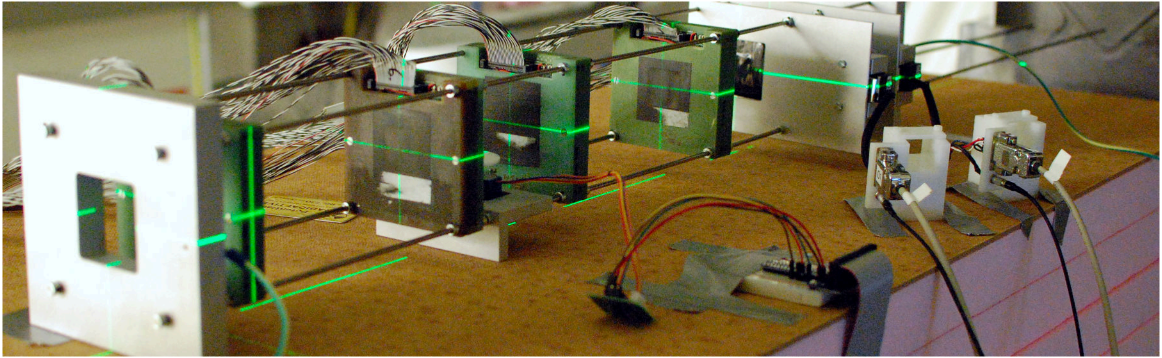


Imaging with ion beams at MedAustron

2[nd] Ionimaging Workshop, 11[th] of June, 2019

Felix Ulrich-Pur on behalf of the protonCT group at HEPHY/TU Wien

TECHNISCHE UNIVERSITÄT WIEN

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

MedAustron

The MedAustron facility

Image: MedAustron[1]

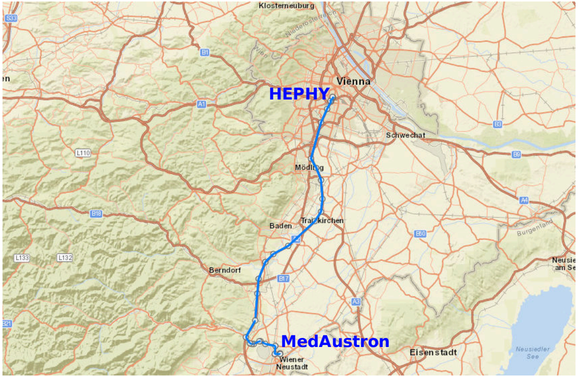


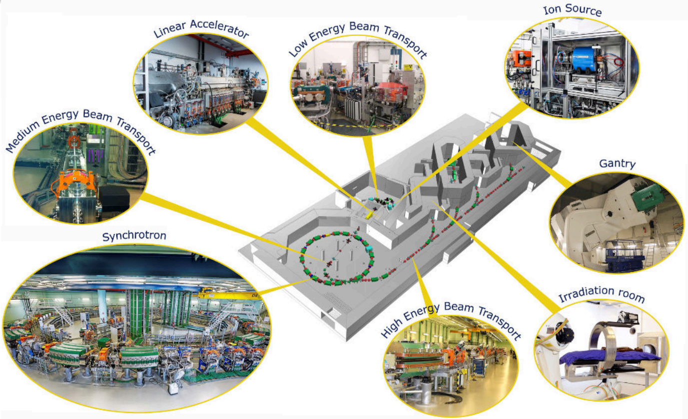
Image: ArcGIS[2]

[1] https://medaustron.at

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

The MedAustron facility

- **Synchrotron accelerator complex**
  - Circumference: 77.4 m
  - 4 slots for ion sources:
    1. Protons
    2. Carbon ions
    3. Redundant source
    4. Unused, could be used for He
  - Energies:
    - Protons: 60 MeV to 800 MeV, Clinical energies $\leq$ 252.7 MeV
    - Carbon ions: 120 MeV/u to 400 MeV/u



The MedAustron facility

- **Synchrotron accelerator complex**
  - Four irradiation rooms:
    - ★ Beam only in one room at a time
    - IR1 Exclusive to research, protons up to 800 MeV, low rates
    - IR2 Clinical, horizontal & vertical beamline
    - IR3 Clinical, similar to room 1 (Limited to clinical energies)
    - IR4 Clinical, gantry, only protons

- **Beam parameters:**
  - Beam delivery: pencil beam scanning
  - 5 s spill
  - FWHM: 7 mm to 21 mm
  - Clinical: 10^8 particles/s to 10^9 particles/s
  - Research: NEW $\geq 10^3$ particles/s

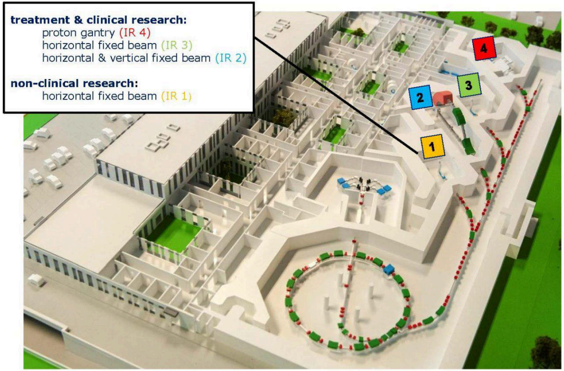


Image: MedAustron

The MedAustron facility

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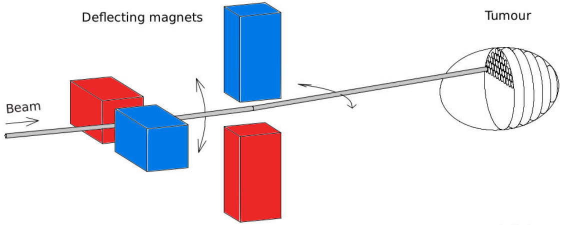


Image: Active scanning

Beam parameters:

- Beam delivery: pencil beam scanning
- 5 s spill
- FWHM: 7 mm to 21 mm
- Clinical: 10^8 particles/s to 10^9 particles/s
- Research: NEW $\geq 10^3$ particles/s

The MedAustron facility

➛ Cancer Therapy

- First patient treated in 2017
- Today: ≈ 27 patients/d
- Carbon ion treatment starts next month (July 2019)
- Treatment during the week

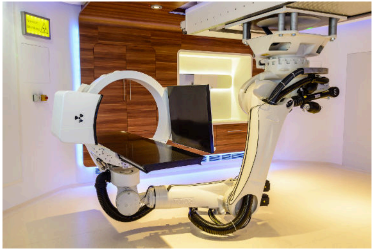


Image: Treatment room

➛ Research

- Regular beamtimes on weekends, nights
- TU Wien, MedUni Wien
- Imaging with ions officially part of the research strategy of MedAustron since 2018

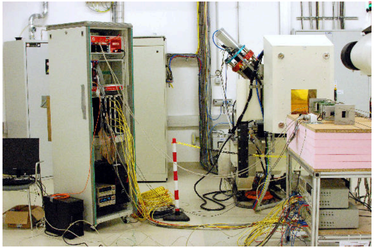
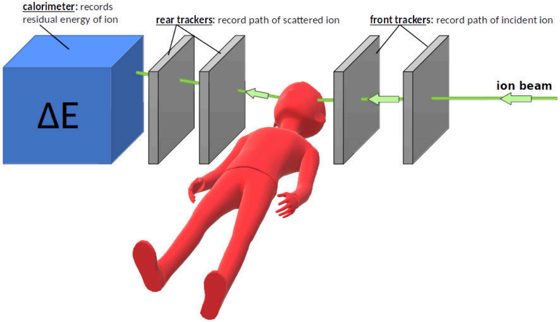


Image: IR1: research only

TU WIEN HEPHY MedAustron

Imaging with ion beams at MedAustron: Overview

- **Overall goal: clinical implementation of a pCT setup at MedAustron**
  - Single particle counting:
    - Rate had to be reduced
  - Tracking telescope prototype is operational:
    - First test: track based multiple scattering tomography
  - Implementation of a calorimeter ongoing:
    - Get a full pCT setup
  - First reconstruction attempts with simulated data
  - Hardware upgrade

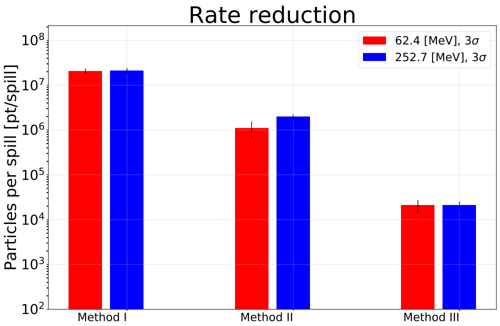


Rate reduction

- Clinical rates (10^9 particles per 5s) are too high
- Three different reduction methods for IR1

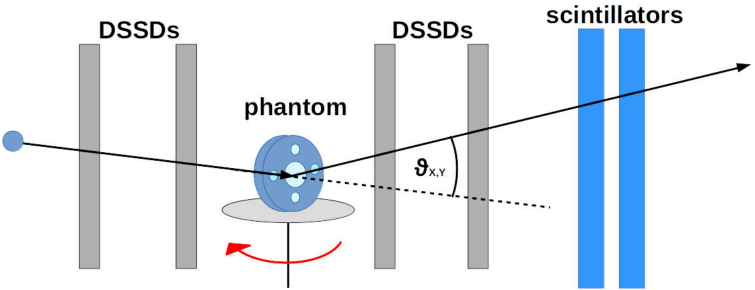
Nominal rate	10^9 particles per 5s
Method I	$\mathcal{O}(10^7)$ particles per 5s
Method II	$\mathcal{O}(10^6)$ particles per 5s
Method III	$\mathcal{O}(10^4)$ particles per 5s

- **Now: rates down to** $\sim$kHz
- Will be officially maintained by MedAustron
- Sufficiently low for our detectors
  - First tests with tracker



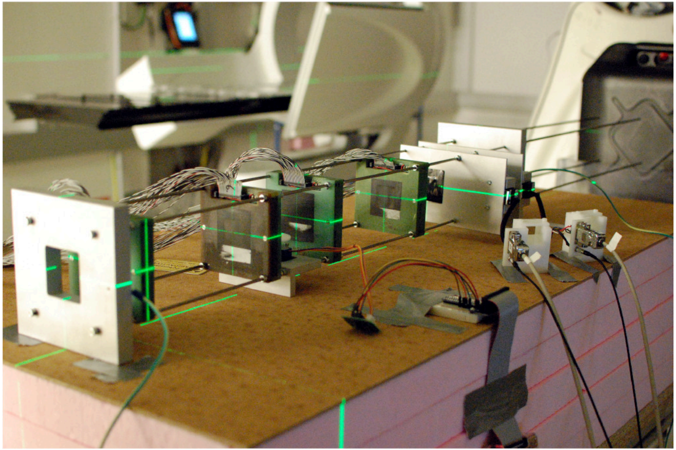
Tracker – Setup for multiple scattering tomography

- Track based, no calorimeter needed
- Reconstruction of material budget $\frac{l}{X_0}$
- Setup:
  - Double sided silicon strip detectors (DSSD)
  - Aluminum phantom on a rotating table
  - Plastic scintillators as trigger



Tracker – Prototype

- Four double-sided silicon-strip sensors ($(2.56 \times 2.56)\,\mathrm{cm}^2$)
  - Thickness of 300 μm
  - X-side: p-doped with a pitch of 50 μm
  - Y-side: n-doped with a pitch of 100 μm
- VME-based detector readout
  - APV25 ASIC [1] initially developed for CMS (BELLE-II)
  - Prototype readout for Belle-II experiment [2]
  - Achieved event-rate ≈ 30 Hz
    - ★ Pure, raw, non-optimized, event-by-event readout



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

[2] https://doi.org/10.5170/CERN-2009-006.417

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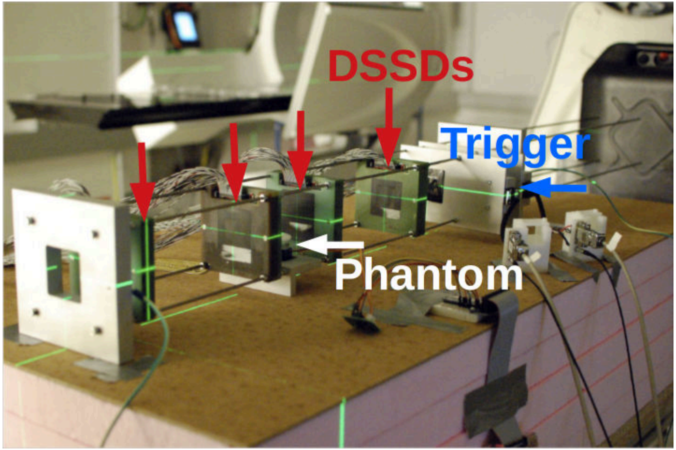

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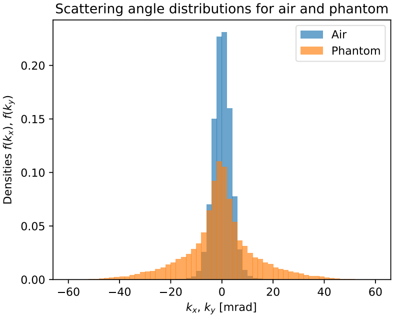
Tracker – Multiple scattering tomography algorithm

- Interpretation of Highland formula as a Radon transform

$$\Theta^2(L) \approx \left(\frac{13.6\,\mathrm{MeV}}{\beta c p}\cdot z\right)^2 \int_L \frac{1}{X_0(x,y,z)}|ds|$$



- Calculation of kink angle for each track
- Projection on phantom plane, sort into pixels
- Calculate width of kink angle distribution per pixel

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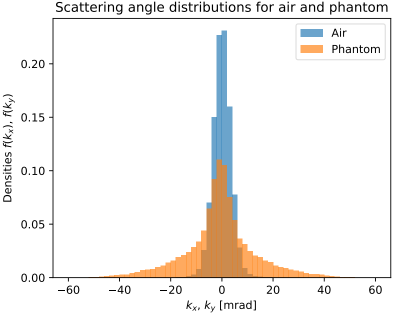

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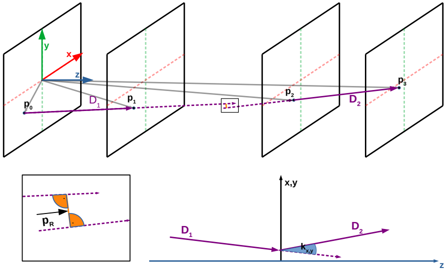

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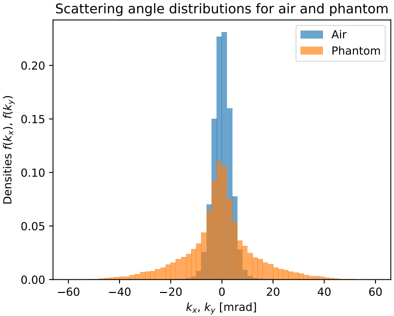

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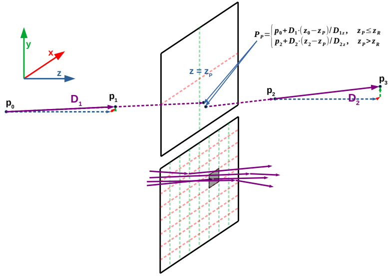

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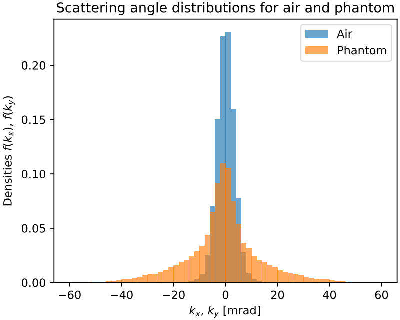
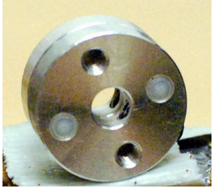
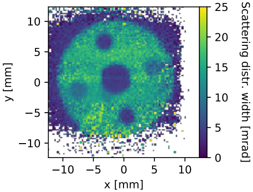


Tracker – Multiple scattering tomography results

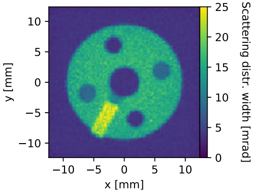
Experiment:

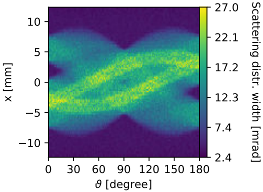




- Pololu mounting hub as phantom
  - Plastic and iron screws
- A single projection with
  - 100.4 MeV proton beam
  - ≈ 47 008 tracks
- Clear phantom-air contrast
- Possibly a plastic-air contrast

Simulation:



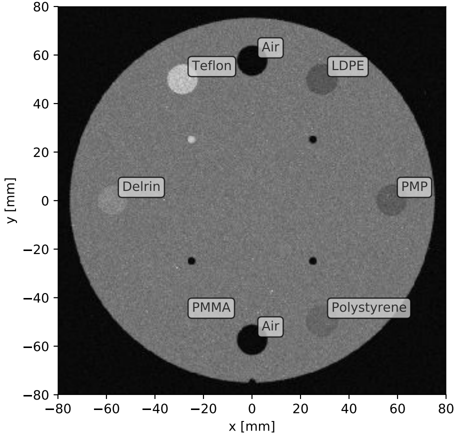


- Geant4 simulations of the measurements
  - Full 180° projections and uniform beam
  - 10^6 particles per projection
  - Implementing image reconstruction workflow [3]
  - Using scikit-image [4] tool as a reconstruction tool

[4] https://doi.org/10.1016/j.nima.2019.05.087

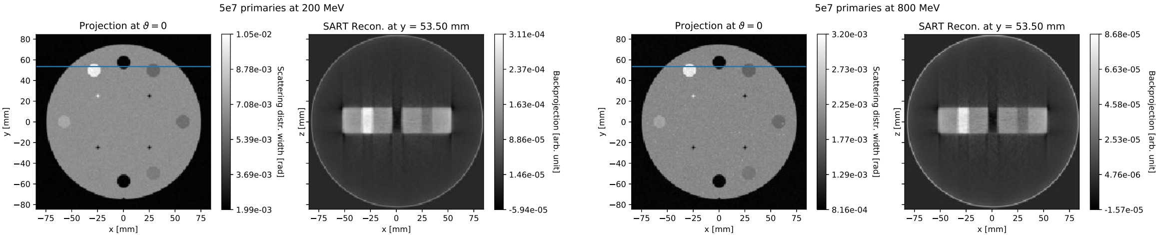
Tracker – Multiple scattering tomography results

- Geant4 simulation to test if different materials can be distinguished
- Cylindrical PMMA phantom (similar to Catphan)
  - thickness: 5 cm
  - radius: 15 cm
- Holes filled with different materials
- 5×10^7 particles per projection
- 180 projections with 1° step size
- Pixelsize: 1 mm^2



Tracker – Multiple scattering tomography results

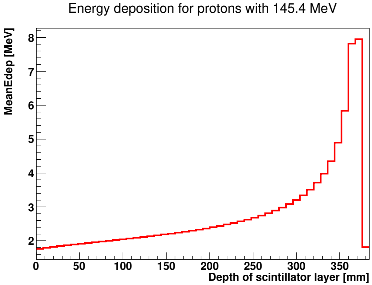
- Multiple scattering tomography with different primary proton beam energies
- SART algorithm for reconstruction
- Different materials can be distinguished



Calorimeter – Full pCT setup

- Implementation of TERA range calorimeter [5]
  - 42 Scintillator slices ($3 \times 300 \times 300\,\mathrm{mm}^3$), SIPMs
  - Can measure protons up to 150 MeV
  - Readout via USB connection (DAQrate $< 1\,\mathrm{MHz}$)
  - first full pCT measurement planned for July 2019

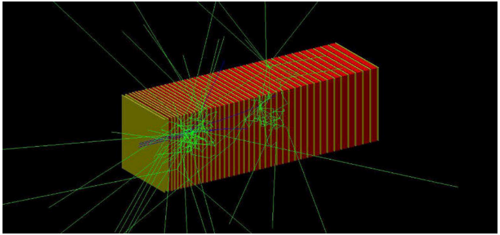
- Synchronisation via AIDA2020 trigger and logic unit [6]
  - Exclusive trigger number per particle to correlate tracks and energy loss



[5] https://doi.org/10.1016/j.nima.2013.05.110

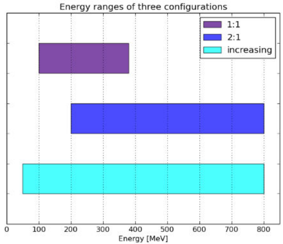
Calorimeter – Thoughts about upgrade solution for higher energies

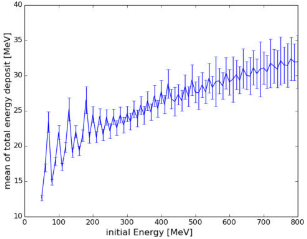
- Calorimeter can only stop protons $< 150\,\mathrm{MeV}$
- First thoughts: higher energies should improve energy resolution ($\propto \frac{1}{\sqrt{E}}$)
- First modification attempts for current calorimeter
  - Modify to stacked calorimeter
  - 42 scintillator slices
  - Different absorbers of varying sizes
  - Based on Geant4 simulation
- Requirements
  - Stop higher protons energies
  - Cover a large energy range
  - Energy resolution $< 1\%$
- Brass absorbers with varying thickness
  - Same, twice and linearly increasing thickness



Calorimeter – Thoughts about upgrade solution for higher energies

- Stacked calorimeter offers broad energy range, but sampling fluctuations worsen energy resolution
- Different approach for “high energy” calorimetry has to be considered
- Range calorimeter can still be used for our pCT setup with energies below 150 MeV ($\frac{\sigma(E)}{E} \leq 1\%$)
- First measurement with full pCT setup planned for July 2019 at MedAustron with lower energies
  - 24h beamtime with upgraded tracker (new sensors, 6 planes) and new DAQ (zero-suppressed readout, kHz instead of Hz)





Reconstruction –TIGRE toolbox

- **TIGRE: Tomographic Iterative GPU-based Reconstruction Toolbox**
- Developed for cone beam CT (CBCT)
  - Used by collaborating group at MedUni Vienna for CBCT
- Single or multi-GPU computation
- Modular structure
- Forward and backprojection ($A(x)$) are optimized for GPU computing
- Algortihms are written in high-level language (Python, Matlab)

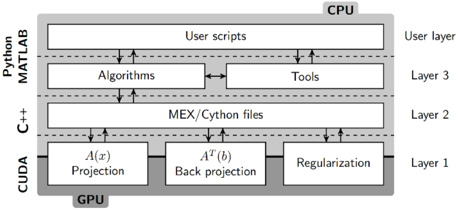


Image: TIGRE [7]

- Available algorithms:
  - Filtered back projection, FDK
  - Iterative algorithms (SART, OS-SART,..)
  - Custom algorithms

[7] https://arxiv.org/abs/1905.03748

Reconstruction– First test of TIGRE toolbox

- **pCT reconstruction**
  - Using straight line approach
  - Bragg-Kleeman approximation [8]
- Tested FBP and OSSART (5 iterations)
  - 90 projections, 5×10^5 particle/projection
- GPU-cluster at HEPHY (4x NVIDIA GTX 1080 TI)
  - Reconstruction time: few s

- **pCT simulation** with ideal detectors
  - Can measure ΔE_i and $\vec{x_i}$
- cyclindrical phantom (d=1 cm)
  - Homogenous material: l=1 cm
  - Composite materials: l= 5 mm per layer

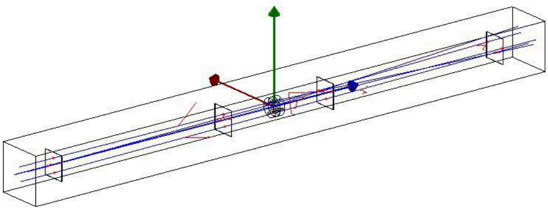
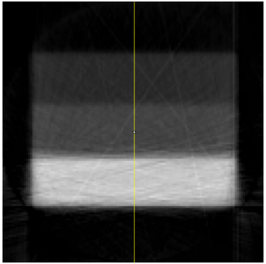


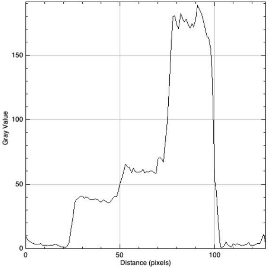
Image: Geant4 pCT setup

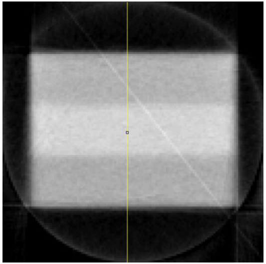
Reconstruction – composite materials

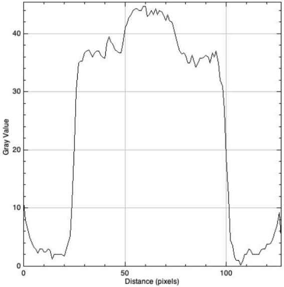
- **iron - glass - plastic**
  - 220 MeV protons
  - SP error $< 6\%$

- **muscle - bone - tissue**
  - 120 MeV protons
  - SP error $< 6\%$

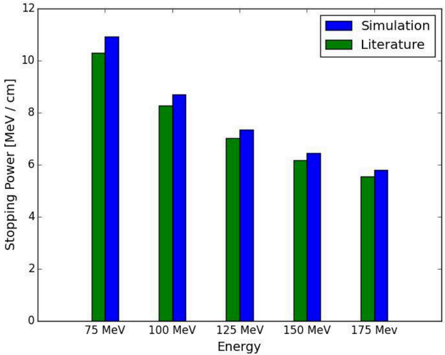








Reconstruction – homogeneous material



- SP reconstruction of a homogeneous cylinder (G4_A-150_TISSUE)
  - l= 1 cm, r= 1 cm
- Stopping power errors between 4 and 6%
- Results can be used as first estimate for iterative reconstruction with MLP formalism
- Next steps:
  - Implementation of MLP formalism (in TIGRE?)
  - Or use a better suited framework, supported and used by the pCT community (RTK,..)

Next steps – Prototype upgrades

- Hardware:
  - **Tracker upgrade**
    - New unirradiated DSSDs (6 planes)
    - New Belle-II DAQ with zero-surpressed data
  - **First full pCT measurement at MedAustron in July 2019**
    - Including new tracker sensors & electronics
    - Test of ATLAS MALTA DMAPS with **high rate capability** [9]
  - Investigate other options for **calorimetry**
- Reconstruction:
  - **MCS tomography** for higher energies, different ions and **hull detection** ongoing
  - Implementation of MLP formalism in reconstruction
  - Investigate other imaging tools (**RTK**,..)

Image: **MALTA pixel sensor**

[8] 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
  - Low fluxes for protons
- Experimental program for ion beam imaging
  - Part of MedAustron research strategy
- Tracker is operational
  - Used for scattering angle imaging
- Implementation of calorimeter and TLU
- Full pCT setup in July 2019
- Image reconstruction and calorimeter alternative is work in progress
- *Overall goal: clinical implementation at MedAustron*

2017 — First treatment at MedAustron

pCT project kickoff

2018

Tracker is operational

2019

800 MeV and Carbon

Acknowledgements

Group members

- Thomas Bergauer
- Alexander Burker
- Albert Hirtl
- Christian Irmler
- Stefanie Kaser
- Florian Pitters
- Vera Teufelhart

Collaborators

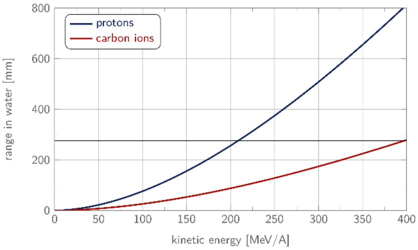
- EBG MedAustron
- MedUni Vienna

Thank you for your attention

Backup – MedAustron

Beam parameters for non-clinical research at MedAustron:

particles	protons	carbon ions
particles per spill	$\lesssim 10^{10}$	$\lesssim 4 \times 10^{8}$
extraction duration	[0.1 , 10]s	[0.1 , 10]s
beam energy	[60 , 800]MeV	[120 , 400]MeV/nucleon
magnetic rigidity	[1.4 , 4.88]T m	[3.25 , 6.35]T m



- 27 cm **depth for carbon ions** goal for therapy
- design of accelerator according to that requirement
  - for carbon ions achieved at 400 MeV/nucleon
  - protons available only $\leq$ 800 MeV
- **magnetic rigidity** $B\rho = p/q$

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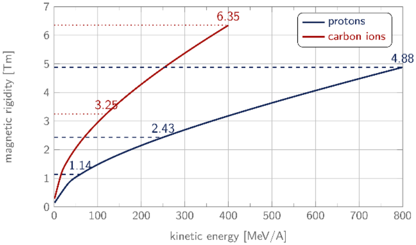

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Accelerator layout

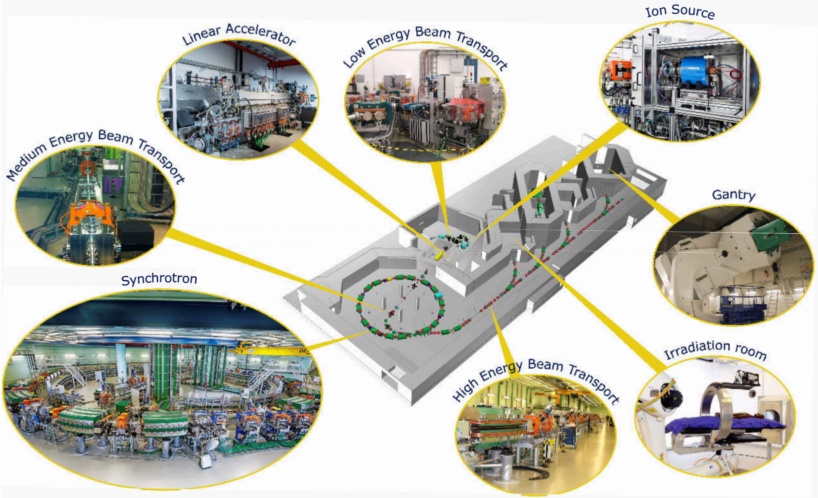
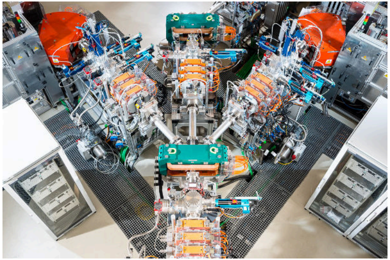


Image: MedAustron

Accelerator layout – Ion source

Image: MedAustron

Accelerator layout – Ion source



- 3 identical ECR sources
  - one to produce $H_3{}^+$
  - one to produce C^{4+}
  - one redundant source
- a fourth ECR source could be installed additionally
  - He ions are discussed
  - any ion fulfilling

    $q/m=1/3$

    could be accelerated
- ions are extracted at a kinetic energy of 8 keV/nucleon

Accelerator layout – Low energy beam transport

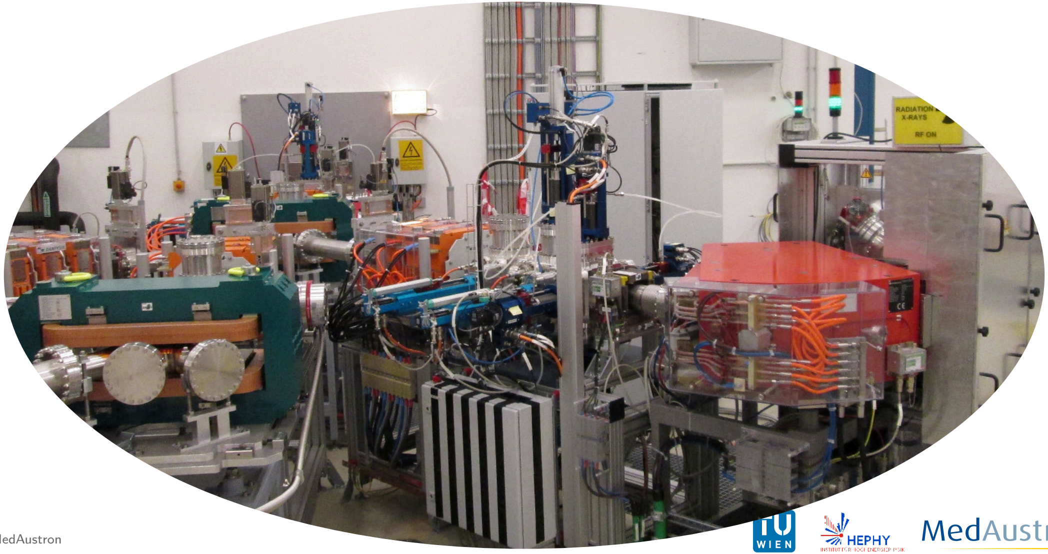


Image: MedAustron

Accelerator layout – Linear accelerator

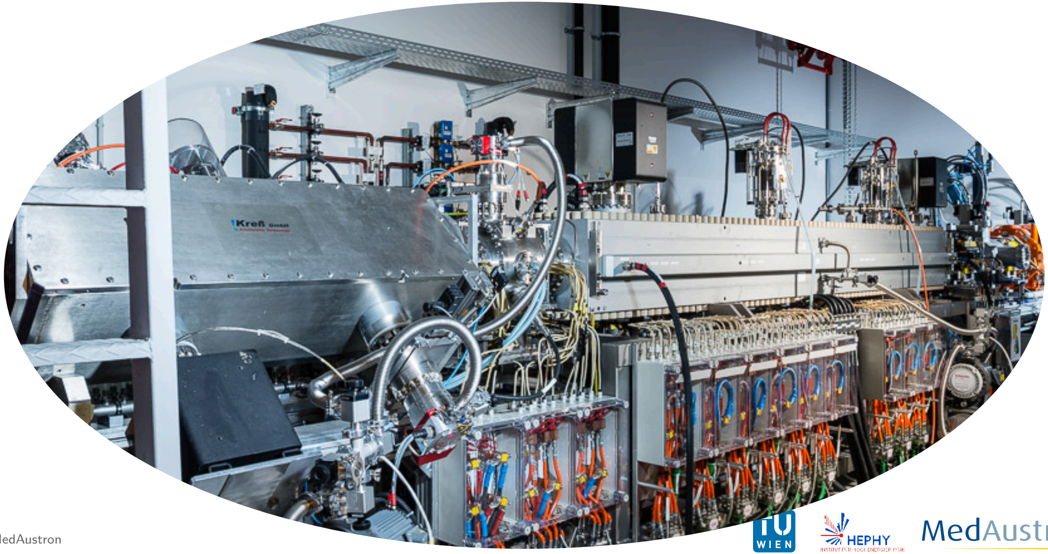


Image: MedAustron

Accelerator layout – Linear accelerator

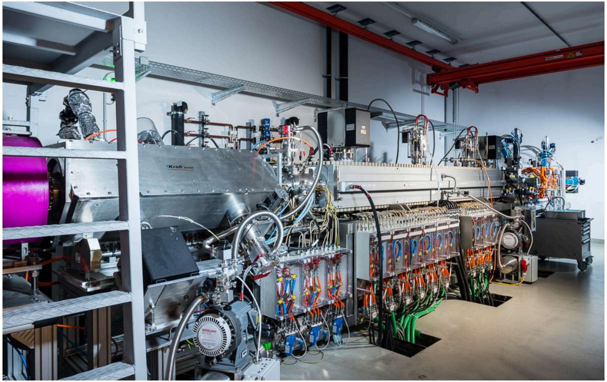


Image: MedAustron

- RFQ
  - bunching, focusing, accelerating of the particle beam
  - RF potential difference: 70 kV
  - extraction energy of the particles 400 keV
- IH-structure – interdigital H-mode-structure
  - RF potential difference: 500 kV
  - extraction energy of the particles: 7 MeV
- at the end of injection chain a stripping foil removes remaining electrons from ions

Accelerator layout – Synchrotron

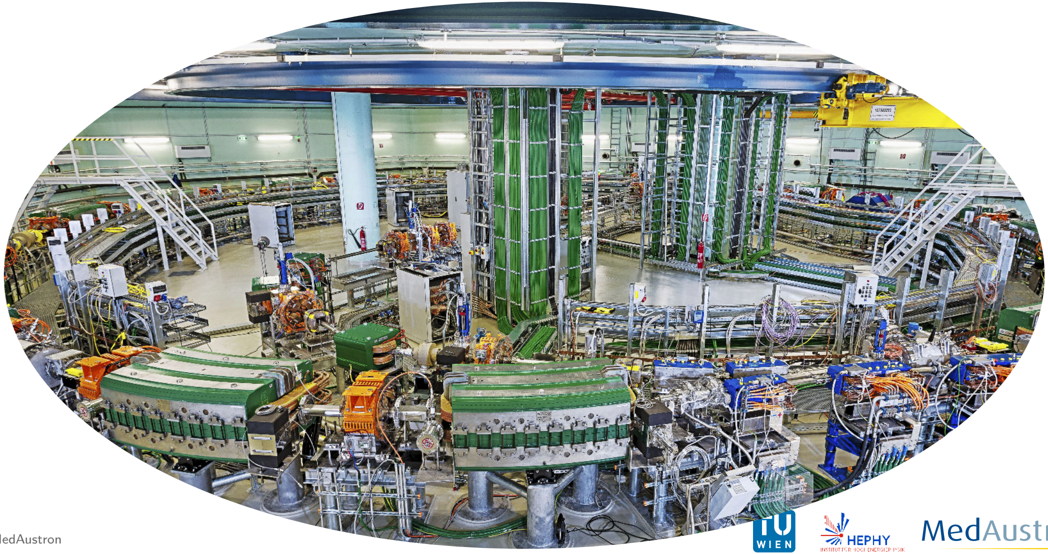


Image: MedAustron

Accelerator layout – Synchrotron

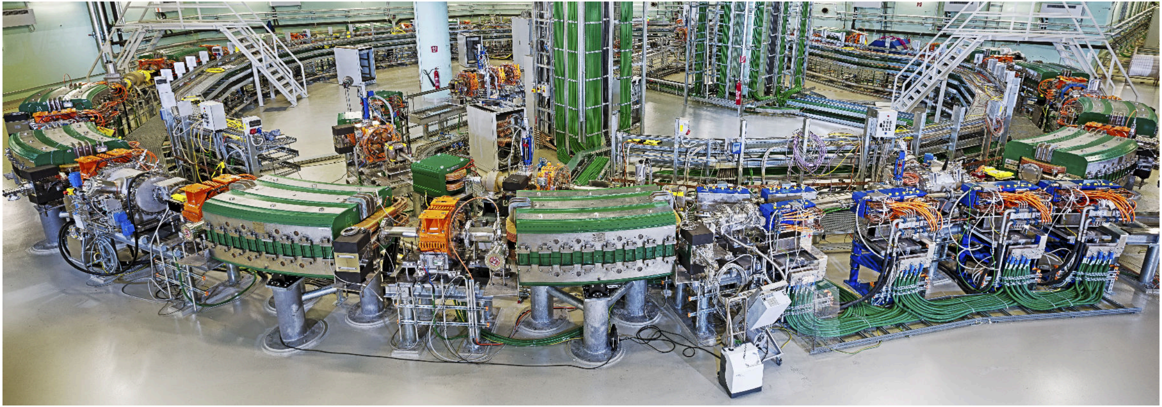


Image: MedAustron

- circumference 78 m
- radius 12 m
- 16 dipole magnets
- 24 quadrupole magnets
- 1 RF cavity for acceleration

Accelerator layout – High energy beam transport

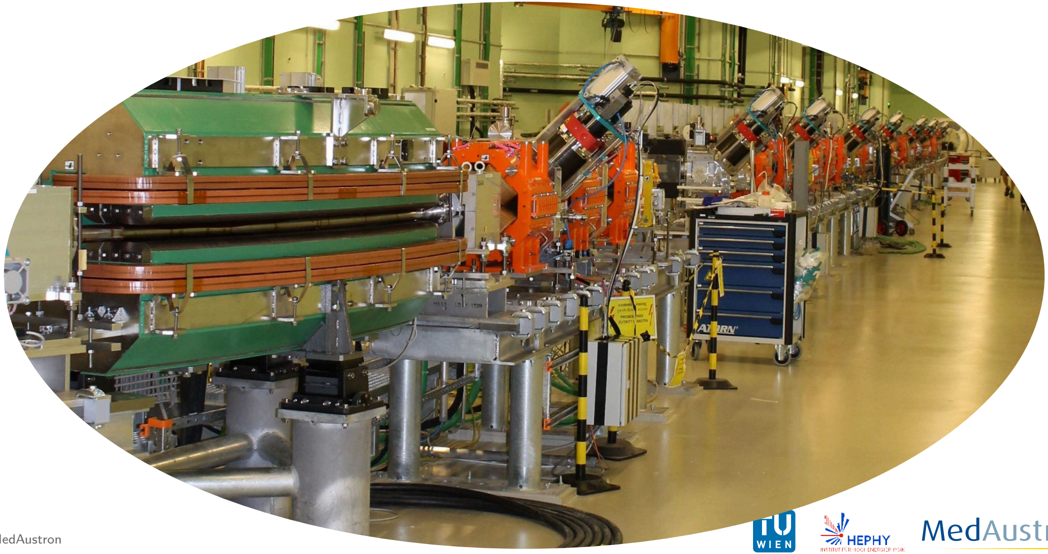
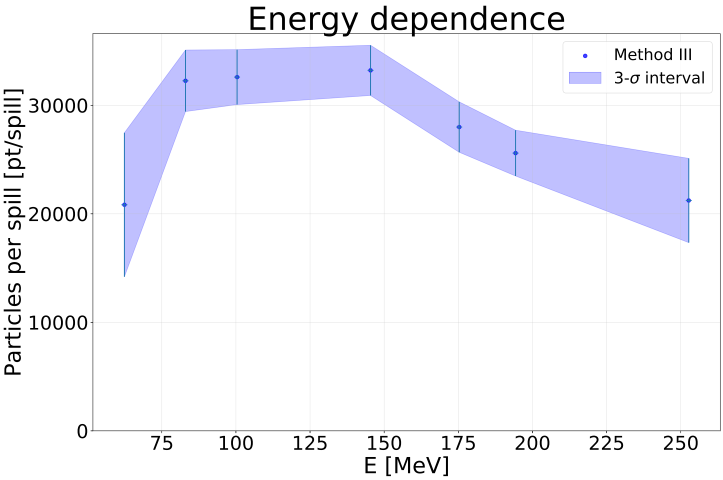


Image: MedAustron

Backup – Rate reduction



Backup – MCS tomography

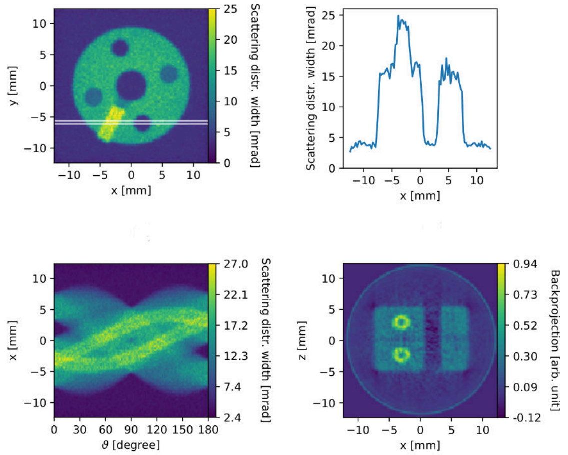
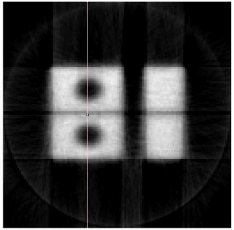
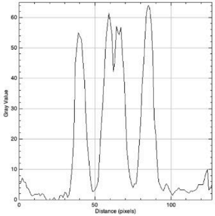


Image: MCS tomography [3]

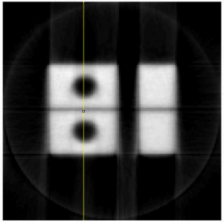
Backup – Reconstruction – Different projectiles

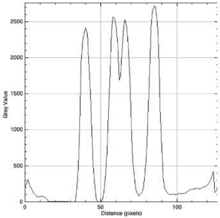
- **protons:** 100 MeV





- **carbon ions:** 150 MeV/u





- Aluminum cylinders with plastic and iron screws
- slice along red line

Backup – Calorimeter

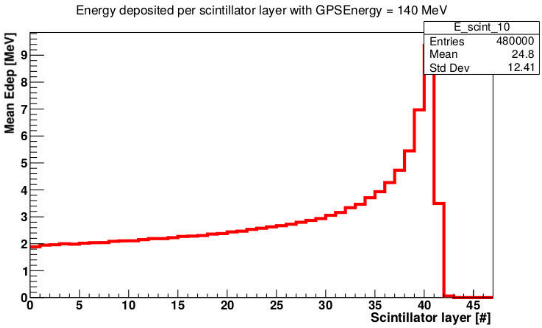


Image: unmodified TERA calorimeter

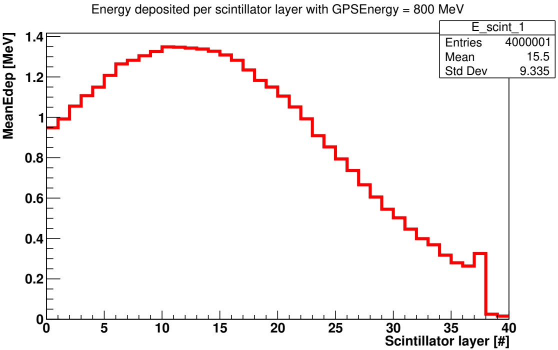


Image: stacked Calorimeter with brass absorbers (modified TERA calorimeter)

Resources I

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Resources II

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