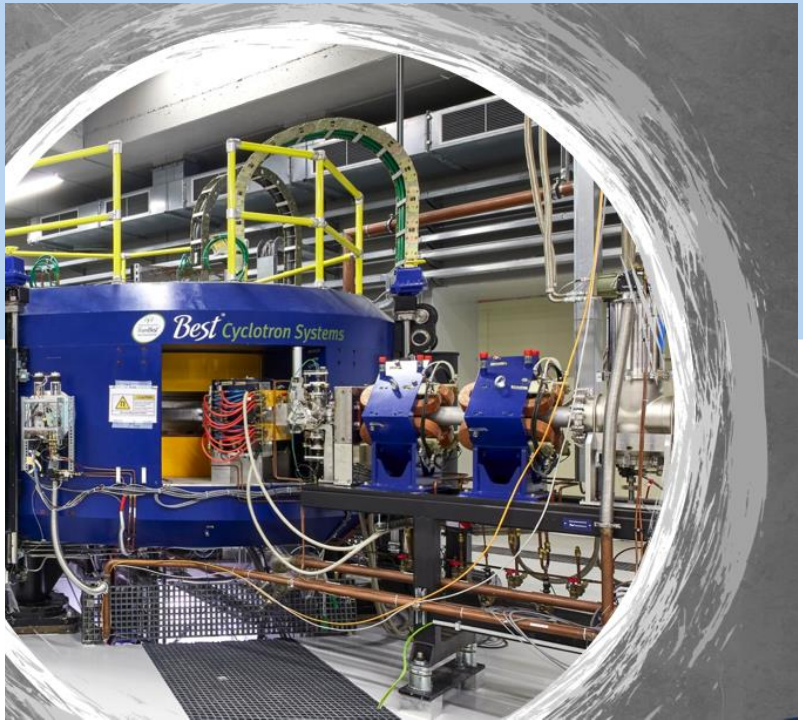
Development of Beam Monitors for Ultra High Dose Rate Radiotherapy

Umberto Deut[1,2]
PhD Student

[1] Department of Physics, University of Turin, Turin 10125, Italy
[2] National Institute of Nuclear Physics (INFN), Section of Turin, Turin 10125, Italy



International Workshop on future research program with the high power cyclotron of SPES-LNL

12-13 May 2025, Legnaro

Collaborations and Facilities

Turin’s Medical Physics

Focus Research Areas:
Radiotherapy, radiobiology, acceleration techniques, dosimetry, and particle detectors.

Research Collaborations:
Active involvement in FRIDA and MIRO collaborations exploring advanced electronics and detector technologies.

National Network:
Collaboration spans 7 INFN sections: LNS, Catania, Roma, Pisa, Torino, Milano, and Trento.

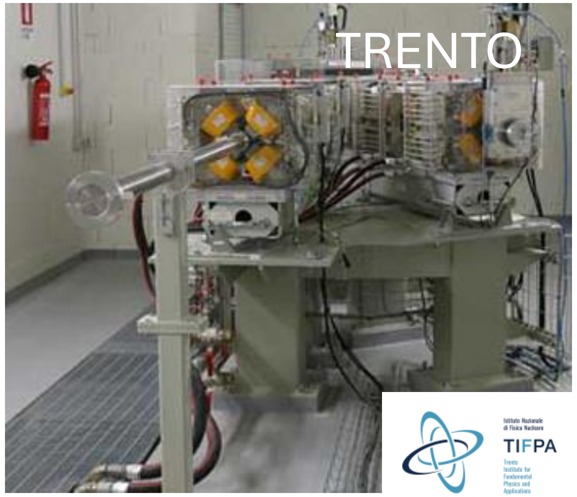
Facility Integration:
Connection of multiple research facilities and experts within the Italian National Institute for Nuclear Physics (INFN).

Particle Sources:
Research utilizes electron, photon, and proton facilities across various INFN sections.

FLASH Radiotherapy with hIgh Dose-rate particle beAms

MIRO
Minibeam Radiotherapy

INFN
Istituto Nazionale di Fisica Nucleare



Technologies

We tested many technologies under ultra high dose rate (UHDR) beams to support further FLASH effect understanding:

- IC chambers
- Silicon and diamond detectors
- Multichannel readout electronics

Pulsed beams:

- UHDR Electron beams (accelerated currents up to 100 mA, around 10^12 electrons per pulse, pulse duration between 0.2 μs and 4 μs and PRF between 1 Hz and 250 Hz)
- Clinical Photons

Proton beams:

- IBA cyclotron 230 MeV up to **200nA**, 100ms beam on time
- Varian cyclotron 250MeV up to **800nA**, up to 1s beam on time

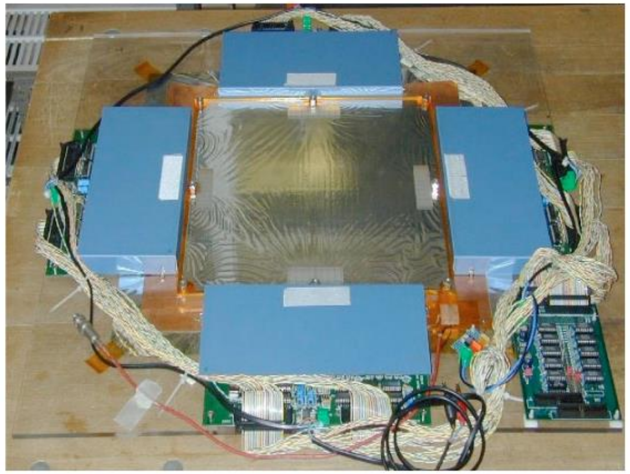
Ionization Chambers

Ionization chambers are used in conventional beams as dosimeters and beam monitor.

Key Components of a Parallel-Plate Ionization Chamber:

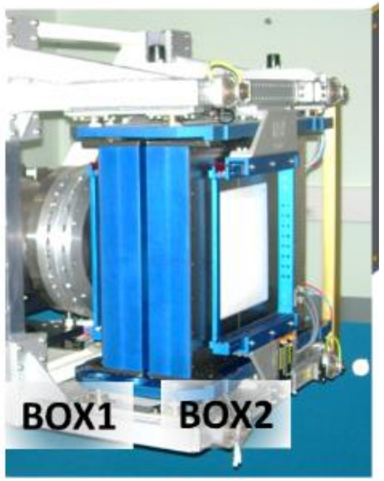
- **Polarizing Electrode**: Applies a voltage to establish a uniform electric field between the plates.
- **Measuring Electrode**: Collects the ion pairs created by ionizing radiation
- **Guard Ring**: Shapes the electric field and reduces edge effects for accurate measurements.

We started from →



Pixel-segmented IC

Amerio S et al. Dosimetric characterization of a large area pixel-segmented ionization chamber. https://doi.org/10.1118/1.1639992.



Multi gap IC and CNAO dose delivery system

Giordanengo S et al. Fluence Beam Monitor for High-Intensity Particle Beams Based on a Multi-Gap Ionization Chamber and a Method for Ion Recombination Correction. https://doi.org/10.3390/app122312160.

BUT

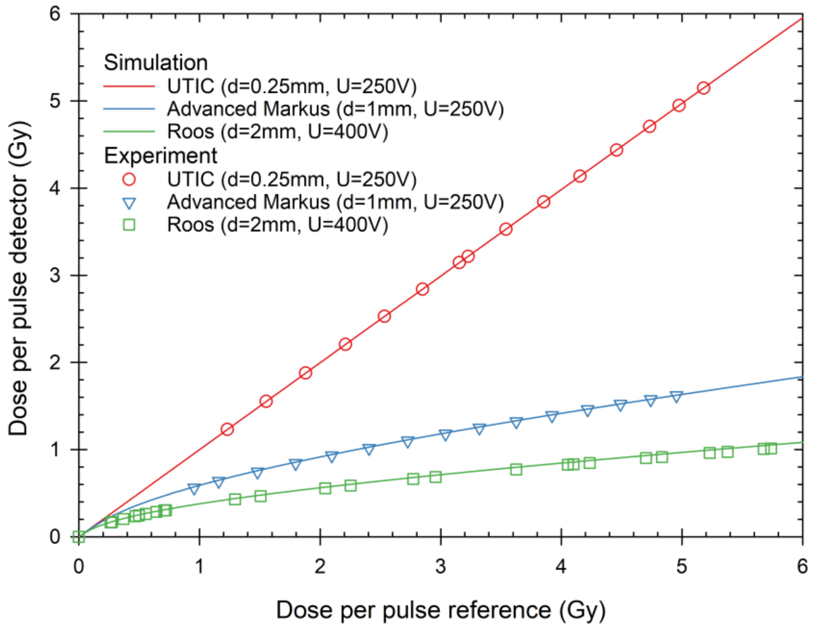
Standard ICs are ineffective for monitoring UHDR beams due to significant ion recombination which causes saturation of the collected charge

Proposed Solutions:

Gas Mixture Modification: Replacing air or traditional Ar–CO_2 mixtures with helium reduces ion density and enhances charge collection efficiency

Ultra-Thin Chambers: Designing chambers with reduced air gaps (e.g., 0.5 mm) minimizes recombination effects

Two-Voltage Method:Applying two different voltages to calculate a correction factor for recombination, improving measurement accuracy.



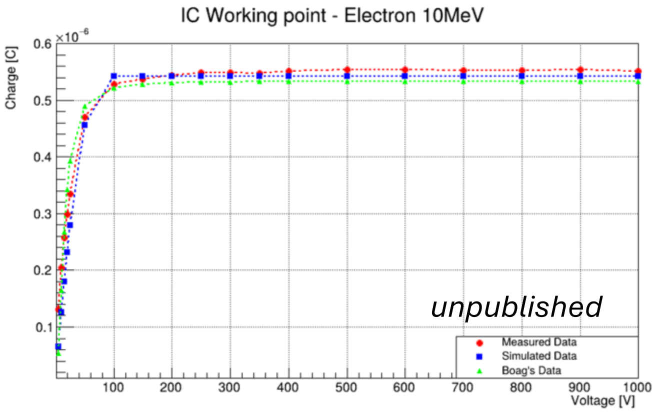
https://www.ptwdosimetry.com/en/about/news-events/news/flash-radiotherapy-dosimetric-challenges-and-solutions

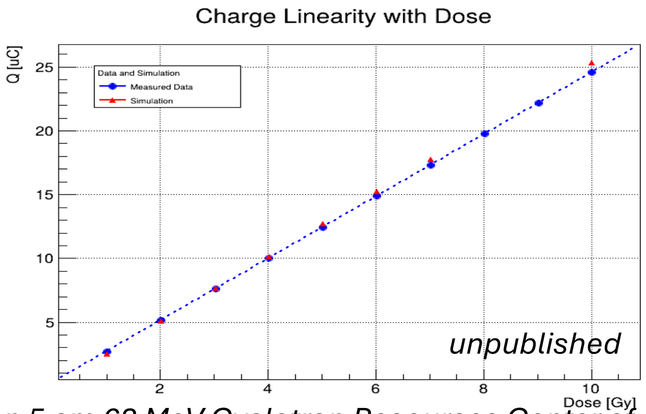
Ionization Chambers

Our approach:

Numerical simulations following state-of-the-art literature* to simulate different electrode gap thickness, materials and study recombination effects. The adopted finite volume method (FVM) allows to extend the results at high electric fields and current gradients (plasma).

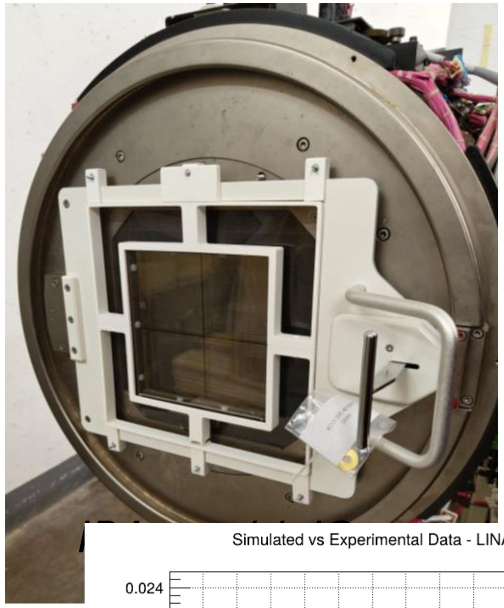
Numerical Simulations

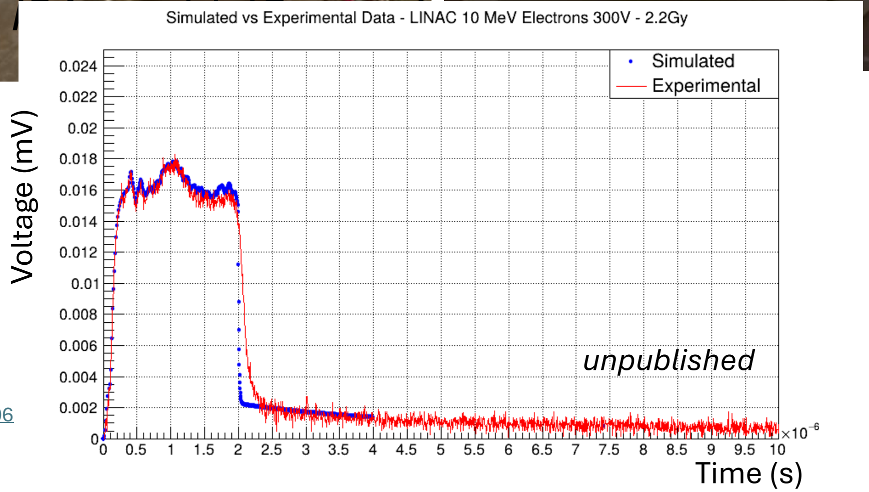




Simulation of a 15x15cm IBA stealth IC on 5 cm 62 MeV Cyclotron Resources Center of the Université catholique de Louvain (Louvain-la-Neuve, Belgium)

Stealth Ionization Chamber for Electron and Proton Beam Monitoring





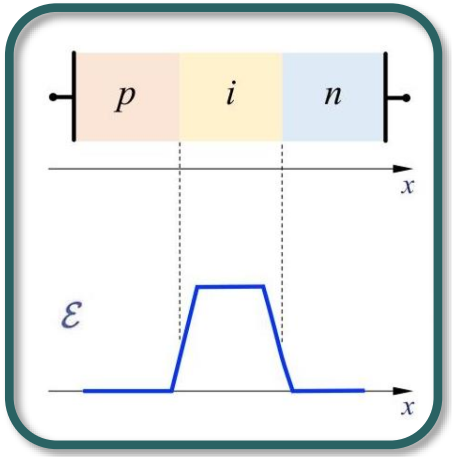
* Paz-Martín J. et al. Numerical modeling of air-vented parallel plate ionization chambers for ultra-high dose rate applications. https://doi.org/10.1016/j.ejmp.2022.10.006
Gotz M et al. Anew model for volume recombination in plane-parallel chambers in pulsed fields of high dose-per-pulse. https://doi.org/10.1088/1361-6560/aa8985
Bancheri J et al. A semi-analytical procedure to determine the ion recombination correction factor in high dose-per-pulse beams. https://doi.org/10.1002/mp.17005

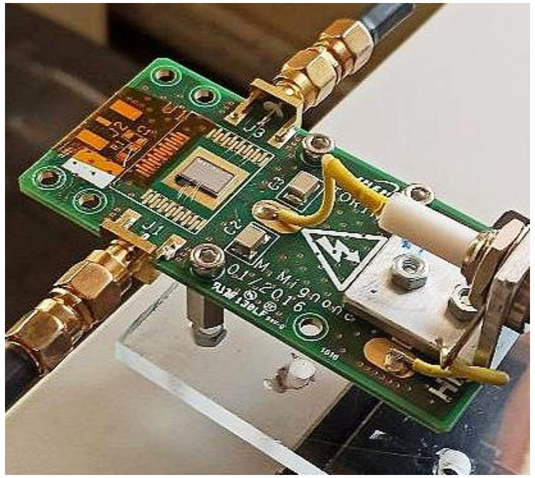
Main Contributor: Franco Mostardi

Thin Silicon Detectors

Silicon devices in Turin: used so far for *single particle counting* → With **TERA08** signal can be integrated

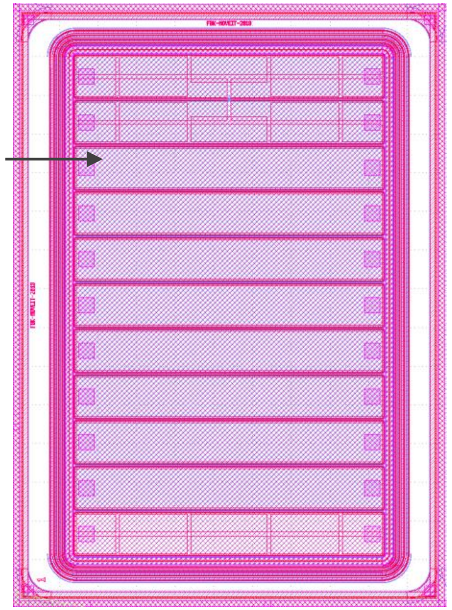
FONDAZIONE BRUNO KESSLER





- **11 strips sensor (pin) [MoVeIT]**
- Strip area $2.2 mm^2$, active thickness 45 μm, total thickness 615 μm)

2.2 mm²

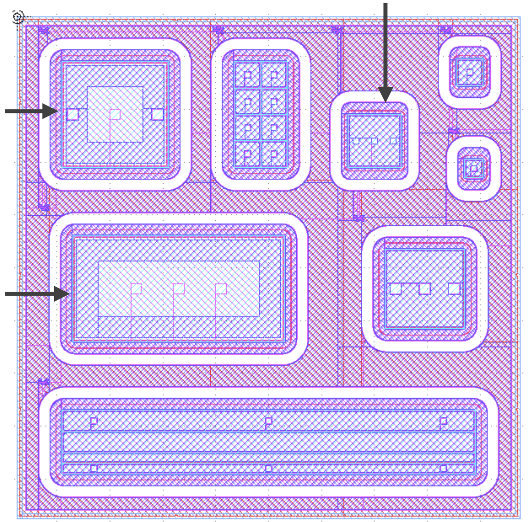


- **3 pad sensors (pin) [eXFlu]**
- Areas 2/1/0.25 mm^2, active thickness **45/30 μm**, total thickness 615 μm)
- (Thanks to **Valentina Sola**)

0.25 mm²

1 mm²

2 mm²

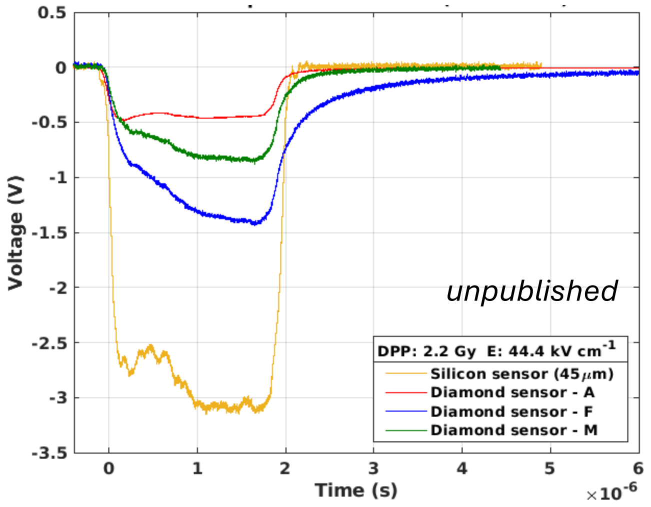


Comparison of **different areas and thickness** on UHDR beams

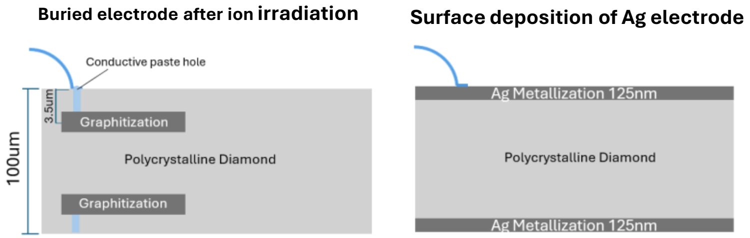
Silicon and Diamonds Beam Monitors

Beam Monitoring with Polycrystalline Diamonds

Turin's Linac (10 MeV electrons)

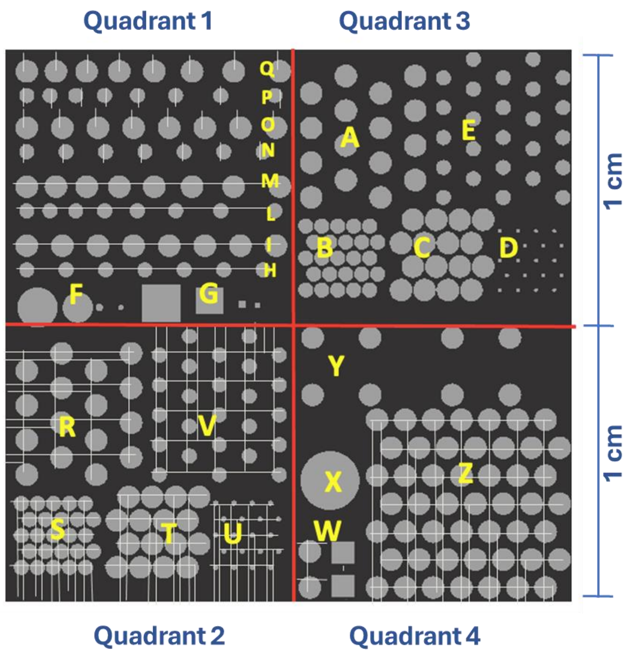


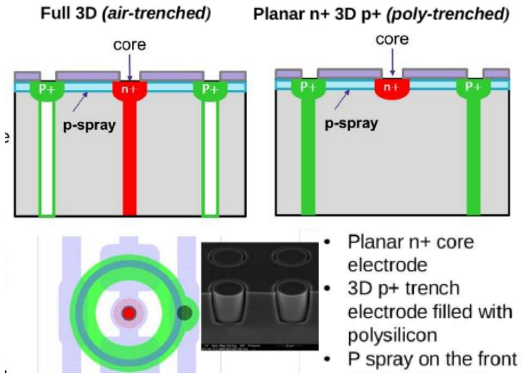
Different electrode fabrication strategies on commercial polycrystalline diamonds have been explored



In collaboration with UniTo's solid state physics group (F. Picollo, P. Olivero, http://www.solid.unito.it/RICERCA/Diamante/Diamante_index.html)

New production of trench isolated silicon detectors





Courtesy of Anatoly Rozenfeld and Emanuele Maria Data
A.Rosenfeld "Novel detectors for silicon based microdosimetry, their concepts and applications", NIM A, 809, 156-170, 2016
A.Rosenfeld "From High Energy Physics to Medical Physics: Detectors for Particle Therapy and Space", Centre for Medical Radiation Physics, School of Physics, University of Wollongong.

- Precise active area
- Possible microdosimetry
- Optimal spatial collection of the signal for the electronics

Main Contributors: Diango Montalvan Olivares and Umberto Deut

Silicon Detectors and Proton Beams

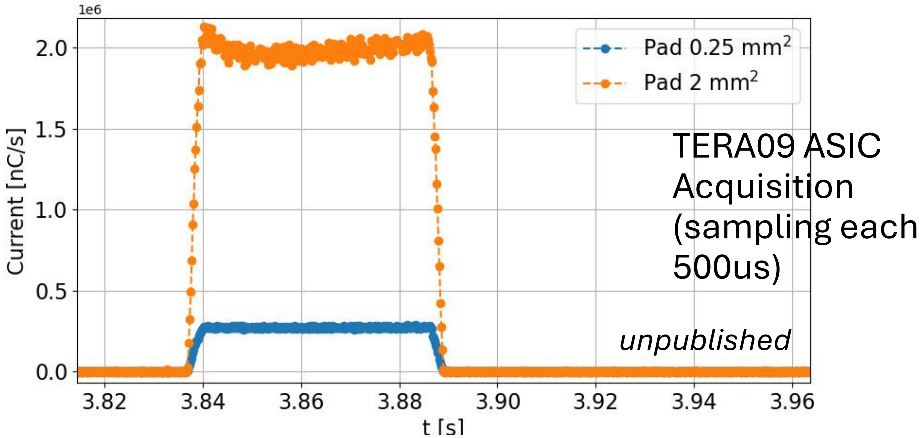
HPTC Varian’s Superconductive Cyclotron ProBeam (250MeV)

HollandPTC Proton Therapy Centre

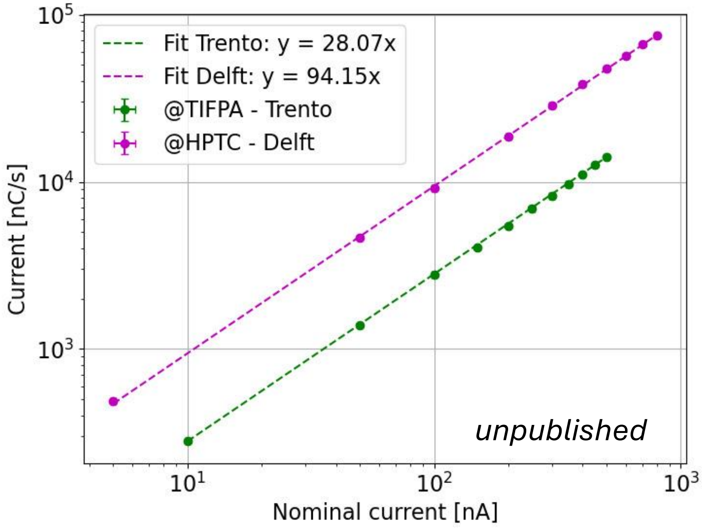
Horizon 2020 European Union Funding for Research & Innovation

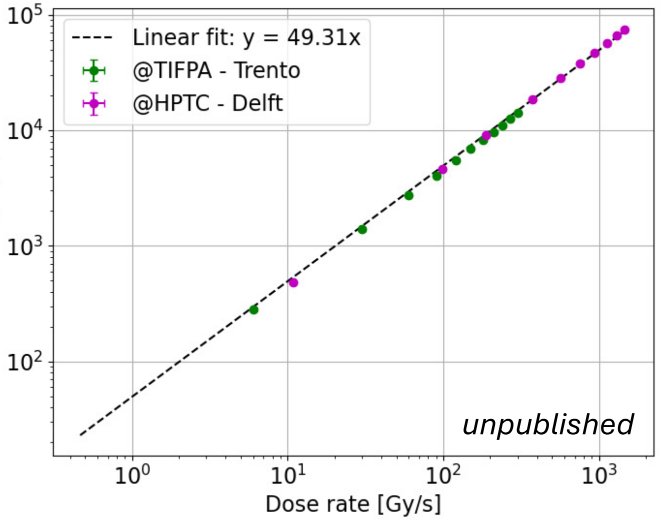
RADNEXT

Measurement campaing funderd by Horizon 2020 and Radnext Project (https://radnext.web.cern.ch/transnational-access/



Detector Performance up to 800nA proton beam

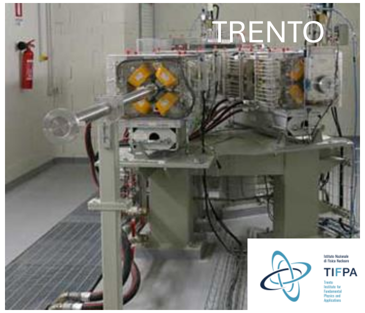


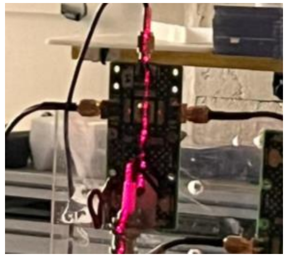


Main Contributor: Arianna Ferro

Silicon Detectors and Proton Beams, Temporal Resolution

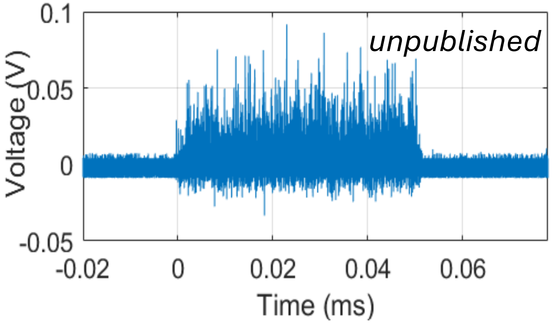
Trento IBA's Proteus TM 235 Cyclotron beamline



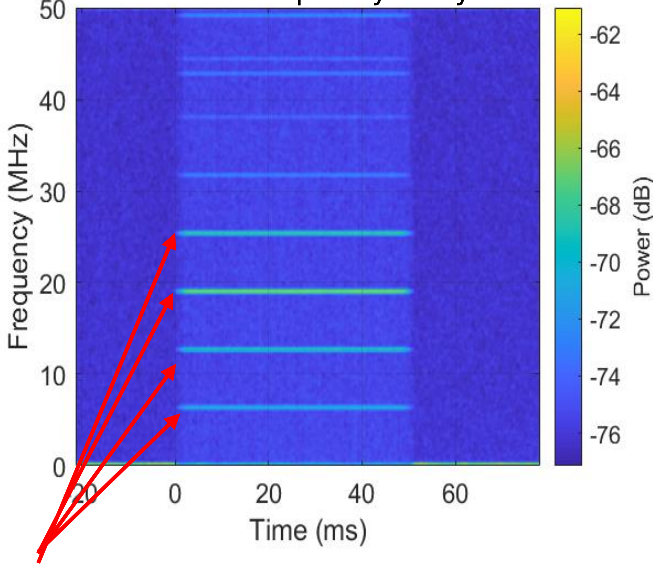


Silicon Detector on PCB centered along the beamline

Oscilloscope Signal (10ns sampling rate)



Time-Frequency Analysis



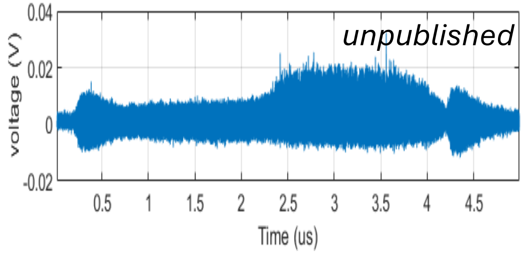
Nanobunches appear in subfrequencies of the main nominal frequency of the accelerator (106.3MHz)

LinearBeam

Linear Proton Accelerator

Main RF: 3GHz
Injector RF: 428 MHz
Beam currents: up to 30uA
Energy: 102MeV

Oscilloscope Signal (10ns sampling rate)



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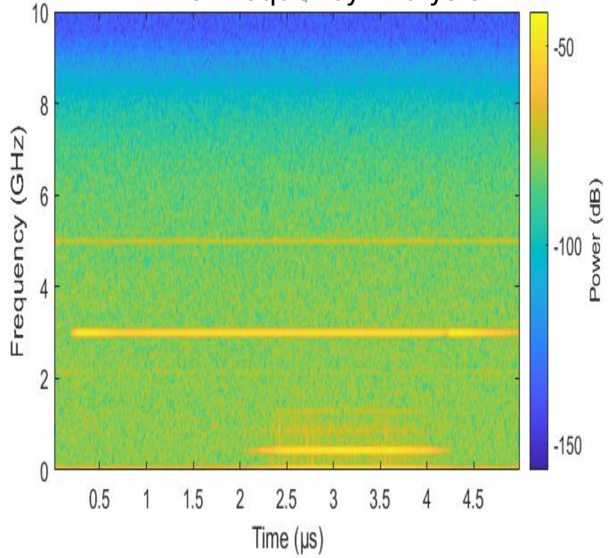
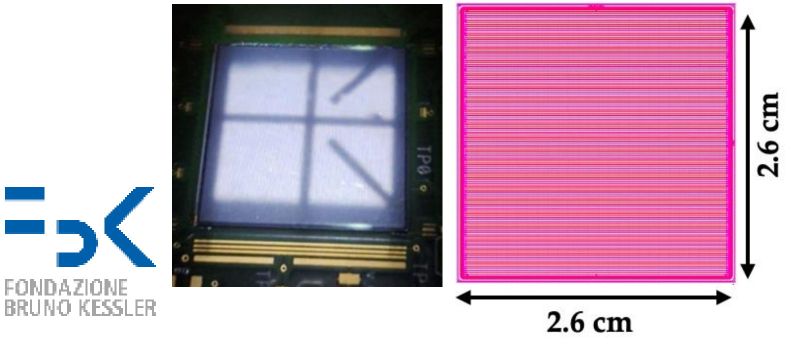


Silicon Detectors for Beam Profiles

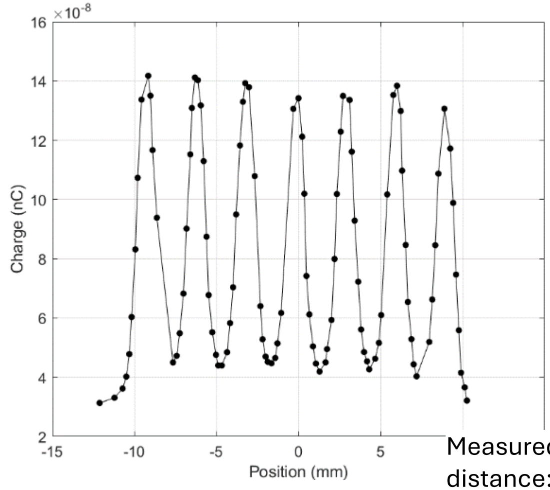
Beam Profiles with high spatial resolution with large area detector

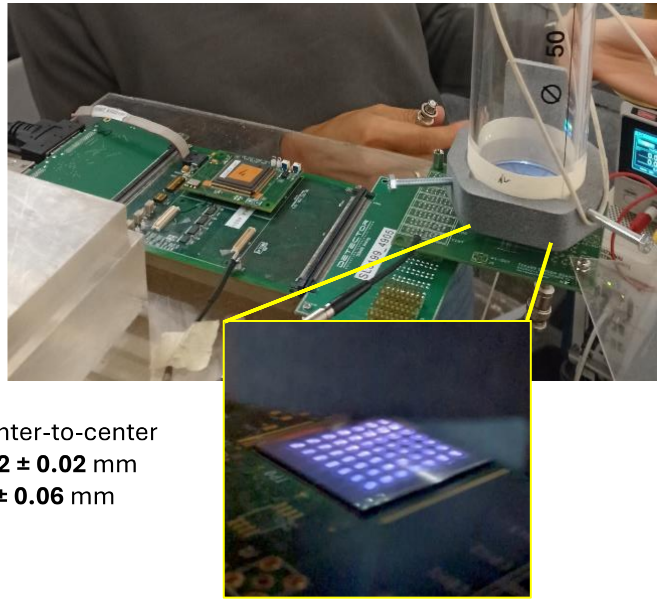


Large Area Silicon Sensor:

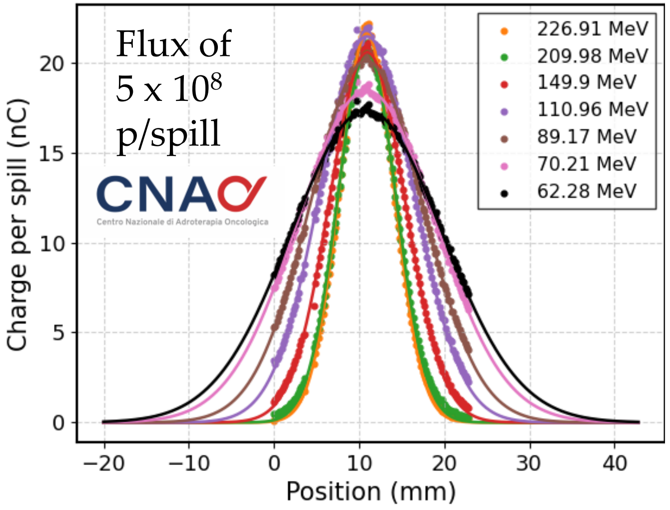
- **146 strips**
- Area: **2.7x2.7** cm^2
- Width: **114um**
- Pitch: **180um**
- Thickness: **60um**
- No Gain

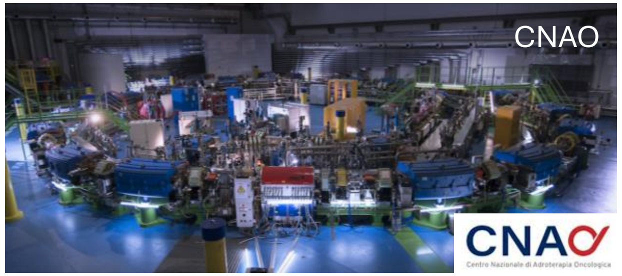
Elekta LINAC 10MeV **Electron** Beam Grid Minibeam profile projection





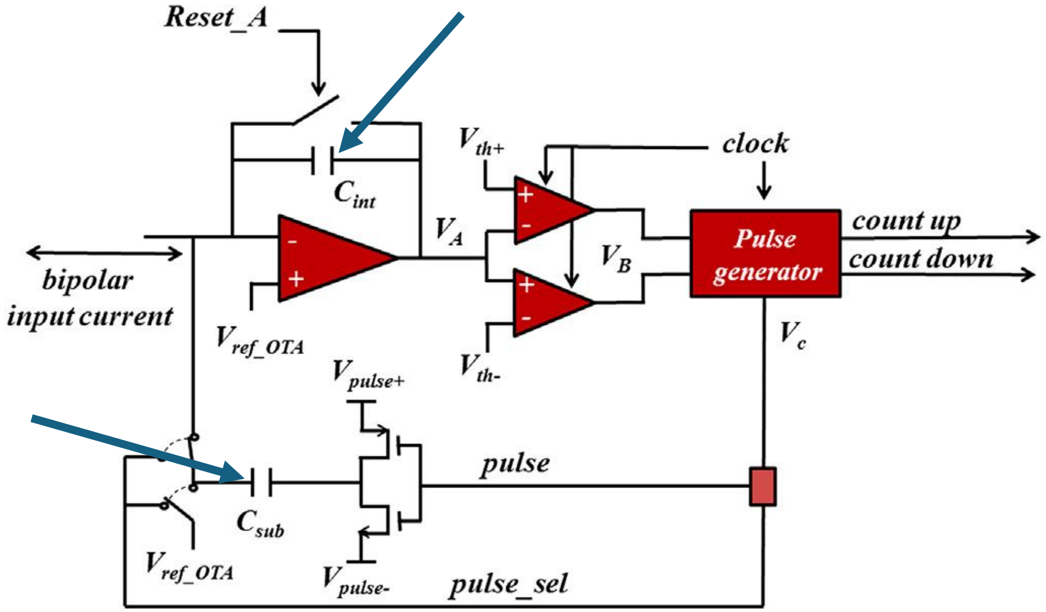
Measured center-to-center distance: **3.02 ± 0.02** mm
FWHM: **1.17 ± 0.06** mm





Improvements on Readout Electronics

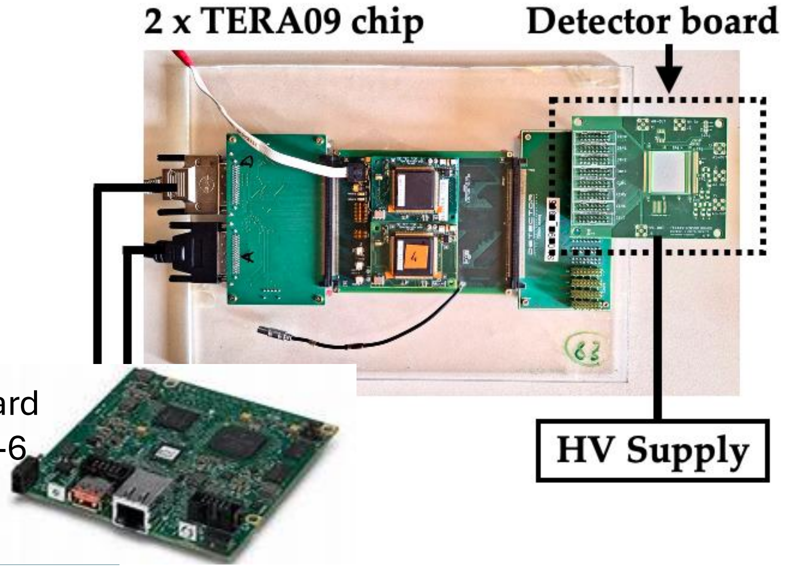
Multichannel Readout Electronics:
- "Tera09" ASIC
- 128 channels
- 50MHz frequency
- Max current per channel: few uA



Readout with ASIC TERA09 (64 CHNs each)

- Current-to-frequency converter (based on recycling integrator architecture)
- 50MHz (Tera09) frequency
- Current readout sampling rate: ~500us
- Max instantaneous current per channel ~12 μA

National Instruments sbRIO-9606 CompactRIO Single-Board Controller with Xilinx Spartan-6 LX45 FPGA

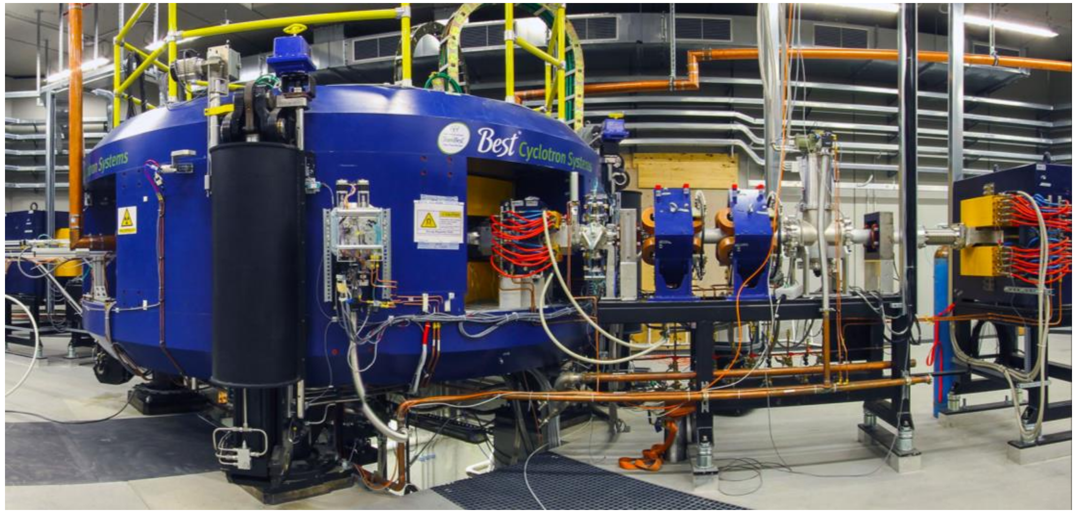


Fausti F et al. Design and characterization of a 64 channels ASIC front-end electronics for high-flux particle beam detectors. https://doi.org/10.1016/j.nima.2
Mazza G et al. A 64-channel wide dynamic range charge measurement ASIC for strip and pixel ionization detectors. https://doi.org/10.1109/TNS.2005.852702.

LNL High Power Cyclotron

Future research directions with possible LNL collaboration:

- **Macroscopic Effects of Radiation Damage**:
- **IC Charge Transport Simulation**:
- **Hybrid Detection System**:
- **Next-Generation Electronics Testing**:



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- **Macroscopic Effects of Radiation Damage**: Study the long-term effects of radiation exposure on detector performance and stability.
- **IC Charge Transport Simulation**:
- **Hybrid Detection System**:
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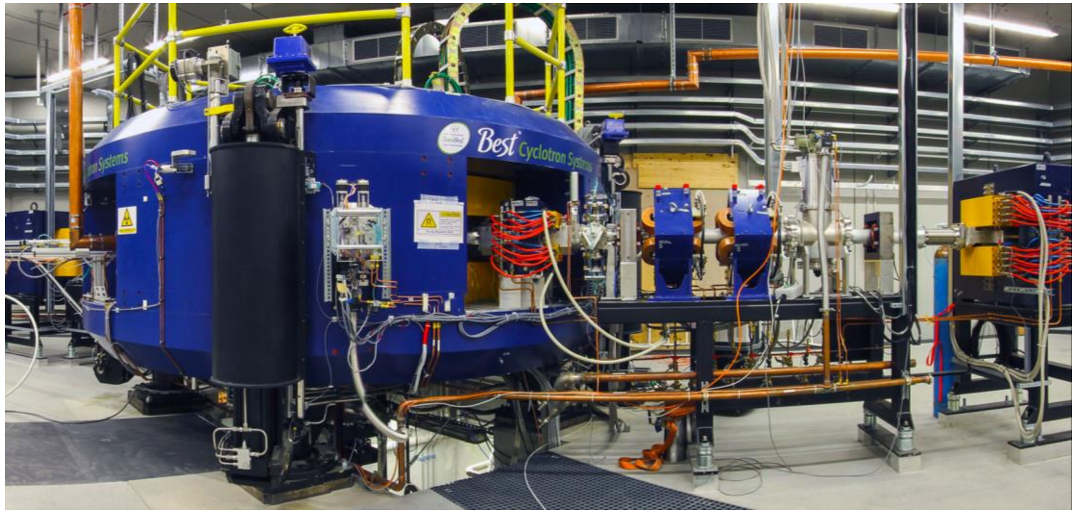
Studies of Radiation-Induced Damage:

- Photons vs. Neutrons vs. Protons
- Short, Intense vs. Long-Term Irradiations
- Defect Types (point defects, displacement damage)



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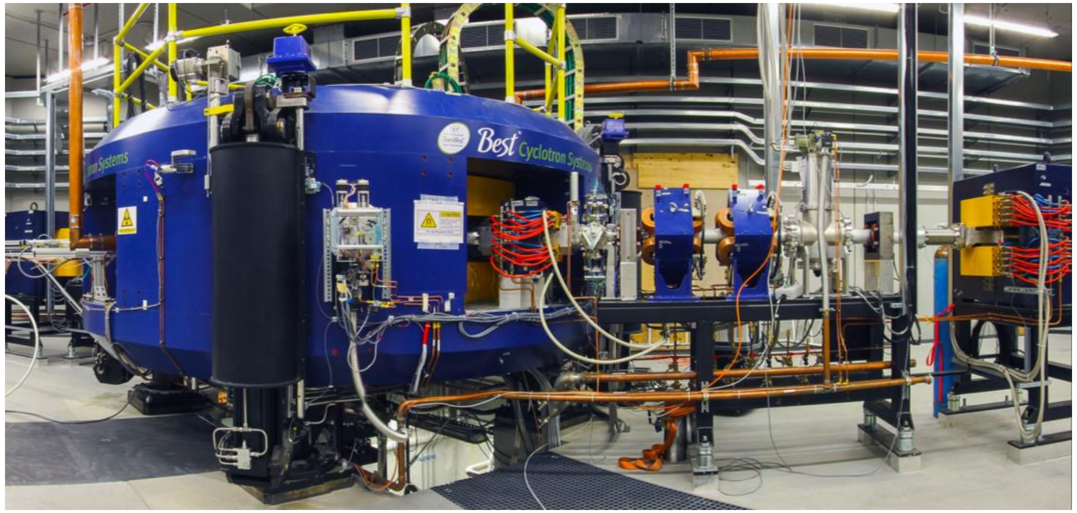
- **IC Charge Transport Simulation**:
  Validate a charge transport model for ionization chambers using a finite volume method to improve predictive accuracy in detector response simulations.
- **Hybrid Detection System**:
- **Next-Generation Electronics Testing**:

Validation of the charge transport analytical simulations at high beam currents



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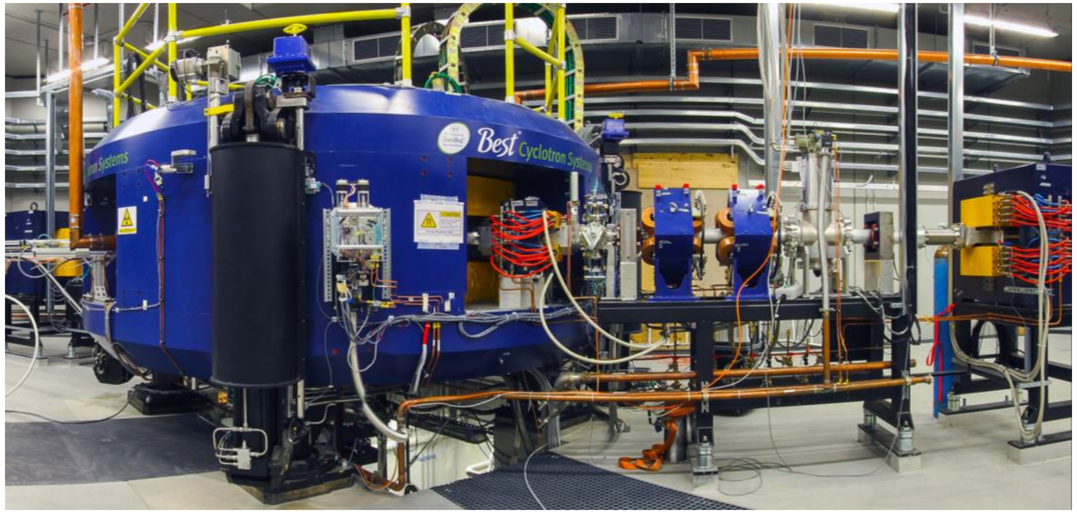
- **Hybrid Detection System**:
  Test an integrated system combining an ionization chamber (IC) with a silicon sensor for enhanced spatial and temporal resolution.
- **Next-Generation Electronics Testing**:



LNL High Power Cyclotron

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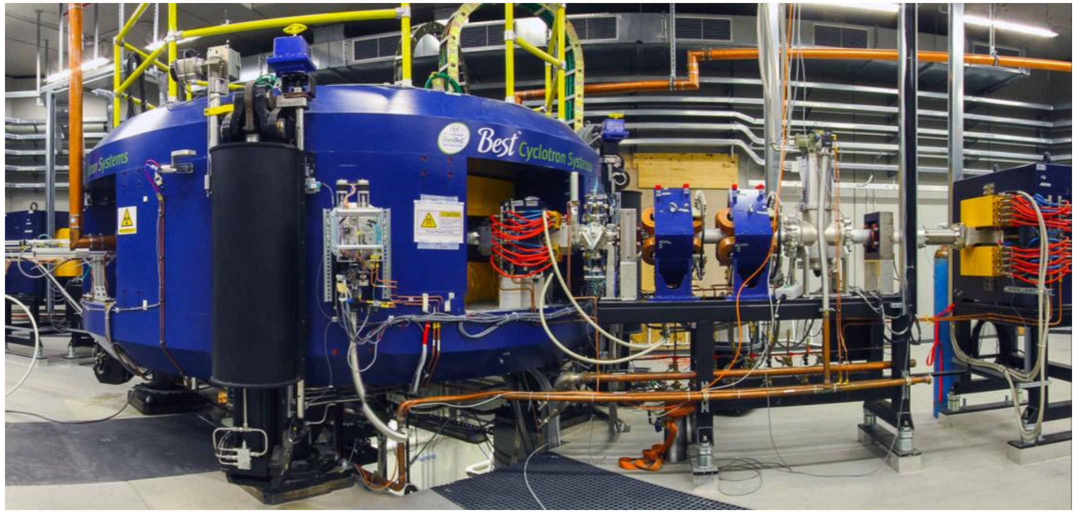
- **IC Charge Transport Simulation**: Validate a charge transport model for ionization chambers using a finite volume method to improve predictive accuracy in detector response simulations.
- **Hybrid Detection System**: Test an integrated system combining an ionization chamber (IC) with a silicon sensor for enhanced spatial and temporal resolution.
- **Next-Generation Electronics Testing**: Evaluate the performance of upcoming new TERA ASIC featuring variable dynamic range under UHDR pulsed beam conditions.

Exploit the full dose rate range of the LNL accelerator for readout electronics characterization



Thank you

umberto.deut@unito.it