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STATUS OF THE CARBON COMMISSIONING AND ROADMAP PROJECTS OF THE MEDAUSTRON ION THERAPY CENTER ACCELERATOR

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Abstract

The synchrotron-based MedAustron Particle Therapy Accelerator MAPTA located in Austria, delivers proton (p) beams for medical treatment in the energy range 62-252 MeV since the year 2016 and is in preparation to provide carbon ions (C^{6+}) in the range 120-400 MeV/nucleon to the clinically used ion therapy irradiation rooms. In addition, carbon and proton beams will be provided to a room dedicated to research, with protons up to 800 MeV. Following beam generation at the ion sources and pre-acceleration, the beam is injected into a 77 m long synchrotron, that accelerates particles up to the required energy for clinical treatment, see Fig. 1. A 3rd-order resonance slow extraction is used to extract particles from the synchrotron in a controlled process and transfer the beam to 4 irradiation rooms with a spill length (0.1) 1÷10 seconds, to facilitate the control of the delivered dose to the patient. Recently, commissioning of the accelerator with carbon ions from the source to the horizontal beam line of the second irradiation room has been successfully completed. Carbon and high energy proton commissioning continues for the other beam lines. In parallel, the installation of the proton Gantry is ongoing. A review of carbon commissioning, the accelerator status and an outlook to future roadmap projects are presented.

INTRODUCTION

The MedAustron accelerator delivers proton and carbon ion beams for cancer treatment to four irradiation stations and in full operation is expected to treat up to 1200 patients per year. The center also provides infrastructure installations for clinical and non-clinical research with researchers coming from national and international research institutes. At this stage, the patient treatment is performed with protons in two rooms, and by the first 5 months of 2019, about 100 patients have been treated, with a weekly machine uptime during clinical operation > 95%.

ACCELERATOR LAYOUT

The accelerator is a design originating from the PIMMS and CNAO [1, 2, 3]. Three Supernanogan Electron Cyclotron Resonance Ion Sources (ECRIS) are designed to provide either H_3^+ and $^{12}C^{4+}$ beams to a low energy transfer line (LEBT) and subsequently to a Linac consisting of a 400 keV/n RFQ and an interdigital H-mode (IH) DTL that accelerates the beam to 7 MeV/n. A multi-turn injection from the Medium Energy Transfer Line (MEBT) accumulates particles into the synchrotron. Following RF capture and acceleration, the beam is extracted by a third-order resonant slow extraction mechanism, driven by a resonant sextupole and a betatron core.

The high energy beam transfer line (HEBT) transports the beam into four irradiation rooms (IR): Room 1 dedicated to research, Room 2 with two beamlines horizontal and vertical, Room 3 with a horizontal beamline and Room 4 hosting a proton Gantry based on a PSI design [4, 5]. The fixed beamlines of IR1, IR2 and IR3 provide protons and carbon [6, 7]. IR1 accommodates also protons 800 MeV.

Figure 1: MedAustron synchrotron hall.

ACCELERATOR PARAMETERS

High level requirements for clinical treatment with extension to non-clinical research define the accelerator parameters. Main parameters are listed in Table 1.

Table 1: MedAustron Accelerator Beam Parameters

Synchrotron circumference	77.6 m
Energy range protons	62.4÷252.7 (800) MeV
Energy range carbon ions	120÷402.8 MeV/n
Number of particles/spill (maximum)	p: 2×10^{10} C^{6+}: 1.5×10^9
Horizontal extraction tune $Q_{x,ext}$	1.666
Vertical extraction tune $Q_{y,ext}$	1.78
Spill length carbon/proton	4 s / 5 s
Irradiation field at patient	20 cm × 20 cm
Spot size FWHM at iso-center	p: 7÷21 mm C^{6+}: 6.5÷9.5 mm

CARBON COMMISSIONING

The carbon commissioning from the ion source to the horizontal beam line of the irradiation room IR2 has been completed in 2018 in an integrated time of ~ 6 weeks. The

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time for beam commissioning is limited since the machine is already in clinical use for proton therapy and in addition the available machine time is shared amongst several users.

Here below, we present the beam commissioning steps and procedures. In parallel, commissioning of all beam diagnostics devices for use with carbon was also completed.

Carbon Ion Beam Requirements

Main requirements on the carbon beam parameters as defined by medical physics are shown in Table 2.

Table 2: Carbon Ions Clinical Requirements

Beam parameter	Requirement
Penetration depth in water, "Range"	30÷270 mm
Beam spot size at patient, FWHM	6÷10 mm
Beam size symmetry (ellipticity)	± 10%
Beam position - Hor., Vert.	± 500 µm
Intra-spill position variation	± 300 µm
Intra-spill range variation	± 300 µm

The range above is equivalent to carbon energies 120÷402.8 MeV/n. Requirements need to be met at two room locations: design iso-center and 50 cm upstream.

Ion Source and Injector Commissioning

The three Supernanogan ECR Ion Sources from Pantechnik [8] are used for different ion species. Source S1 is used to generate proton beams, S2 for carbon ions. Source S3 serves as spare and future ion species. Source S2 was recently commissioned for the carbon in IR2-H project and tuned for stable operation. During the source commissioning, main goals were: i) nominal beam intensity and stability ii) nominal Twiss parameters, e.g. nominal emittance iii) nominal beam position. Ion source S2 commissioning was successful in terms of extracted beam intensity and stability as shown in Fig. 2, for more details see [9].

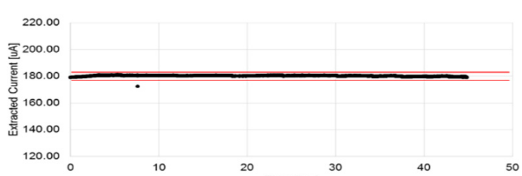

Figure 2: Carbon ion current as extracted from the source.

The injector section includes an RFQ, buncher cavity, interdigital H-type drift tube Linac and debuncher cavity, and the stripping foil. By scanning the optics parameters in a limited range, higher transmissions for carbon ions than for proton have been achieved with only minor adaptations.

A stripping foil converts C^{4+} into C^{6+} and H_3^+ into 3 p, while a pepper-pot like device degrades the transmission to 50, 20 and 10%, respectively referred as deg50, 20, 10.

A MEBT orbit correction and a scan of the last two correctors prepare the beam for injection in the synchrotron.

Multi-turn Injection

The beam is thus injected into the synchrotron by a multi-turn injection painting in the horizontal plane.

The initial height of an injection bump is created by two synchrotron kickers with a fall time of 80 µs. Synchronized with the injection bump, a fast deflector in the injector is turned on/off to select 26 µs (13 turns) fraction of the continuous beam pulse from the source.

In addition, goal of the multi-turn injection is to optimize the beam intensity and the horizontal emittance. A multi-parameter space optimization included the injection electrostatic and magneto-static septa, injector correctors, pulse length, the injection bump height and fall time and synchronization.

An initial large vertical emittance has been measured. Moving the injection tunes far from resonance lines, see Fig. 3, and improving the matching between the synchrotron and MEBT optics reduced the vertical emittance by a factor 3.6, and close to the design value.

As a result, emittances are close to design, see Table 3, and the flattop beam intensity is $1.5{\times}10^9$ ions, larger than the initial goal. However, the beam intensity had to be considerably reduced to fit to patient safety standard values.

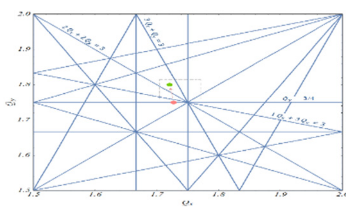

Figure 3: Injection tunes footprint. Vertical emittance could be decreased by moving the tunes.

Table 3: Measured Synchrotron Normalized Emittances ($\pi \cdot$ mm $\cdot$ mrad) Carbon Ions deg20. Design Value is 0.7482

Energy	Horizontal emittance	Vertical emittance	Ratio (V/H)
120 MeV	0.93	0.96	1.05
400 MeV	0.82	0.90	1.10

Synchrotron: RF Capture and Acceleration

The beam is then injected in the synchrotron horizontal plane "off-momentum", at 20 mm inner from the synchrotron closed orbit/vacuum chamber center.

Using the MADX [10] orbit correction module, after 2 iterations the initial ±4 mm orbit distortion was reduced to ±0.1 mm, as shown in Fig. 4 for the 400 MeV/n beam.

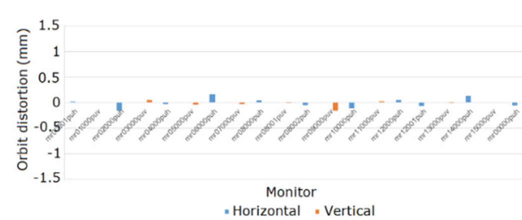

Figure 4: Orbit correction in synchrotron C^{6+} 400MeV/n.

The RF beam capture process is then optimized. The capture voltage and bucket size are pre-calculated based on the measured momentum spread and emittances. The capture voltage is then ramped adiabatically in 200 ms showing virtually no losses, as shown in Fig. 5.

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During acceleration, the dipoles' field is ramped at 3 Tesla/s, and bam movement is reduced to < 0.3 mm by the RF system radial loops, minimizing transverse losses. Fig-ure 5 shows a carbon cycle in the synchrotron with beam intensity reduced/optimized for clinical treatment.

Acceleration was achieved without the B-train feature (dipole field values sent to RF system for synchronization).

Then, an RF phase jump moves the beam to the bucket separatrix and the momentum spread stretches until dp/p~4‰ is met. RF channeling is being implemented [11].

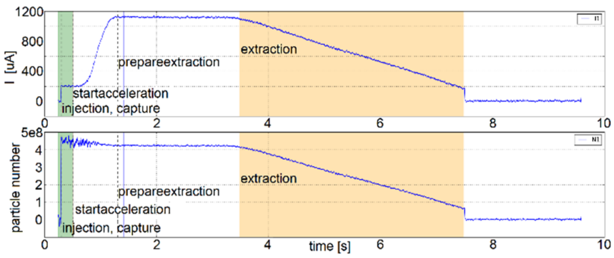

Figure 5: Carbon cycle in the synchrotron for 402.8 MeV/n deg100, 4 s extracted spill. Beam losses are minimized.

3rd Order Resonance Slow Extraction

In preparation for extraction, a third order resonance is excited by a resonance sextupole in a dispersion free region and the horizontal tune is set close to teh third order value 2/3 or Q_x=1.666. The coasting beam is then slowly accelerated into the resonance by an inducting field of a betatron core, with fixed optics during extraction.

The chromaticity settings were found by tracking simulations, as the Hardt condition [1] does not account for amplitude dependent tune terms and bending of the separatrix.

Tune and chromaticity required fine adjustment. The tune/chromaticity response to a strength variation of each quadrupole/sextupole family was measured. A system of linear equations was used to predict the correction to each magnet family and to obtain the desired values in just one iteration, see Fig. 6.

High Energy Transfer Lines Commissioning

Strategy for HEBT commissioning was to define the accelerator settings for 2 up to 5 major energies. In parallel, it was essential to optimize the magnetization cycles and control the magnetic field stabilization of dipoles.

An optimization of the extraction electrostatic, magnetostatic septa and first corrector aimed at preserving the beam intensity and align the beam at the extraction line entrance.

Closure of dispersion was performed by adjusting the strength of the first quadrupole triplet to minimize the variation of the horizontal intra-spill beam position, Fig. 7.

Point-to-point steering for the highest energy was performed by varying the correctors' strength while modulating the strength of downstream quadrupoles. Once a reference trajectory was established, it was used to correct the orbit of the other energies via the MADX orbit correction module.

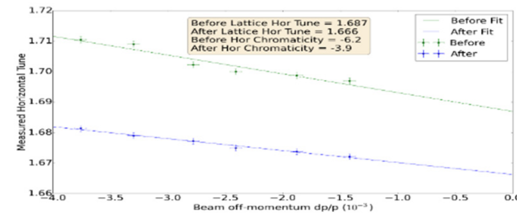

Figure 6: Measurement of horizontal lattice tune and chromaticity before and after the optimization.

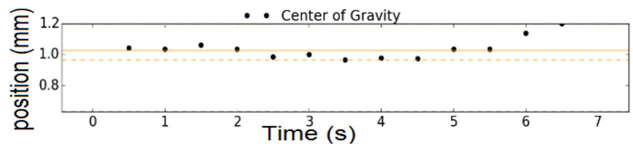

Figure 7: Dispersion closed by minimizing the Hor. intra-spill beam position variation to ± 0.1 mm.

Carbon Ion Beam Parameters in the Room

The beam size adjustment has been performed using the last two quadrupoles. By defining the settings of just five energies, the spot size FWHM could be adjusted within the required 6÷10 mm over the full energy range, see Fig. 8, also keeping the beam size symmetry within tolerances.

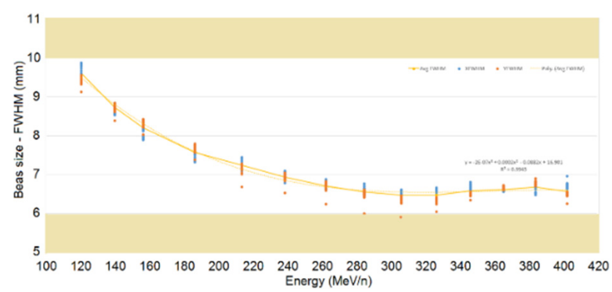

Figure 8: Carbon beam size at iso-center 6÷10 mm.

Requirements were simultaneously met at the two requested locations in the room: design iso-center and 50 cm upstream. Finally, an orbit response matrix scheme using the last two correctors has been used to achieve a centered beam horizontally ± 300 μm and vertically ± 50 μm without the use of scanning magnets feedback. As a result all clinical requirements in Table 2 have been fulfilled.

Carbon beam commissioning has been completed for the horizontal beam line of the irradiation room IR2, with patient treatment expected to start in July 2019, Table 4.

Table 4: MedAustron Commissioning Status and Schedule

Rooms	Proton	Carbon	Proton 800
Room 1	*Researching*	*in 2019*	*in 2019*
Room 2 Hor.	*Treating*	*July 2019*	-
Room 2 Vert.	*Treating*	*in 2020*	-
Room 3	*Treating*	*in 2020*	-
Room 4 Gantry	*in 2021*	-	-

SUMMARY

Since more than two years, patient treatment at MedAustron is ongoing with proton beams, with a continued ramp

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up in the number of patients. Protons are available for patient treatment and research in all rooms with fixed beam lines. The machine is remarkably stable in terms of its beam parameters robustness and reproducibility. Recently, carbon commissioning has been successfully completed for a first irradiation room with high beam intensity and transmissions, no use of b-train and at design beam parameters. A number of performance improvement projects are ongoing. Further commissioning milestones are protons 800 MeV, carbon commissioning in the rooms IR1, IR2-V, IR3 and the Gantry beam line with protons.

REFERENCES

[1] P. Bryant et al., "Proton-ion medical machine study (PIMMS)" Part I and II, CERN, Geneva, Switzerland, Rep. CERN/PS 99-010 and CERN/PS 2000-007, May 2000.

[2] U. Amaldi and G. Magrin "The path to the italian national centre for ion therapy", Ed. Mercurio Cardo, Italy, 2005.

[3] M. Benedikt *et al.*, "Overview of the MedAustron Design and Technology Choices", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper MOPEA020, pp. 109-111.

[4] E. Pedroni *et al*. "The PSI Gantry 2: a Second Generation Proton Scanning Gantry", *Z. Med. Phys*., vol. 14, no. 1, pp. 25-34, 2004.

[5] M. Benedikt, "Optics design of the extraction lines for the MedAustron hadron therapy centre," *Nucl. Instrum. Methods Phys. Res. A*, vol. 539, pp. 25-36, 2005.

[6] C. Schmitzer *et al.*, "Status of Carbon Commissioning of the MedAustron Therapy Accelerator", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 457-459. doi:10.18429/JACoW-IPAC2018-MOPML027

[7] C. Kurfuerst *et al.*, "Status of the MedAustron Beam Commissioning with Protons and Carbon Ions", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 665-668. doi:10.18429/JACoW-IPAC2018-TUPAF004

[8] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*, CRC Press, 1966.

[9] N. Gambino *et al.*, "Impact of Ion Source Stability for a Medical Accelerator", unpublished.

[10] MADX - Methodical Accelerator Design code CERN, https://madx.web.cern.ch/madx/.

[11] A. De Franco *et al.*, "Slow Extraction Optimization at the MedAustron Ion Therapy Center: Implementation of Front End Acceleration and RF Knock Out", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 453-456. doi:10.18429/JACoW-IPAC2018-MOPML025