Updates and future plans for ion imaging at MedAustron

A. Hirtl for the HEPHY / TU Wien ion imaging collaboration

TU Wien, Atominstitut

The 3rd Ion Imaging Workshop 2022, Munich, 2022-10-13

Therapy and research at MedAustron

Synchrotron ≈ 50 km south of Vienna

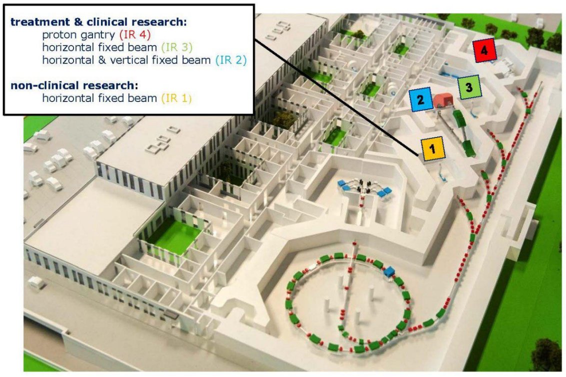


Image: MedAustron

Four irradiation rooms:

- IR1: **exclusive to research**
  - protons: [60,252] MeV & 800 MeV
  - carbon ions: [120,400] MeV/nucleon
- IR2, IR3, IR4: clinical use

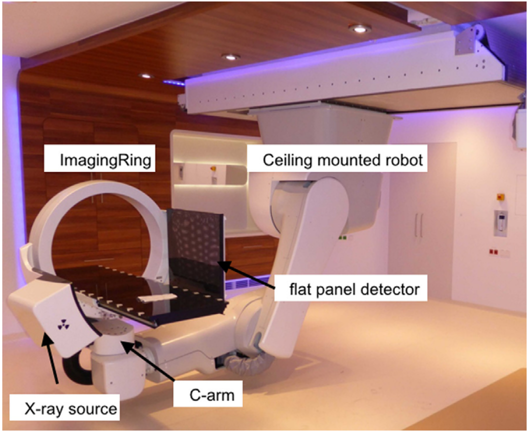
Beam parameters:

- pencil beam scanning (field 20 cm × 20 cm)
- [7,21] mm FWHM spot size
- nominal (clinical) rate:
  - protons ≈ 10^9 particles/s
  - carbon ions ≈ 10^7 particles/s

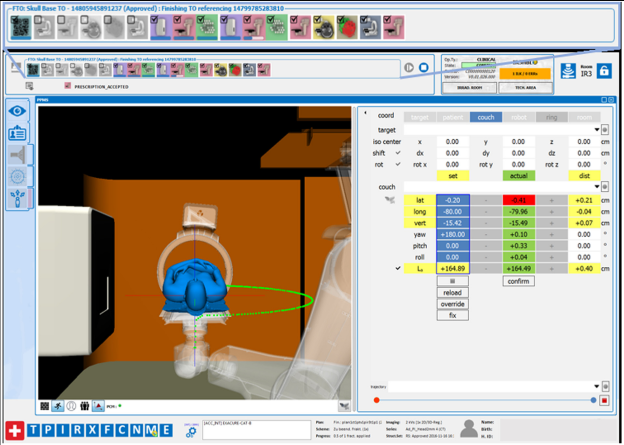
  ⇒ too high for most detectors
- low flux commissioned ⇒ more later

Irradiation rooms – Workflow

Patient alignment system



Radiation Therapy Software System

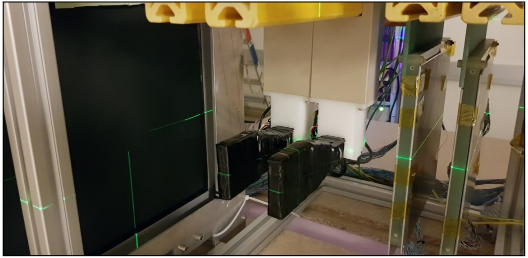


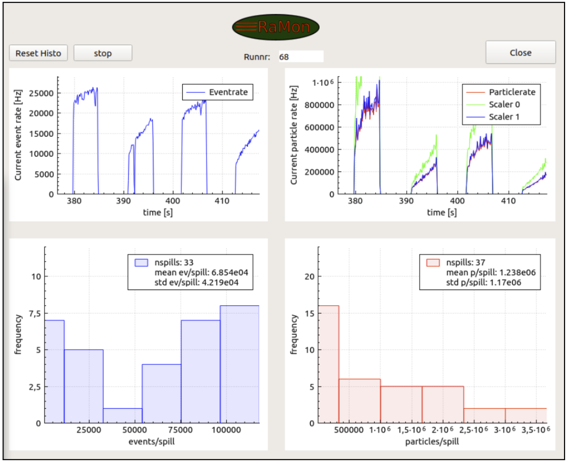
Images: Stock et al. (2018)

Low flux in physics mode

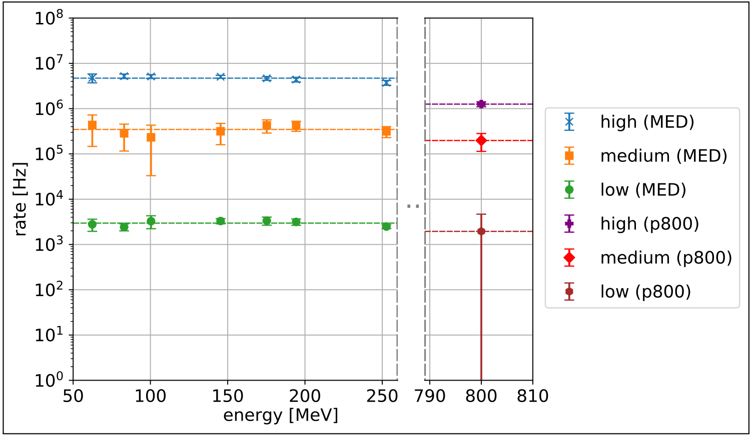
Real-time beam monitoring

- nominal flux too high for single particle tracking
- flux reduction commissioned
  $\Rightarrow$ *details: Felix Ulrich-Pur et al. 2021*
- beam diagnostics blind at low flux
  - dedicated beam monitoring developed





Commissioned low flux rates



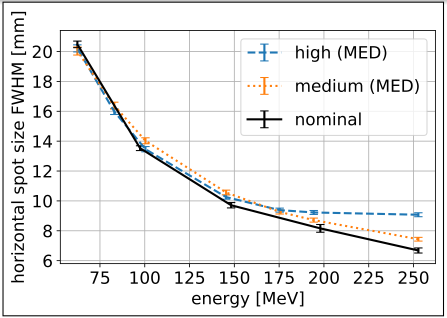
Clinical energies

high (MED)	≈ 4.7 MHz
medium (MED)	≈ 350 kHz
low (MED)	≈ 3 kHz

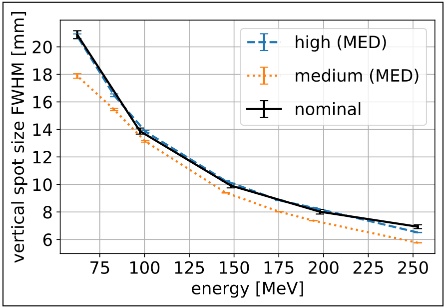
800 MeV

high (p800)	≈ 1.25 MHz
medium (p800)	≈ 200 kHz
low (p800)	≈ 2 kHz

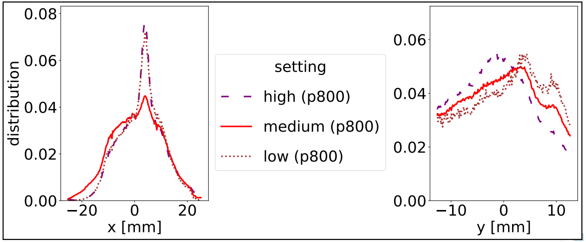
Spot sizes



horizontal spot size FWHM [mm]
energy [MeV]
high (MED)
medium (MED)
nominal
6
8
10
12
14
16
18
20
75
100
125
150
175
200
225
250



vertical spot size FWHM [mm]
energy [MeV]
high (MED)
medium (MED)
nominal
6
8
10
12
14
16
18
20
75
100
125
150
175
200
225
250

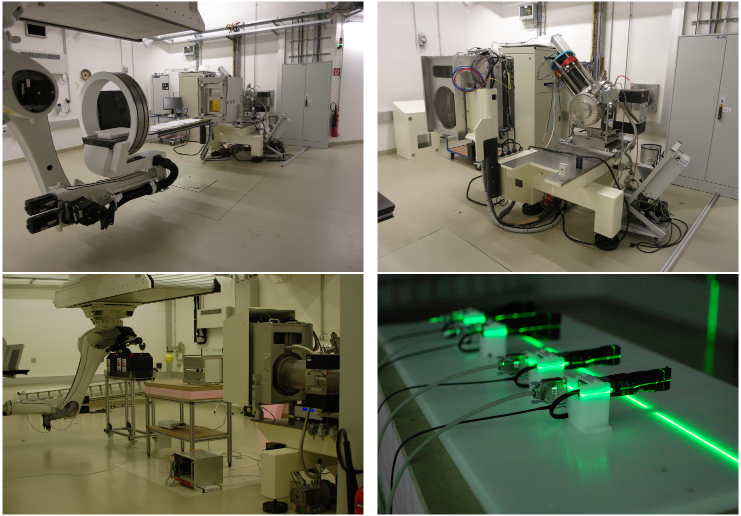


distribution
x [mm]
y [mm]
setting
high (p800)
medium (p800)
low (p800)
0.00
0.02
0.04
0.06
0.08
−20
0
20
−10
10

Implementation of research projects at MedAustron

- research groups have regular access to beam times at MedAustron
  - dedicated irradiation room ⇒ more later
  - beam times only on weekends
- three 8 h shifts per day
  - early bird (EB): 6 am – 2 pm
  - royal (RO): 2 pm – 10 pm
  - vampire (VA): 10 pm – 6 am
- office space and basic infrastructure (labs and equipment) available at MedAustron
  - basic electronics (rack, VME crate with modules), oscilloscope, 1 T magnet
  - dosimetric equipment (various ionisation chambers), TLD reader and oven
  - x-ray source
  - pre-clinical lab (with micro-PET/SPECT/CT)

Non-clinical irradiation room – IR1

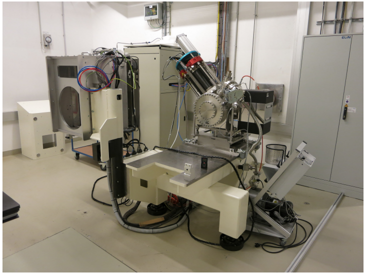
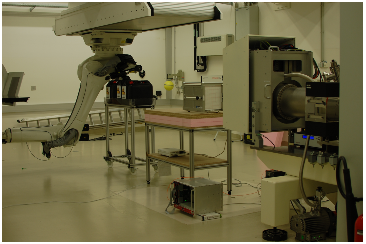
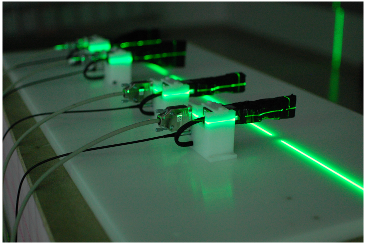


Images: MedAustron & A. Burker

Room properties

- area of 8 m × 12 m = 96 m^2
- LASER positioning system
- two iso-centres (one used)
- robotic positioning system with imaging ring (CT)
- can be monitored from the control room by webcam

Non-clinical irradiation room – IR1

Images: MedAustron & A. Burker

Special features for research

- full clinical work flow
  - all ions
  - scanning
- physics mode of accelerator
  - low flux $\Rightarrow$ no scanning!
- proton energies up to 800 MeV
  - energies between 250 MeV and 800 MeV possible

Irradiation rooms – Summary

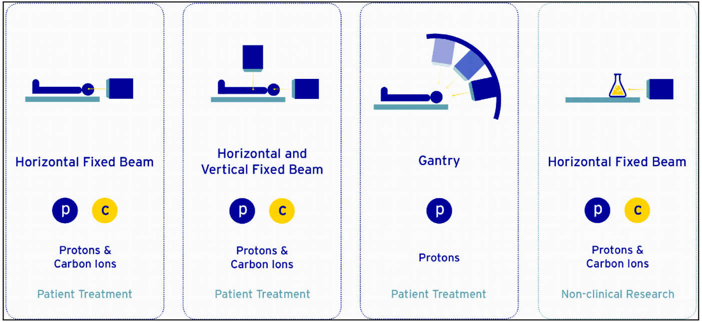


Image: MedAustron

Milestones:

- first proton treatment 12-2016
- first carbon treatment 07-2019
- gantry clinically used since 05/2022
  - not all angles commissioned yet

Outlook:

- commissioning of helium ions started

Ion imaging at TU Wien and HEPHY

How it started

- Joint ion imaging project of TU Wien and HEPHY started in 2017
  - long-term experience in detector development at HEPHY
- Access to regular beam times at the MedAustron facility
- Establishment of full workflow from scratch to implement ion imaging
  1. hardware – trackers and calorimeter/range telescope
     $\Rightarrow$ *details: Ulrich-Pur et al. 2020*
  2. software – data readout, processing and 3D image reconstruction
- Collaboration with Medical University of Vienna (2019)
  - experience in CT image reconstruction
  - TIGRE toolbox (developed for conventional CT) applied to the ion CT reconstruction problem
    $\Rightarrow$ *details: Kaser et al. 2021*

Ion imaging at TU Wien and HEPHY

How it started

- Joint ion imaging project of TU Wien and HEPHY started in 2017
  - long-term experience in detector development at HEPHY
- Access to regular beam times at the MedAustron facility
- Establishment of full workflow from scratch to implement ion imaging
  1. hardware – trackers and calorimeter/range telescope
     ⇒ *details: Ulrich-Pur et al. 2020*
  2. software – data readout, processing and 3D image reconstruction
- Collaboration with Medical University of Vienna (2019)
  - experience in CT image reconstruction
  - TIGRE toolbox (developed for conventional CT) applied to the ion CT reconstruction problem
    ⇒ *details: Kaser et al. 2021*

⇒ demonstrator based on existing technology built

Sketch of experimental set-up tested at MedAustron

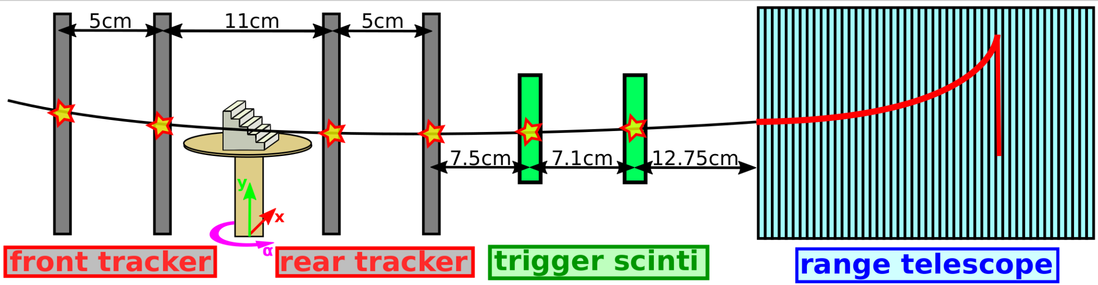
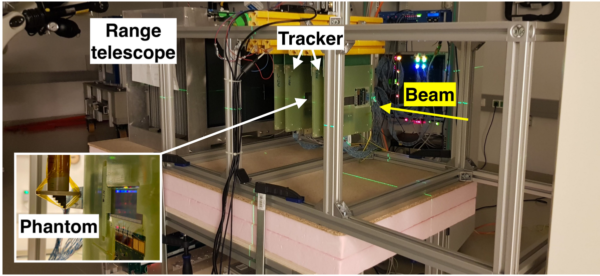
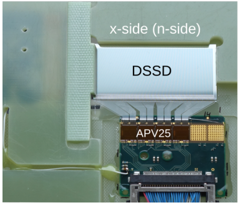


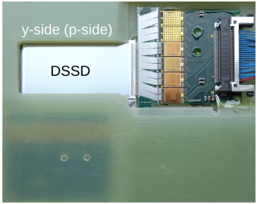
Image: iCT demonstrator set-up (⇒ *Ulrich-Pur et al. 2021*)

- demonstrator based on double sided silicon strip detectors (DSSDs) and a range telescope
- synchronisation via AIDA2020 trigger and logic unit (TLU) (⇒ *Cussans 2017*)
  - exclusive trigger number per particle to correlate tracks and energy loss
- an aluminium cube with a stair profile (side length of 1 cm) on a rotating table was imaged
- image reconstruction using an iterative algorithm available in TIGRE

Demonstrator at MedAustron

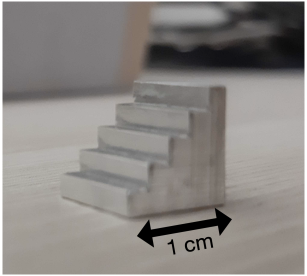




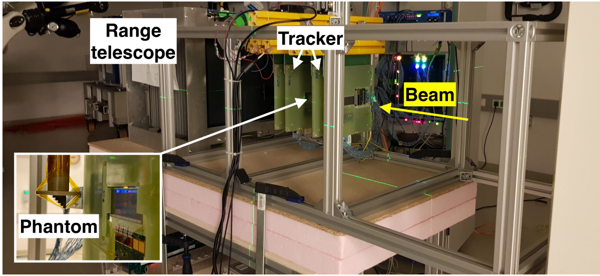


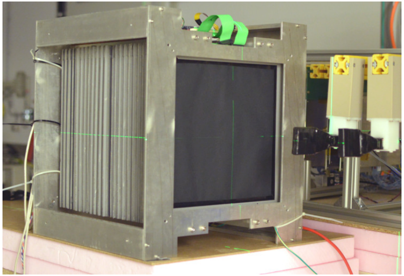
Particle tracking:

- 4 DSSDs $(2.56 \times 5.12)\ \mathrm{cm}^2$
- 300 µm thickness and 512 strips
- pitch: 50 µm (X), 100 µm (Y)
- tracker readout: APV25 chip & Belle-II SVD readout chain
  $\Rightarrow$ *details: French et al. 2001*
- tracking with Corryvreckan
  $\Rightarrow$ *details: Dannheim et al. 2021*



Demonstrator at MedAustron





Particle tracking:

- 4 DSSDs (2.56 × 5.12) cm^2
- 300 µm thickness and 512 strips
- pitch: 50 µm (X), 100 µm (Y)
- tracker readout: APV25 chip & Belle-II SVD readout chain
  ⇒ *details: French et al. 2001*
- tracking with Corryvreckan
  ⇒ *details: Dannheim et al. 2021*

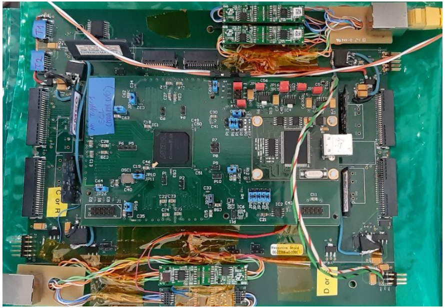
Energy measurement:

- range telescope using plastic scintillators with SiPMs
- 42 slices (3 × 300 × 300 mm^3)
- can measure protons up to 140 MeV
- USB readout (DAQrate ≈ 15 kHz)
  ⇒ *details: Bucciantonio et al. 2013; claim DAQrate* < 1 MHz
- SiPM power supply unstable

⇒ complete redesign of mainboard

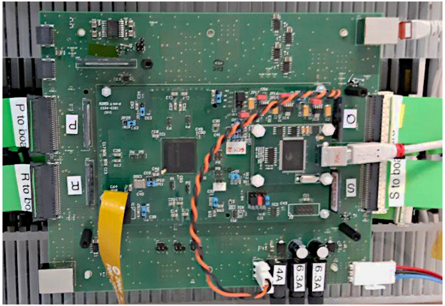
Mainboard before and after & a bug

Original:



Domestic bug:

New:



After redesign:

- ➛ stable operation possible

≈ 900 pCT events per second

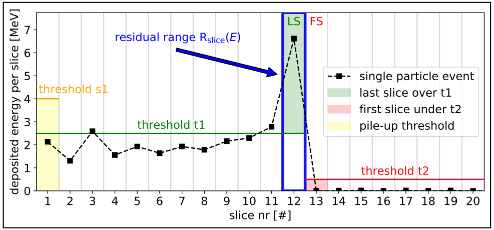
Calibration of range telescope

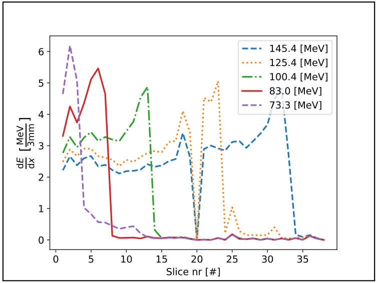
Calibration of range telescope

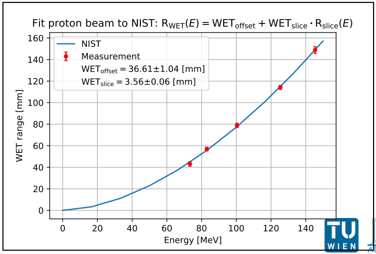
- estimation of mean water equivalent thickness (WET) of the calorimeter components
  - ranges are measured for different proton energies
  - comparison to NIST data for WET estimation of trigger scintillators and TERA scintillators

Range determination

- last slice over threshold and first slice under threshold defines range

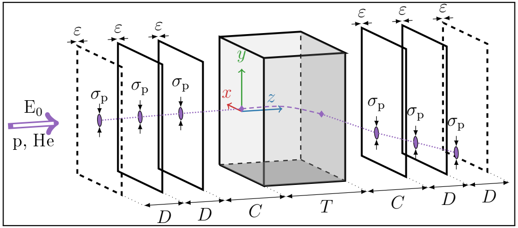






Particle tracking & influence of detectors

Variation of tracker parameters

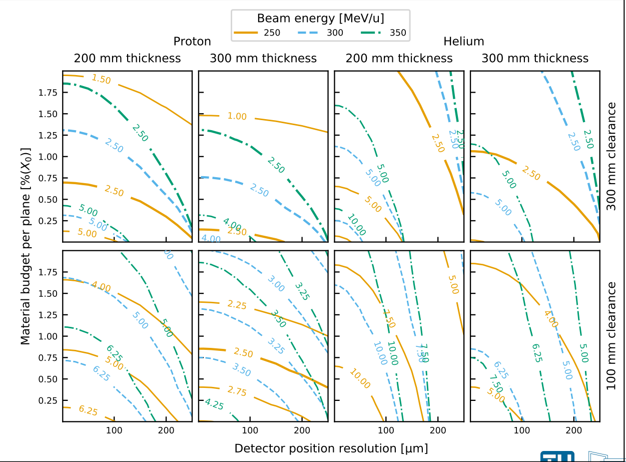


- study system parameters with MC
  - by varying X_0, clearances, energy, . . .
- iso-resolution contours (image right)
  - resolution achievable from tracking (path estimate) only
- huge parameter space!

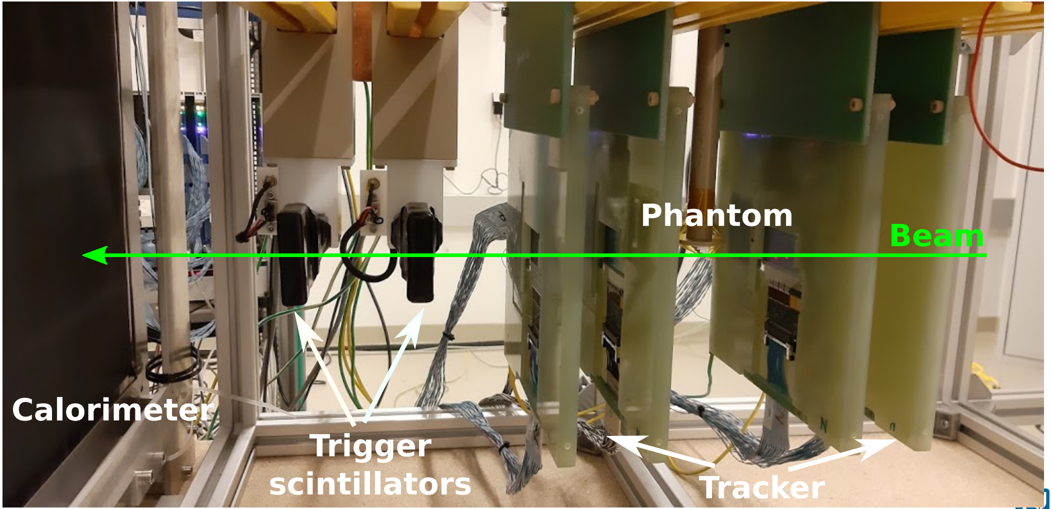
$\Rightarrow$ *details: Burker et al. 2020*

Images: PhD A. Burker

Achievable resolution in [lp/cm] for p & He



Testbeam at MedAustron



2D projections

Performed measurements:

- 100.4 MeV protons
- 80 projections with $\approx 2.5 \times 10^6$ events (24 min) each
  - only $\approx 6.5 \times 10^5$ synchronized events per projection (mean event rate $\approx$ 450 Hz)

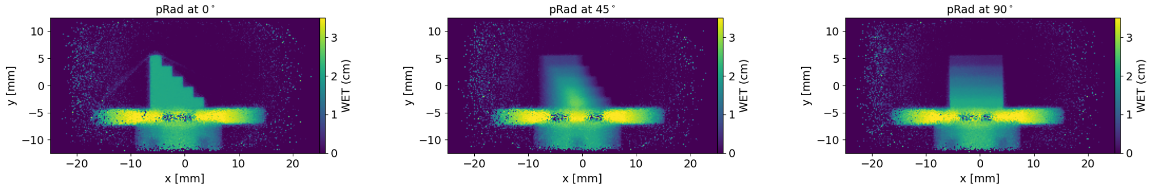
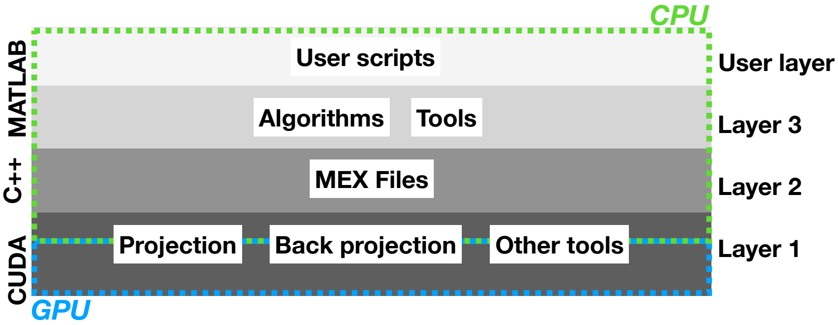


Image reconstruction:

- using TIGRE – **T**omographic **I**terative **G**PU-based **RE**construction toolbox
  - open source framework developed for x-ray CT
    $\Rightarrow$ *details: Biguri et al. 2016*

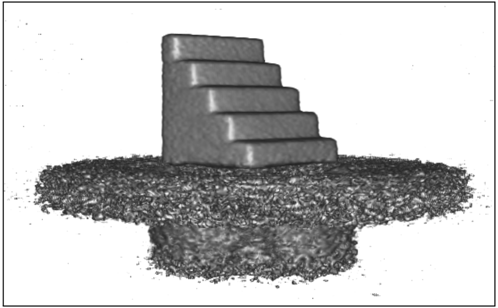
The TIGRE toolbox

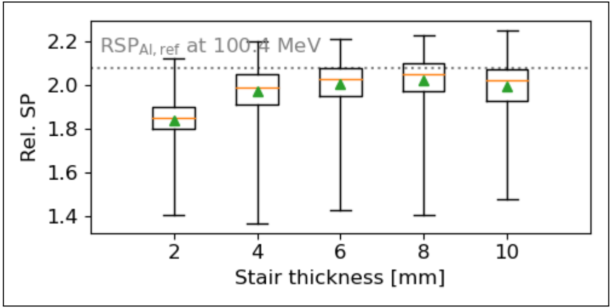
- iterative (and direct) reconstruction algorithms



- TIGRE suitable for ion CT image reconstruction
  - straight-line approach for ion path → data cuts for improved image resolution
    ⇒ *details: Kaser et al. 2021*

RSP reconstruction from experimental data



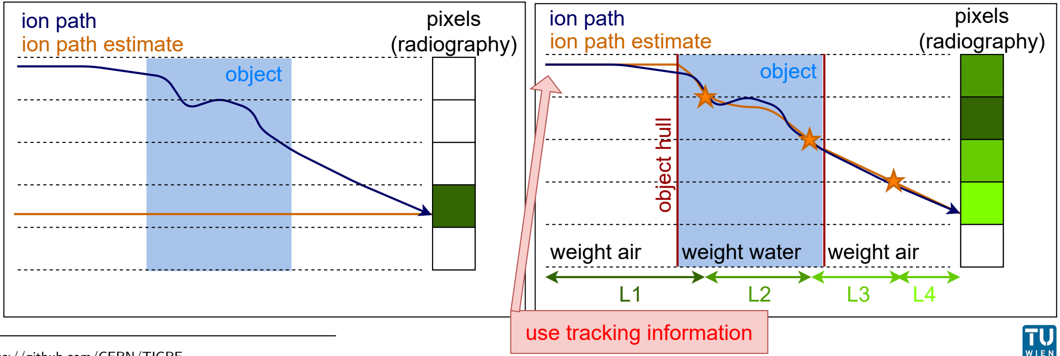


- stair profile clearly visible in the reconstruction (OS-SART with 10 iterations), straight line and cuts
  - orange line: median value; green triangle: average RSP in a ROI
- MPV error below 1 % could be achieved

Improving the reconstruction workflow with TIGRE I

Pre-processing step to allow for ion CT reconstruction implemented

- basic idea: assign one ion to multiple pixels depending on path estimate
  ⇒ *details: Collins-Fekete et al. 2016*
- implementation using CUDA → **now part of the TIGRE toolbox**[a]
- extension tested with **Monte Carlo data**

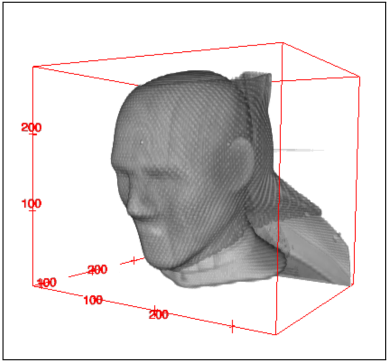


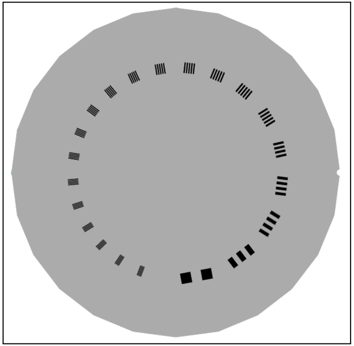
[a] https://github.com/CERN/TIGRE

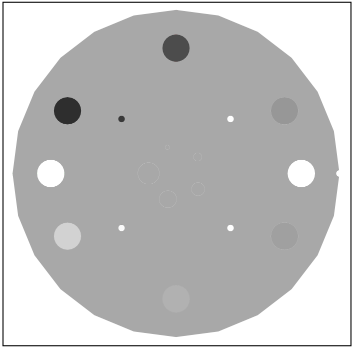
Improving the reconstruction workflow with TIGRE II

Phantoms:

- phantom patient for stereotactic end-to-end verification (STEEV) (CIRS, Norfolk, VA, USA)
- Catphan® 528 & 404 (The Phantom Laboratory Incorporated, Salem, NY, USA)



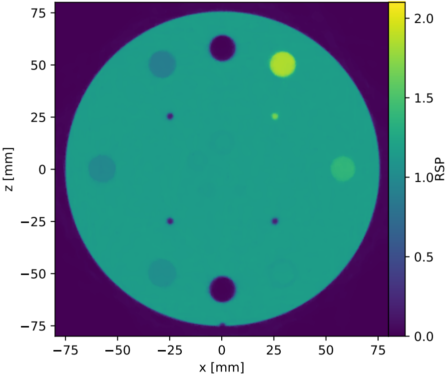




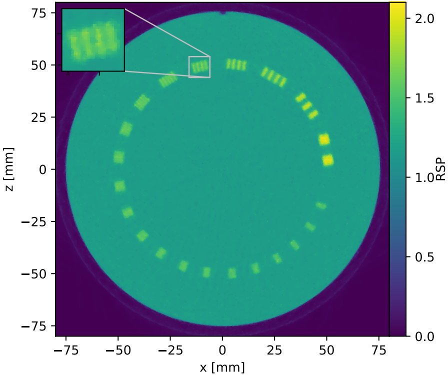
Acknowledgement: B. Knäusl and M. Stock for providing the CT image of the CIRS head phantom.

Reconstructions of CTP modules

- CTP404 (Sensitometry)



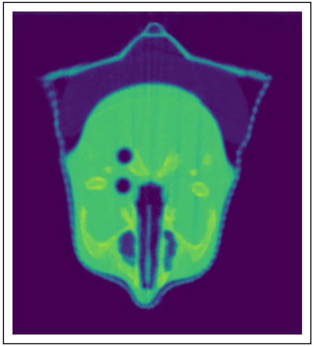
- CTP528 (High Resolution)



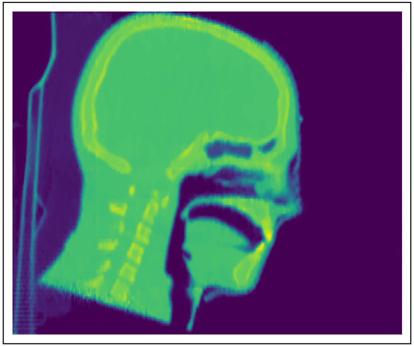
- MAPE $<$ **0.5%**
- Resolution: **6 lp/cm** (non-ideal data set) and **8 lp/cm** (ideal data set)

Reconstructed head phantom

- CT scan of head phantom implemented in GATE
- 90 proton radiographs ($\approx$ 50 protons/pixel) used for reconstruction (ASD-POCS algorithm)
  $\Rightarrow$ *details: Kaser et al. 2022*

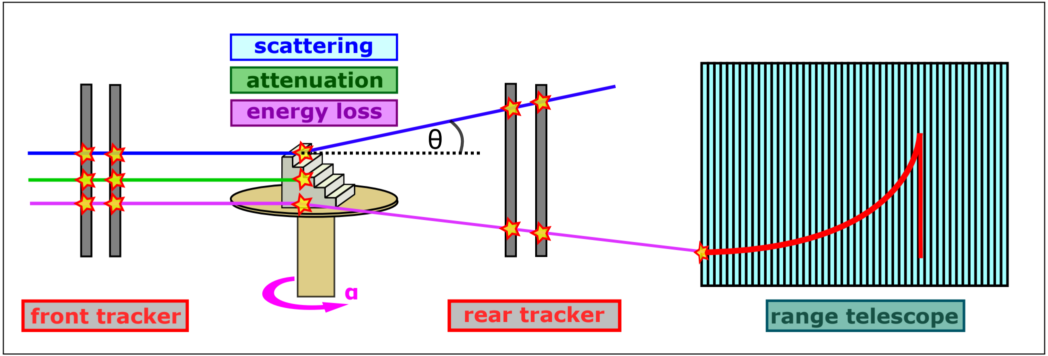


- Reconstructed *XZ*-plane



- Reconstructed *YZ*-plane

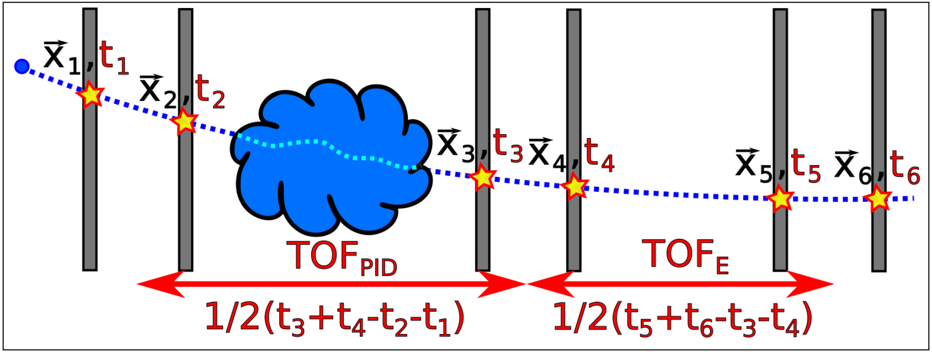
Other investigated modalities with the demonstrator



- multiple Coulomb scattering imaging
- fluence loss (attenuation) imaging

$\Rightarrow$ see talk by S. Kaser tomorow 14.10.2022 at 15:40

Future direction: time-of-flight iCT



- 4D tracking using fast detectors ⇒ low-gain avalanche detectors (LGADs)
- residual energy estimated via time-of-flight (TOF) measurement

⇒ see talk by F. Ulrich-Pur tomorow 14.10.2022 at 11:40

From low flux commissioning to synergies with MedAustron

Beam diagnostics at MedAustron

- blind at low fluxes
- suffers from radiation damage after long use

Idea to implement new monitoring system based on

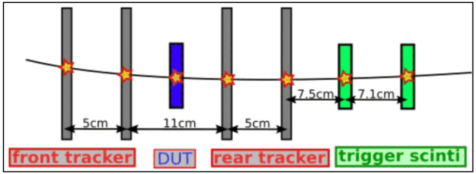
- radiation hard detectors
- with high dynamical range to cover
  - Hz to MHz region for research
  - GHz for regular therapy
  - $>$ GHz for FLASH therapy
- survive the harsh conditions as long as possible
- be operated under high-vacuum conditions without additional cooling

$\Rightarrow$ detectors based on silicon carbide – SiC

SiC properties

- wider band gap & less dark current
- fast signals & radiation hard

Functionality tested at MedAustron



Images: P. Gaggl

From low flux commissioning to synergies with MedAustron

Beam diagnostics at MedAustron

- blind at low fluxes
- suffers from radiation damage after long use

Idea to implement new monitoring system based on

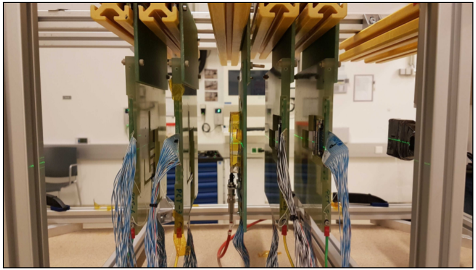
- radiation hard detectors
- with high dynamical range to cover
  - Hz to MHz region for research
  - GHz for regular therapy
  - $>$ GHz for FLASH therapy
- survive the harsh conditions as long as possible
- be operated under high-vacuum conditions without additional cooling

$\Rightarrow$ detectors based on silicon carbide – SiC

SiC properties

- wider band gap & less dark current
- fast signals & radiation hard

Functionality tested at MedAustron



Images: P. Gaggl

From low flux commissioning to synergies with MedAustron

Beam diagnostics at MedAustron

- blind at low fluxes
- suffers from radiation damage after long use

Idea to implement new monitoring system based on

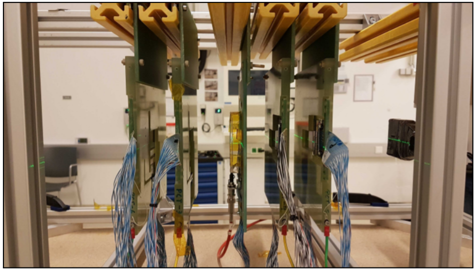
- radiation hard detectors
- with high dynamical range to cover
  - Hz to MHz region for research
  - GHz for regular therapy
  - $>$ GHz for FLASH therapy
- survive the harsh conditions as long as possible
- be operated under high-vacuum conditions without additional cooling

$\Rightarrow$ detectors based on silicon carbide – SiC

SiC properties

- wider band gap & less dark current
- fast signals & radiation hard

Functionality tested at MedAustron

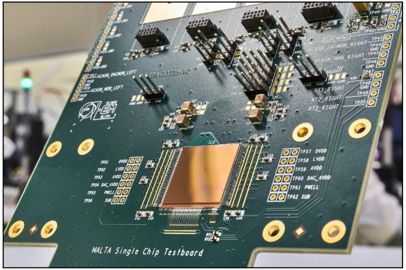


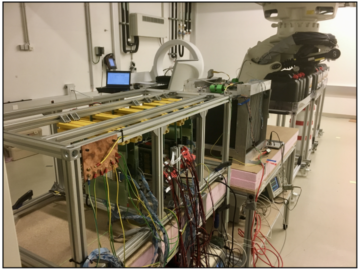
Use in microdosimetry?

Images: P. Gaggl

Other detector options for tracking

MALTA HV CMOS from CERN





- 4 sensor planes tested in a joint beam time at MedAustron by a team from CERN
  - 512×512 squared pixels with 36.4 µm pitch $\Rightarrow$ area 1.8 cm^2
  - functioning was demonstrated
- could be used for tracking at high rates
  - HEPHY is developing DMAPS sensors for other HEP projects

Summary & Outlook

Summary

- started ion imaging effort in 2017 as common effort of HEPHY & TU Wien
  - hardware expertise at HEPHY
- regular access to beam times at MedAustron in a dedicated irradiation room
  - currently protons (low flux!) and carbon ions available
  - helium ions in commissioning phase
- full iCT workflow established
  - implemented demonstrator system & established image reconstruction
  - 3 PhDs finished (tracking, calorimetry & image reconstruction)

Outlook

- TOF-iCT based on fast detectors (LGADs)
- funding required
  - Austro-French joint projects (ANR – FWF) with S. Rit (CREATIS – HEPHY – TU Wien)
  - iCT activities in synergy with other hardware projects at HEPHY
- increase in hardware activities required!

Effort of many!

Staff

- Thomas Bergauer
- Christian Irmler
- Florian Pitters
- numerous engineers and technicians from HEPHY

MSc

- Benjamin Huber
- Benjamin Kirchmayer
- Vera Teufelhart

BSc

- many BSc students

PhDs

- Alexander Burker (PhD tracking)
- Stefanie Kaser (PhD image reconstruction)
  ⇒ talk tomorow at 15:40
- Felix Ulrich-Pur (PhD calorimetry & TOF)
  ⇒ talk tomorow at 11:40

Collaborators

- Sepideh Hatamikia (ACMIT)
- Wolfgang Birkfellner, Dietmar Georg (MedUni Wien)
- Ander Biguri (University of Cambridge)
- Simon Rit & Nils Krah (CREATIS)

References & Appendix

References

Biguri, Ander et al. (Sept. 2016). "TIGRE: a MATLAB-GPU toolbox for CBCT image reconstruction". In: Biomedical Physics & Engineering Express 2.5, p. 055010. DOI: 10.1088/2057-1976/2/5/055010.

Bucciantonio, M. et al. (DEC 21 2013). "Development of a fast proton range radiography system for quality assurance in hadrontherapy". In: NIM A 732. 13th Vienna Conference on Instrumentation, Tech Univ Vienna, Vienna, AUSTRIA, FEB 11-15, 2013, 564–567. DOI: 10.1016/j.nima.2013.05.110.

Burker, A. et al. (2020). "Single particle tracking uncertainties in ion imaging". In: DOI: 10.48550/ARXIV.2008.08422. URL: https://arxiv.org/abs/2008.08422.

Collins-Fekete, Charles-Antoine et al. (Nov. 2016). "A maximum likelihood method for high resolution proton radiography/proton CT". In: Physics in Medicine and Biology 61.23, pp. 8232–8248. DOI: 10.1088/0031-9155/61/23/8232. URL: https://doi.org/10.1088/0031-9155/61/23/8232.

Cussans, David (Dec. 2017). "Triger Logic Unit ready". In: URL: http://cds.cern.ch/record/2297522.

Dannheim, D. et al. (Mar. 2021). "Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data". In: Journal of Instrumentation 16.03, P03008. DOI: 10.1088/1748-0221/16/03/p03008.

French, M.J. et al. (2001). "Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker". In: NIM A 466.2. 4th Int. Symp. on Development and Application of Semiconductor Tracking Detectors, pp. 359–365. ISSN: 0168-9002. DOI: 10.1016/S0168-9002(01)00589-7.

Kaser, Stefanie et al. (2021). "First application of the GPU-based software framework TIGRE for proton CT image reconstruction". In: Physica Medica 84, pp. 56–64. DOI: 10.1016/j.ejmp.2021.03.006.

Kaser, Stefanie et al. (2022). "Extension of the open-source TIGRE toolbox for proton imaging". In: Zeitschrift für Medizinische Physik. DOI: 10.1016/j.zemedi.2022.08.005.

Stock, Markus et al. (2018). “The technological basis for adaptive ion beam therapy at MedAustron: Status and outlook”. In: ZEITSCHRIFT FUR MEDIZINISCHE PHYSIK 28.3, 196–210. ISSN: 0939-3889. DOI: {10.1016/j.zemedi.2017.09.007}.

Ulrich-Pur, F et al. (2020). “Imaging with protons at MedAustron”. In: NIM A 978, p. 164407. DOI: https://doi.org/10.1016/j.nima.2020.164407. URL: http://www.sciencedirect.com/science/article/pii/S0168900220308044.

Ulrich-Pur, F et al. (2021). arXiv: 2106.12890 [physics.med-ph].

Ulrich-Pur, Felix et al. (2021). “Commissioning of low particle flux for proton beams at MedAustron”. In: NIM A 1010, p. 165570. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2021.165570. URL: https://www.sciencedirect.com/science/article/pii/S0168900221005556.