Non-clinical test beams at MedAustron

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

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

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

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

- Treatment during the weekdays
- First patient treated in 2016
- Currently: \( \approx 27 \text{ sessions/d} \)
- 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
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

Preview of the RAte MONitor for the AIDATLU-producer in EUDAQ2
Rate reduction—Results

Clinical energies (< 252.7 MeV)

<table>
<thead>
<tr>
<th>Setting</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal rate</td>
<td>$10^{10}$ p per 5s</td>
</tr>
<tr>
<td>Method I</td>
<td>$\mathcal{O}(10^7)$ p per 5s</td>
</tr>
<tr>
<td>Method II</td>
<td>$\mathcal{O}(10^6)$ p per 5s</td>
</tr>
<tr>
<td>Method III</td>
<td>$\mathcal{O}(10^4)$ p per 5s</td>
</tr>
</tbody>
</table>

Now: rates down to $\sim$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: $\Delta E$
- Pass rear tracker
- Deposit energy in calorimeter: $E - \Delta E$

Proton/ion CT:
- $\Delta E$ and path estimate
- 3D image of stopping power

Multiple coulomb scattering CT:
- Only path estimate
- 3D image of material budget

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pCT setup – Tracker

- 6 DSSD modules
  - Size: \((2.56 \times 5.12) \text{ cm}^2\)
  - Thickness: 300 \(\mu\text{m}\)
  - X-side:
    - 512 p-doped strips
    - Pitch: 50 \(\mu\text{m}\)
  - Y-side:
    - 512 n-doped strips
    - Pitch: 100 \(\mu\text{m}\)

- VME-based readout
  - APV25 chip [3]
  - Belle-II SVD readout chain [4]
  - Achieved event-rate
    - 250 Hz raw data
    - 500 Hz zero suppressed
    - \textit{Limited by VME bus speed}
    - \textit{Implementing GbE readout}
pCT setup – Calorimeter

Implementation of range telescope (formerly TERA [5])

- 42 slices to sample energy loss
- Plastic scintillators with SiPMs
- Size: $3 \times 300 \times 300$ mm$^3$ each
- Can measure protons up to 140 MeV
- Readout via USB connection (DAQrate < 1 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)
  - $R = 1 \text{ cm}$, $L = 1 \text{ cm}$
  - Cylindrical cutouts
  - Cutouts were partially filled with plastic

- Aluminum cube
  - $1 \text{ cm} \times 1 \text{ cm} \times 1 \text{ cm}$
  - 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
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**
  - Forward and backprojection are optimized for GPU computing
  - Algorithms are written in high-level language (Python, Matlab)
  - Several reconstruction algorithms implemented
  - Initially developed for cone beam CT (CBCT)

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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
- $1 \times 10^6$ 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
Thank you for your attention

Contributors

- Thomas Bergauer
- Alexander Burker
- Albert Hirtl
- Christian Irmler

Collaborators

- EBG MedAustron
- MedUni Vienna

Acknowledgements

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Accelerator layout

Image: MedAustron
Accelerator layout – Synchrotron

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

Image: MedAustron

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Advantages of ion-beam therapy over photon therapy

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

**Photon therapy:**

\[
I = I_0 e^{-\mu x}
\]

**Ion-beam therapy:**

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

with \( S(E) = -\frac{dE}{dx} \)
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 ($\approx 1 - 3\%$)

\[
H U = 1000 \times \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}}
\]

\[
R S P = \frac{S(x)}{S(x)_{\text{water}}}
\]

Image: Conversion from HU to RSP [7]

- Solution: direct measurement of stopping power (imaging with ions)
Imaging in a nutshell:

- **Forward projection** $p_i$ (Radon transform):

  \[
  R[f(x, y)] = \int_{\gamma(\alpha, r)} f(x, y) \, ds \equiv p
  \]

- Insert physics to define forward projection:

  \[
  \int SPR(x, y) \, dl = b(E_{in}, E_{out})
  \]

  \[
  p_i = b(E_{in}, E_{out})_i \approx \sum w_{i,j} SPR(x, y)_j
  \]

- 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
- Algorithms are written in high-level language (Python, Matlab)

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

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Image: TIGRE [8]

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

Front-end power supply

VME bus

EPICS

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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 $\rightarrow$ 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
- Residuals are wider than tracker resolution
  - Pitch / $\sqrt{12} \approx 29 \, \mu m$
- 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
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
Scattering angle distribution is centered around zero.

Its width depends on the integrated material budget $\varepsilon$ that particles pass:

\[ \varepsilon = \frac{x}{X_0} \]

Using the Highland formula, $\varepsilon$ 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.
References


References II

