A SYNCHROTRON BASED PARTICLE THERAPY ACCELERATOR

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Abstract

Danfysik and Siemens have entered a cooperation which covers the exclusive turn-key delivery of accelerator systems by Danfysik to Siemens Particle Therapy*. The accelerators will consist of an injector, a compact and simple synchrotron and a choice of fixed-angle horizontal, vertical and semi-vertical beamlines together with gantry systems. The optimized lattice of the synchrotron, including the design of injection and extraction systems, provides large transverse phase space acceptance with minimum magnet apertures. The beam can be accelerated to the maximum magnetic rigidity of 6.6 Tm in less than 1 s and slowly extracted during up to 10 s. The intensity for protons and carbon ions will be well beyond the needs of scanning beam applications. The design and performance specifications of the accelerator system, in particular the synchrotron, will be described.

INTRODUCTION

The present accelerator system follows the lines of modern light-ion therapy accelerators like HIT (the Heidelberg ion beam therapy centre) built by GSI [1] in having an LEBT with a number of ion sources, RFQ and LINAC acceleration into a synchrotron and a HEBT system. The main parameters appear from Table 1.

Table 1: Main parameters of the PT facility

Proton energy range	50-250 MeV/u
Carbon energy range	85-430 MeV/u
Ramping time	< 1 s
Extraction time	< 10 s
Max. number of protons extracted	$2{\cdot}10^{10}$
Max. number of C ions extracted	$1{\cdot}10^{9}$
Intensity variation	0.001-1
Ion species	p, He, C, O
Ion source energy	8 keV/u
Injection energy into synchrotron	7 MeV/u
Beam width (FWHM) at iso-center	4-10 mm in vacuum
Transverse field for scanning	$200{\times}200$ mm^2

In the present contribution, we will review some aspects of the present design in particular the synchrotron.

Descriptions of the accelerator system at an earlier stage can be found in [2].

As the present design will be used in all accelerator systems within future Siemens Particle Therapy projects, already during the design phase considerations have been given to aspects of series production, easy maintenance and reliability. In addition, the number of different components has been minimised by use of the same components in various parts of the machine.

LEBT, RFQ, LINAC AND MEBT

The injection system will consist of 1: two ECR ion sources, 2: a Low Energy Beam Transport, 3: an RFQ accelerating the beam from 8 keV/u to 400 keV/u, 4: an IH LINAC accelerating the beam to 7 MeV/u, and 5: a Medium Energy Beam Transport. The design of these systems has followed closely that of the HIT facility with minor modifications.

SYNCHROTRON

The lattice functions in one of the 6 identical periods of the synchrotron are shown in fig. 1 and the main parameters of the synchrotron appear from table 2.

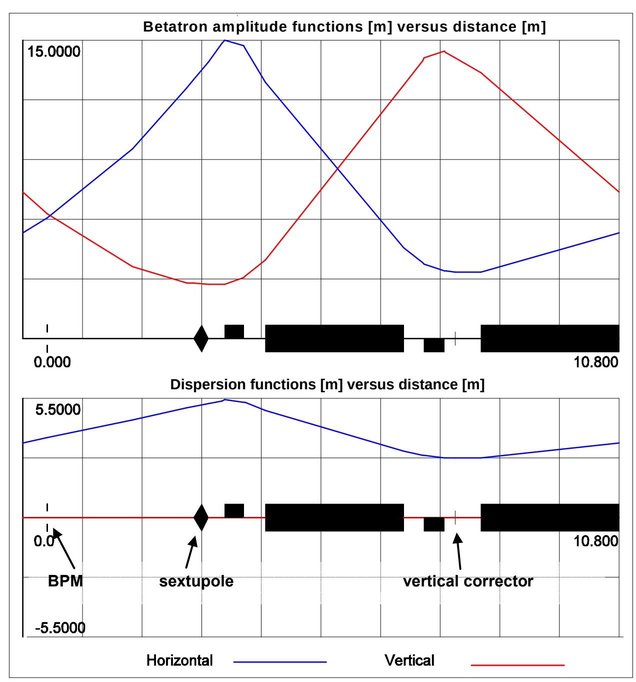

Figure 1: Lattice functions in one period of the synchrotron. In addition to the dipoles and quadrupoles, the position of the beam position monitor (BPM), the sextupole and the vertical corrector is shown.

* Siemens Particle Therapy products and solutions are works in progress and require country-specific regulatory approval prior to clinical use.

Injection

The beam is multi-turn injected into the synchrotron using a thin electrostatic septum and an injection bump collapsing during some 20 μs. Simulations show that effectively more than 10 turns can be injected. The electrostatic injection septum deflecting the beam by 7.5° is made of two inclined straight sectors each consisting of sheets of 0.1 mm thin molybdenum foil. The voltage on the electrode is 112 kV. The magnetic field of the three fast ramped bumper magnets generating the injection bump is produced by a ferrite yoke in vacuum, excited by an un-cooled coil. Considering the relatively modest vacuum requirements, this solution is preferred to bumpers consisting of an external yoke around a ceramic chamber.

Table 2: Lattice parameters of synchrotron

Property	**Units**	**Value**
Circumference	m	64.8
Vacuum chamber aperture h×v	mm×mm	150×55
Transverse acceptance h×v	π mm·mrad	165×55
Betatron tunes		~1.7/1.8
Natural chromaticity		-0.17/-0.86
Transition energy		1.7
Quadrupole strengths	T/m	5.6/3.6

Magnets

The synchrotron will be operated with the usual magnet ramps consisting of accelerating sections and flat bottoms and tops.

Strict tolerances of the magnetic fields, both during the flat parts and the accelerating sections are required inside the aperture for the circulating beam. Particular attention is paid to control the magnetic field at the extraction flat-top due to the long extraction times starting immediately after reaching the extraction energy. Control of the field at the larger betatron amplitudes used during injection and extraction is also necessary.

During the design of the magnets the weights of the magnets have also been minimized. The main parameters of the magnets are given in table 3 below.

Table 3: Parameters of magnetic elements

Property	**30° dipole**	**Quadrupole**	**Sextupole**
Maximum magnetic field	1.43T	6 T/m	8.5 T/m^2
Magnetic length	2500mm	348mm	260mm
Yoke aperture	160x65mm^2	Ø130mm	Ø150mm
Magnet weight	8t	0.6t	0.1t

Magnet Power Supplies

The 12 main dipoles are excited in pairs by 6 Magnet Power Supplies (MPS). The two families of 6 quadrupoles each are each excited by one MPS each, whereas individual MPS are used for the 6 sextupoles and the 6 correctors. The MPS are designed for small tracking errors (< 10 ppm).

Closed Orbit Correction

With the required alignment and magnet tolerances closed-orbit errors of up to 6 and 11 mm are predicted in the horizontal and vertical planes, respectively. These errors can be corrected to around 1 mm with the 6 main dipole power supplies and the 6 vertical corrector magnets.

RF

The synchrotron RF System consists of a ferrite loaded RF cavity, a solid-state RF power amplifier, and the associated low-level RF control system.

Two key parameters for the RF Cavity are the operating frequency range of 1-7 MHz and the maximum acceleration voltage of 2.5 kV.

Two ferrite sub-assemblies each consisting of 12 ferrite rings (FX8C12) are excited by bias windings. The accelerating voltage is provided to the beam over a ceramic gap.

The theoretical time-dependent functions for frequency and amplitude of the accelerating voltage are provided in digital form by the Accelerator Control System (ACS) to the Device Control Unit (DCU). The generation of the analog RF signals occurs in the DDS (Direct Digital Synthesizer) and the DAC. From the DDS and DAC, reference signals are fed into two control loops, which control the RF power amplifier and the Ferrite Bias Supply, which in turn feed the RF Cavity.

The solid-state power amplifier is a commercial unit built with separate power modules for redundancy.

Extraction ystem

Ions can be extracted for 1-10 s from the synchrotron using a third-order resonance extraction. The extracted particles are first deflected 6 mrad by a thin, 0.1 mm, straight foil septum similar to the injection septum, but with one straight sector only. In the following straight section the extracted beam particles clear the thickness of two thick magnetic septa deflecting the beam by 4.1° + 7.7°, which is sufficient to get clear from the downstream synchrotron magnets.

VACUUM SYSTEM

The requirements to the vacuum system differ for the various parts of the accelerator system. The lowest average pressure is required in the synchrotron, where the beam has to circulate for up to 30 s. Hence a pressure below 10^{-9} mbar is required here. In the LEBT and MEBT, a pressure around 10^{-8} mbar will be sufficient,

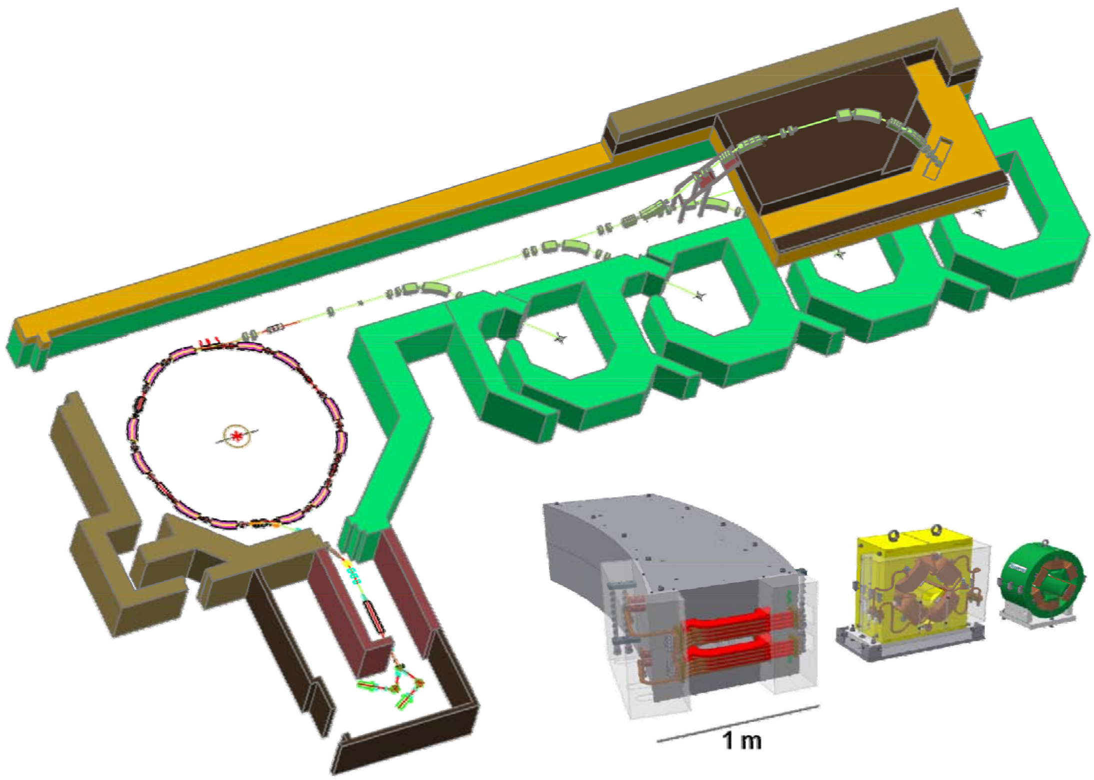

Figure 2: Layout of PT facility with three horizontal and one semi-vertical beamlines. The three main magnets in the synchrotron are shown in the foreground with an enlarged scale.

and in the HEBT a very moderate pressure of 10^{-6} mbar will be sufficient.

The vacuum system will be built according to normal UHV practice, and the synchrotron vacuum system will be baked ex-situ before installation. The vacuum system has been designed to ensure high reliability and requires limited maintenance due to the choice of components. In addition, the system has been designed for quick repair following a vacuum failure to allow continued operation of the accelerator facility within 10 hours after localization of the failure.

HEBT

Transport of the high-energy particles extracted from the synchrotron to the treatment rooms is made with a number of beamlines. The ion-optical layout allows for a beam size (FWHM) at the iso-center between 4 and 10mm with the last quadrupole doublet, and in addition the dispersion will vanish at this location. In practice, the beam will be widened somewhat by the unavoidable multiple-scattering in the dose monitors and vacuum windows.

In addition to the above requirements, the optics is designed to minimize the aperture of the magnets.

Steering of the beam through the beamlines will be performed with a number of steering magnets and downstream beam position and profile detectors (Multi Wire Proportional Chambers). A semi-automatic system will measure the beam position displacement for varying quadrupole currents, and subsequent correction of the beam to the quadrupole centers will be performed. Finally, the beamline will steer the beam to the nominal angle and position at the iso-centers.

A high degree of modularity goes into the design of the facility, in particular the HEBT. The 45° bends in the HEBT beamlines are made of a 15° and a 30° dipole magnet, similar to those of the synchrotron. Likewise, the quadrupole profiles used in the HEBT will also be used in the MEBT and LEBT.

CONCLUSIONS

We have described an accelerator system for particle therapy designed for serial production, emphasizing here aspects of the synchrotron.

Manufacture of the first system is in progress.

ACKNOWLEDGEMENT

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REFERENCES

[1] H. Eickhoff et al., Proc. EPAC 2004, p. 290.
[2] S.P. Møller et al., Proc. EPAC 2006, p. 2302 and 2305.

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