New Time-Of-Flight Ion Computed Tomography System Based on Low Gain Avalanche Diodes

27th International Workshop on Radiation Imaging Detectors
29th June 2026

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on behalf of the ion CT group of TU Wien, the Marietta-Blau-Institute and the HADES LGAD group at GSI

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Improving ion beam therapy with ion imaging

Motivation – improving treatment planning

Advantages of ion beam therapy

- energy deposition (dose) of ions **strongly localised** ($S \propto \frac{1}{v^2}$)
  - relatively low entrance dose and rapid distal dose fall-off (Bragg peak)
  - accurate dose deposition
  - allows treatment of tumors close to critical organs, e.g. optical nerve

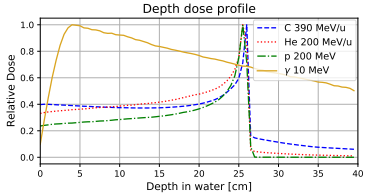


Figure: Bragg peak

photon therapy:

$$I = I_0 e^{-\mu x}$$

ion-beam therapy:

$$\bar{R}(E_0) = \int_{E_0}^{0} \frac{1}{S(E)} \mathrm{d}E$$

$$\text{with } S(E) = -\frac{\mathrm{d}E}{\mathrm{d}x}$$

photon therapy: **proton therapy:**

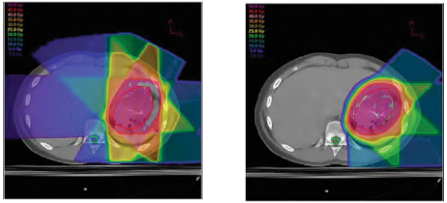


Figure: Linz 2016

Motivation – improving treatment planning

Treatment planning based on x-ray CT

- conversion errors from Hounsfield units (HU) to relative stopping power (RSP) lead to range errors (Schaffner et al. 1998)

$$HU = 1000 * \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}}$$

$$\Downarrow$$

$$\text{RSP} = \frac{S(E)}{S(E)_{\text{water}}}$$

- solution: direct measurement of stopping power using ions in plateau region
  - **ion computed tomography (iCT)**

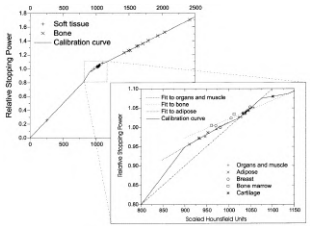


Figure: HU→RSP conversion (Schaffner et al. 1998)

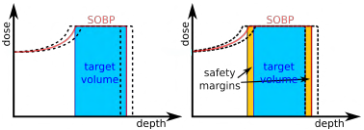
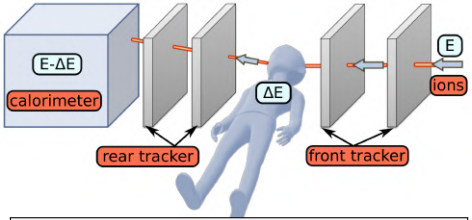


Figure: range uncertainties

Ion computed tomography (iCT)

- **i**on **c**omputed **t**omography allows determining the relative stopping power (RSP) distribution inside a patient directly
  - improves treatment planning accuracy
  - requires tracking and energy measurement



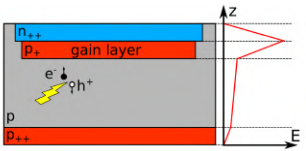
$$\mathrm{WEPL}(E, \Delta E) = \int_L \mathrm{RSP}\left(\vec{x}(s)\right) \mathrm{d}s$$

- several prototypes have been developed (Johnson 2024)
  - still no clinical system exists so far
- meeting all clinical requirements at once is challenging
  - RSP accuracy $< 1\,\%$
  - energy resolution $< 1\,\%$
  - DAQ rate $> 10^6$-10^7 Hz
- 4D-tracking detectors would offer perfect solution (Ulrich-Pur et al. 2022)
  - 4D-tracking iCT system
  - incorporate time-of-flight (TOF) measurements into imaging process

LGAD-based TOF-iCT system

Low Gain Avalanche Diodes (LGADs)

- thin silicon detector optimized for timing performance
  - gain layer exhibits high electric fields ($> 300\,\mathrm{keV/cm}$)
    - leads to intrinsic signal amplification
    - results in large signals with short rise times ($< 1\,\mathrm{ns}$)



- why low gain?
  - high gain also amplifies noise
    - leads to temporal signal fluctuations (time jitter)
    - deteriorates time resolution
  - LGADs are operated at controlled low gain ($\approx$ 10-30)
    - to optimize SNR and time resolution

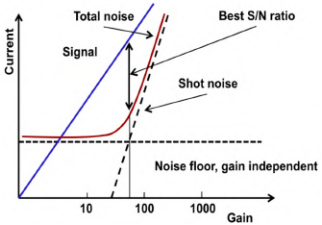
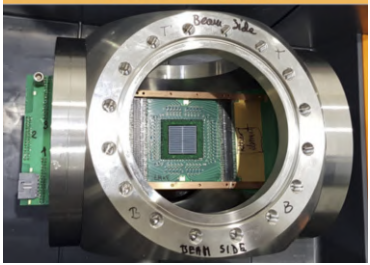


Figure: Sadrozinski et al. 2017

Low Gain Avalanche Diodes (LGADs)

- LGADs are promising candidates for 4D-tracking
  - time resolutions down to 30-50 ps possible
  - high spatial resolution ($< 100\,\mu m$)
  - low material budget ($X/X_0 \ll 1\,\%$)
  - radiation hard ($\approx 10^{15} n_{eq}/cm^2$)
  - large sensor areas $\mathcal{O}(cm^2)$
  - high particle rates (e.g. $10^8\,p/s/cm^2$ at HADES)
- high interest in high energy physics community
  - CERN high luminosity upgrade
    - ATLAS High-Granularity Timing Detector (HGTD)
    - CMS Endcap Timing Layer (ETL)
  - HADES T0 detector at GSI
  - beam monitoring system for HEP applications

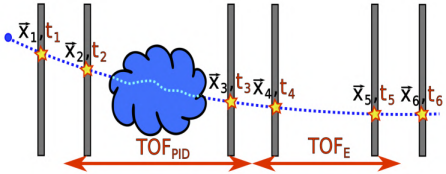
HADES T0 detector



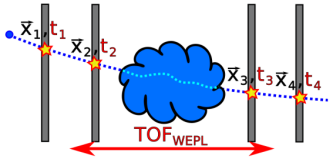
- but also medical applications
  - ion therapy beam quality monitor (Vignati et al. 2023)
  - **ion imaging**

LGAD-based TOF-iCT system - overview

- **LGAD-based “standard” TOF-iCT system**
  - requires 6 4D-tracking layers
  - TOF in air for residual energy determination (Ulrich-Pur et al. 2022)
  - TOF through object + energy loss for PID (Rovituso et al. 2017)



- **second approach: “sandwich” TOF-iCT**
  - indirect WEPL measurement via TOF through object (Ulrich-Pur et al. 2023)
  - no need for residual energy detector
  - requires only 4 4D-tracking layers



Current TOF-iCT system

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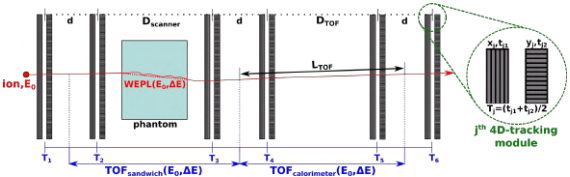
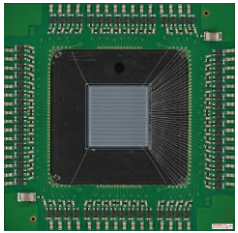
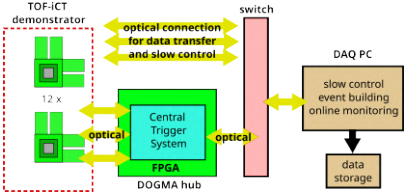




- small, but full TOF-iCT system
  - 12 single-sided LGAD strip sensors (8.6 mm × 8.6 mm)
  - **540 LGAD channels!**
- DOGMA readout system (GSI)
  - FPGA-based leading edge-discriminator and TDC
  - optical trigger and data transfer



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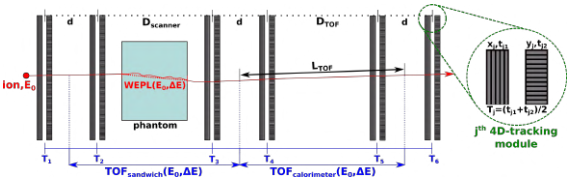

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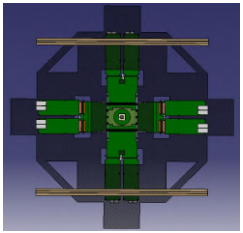
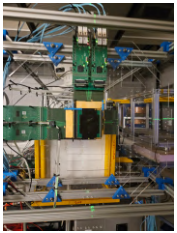
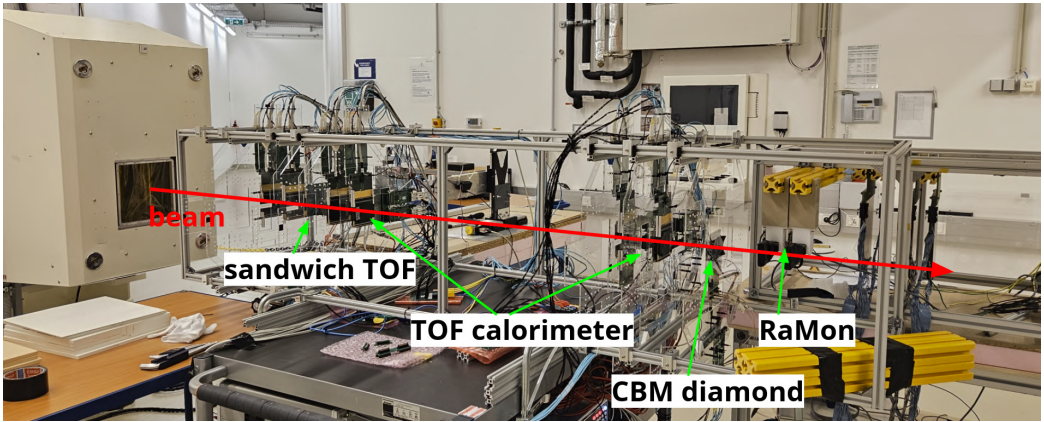




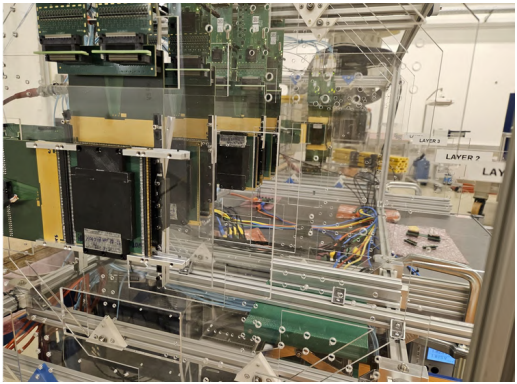
Current TOF-iCT system - He imaging

- TOF-iCT system at MedAustron



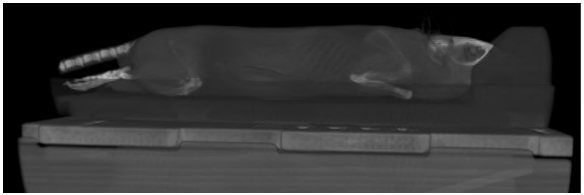
Current TOF-iCT system - He imaging

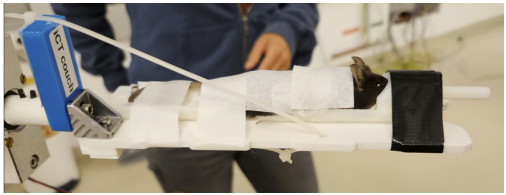
- calibration prior to measurements
  - setup alignment run with 402 MeV/u using the Corryvreckan framework
  - energies between 63.3 MeV/u and 205.2 MeV/u for time walk and TOF calorimeter calibration
- imaging experiments
  - WET measurement of tissue-equivalent slabs
  - helium radiography of mice
  - RSP reconstruction of plastic cylinder using the RTK framework (WIP)



Current TOF-iCT system - He imaging

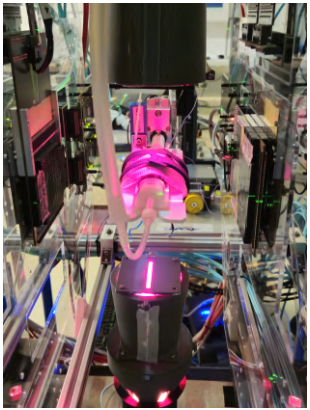
- HeRad of a sacrificed mouse
  - mouse was placed on a 3D-printed couch
  - several HeRads at $\approx 125\,\mathrm{MeV/u}$
- a micro-CT was taken the day before for comparison



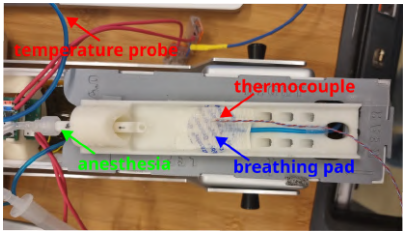


Current TOF-iCT system - He imaging

- In-vivo imaging of mice
  - MedUni Wien, FW Wiener Neustadt

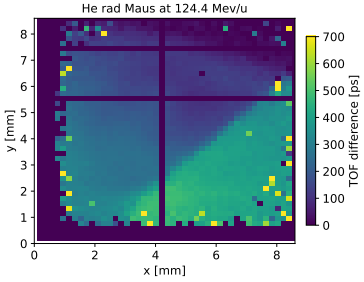


- monitoring of vital parameters
  - breathing pad
  - anal temperature probe
  - thermocouple for surface temperature
  - automated temperature management with two IR lamps and 3D-printed arpertures



Current TOF-iCT system - He imaging

- performance of the TOF-iCT system
  - single particle tracking at $> 10^7$ p/s
  - max trigger rate with DOGMA 200 kHz
  - time frame window of 4 µs
  - currently only 1.2×10^6 track/min
  - speed improvement WIP
- other than that new system performed quite well
  - first radiographs could be reconstructed
- full analysis is still ongoing
  - image stitching



LGADs for mixed He/C beams

Mixed He/C beams

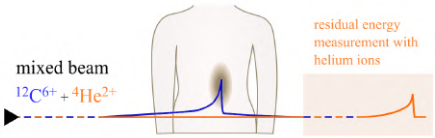


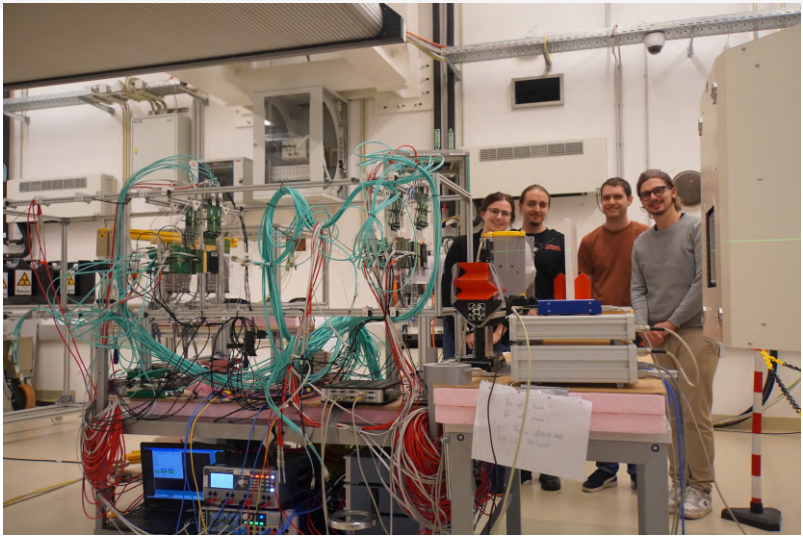
Figure: Mixed He/C beam (Kausel et al. 2025)

- Main concept
  - He and C ions have almost identical $\frac{q}{m}$
  - same energy per mass
  - different ranges
  - simultaneous treatment and range verification

- mixed beam project led by Matthias Kausel and Elisabeth Renner
  - sequential injection of He and C (double multiturn injection scheme)
  - first mixed beam in a clinical facility Kausel et al. 2025

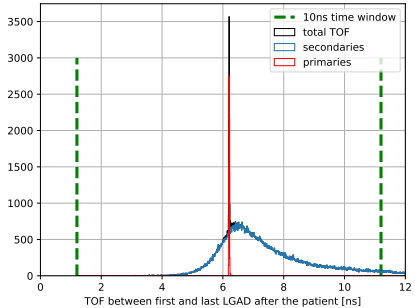
- range verification via TOF
  - LGAD-based TOF calorimeter
  - use 4D information for particle identification (PID)

Mixed Beam Experiment with 200MeV/u He



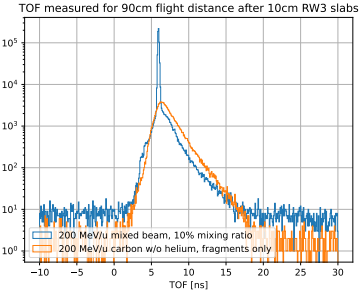
Experiment vs Simulation

- simulation



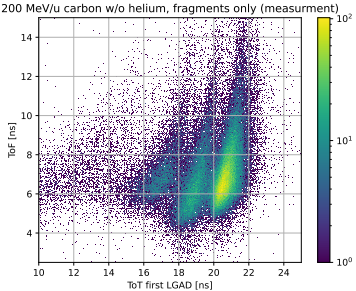
- sharp TOF peak from primaries
- TOF background mainly from C fragments

- experiment

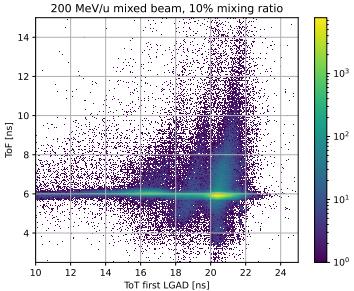


Particle Identification

- Carbon only (measurement)



- Mixed beam (measurement)



- Time over Threshold could be used for PID
- proper PID still under investigation

Summary and Outlook

Summary and outlook

- LGADs are promising 4D-tracking detectors with many applications
  - well-suited for ion imaging
- full TOF-iCT system was built
  - in and ex-vivo measurments of mice with MedUni Wien and FH Wiener Neustadt
  - first mixed beam experiment with LGADs
  - 3D RSP reconstruction is WIP
- long term goal: large-area system
  - requires dedicated ASIC which can handle high rates and large number of channels
  - dedicated module design to build low-mass large area system

Acknowledgements

Thank you for your attention!

- **TU WIEN/MBI**
  - Julius Altmüller
  - Thomas Bergauer
  - Harald Handerkas
  - Albert Hirtl
  - Matthias Kausel
  - Stephan Kwas
  - Julia Müllner
  - Elisabeth Renner
- **CREATIS**
  - Simon Rit
  - Aurelien Coussan
- **MedUni Wien**
  - Barbara Knäusl
  - Tina Pfeiffer
  - Lorenz Wolf
- **FH Wiener Neustadt**
  - Katharina Hill
  - Vanessa Fröhlich
  - Silvia Stocchiero
- **FBK**
  - Ashish Bisht
  - Matteo Centis Vignali
- **GSI**
  - Tetyana Galatyuk
  - Henning Heggen
  - Mladen Kis
  - Yevhen Kozymka
  - Sergey Linev
  - Jan Michel
  - Jerzy Pietraszko
  - Christian Joachim Schmidt
  - Michael Träger
  - Michael Traxler

This research was funded in part by the Austrian Science Fund (FWF) Erwin-Schrödinger Grant Nr. J 4762-N, GSI-TU Darmstadt F&E, DFG GRK 2128 and DFG IGRK 2891. The financial support of the Austrian Ministry of Education, Science, and Research is gratefully acknowledged for providing beam time and research infrastructure at MedAustron. We also thank Marie Wegner and Elisabetta Gargioni for providing the mouse phantom.

Backup slides

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