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GANTRY BEAMLINE AND ROTATOR COMMISSIONING AT THE MEDAUSTRON ION THERAPY CENTER

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Abstract

The MedAustron Particle Therapy Accelerator located in Austria delivers proton beams in the energy range 60-250 MeV and carbon ions 120-400 MeV/n for tumour treatment in three irradiation rooms. Proton beams up to 800 MeV are also provided to a separate room dedicated to research. Over the last two years, in parallel to clinical operations, we have completed the installation and commissioning of the proton gantry beamline with the first patient treated in May 2022. In this paper, we provide an overview of the gantry beamline commissioning including the world-wide first "rotator" system used to match the slowly extracted asymmetric beams to the coordinate system of the gantry. Using the rotator, all beam parameters at the location of the patient become independent from the gantry rotation angle. The presented overview of the beamline commissioning includes technical solutions, main results and the first rotator measurements.

INTRODUCTION

The MedAustron accelerator delivers proton and carbon ion beams for cancer treatment to three irradiation rooms with the goal of treating 800 patients per year.

Figure 1: Bird view of the MedAustron gantry laying in the horizontal position. The gantry entrance is in the lower-right corner of the picture.

The center also provides infrastructure installations for external research institutes internationally. Following the commissioning of the gantry beamline, shown in Figure 1, all rooms at MedAustron are now operational. Since the first patient in 2016, about 1400 patients have been treated with protons and carbon ions using approximately 35,000 single fractions with a weekly machine uptime during clinical operation > 96%. Accelerator parameters are defined by requirements for clinical treatment and research. Accelerator and beam parameters for the fixed beamlines are shown in Table 1.

Table 1: MedAustron Accelerator and Beam Parameters

Parameter	Value
Synchrotron circumference	77.6 m
Energy range for protons	62.4÷252.7 (800) MeV
Energy range for carbon ions	120÷402.8 MeV/n
Spot size FWHM: at the isocenter	p: 7÷21 mm C^{6+}: 6.5÷9.5 mm
Number of particles/spill (max)	p: 2×10^{10} C^{6+}: 1.5×10^{9}
Spill length carbon/proton	4 s / 10 s
Irradiation field at the patient	20 cm × 20 cm

HEBT AND GANTRY LAYOUT

The MedAustron accelerator design originates from the Proton Ion Medical Machine Study (PIMMS) and National Centre for Oncological Hadrontherapy (CNAO) as described in [1, 2].

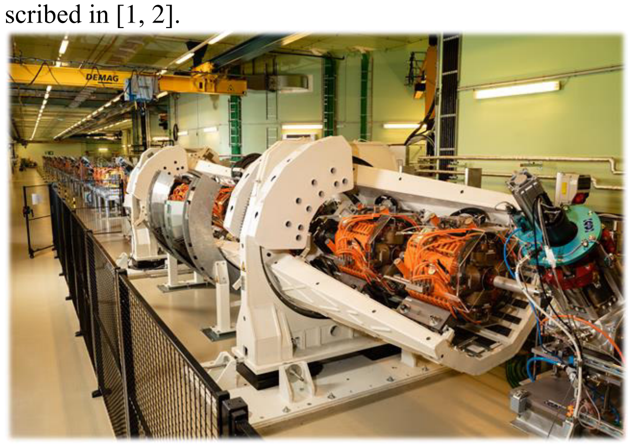

Figure 2: World-wide first rotator system (white structure) in the high energy beam transfer line. Seven quadrupoles (orange) are mounted on the structure and rotated synchronously with the gantry located downstream. With a rotator, the beam parameters at the gantry isocenter become independent from the gantry rotation angle.

The High Energy Beam Transfer line (HEBT) transports the beam from the synchrotron into four irradiation rooms:

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- Room 1: with a fixed horizontal beamline dedicated to research;
- Room 2: with a fixed horizontal and a fixed vertical beamline intersecting at a common isocenter;
- Room 3: with a fixed horizontal beamline;
- Room 4: with a rotating proton gantry.

The fixed beamlines deliver proton and carbon beams [3]. 800 MeV protons are also available in Room 1 for research. The gantry is based on the Paul Scherrer Institute (PSI) design [4, 5]. The rotator, shown in Figure 2, is a section of the HEBT located upstream of the gantry.

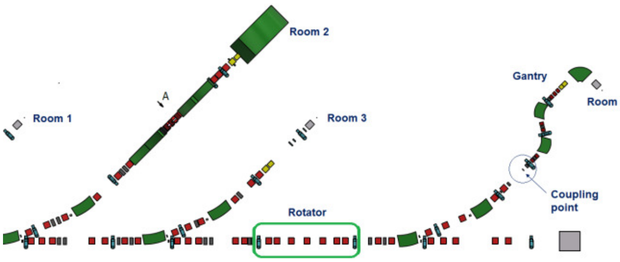

Figure 3: High energy beam transfer line layout showing the fixed beam lines, the rotator and the gantry.

The rotator system is a 9.9 m long straight dispersion-free section of the high energy beam transfer line consisting of seven quadrupoles which physically rotate with respect to the nominal beam path by half the gantry angle [6]. The aim of the rotator is to map the incoming beam distribution from the fixed beam line to the local reference system of the gantry and therefore decouple the beam parameters at the gantry isocenter from the rotation angle. The theoretical concept of a rotator exists since almost two decades [6]; first proposed in [7].

A 20 m long 1:1 achromatic deflection module transfers the beam from the rotator exit to the gantry entrance.

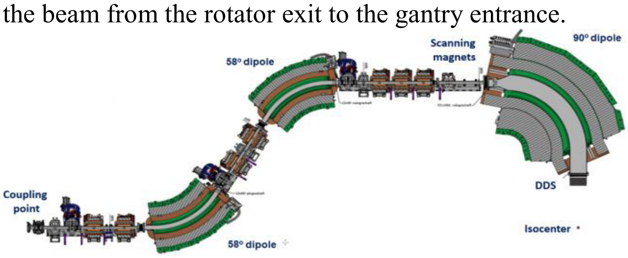

Figure 4: Gantry beamline, beam entrance from the left.

Table 2: MedAustron Gantry Beamline Parameters

Parameter	Value
Gantry beam line rotating part	15.9 m
Gantry rotation angle	180°
Gantry weight	≈ 220 tons
Energy range for protons	62.4÷252.7 MeV
Spot size FWHM at DDS system	> 6 mm
Spot size FWHM at gantry isocenter	7÷21 mm
Number of protons/spill	2×10^{10}
Spill length for protons	10 s
Irradiation field at patient location	20 cm × 12 cm

The rotating gantry beamline, shown in Figure 4, starts at the coupling point with the fixed HEBT and consists of two quadrupole doublets, two 58° dipoles, a final quadrupole triplet, the 90° dipole and the Dose Delivery System (DDS) with beam monitors upstream of the patient. Vertical and horizontal scanning magnets are located upstream of the 90° dipole to allow for parallel scanning. The gantry parameters are shown in Table 2.

GANTRY BEAMLINE AND ROTATOR COMMISSIONING

Beam commissioning started from the high energy transfer line with goal of transporting the beam through the HEBT, the rotator, the deflection module and gantry, and delivering it to the gantry room with required parameters. At the room isocenter, the beam must be centered ± 0.5 mm, with beam angle ± 0.2 mrad with respect to the gantry optical axis, round in size within ± 10%, with symmetrical horizontal/vertical profiles and with FWHM larger than 6 mm, as requested by medical physicists.

HEBT Beamline and Rotator Commissioning

We matched the HEBT optics to obtain an achromatic line with $\beta_{x,y} = 1$ m, $\alpha_{x,y} = 0$ and the bar-of-charge particle distribution oriented "upright" in the horizontal phase space at the rotator entrance. Under these circumstances, the horizontal and vertical emittances have the same projections on the momentum/angle axes in the phase space, as pre-condition for parallel-to-point gantry optics. For the HEBT and gantry optics design including beam scattering in the room, we used the codes WinAgile, MADX/PTC and FLUKA [8 - 10].

Afterwards, an initial orbit correction was performed along the line to minimize the beam off-set and angle at the rotator entrance, so to obtain a beam invariant with the rotation angle, and to avoid beam scraping inside the rotator.

The rotator functionality and concepts have been thoroughly tested and validated by an intense beam measurement campaign, see Figure 5.

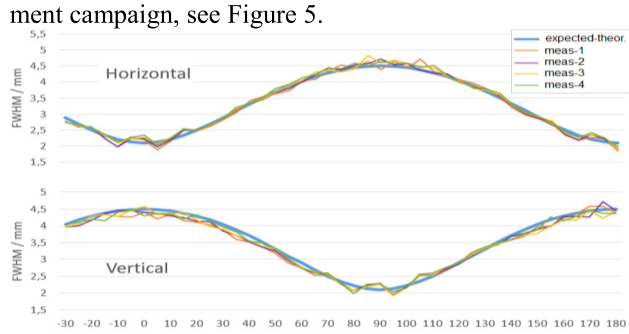

Figure 5: Beam sizes on a monitor located at the rotator exit as a function of the gantry angle (rotator angle = ½ of the gantry angle). Comparison of the beam size as expected from the rotator theory with four sets of measurements.

Furthermore, the horizontal beam size at the rotator entrance was estimated to be about 300 μm, compared with simulations and concluded that the bar-of-charge was oriented upright in the horizontal phase space as required. Since the rotator contains no correctors, we have implemented a dedicated method to compensate for the rotator

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quadrupole misalignments during rotation. The method uses HEBT correctors upstream of the rotator to align the beam at the rotator exit.

With this method, the beam position and angle have been successfully aligned at the exit of the rotator. This was inferred on the two monitors downstream where plots of the beam positions described circles with radius in the order of 0.2 mm during the rotator rotation. In this way, we accomplished the first experimental proof of the rotator concept.

Gantry Beamline Commissioning

Two gantry optics have been considered: point-to-point optics, mapping an input particle position coordinate into its output position coordinate, and parallel-to-point optics, mapping an input particle angular coordinate into its output position coordinate. The latter has been selected since it fits better to the design constraints imposed on the beam size at the DDS monitor.

Initial beam commissioning was performed for the gantry angles*: 0°, 60°, 90°, 150° as requested by medical physicists and additional angles will be provided†.

Commissioning the rotating part of the gantry was a challenge: the beam should enter and exit the gantry centered and well aligned. Any “permanent” magnet-misalignments or “dynamic” misalignments caused by mechanical gantry deformations during the gantry rotation translate into a beam misalignment in the gantry isocenter challenging the correctors. The parallel-to-point imaging requires a precise orientation of the horizontal bar-of-charge as well as identical input α and β functions in both planes.

Commissioning started with beam alignment at the gantry entrance using upstream correctors and the quadrupole scan technique.

The mechanical deformation of the gantry structure during rotation affected the beam positions at the DDS and isocenter, requiring a fine beam steering procedure for each gantry angle. Figure 6 shows the isocenter beam monitor mounted directly on the gantry as used during beam commissioning at different gantry angles.

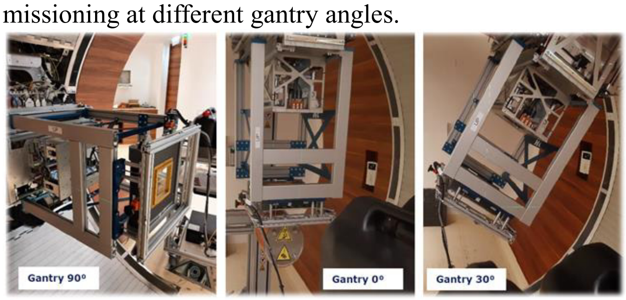

Figure 6: Beam commissioning: beam monitor mounted on holder frame in the gantry room at different gantry angles.

After commissioning, the machine settings and beam parameters have been validated by final acceptance tests. The gantry irradiation room finally ready for patient treatment is shown in Figure 7.

Figure 7: Gantry room: automatic patient positioning system and rolling floor. Gantry at 60°, beam entry from left.

Main Results

Initial measurements at the isocenter showed that the horizontal and vertical beam sizes were already within specifications over the whole energy range. Therefore, the gantry quadrupole strengths did not require any energy dependent adjustments.

Most importantly, the beam size at the patient was independent from the gantry rotation angle, as shown in Figure 8, which fully validates the rotator concept.

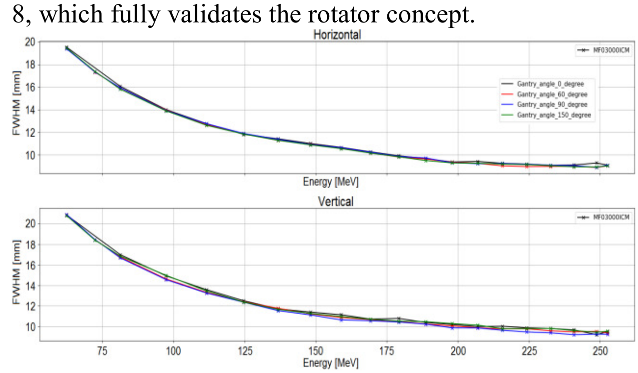

Figure 8: Horizontal (top) and vertical (bottom) beam sizes measured at isocenter as a function of energy for four different gantry angles. The beam sizes are independent from the gantry rotation angle.

CONCLUSIONS

Since more than five years, patient treatment is ongoing at MedAustron with a continuous ramp up in the patient throughput. Beam commissioning of the proton gantry including the first rotator have been completed. The gantry was handed over for final testing and certification leading to the first patient treatment, just recently. Following the gantry commissioning, all rooms at MedAustron are now operational. The rotator, designed, built, installed and tested at MedAustron, is the first system of its kind worldwide. The rotator concept was successfully proven to work assisting the gantry and resulting in a beam size at isocenter which is invariant with the gantry rotation angle, thus validating the rotator concept and its theoretical model.

*Gantry angle 0° corresponds to the beam pointing downwards, 90° in the horizontal direction and to the right, while 180° pointing upwards.

†Gantry angle 60° was commissioned but not yet ready for medical treatment.

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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] M. Pivi *et al.*, "Status of The Carbon Commissioning and Roadmap Projects of the MedAustron Ion Therapy Center Accelerator", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne Australia, May 2019, pp. 3404-3407. doi:10.18429/JACoW-IPAC2019-THXXPLS1

[3] C. Kurfürst *et al.*, "Status of the MedAustron Beam Commissioning with Protons and Carbon Ions" in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, BC, Canada, Apr.-May 2018, pp. 666-668 doi:10.18429/JACoW-IPAC2018-TUPAF004

[4] E. Pedroni *et al.*, "The PSI Gantry 2: a Second Generation Proton Scanning Gantry" *Z. Med. Phys.* 14 (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] M. Benedikt and C. Carli, "Optical design of a beam delivery system using a rotator", CERN/PS 96-41 (DI), 1996.

[7] L. C. Teng, private communications, int. rep. LL-134, 1986.

[8] P. Bryant "AGILE, A Tool For Interactive Lattice Design" in *Proc. European Particle Accelerator Conf. (EPAC2000*), Vienna, Austria

[9] http://madx.web.cern.ch/madx/

[10] https://fluka.cern/