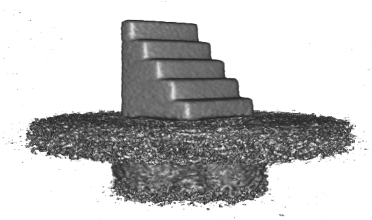
The TIGRE toolbox and its application to ion imaging



Stefanie Kaser on behalf of the Vienna ion CT collaboration
7th Annual Loma Linda Workshop

August 4th, 2021

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Introduction – Ion imaging group at TU Wien / HEPHY

- MedAustron: cancer treatment with protons, carbon ions
- Regular beamtimes available for non-clinical research
- Experimental program for ion beam imaging
  - Intermediate goal: Build ion CT demonstrator
- Joint project of HEPHY/TU Wien established
- Tracker is operational (2018)
- Range telescope is operational (2020)
- **First full pCT in October 2020**

Overall goal: clinical implementation

2017	First patient treatment Kickoff of ion CT project
2018	Operational tracker
2019	
2020	Operational range telescope Full pCT measured
2021	800 MeV p^+ commissioned Setup improvements

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Introduction – MedAustron I

- Ion therapy and research center
- Located in Wiener Neustadt, about 50 km south of Vienna

Image: MedAustron

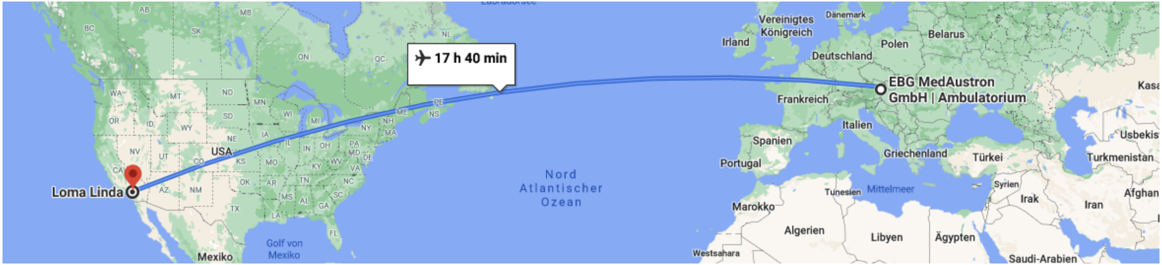

Image: Google Maps

Introduction – MedAustron II

Synchrotron accelerator complex

- Four irradiation rooms:
  - IR1: **Exclusive to research**
    (protons from 60 to 800 MeV, Carbon ions from 120 to 400 MeV/u)
  - IR2, IR3, IR4: Clinical use
    (Limited to clinical energies)
  - Beam only in one room at a time
- **Beam parameters:**
  - Beam delivery: pencil beam scanning
  - Spotsize: 7 mm to 21 mm FWHM
  - Clinical rates:
    - Protons ($\approx 10^9$ particles/s)
    - Carbon ions ($\approx 10^7$ particles/s)
  - Research: low flux settings were commissioned (Ulrich-Pur et al. 2021b)
    - $\geq 2.4 \times 10^3$ particles/s

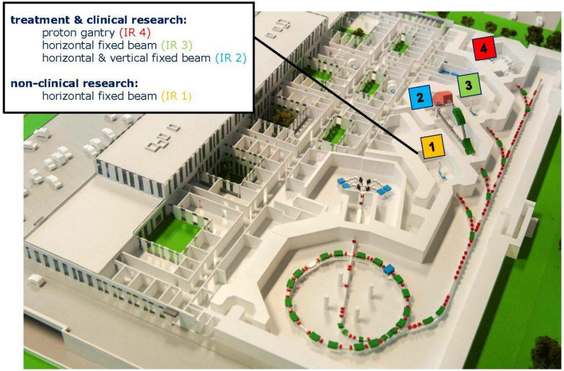

Image: MedAustron

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Introduction – MedAustron III

Cancer therapy

- Treatment during the weekdays
- First patient treated in 2016
- Currently: $\approx$ 30 sessions/d
- Carbon ion treatment since July 2019

Image: Treatment room

Research

- Regular beamtimes on weekends
- TU Wien/HEPHY, MedUni Wien

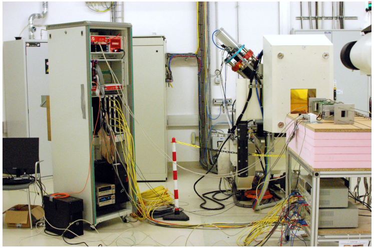

Image: IR1: research only

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Introduction – Starting point and challenges

- Joint ion imaging project of TU Wien and HEPHY
  - Profit from long-term experience on detector development from HEPHY
- Exclusive possibility to regularly conduct measurements at the MedAustron facility
- **Challenge:** A full workflow is needed to develop an ion CT demonstrator
  - Hardware part – trackers and calorimeter/range telescope
  - Software part – data readout, processing and **3D image reconstruction** is needed
  - Reconstruction workflow needs to be able to handle non-ideal measurement data
- Collaboration with MedUni Vienna (2019)
  - Experience in CT image reconstruction
  - **TIGRE toolbox**

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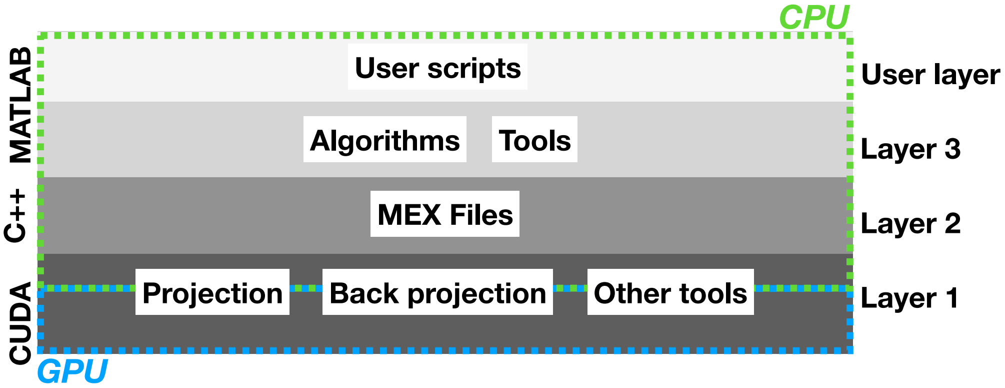
Introduction – TIGRE toolbox I

- **TIGRE: Tomographic Iterative GPU-based Reconstruction Toolbox**
  - Detailed description in Biguri et al. (2016)
- Developed for cone beam CT (CBCT)
- Single or multi-GPU computation → **fast**
- Layered structure
  - Code can be added/modified in a **modular** way
- Forward and backprojection operators are optimized for GPU computing
- **Wide variety of available algorithms** (direct, iterative)
- They are written in high-level language (Matlab, Python)
  - **User friendly** → only a few lines of Matlab code are necessary to perform a CT reconstruction

Introduction – TIGRE toolbox II



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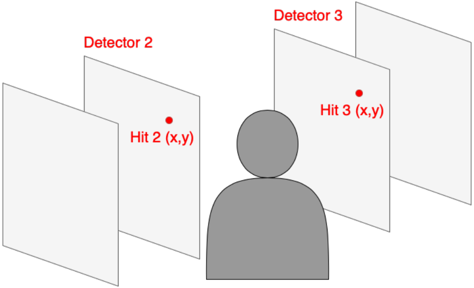
Method – Establishing a preliminary reconstruction workflow I

- The properties of TIGRE made it a suitable candidate for ion imaging
- Without modification → only straight-line approach possible
  - Non-straight ion path leads to limited spatial resolution
- We introduced additional *position cuts* on the projection data
- These cuts were based on the detector position upstream and downstream the phantom:
  - $\text{abs}(\text{hit}_3 - \text{hit}_2) < \delta$



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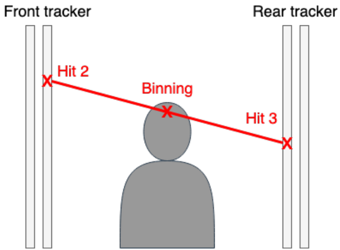
Method – Establishing a preliminary reconstruction workflow II

- Binning in central plane between trackers
- **Measurement**: WEPL obtained from range telescope measurement
- **Simulation**: Projection value per pixel is calculated using the range definition of Donahue et al. (2016)
- $R = \int_0^{E_{\text{in}}} \frac{\mathrm{d}E}{SP} = \frac{1}{\kappa}[\beta E_{\text{in}}^q + \alpha E_{\text{in}}^p + \frac{h}{g}(\exp(-gE_{\text{in}}) + gE_{\text{in}} - 1)]u$
- $\text{WEPL} = \int_0^{E_{\text{in}}} \frac{\mathrm{d}E}{SP} - \int_0^{E_{\text{out}}} \frac{\mathrm{d}E}{SP} = R_{\text{water}}(E_{\text{in}}) - R_{\text{water}}(E_{\text{out}})$
- E_{out} is directly taken from the last detector plane (idealized setup)

- **Reconstruction** on a Nvidia Quadro K620



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Results – Experimental setup I

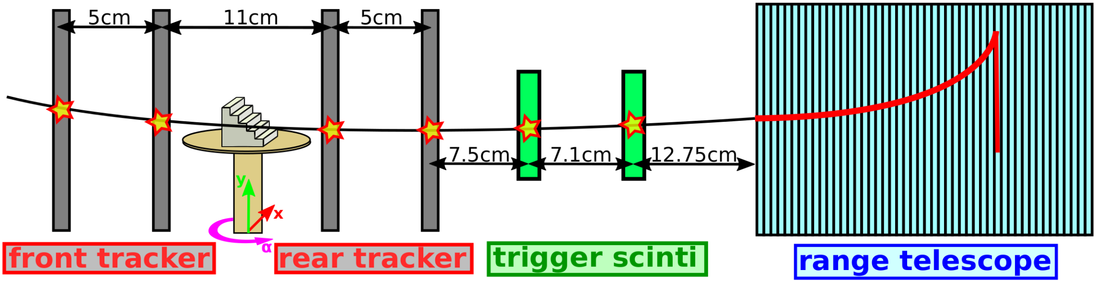
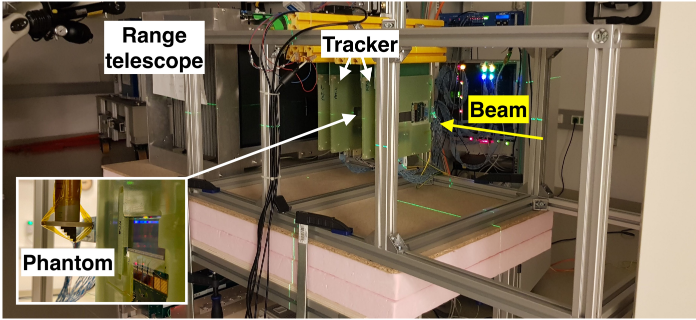
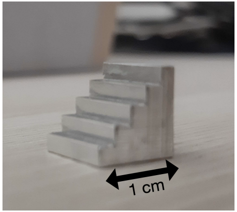


Image: iCT demonstrator setup (Ulrich-Pur et al. 2021a)

Results – Experimental setup II

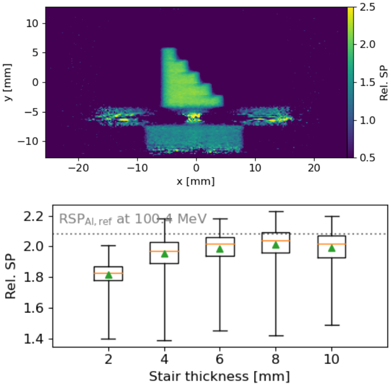




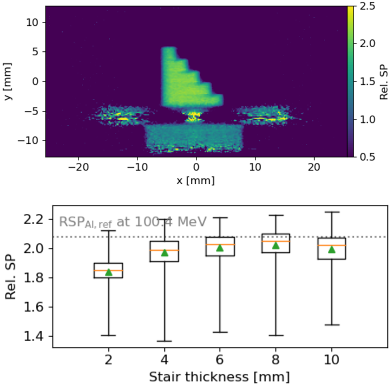
- 80 proton CT projections were measured with an ion CT demonstrator at MedAustron ($\approx$ 100 p^+ per pixel)
- An aluminum cube with a stair profile (side length of 1 cm) was imaged at 100.4 MeV
- Setup is described in Ulrich-Pur et al. (2021a)
- The projections were reconstructed with OS-SART (10 iterations)

Results – Experimental setup III

➙ 3 σ cuts only



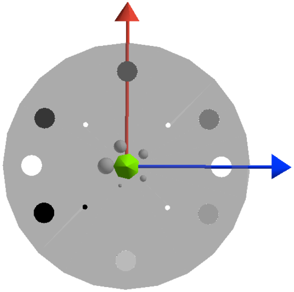
➙ 3 σ cuts + 0.5 mm position cuts



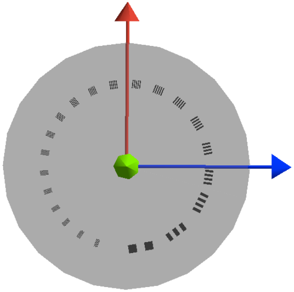
➙ Small, but measurable impact of position cuts for a small phantom

Results – Monte Carlo simulations I

- Projection data of Catphan modules were created in Geant4 (Agostinelli et al. 2003)
- Ideal detectors (can measure ΔE_i and $\vec{x}_i$) were assumed
- Straight line approach and cuts for non-straight paths were used
- 90 projections, 200 protons/pixel
- Reconstruction of central phantom part ($400 \times 20 \times 400$ voxels) with ASD-POCS and OS-SART

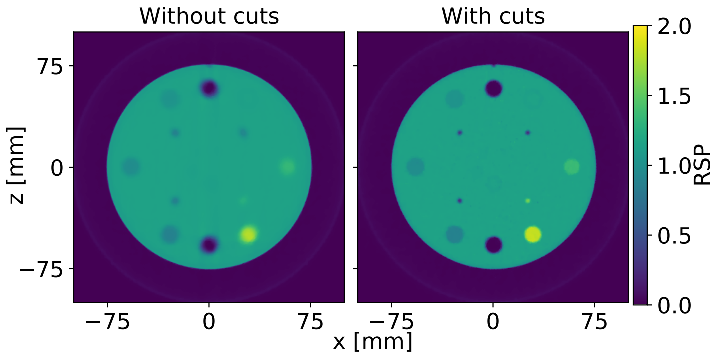


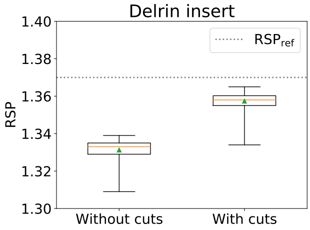
Sensitometry module



High resolution module

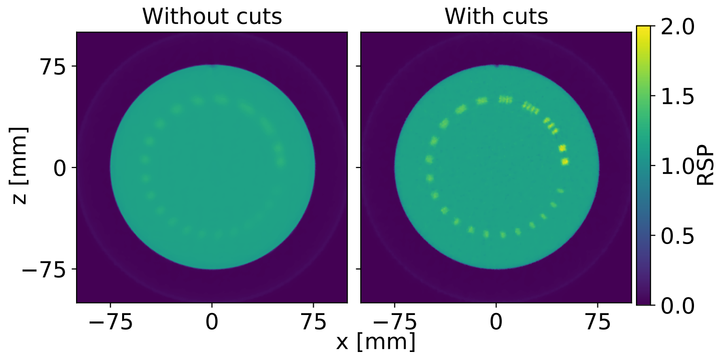
Results – Monte Carlo simulations II

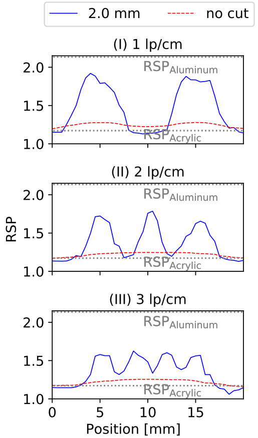




- Before 2 mm cuts: ≈ 3% deviation from reference value on average for Delrin insert
- After 2 mm cuts: ≈ 1% deviation from reference value on average for Delrin insert

Results – Monte Carlo simulations III





- Line pair resolution could be improved with cuts
- Problem remains: high data rejection rate! → ASD-POCS yielded better results than OS-SART

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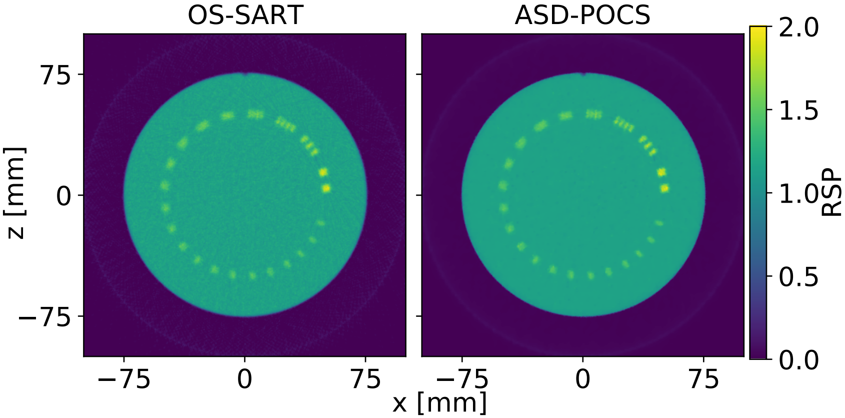
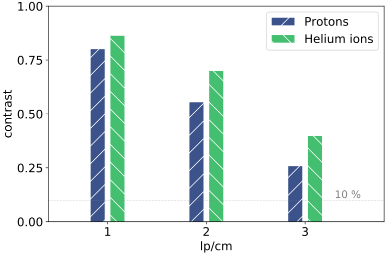
Results – Monte Carlo simulations IV



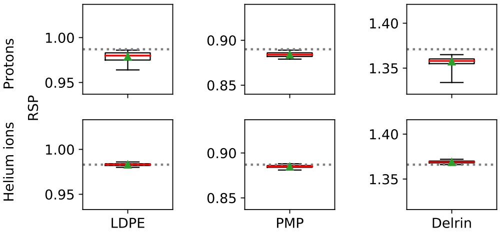
Results – Monte Carlo simulations V

- Method can also be applied to HeCT → lower data rejection rate, better contrasts and RSP accuracy
- Results of proton and HeCT using a 2 mm position cut and ASD-POCS reconstruction

- High Resolution module
- $\mathrm{MTF}_i = \frac{\langle \mathrm{RSP}_{\mathrm{max}} - \mathrm{RSP}_{\mathrm{min}} \rangle}{\mathrm{RSP}_{\mathrm{ref,max}} - \mathrm{RSP}_{\mathrm{ref,min}}}$



- Sensitometry module



Results – Technical note

➛ Interested? Great! Reach out to us and/or read the full study (Kaser et al. 2021)!

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Technical note

First application of the GPU-based software framework TIGRE for proton CT image reconstruction

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Outlook – First steps to improved ion imaging with TIGRE

- TIGRE offers multiple incentives to use it for ion imaging
  - Fast (multi-GPU computation possible), easy-to-use, multiple algorithms implemented,...
- Preliminary workflow needs to be further improved
- ion CT fits well with CUDA architecture since single ions are independent of one another
  - Treat ions separately in the imaging problem
  - GPU: use one thread per ion
  - Memory usage can significantly speed up/slow down the calculation
- Investigation of optimized ion CT projections
  - Based on Collins-Fekete et al. (2016)
- Keep the same layered structure for TIGRE to provide a user-friendly Matlab header to a underlying CUDA-accelerated script

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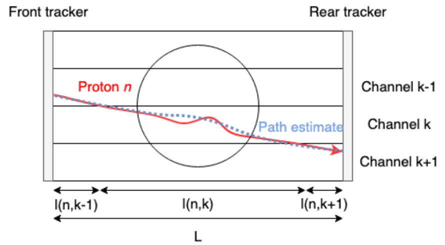
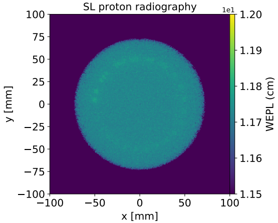
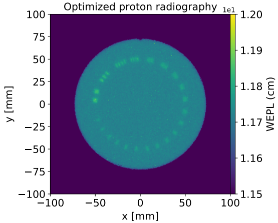
Outlook – Optimized radiographies

- Projection value of protons is assigned to multiple channels, depending on their path estimate
- Weight of projection value depends on length spent in the respective channel
- $$\mathrm{WET}_k = \frac{\sum_n^N \frac{l_{k,n}^2}{L_n^2} \mathrm{WEPL}_n}{\sum_n^N \frac{l_{k,n}^2}{L_n^2}}$$
  - l … length spent in the respective channel
  - L … overall channel length
  - WEPL … water equivalent path length of a specific proton n
  - WET .. water equivalent thickness assigned to channel k







Conclusion

- TIGRE is suitable for ion CT image reconstruction
- Additional data cuts were used
- CUDA acceleration → fast reconstruction results (under a minute for the investigated reconstructions)
- Cuts reject a major fraction of the initial data
- Solution: Sophisticated path estimate (MLP, CS)

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