Ion imaging and material determination using a beam telescope

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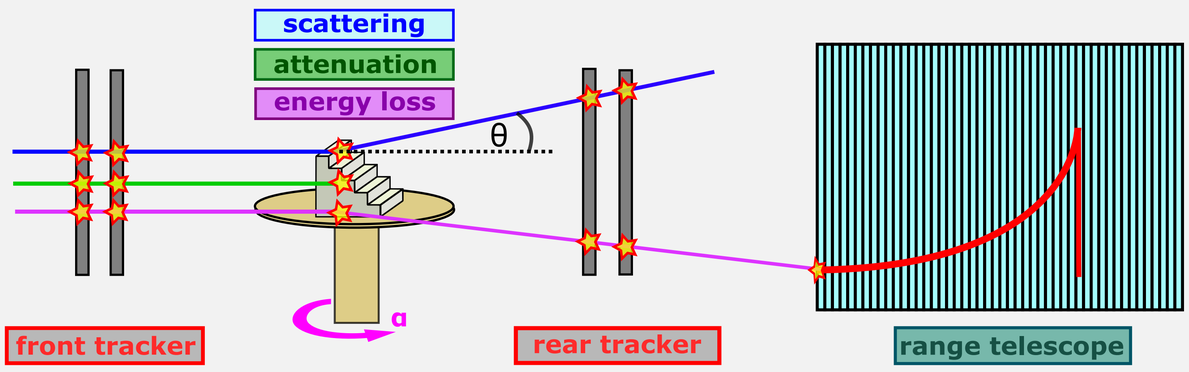
Introduction & Motivation

- x-ray imaging based on beam attenuation ⇐ linear attenuation coefficient μ
- ion imaging based on
  - multiple Coulomb scattering (MCS) ⇐ **material budget/scattering power** [1, 2]
  - beam attenuation ⇐ **linear nuclear inelastic cross-section** κ [3]
  - energy loss ⇐ **relative stopping power (RSP)** ⇐ goal: improve ion-beam therapy treatment planning [4]

Method



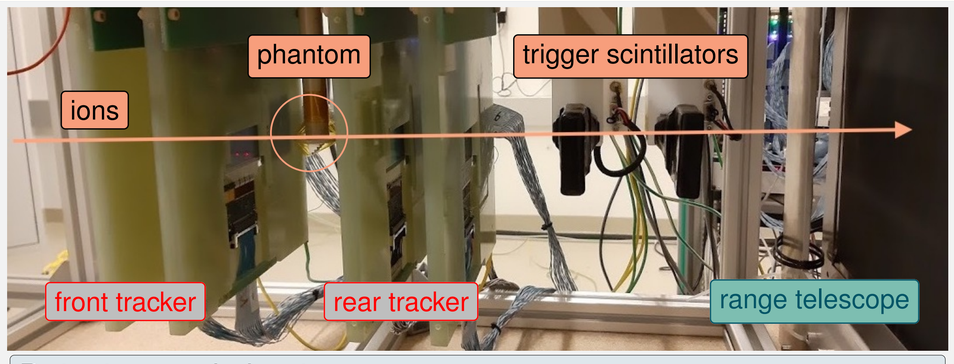
Proton/ion CT and radiography:

- calculate path estimate from **tracker** measurements and further measure
  - scattering angle for each ion ⇐ **tracker** ⇐ scattering power/material budget
  - beam attenuation ⇐ **tracker** ⇐ κ
  - ΔE for each ion ⇐ **calorimeter** / **range telescope** ⇐ RSP

Project objectives & Long-term vision

- **functional ion computed tomography (iCT) demonstrator** at MedAustron
  - measurement results of three ion imaging modalities
- upgrade based on **4D-tracking detectors** under investigation
  - **long-term goal:** make ion-beam imaging usable in the clinic
  - reduction of RSP error for accurate treatment planning

iCT demonstrator

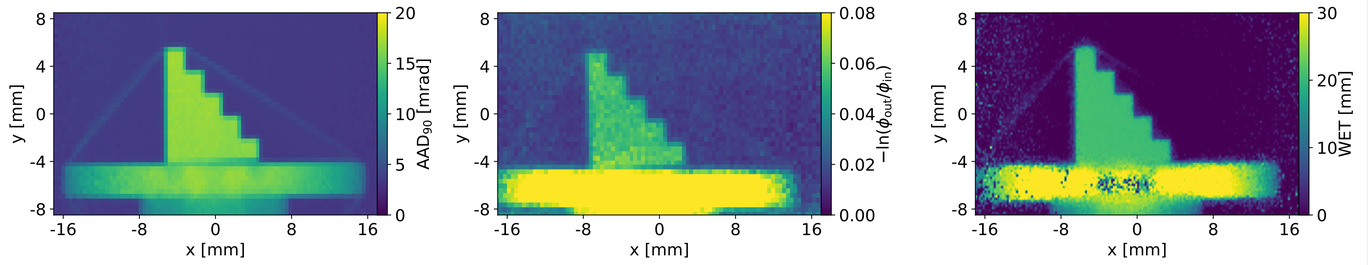


Detectors and phantom:

- double-sided silicon strip detectors for tracking [5]
- scintillator based calorimeter / range telescope [6]
- synchronization via AIDA2020 TLU
- 1 cm^3 Al stair phantom [7]
- setup tested at MedAustron

Results obtained with the iCT demonstrator

phantom

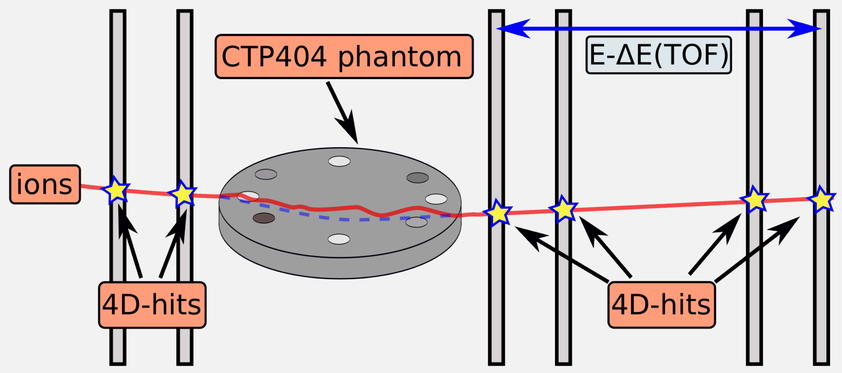


scattering pRad | attenuation pRad | energy-loss pRad

Performed measurements:

- phantom alignment always based on scattering proton radiography (pRad)
- energy-loss, scattering and attenuation pRads at multiple energies and angles [8, 9] → images: 100.4 MeV, 0°
- Attenuation pRad: trigger scintis **in front** of upstream tracker
- **DAQ rate between 1 and 30 kHz (depending on imaging modality)**

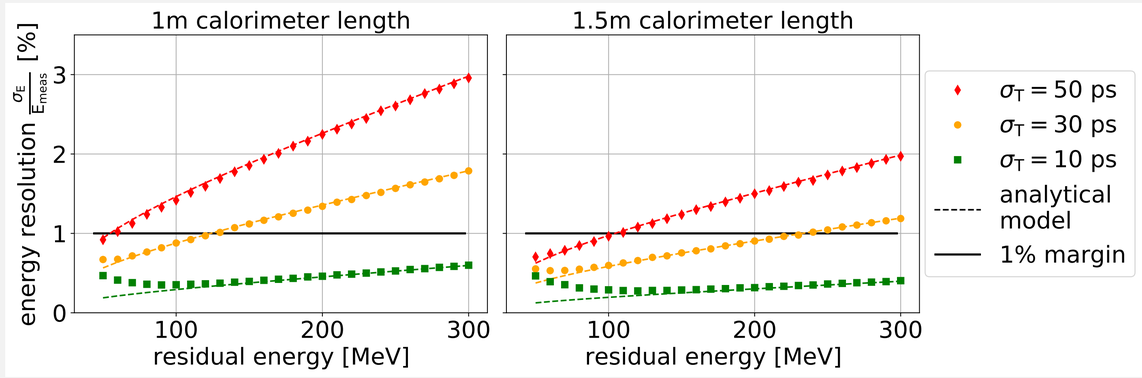
Feasibility study of a TOF-based iCT system



Simulation and optimization of a TOF-iCT system [10]:

- simultaneous measurement of position and time via 4D-tracking detectors
  - **improves rate capability**
  - allows energy loss determination via time-of-flight measurements
- detector model based on Low Gain Avalanche Detectors (LGADs)
  - influence of several system parameters on RSP image quality was studied

Energy loss determination via time-of-flight



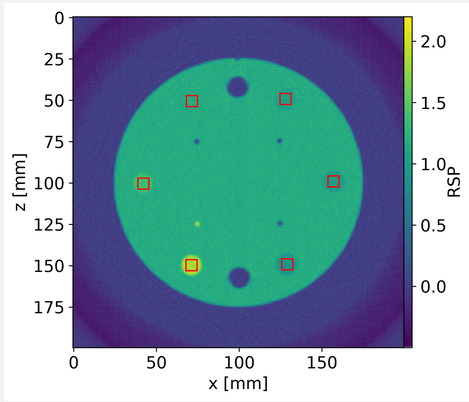
Energy resolution ideally $< 1\,\%$:

- mainly influenced by beam energy, intrinsic time resolution and TOF calorimeter length

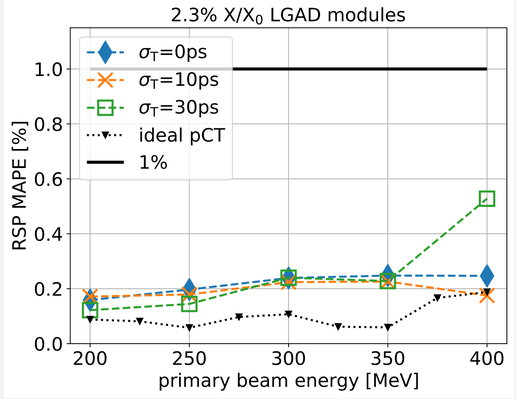
Accuracy of energy measurement:

- implementation of dedicated calibration procedure reduced relative error of energy measurement to $< 0.22\,\%$

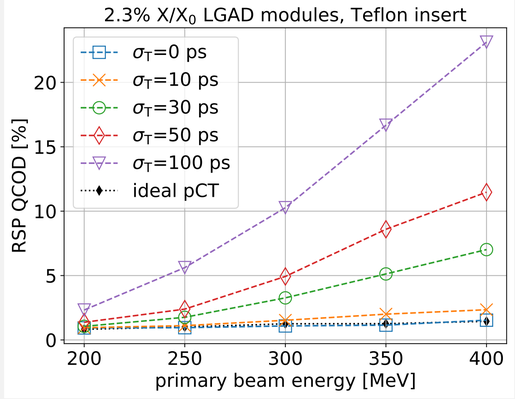
Results obtained with the TOF-iCT system



RSP map



RSP accuracy



RSP resolution

Image reconstruction and analysis:

- reconstruction of RSP map via distance-driven binning [11]
- RSP accuracy was determined in 6 inserts
  - no systematic dependence on any system parameter after calibration
  - RSP error always $< 0.6\,\%$
- RSP quartile coefficient of dispersion (QCOD) as a measure for the RSP resolution
  - mainly depends on beam energy, intrinsic time resolution and TOF calorimeter length
  - would benefit from energy modulated beam

Summary

- Three different ion imaging modalities (energy-loss pRad, scattering pRad and beam attenuation pRad) were measured with an iCT demonstrator
- A system upgrade using TOF measurements (based on LGAD technology) was studied using Monte Carlo simulations

Outlook

- First tests with HADES LGAD strip sensors [12] in 2022/2023
- **Development of a TOF-iCT demonstrator system based on trench-isolated LGAD strip sensors from FBK planned**

References and acknowledgements

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