IonCT system based on LGAD sensors

Silicon@GSI: Kick-off event, Darmstadt, Germany

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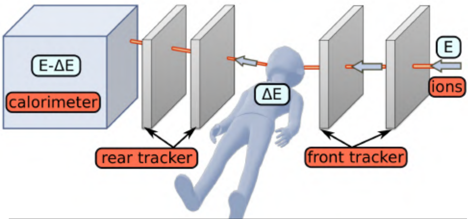
and the ion CT group of HEPHY and TU WIEN

Ion computed tomography (iCT)

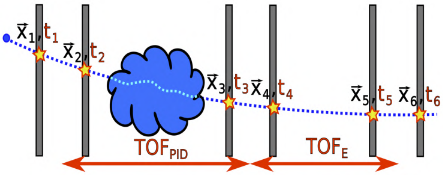
- **i**on **c**omputed **t**omography allows determining the relative stopping power (RSP) distribution inside a patient directly
  - improves treatment planning accuracy
  - requires tracking and energy measurement



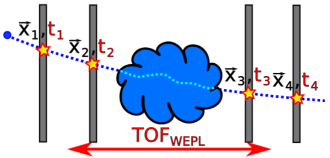
$$\int_L \text{RSP}\left(\vec{x}(s)\right) \mathrm{d}s = \text{WEPL}(E, \Delta E)$$

- several prototypes have been developed (Johnson 2018)
  - 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
  - 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)

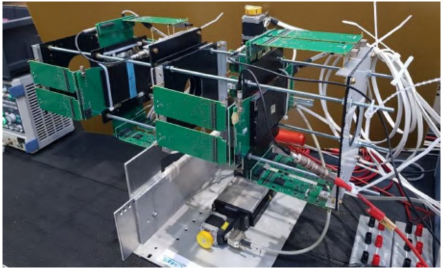


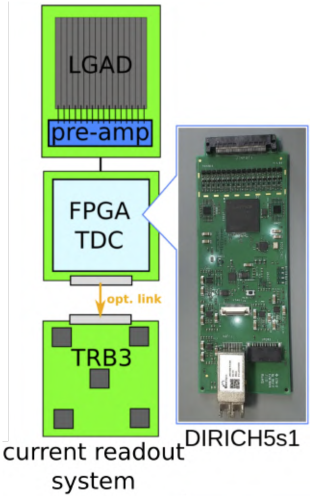
- **second approach: “sandwich” TOF-iCT**
  - indirect WEPL measurement via TOF through object (Ulrich-Pur et al. 2023)
  - no need for residual energy detector
  - requires only 4 4D-tracking layers



TOF-iCT demonstrator - first setup

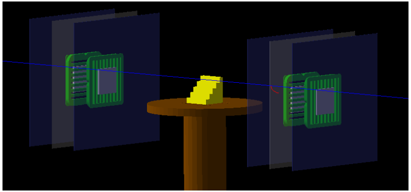
- TOF-iCT demonstrator at GSI
  - four $1 \times 1\,\mathrm{cm}^2$ FBK LGAD strip sensors (100 µm pitch)
  - discrete front-end electronics
  - FPGA-based TDCs with leading-edge discriminator
    - 4x DIRICH5s1 (32 channels per DiRICH)
  - imaging of small objects $\mathcal{O}(< 1\,\mathrm{cm}^2)$

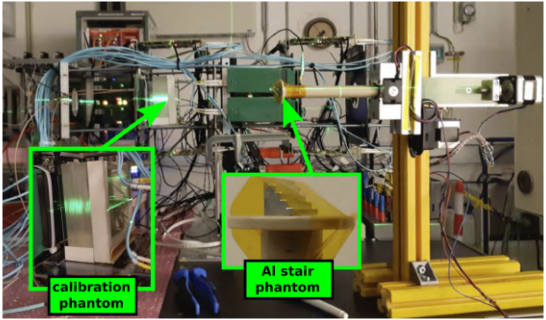


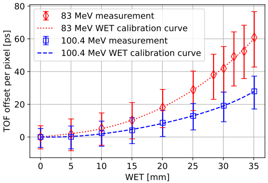


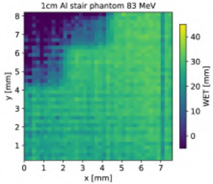
TOF-iCT demonstrator - first experiments

- 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



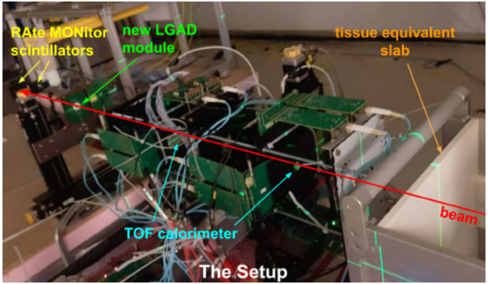


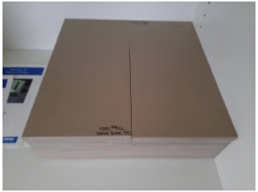


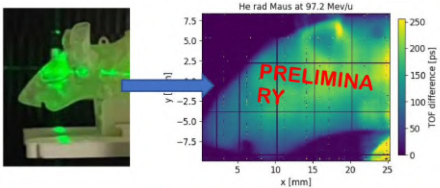


TOF-iCT demonstrator - first experiments

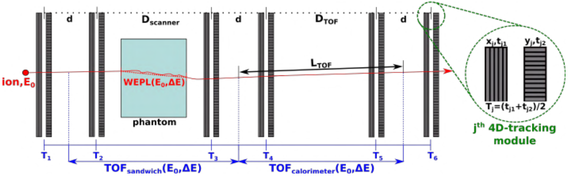
- first experimental TOF-based He radiography (TOF-HeRad)
  - now TOF calorimeter instead of sandwich TOF
  - SP measurements of bone and plastic water with p and He ions
  - TOF-HeRad of a plastic mouse head
    - required image stitching

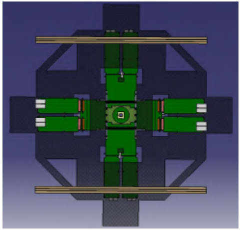




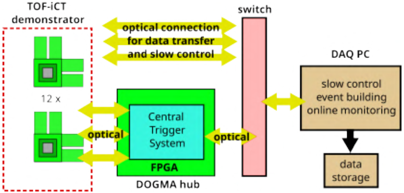


TOF-iCT demonstrator - current upgrade



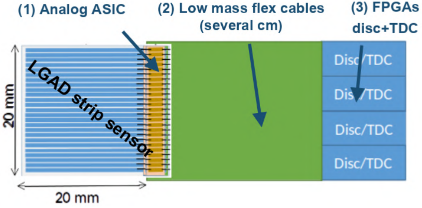


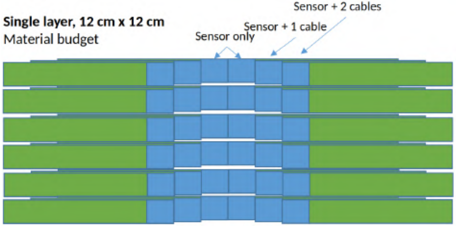
- small, but full TOF-iCT system
  - 12 single-sided LGAD strip sensors with upgraded front-end-electronics
  - DOGMA readout system with optical data transfer
- full ion CT of a live mouse is planned



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
- 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

- LGADs are promising 4D-tracking detectors with many applications
  - well-suited for ion imaging
- two possible scanner concepts
  - “standard” TOF-iCT system with 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 and first TOF-HeRad of a plastic mouse was successfully recorded at MedAustron to show proof-of-principle
  - further measurements with upgraded demonstrator system planned
- long-term goal: large-area 4D-tracking system

Thank you for your attention!

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Backup slides

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

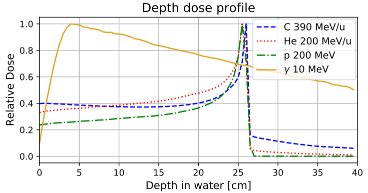


Figure: Bragg peak

photon therapy:

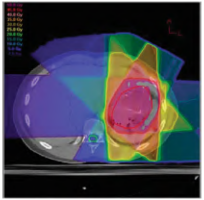
$$I = I_0 e^{-\mu x}$$

ion-beam therapy:

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

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

photon therapy:



proton therapy:

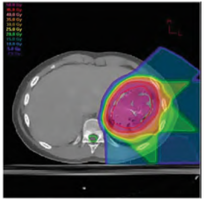


Figure: treatment plans (Linz 2016)

Motivation – 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)

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

$$\Downarrow$$

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

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

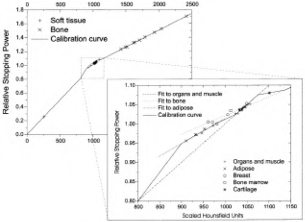


Figure: HU→RSP conversion (Schaffner et al. 1998)

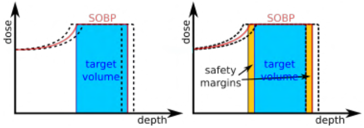
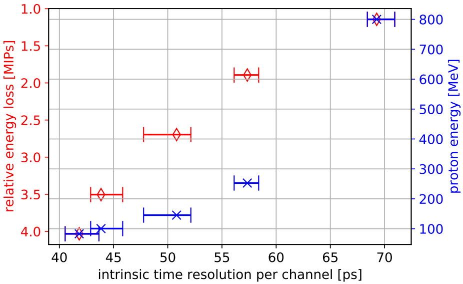


Figure: range uncertainties

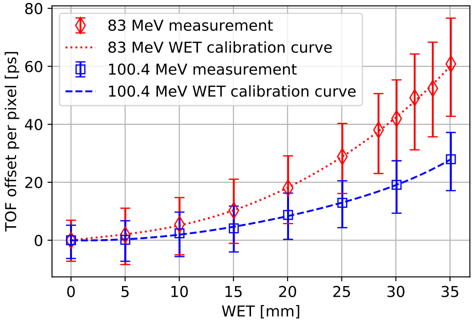
TOF-iCT demonstrator - sensor performance

- time-walk and offset correction was performed for each LGAD channel
  - synchronisation of all LGAD channels in each 4D-tracking layer
- intrinsic time resolution was measured for different beam energies
  - energies between 83 and 800 MeV
  - time resolution improves with lower beam energy
    - higher signal-to-noise ratio in detector at lower beam energies
    - median time resolution per channel between 42 ps (4.03 MIPs) and 68 ps (1.14 MIP)



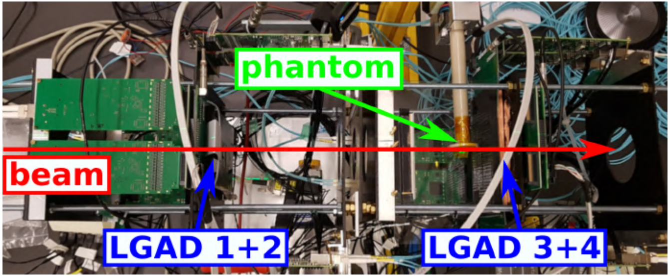
TOF-iCT demonstrator - WET calibration

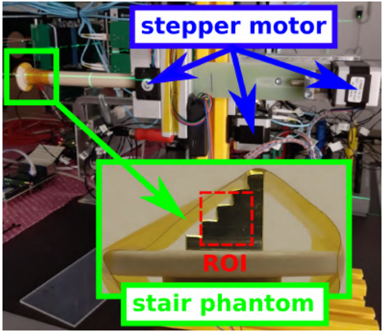
- TOF per pixel was measured for different PMMA absorber thicknesses at two different beam energies
- 5th-order polynomial was used to fit the increase in TOF to the corresponding WET



TOF-iCT demonstrator - pRad

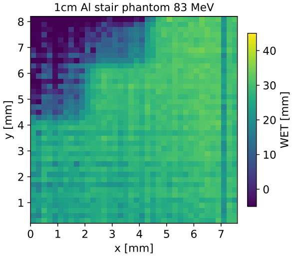
- Al stair phantom was mounted on rotational table
  - due to alignment and size of sensors, only part of phantom could be imaged (ROI)
- pRads were recorded at 83 and 100.4 MeV

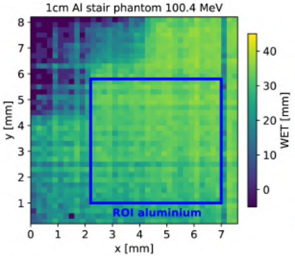




TOF-iCT demonstrator - pRad

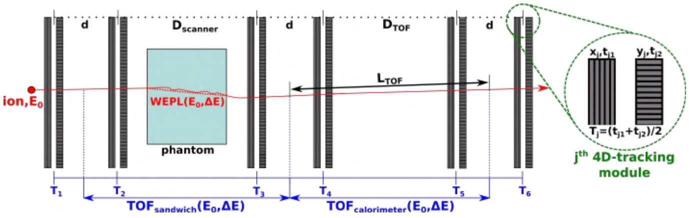
- increase in TOF was measured in $0.2 \times 0.2\,\mathrm{mm}^2$ pixels projected onto the last two LGAD planes (i.e. 2×2 LGAD strips per pixel)
  - WET calibration was applied and WET was collected in centre of phantom (blue square)
- Al stair phantom still clearly visible
  - however, WET overestimated (measured WET: $\approx 29\,\mathrm{mm}$, theory: $\approx 20.8\,\mathrm{mm}$)
  - upgrade of setup and more tests will follow





TOF-iCT demonstrator - next steps

- current setup consists of only 2 4D-tracking layers
  - allows only straight-line approximation
- upgrade of current setup with more layers planned (Erwin-Schrödinger grant)
  - main goal: record first TOF-based iCT
  - additional 4D-tracking layers will allow implementation of MLP
  - more experimental data for TOF through matter will be recorded to further test and improve sandwich TOF-iCT models



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