LAYOUT AND OPTICS OF THE MedAustron HIGH ENERGY BEAM TRANSFER LINE

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Abstract

The MedAustron accelerator complex, which is currently in its final design stage at CERN, is based on the optical principles developed within the Proton Ion Medical Machine Study (PIMMS) [1]. This paper describes how these principles are practically applied in the layout and optics of the High Energy Beam Transfer line (HEBT) of the MedAustron accelerator facility. Special attention is directed to the optics of the gantry which is designed to fit into the PSI gantry-2 hardware layout, which is foreseen to be copied in collaboration with PSI.

INTRODUCTION

MedAustron [2] is a particle accelerator based hadron-therapy and research center that is currently in its final design stage. While the civil engineering is advancing in Wiener Neustadt, Austria, the design and procurement of the accelerator equipment is being performed at CERN and in collaboration with PSI. For clinical treatment, protons of up to 250 MeV or C^{6+} ions up to 400 MeV/u will be extracted from the synchrotron and guided via the high energy beam transfer line (HEBT) (Figure 1) to one of the four irradiation rooms (IR). IR-1 is dedicated to non-clinical research and is shielded for 800 MeV proton operation. The IRs 1 and 3 are equipped with a horizontal beam line, IR-2 with horizontal and vertical beam lines and IR-4 with a proton gantry.

OPTICAL CONCEPT

The applied optical concept was developed in the PIMMS [1]. It implies that the HEBT is built up from distinct modules (Figure 1). The most significant feature is that beam size can be changed at the focal point in any IR by altering the strength of seven quadrupoles inside the "combined beta and phase stepper" module in the common part of the main extraction line while keeping all other magnet settings constant. The optical conditions at the end of the combined beta and phase stepper are transported by a sequence of telescopic modules to the focal point in the IR. While the principle of the combined beta and phase stepper is simple and attractive, it does potentially interfere with those closed orbit corrections that cross the module. However, providing the module itself is perfectly aligned and presented with a centered beam then the upstream and downstream corrections will not be affected by beam size changes.

DISPERSION SUPPRESSOR WITH INTEGRATED CHOPPER

The beam parameters at the exit from the synchrotron and entry to the extraction line are special in that the beam has the shape of a "bar-of-charge" in the horizontal phase space with energy independent dimensions. The description of the bar-of-charge, as a diameter of an unfilled Twiss ellipse, with help of Twiss functions is used for simplicity only. This choice is used for aperture calculations.

The first module of the main extraction line is a dispersion suppressor with an integrated chopper. In order

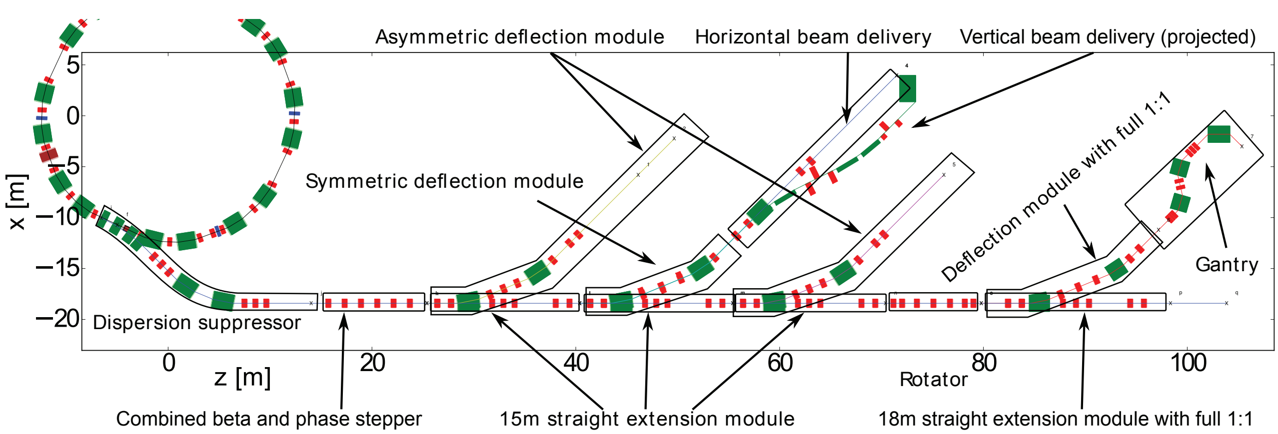

Figure 1: The layout of the MedAustron HEBT is built up from distinct functional building blocks.

to be able to rapidly turn the treatment beam on and off ($< 300\mu s$) four series-connected chopper kickers are installed. Once powered, a four-magnet bump is created and the beam passes around an intermediate beam dump (Figure 2). The features of this configuration are:

- It is failsafe.
- After passing the dump block, the closed bump returns the beam to the design orbit.
- Any kicker power converter ripple is self-compensating.
- Upstream of the beam dump, there are beam position and intensity monitors. At the start of each cycle the beam is directed onto the dump until the beam profile has stabilized [3]. Future upgrades may include instrumentation of the dump with an energy verification system [4].

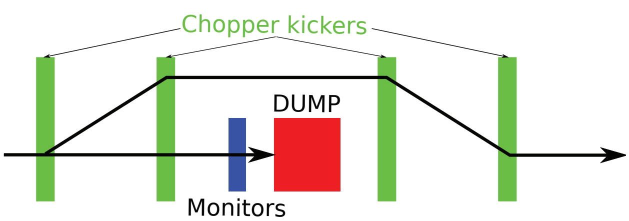

Figure 2: The 4 kicker beam chopping principle.

BETA AND PHASE STEPPER MODULE

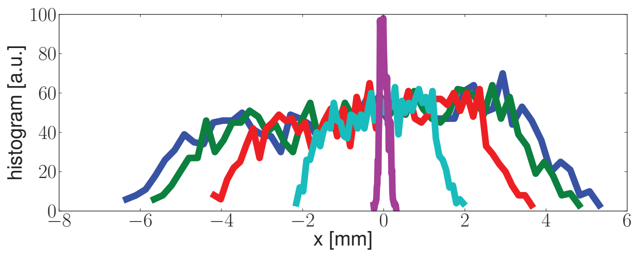

Figure 3: The projection of the horizontal phase space on the x-axis for various phase advances.

The beam size at the focal point in any IR is adjusted by the "beta and phase stepper" module in the following ways:

- The horizontal beam size is changed by adjusting the horizontal phase advance. Changing the phase advance rotates the bar-of-charge inside the Twiss ellipse leading to different sizes projected onto the x-axis (Figure 3).
- The vertical emittance of the extracted beam is subject to adiabatic damping. The beta and phase stepper can adjust the incoming vertical betatron amplitude function $\beta_y = 3m$ to both compensate this effect and to magnify the beam size to the requested value. Depending on the energy, the vertical β_y function must vary over the range $\beta_{y,in}$ = 2 - 27 m.

Beam sizes between 4 and 10 mm FWHM can be achieved at all energies at the focal points in the IRs.

TELESCOPIC MODULES

There are two kinds of telescopic modules that transfer the beam size at the exit of the beta and phase stepper to the focal point in an IR.

- "Normal" $1:1$ modules transfer $\beta_{x,in} = \beta_{x,out}$, $\alpha_{x,in} = \alpha_{x,out}$. In order to provide an identity transfer for any β_y function at the modules entrance, the vertical phase advance μ_y is an integer multiple of π. Where applicable, the dispersion bump must be closed. As an example the optics of the vertical beam line is shown in Figure 4.
- In some cases, a "True" $1:1$ telescopic module is required which implies that in addition, the horizontal phase advance μ_x must be an integer multiple of π (see rotator module in Figure 1 and O - P in Figure 5).

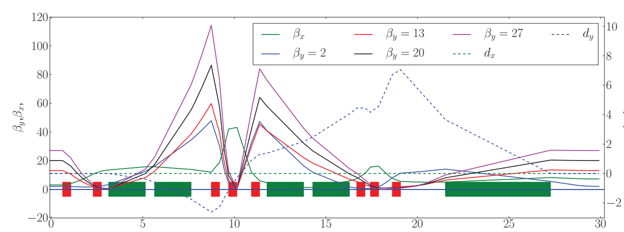

Figure 4: Beam optics of the vertical beam line as an example of a normal $1:1$ module for various operationally-used vertical β_y functions. In the horizontal plane, the Twiss functions are constant as the beam size at the IR is adjusted by the rotation of the bar-of-charge in the horizontal phase space.

PROTON GANTRY AND ROTATOR

The gantry in IR-4 is designed for protons with energies of up to 250 MeV. A collaboration with PSI has been established to jointly build the PSI gantry-2 hardware design. As the gantry was designed for a cyclotron, the optics has been adapted to fit the requirements of the MedAustron synchrotron and HEBT.

The rotator module in the main extraction line (N - O in Figure 5) is used to match the Twiss functions (including the dispersion function) into the gantry independent of the gantry angle, while keeping all the magnet settings constant. The rotator is a "True" $1:1$ module consisting of 7 quadrupoles that are physically rotated by half the gantry rotation angle. The current baseline is to rotate each quadrupole in its own individual support (Figure 6). In order for the concept to work, the bending module from the rotator exit to the gantry entry point, must also be a True $1:1$ module.

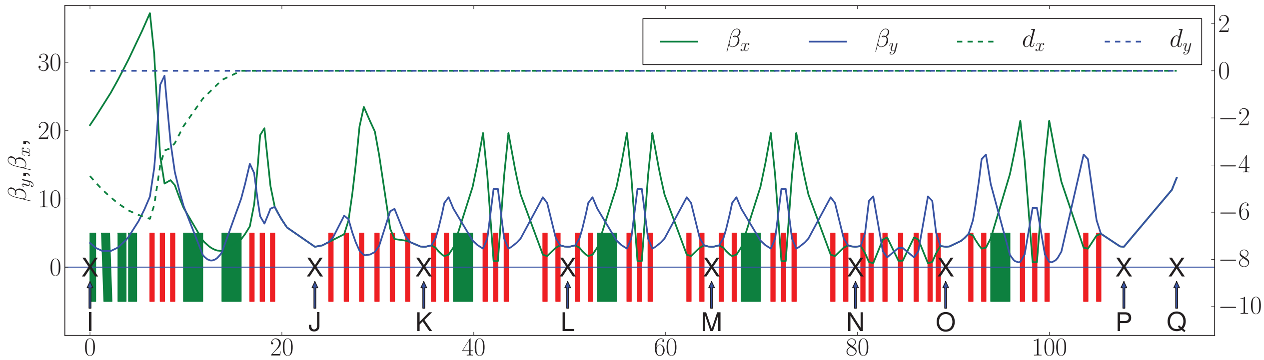

Figure 5: The optics of the main extraction line is built up from a dispersion suppressor (I - J), a beta and phase stepper (J - K) and a number of telescopic modules. The configuration of $\beta_y = 3$ at the exit of the beta and phase stepper is shown.

Figure 6: Schematic view of the rotator mechanics.

While the description using the Twiss functions is still applicable in the unrotated case, the σ-matrix formalism must be used to study the beam sizes in the rotated case (Figure 7). Considering the many operational constraints and configurations (incoming vertical beam size and rotation angle), the module is surprisingly well behaved. The effect of rotational errors on this concept was studied and found to be negligible.

The rotating gantry vacuum system is connected to the rest of the HEBT by a windowless rotating interface in order to avoid beam blow up due to scattering. Following the PSI design, the final large aperture dipole will not have a separate vacuum chamber, but the yoke itself will be used for this purpose.

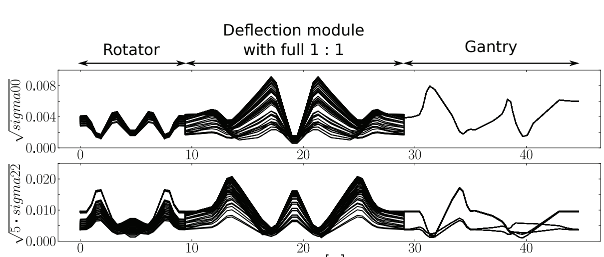

Figure 7: The beam size in the section from the rotator to the focal point for various gantry angles. (beam sizes are described by the σ matrix formalism)

ACTIVE SCANNING

Active scanning is applied to scan the pencil beam over the target area (20 x 20 cm^2 in IR-1 to IR-3, 12 x 20 cm^2 in the gantry). In order to produce quasi-parallel scanning, the scanning magnets are placed more than 7 m upstream of the focal point in horizontal lines. In the vertical beam line and the gantry, the scanning magnets are located upstream of the final bending dipole. While this requires large aperture dipoles, it does allow the scanning magnets to be placed 90° phase advance upstream from the focal point, making the scanning parallel. As the horizontal scanning offset in the final gantry dipole would give rise to a non-negligible change of the beam size at the focal point, a corrector quadrupole is installed and connected in series to the horizontal scanning magnet.

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