STATUS OF PROTON BEAM COMMISSIONING OF THE MEDAUSTRON PARTICLE THERAPY ACCELERATOR

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Abstract

MedAustron is a synchrotron-based ion beam therapy centre, designed to deliver clinical beams of protons (60-250 MeV) and carbon ions (120-400 MeV/u) to three clinical irradiation rooms (IR) and one research room, which can also host 800 MeV protons. The commissioning activities for the first treatments with proton beams in IR3 have been completed and commissioning of IR1-2 is ongoing. The present paper describes the activities which took place during the last year, which involved all accelerator components from the ion source to the IR.

INTRODUCTION

The MedAustron accelerator provides beam rigidities of up to 6.4 Tm. Its layout is shown in Fig. 1. The design originates from those of PIMMS [1] and CNAO. The injector produces 7 MeV/n beams of H^+/C^{6+} for injection into the synchrotron. After acceleration, the beam is extracted via a third-integer resonant slow extraction, driven by a betatron core. The high energy beam transfer line (HEBT) adapts the transverse and longitudinal beam properties and transports the beam into one of the four IRs: IR1 with a horizontal (H) beamline for non-clinical research, IR2 with H and vertical (V) beamlines for clinical treatment, IR3 with an H beamline for clinical treatment and IR4 with a gantry for proton clinical treatments. Since last year [2], the commissioning of the accelerator for proton clinical treatments in IR3 is completed, first proton beams were sent to IR1/2-H, IR2-V is installed and magnets for IR4 are in tendering process.

COMMISSIONING STRATEGY

The clinical penetration depths in water (range) of the proton beams are 30-380 mm, with 255 steps of 1 mm up to 190 mm range and 2 mm thereafter, corresponding to kinetic energy steps of 0.5-1.0 MeV. In addition, each beam of a given energy should be delivered in 5 s spills with 4 different intensity levels. The main tolerance specifications for the beam properties for all 1020 combinations for the accelerator commissioning are given in Table 1. In addition, the expected intensity is 1e10 protons per spill, the 'dead-cycle' time between spills is 2 s and the peak-over-mean of the extracted beam intensity within the spill (for 5 ms averaging time and 10 kHz sampling) is 5.

The commissioning started with the optimization of beam properties for the highest energy and highest intensity. The subsequent fine-tuning was done for 4 *main* energies equally interspaced in the clinical energy range. The beam parameters at the IR3-isocenter (IC) were checked and fine-tuned in collaboration with the medical physicists.

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Table 1: Specifications for Accelerator Commissioning

Parameter at the IC	Tolerance
Absolute Range	± 0.3 mm
Range variation within spill	± 0.15 mm
Absolute Position	± 0.5 mm
Position variation within spill	± 0.25 mm
Absolute Size	40% of Monte Carlo model and 10 % of 3rd order polynomial fit
Symmetry	Min{10%, 1 mm}
Size variation within spill	± 5 %

INJECTOR

The main recent activities in the injector consisted in the commissioning of a passive absorber system, called degrader.

Degrader

The degrader consists of 3 moving copper plates with a regular pattern of holes of different diameters. It is used to reduce the injected beam current by nominally 50%, 80% and 90% without affecting transverse and longitudinal beam parameters.

SYNCHROTRON

The main recent commissioning activities in the synchrotron consisted in fast acceleration ramps [3] and the setup of the resonant extraction for the 4 main energies [3-5].

Acceleration

The Synchrotron RF (SRF) frequency program and the delay between SRF waveforms and the waveforms of the main bending magnets were empirically adjusted to allow open-loop acceleration. The maximum magnetic field variation from flat-bottom to flattop for clinical proton beams is by a factor of 6.3. The SRF radial loop regulation allows compensation for current regulation errors from the main bending magnets and the field stabilization time at flattop.

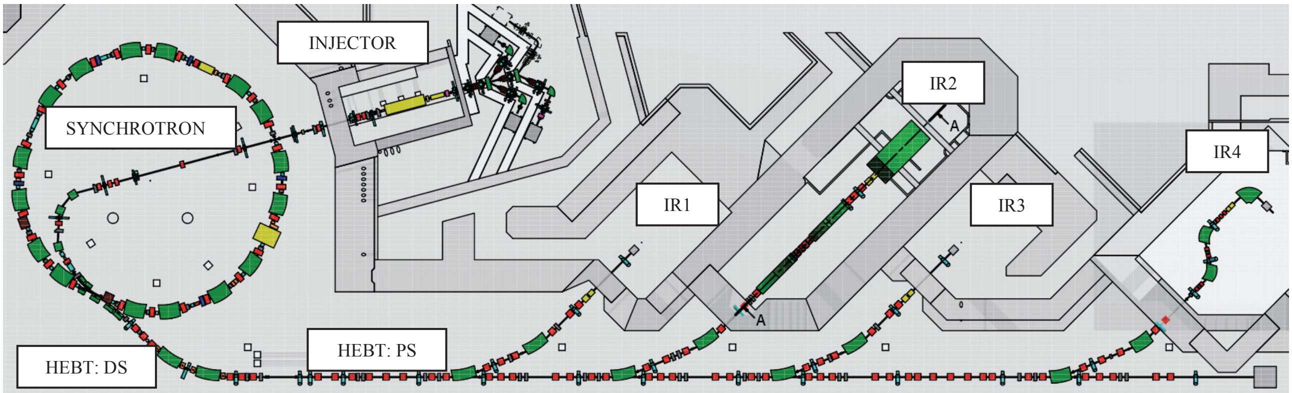

Figure 1: The MedAustron accelerator (DS: dispersion suppressor, PS: Phase-Stepper).

The resulting beam relative momentum oscillations for ramps up to 2.25 T/s are within ±0.5e-4. The SRF voltage program was tuned to minimize losses and provide the correct voltage for the RF phase jump before slow extraction [3].

Resonant Extraction Tuning

Orbit correction results in closed-orbit errors below ± 1 mm for all 4 energies with the same normalized strengths of less than 0.4 mrad. Orbit bumps around the extraction septa proved their optimal positioning. The tunes and chromaticities were adjusted to reach the design values for extraction, as summarized in Table 2.

Table 2: Flattop Measurements

Parameter	Result over the 4 main energies
$Q_H - Q_{H\_design}$	0.001 ± 0.001
$Q'_H - Q'_{H\_design}$	0.1 ± 0.2
$Q_V - Q_{V\_design}$	-0.003 ± 0.004
$Q'_V - Q'_{V\_design}$	-0.1 ± 0.1

The resonant sextupole is ramped in 25 ms and its strength was fine-tuned to provide the lowest losses. Before extraction, the beam momentum distribution is flattened and increased by a factor 2 to ±2e-3 via a so-called RF phase jump, as shown in Fig.3. The beam is then longitudinally driven through the resonance via a betatron core. The electrostatic and magnetic extraction septa were tuned to provide high intensity beams centered in the beginning of the HEBT. An example of the extracted beam intensity is show in Fig.4. The peak-over-mean ratio is 3.5±1 for all energies (for 5 ms averaging time of a 10 kHz signal) and the main ripple contribution is at 4 kHz, which corresponds to the switching frequency of the power supply of the synchrotron bending magnets.

HIGH-ENERGY BEAM TRANSFER LINE

The main commissioning activities in the HEBT [6] consisted in the dispersion suppression, the beam alignment using quadrupole variation methods, the beam chopping and the optics adjustment for the 4 main energies.

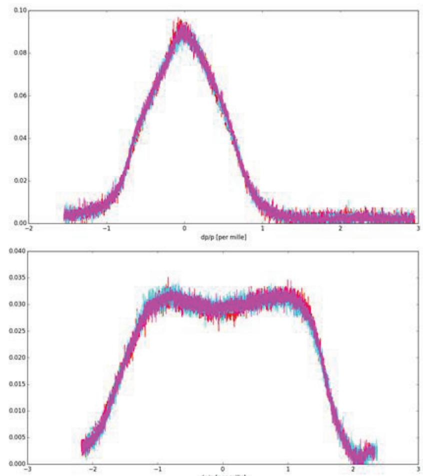

Figure 3: Empty-bucket measurement before (top) and after (bottom) the phase jump for 3 different cycles, showing the beam momentum distribution.

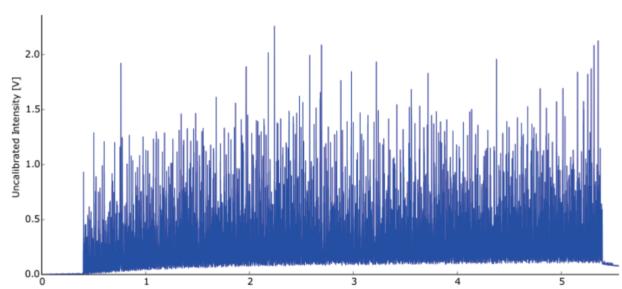

Figure 4: Extracted spill intensity in the HEBT over time

Dispersion Suppression and Chopping

The first section of the HEBT is dedicated to provide a safe and fast beam chopping system and to close the H dispersion resulting from the slow extraction. Indeed, the beam extracted from the synchrotron has leading and trailing edges, during which its longitudinal and transverse beam properties are not constant. These parts are cut according to the measured range, position and beam width variation within the spill at the IC. They are however used to indirectly estimate the dispersion function and minimize it by scaling the strengths of the first quadrupole triplet. An example of a beam before dispersion correction is shown Fig. 5.

ISBN 978-3-95450-147-2

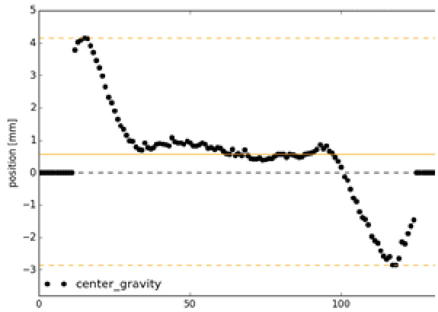

Figure 5: H position along the spill without chopping: before dispersion correction.

After correction, the dispersive beam movement is reduced from 7 mm to 0.8 mm.

Beam Alignment

Beam alignment was carried out using quadrupole variation methods, concentrating on hand-over positions in the HEBT where both position and beam angle were minimized. The procedure was carried out for the highest and lowest energies and the interpolation for intermediate energies was checked. The achieved alignment is within ±1 mm in both planes with maximum corrector strengths of 2.3 mrad at the HEBT entrance and less than 1 mrad thereafter in the H plane and less than 0.5 mrad in the V plane.

Spot Size Adjustment

The transverse beam properties in the IC were adjusted: using the PS quadrupoles to modify the H phase advance and rotate the bar-of-charge [1], the triplet before the PS to adjust the V beta function and the last quadrupole magnet as a final adjustment. An example adjustment of the H spot size via the PS is shown in Fig. 6.

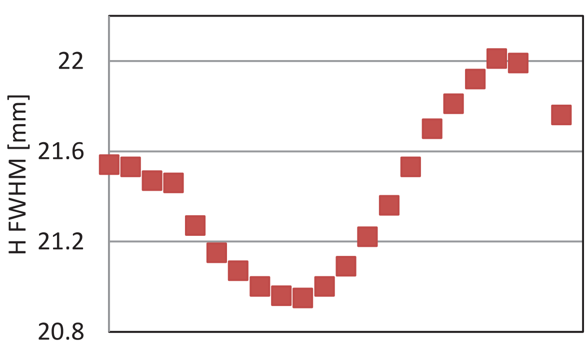

Figure 6: H spot size in air at the IC for 62 MeV for different PS settings.

This was performed for the highest and lowest beam energies and the remaining energies checked after interpolation. The spot sizes range from 22 mm at 62.4 MeV to 8 mm at 252.7 MeV. It was observed that the intensity has an influence on the V beam size, resulting in a 3 times smaller V emittance in the HEBT for 10-times lower intensity. This effect was mitigated by decreasing the vertical tune at injection by 0.02 for low intensities. We thus obtain lower than 4% beam asymmetry for all energies and intensity levels.

Energy Adjustment

The final adjustments in the synchrotron were performed by measuring the beam penetration depth in the IC and requesting a different extracted energy to reach the required range.

GENERAL

To allow reproducible beam operation with time and when changing ion species and treatment rooms, magnetization and demagnetization cycles were commissioned for all magnetic elements. In addition, an accelerator quality assurance procedure [6] was setup to verify the beam properties evolution with time.

The average intensities in the IC range from 1.2e10 to 1.8e10 protons per spill (for respectively 62 MeV and 253 MeV). The transmission in the different accelerator sections are summarized in Table 3.

Table 3: Losses

Accelerator Section	Transmission
Source to Linac exit	45 %
To injector exit	95 %
After synchrotron injection	25 %
Before extraction	50 %
To IC	65 %

The cycle dead-time between one spill and the next is 3-3.5 s. The limitation is linked to the regulation of extraction elements. Improvement is also needed on the reduction of the intensity variations within the spill.

CONCLUSION AND OUTLOOK

In summary, the full accelerator chain was commissioned for proton clinical treatment in IR3, with beam quality exceeding the requirements in terms of intensity and symmetry. The major recent commissioning efforts concentrated on the synchrotron and the HEBT. First proton beams were sent to IR2-H and IR1. The installation of the IR2-V is being completed and the tendering of IR4 gantry magnets is ongoing.

ACKNOWLEDGEMENT

The authors acknowledge the support of the colleagues from the Therapy Accelerator and Medical Divisions, as well as the important contributions from M. Pullia, L. Falbo (CNAO), V. Lazarev (Siemens), as well as the support of CERN.

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ISBN 978-3-95450-147-2