

Imaging with ion beams at MedAustron

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TECHNISCHE
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1 The MedAustron facility

2 Motivation for imaging with ions

3 Our prototype

4 Next steps



The MedAustron facility



Image: MedAustron¹



Image: ArcGIS²

¹<https://medaustron.at>

²<http://www.arcgis.com/home/webmap/viewer.html?useExisting=1>

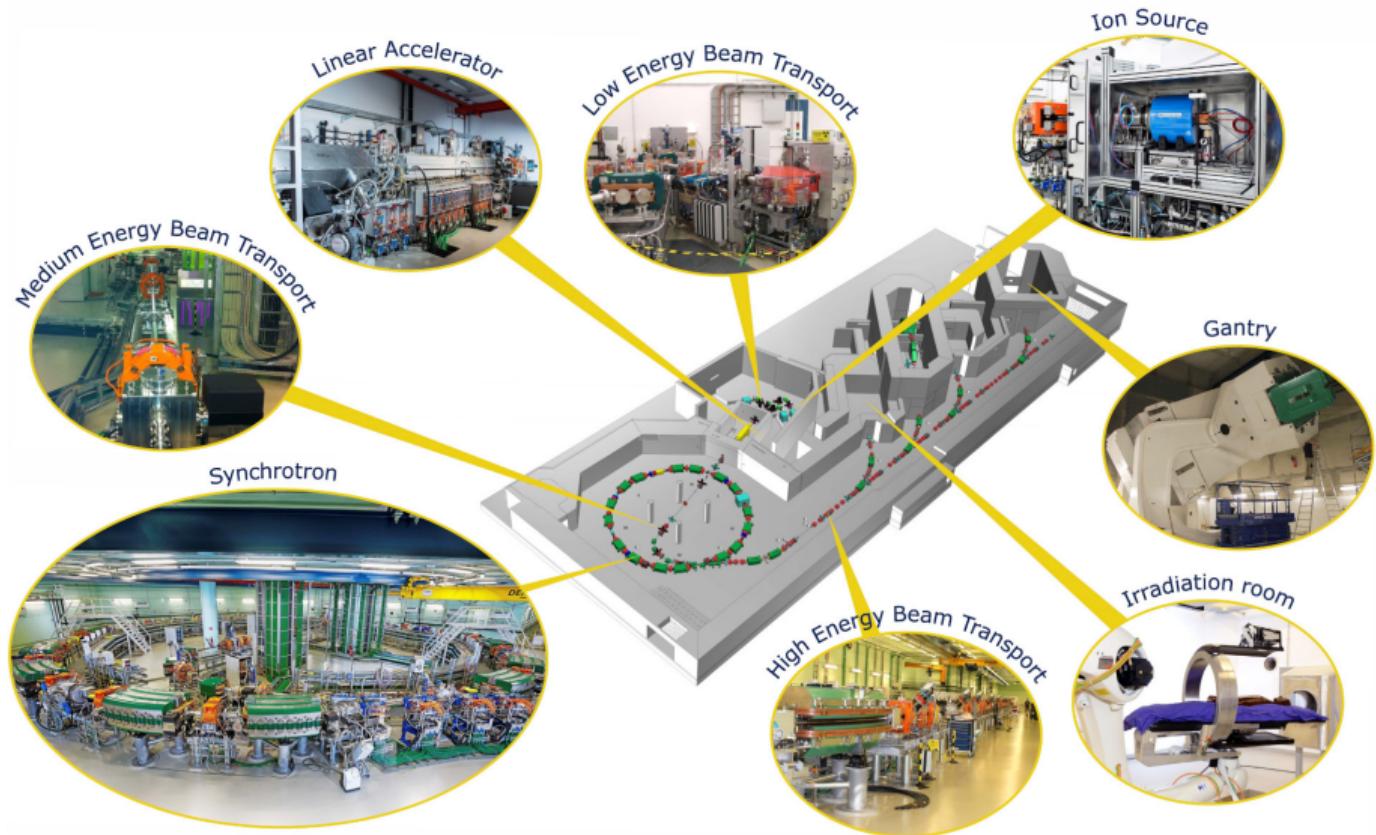


Image: MedAustron

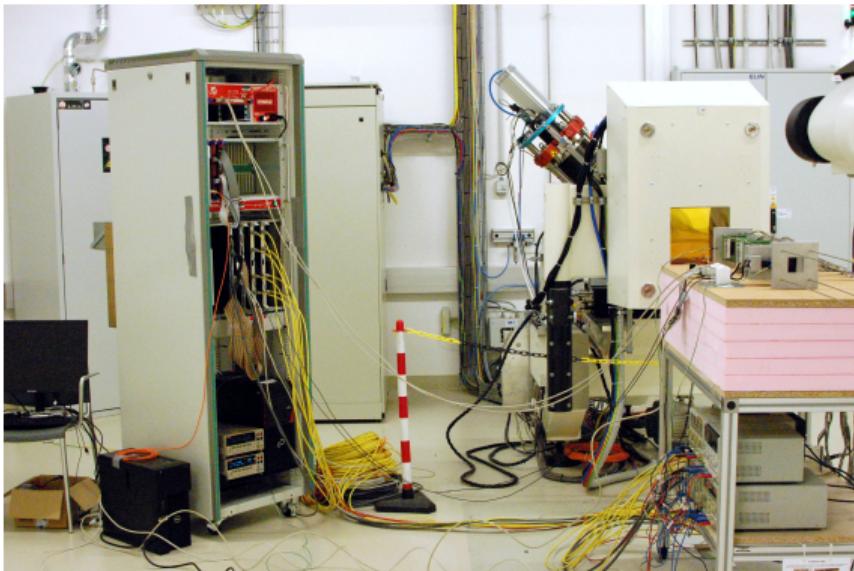


Image: MedAustron

The MedAustron facility

- Accelerator complex
 - ▶ Protons 60 MeV to 250 MeV (clinical)
 - ▶ Carbon ions 120 MeV/u to 400 MeV/u
 - ▶ Spill extraction $\approx 10^9$ particles per 5s
- Cancer therapy and clinical research
- Non-clinical research (NCR)
 - ▶ TU Wien, MedUni Wien
 - ▶ Regular beamtimes on weekends, nights
 - ▶ NCR offices, separate irradiation room
- Four irradiation rooms

Beam only in one room at a time

IR1 Exclusive to NCR, protons up to 800 MeV

IR2 Clinical, horizontal & vertical beamline

IR3 Clinical, similar to room 1
(Limited to clinical energies)

IR4 Clinical, gantry, only protons

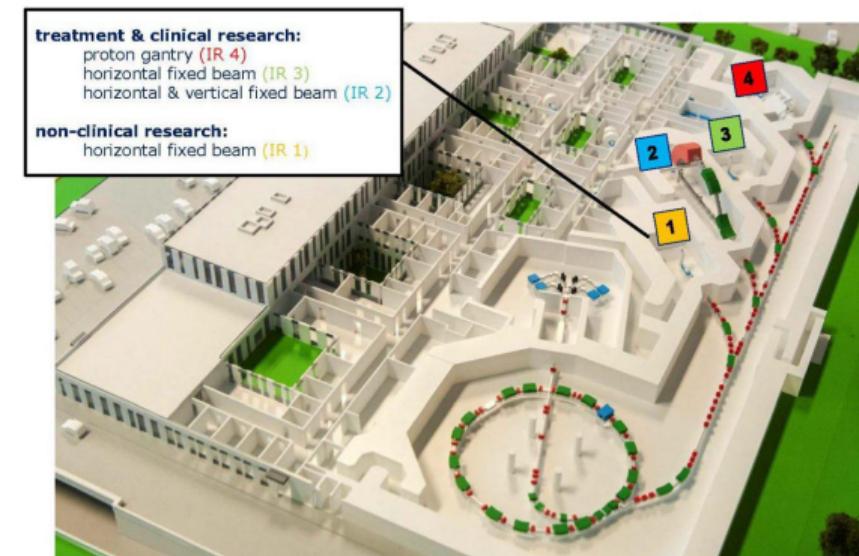


Image: MedAustron

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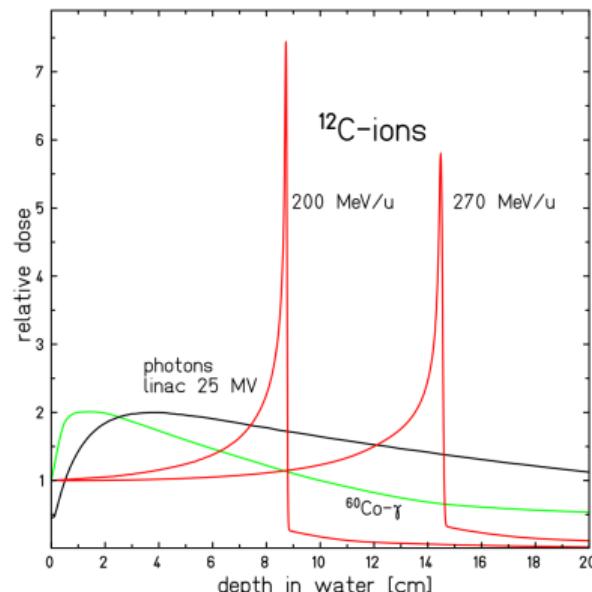


Motivation for imaging with ions

Motivation for therapy with ions

- Dose profile advantage over photons
 - ▶ Inverted profile compared to photons
 - ★ Low dose on entrance channel
 - ★ Protons: primaries are stopped \approx at the range
 - ★ Carbon: low dose on exit channel, due to secondaries
 - ▶ Energy dependent range
 - ★ Superposition \rightarrow Spread-out Bragg-Peak
 - ★ Ability to map dose-deposition to target
- Medical advantages

Treatment planning based on X-ray CT scans



Dose profiles of photons and carbon ions as function of penetration depth. Image: Schardt et al. 2010³

³<https://doi.org/10.1103/RevModPhys.82.383>

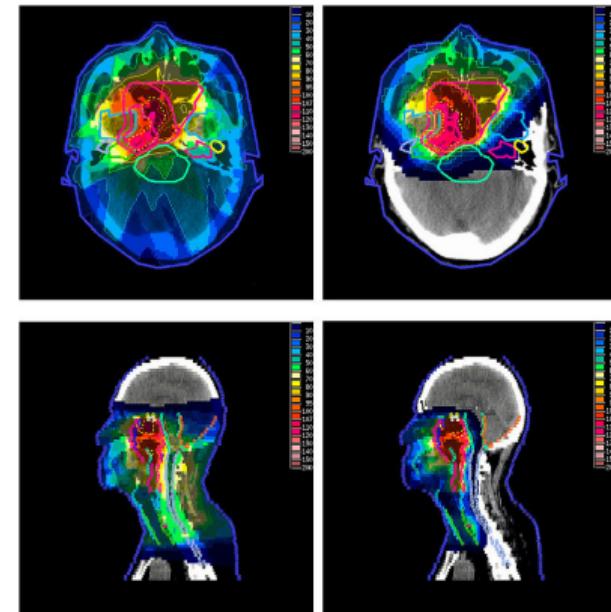
Motivation for imaging with ions

Motivation for therapy with ions

- Dose profile advantage over photons
- Medical advantages
 - ▶ Accurate dose-deposition
 - ★ Treatment of tumours close to radio-sensitive tissues, e.g. optical nerve
 - ▶ Reduced integral dose
 - ★ Advantage for treatment of children, young adults (secondary malignancies)
 - ▶ Direct ionization of charged particles
 - ★ Treatment of oxygen deprived tumours
 - ▶ High relative biological effectiveness (RBE)
 - ★ Many double-strand breaks → Increased cell mortality in tumours

Treatment planning based on X-ray CT scans

⁴<https://doi.org/10.1186/1748-717X-3-4>



Dose comparison for photon (left) and proton (right)⁴ treatment plans. Image: Taheri-Kadkhoda et al. 2008⁴

Motivation for imaging with ions

Motivation for therapy with ions

- Dose profile advantage over photons
- Medical advantages

Treatment planning based on X-ray CT

- Different interactions with matter
- CT provides Hounsfield Units (HU)
- Treatment planning interested in range
- Conversion HU → stopping power
 - ▶ Introduces conversion errors
 - ▶ Material-dependent ambiguities

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

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

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

$$S(E) = -\frac{dE}{dx}$$

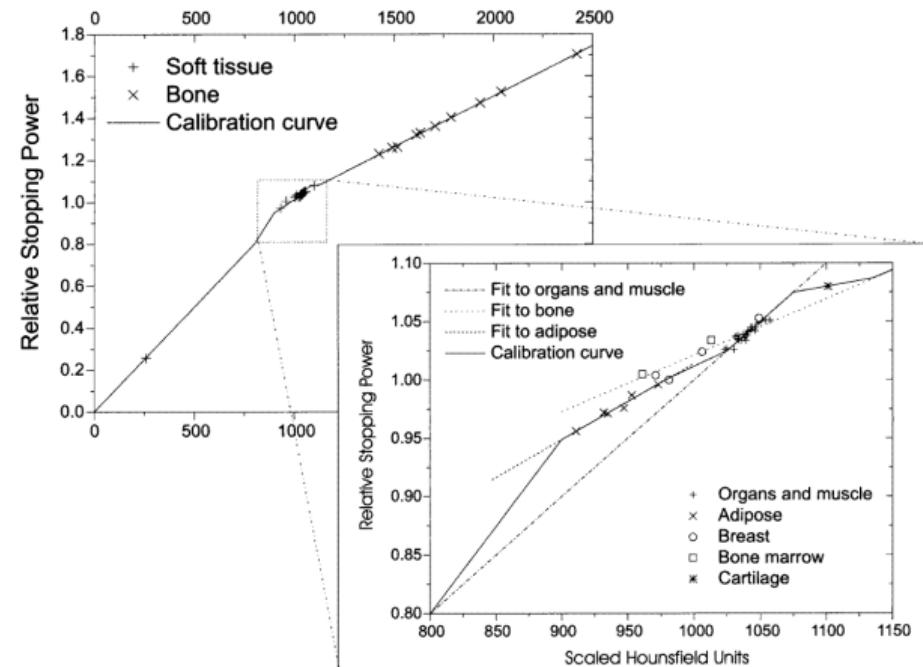
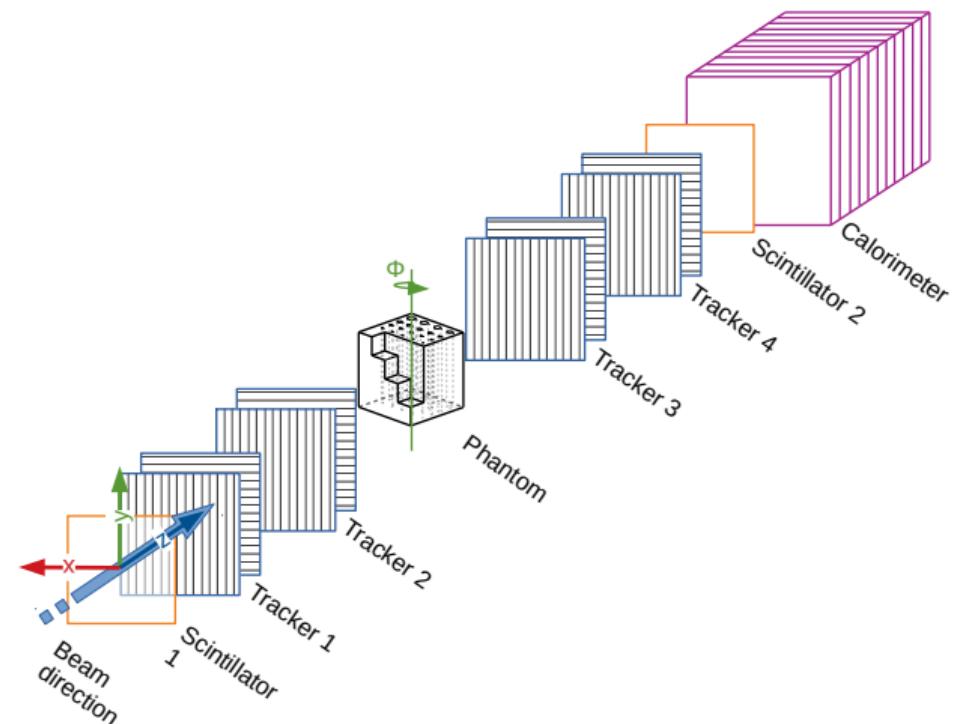


Image: Schaffner and Pedroni 1998⁵

⁵<http://iopscience.iop.org/article/10.1088/0031-9155/43/6/016>

Motivation for imaging with ions – Proton CT

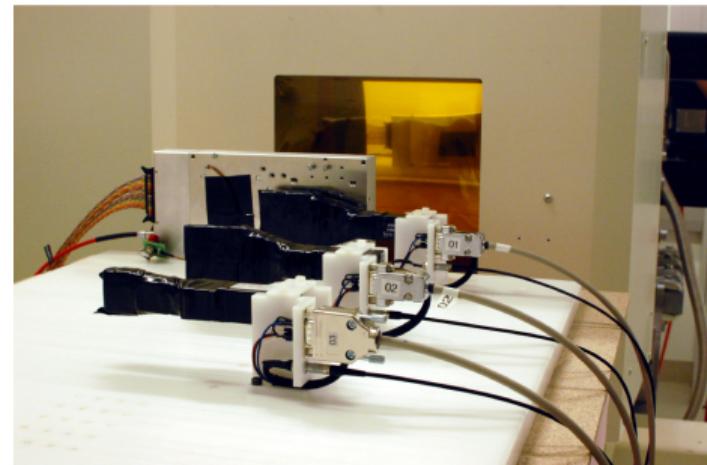
- Object to be irradiated
 - ▶ Phantom or patient
 - ▶ Rotation ϕ around y-axis
- An ion beam along the z -axis
- Trackers before and after object
 - ▶ Measure inbound and outbound position and direction
- Calorimeter at the very end
 - ▶ Measurement of residual energy
- Scintillators (and a trigger logic)
 - ▶ Synchronous operation
 - ▶ Individual proton tracks
- Image reconstruction
 - ▶ Determine 3d stopping power distribution of object



Motivation for imaging with ions – Pre-requirements

Concerns in data acquisition

- Clinical beam has high flux of $\approx 10^9$ particles per 5s
 - ▶ Tracker cannot separate tracks at high rate



Solution

- Rate reduction \Rightarrow joint effort with accelerator physicists
 - ▶ Extraction parameter adaptations
 - ▶ Operation below beam delivery system noise threshold
 - ★ Beam signal not distinguishable from noise
 - ★ No pencil beam scanning
 - ▶ Scintillator-coincidence counting to confirm rates
- However: current tracker too slow for clinical pCT
 - ▶ Upgrade sensors/readout electronics
 - \Rightarrow Imaging at higher rates

⇒ Also see Peter Paulitsch poster⁶

⁶Paulitsch n.d., <https://indico.cern.ch/event/716539/contributions/3246159>

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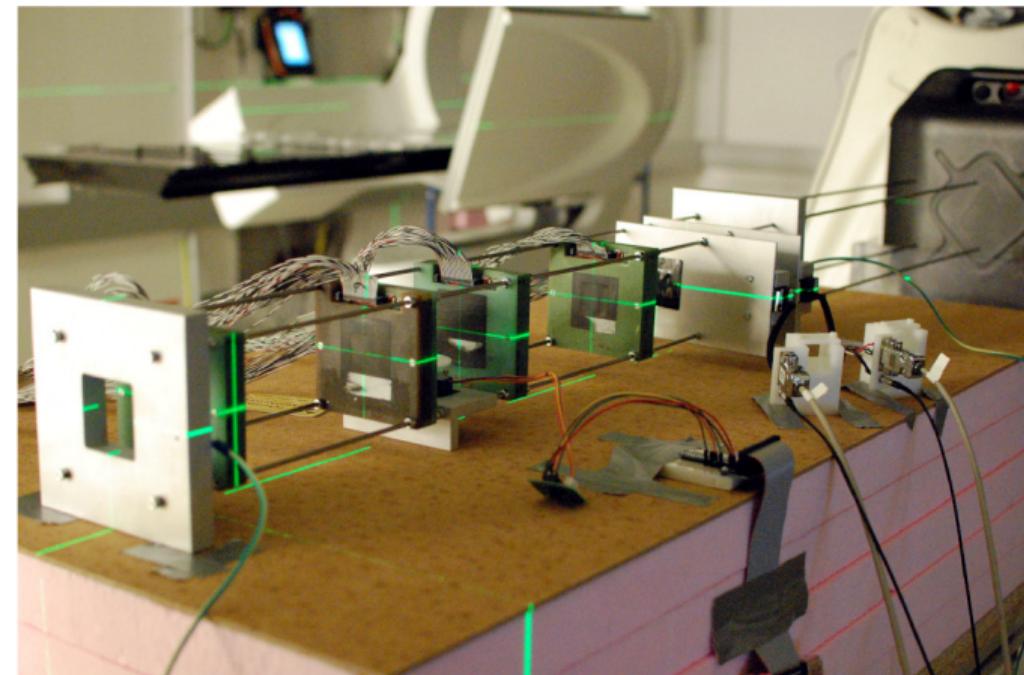
3 Our prototype

4 Next steps



Our prototype

- Four tracking detectors
 - ▶ Arranged in pairs of two
 - Triggered by a coincidence of two scintillator signals
 - Rotating sample table between tracker pairs
 - Calorimeter is a work-in-progress
 - ▶ Not yet operational
 - Goal: proton CT at MedAustron
 - Currently: material budget imaging, proton scattering as signal
- Method: Schütze and Jansen 2018⁷



⁷https://doi.org/10.1007/978-981-13-1316-5_31

Our prototype – Detector stats

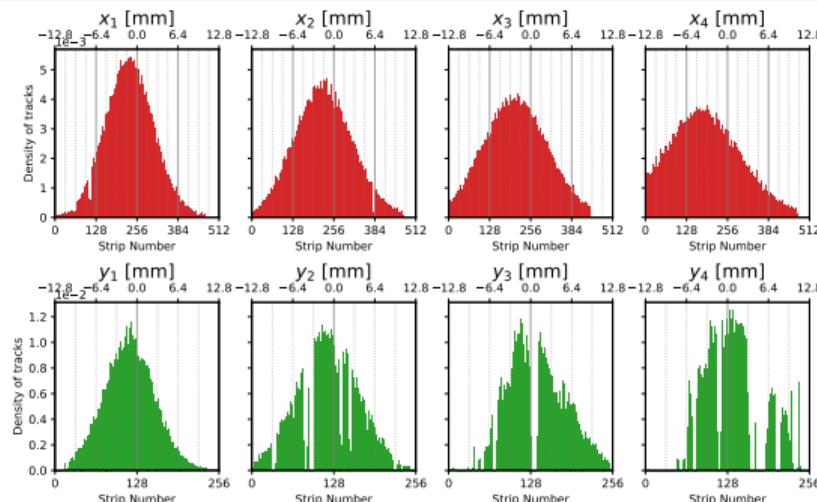
- Double-sided silicon-strip sensors
 - ▶ Thickness of 300 µm, orthogonal strips
 - ▶ X-side: p-doped with a pitch of 50 µm
 - ▶ Y-Side: n-doped with a pitch of 100 µm
- Sensitive area of $(2.56 \times 2.56) \text{ cm}^2$
 - ▶ Number of strips 512 (X), 256 (Y)
- VME-based detector readout
 - ▶ APV25 chip from CMS tracker
French et al. 2001⁸
 - ▶ Prototype readout for Belle-II experiment
Friedl et al. 2008⁹
 - ▶ Achieved event-rate $\approx 30 \text{ Hz}$
 - ★ Pure, raw, non-optimized, event-by-event readout



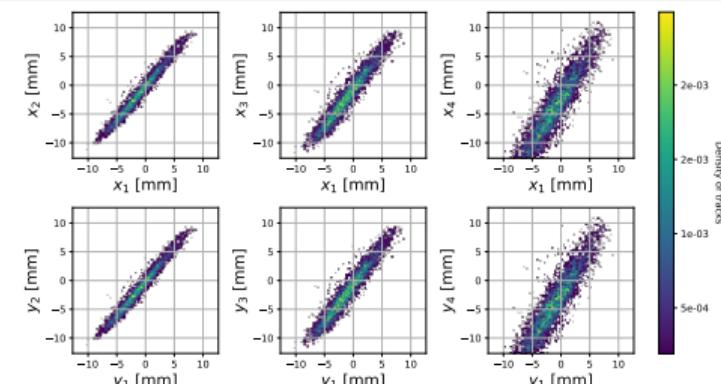
⁸[https://doi.org/10.1016/S0168-9002\(01\)00589-7](https://doi.org/10.1016/S0168-9002(01)00589-7)

⁹<https://doi.org/10.5170/CERN-2009-006.417>

Our prototype – Pre-processed data at 145.4 MeV

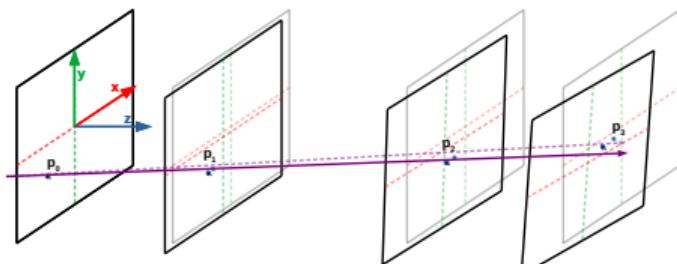


- Hit-profiles on each plane
- Many bad (noisy) strips on y-axis
 - ▶ Due to use in radiation hardness study
- Beam offset and angle are visible
 - ▶ Misalignment is apparent



- Hit-coordinates on plane_1 vs plane_i
- Expected correlation
 - ▶ Thin, 45 degree line through zero
- Measured correlation
 - ▶ Wide line, due to scattering
 - ▶ $\mathcal{O}(\text{mm})$ offset, increases with i

Our prototype – Tracker alignment at 252.7 MeV



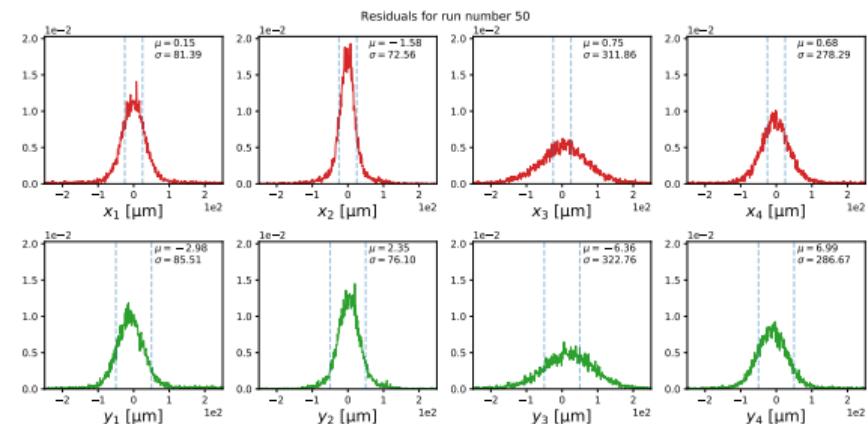
Alignment with EU Telescope Rubinskiy 2010¹⁰

1 Fit tracks through measured hits

- ▶ Kalman filter with deterministic annealing
Frühwirth and Strandlie 1999¹¹

2 Hand track fits to alignment algorithm

- ▶ Millepede-II Blobel 2006¹²
- ▶ Simultaneous least squares fit with constraints



3 ... which returns alignment constants

- ▶ x, y -shifts, z -rotations

4 Estimate track resolution at each module

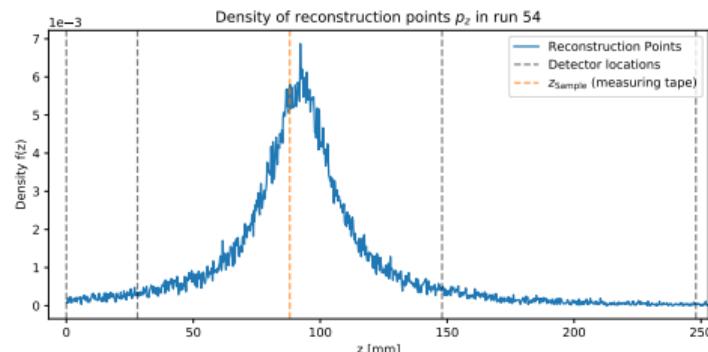
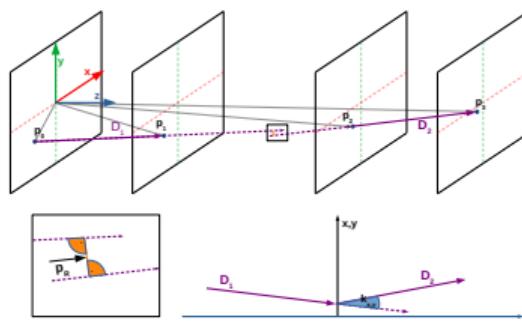
- ▶ Re-fit tracks through aligned hits
- ▶ Obtain residual distribution

¹⁰<https://www.eudet.org/e26/e28/e86887/e107460/EUDET-Memo-2010-12.pdf>

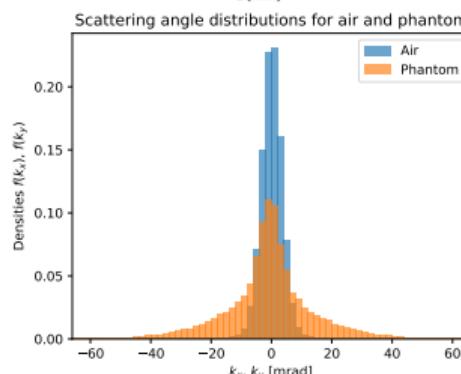
¹¹[https://doi.org/10.1016/S0010-4655\(99\)00231-3](https://doi.org/10.1016/S0010-4655(99)00231-3)

¹²<https://doi.org/10.1016/j.nima.2006.05.157>

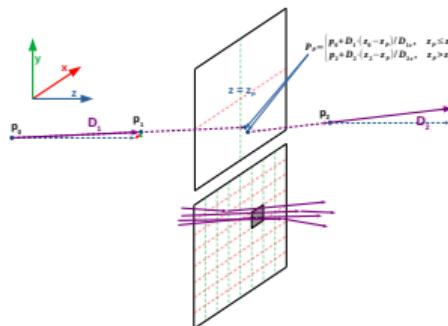
Our prototype – Scattering angle imaging I



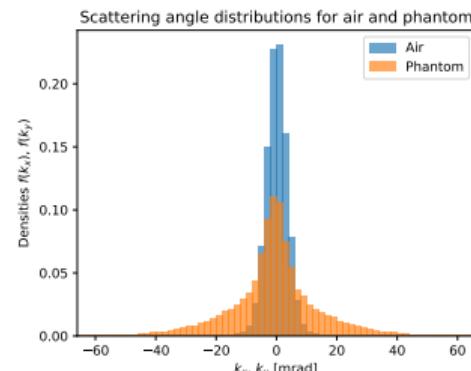
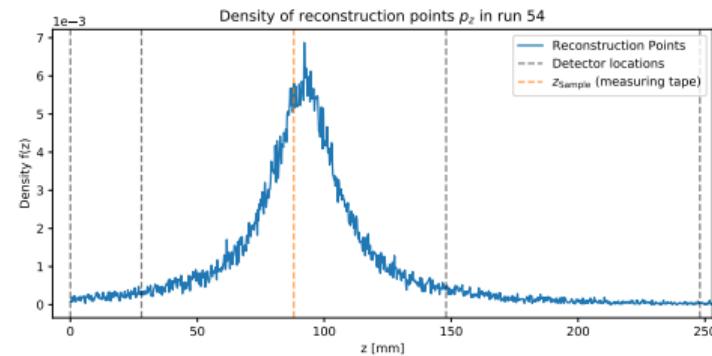
- 1 Extrapolate tracks to reconstruction point P_R
 - ▶ Point closest to both lines
 - ▶ Apply distance-cut to select close tracks
- 2 Calculate kink angles for each track
 - ▶ Angle between in- and outbound track segments
- 3 Project onto phantom plane, sort into pixels
- 4 Display width of kink angle distribution per pixel
 - ▶ Forward projection, repeated over 180° , 1° steps



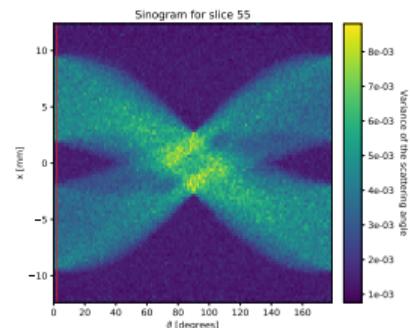
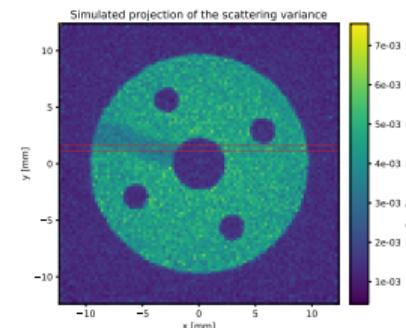
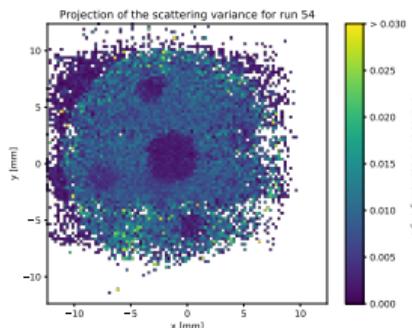
Our prototype – Scattering angle imaging II



- 1 Extrapolate tracks to reconstruction point P_R
 - ▶ Point closest to both lines
 - ▶ Apply distance-cut to select close tracks
- 2 Calculate kink angles for each track
 - ▶ Angle between in- and outbound track segments
- 3 Project onto phantom plane, sort into pixels
- 4 Display width of kink angle distribution per pixel
 - ▶ Forward projection, repeated over 180° , 1° steps



Our prototype – Scattering angle imaging III



- Pololu mounting hub as phantom
- A single projection with
 - ▶ 100.4 MeV proton beam
 - ▶ $\approx 47\,008$ tracks
- Clear phantom-air contrast
- Possibly a plastic-air contrast

- Geant4 simulations of the measurements
 - ▶ Full 180° projections and uniform beam
 - ▶ 10^6 particles per projection
 - ▶ Implementing image reconstruction workflow

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Next steps – Reconstruction

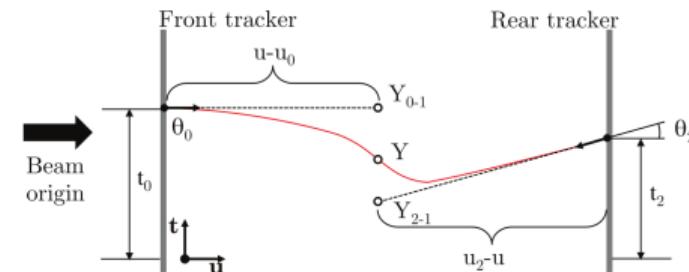
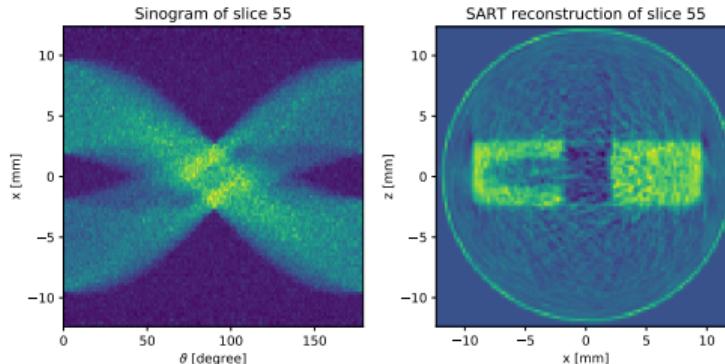


Image: Collins-Fekete et al. 2017¹⁶

- 3D image reconstruction
 - ▶ Preliminary images available
 - ▶ No established workflow yet
- Frameworks we are investigating
 - ▶ scikit-image Walt et al. 2014¹³
 - ▶ TIGRE Biguri et al. 2016¹⁴
 - ▶ Reconstruction Toolkit (RTK) Rit et al. 2014¹⁵

¹³<http://scikit-image.org/>

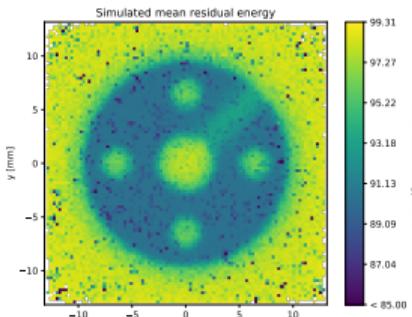
¹⁵<http://www.openrtk.org/>

¹⁴<https://github.com/CERN/TIGRE>

¹⁶<https://doi.org/10.1088/1361-6560/aa58ce>

- Most likely path estimate
 - ▶ No step function in kink angles
 - ▶ Estimate with cubic spline function
 - ▶ Will increase resolution of final images

Next steps – Calorimetry



Geant4 simulation of residual energy



AIDA2020 Trigger Logic Unit
Cussans 2017¹⁷



- Implement existing Calorimeter
Bucciantonio et al. 2013¹⁸
 - ▶ 48 Scintillator slices, silicon photomultipliers
 - ▶ Readout via USB connection
- Shared trigger and busy logic
 - ▶ Energy loss and track per particle

¹⁷<https://doi.org/10.1016/j.nima.2013.05.110>

¹⁸https://cds.cern.ch/record/2297522/files/AIDA-2020-D5_2.2.pdf

Next steps – Prototype upgrades

→ Short term

- ▶ Replacement of pre-irradiated sensors from radiation hardness study
- ▶ Optimizations in sensor-readout
 - ★ Zero-suppressed data
 - ★ Gigabit-ethernet instead of VME

→ Medium term

- ▶ Upgrade to high-rate pixel detectors (HV-CMOS)
- ▶ Investigate other options for calorimetry
- ▶ Requirements for a clinical application

→ Long term

- ▶ Clinical implementation at MedAustron

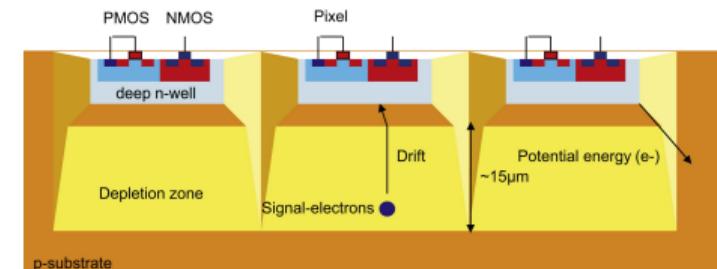
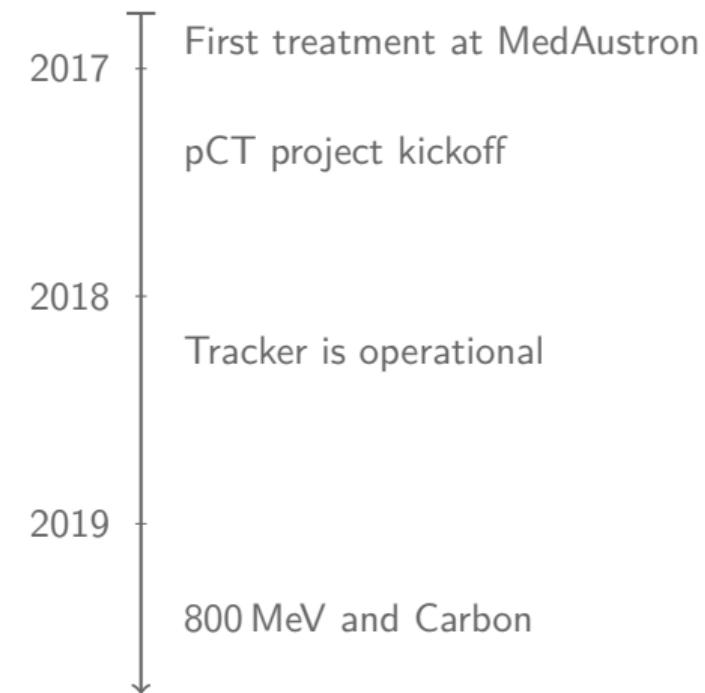


Image: Perić et al. 2013¹⁹

¹⁹<https://doi.org/10.1016/j.nima.2013.05.006>

Summary

- MedAustron: cancer treatment with protons, carbon ions
- Regular beamtimes available for non-clinical research
 - ▶ One exclusive irradiation room
 - ▶ Up to **800 MeV** or 400 MeV u^{-1} carbon ions
- Experimental program for ion beam imaging
- Tracker is operational
 - ▶ Used for scattering angle imaging
 - ▶ Most-likely path estimates will be added
- Calorimeter in near future
- Image reconstruction is work in progress
- ***Overall goal: clinical implementation at MedAustron***



Acknowledgements

Group members

- Thomas Bergauer
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- Stefanie Kaser
- Peter Paulitsch
- Vera Teufelhart
- Felix Ulrich-Pur
- Manfred Valantan

Collaborators

- Andrea De-Franco
- Claus Schmitzer

Thank you for your attention



5 Backup

6 Resources



Backup – Some numbers from the literature (Source: Poludniowski et al. 2015²⁰)

Estimated uncertainty for stopping-power ratio

- HU-SR conversion
 - ▶ Lung $\approx 5.0\%$
 - ▶ Bone $\approx 2.4\%$
 - ▶ Soft tissue $\approx 1.6\%$
- proton CT $< 1\%$

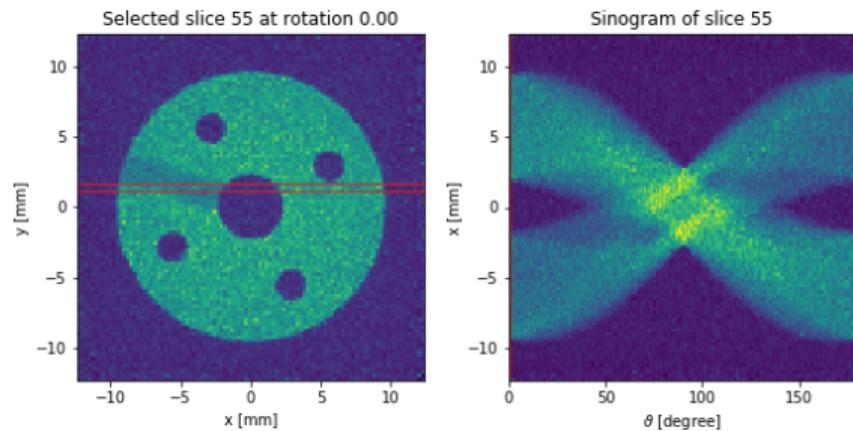
Target parameters

- Proton energy
 - ▶ ≥ 200 MeV (head)
 - ▶ ≥ 250 MeV (body)
- Maximum dose to patient < 20 mGy
- Spatial resolution ≈ 1 mm
- Residual energy resolution $< 0.6\%$ (200 MeV)

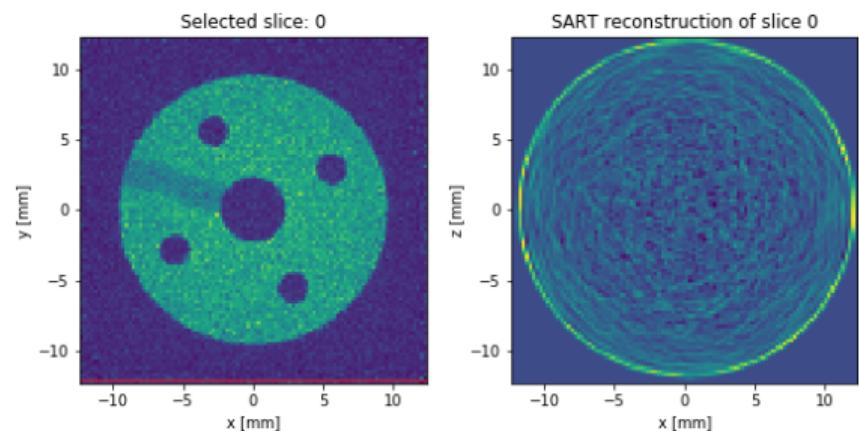
²⁰<https://doi.org/10.1259/bjr.20150134>

Backup – Animations

Simulated projections



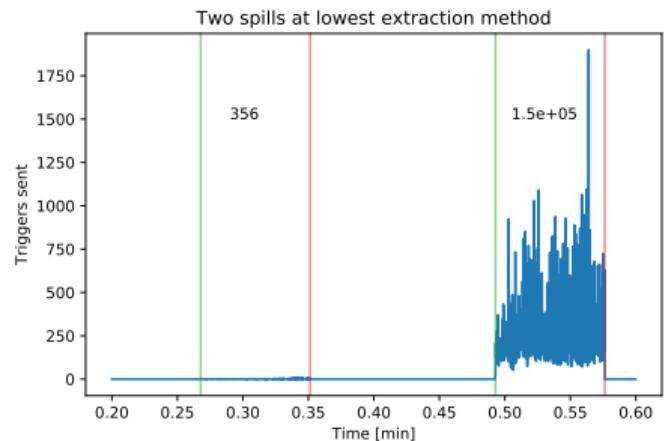
Reconstructions for each y -Slice



Backup – Rate reduction

- Three different reduction methods
 - ▶ Adjustments of accelerator component parameters
 - ▶ No detailed study has been performed
 - ▶ Methods can be combined for stepwise reduction
 - ▶ Each method increases variance of particles per spill
 - ★ Lowest method ⇒ highest fluctuations

Nominal rate	10^9 particles per 5s
Method I	10^7 to 10^8 particles per 5s
Methods I & II	10^4 to 10^6 particles per 5s
All Methods	1 to 10^5 particles per 5s



5 Backup

6 Resources



Resources I

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Resources II

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Resources III

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