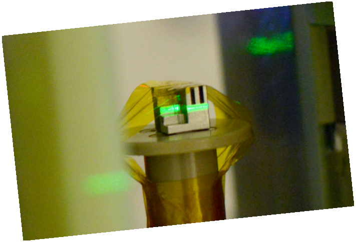
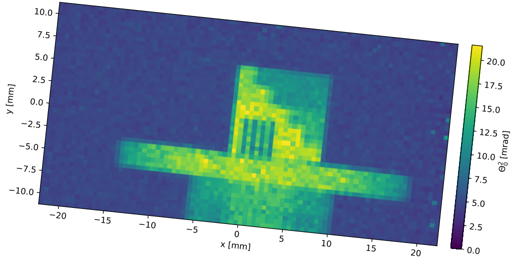
Non-clinical test beams at MedAustron





BTTB2020, 27^{th} of January, 2020

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

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MedAustron

Image: MedAustron

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

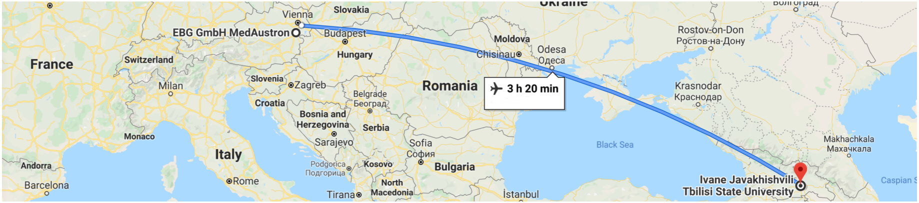


Image: Google Maps

MedAustron

Synchrotron accelerator complex

- Circumference: 77.4 m
- Energies:
  - Protons: 60 MeV to 800 MeV, Clinical energies $\leq$ 250 MeV
  - Carbon ions: 120 MeV/u to 400 MeV/u

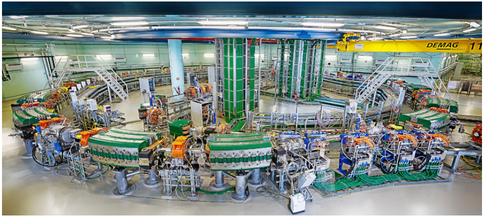


Image: MedAustron

- 4 slots for ion sources:
  - Protons
  - Carbon ions
  - Redundant source
  - Unused, could be used for He

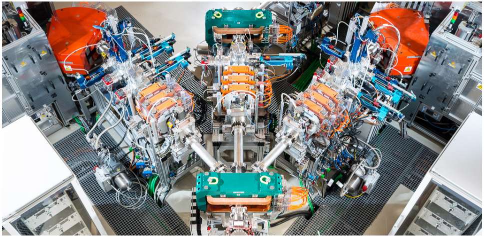
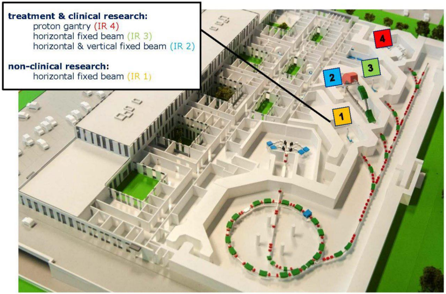


Image: MedAustron

MedAustron

Synchrotron accelerator complex

- ➛ Four irradiation rooms:
  - IR1: **Exclusive to research**
    (protons up to 800 MeV, low rates)
  - IR2, IR3, IR4: Clinical use
    (Limited to clinical energies)
  - Beam only in one room at a time
- ➛ **Beam parameters:**
  - Beam delivery: pencil beam scanning
  - 5 s spill
  - Spotsize: 7 mm to 21 mm FWHM
  - Clinical rates:
    - ★ Protons: 10^9 particles/s
    - ★ Carbon ions: 10^7 particles/s
  - Research: $\geq 10^3$ particles/s



treatment & clinical research:
proton gantry (IR 4)
horizontal fixed beam (IR 3)
horizontal & vertical fixed beam (IR 2)

non-clinical research:
horizontal fixed beam (IR 1)

Image: MedAustron

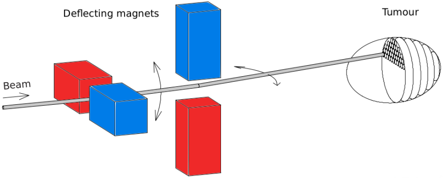


Image: Active scanning

MedAustron

Cancer therapy

- Treatment during the weekdays
- First patient treated in 2016
- Currently: ≈ 27 sessions/d
- Carbon ion treatment since July 2019

Research

- Regular beamtimes on weekends and during nights
- TU Wien/HEPHY, MedUni Wien

Image: Treatment room

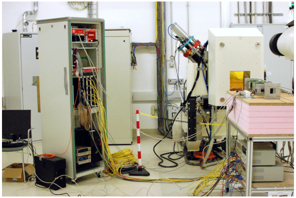
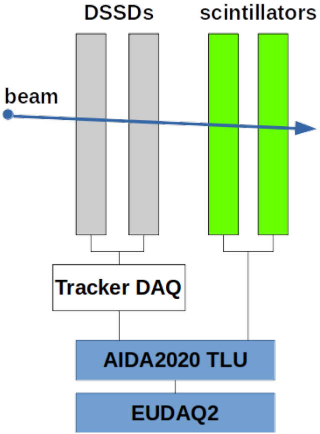


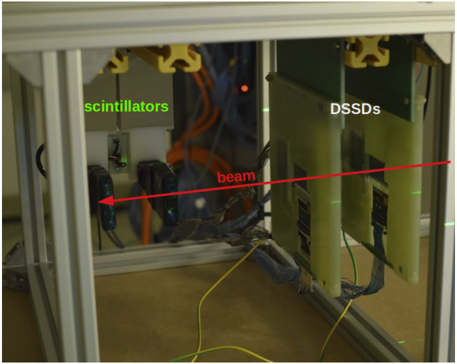
Image: IR1: research only

Rate reduction– Overview

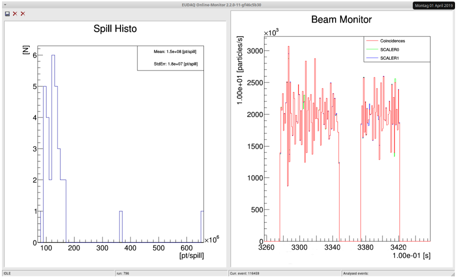
- Clinical rates (10^{10} particles per 5s) are too high for our current system
- pCT group commissioned three different reduction methods for IR1 with MedAustron
- Beam monitor was developed
  - RAte MONitor:
    - Plastic scintillators
    - AIDA 2020 TLU [1]
    - Rate Monitor for AIDATLU-producer implemented in EUDAQ2 [2]
  - Double-sided Silicon strip detectors (DSSD) for beam profile monitoring



Rate reduction– RAte MONitor



- ➛ Beam monitor setup at MedAustron


EUDAQ Online-Monitor 2.2.0-11-gf46c5b30

Montag 01 April 2019

Mean: 1.5e+08 [pt/spill]

StdErr: 1.8e+07 [pt/spill]

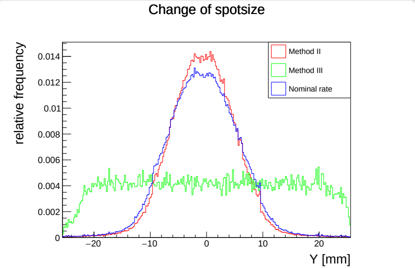
IDLE | run: 796 | Curr. event: 116459 | Analysed events:

- ➛ Preview of the RAte MONitor for the AIDATLU-producer in EUDAQ2

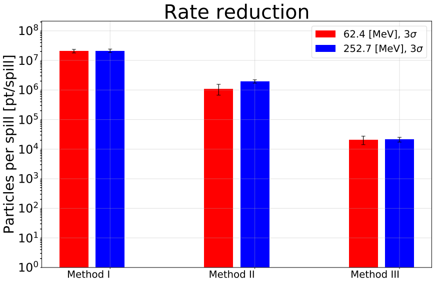
Rate reduction– Results

Clinical energies (< 252.7 MeV)

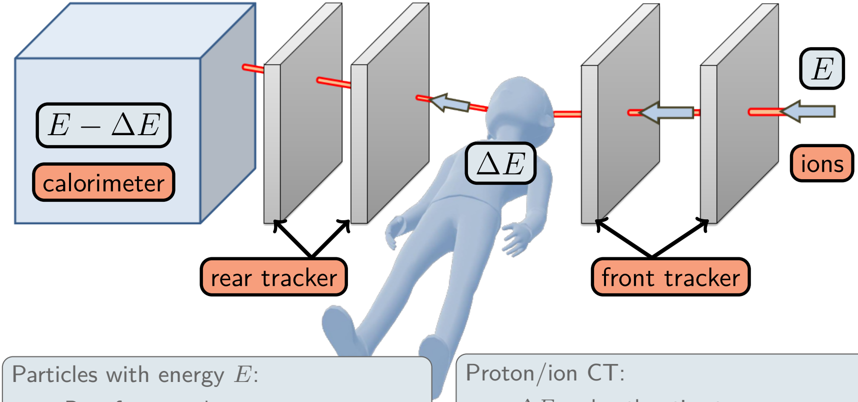
Setting	**Rate**
Nominal rate	10^{10} p per 5s
Method I	$\mathcal{O}(10^7)$p per 5s
Method II	$\mathcal{O}(10^6)$p per 5s
Method III	$\mathcal{O}(10^4)$p per 5s



- **Now: rates down to** ~kHz
- Spot size varies between 0.8 and 4.5 cm FWHM
- Sufficiently low for our pCT system
- Low flux commissioning for 800 MeV ongoing
- Low flux for Carbon and possibly He planned



Imaging with ion beams – Overview



Particles with energy E:

- ➛ Pass front tracker
- ➛ Lose energy in object: ΔE
- ➛ Pass rear tracker
- ➛ Deposit energy in calorimeter: $E - \Delta E$

Proton/ion CT:

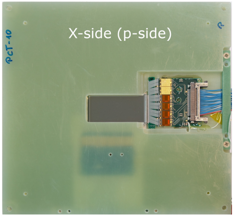
- ➛ ΔE and path estimate
- ➛ 3D image of stopping power

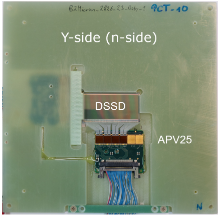
Multiple coulomb scattering CT:

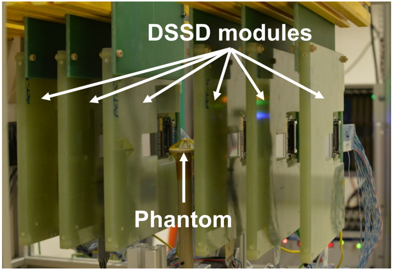
- ➛ Only path estimate
- ➛ 3D image of material budget

pCT setup – Tracker

- 6 DSSD modules
  - Size: $(2.56 \times 5.12)\,\mathrm{cm}^2$
  - Thickness: 300 µm
  - X-side:
    - 512 p-doped strips
    - Pitch: 50 µm
  - Y-side:
    - 512 n-doped strips
    - Pitch: 100 µm
- VME-based readout
  - APV25 chip [3]
  - Belle-II SVD readout chain [4]
  - Achieved event-rate
    - 250 Hz raw data
    - 500 Hz zero suppressed
    - *Limited by VME bus speed*
    - *Implementing GbE readout*







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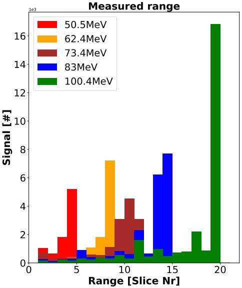
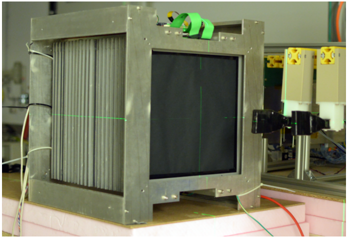
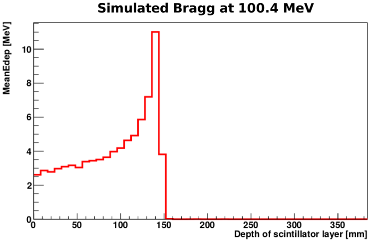
pCT setup – Calorimeter

Implementation of range telescope (formerly TERA [5])

- 42 slices to sample energy loss
- Plastic scintillators with SiPMs
- Size: $3 \times 300 \times 300\,\mathrm{mm}^3$ each
- Can measure protons up to 140 MeV
- Readout via USB connection (DAQrate $< 1\,\mathrm{MHz}$)
- Port from old DAQ (LabView) to C++(EUDAQ2)



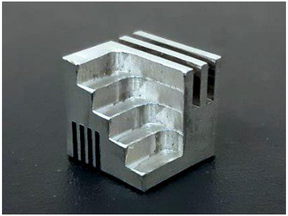




pCT setup – Used phantoms

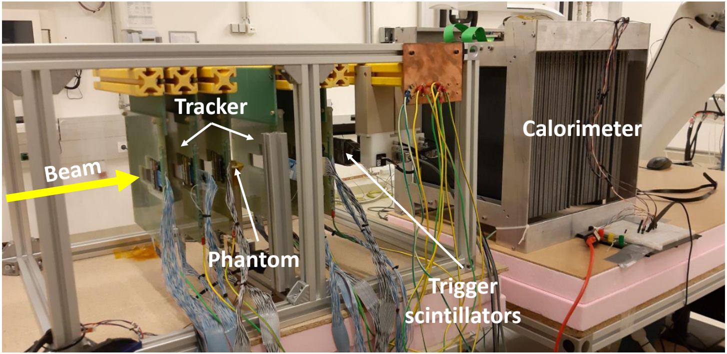
- Two objects to be imaged (phantoms) used
- Mounted on a rotating table
- Imaged at different angles

- Aluminum cylinder (Pololu mounting hub)
  - $R = 1\,\mathrm{cm}$, $L = 1\,\mathrm{cm}$
  - Cylindrical cutouts
  - Cutouts were partially filled with plastic



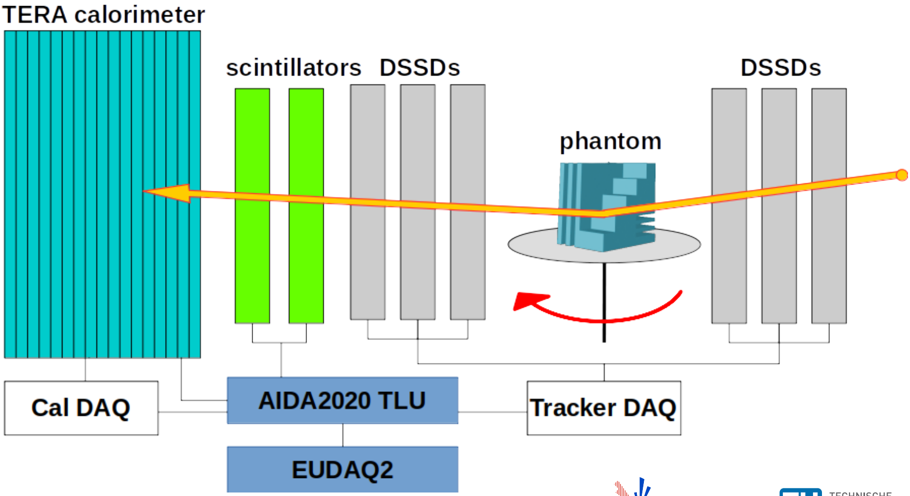
- Aluminum cube
  - $1\,\mathrm{cm} \times 1\,\mathrm{cm} \times 1\,\mathrm{cm}$
  - With cutouts and steps

pCT setup – Full Setup

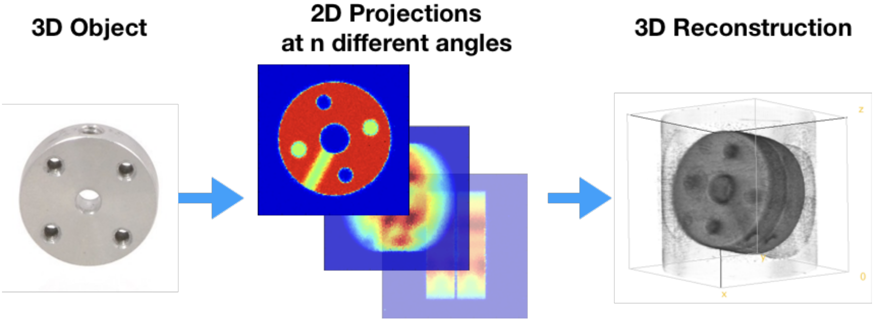


- Synchronisation via AIDA2020 trigger and logic unit (TLU) [1]
- Exclusive trigger number per particle to correlate tracks and energy loss

pCT setup – Full Setup



3D Reconstruction – Overview

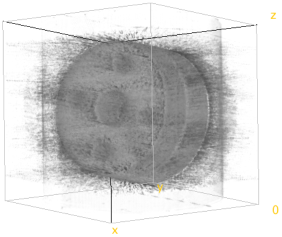


- Reconstruction consists of two essential steps
  - Forward projection → 2D radiographs
  - Back projection → Reconstruction of a 3D object from several radiographs taken at different angles

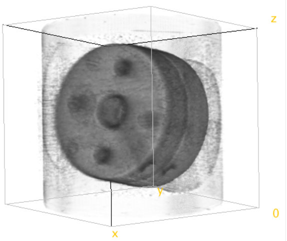
3D Reconstruction – Preliminary simulation results

- **Reconstruction framework: TIGRE**[1]
  - Forward and backprojection are optimized for GPU computing
  - Algortihms are written in high-level language (Python, Matlab)
  - Several reconstruction algorithms implemented
  - Initially developed for cone beam CT (CBCT)

Pololu Mounting Hub



Reconstruction using FBP
(analytical method)



Reconstruction using OS-SART
(iterative method)

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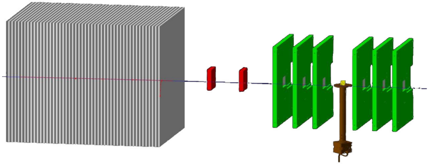
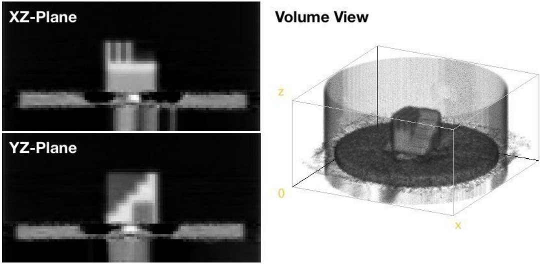
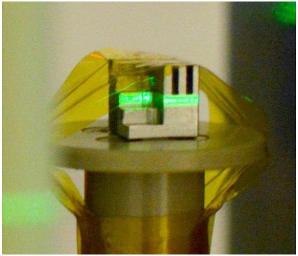
[1] Tomographic Iterative GPU-based REconstruction toolbox

Simulation of pCT setup

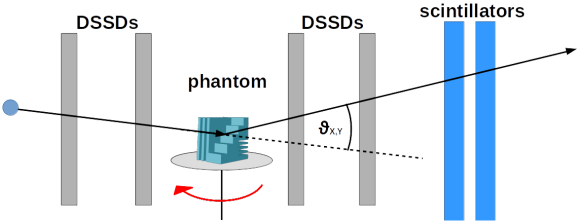


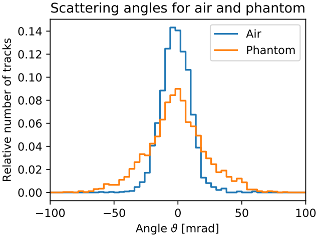
- Geant4 simulation of the full pCT setup exists
- Protons with 100.4 MeV
- 1×10^6 primary particles /projection





Multiple Coulomb Scattering Radiography (MCSR)

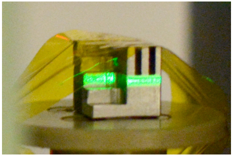


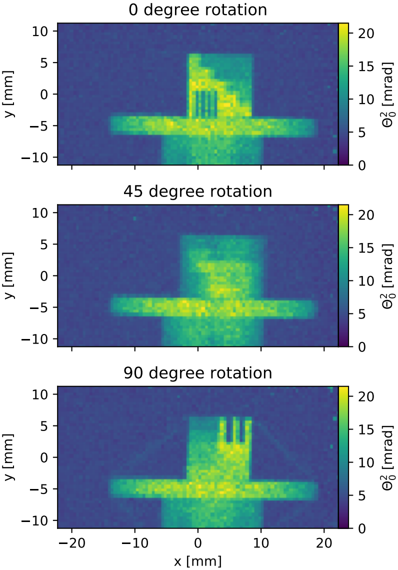


- Position-resolved beam widening due to multiple Coulomb scattering
  - Phantom plane is divided into bins
  - Each bin is associated with tracks that pass through it
  - Scattering angle distribution width is calculated for these tracks
  - No energy loss data used

Preliminary MCSR Testbeam Results

- 100.4 MeV proton beam
- 3 rotation angles (0°, 45° and 90°)
  - 10^6 triggers per projection
  - Currently 90 min per projection
- Clear phantom-air contrast
- Stair profile can be distinguished
- Sensitive enough for Kapton tape





Summary and outlook

- MedAustron: cancer treatment with protons, carbon ions
- Regular beamtimes available for non-clinical research
    - One exclusive irradiation room
    - Protons: up to 800 MeV and with low fluxes
    - Carbon ions: up to 400 MeV u^{-1}
- Further low flux commissioning is planned
- Experimental program for ion beam imaging (2018)
    - Ion computed tomography
    - Multiple Coulomb scattering (MCS) imaging
- First preliminary MCS testbeam results
- Commissioning of full pCT setup ongoing (since mid 2019)
    - Investigation of other calorimeter options (time-of-flight calorimeter talk on Thursday)
- Image reconstruction is work in progress

Longterm goal: clinical implementation at MedAustron

Acknowledgements

Thank you for your attention

Contributors	➛ Thomas Bergauer	➛ Stefanie Kaser
	➛ Alexander Burker	➛ Florian Pitters
	➛ Albert Hirtl	➛ Vera Teufelhart
	➛ Christian Irmler	
Collaborators	➛ EBG MedAustron	➛ MedUni Vienna

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Accelerator layout

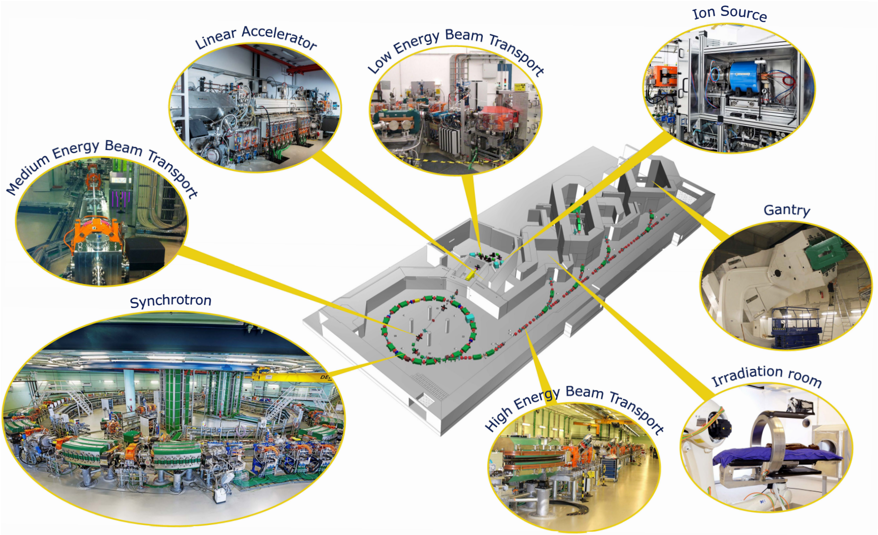


Image: MedAustron

Accelerator layout – Synchrotron

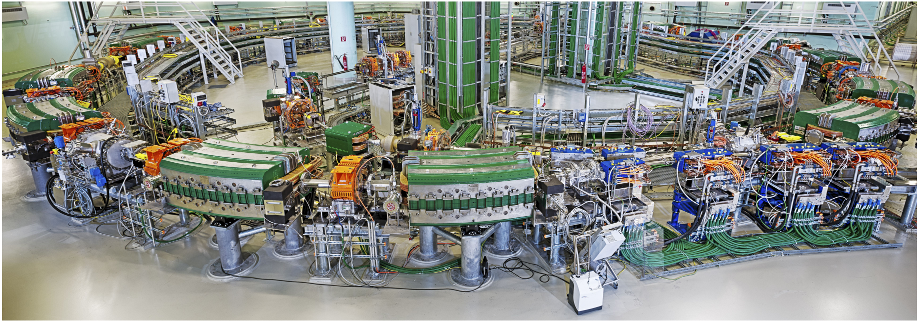


Image: MedAustron

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

Backup – Particle Therapy

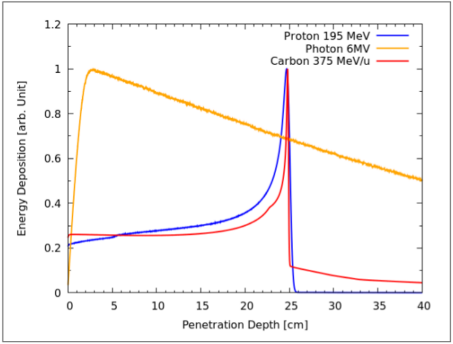


Image: Bragg peak

Photon therapy:

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

Advantages of ion-beam therapy over photon therapy

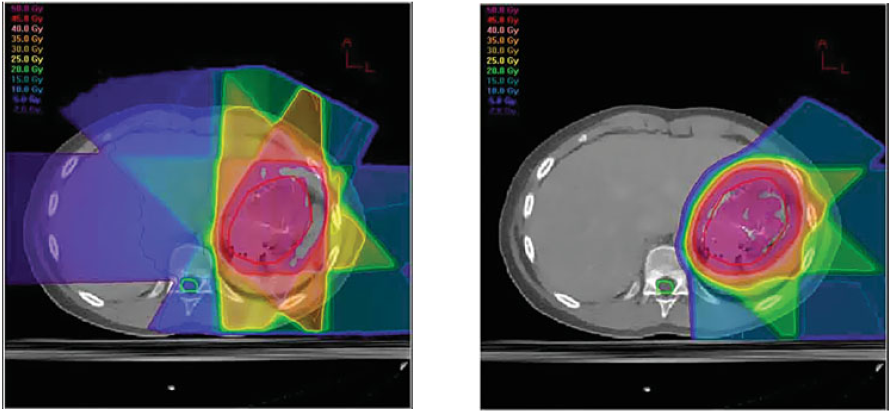
- Energy deposition (dose) in ion-beam therapy **strongly localised** $(S \propto \frac{1}{v^2})$
  - Accurate dose-deposition
  - Treatment of tumors close to radio-sensitive tissues, e.g. optical nerve

Ion-beam therapy:

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

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

Backup – Particle Therapy



Photon therapy:

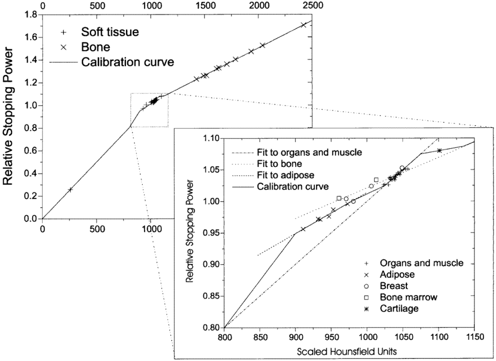
Proton therapy:

Image: Dose comparison for photon (left) and proton (right) treatment plans. [6]

Backup – Treatment Planning

Treatment planning based on X-ray CT

- Conversion from Hounsfield units (HU) to relative stopping power (RSP) prone to ambiguities and range errors ($\approx 1 - 3\%$)



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

$$\Downarrow$$

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

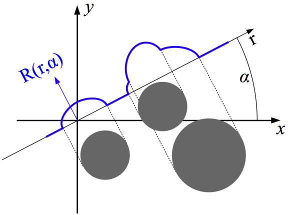
Image: Conversion from HU to RSP [7]

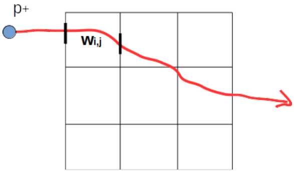
- Solution: direct measurement of stopping power (imaging with ions)

Backup – Reconstruction

Imaging in a nutshell:

- **Forward projection** $\mathrm{p_i}$ **(Radon transform):**
  $$\boxed{R[f(x,y)] = \int_{\gamma(\alpha,r)} f(x,y)\,\mathrm{d}s \equiv p}$$
- Insert physics to define forward projection:
  $\int SPR(x,y)\,\mathrm{d}l = b(E_{in}, E_{out})$
  $$\boxed{p_i = b(E_{in}, E_{out})_i \approx \sum w_{i,j} SPR(x,y)_j}$$
- Forward projection is a **set of linear equations** $Ax = b$, with b_i as a function of the **residual energy** of particle i, x_j as the SPR in voxel j and $A_{i,j}$ as the **particle's pathlength** through voxel j
- **Backprojection** means solving linear equations $Ax = b \Rightarrow x = SP$





Backup – 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)

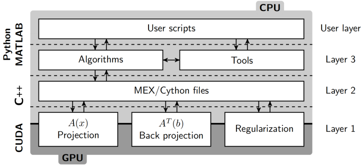


Image: TIGRE [8]

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

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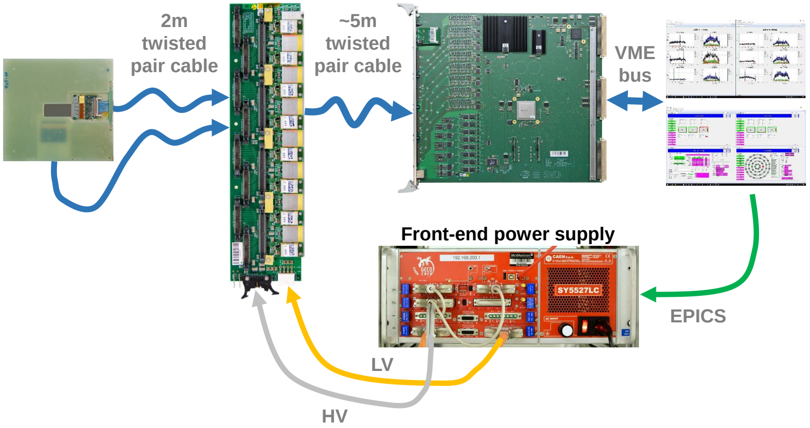
[7] `https://arxiv.org/abs/1905.03748`

Backup – Tracker readout system



6 DSSD modules:
2 x 4 APV25 chips, 128 channels each

2 Junction boards:
rad-hard DC/DC converters

2 FADC boards:
signal digitization, zero supression and VME interface

EPICS based slow and run control:
data readout via VME bus

2m twisted pair cable

~5m twisted pair cable

VME bus

Front-end power supply

EPICS

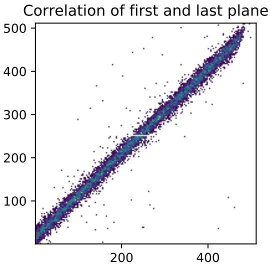
LV

HV

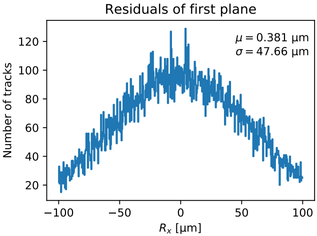
Backup – Tracker alignment

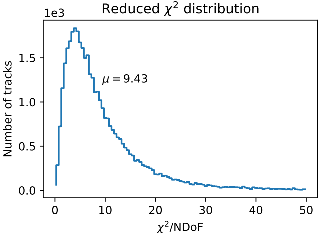
- 252.7 MeV beam with no phantom
- Corryvreckan framework[1] for track fitting, alignment
  1. Custom event loader for pixel hits
  2. ClusteringSpatial: hits → clusters
  3. Prealignment: initial guess for alignment, using plane correlations
  4. TrackingSpatial: fit pre-aligned tracks
  5. AlignmentTrackChi2: use track-fits to align detectors
  6. TrackingSpatial: fit aligned tracks, obtain residuals

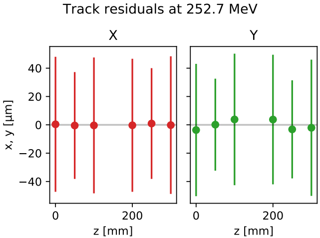
- Hits correlate well
- Widening might be caused by multiple Coulomb scattering and low energy



Backup – Tracker alignment



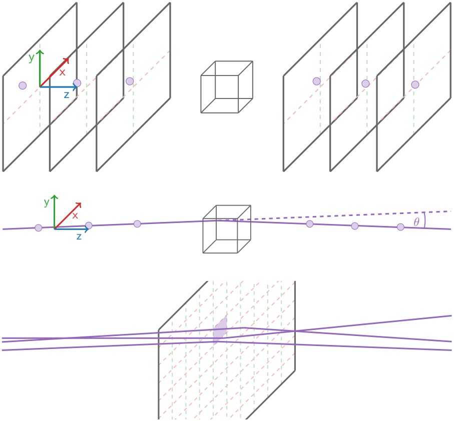




- Residuals are wider than tracker resolution
  - Pitch / $\sqrt{12} \approx 29\,\mu\text{m}$
- Mean reduced chi-square a lot larger than 1
- Some planes not perfectly centered in y
- Might be due to using straight lines and low beam energy
- Analysis ongoing

Backup – Multiple scattering radiography

1. Use only tracker clusters to radiograph a scattering body
   - No energy measurement
2. Fit tracks separately for tracker triplets before and after scatterer
3. Calculate angle between tracks
   - x- and y-direction: two independent measurements
4. In each bin:
   1. Collect distribution of scattering angles for intercepting tracks
   2. Calculate width (variance) of the distribution of angles

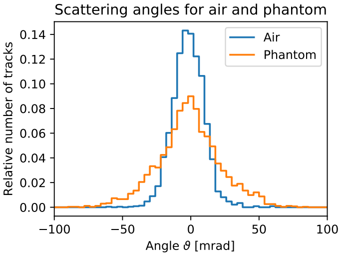


Backup – Multiple scattering radiography

- Scattering angle distribution is centered around zero
- Its width depends on the integrated material budget ε that particles pass
  - $\varepsilon = x/X_0$
- Using the Highland formula, ε can be reconstructed:

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

  - This analysis is still ongoing



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