HEBT COMMISSIONING FOR HORIZONTAL BEAMLINE PROTON TREATMENTS AT MEDAUSTRON

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Abstract

MedAustron has completed its proton commissioning activities for clinical treatment in the horizontal Irradiation Room 3 (IR3). Work involved the preparation of 255 energies in clinical range (60 – 250 MeV) for one spill length, one spot size and 4 intensity levels. After resonant slow extraction, the beam crosses four different functional areas in the High Energy Beam Transfer Line (HEBT): the dispersion suppressor (DS), the phase shifter stepper (PSS), two straight extension modules and a deflection module to IR3. Quadrupole-variation methods were applied to center the beam in the beamline. The DS section was commissioned to provide high intensity beams with closed dispersion. The PSS section was commissioned to provide symmetric and minimal spot sizes at the iso-center in the room (after scattering in the nozzle and air). The definition of the 255 clinical energies was given by the Medical Physics team after measuring the beam ranges at the iso-center.

INTRODUCTION

MedAustron is a synchrotron based hadron therapy and research center. Its design originates from those of PIMMS [1] and CNAO [2]. After the successful injector commissioning [3] [4], the synchrotron RF commissioning [5] together with the slow extraction commissioning [6] could be recently completed. Based on these milestones, major effort went into the preparation of the HEBT for patient treatment. The steps described in this paper allowed to obtain the spot at the iso-center as shown in Fig. 1. The main clinical tolerance specifications for the beam properties in the treatment rooms are given in [7].

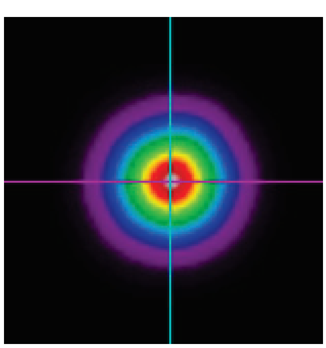

Figure 1: Spot measured in IR3. The FWHM is 7.6 mm in air at the iso-center in this example for 250 MeV.

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Specifically developed automatic data acquisition tools [8] and standardised analysis tools [9] greatly enhanced the commissioning progress.

The HEBT (see Fig. 2) is composed of the following functional modules:

- DS with integrated chopping system
- PSS to adjust the beam sizes at the IR's focal point
- 1:1 telescope-extension modules
- Deflection module towards IR3

The standard handover parameters between modules are: β_x= 3 m, α_x= 0, D_x= 0 m β_y= 3 m, α_y= 0 and D_y= 0 m.

ORBIT CORRECTION

To allow for the orbit correction, 18 single plane correctors were installed along the HEBT to IR3. They are capable of producing a kick-angle of 4.9 mrad at top magnetic rigidity of 6.4 Tm for 400 MeV/n Carbon ions. The mechanical alignment uncertainty along the HEBT is of +/- 0.3 mm and is one of the sources of orbit excursions. Additionally of importance are the possible remanent fields of switching dipoles in the HEBT, which may induce orbit distortions in the horizontal plane. They are avoided by implementing a degaussing procedure when the irradiation room is changed, consisting of 14 current ramps from the maximum current to zero. After the procedure, the residual magnetic field at the magnet center is of the order of 0.1 mT.

The standard operation mode of the HEBT magnets is to keep a constant current from the beginning of the cycle until its end. However, the bending magnets revealed field errors up to 0.7 % at the entrance and exit of the magnets when ramping the current at the required ramp rate. Their operation mode was therefore adapted to perform a magnetic washing at every cycle like in the synchrotron .

At the beginning of the HEBT, directly after the main ring extraction, no perfect measurement and correction of both beam angle and position is feasible. The first DS section was hence set-up for intensity maximization.The proper horizontal angle and position correction was performed in the first straight section using the dipole and the downstream corrector. This is especially critical for the beam passage through the PSS, where good alignment and centering is needed. The determination of the optimal corrector strengths was done for 4 main equally spaced energies. All other energies were obtained through interpolation. Downstream the PSS, in the straight line, the correctors could be kept energy independent with strengths below 0.6 mrad. The optimal corrector strengths through the HEBT were determined through beam based alignment methods.

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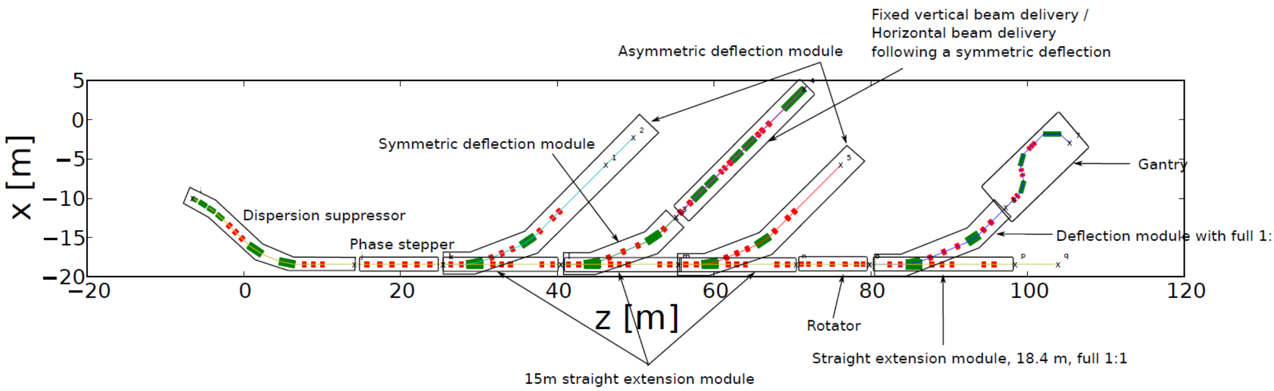

Figure 2: HEBT layout.

In the deflection module towards IR3, the steering was done based on diagnostic monitors placed directly at the iso-center. Due to the dispersion-closing design of the deflection module, the last dipoles cannot be used for steering. The achieved number of protons in the treatment room for different energies is shown in Table 1.

Table 1: Number of Protons in IR3 for Different Energies

Energy [MeV]	Number of protons
62.4	1.2e10
97.6	1.5e10
198	1.5e10
252.7	1.8e10

Beam Based Alignment

The relative measurement of the center of gravity (cog) with the diagnostic elements was repeatably proven to be significantly more reliable than the absolute position value. In order to hence minimise the limitations of absolute position determination and center the beam through the active elements, the final alignment of the beam through the HEBT was based on quadrupole strength variations. An example of such a measurement and its analysis can be seen in Fig. 3. In this example, the strength of one corrector was scanned, and for each of its strengths, two different fields of one downstream quadrupole were set in order to determine the position of minimum beam movement.In some sections of the HEBT, scans of two steering elements, while changing the strength of several quadrupoles, were performed.

DISPERSION SUPPRESSOR

The DS is the section from the start of the first, thin magnetic extraction septum up to the start of the PSS. It contains 6 independently powered quadrupoles. The purpose of this module is to close the dispersion, provide at the output the Twiss function required at the PSS and include a fast chopping mechanism.

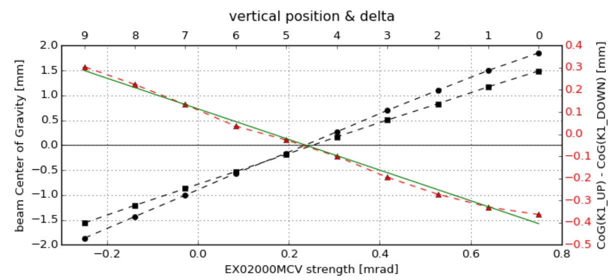

Figure 3: The black lines show the measured cog for the two different quadrupole strengths. The red line illustrates their difference, and the green line shows its linear fit. The smallest beam movement through the quadrupole is hence for a corrector strength of 0.165 mrad.

Closing the Dispersion

To close the dispersion coming from the synchrotron in the HEBT, the strengths of the first triplet were linearly scanned. The criteria for closing this ring dispersion is that the inter-spill movement on a diagnostic device in a non-dispersive region is minimised. The beam cog movement before closing the dispersion and after properly setting up the first triplet is depicted in Fig. 4. Closing the dispersion hence greatly reduced the beam movement within the spill. Additionally minimised with the chopper mechanism were at the beginning and at the end of the spills:

- the beam movement on a monitor in a dispersive region to ensure that only the central energy is extracted and no energy fluctuations are transported downstream and
- the intra-spill position, size and range variations on the monitor in the iso-center

Rematching

To adapt the beam vertical parameters to the entrance of the PSS, the second triplet needed to be rematched in order to provide the required Twiss function at the entrance of the phase stepper. To achieve this, quadrupole scans were performed. Using the transfer matrices, these allow to obtain the Twiss parameters at the quadrupole location.

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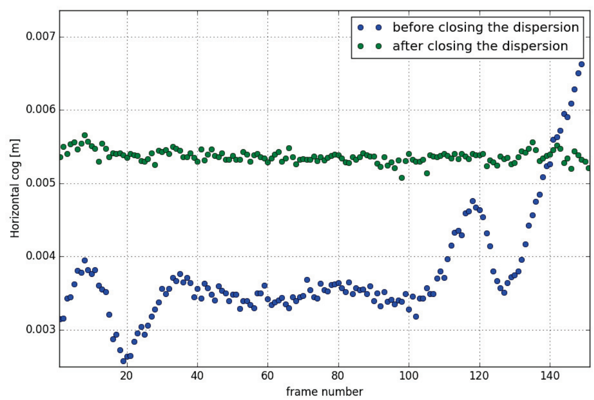

Figure 4: Cog movement during spill before (in blue) and after (in green) closing the dispersion.

PHASE SHIFTER STEPPER

After the DS, the beam traverses the PSS, which is used to control the beam size for the downstream modules. It is composed of six quadrupole magnets powered by independent power supplies to control five variables: β_x, α_x, μ_x, β_y and α_y. The beam shape coming from the extraction is a "bar of charge" in the horizontal plane with energy-independent beam emittance (and size up to the PSS), while it is Gaussian in the vertical plane with an energy dependent geometric emittance [1]. The 'phase shifter' functionality of the PSS adapts the horizontal phase advance μ_x keeping β_x at the end of the module constant while its 'shifter' function at the same time sets the needed variation of β_y [10]. Downstream the PSS telescope modules project the adjusted beam size from the end of the PSS to the iso-center in IR3. This way the beam size is adapted to the one required for patient treatment. The measured change of the horizontal spot size during a PSS phase advance scan is shown in Fig. 5.

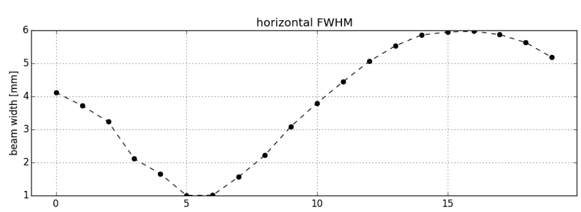

Figure 5: Change of horizontal FWHM, measured on a profile monitor downstream the PSS when changing the μ_x.

Spot Size and Symmetry

The PSS settings were set to minimize the spot size, while keeping the beam symmetric in both planes at the iso-center. They were identified for 4 main energies and interpolated for the intermediate ones. The horizontal and vertical spot sizes at the iso-center for 255 energies is shown in Fig. 6.

During the commissioning of different intensities, an intensity dependent vertical FWHM was noticed. For intensities below 20 % of the nominal intensity, the vertical emittance is a factor 3 lower. This effect was mitigated by decreasing the vertical tune at injection for lower intensities, thus obtaining symmetric beams (< 4 %) for all energies and intensities, well below the specified 10% tolerance. .

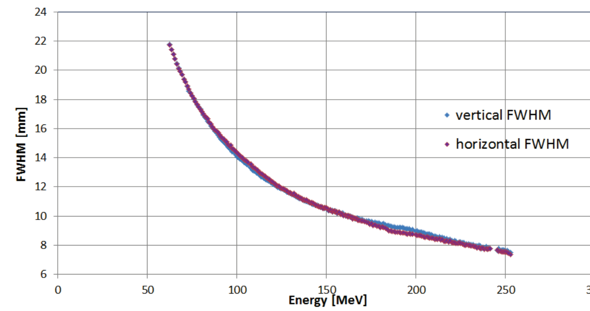

Figure 6: The horizontal and vertical FWHM for 255 energies.

CONCLUSION AND OUTLOOK

The beam was successfully centered through the HEBT based on quadrupole variation methods. The dispersion from the ring was closed and the optics rematched for the entrance to the PSS, where the quadrupole strengths were adjusted for spot size and symmetry at the iso-center. An iterative period with medical physicists allowed to fine-tune the machine settings based on the measured beam penetration depths in water and the scattered beam transverse profiles in air at the iso-center. Thus, the accelerator team provided 255 medical cycles for safe and reproducible delivery of beams for the clinical commissioning in IR3. Furthermore the machine performance and its reproducibility will be monitored through a dedicated quality assurance [11].

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