THE MEDAUSTRON PROTON GANTRY

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Abstract

The MedAustron project realizes a synchrotron based accelerator facility in Austria for cancer treatment with protons and carbon ions, currently in the construction phase. In order to allow full patient treatment flexibility, one of the four treatment rooms will be equipped with a proton gantry. While its hardware design is a copy of the PSI Gantry 2, different constraints on the beam optics must be accounted for as MedAustron uses a synchrotron as particle accelerator and a rotator to match the beam optics into the rotated coordinate system, as compared to the cyclotron of the PSI PROSCAN facility.

This paper presents the current status of the hardware design and procurement and a review of the design characteristics of the PSI Gantry 2 for the MedAustron case. In particular the stability of the beam parameters during beam scanning over the treatment scan area is investigated in detail. To achieve utmost parallel active scanning performance, the magnet design parameters (edge angles, corrector quadrupole, tapered dipole) have been optimized for PSI Gantry 2. Equivalent studies are undertaken for the MedAustron requirements and constraints in this paper.

INTRODUCTION

MedAustron has decided to use the state-of-the-art PSI gantry 2 design under license of PSI for its own purposes. In the following we review briefly the design characteristics of the PSI Gantry 2 and then analyze the performance of the system for the *MedAustron* case.

PSI GANTRY 2 DESIGN CHARACTERISTICS

The PSI proton Gantry 2 [1, 2, 3] has been designed with several attractive features in mind: It is compact in size, allows comfortable patient and equipment access and offers parallel scanned beams over an treatment area of 20×12 cm. PSI Gantry 2 has an iso-centric design. The rotation is one-sided and limited to the angular range between $-30\,^\circ$and $+\,180\,^\circ$. This allows fixed permanent floors and walls in vicinity of the iso-center.

The beam line has a length of 15.6 m (see Fig. 1) and is composed of two quadrupole doublets, one triplet, two $58\,^\circ$ and one $90\,^\circ$ dipole. The scanning dipoles are located just before the last $90\,^\circ$ bending magnet. The two $58\,^\circ$ dipoles use edge angles of $e_1 = e_2 = 10.78\,^\circ$ which helps to achieve the optical performance. Two sextupoles that can be parasitically used as orbit correctors, a vertical corrector and a special correction quadrupole powered

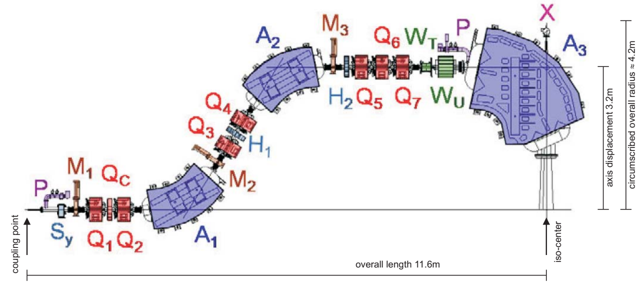

Figure 1: Beamline (magnet) layout of the PSI Gantry 2.
A. . . Dipoles, Q. . . Quadrupoles, W. . . Scanning dipoles, H. . . Combined orbit corrector & sextupole, S. . . Orbit corrector, M. . . Beam diagnostics, P. . . Vacuum ports

in series with the horizontal scanning magnet complete the beam line. The quadrupoles have a round aperture with a radius of $r = 3.8$ cm, while the dipoles have a rectangular aperture $a/b_{58^\circ} = 4.5/2.65$ cm and $a/b_{90^\circ} = 13.0/7.4$ cm. This design offers the following properties:

- Parallel scanning in both transverse directions
- 1:1 size imaging from coupling point to iso-center
- Achromaticity
- Focal invariance during double transverse scanning

In terms of beam optics the PSI Gantry 2 is characterized by (see Fig. 2),

$$\begin{aligned} \beta_{x,\text{in}} = \beta_{x,\text{out}} = \beta_{y,\text{in}} = \beta_{y,\text{out}} = 0.3\,\text{m} \\ \alpha_x = \alpha_y = D_x = D_y = D'_x = D'_y = 0 \\ \mu_x = 3\cdot\pi, \mu_y = 2\cdot\pi. \end{aligned} \quad (1)$$

The measured performance of the PSI Gantry 2 system matches well the design values [3].

At PSI the proton beam is generated from a superconducting cyclotron, the energy is adjusted via a degrader and the beam subsequently collimated in order to achieve the desired and equal beam parameters and sizes at all energies. A single beam size $\sigma_x = \sigma_y = \pm 3$ mm is available. The particle distributions in both transverse phase spaces at the coupling point are chosen to be identical, thus requiring no special coordinate system transformation (round beam method [4]).

MedAustron LAYOUT & REQUIREMENTS

MedAustron [5, 6] uses a synchrotron to accelerate the proton and carbon ion beams to the desired energy. The *MedAustron* Gantry will – like at PSI – be limited to protons in the range $60 - 250$ MeV.

Due to the resonant extraction process the particle distribution and transverse beam phase spaces extracted from the

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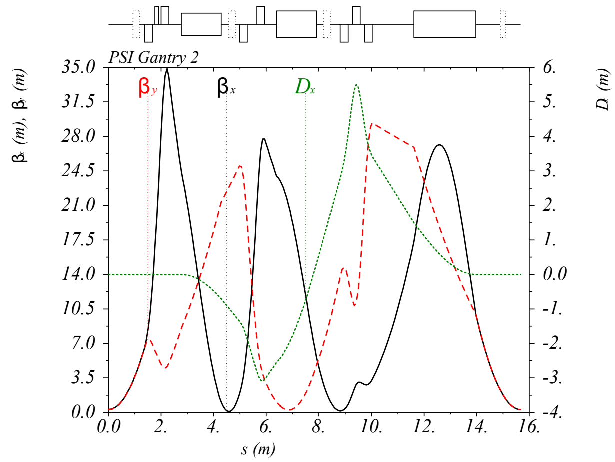

Figure 2: PSI Gantry 2 beam optics characteristics ($\beta_{x,\mathrm{in|out}} = \beta_{y,\mathrm{in|out}} = 0.3\,\mathrm{m}$).

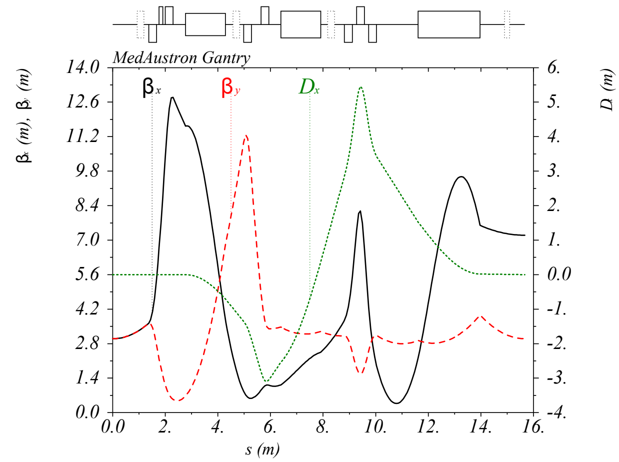

Figure 3: *MedAustron* Gantry nominal beam optics characteristics ($\beta_y = 3\,\mathrm{m}$).

synchrotron are unequal – Gaussian in the vertical, trapezoidal in the horizontal plane ("bar of charge") [4]. At *MedAustron*, several different beam sizes at the iso-center ranging from $4-10\,\mathrm{mm}$ can be chosen. This is adjusted via a phase stepper and betatron matching module in the common part of the main extraction line [7]. In the horizontal plane the module allows rotating the bar of charge in the horizontal phase space, while keeping the β_x function the same. In the vertical plane the vertical beta function is altered.

After the phase-stepper module, the beam is transported to the individual irradiation rooms via 1:1 optical modules. Compared to other synchrotron-based facilities, *MedAustron* will not apply gantry-angle dependent settings in the Gantry, but make use of the rotator concept [4]. A set of 7 quadrupoles upstream of the Gantry is rotated by half the gantry angle. This allows to match the transfer line optics to the rotated Gantry eigensystem. In between this module and the Gantry a full 1:1 module is used.

The same mechanical layout of the Gantry will be used at *MedAustron* as well as the conceptual magnet design. The PSI beam diagnostic is replaced by the *MedAustron* standard HEBT diagnostic, scintillating fiber hodoscopes. Compared to PSI, the gantry room has been designed slightly more spacious, allowing for simplified access and installation & maintenance concept.

Due to the maximal $1\,\mathrm{Hz}$ cycle repetition rate of the *MedAustron* synchrotron, the beam energy can only be changed at a much lower rate as compared to PSI, where it can be altered within $\approx 80\,\mathrm{ms}$ via the degrader. Accordingly PSI Gantry magnets have been designed for a higher dB/dt rate. Where appropriate *MedAustron* may decide to relax the corresponding magnet parameters in order to simplify the design.

BEAM OPTICS

Given the *MedAustron* requirements described in the previous section, the following beam optics constraints apply for the *MedAustron* Gantry: The phase advance μ_x in the horizontal plane has no constraints. The dispersion D_x and its derivative D'_x must be matched to zero in the bending plane. β_x has to be amplified, as it has been calculated [4] that the FWHM of the "bar of charge" is reduced and needs compensation. A $1:1.55$ magnification in beam size via the horizontal β_x is done.

The vertical beam profile is Gaussian, the beam size is controlled by adjusting the β_y $(2-27\,\mathrm{m})$ function in the phase-stepper module. On the Gantry the vertical β_y function must be matched to reproduce the same value at entry and exit including an integer multiple of $\mu_y = n\cdot\pi$ for the phase advance. This is needed in order to feature this telescope module functionality for *any* incoming $\beta_{y,\mathrm{in}}$ to the exit.

Figure 3 shows the matched optics for the *MedAustron* Gantry given the optical parameters and constraints summarized as (2):

$$\begin{aligned}\beta_{x,\mathrm{in}} = 3\,\mathrm{m},\, \beta_{x,\mathrm{out}} = 2.4\cdot 3 = 7.2\,\mathrm{m}\\ \beta_{y,\mathrm{in}} = \beta_{y,\mathrm{out}} = 2-27\,\mathrm{m}\\ \alpha_x = \alpha_y = D_x = D'_x = 0\\ \mu_y = n\cdot\pi\end{aligned} \qquad (2)$$

BEAM OPTICS DURING ACTIVE SCANNING

The horizontal and vertical scanning dipoles are located upstream of the last bending dipole. While this implies a large aperture 90 degree dipole, it features the advantage of parallel beam scanning. Due to the large beam offset at the exit, the exit edge angle of the dipole defines the position of the horizontal and vertical scanning magnets (Fig. 4), while

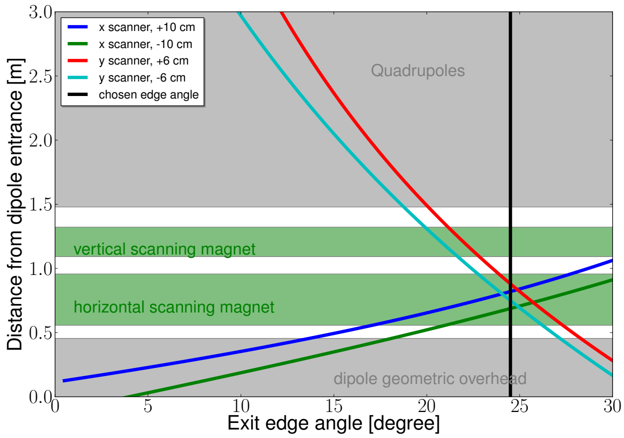

Figure 4: Distance from the optimal scanning magnet position (focal point) to the 90° dipole entrance as a function of 90° dipole exit edge angle, obtained by back-tracking of parallel beams at two extremities of the scan area (-10/-6 and +10/+6 cm).

the entrance edge angle can be neglected in this considerations to first order. By tracing parallel beams from the iso-centric plane backwards through the last bend, the focal points, which ideally coincide with the scanning magnet positions, can be found. In fact, fixing the exit edge angle uniquely determines these locations. In practice the available space constrains the possible choice. The PSI design choice is a common focal point in the horizontal scanning magnet.

The entrance edge angle is used to help adjusting the beta functions while matching the optics at the iso-center. The PSI Gantry 2 optics has been optimized using values of $e_1 = 12.2\,°$ and $e_2 = 24.4\,°$. The same principles are applicable for *MedAustron*, hence these values will be used unaltered.

While the beam is scanned in x, the phase advances μ_x/μ_y and the dispersion D_x change, but the order of magnitude is negligible in practice. However, a significant change can be seen for the β_x/β_y functions, these can vary up to 8% from the desired value. This change corresponds to a tilt of the focal plane at the iso-center. In order to counter-act this effect in the horizontal plane, the horizontal scanning magnet is equipped with tapered poles. In the vertical plane a correction is needed as well, however it cannot be done passively like the tapering of the poles, but has to be done actively by powering a corrector quadrupole synchronously with the horizontal scanning magnet. For the *MedAustron* optics the same principle applies, only the strength of the corrector quadrupole has to be adjusted to the *MedAustron* optics.

STATUS & CONCLUSIONS

The design of PSI Gantry 2 has been studied with respect to feasibility of realization, performance and maintainability for the *MedAustron* implementation. It was found, that the hardware design of the PSI Gantry 2 is suitable for the synchrotron-generated proton beam at *MedAustron* without modifications. Related minor adaptations of the mechanical layout are envisaged and mechanical engineering work is under way. The magnet system will be a direct re-implementation of the PSI system, yet a detailed magnet design check still has to be done. The vacuum system is foreseen to be unaltered except for the vacuum pumps. In particular the special vacuum chamber of the 90° dipole has proven to provide stable vacuum conditions over the past years at PSI. Therefore no changes are envisaged.

Beam optics simulations up to second order using MAD-X have confirmed that active parallel scanning can be achieved over the full scanning area which is in accordance with the experience at PSI. Important is the proper design of the tapered scanning magnet, the quadrupole corrector and the 90° dipole edge angles. All this has been optimized for the PSI Gantry 2 and the present study has not revealed essential deviations from these.

Careful mechanical design of the rotator will ensure that the beam quality is not diminished for rotated Gantry positions. A more detailed engineering design of the rotator is presently conducted.

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