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STATUS OF PROTON BEAM COMMISSIONING AT THE MEDAUSTRON ION BEAM THERAPY CENTRE

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Abstract

The MedAustron accelerator (Wiener Neustadt, Austria) will deliver clinical beams of protons (60 - 250 MeV) and carbon ions (120 - 400 MeV/n) to three ion beam therapy irradiation rooms (IR). Clinical beams and proton beams up to 800 MeV will be provided in a fourth IR, dedicated to non-clinical research. A slow-extracted proton beam of maximum clinical energy reached for the first time the IR3 in October 2014, thus providing the technical proof-of-principle of the entire accelerator chain. The main characteristics of the MedAustron accelerator system are presented, along with the results obtained along the ongoing commissioning.

INTRODUCTION

MedAustron is a synchrotron-based ion beam therapy centre. The accelerator supports beam rigidities up to 6.4 Tm. The accelerator layout is shown in Fig. 1. Its design [1] originates from those of PIMMS [2] and CNAO [3]. The injector produces beams of H_3^+ or C^{4+}, which are chopped with a fast electrostatic deflector, then bunched and pre-accelerated to 7 MeV/n with a Radiofrequency Quadrupole (RFQ) and an IH-DTL linac. In the Medium Energy Beam Transfer line (MEBT), the beam is stripped to H^+ or C^{6+} before injection into the synchrotron. The synchrotron has a superperiod of 2 with non-dispersive regions for injection and the Radiofrequency (RF) cavity. After acceleration, the beam is extracted via the third-integer resonance in the High Energy Beam Transfer Line (HEBT). Since last year [4-5], the installation of accelerator components for proton treatments in the two horizontal beam lines of IR2 and IR3 has been completed and a first beam of protons at 62.5 MeV reached IR3 in October 2014. Beam commissioning is currently resuming and passing the torch to medical commissioning.

INJECTOR AND MEBT

The commissioning of the beam from the source to the end of the MEBT has been completed at the end of 2014 with very positive results, in terms of intensity, transmission and stability. The main contributors to this progress have been: the extensive work on the IH stability (cooling and setpoint adjustment), optimization of the IH quadrupole strengths, steering at the source exit and in the matching section between RFQ and linac and finally, the increase of the RFQ output energy. The appropriate choice of the operation point of the linac was critical in stabilizing the energy of the beam injected into the ring. A summary is shown in Table 1.

Table 1: Results of Commissioning up to the MEBT

Parameter	Performance
S1 current	650 µA
Linac exit current (H_3^+)	290 µA ± 3 %
Transmission through RFQ+Linac	45 %
MEBT exit current (H^+)	805 µA ± 2%
Transmission through MEBT	93 %
Energy Stability	± 0.1 %

SYNCHROTRON INJECTION

Multi-turn Injection

The injection in the ring is performed in 16 turns via a linearly decaying π orbit bump of 41 mm horizontal amplitude with 100 µs linear decay time. The resulting horizontal RMS geometric beam emittance is around 8 µm and the maximum injected number of particles is $6\cdot10^{10}$ protons, corresponding to 6 effective injection turns. Without orbit correction, the measured beam closed orbit errors are within ± 7 mm in the horizontal (H) plane and ± 2 mm in the vertical (V) plane.

RF Capture

The debuncher phase and amplitude were adjusted by measuring the time-of-flight coming from the phase probes in the MEBT and by maximizing the debunching time of a 1 µs injected beam pulse length. The results were confirmed by empty-bucket measurements and show that the RMS injected momentum spread can thus be decreased from $1.6\cdot10^{-3}$ to $0.5\cdot10^{-3}$.

The capture RF frequency (~ 470 kHz) was chosen by maximizing locally the signal on the current transformer and the sigma signal on the pickups. The voltage is adiabatically ramped to 170 V over 150 ms.

Beam Instability

With injected intensities over $1\cdot10^{10}$ protons (1 mA), erratic and strong beam losses were observed, with both unbunched and bunched beam. The variability of this effect is very strong in time. The common patterns are beam losses of nearly 90 % in around 100-300 ms, starting 0.1 to 3 s, when using an artificially prolonged injection flat-bottom (FB). These losses are correlated with coherent beam orbit oscillations in the V plane, with characteristic frequencies ~120 kHz and exponential rise times of 0.1 - 0.3 s, see Fig. 2.

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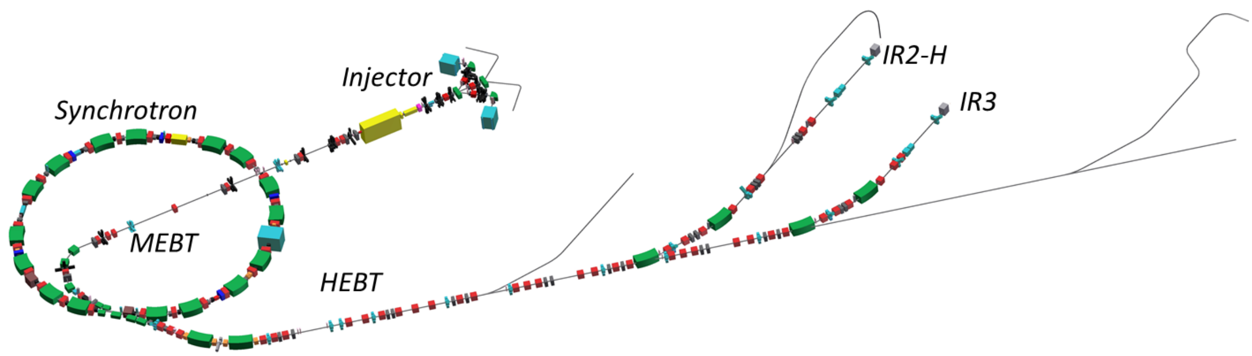

Figure 1: Accelerator elements presently under commissioning (overall length is 110 m).

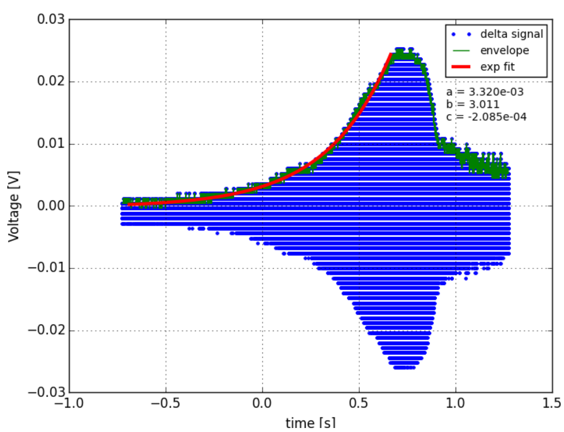

Figure 2: Delta signal from a V pickup, fitted with the exponential function $a \cdot e^{bt} + c$.

This effect was first observed when scanning the bending magnet current at injection. This gave an optimum in injected beam current but also revealed a stable and unstable area around this optimum current. A study was carried out to exclude that these effects originate from hardware anomalies or beam loss induced charge-up. The tunes and chromaticities have been automatically scanned [6] to investigate stable high injection regions around the design values of 1.74 / 1.79 (H/V) and for negative chromaticities of equal amplitude in both planes. The maximum space charge detuning at injection was estimated to be -0.04 [7].

ACCELERATION

Power Supply Regulation

Extensive work was done to enable a smooth current regulation of the synchrotron magnets' power supplies and to determine their response delays. The main bending magnets are the components with the slowest and most delicate response. The 2 kHz regulation loop was optimized to achieve current errors below 0.1 % for ramps of up to 3 T/s. It was determined that artificial delays of 9 ms for the RF frequency program and 4.5 ms for quadrupole, sextupole and corrector power supplies had to be introduced to allow synchronization and acceleration.

Ramp Generation

In order to generate ramps for different cycles in the main ring, recent addenda to the control system software include: an eight-polynomial fitting of all the measured magnetic fields for continuous conversion from/to current/magnetic field, the introduction of individual delays to any ramp, an optimizer to deliver smooth ring bending magnet current ramps and a correction factor for the programmed RF frequency ramp.

RF Cavity

The proton beam has been accelerated to up to 800 MeV with a slow ramp of 0.125 T/s and a constant voltage of 170 V. The programmed RF frequency ramp had to be empirically adapted with a linear scaling factor in order to allow open-loop acceleration for protons. In addition, the radial and phase loops have been tuned based on the beam response. This is a critical point for the slow extraction. Recent tests to increase the ramp rate have successfully reached 0.5 T/s and are ongoing. The power supplies are capable of ramping at up to 3 T/s.

SLOW EXTRACTION

Throughout the injection and acceleration, the beam is kept at around $+3 \cdot 10^{-3}$ momentum offset, since this maximizes the available aperture and since for slow extraction, the H machine tune is set to 5/3.

Orbit

Orbit bumps at the position of the H scrapers were used to verify the pickup calibration. A discrepancy compared to the sensitivities measured before installation of 13 % was thus identified and corrected.

The measured dispersion is shown in Fig. 3. This has been measured by using a linear ramp of the radial loop programmed position from +25 mm to -25 mm and assume a gamma transition of 1.99. The results are consistent with measurements performed at FB by changing the bending magnet current and measuring the turn-by-turn position with an artificially bunched beam (1 μs injection pulse). With this input, the non-dispersive part of the orbit could be corrected using maximum correctors strengths of 0.4 mrad. The resulting closed-orbit error is reduced to ±1.0 mm in both planes.

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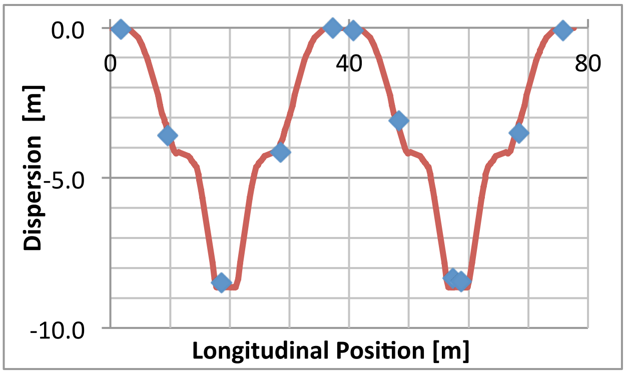

Figure 3: Measured dispersion (blue) at 250.3 MeV flat-top (FT) compared to the output of MADX (red line).

Optics Matching

The H and V chromaticities were measured at FT using a BBQ system and revealed good tune linearity with dispersive beam positions at up to 60% of the good-field region. Constant offsets of -0.066 / +0.004 (V/H) compared to MADX results allowed to rematch the quadrupoles to reach an error to the design tunes lower than $5{\cdot}10^{-3}$ / $0.5{\cdot}10^{-3}$ (V/H). The chromaticities offsets were found to be 0.1 / -0.9 (V/H).

RF Phase Jump

RF gymnastics is performed to spread the beam in momentum space in order to smoothen the extracted beam flux. The beam is then driven longitudinally towards the resonance by the ramping of the betatron core. The first implementation of this scheme achieved constant extraction fluxes for half of the spill time.

HEBT

The beam is extracted to the HEBT where its transverse beam properties are adapted [8] to the requirements at the IR. The characteristic distributions (gaussian in V and quasi-uniform [1] in H) coming from the slow extraction are visible on Fig. 4.

CONCLUSION AND OUTLOOK

Intensity and Cycle Optimization

The present goal is to provide a proton beam of the highest clinical energy of 4x4 mm FWHM spot size at IR isocenter (as in vacuum), optimized for intensity, cycle time and spill quality/time. The current status in terms of intensity optimization is summarized in Table 2.

When the optimization is completed for the highest clinical energy, 20 different machine cycles of different beam energies must be created using scaling and individual fine-tuning.

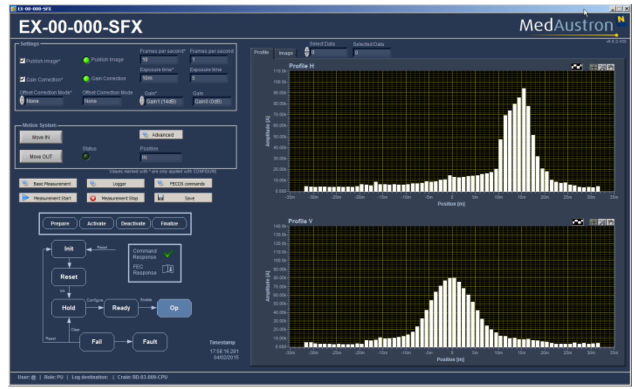

Figure 4: Beam profiles from a Scintillating Fiber Hodoscope (top: H, bottom: V).

Table 2: Status of Intensity Optimization

[design values]	Protons (10^{10})	Transmission (%)
MEBT exit	16 [7.5]	42 [57]
After injection	4 [1.5]	20 [20]
After capture and acceleration	1 [1.3]	25 [86]
After extraction, in IR	0.5 [1]	60 [78]

Future Perspective

An iterative period with the medical physics team will fine-tune the 20 machine cycles based on the measured beam penetration depths in water and the scattered beam transverse profiles in air at the isocenter. This is a pre-condition to finally creating 255 cycles with beam penetration depths in water of 3-38 cm (equivalent to ~ 60-250 MeV), for safe and reproducible delivery of beams for the clinical commissioning in IR2 and IR3.

In parallel, major steps were achieved towards the certification of the therapy accelerator (classified as class IIb medical device) according to the Medical Device Directive.

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