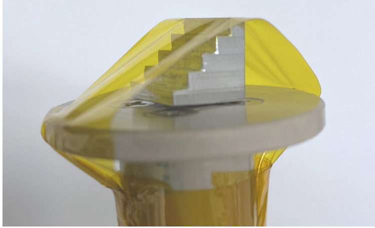
Studies of different ion imaging modalities at MedAustron



Stefanie Kaser on behalf of the ion CT group of HEPHY and TU Wien
3rd Ion Imaging Workshop
October 13th-14th, 2022
Munich, Germany

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

Introduction – MedAustron I

Image: MedAustron (https://www.medaustron.at/)

- Ion therapy and research centre
  - Synchrotron accelerator complex
- Located in Wiener Neustadt, about 50 km south of Vienna
- Four irradiation rooms
  - One exclusive to research

Introduction – MedAustron II

Irradiation rooms:

- IR1: **Exclusive to research**
  - Protons from 60 to 800 MeV
  - Carbon ions from 120 to 400 MeV/u
- IR2, IR3, IR4: Clinical use (clinical energies)
- Beam only in one room at a time

Beam parameters:

- Spotsize: 7 mm to 21 mm FWHM
- Research: low flux settings were commissioned (Ulrich-Pur et al. 2021b)
  - $\geq 2.4 \times 10^3$ particles/s

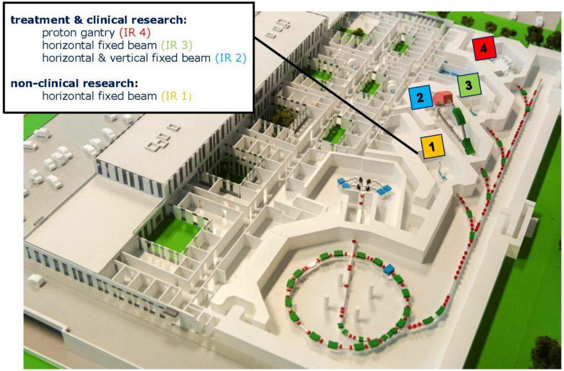


Image: Stock et al. 2015

Experimental setup – iCT demonstrator system I

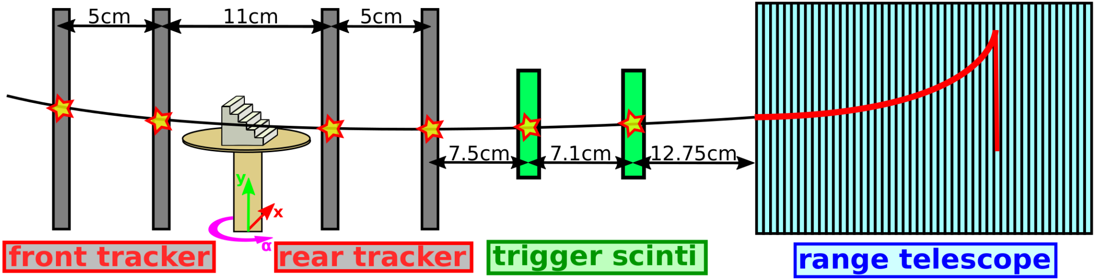


Image: iCT demonstrator setup (Ulrich-Pur et al. 2021a)

Experimental setup – iCT demonstrator system II

Tracking

- 4 DSSD modules
  - Size: $(5.12 \times 2.56)\,\text{cm}^2$
  - Thickness: 300 µm
  - 512 p-doped (X) / n-doped (Y) strips
  - Pitch: 50 µm (X), 100 µm (Y)
- Readout: APV25 chip (French et al. 2001) & Belle-II SVD readout chain

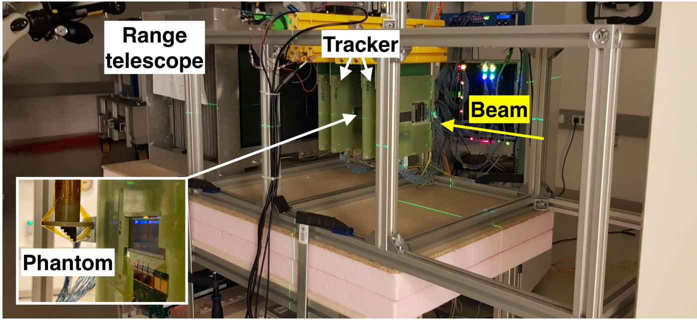
Energy measurement

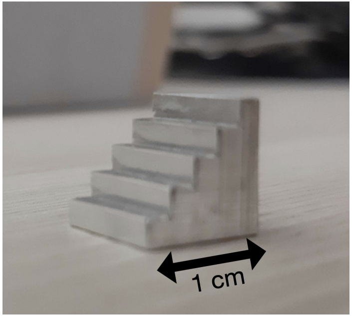
- Range telescope: Plastic scintillators with SiPMs
  - 42 slices $(3 \times 300 \times 300\,\text{mm}^3)$
  - Can measure protons up to 140 MeV
- Readout via USB connection (DAQrate ≈ 15 kHz)

In total: ≈ ***900 pCT events per second***

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK
TU WIEN TECHNISCHE UNIVERSITÄT WIEN

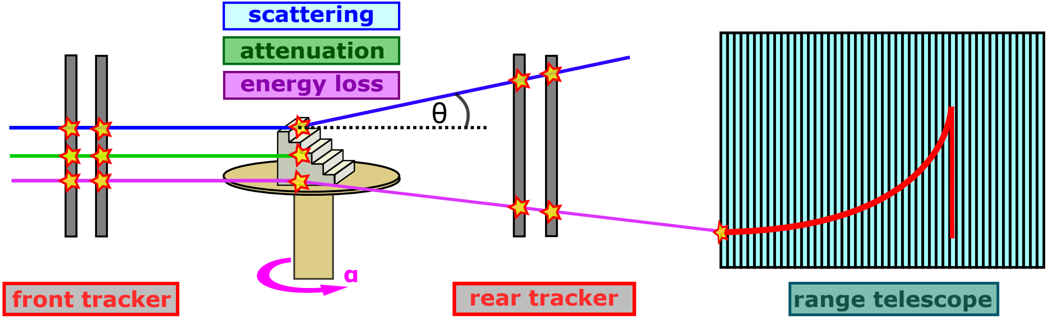
Experimental setup – iCT demonstrator system III





Phantom image: Ulrich-Pur et al. 2021c (adapted)

Experimental setup – imaging modalities

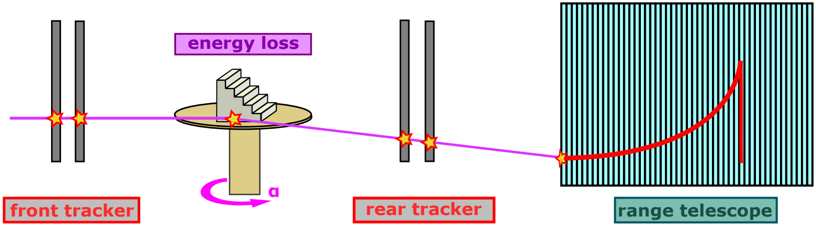


- Energy loss ⇐ **relative stopping power (RSP)** ⇐ goal: improve ion-beam therapy treatment planning (Meyer et al. 2019)
- Multiple Coulomb scattering (MCS) ⇐ **material budget/scattering power** (Schütze et al. 2018; Krah et al. 2020)
- Beam attenuation ⇐ **linear nuclear inelastic cross-section** κ (Quiñones et al. 2016)

Results – imaging based on energy loss I

$$WEPL_i = \int_{\tau_i} RSP(x)dl = \int_{E_{in}}^{E_{out}} \frac{1}{SP} dE$$

...energy loss according to Bethe 1930; Bloch 1933

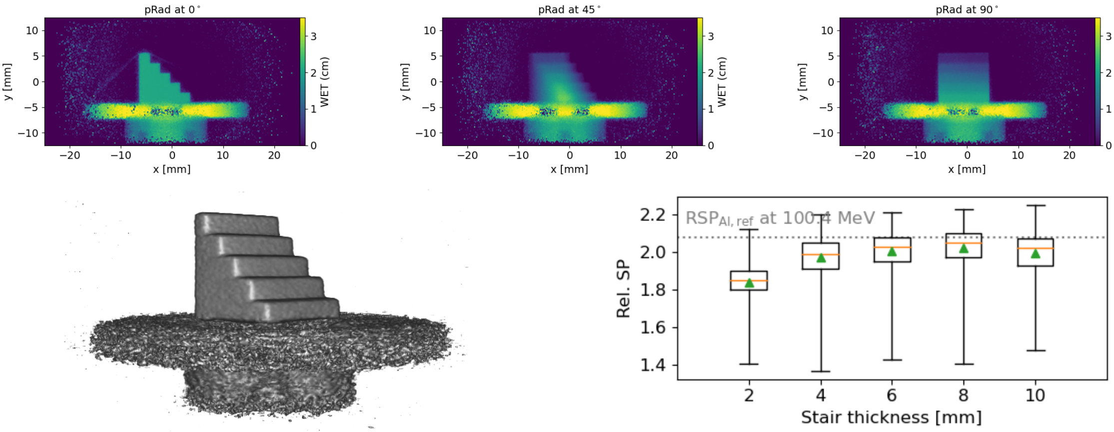


- Alignment and tracking with **Corryvreckan** (Dannheim et al. 2021)
- Binning/analysis with customized C++ and python scripts
- Image reconstruction with **TIGRE** (Biguri et al. 2016)[a]

[a] Authors would like to thank Wolfgang Birkfellner, Dietmar Georg and Sepideh Hatamikia for their contributions to this work.

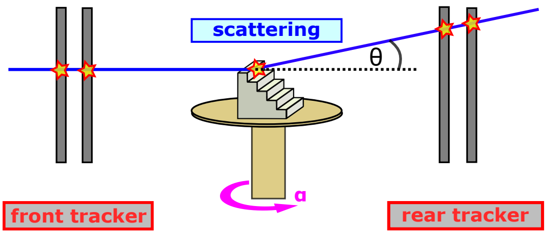
Results – imaging based on energy loss II

- 80 proton radiographs measured → two full days
- Reconstructed image published in Ulrich-Pur et al. 2021c



Results – scattering imaging I

$$\Theta_0 = \left(\frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]\right)$$ ... Highland formula for thin absorbers



- Alignment, tracking and analysis of measurement data with **Corryvreckan** (Dannheim et al. 2021)
  - Kink angle calculation implemented in the software
- Analysis following the method of Jansen et al. (2018)
  - Scattering imaging with electrons

Results – scattering imaging II

➛ Aluminium phantom

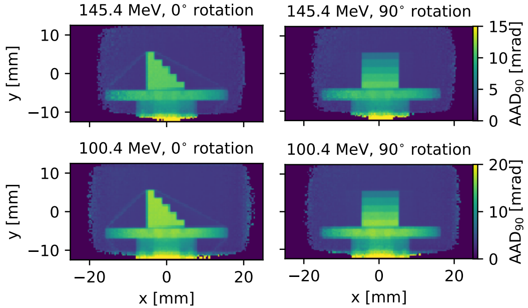


Image: Kaser et al. 2022a

➛ PMMA phantom

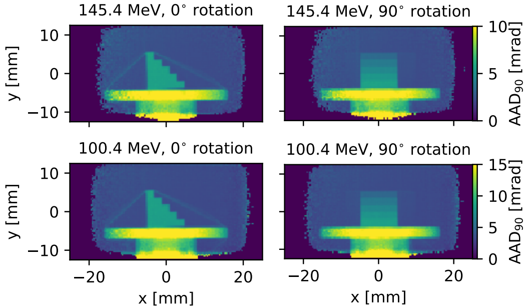


Image: Kaser et al. 2022a

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK
TU WIEN TECHNISCHE UNIVERSITÄT WIEN

Results – scattering imaging III

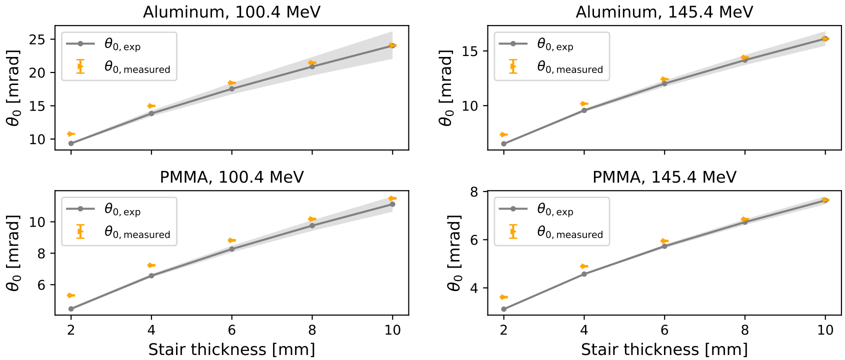
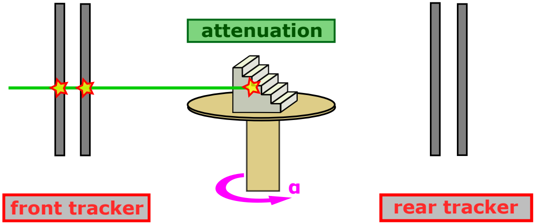


Image: Kaser et al. 2022a

- Calibration → **material budget**
- Improvement possibilities: scattering power → Krah et al. 2020

Results – beam attenuation imaging I

$$\phi_{out} = \phi_{in} \cdot \exp\left(-\int_{z_{in}}^{z_{out}} \kappa(\tau(z))d\tau(z)\right)$$ ...exponential decrease of beam intensity



- Per pixel, compare initial and residual beam fluence
  - Counting of single particles, not measuring an average quantity
- Analysis with **Corryvreckan** and customized python scripts
  - Full implementation in Corryvreckan is WIP

Results – beam attenuation imaging II

- In theory:
  - 2 hits upstream, 2 downstream if proton passed the phantom
  - 2 hits upstream, 0 hits downstream if proton got absorbed
- Reality looks different: (elastic) scattering, ghost hits, detector noise, absorption in the tracker…
- MC simulations to understand the problem

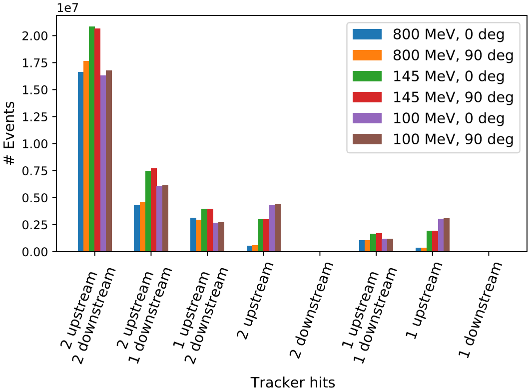
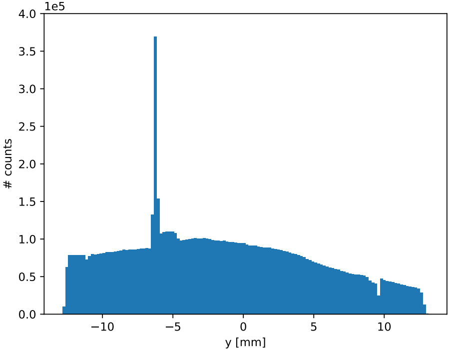


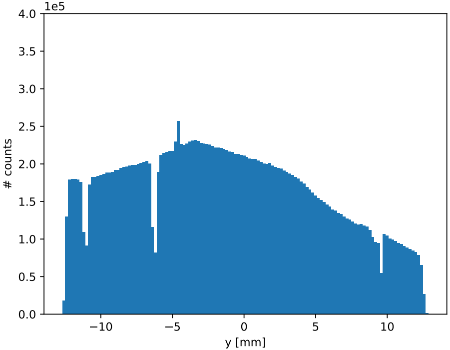
Image: Kaser et al. 2022b

Results – beam attenuation imaging III

- Detector hits (y-direction, 800 MeV) **without** masking...



- Detector hits (y-direction, 800 MeV) **with** masking...



Results – beam attenuation imaging IV

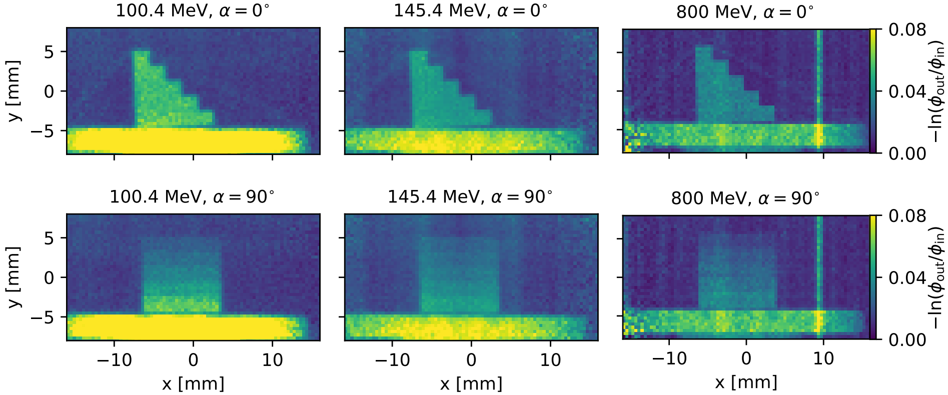
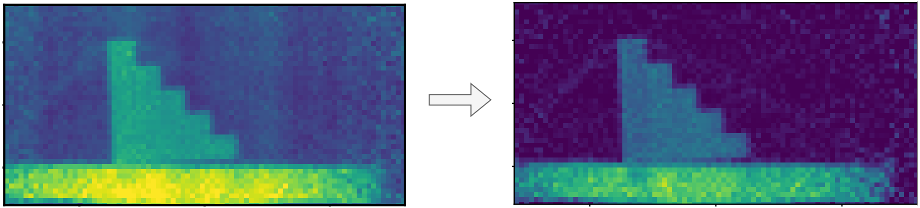


Image: Kaser et al. 2022b

Results – beam attenuation imaging V



Images: Kaser et al. 2022b

- **Removing the background in attenuation imaging**
  - Use "empty" radiograph as reference
  - If a strip becomes noisy during the measurement, this can again lead to artefacts

Results – beam attenuation imaging VI

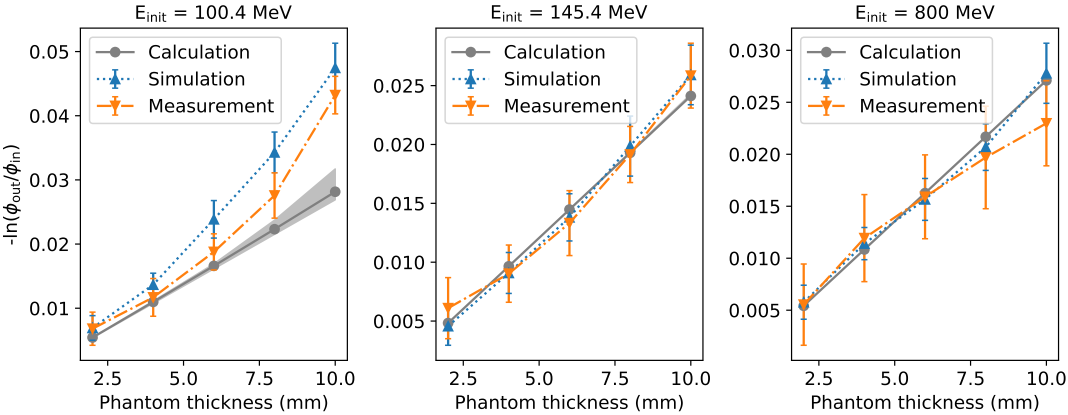
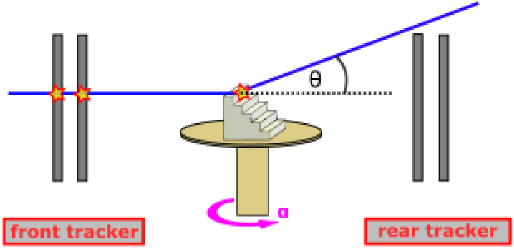


Image: Kaser et al. 2022b

Results – beam attenuation imaging VII

➛ Measurement values at 100.4 MeV higher than expected → investigating potential sources of the discrepancy... *use Monte Carlo simulations!*

1. κ is not constant below ≈100 MeV
   - Increasing κ with decreasing energy
   - Different models to describe this behaviour → reference value
2. Energy loss in trackers and phantom could be underestimated
3. **Location of silicon detectors**



Results – beam attenuation imaging VIII

- $p_i \approx \sum \kappa \cdot \Delta z \quad \rightarrow \quad \boxed{\kappa \approx p_i / z}$

  with $p_i = -\ln(\phi_{\text{out}}/\phi_{\text{in}})$
- Measurement value at 800 MeV matches well with an existing measurement (Dietrich et al. 2002)

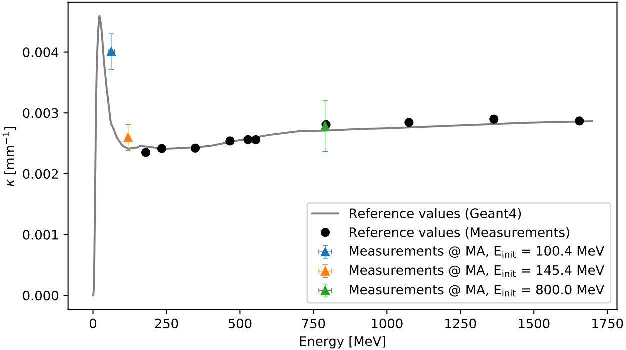


Image: Kaser et al. 2022b

Summary

- Multiple imaging modalities were investigated with an iCT demonstrator
  - Energy-loss imaging, scattering imaging, beam attenuation imaging
- Measurements were conducted at MedAustron
  - iCT demonstrator system
- Phantoms: aluminium and PMMA stair profiles
- Energies: 100.4 MeV, 145.4 MeV, 800.0MeV

Acknowledgements

Thank you for your attention!

TU Wien/HEPHY

- Thomas Bergauer
- Alexander Burker
- Albert Hirtl
- Christian Irmler
- Florian Pitters
- HEPHY technicians
- MedAustron staff
- BSc and MSc students

GSI GmbH

- Felix Ulrich-Pur

This project received funding from the Austrian Research Promotion Agency (FFG), grant numbers 869878 and 875854.

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

References

Bethe, Hans (1930). In: *Annalen der Physik* 397.3, pp. 325–400. DOI: 10.1002/andp.19303970303.
Biguri, A. et al. (2016). In: *Biomed. Phys. & Eng. Express* 2, p. 055010. DOI: 10.1088/2057-1976/2/5/055010.
Bloch, Felix (1933). In: *Annalen der Physik* 408.3, pp. 285–320.
Dannheim, Dominik et al. (2021). In: *JINST* 16.03, P03008. DOI: 10.1088/1748-0221/16/03/P03008.
Dietrich, FS et al. (2002). In: *Journal of Nuclear Science and Technology* 39.sup2, pp. 269–271. DOI: 10.1080/00223131.2002.10875091.
French, M.J. et al. (2001). In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 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.
Jansen, Hendrik and Paul Schütze (2018). In: *Applied Physics Letters* 112.14, p. 144101. DOI: 10.1063/1.5005503.
Kaser, S et al. (2022a). In: *Journal of Instrumentation* 17.01, p. C01010. DOI: 10.1088/1748-0221/17/01/C01010.
Kaser, Stefanie et al. (2022b). In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, p. 167069. DOI: 10.1016/j.nima.2022.167069.
Krah, Nils et al. (2020). In: *PMB* 65.22, p. 225015. DOI: 10.1088/1361-6560/abbd18.
Meyer, S et al. (2019). In: *PMB* 64.12, p. 125008. DOI: 10.1088/1361-6560/ab0fdf.
Quiñones, CT, JM Létang, and S Rit (2016). In: *PMB* 61.9, p. 3258. DOI: 10.1088/0031-9155/61/9/3258.
Schütze, Paul and Hendrik Jansen (2018). In: *Proceedings of International Conference on Technology and Instrumentation in Particle Physics 2017*. Ed. by Zhen-An Liu. Singapore: Springer Singapore, pp. 164–170. ISBN: 978-981-13-1316-5. DOI: 10.1063/1.5005503.

Stock, Markus et al. (2015). In: *International Journal of Particle Therapy* 2.3, pp. 474–477. DOI: 10.14338/IJPT-15-00022.1.

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

Ulrich-Pur, Felix et al. (2021b). In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, p. 165570. DOI: 10.1016/j.nima.2021.165570.

Ulrich-Pur, Felix et al. (2021c). In: *arXiv preprint arXiv:2106.12890*. Accepted in Journal of Physics: Conference Series.