OVERVIEW AND STATUS OF THE MEDAUSTRON ION THERAPY CENTER ACCELERATOR

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Abstract

The synchrotron-based MedAustron Particle Therapy Accelerator MAPTA located in Wiener Neustadt, Austria, has successfully delivered the first beams for medical treatment after being certified as a medical device in December 2016. This represented a major milestone for the facility whose original design originated more than a decade ago and construction started five years ago. The accelerator delivers clinical proton beams in the energy range 62-252 MeV and is designed to provide C^{6+} carbon ions in the range 120-400 MeV/n to three ion therapy irradiation rooms, including a room with a proton Gantry. Proton beams of up to 800 MeV will be provided to a fourth room dedicated to non-clinical research. A third-order resonance extraction method is used to extract particles from the synchrotron in a slow controlled process over a spill time of 0.1-10 seconds to facilitate the measurement and control of the delivered radiation dose during clinical treatments. Presently, proton beams are delivered to the horizontal beam lines of three IRs. In parallel, beam commissioning of the vertical beam line of the second IR, commissioning of the accelerator with carbon ions and the installation of the Gantry beam line are ongoing. The main characteristics of the accelerator and the results obtained during the commissioning are presented.

INTRODUCTION

The accelerator complex layout is shown in Figure 1, with a design originating from the PIMMS [1] and CNAO [2]. Three ion sources are designed to provide either H_3^+ and C^{4+} beams to a low energy transfer line (LEBT) and subsequently into the Linac (consisting of RFQ and an IH mode DTL) that accelerates the beam to 7 MeV/n. The beams are directed into a fixed target foil to generate H^+ or carbon ion C^{6+} beams. A horizontal multi-turn injection from the medium energy transfer line (MEBT) accumulates particles into the synchrotron. Following acceleration to the required energy the beam is prepared and extracted into the high energy beam transfer line (HEBT) by a third-order resonant slow extraction, driven by a resonant sextupole and a betatron core. The extraction section transports the beam into four irradiation rooms (IRs): IR1 with a horizontal beamline for non-clinical research (NCR), IR2 with a horizontal and a vertical beamline, IR3 with a horizontal beamline and IR4 with a Gantry for proton clinical treatment. IR1, IR2 and IR3 are designed to provide also carbon ion beams.

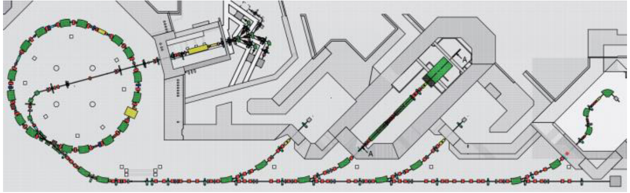

Figure 1: MedAustron accelerator layout: injector, synchrotron and extraction to four rooms including a Gantry.

COMMISSIONING STATUS

Beam commissioning is ongoing with protons and carbon ions to prepare the therapy accelerator for clinical treatment and non-clinical research purposes. The full accelerator chain was first commissioned with proton beams up to IR3 [3].

During last year, the full commissioning of the horizontal beam lines leading into the irradiation rooms IR1 and IR3 has been completed and since August 2016 proton beams can be delivered to IR1 in clinical quality (255 clinical proton energies, 4 mm spot size in vacuum, 5 sec

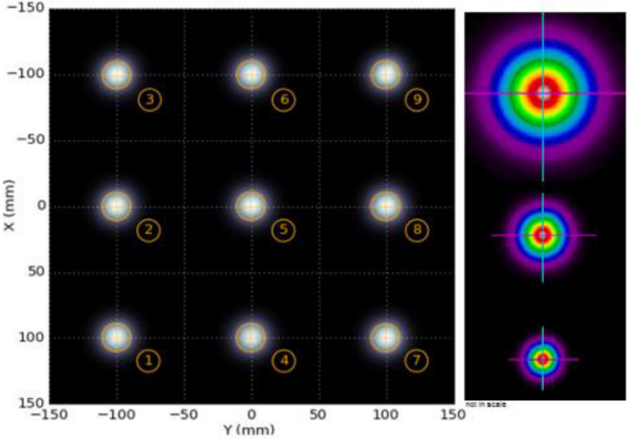

Figure 2: Proton beams at room isocenter. Left: 3×3 beams centered within ±0.5 mm tolerance in a map of the 200×200mm irradiation field. Right: 62, 136 and 252MeV symmetric beam with respect. Fwhm=21,10.3 and 6.5mm.

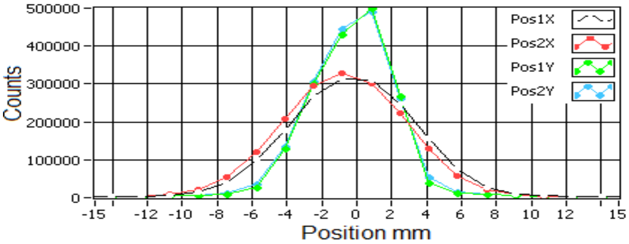

Figure 3: First carbon ion beam sent to the irradiation room IR2 as detected by the nozzle monitor.

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spill length and 4 beam intensities) for non-clinical research and since December 2016 the irradiation room IR3 is dedicated to clinical treatment of patients with proton beams (2 beam intensities). Proton beams measured in the irradiation room are shown in Figure 2.

The beam commissioning of the IR2 horizontal beam line with protons has been completed and the medical commissioning is ongoing. The beam commissioning of the IR2 vertical beam line has started. Furthermore, first carbon ion beams have been recently sent into the irradiation room IR2-H as shown in Figure 3.

IR4 hosts a Gantry beamline which is based on a design from PSI [4]. The rotating structure supporting the beam line has been built and installed while magnets are under construction. The optics and beamline is currently being adapted to meet the specifications. A summary of the commissioning status is shown in Table 1.

Table 1: MAPTA Commissioning Status (Particle: proton, carbon. Beamlines: Hor., Ver., Gantry; ✓= completed)

Room	**Proton**	**Carbon**	**Horizontal**	**Vertical**	**Gantry**
IR1	✓	..	✓	*n.a.*	*n.a.*
IR2	✓	Started	Medical commissioning	Beam commissioning	*n.a.*
IR3	✓	..	✓	*n.a.*	*n.a.*
IR4	..	*n.a.*	*n.a.*	*n.a.*	Construction

Synchrotron

In Q3-2016, a major repair work in the synchrotron was required. The main ring dipoles have shims on both ends of both yokes. The strong magnetic fields up to 1.5 Tesla possibly in combination with the ramp rate, caused a too high stress for the glued connection and shims detached from the dipoles. In collaboration with CERN, a mechanical upgrade was implemented consisting of custom-made aluminium clamps pulled into the counter-bore and fixing the wedge. The repair of all 16 dipoles lasted one week and the beam re-commissioning of the synchrotron and HEBT only a few days, thanks to the high quality work of the repair.

The beam re-commissioning consisted primarily of orbit correction in the synchrotron and the downstream sections. The vertical closed-orbit has been corrected considerably by ± 3 mm while the horizontal closed-orbit by up to 0.5 mm.

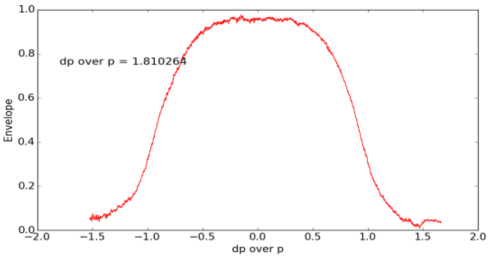

Figure 4: Δp/p as measured *via* empty bucket scan [5], 136MeV proton beam.

Table 2: Stack Momentum Width after RF Phase Jump

Energy (MeV)	**RF-PJ Voltage-kV**	***Δp/p***
62.4	0.65	2.3×10^{-3}
136.8	2.5	1.75×10^{-3}
198.0	4.0	1.5×10^{-3}
252.7	4.0	1.3×10^{-3}

The horizontal chromaticity was verified to be close to the design value (Q’x = -4.0) for extraction as shown in Figure 5, as well as the on-momentum resonant tune [6], and both hardly affected by the repair. For the first time, following the repair, the normalized emittance measured before extraction for both highest and lowest clinical proton energies 252MeV and 62MeV and for both planes was found to be below the design value 0.52 π·mm·mrad.

At this stage, an RF phase jump [7] have been effectively implemented to create a homogeneous momentum distribution for extraction Δp/p~1-2.5×10^{-3}, as shown in Figure 4 and Table 2.

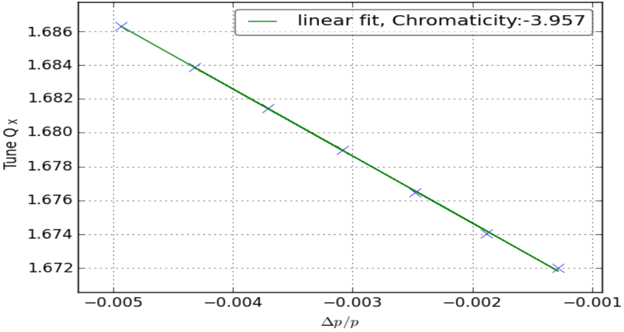

Figure 5: Chromaticity, obtained from tune scan 252MeV p. The resonant tune at *dp/p* zero- crossing is Q_x=1.667.

HEBT / IR Rooms Optics Matching

Commissioning of the beam to IR3, including dispersion correction, quadrupole matching and beam alignment in the HEBT were performed at an earlier stage [3].

Since last year, commissioning of IR1 and IR2 rooms has been carried out. An orbit correction in the HEBT was also performed after the repair of the main ring dipoles.

The IR1 and IR2 beam line optics have been rematched with respect to the design optics to provide small and symmetric beam spot sizes at the isocenter. In IR1, the vertical spot size was larger at isocenter and quadrupole re-matching was needed to reduce β_y and avoid beam scraping. Conversely in IR2, the horizontal spot size was larger and a fine adjustment of the μ_x horizontal phase advance caused a phase space rotation of the bar-of-charge and reduced the spot size at isocenter.

To facilitate inter-exchange of patient treatment plans between rooms, the optics was finely adjusted so that spot sizes in IR2 match the spot sizes in IR3. The beam was also commissioned at two different room positions, the nominal isocenter and 50 cm upstream. The latter is closer to the vacuum nozzle to reduce particle scattering and obtain even smaller spot sizes for treatments: 12 mm for 62MeV and 6 mm for 252MeV. Beam spot sizes in both rooms and both treatment positions are shown in Figure 6.

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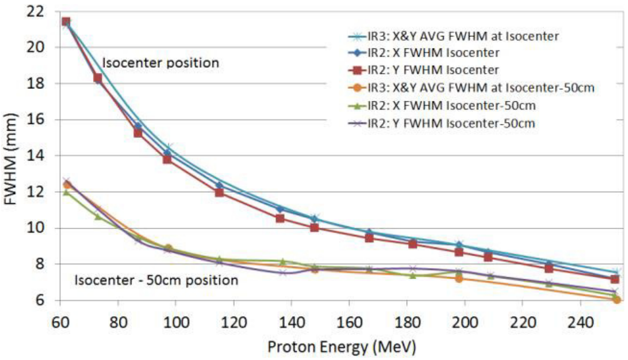

Figure 6: Proton beam sizes (FWHM) vs energy at two isocenter positions. Beam sizes in IR2 match IR3 ones.

Furthermore, a fine adjustment of the main ring flat-bottom vertical tune by ΔQ_y=0.02 for low intensity beams was introduced to correct for an intensity dependent spot size asymmetry at isocenter.

Beam Alignment in the Irradiation Rooms

Since last year, methods for centering the beam (±0.5 mm) with small incident angles (±0.4 mrad) at isocenter have been optimized. Beam alignment tolerances are ±0.5 mm at isocenter with active feedback loop and ±1.0 mm at the upstream scanning magnets. To minimize the beam position at the last quadrupole, the strengths of the last two correctors are varied while the last quadrupole is modulated and the beam position monitored downstream [8], as shown in Figure 7. A scan of the correctors is also performed to minimize the beam position at the isocenter, see Figure 8. Unique corrector's strengths are found that minimize the beam position and angle in this section.

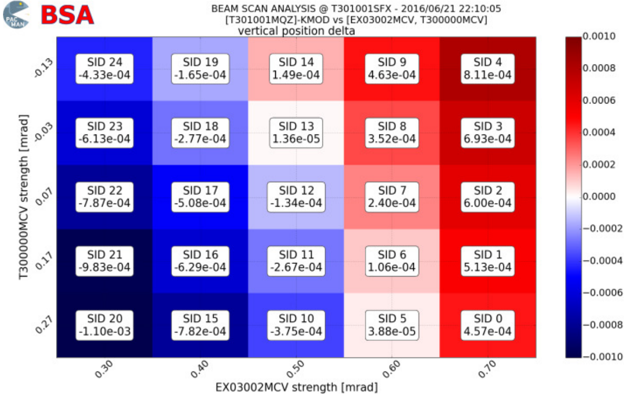

Figure 7: Correctors scan and quadrupole modulation: vertical beam position difference at downstream monitor.

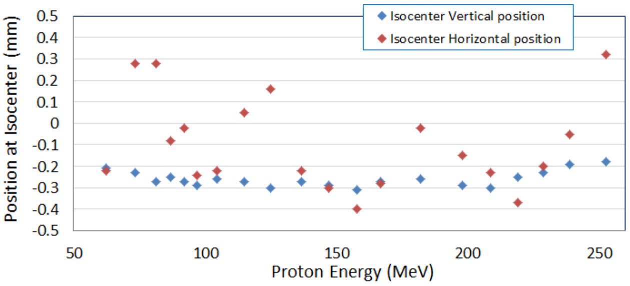

Figure 8: Beam position at room isocenter measured without scanning magnet correction.

Alternatively, quadrupole scans are used to verify the beam centering most reliably and perform beam alignment. The inferred beam positions are fed to the orbit correction module of MAD-X [9] to calculate a new set of corrector strengths *via* singular value decomposition method. Usually, few iterations are needed to minimize the beam offsets.

Typically, the accelerator settings are fine-tuned for up to 5 equally spaced clinical energies including highest and lowest, while the remaining 250 energies are set by interpolation.

Carbon Ion Beams

First commissioning steps were performed with carbon ions. A pilot carbon ion beam was injected, accelerated and extracted into the irradiation room, using the machine parameters corresponding to the same beam rigidity of a proton beam. The beam was well centered, as shown in Figure 3 above, without applying an additional orbit correction. Up to ~4.5×10^8 ions were measured in the synchrotron before extraction. Subsequently, also a carbon ion beam with minimum clinical energy 120 MeV/n was successfully sent into the room.

Machine Improvements

Further improvements are directed at resolving a fast vertical beam instability at injection [3] in the synchrotron, beam losses at RF capture [10], and emittance blow up at extraction.

Future machine developments at MedAustron meant also to reduce treatment time are discussed in more details in the contribution [11].

SUMMARY AND CONCLUSIONS

In December 2016, patient treatment has started using protons at MedAustron after the Particle Therapy Accelerator has successfully been certified as a medical device. Furthermore protons in clinical quality are available for non-clinical research purposes. The further commissioning of the facility has been carried out according to the plans and proton beams are available for medical commissioning in the horizontal beam line of IR2. Commissioning has started for the vertical beam line and carbon ions. For both, first beams have been obtained at the isocenter of the treatment rooms.

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