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INJECTOR AND SYNCHROTRON COMMISSIONING OF HELIUM ION BEAMS AT THE MEDAUSTRON ION THERAPY CENTER

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Abstract

MedAustron is a synchrotron-based ion cancer therapy facility located in Austria. Patients are treated with proton and carbon ion beams in an energy range of 62-252 MeV and 120-402 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 is dedicated to non-clinical research. In 2021, a development project started, which aims at commissioning helium ion ($^4He^{2+}$) beam up to the non-clinical irradiation room. A first major milestone was reached by completing the commissioning of helium in the ECR ion source branch, the LEBT and the LINAC section, where the beam is accelerated up to 7 MeV/u. In this work we discuss the challenges and main results achieved during the injector commissioning (i.e. emittance, intensity and transmission efficiency). Furthermore, recent outcomes from the injection of $^4He^{2+}$ beam into the synchrotron as well as acceleration and extraction results are presented.

INTRODUCTION

In recent years, the interest in high-energy helium ion beams increased significantly. Helium ion beams promise a broad field of applications in clinical as well as in non-clinical research environments [1]. The latter can be applied in ion therapy [2], tomographic imaging [3] and mixed helium and carbon ion beam irradiation, which could enable range verification during carbon ion beam treatment [4]. Despite these promising applications, high-energy helium ion beams are only available at a few accelerators worldwide. The increased interest paired with the limited availability creates the unique opportunity for accelerator facilities to establish themselves in the forefront of research on high-energy helium ion beams and their applications.

The MedAustron facility [5], located in Austria, is a state-of-the-art synchrotron-based ion accelerator complex that provides irradiation with proton and carbon ion beams in an energy range of 62-252 MeV and 120-400 MeV/u, respectively. Recently, it was decided to additionally provide 20-402.8 MeV/u $^4He^{2+}$ beams for non-clinical research purposes at MedAustron. After starting the helium ion beam commissioning efforts in early 2021, the first major milestone was reached in late 2022, when the commissioning of the injector was completed. At the moment the commissioning of the synchrotron is ongoing.

In this publication the commissioning of $^4He^{2+}$ beam in the MedAustron injector and preliminary results of the synchrotron commissioning are presented.

COMMISSIONING CHALLENGES

The commissioning of an ion beam at an already operational medical particle accelerator poses certain challenges. Most prominently, the overall available beam time is used for clinical treatment, which limits research activities to night shifts or weekends. Parallel research and development activities must fulfill strict SOPs (Standard Operating Procedures) in order to ensure the safety of the patients and personnel.

In order to guarantee the highest safety standards, the dedicated ECR ion source for helium beam generation was transferred into a testing environment which decoupled it completely from the rest of the accelerator. This allowed for source commissioning during patient treatment with clinical proton and carbon beams generated by the other two installed ECR ion sources. The clinical beam line starting from the low-energy-beam-transfer (LEBT) could only be accessed during dedicated helium commissioning shifts.

Furthermore, compared to the commissioned proton and carbon ion beams, the helium ions feature a different charge-to-mass ratio for which the Linear Accelerator (LINAC) cavities are not optimized. Therefore, higher losses and an overall lower transmission compared to proton and carbon operation are expected within the LINAC.

INJECTOR COMMISSIONING

The commissioning of the injector, which is shown in Fig. 1, is the first milestone in the provision of helium ion beam at the MedAustron accelerator facility. It was completed by the end of 2022.

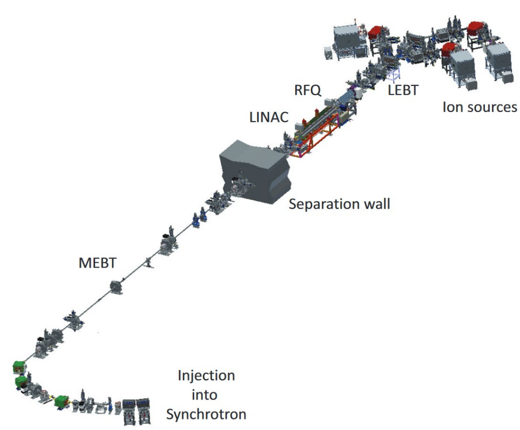

Figure 1: Overview of the MedAustron injector [6].

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Ion Sources

The commissioning process started with the set-up of the dedicated ECR ion source for production of $^{4}He^{2+}$. The corresponding procedure was already reported in [7]. During some iterative optimizations, the beam energy was recommissioned at source level to 8 keV/u using the same procedure as presented in [7]. For this energy the extracted beam current reached in the source branch is 640 µA.

Low-Energy-Beam-Transfer (LEBT)

The extracted $^{4}He^{2+}$ beam was characterized in terms of emittance measurements. These measurements were used to set up a Trace3D [8] simulation of the LEBT with the aim of matching the beam optics to the acceptance criteria at the RFQ entrance plane. As already reported in [7], application of the simulated machine configuration together with steering optimizations allowed for a transmission of approximately 90% through the LEBT.

Linear Accelerator (LINAC)

The LINAC features an RFQ for acceleration to 400 keV/u and a KONUS IH-mode DTL [9] for further acceleration to 7 MeV/u. In between these acceleration devices the elements of the Intertank-Matching-Section (IMS) are used to match the beam to the acceptance parameters in the IH-DTL entrance plane.

As a preparatory task to the LINAC commissioning, the optical matching to the RFQ acceptance criteria was optimized via scans of the optical elements in the LEBT. A transmission of around 60% was reached, which is ten percentage points lower with respect to proton and carbon ion beams. The lower transmission is expected considering that the RFQ is designed to accelerate proton ($^{3}H^{+}$) and carbon ion ($^{12}C^{4+}$) beams with a charge-to-mass ratio of 1:3, and thus not optimized for $^{4}He^{2+}$ with a charge-to-mass ratio of 1:2.

For the LINAC commissioning the limited instrumentation and the resulting uncertainties in beam properties did not allow to retrieve the initial machine configurations from simulations. By re-scaling and adapting the LINAC configuration of the proton and carbon operation a suitable set-point could be found. Similar to the commissioning of the LEBT, the IMS elements as well as the cavity parameters were optimized for minimum losses within the IH-DTL. A $^{4}He^{2+}$ beam current of around 190 µA was achieved at the end of the LINAC section as shown in Fig. 2.

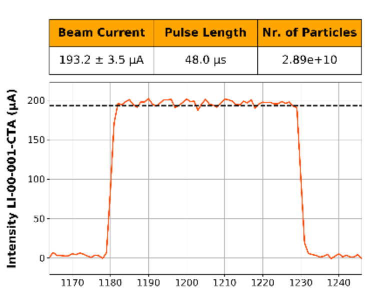

Figure 2: Helium ion beam current after the LINAC section.

In comparison to the proton and carbon operation, the helium ion beam transmission through the IH-DTL is lower, which is again due to the different charge-to-mass ratio.

At the end of the LINAC section a foil stripper strips $^{3}H^{+}$ to H^{+} and $^{12}C^{4+}$ to $^{12}C^{6+}$, while the commissioned $^{4}He^{2+}$ is unaffected. Consequently, the charge-to-mass ratio of the already commissioned carbon ions is the same as the one of the helium ions after this stripping foil.

Finally, the energy of the helium ion beam was verified using a new time-of-flight set-up available in the medium-energy-beam-transfer (MEBT) [10]. A stable and reproducible beam energy of around 7.1 MeV/u was measured, which is well within the acceptance interval of the synchrotron injection.

Medium-Energy-Beam-Transfer (MEBT)

Due to the equivalent charge-to-mass ratio, an initial configuration for the MEBT could be easily found by applying machine settings of carbon operation. Consequently, the MEBT commissioning efforts mainly focused on the orbit correction followed by the synchrotron injection optimization.

The MEBT beam commissioning started with optimizing the LINAC optics for a focused beam at the stripping foil in order to minimize scattering effects. The orbit correction in the MEBT straight section aimed to center the beam in the respective quadrupoles. The beam steering was performed using horizontal and vertical corrector (kicker) magnets.

The MEBT commissioning activities continued with the orbit correction in the arc section of the beam line, again aiming to center the beam in the respective quadrupole magnets. Firstly, a rough beam steering in the horizontal plane using the dipole magnets was performed, before continuing with a fine beam steering in both transverse planes using the available corrector magnets.

The last step in the MEBT commissioning process was the optimization of the multiturn injection into the synchrotron. This included the optimization of the magnetic and electrostatic injection septa strengths, the adaptation of the injection time to 30 µs, which is determined by a fast deflector located in the LEBT, as well as the adjustment of the injection orbit bump parameters. At the end of the injection optimizations a helium ion beam of 1.3 mA could be measured in the synchrotron.

Table 1: Injector beam currents and transmissions.

Position	**Current**	**Transmission** **(from prev. section)**
Source	640 µA	-
LEBT	570 µA	89%
LINAC	190 µA	32%
MEBT	170 µA	94%

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FIRST SYNCHROTRON COMMISSIONING RESULTS AND OUTLOOK

The helium ion beam commissioning of the synchrotron, see Fig. 3, is progressing faster than anticipated due to the high quality of the injected beam and the application of similar initial settings as for carbon operation. The commissioning process involves several key steps, including establishing a stable orbit and optics at flat-bottom energy, capturing and accelerating the beam with minimal losses, optimizing the optics at flat-top energy, and preparing the extraction of the beam towards the high-energy-beam-transfer (HEBT).

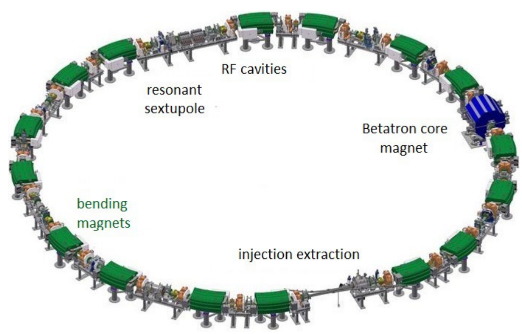

Figure 3: Overview of the MedAustron synchrotron.

The synchrotron was initially commissioned for an energy range of 62.4 MeV/u to 252.4 MeV/u, which provides similar penetration depths as the proton beams at MedAustron. However, for research purposes, a larger range of beam energies from 20 MeV/u up to 402.8 MeV/u have been extracted and delivered to the room. The beam is captured with an efficiency of approximately 90% and accelerated to extraction condition with an efficiency of more than 90%. As a result, more than 80% of the injected beam is being extracted with high reproducibility, and an average intensity of 5×10^9 particles per spill.

The slow extraction was optimized to provide a constant flux for up to 10 second long spills with clinical-ready conditions. Fig. 4 and Fig. 5 illustrate the beam current efficiency in the ring from injection to extraction for key energies.

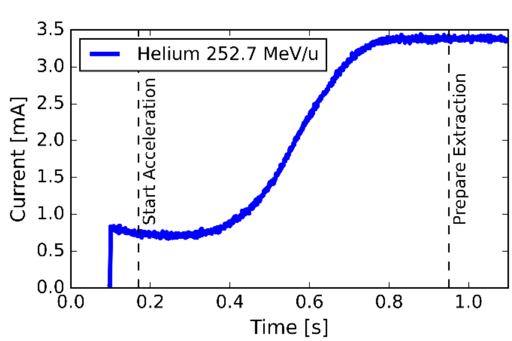

Figure 4: Helium ion beam current during capture and acceleration to 252.7 MeV/u with more than 80% of efficiency at flat-top energy.

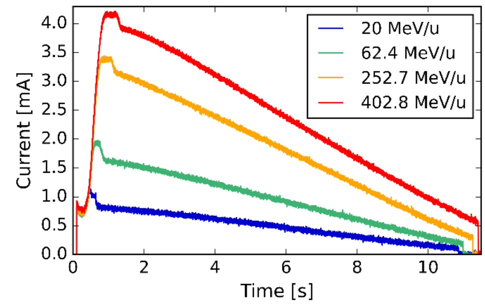

Figure 5: Beam current during capture, acceleration and extraction from the Synchrotron from the lowest to the highest commissioned energies.

Currently, the synchrotron is in its final commissioning stage, where the intensity ripples of the extracted spill are being minimized using the empty bucket RF channelling technique [11]. The beam extracted from the ring reaches the irradiation room as shown in Fig. 6, for all energies, which is a promising outcome for the following HEBT commissioning efforts.

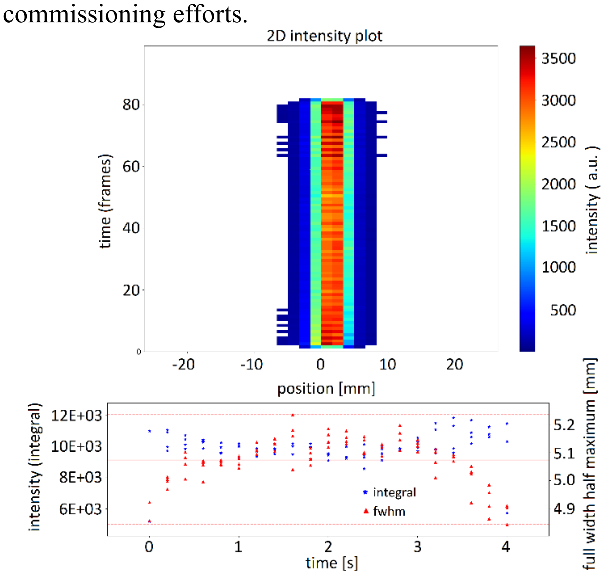

Figure 6: Helium beam 120 MeV/u, horizontal intensity plot (top) and intensity/FWHM (bottom) measured in the irradiation room by the dose delivery system monitors.

CONCLUSION

At the MedAustron accelerator complex high-energy helium ion beams are being commissioned for non-clinical research purposes. In this publication the commissioning of the MedAustron injector, as well as results of the injection, acceleration and extraction of $^4He^{2+}$ in the MedAustron synchrotron are presented. Helium ion beams will be available for non-clinical applications in the respective irradiation room in the near future.

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