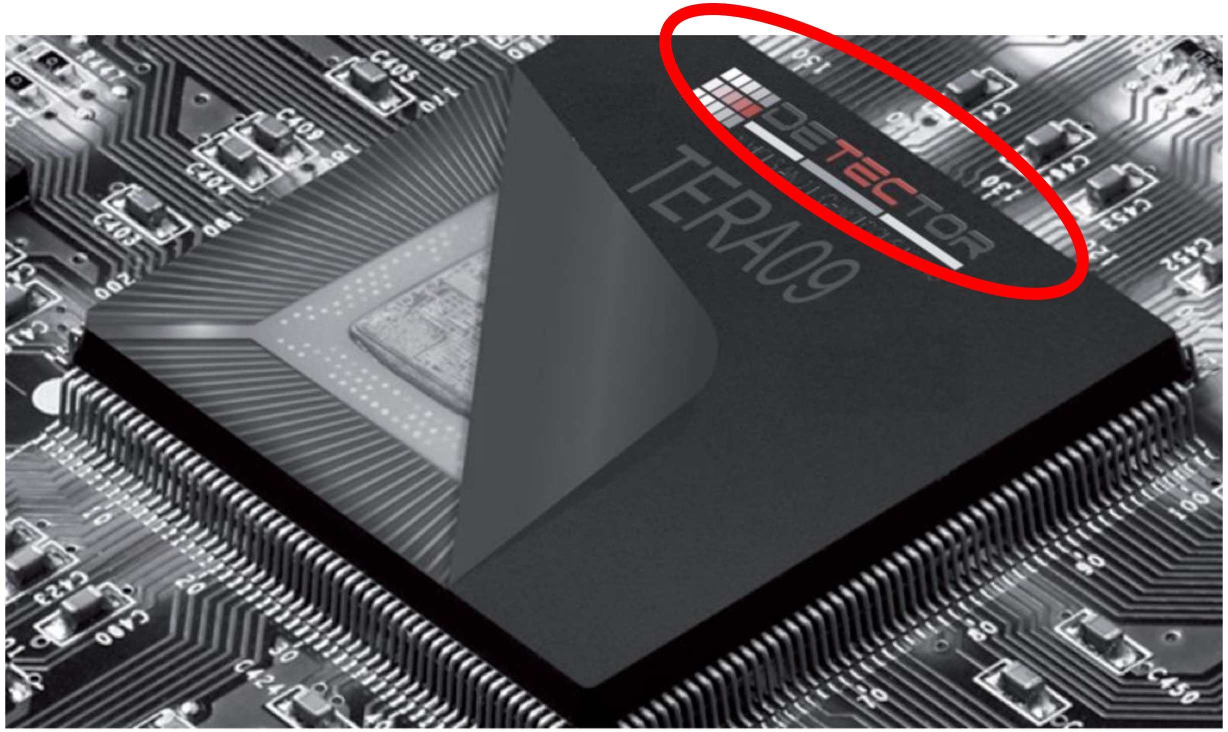
Accuracy assessment of the CNAO Dose Delivery System in the initial period of clinical activity and impact of later improvements on delivered dose distributions
Medical Physics 47,4 (2020) 1468-1480

Multi-Gap Ionization Chamber for high-flux Charged Particle Beams.
Oral presentation, AAPM 57th Annual Meeting and Exhibition
Medical Physics 42, 6 (2015) 3727

A status of the ELIMED multidisciplinary and medical beam-line at ELI-beamlines
IOP Journal of Physics: Conf. Series 777 (2017) 012016 doi:10.1088/1742-6596/777/1/012016

A quick glance into the past ..... the TERA ASIC

- 64 ch. current-to-frequency converter
- deadtime free
- good linearity from few nA to hundreds of µA



* spin-off company of UniTo (2009 ->)

Performances of a VLSI wide dynamic range current-to-frequency converter for strip ionization chambers
Nuclear Instruments and Methods in Physics Research A 405 (1998), 111-120

Radiation damage studies of a recycling integrator VLSI chip for dosimetry and control of therapeutical beams
Nuclear Instruments and Methods in Physics Research A 482 (2002) 752-760

Design and test of a 64-channel charge measurement ASIC developed in CMOS 0.35 µm technology
Nuclear Instruments and Methods in Physics Research A583 (2007) 461-468

Characterization of a front-end electronics for the monitoring and control of hadrontherapy beams
Nuclear Instruments and Methods in Physics Research A586 (2008) 270-275

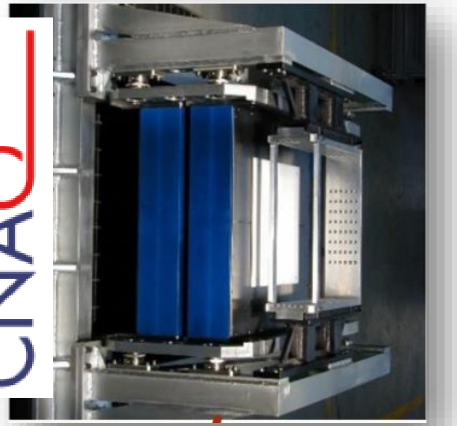
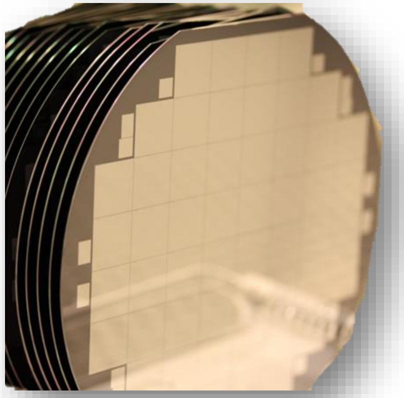
Ionising radiation effects on a 64-channel charge measurement ASIC designed in CMOS 0.35 µm technology
Nuclear Instruments and Methods in Physics Research A 593 (2008) 619-623

A simple method to increase the current range of the TERA chip in charged particle therapy applications
Nuclear Nuclear Instruments and Methods in Physics Research A 798 (2015) 107-110

Design and characterization of a 64 channels ASIC front-end electronics for high-flux particle beam detectors
Nuclear Instruments and Methods in Physics Research A 867 (2017) 1–6

Single Event Upset tests and failure rate estimation for a front-end ASIC adopted in high-flux-particle therapy applications
Nuclear Instruments and Methods in Physics Research A 918 (2019) 54–59

Solid state detectors for p beam monitoring

IONIZATION CHAMBERS		*SOLID STATE DETECTORS*
	→	
Collection times **~ 100 μs**	→	**~ ns**
Sensitivity **~ 10^4 protons**	→	**single protons**
Time resolution **~ no/poor**	→	**< 100 ps**

Not suitable for fast scanning modalities and 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

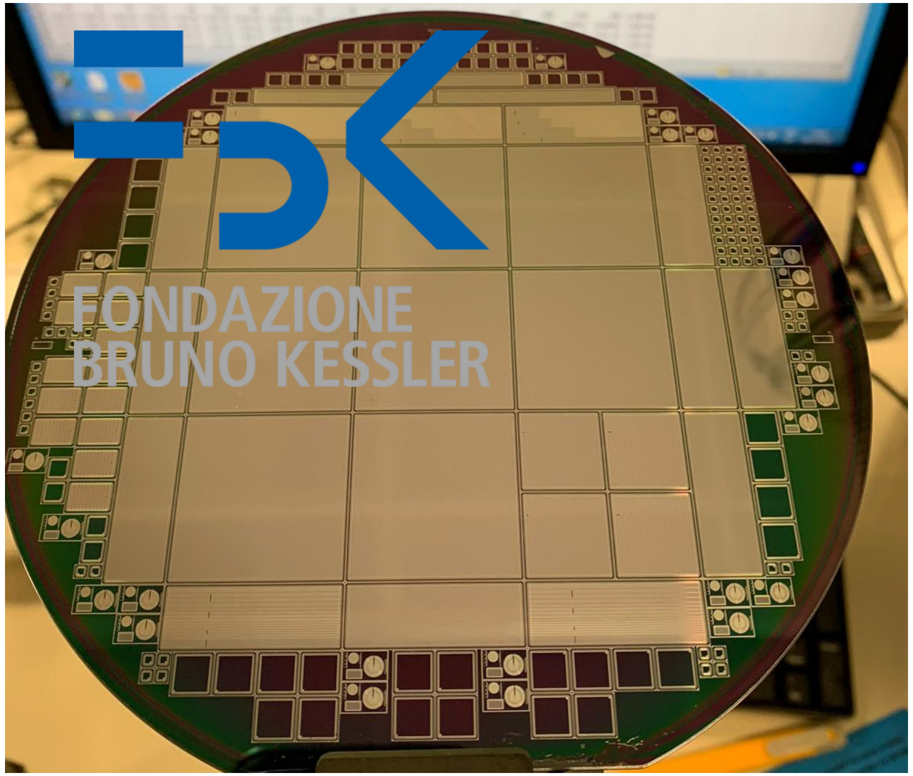
Increased complexity

Thin Low Gain Avalanche Detectors (LGADs)

- thickness of sensitive volume ~ **50 μm**
- internal charge multiplication ~ **5-20**

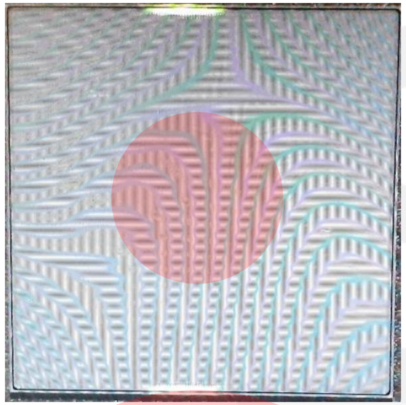
⇨ **Enhanced signal of very small duration** + **Time resolution of tens of ps**

Strip segmentation (strip area ~ 3 mm^2)



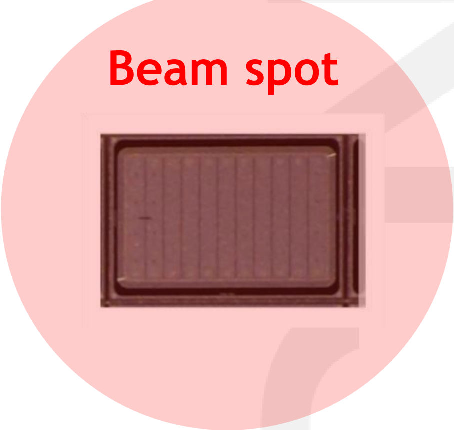
Detectors for proton counting

- Large area (2.7×2,7 cm^2)
- 146 strips



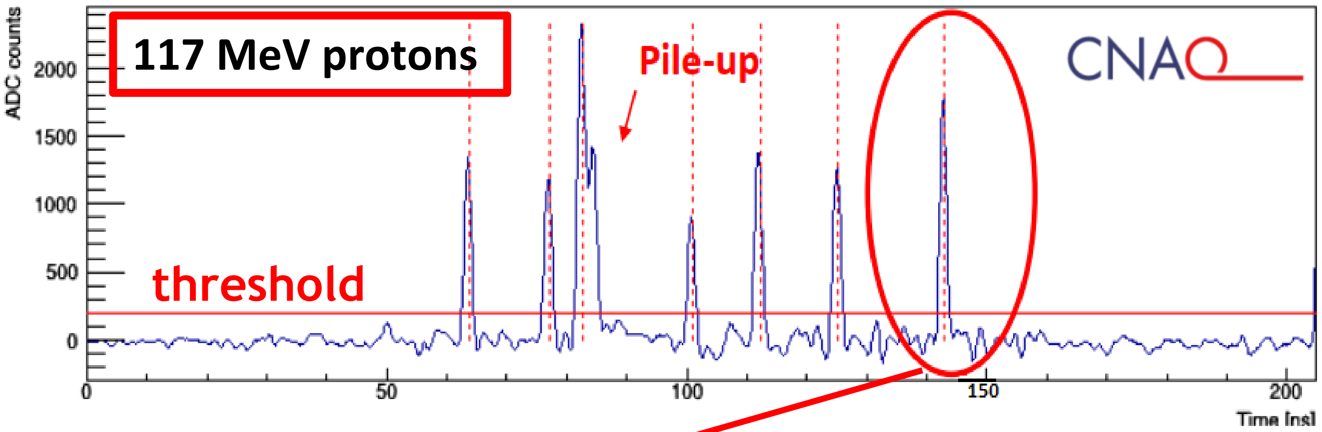
Detectors for timing applications

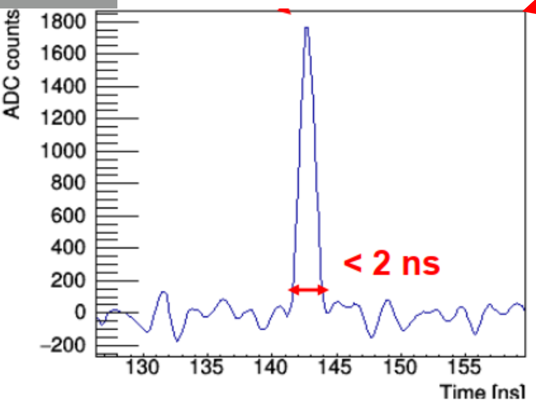
- Smaller size, 11 strips
- Si- substrate removed to reduce total thickness to 70 μm



Proton counting

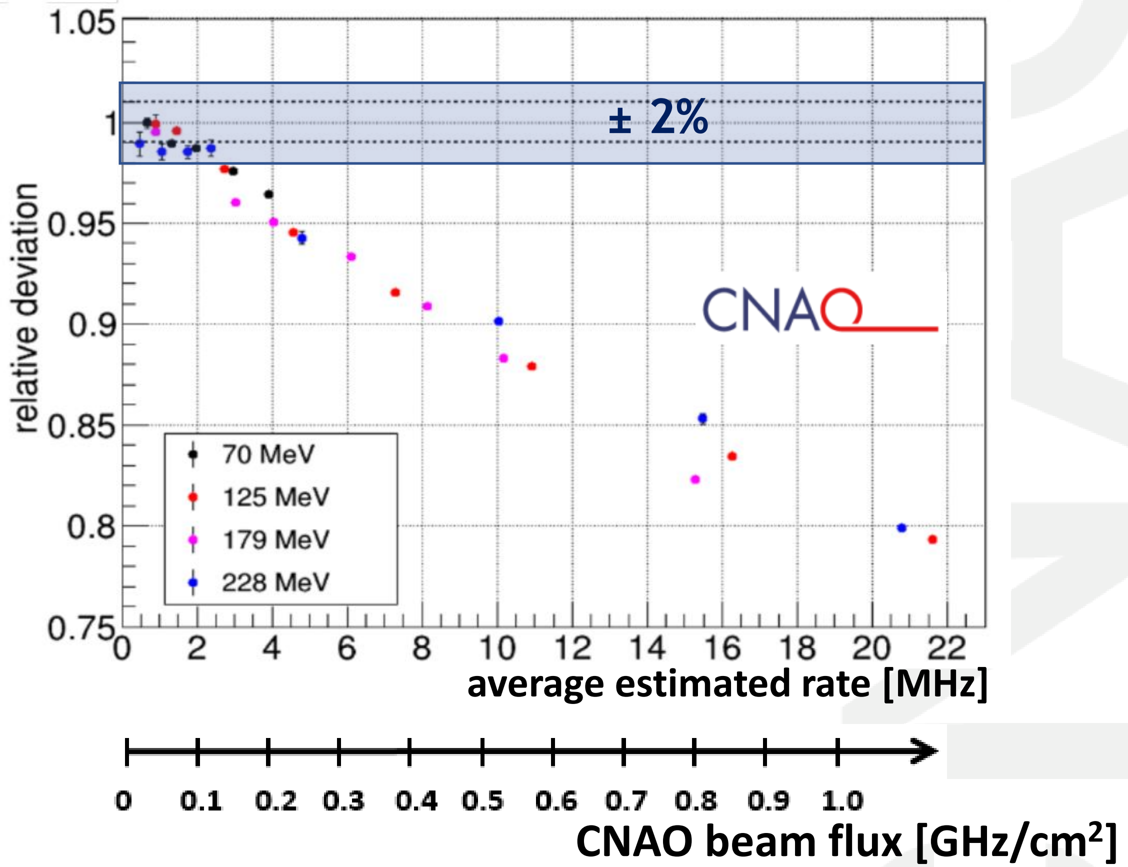
Data collected with strip sensors + digitizer





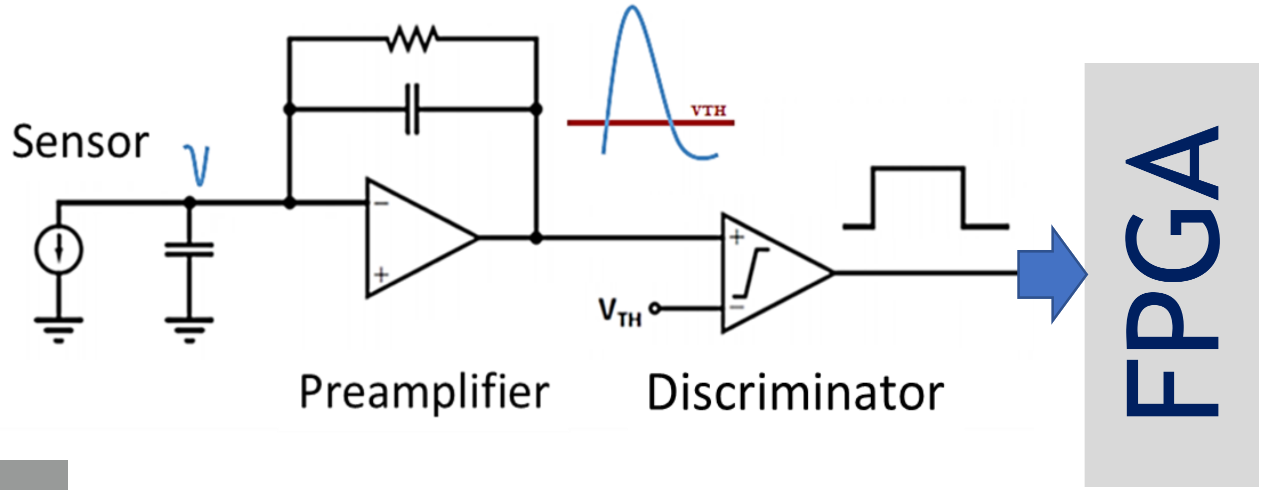
- Short peak duration
- Large Landau fluctuations
- Single particle discrimination
- Signal pile-up

Efficiency studies

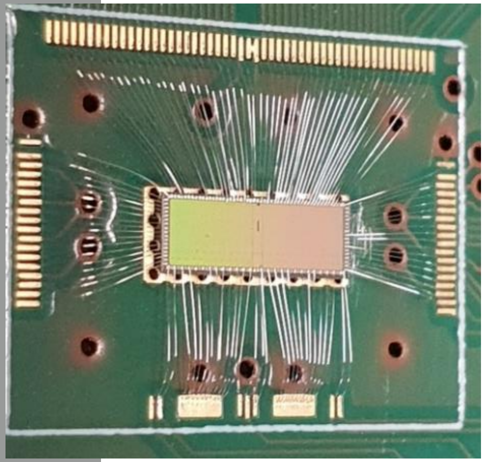


Thin low-gain avalanche detectors for particle therapy applications
J. Phys.: Conf. Ser. 1662 (2020) 012035

Fast front-end electronics for pulse counting

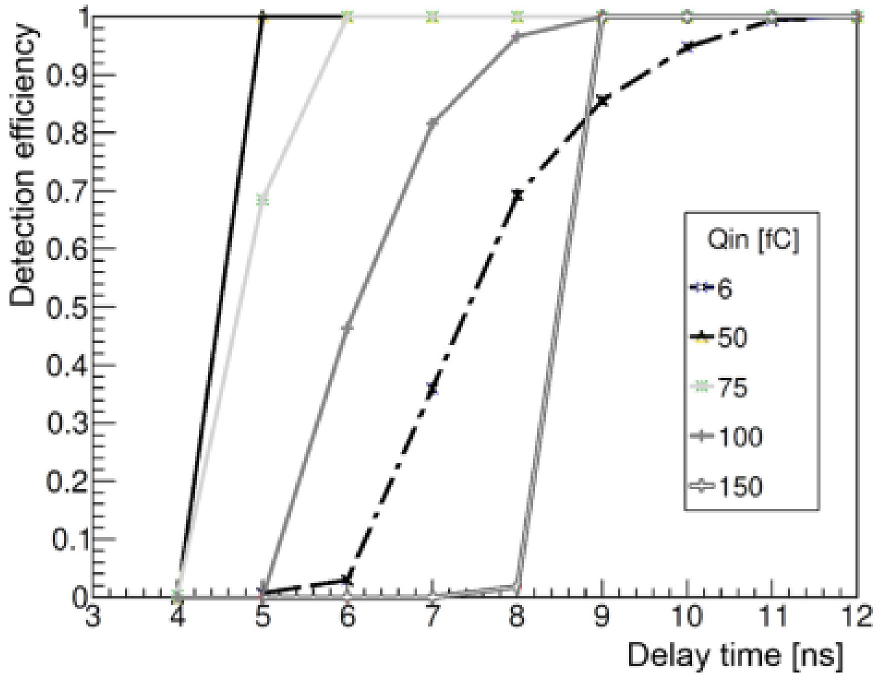


ABACUS



- 24 channels
- UMC 110 nm technology
- Independent V_{TH} for each channel
- Differential output

Detection efficiency vs 2 pulse separation

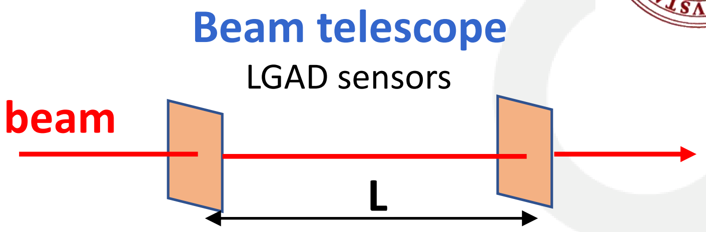


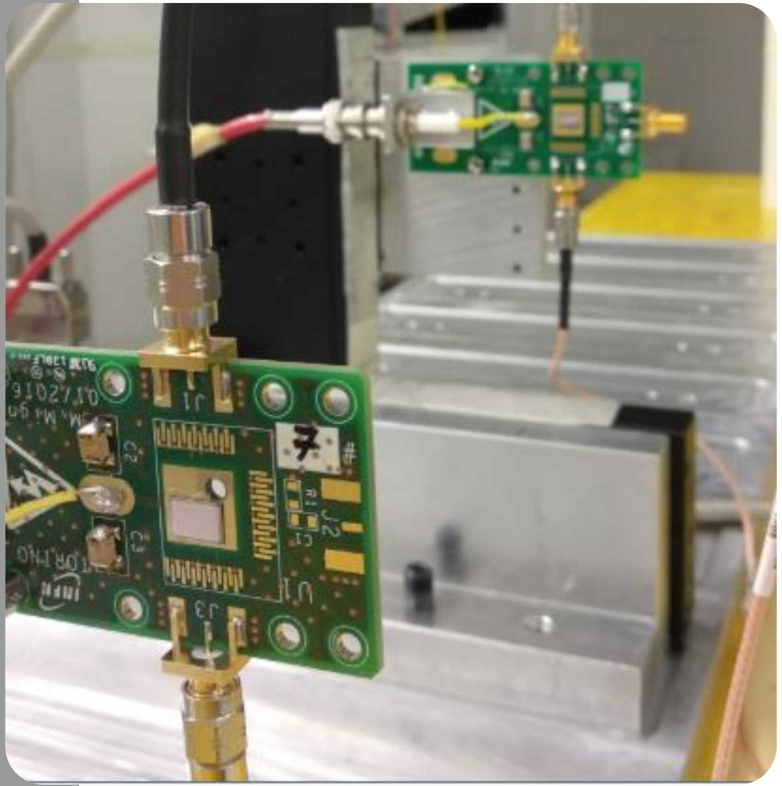
- Deadtime < 10 ns
- 100% efficiency up to f=100 MHz

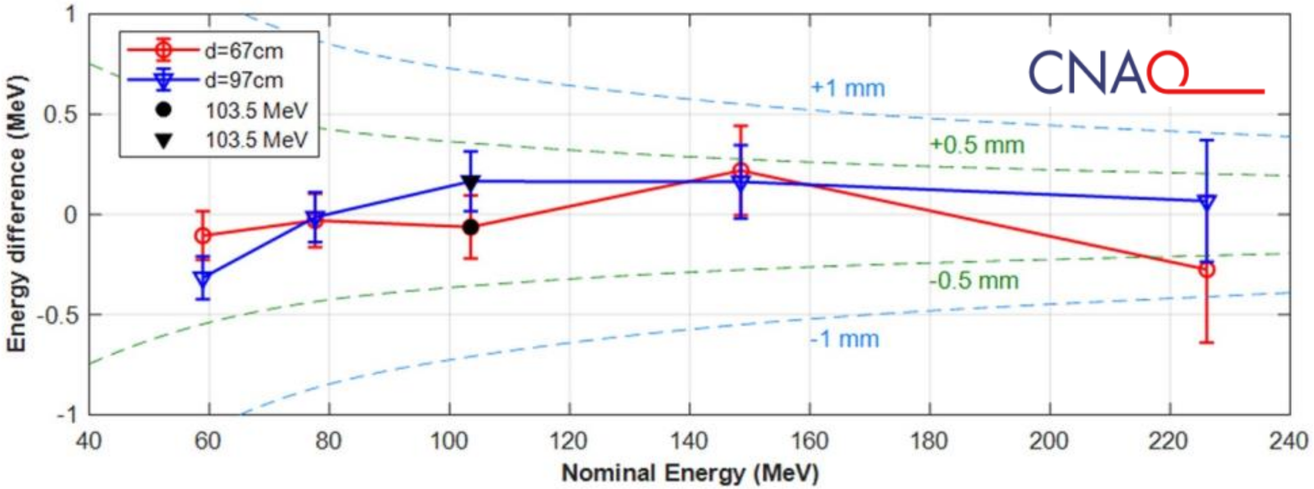
A single ion discriminator ASIC prototype for particle therapy applications
Nuclear Instruments and Methods in Physics Research A 985 (2021) 164666

Timing application: measuring the beam energy

Beam energy/range from time-of-flight



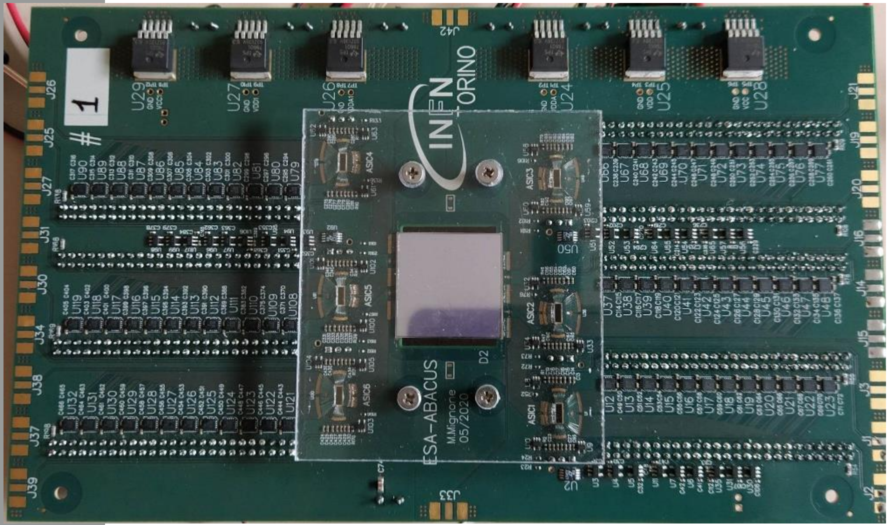




- range can be measured with ±1 mm uncertainty;
- need few ms of active acquisition time;
- requires precise calibration of the system.

A new detector for the beam energy measurement in proton therapy: a feasibility study
Phys. Med. Biol. 65 (2020) 215030

Present ....INFN MoveIT project (2017-2021)

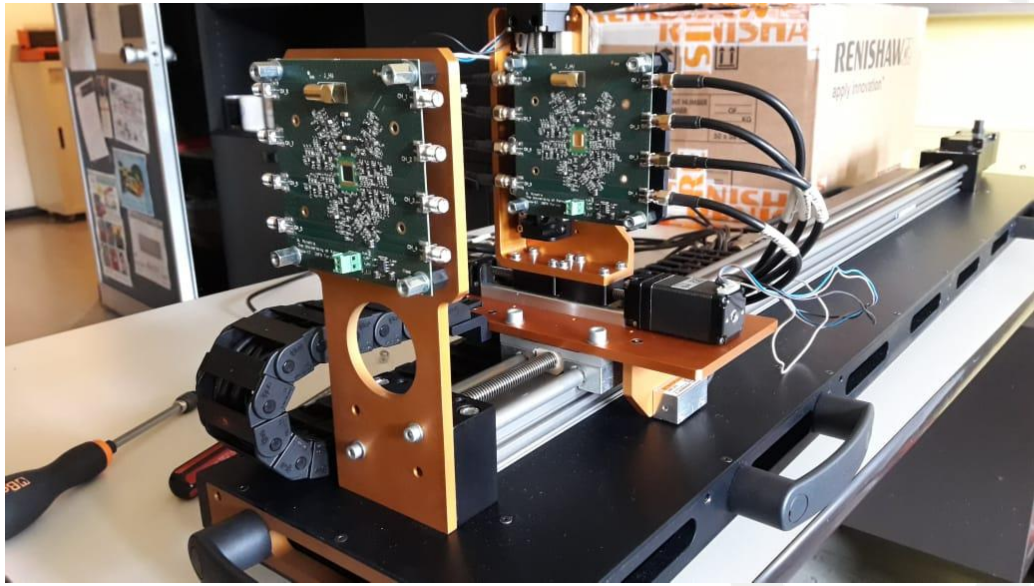


Proton beam particle counter

- Six ABACUS front-end ASIC -> 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

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
- Ready for market



Future ... INFN SIG project (2022-2025)

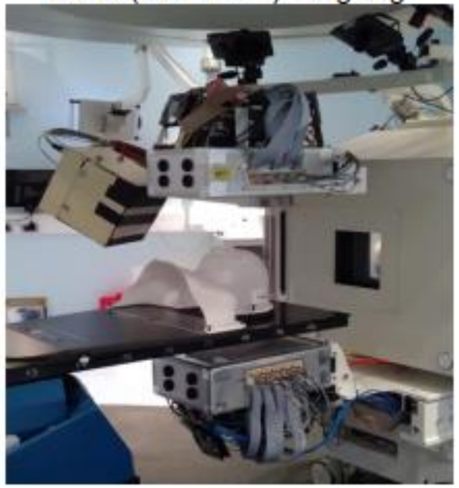
R&D towards an advanced **Superconducting Ion Gantry**

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

Past experience

INSIDE

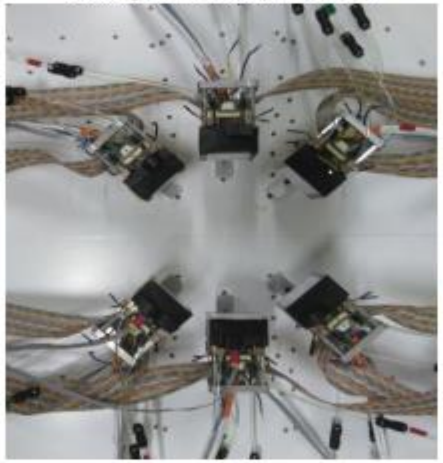
PRIN (2013-2016) - ongoing



in-beam PET + dose profiler

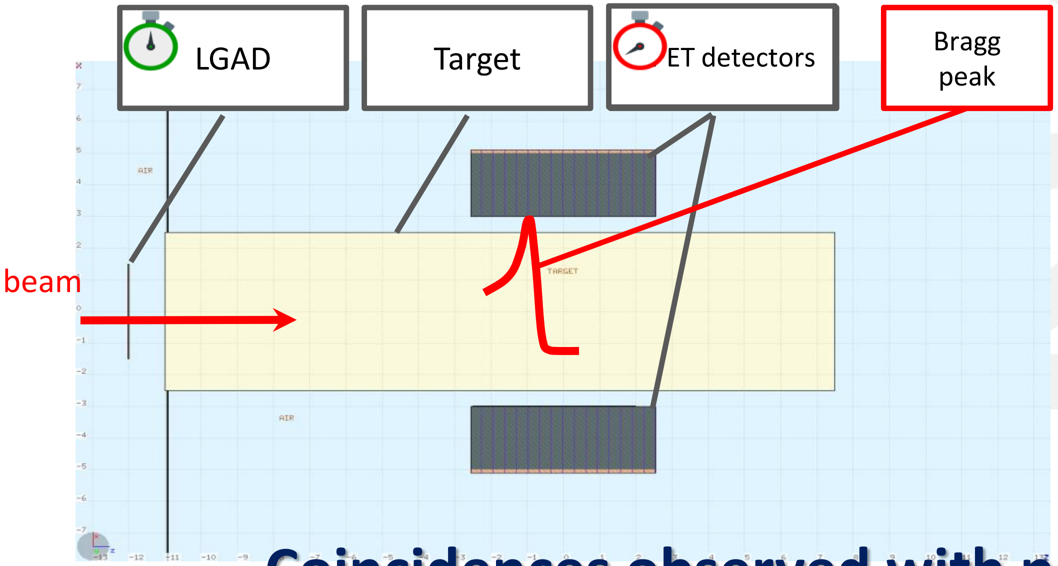
I3PET

Grant giovani CNS5 (2018-2021)



Prompt Gamma Timing (PGT) + in-beam PET

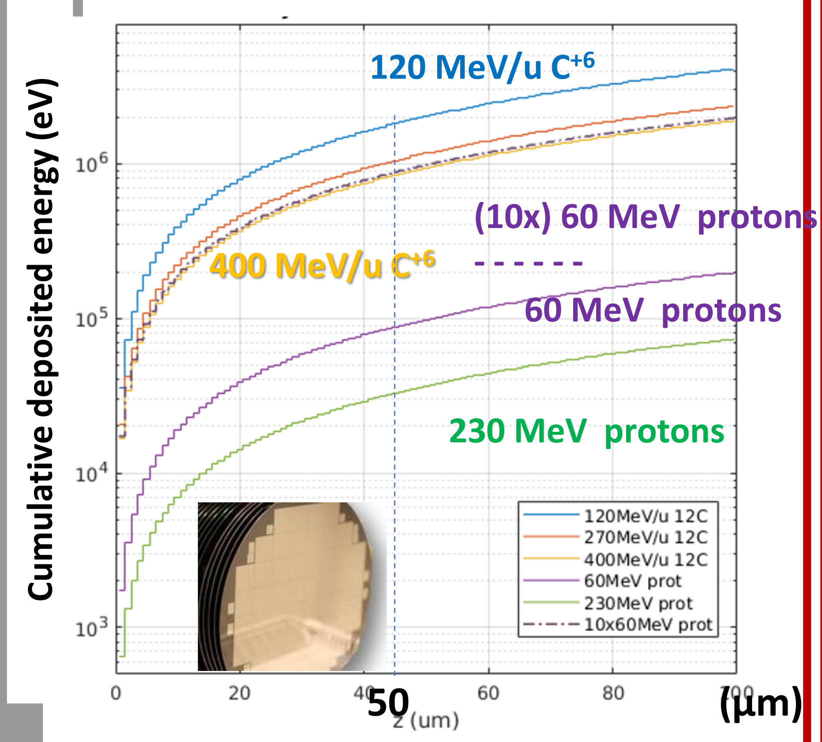
PGT concept



Coincidences observed with protons in a recent beam test @CNAO

Future … INFN SIG project (2022-2025)

Thin planar silicon sensors optimized for ions

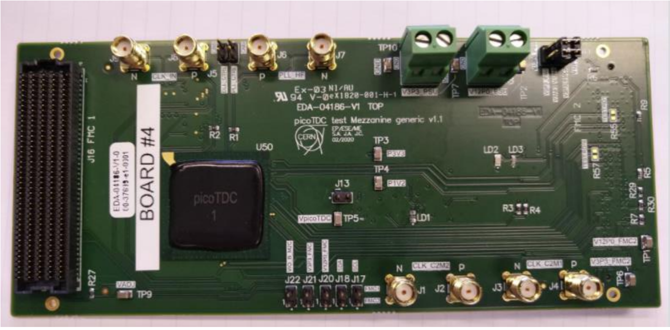


? **Ionization density effects**
Radiation resistance

Incorporate ion crossing time measurement in FE-readout

Provide the **time stamps** for ions with high efficiency (→RVS)

Match existing ASICs at INFN-To for timing with CERN picoTDC



picoTDC board (64 input channels)

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

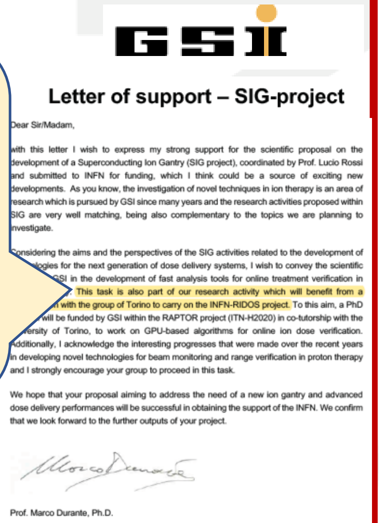
Integration of GPU-based data analysis in the DDS

New GPU-based algorithms to exploit ion treatments (ADAPTIVE PT) with a very fast data analysis for online feedback on the dose delivered.

→ Collaboration with GSI within the **RAPTOR** project (ETN – H2020)

Real-Time Adaptive Particle Therapy Of Cancer

This task is also part of our research activity which will benefit from a collaboration with the group of Torino to carry on the INFN-RIDOS project.



Letter of support – SIG-project

Dear Sir/Madam,

with this letter I wish to express my strong support for the scientific proposal on the development of a Superconducting Ion Gantry (SIG project), coordinated by Prof. Lucio Rossi and submitted to INFN for funding, which I think could be a source of exciting new developments. As you know, the investigation of novel techniques in ion therapy is an area of research which is pursued by GSI since many years and the research activities proposed within SIG are very well matching, being also complementary to the topics we are planning to investigate.

Considering the aims and the perspectives of the SIG activities related to the development of …logies for the next generation of dose delivery systems, I wish to convey the scientific … GSI in the development of fast analysis tools for online treatment verification in … This task is also part of our research activity which will benefit from a …n with the group of Torino to carry on the INFN-RIDOS project. To this aim, a PhD … will be funded by GSI within the RAPTOR project (ITN-H2020) in co-tutorship with the …versity of Torino, to work on GPU-based algorithms for online ion dose verification. Additionally, I acknowledge the interesting progresses that were made over the recent years in developing novel technologies for beam monitoring and range verification in proton therapy and I strongly encourage your group to proceed in this task.

We hope that your proposal aiming to address the need of a new ion gantry and advanced dose delivery performances will be successful in obtaining the support of the INFN. We confirm that we look forward to the further outputs of your project.

Prof. Marco Durante, Ph.D.

INFN-CSN5 - RIDOS
2014-2016

M. Abujami [1,2], D.Bersani[2], P. Cerello[1], R. Cirio[1,2], E. Data[1,2], V.Ferrero[1], E. Fiorina[1], C. Galeone[1,2], S. Garbolino[1], S. Giordanengo[1], O. A. Martì Villarreal[1,2], F. Mas Milian[1,2,3], G. Mazza[1], D.M. Montalván Olivares[2], M. Mignone[1], V. Monaco[1,2], F. Pennazio[1], R. Sacchi[1,2], A. Staiano[1], A. Vignati[1,2],R. Wheadon[1]

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