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STATUS OF HELIUM ION BEAMS COMMISSIONING AT MEDAUSTRON ION THERAPY CENTER

N. Gambino†, G. Guidoboni, M. Kausel, M. Pivi, F. Plassard, V. Rizzoglio,
I. Strasik, L. Fischl, D. Prokopovich, MedAustron EBG, Wiener Neustadt, Austria
L. Penescu, Abstract Landscapes, Montpellier, France
H. Fuchs, Department of Radiation Oncology, Medical University of Vienna, Vienna, Austria

Abstract

MedAustron is a synchrotron-based cancer therapy center located in Lower Austria. Patients are treated with proton and carbon ion beams in an energy range of 62-252 MeV and of 120-400 MeV/u respectively. The facility features three clinical irradiation rooms, among which horizontal and vertical beam lines as well as a proton gantry are available for treatment. A fourth irradiation room (IR1) is dedicated to non-clinical research activities where helium ion beams are commissioned. Due their favourable physical and biological properties, helium ions beams are potential future candidate for cancer treatment. A wide energy range (39.8-402.8 MeV/u) has been commissioned with the support of Monte Carlo simulations. In the commissioned energy range the beam properties (e.g., spot size, roundness, position) have been verified at the IR1 isocenter and fulfil the user requirements. In this work we present the latest status of the commissioning with main focus on the recent results obtained from the commissioning of the synchrotron and transfer line up to the isocenter in IR1.

INTRODUCTION

Helium ion beams for cancer treatment have been studied already since the 1950s at the Lawrence Berkley National Laboratory. First clinical trials were already carried out in 1975 with up to 2000 patients treated, but did not ramp-up further in the upcoming decades [1]. Over the last years the interest in using helium ions for cancer treatment has again increased on an international level. Helium beams have favourable physical and biological properties in between proton and carbon ions. The main advantage of using helium in hadron therapy relies on reduced scattering leading to an improved lateral penumbra with respect to proton ions, as well as on a linear energy transfer (LET) which is located between protons and carbon ions [2]. The neutron production of helium is lower compared to carbon ions and potentially a lower neutron dose than with proton beams can be achieved. For this reason, helium ion beams may be more suited than protons for certain indications, such as paediatric tumour treatments [3]. Existing cancer therapy centres have already commissioned helium ready for clinical use [4]. A large development is also ongoing towards designing and building new accelerators using helium beams [5, 6]. Other promising applications of helium ion beams are for mixed beams experiments, computed tomography (CT) applications and FLASH therapy [7, 8, 9]. At MedAustron helium ion beams are commissioned within the HelioS3 project since 2021 [10]. Aim of HelioS3 is to commission helium for non-clinical research studies and for future potential clinical treatment in an energy range of 39.8 MeV/u to 402 MeV/u.

Injector Commissioning at MedAustron

The first major milestone was reached in late 2022, when the commissioning of the injector was completed [11]. The ion beam generated from the source has an energy of 8 keV/u and is send via a Low-Energy-Beam-Transfer (LEBT) line in the LINAC section. The latter contains a Radio Frequency Quadrupole (RFQ) accelerating the beam up to 400 keV/u, followed by a buncher and an IH-cavity (Interdigital H-mode Drift-Tube Linac), where the energy of the ions reaches 7 MeV/u [12]. The MedAustron injector has the advantage of being equipped with three independent ion sources (Supernanogans from Pantechnik), located an injector hall accessible also during clinical treatment. Two ion sources (S1 and S2) are fully reserved for clinical proton and carbon ion beams production (H_3^{1+} and $12C^{4+}$). The third ion source (S3) is used for the $4He^{2+}$ ions production. The S3 and one part of the LEBT branch are still not part of the clinical accelerator allowing to perform beam measurements (such as long-term stability measurements of the extracted current and emittance measurements for a proper evaluation of the Twiss parameters) in parallel to clinical treatment [10]. The main challenge of the LINAC commissioning with helium is to minimize losses from the LEBT to the exit of the LINAC due to the different charge to-mass ratio of $4He^{2+}$ with respect to the design one of H_3^{1+} and $12C^{4+}$. By scaling and adapting the LINAC configuration of the proton and carbon operation a suitable setpoint for helium was found [11]. The final transmission from LEBT to LINAC section reached with helium is of 32%. The current measured at the end of the LINAC is on the order of 190 μA with a beam energy of 7.1 MeV/u [11]. The helium beam energy was verified using a novel time-of-flight set-up developed in the Medium-Energy-Beam-Transfer (MEBT) [13].

SYNCHROTRON COMMISSIONING

The MedAustron Synchrotron is a 77 m circumference ring where particles are accumulated via a horizontal multi-turn injection from the MEBT. Acceleration to the required energy occurs via a wideband RF cavity in the synchrotron powered by 12 solid state amplifiers connected to a digital Low Level RF system [14]. The beam is extracted into the High-Energy-Beam-Transfer line (HEBT) via a third-order resonant slow extraction, driven by a betatron core magnet and supported by a resonant

† nadia.gambino@medaustron.at

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sextupole [15]. The synchrotron commissioning for helium consisted of the following main steps: a) orbit and optics correction at flat-bottom energy, before acceleration b) RF capture and acceleration with minimum beam losses, c) optics optimization at flat-top energy, after acceleration and d) RF manipulations to prepare the beam for extraction towards the HEBT. The commissioning started in Q4/2022 and ended in Q2/2023. The magnetic settings commissioned for carbon ion beams were used as starting conditions for the commissioning, due to the similar beam rigidity between carbon and helium ions [12]. Table 1 summarizes the achieved performances with helium at the end of the synchrotron commissioning.

Table 1: Measured Beam Properties in the Synchrotron

Energy	**62MeV/u**	**252MeV/u**
Hor. Tune Q_x at extraction	1.6672	1.6671
Hor. Chromaticity ξ_x	-5	-4
Norm. Emittances ε_x/ ε_y [π.mm.mrad]	0.78/0.84	0.76/0.75
dp/p before/after RF Phase Jump [%]	0.06 / 0.7	0.05 / 0.5
Beam loss at Capture/ Acceleration [%]	13/5	10/10
Flat-Top energy efficiency [%]*	82	80

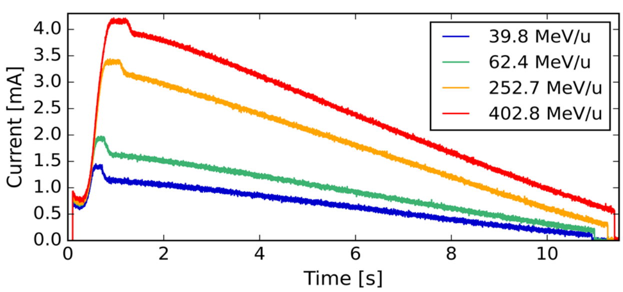

Figure 1: Current-Transformer-Signal measurements after phase jump optimization. A constant flux for 10 sec spill-length with an average intensity of 5×10⁹ particles at flat top was obtained.

Figure 1 shows the extracted beam current from the synchrotron for four main energies. The beam capture has an efficiency of approximately 90%. Acceleration to extraction has an efficiency of more than 90%. More than 80% of the injected beam is being extracted with high reproducibility, for the entire energy range.

HEBT AND IR1 COMMISSIONING

The HEBT commissioning for helium started in Q3/2023 and is planned to be completed by Q2/2024. The beam was commissioned for an energy range between 39.8 MeV/u and 402.8 MeV/u, with main focus on the future clinical energies between 63.2 MeV/u and 258.2 MeV/u. The requirements from the Non-Clinical Research (NCR) team for the beam spot size at the isocenter in IR1 are defined with a beam Full Half Width Maximum (FWHM) between 5-6 mm for the energies above 250 MeV/u. Below the latter, the scattering processes predominate.

A snapshot of the HEBT and IR1 beam line is shown in Figure 2. The Dispersion Suppressor (DS) is integrated with a chopper at the beginning of the HEBT. The DS module allows to close the dispersion and provides proper Twiss function for the next module called Phase Stepper Shifter (PSS). The PSS consists of 8 quadrupoles and was designed to perform substantial variations in the beam optics matching and consequently significant modification of the lattice functions. The PSS controls the beam size for the downstream modules by matching the Twiss parameters. Additionally, it rotates the beam distribution ("bar of charge") in the horizontal phase space by adjusting the phase advance [16]. After the PSS, the beam is deflected towards IR1 via a double bend achromat module along the T1 line. The Twiss parameters defined by the PSS are transported along the T1 line with proper magnification factors to the isocenter. The beam properties are measured with 8 Scintillating Fibre Hodoscope (SFX) monitors along the HEBT and with 2 strip monitors located in the treatment room: the Dose Delivery Monitor (DDM) in the nozzle and the Isocenter Monitor (ICM) [17].

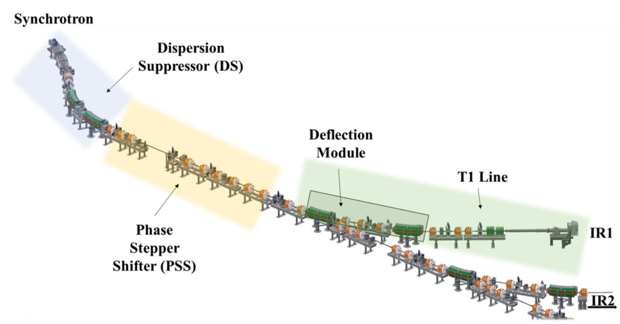

Figure 2: HEBT and IR1 layout with main modules.

The HEBT commissioning for helium consists of the following main steps:

- Initial beam optics set-up using the carbon ion setpoint.
- Beam optics matching to adjust the spot size and verify the intra-spill properties.
- "Rough" beam steering up to deflection module to verify that the transverse beam position in both planes and on all beam positioning monitors is within ±2 mm.
- Final beam steering up to IR1 to verify that the transverse beam position in both planes at isocenter is within ±0.5 mm.

Beam Optics Matching

The beam optics matching and spot size adjustment was performed using the MAD-X and pyMADX codes [18]. The main steps for the matching are: a) initial Twiss parameters and emittance reconstruction at the beginning of the PSS module, b) beam optics rematch of the PSS module, c) beam optics re-matching of the T1 deflection module with the goal to close the dispersion downstream of the

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last dipole in the T1 line and d) apply the sigma matching in the T1 line up to the isocenter in IR1 [19].

The spot size was adjusted for two main beam energies: 258.2 MeV/u and 63.2 MeV/u. A linear interpolation of the quadrupole strengths is applied for all energies in between the main ones. Below and above these energies an extrapolation was applied and the same normalized quadrupole strength was used. With this beam optics configuration, the beam FWHM at the isocenter is measured over the whole energy range. The helium FWHM was compared to the FWHM measured for proton and carbon ions and is shown in Figure 3.

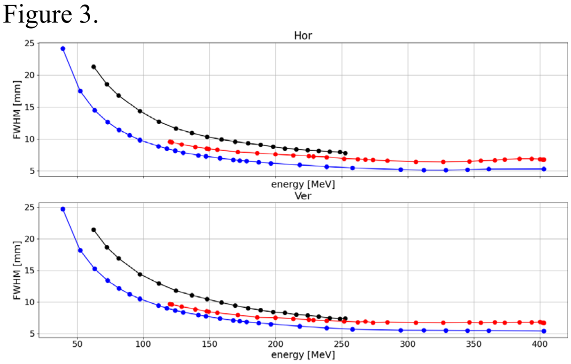

Figure 3: Beam FWHM versus energy measured at the isocenter in IR1 for the proton (black curve), carbon (red curve) and helium (blue curve).

The final analysis of the beam spot size and roundness (ellipticity) at the isocenter in IR1 after the optics matching is shown in Figure 4. As it can be seen from this figure, the beam roundness is below 3 % for all measured energies.

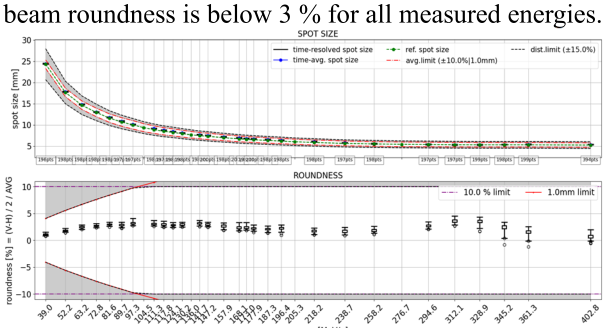

Figure 4: Final beam spot size and roundness measured for 32 energies from 39.8 MeV/u to 402.8 MeV/u.

Beam Orbit Correction

The beam steering is performed with an in-house script called Rapid Alignment Procedure (RAP) and via the Orbit Response Matrix (ORM) formalism [20].

The rough beam steering up to the deflection module was performed for 5 main energies assuring that the transverse beam position in terms of Center of Gravity (CoG) remains within ±2 mm on all SFX monitors. Since a large range of energies is covered, to center the beam within ±0.5 mm at the isocenter, several interpolation nodes for the corrector strengths were needed (3 for the vertical plane and 20 for the horizontal plane). The final beam position measured at the isocenter is shown in Figure 5. The beam angle between DDM and ICM has been also verified to be within ±0.2 mrad.

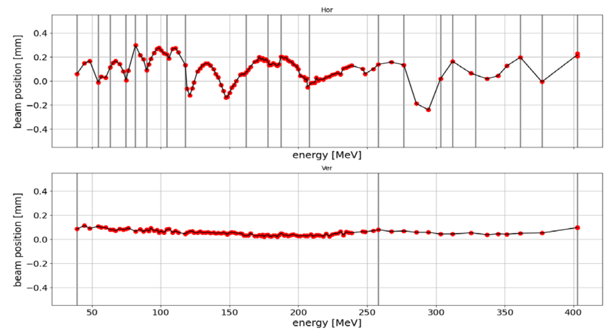

Figure 5 Final beam steering at the isocenter. The grey lines indicate the interpolation nodes.

Range Measurements in IR1

Helium ion ranges were measured in water at the isocenter using PEAKFINDER™ (PTW, Freiburg, Germany). The final energies were tuned assisted by Monte Carlo simulations (OpenGate v9.3 based upon Geant4 v10.3) [21]. The ranges were found to be well within the requirements as shown in Figure 6.

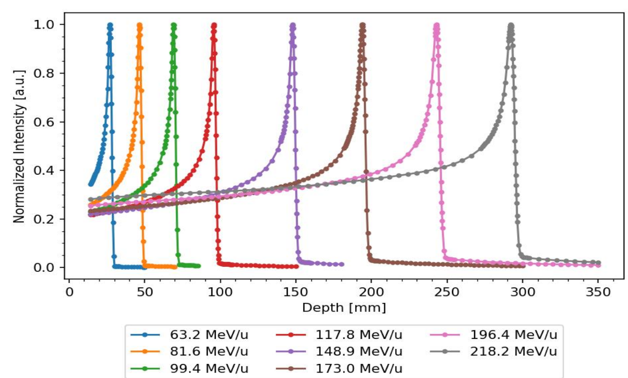

Figure 6: Nine exemplary helium range measurements in water at the isocenter of IR1, covering a potential clinical energy range in water from 3 to 30 cm.

CONCLUSIONS

The helium commissioning at MedAustron is almost completed. The beam properties in terms of energy range, spot-size and beam position fulfill the user requirements. In the upcoming months the commissioning will be focused on the Medical Front-End components in the nonclinical irradiation room IR1 in order to provide to the users modulated scanning pencil beams calibrated in intensity and allowing to test treatment plans with helium.

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