New time-of-flight ion computed tomography system based on LGADs

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on behalf of the ion CT group of TU Wien and the Marietta-Blau-Institute (formerly HEPHY) and the HADES LGAD group at GSI

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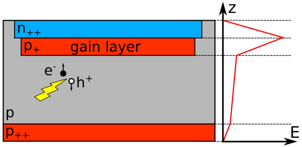
LGAD-based TOF-iCT system

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 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

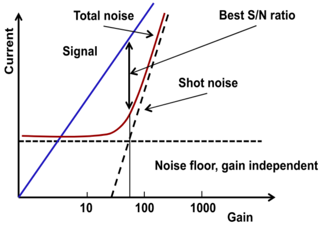
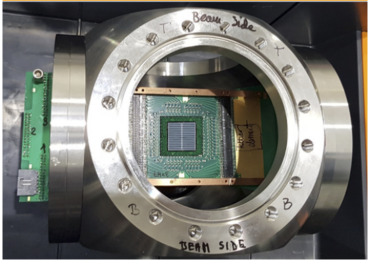


Figure: Sadrozinski et al. 2017

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

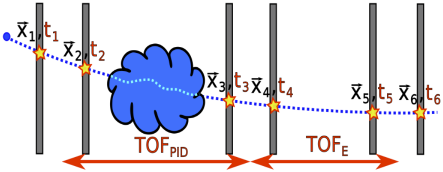
HADES T0 detector



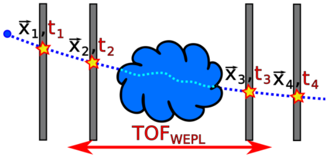
- but also medical applications
  - ion therapy beam quality monitor (Vignati et al. 2023)
  - **ion imaging**

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)



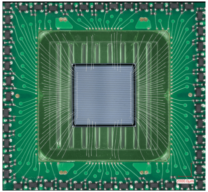
- **second approach: “sandwich” TOF-iCT**
  - indirect WEPL measurement via TOF through object (Ulrich-Pur et al. 2023)
  - no need for residual energy detector
  - requires only 4 4D-tracking layers



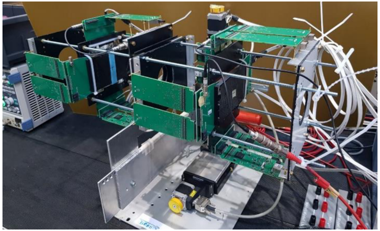
First demonstrator system

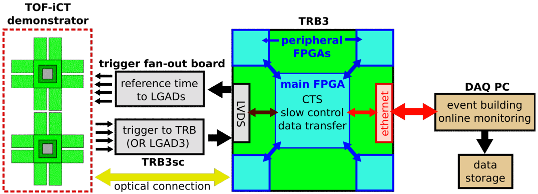
TOF-iCT demonstrator - first setup

- TOF-iCT demonstrator at GSI
  - 4 1x1 cm^2 FBK LGADs (strip pitch $= 100\,\mu$m)
  - discrete front-end electronics
  - FPGA-based TDCs with leading-edge discriminator
    - 4x DIRICH5s1 (32 channels per DiRICH)
  - imaging of small objects $\mathcal{O}(< 1\,\text{cm}^2)$



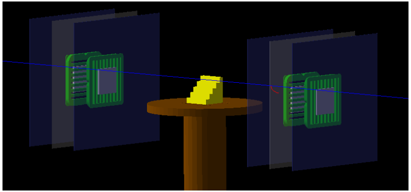
FBK single-sided LGAD strip sensor and FPGA-based TDC

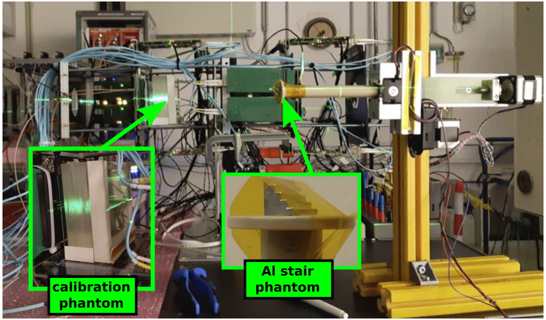


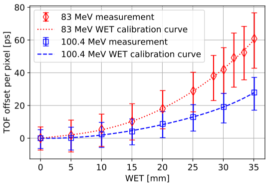


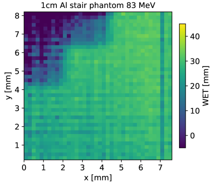
TOF-iCT demonstrator - first experiments

- first experimental TOF-based proton radiography (TOF-pRad) (Ulrich-Pur et al. 2024)
  - 10^5 p/s protons with 83 and 100.4 MeV
  - 1.6 mm PMMA slabs for WEPL calibration
  - Sandwich TOF-pRad of Al stair phantom was recorded



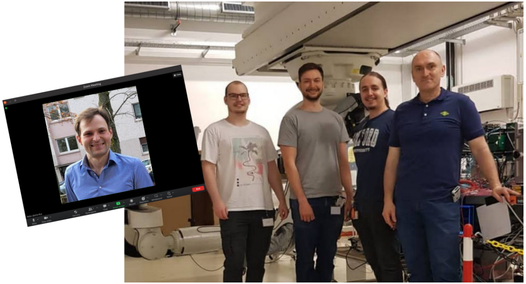


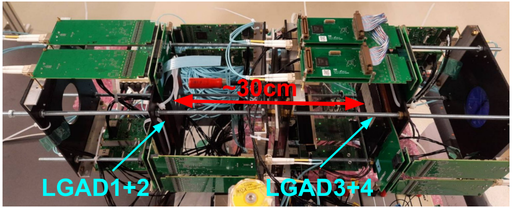




TOF-iCT demonstrator - TOF calorimeter

- second testbeam in June 24
  - TOF-iCT demonstrator operated as TOF calorimeter
  - TOF in air was correlated to beam energy
  - WET measurements were performed
  - different particle rates were tested

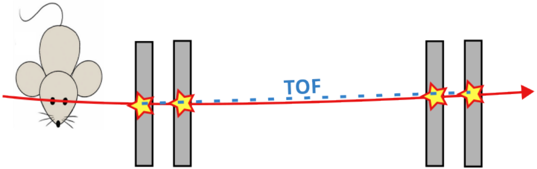




- small changed were made to the TOF-iCT demonstrator
  - added new FPGA TDCs to fully read out all sensors
  - scanner length was increased to 30 cm

TOF-iCT demonstrator - HeRad

- first experimental TOF-based He radiography (TOF-HeRad)
  - testbeam November 2024
  - WET measurements of CIRS slabs with He and TOF-HeRad of mouse phantom

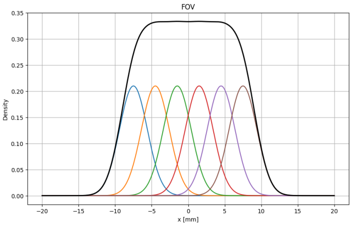


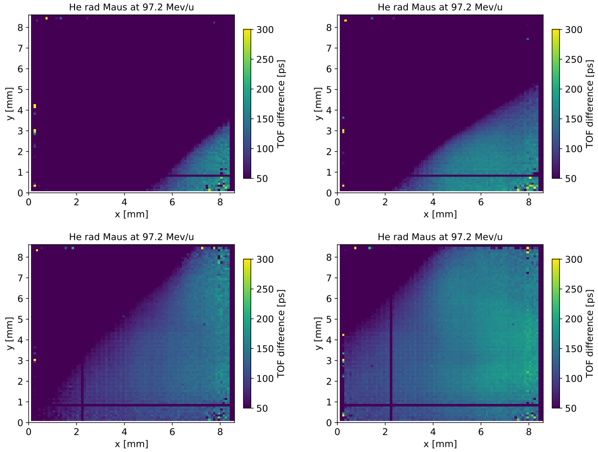
$$E_{\text{kin}} = m_0 c^2 \cdot \left(\frac{1}{\sqrt{1 - \frac{L^2}{c^2 \text{TOF}^2}}} - 1 \right)$$

- TOF-HeRad with 97.2 MeV/u He ions
  - mouse phantom from TU Hamburg (Wegner et al. 2023)
  - mouse head was imaged
    - 28 TOF-HeRads were stitched together
    - mouse preperation and x-ray CT was done by B. Knäusl (MedUni Wien)

TOF-iCT demonstrator - image stitching

- several He-pRADs were recorded after moving the phantom transversally by ≈ half the detector width
- preliminary stitching alogrithm using motor position
  - proper image registration will be performed in the future





TOF-iCT demonstrator - image stitching

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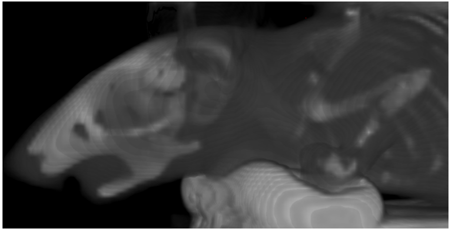
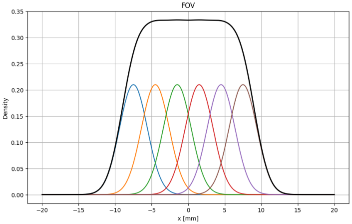
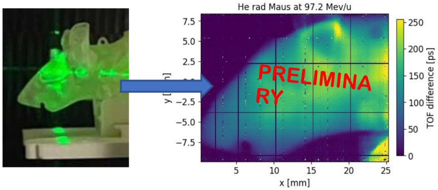
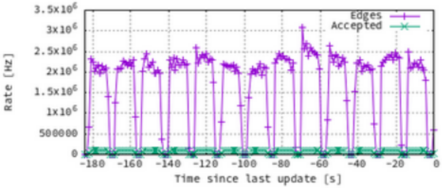






TOF-iCT demonstrator- DAQ speed

- first results with TOF-iCT demonstrator quite encouraging
- but what about speed?
  - during HADES experiment at GSI 10^8 p/s/cm^2 rising edges were detected
  - at MedAustron, on the other hand, a reduced particle flux was used to provide clean 4D particle tracks $\mathcal{O}(100\,\text{kHz}) - \mathcal{O}(4\,\text{MHz})$ rates)
  - however, current DAQ is limited by 100 kHz
- new and faster DAQ system is already available and being tested (DOGMA system)



Current TOF-iCT system

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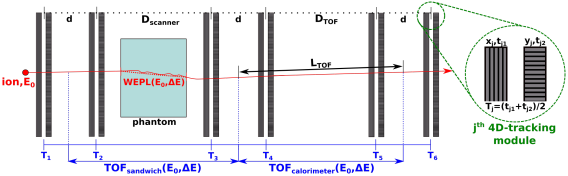
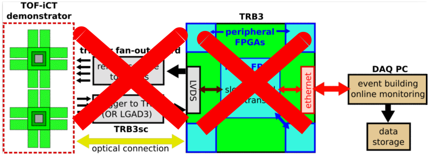
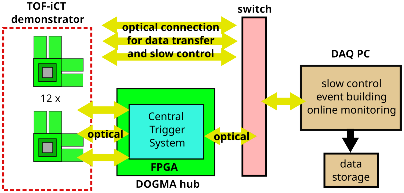




- small, but full TOF-iCT system
  - 12 single-sided LGAD strip sensors with upgraded front-end-electronics
  - **540 LGAD channels!**
- new, faster DOGMA readout system with optical data transfer and trigger



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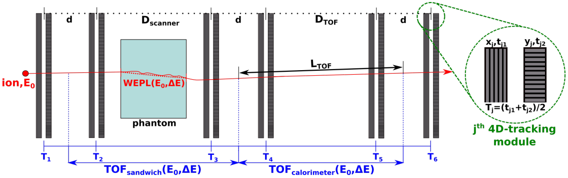

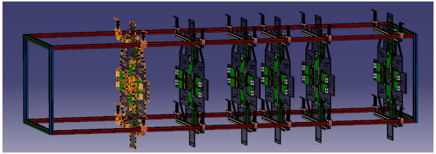

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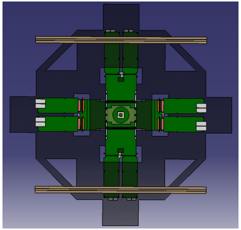
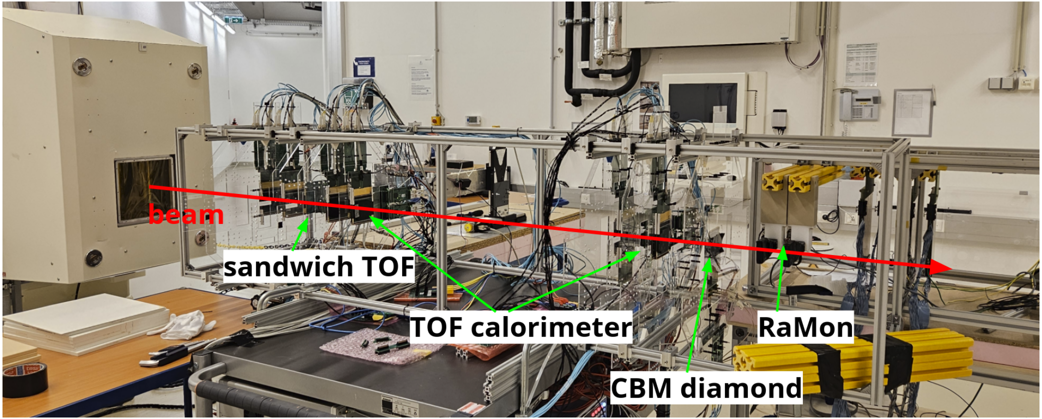


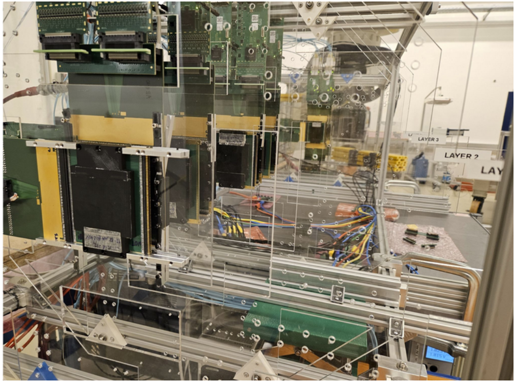
Current TOF-iCT system

- First test of new TOF-iCT system end of June 2025



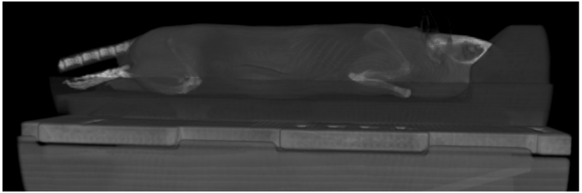
Current TOF-iCT system

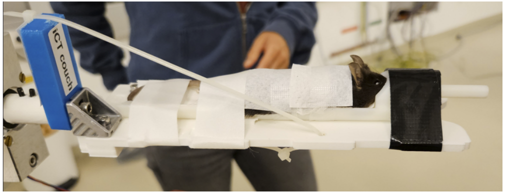
- calibration measurements with protons
  - MIP-like energy loss (comparision to old measurements)
- calibration measurements with helium
  - setup alignment run with 402 MeV/u
  - energies between 63.3 MeV/u and 205.2 MeV/u for TOF calorimeter calibration
- WET measurements
  - WET measurement of RW3 slabs
  - helium radiography of a sacrificed mouse



Current TOF-iCT system

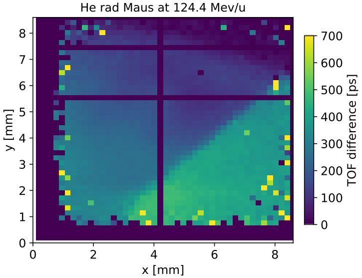
- HeRad of a sacrificed mouse
  - mouse was placed on a 3D-printed couch
  - several HeRads at $\approx 125\,\mathrm{MeV/u}$
- a micro-CT was taken the day before for comparison

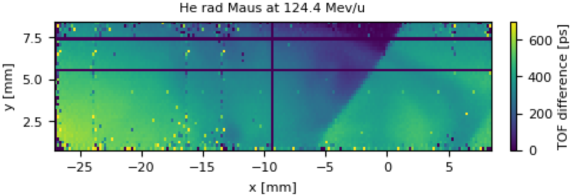




Current TOF-iCT system – preliminary results

- performance of the TOF-iCT system
  - even at clinical intensities data rate limit was not reached (20 Gbps)
  - slower performance than in lab (only 200 kHz DAQ rate)
  - has to be further investigated
- other than that new system performed quite well
  - first radiographs could be reconstructed
- full analysis is still ongoing
  - image stitching and 4D-tracking



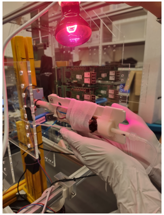


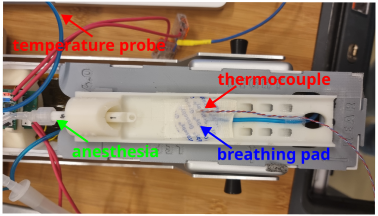
Future plans

In-vivo imaging with live mice

- collaboration with Medical University of Vienna and FH Wiener Neustadt
  - micro-CT, PET, MRI and SPECT available at MedAustron
  - three imaging mice dedicated for ion imaging
  - two test beams in upcoming months
  - mice can be adopted afterwards :)

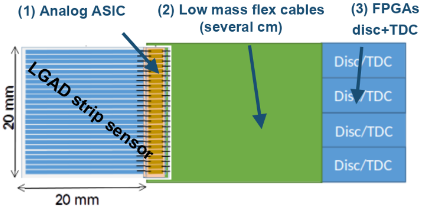
- monitoring of vital parameters
  - breathing pad
  - anal temperature probe
  - thermocouple for surface temperature
  - automated temperature management with two IR lamps WIP

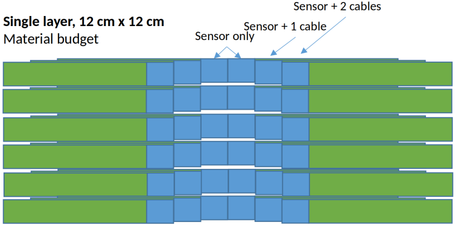




Future large-area 4D-tracking system

- novel LGAD sensors with increased fill factor will be investigated
  - new sensor production with trench-isolated LGADs planned
- upgraded readout electronics with increased number of readout channels
  - dedicated ASIC and FPGA-based TDCs
  - first tests with ASIC for SiC detectors
- dedicated low-mass module design for large active areas (tens of cm^2)
  - low mass flex cables to reduce overall material budget ($X/X_0 < 1\,\%$)





Summary and outlook

Summary

- LGADs are promising 4D-tracking detectors with many applications
  - well-suited for ion imaging
- two different scanner concepts
  - “standard” TOF-iCT system with a TOF calorimeter
  - sandwich TOF-iCT system without a residual energy detector
- TOF-iCT demonstrator system
  - demonstrator system based on LGAD strip sensors was built and tested
  - first sandwich TOF-pRad of an aluminium stair phantom was successfully recorded at MedAustron to show proof-of-principle
  - first experimental TOF-HeRad of a plastic mouse phantom was recorded with a TOF calorimeter
  - systematics of real experiment are being studied

Outlook

- full TOF-iCT with upgraded readout system and improved readout electronics
  - was recently built and tested
  - TOF-iCT of a live mouse is planned together with MedUni Wien
- Improvement of tracking and imaging algorithms
  - 4D-tracking algorithms will be further optimized
  - PID has to be thouroughly investigated
- 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
  - first tests with ASIC for SiC

Thank you for your attention!

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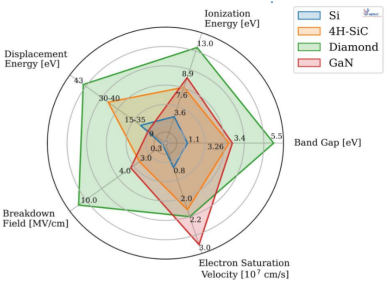
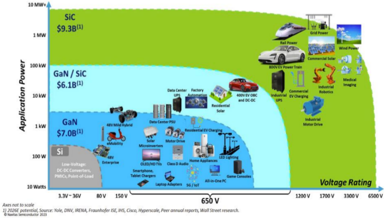
Backup slides

Investigate SiC LGADs

- SiC has a wide bandgap
  - insensitive to visible light
  - no cooling/pA currents even after irradiation
  - allows more lightweight detector design
- high V_{BD}, high high v_{sat}
  - high voltages
  - fast signals (good for timing)
- best industrial availability of wide-bandgap materials
- high ionization energy
  - small signals
  - Improve SNR with SiC-LGADs





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