A NOVEL PROTON AND LIGHT ION SYNCHROTRON FOR PARTICLE THERAPY

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Abstract

A compact synchrotron for a cancer Particle Therapy* system has been designed and is presently under construction. A lattice with six regular super-periods, consisting of two dipole and two quadrupole magnets each, is used. The optimized lattice configuration, including the design of the injection and extraction systems, provides large transverse phase space acceptance with minimum magnet apertures. The result is a synchrotron for PT with light magnets, low values of peak power for pulsed operation and minimum dc power consumption. In addition, industrial production principles are used, keeping ease of construction, installation, and operation in mind. The beam, injected at 7 MeV/amu, can be accelerated to the maximum magnetic rigidity of 6.6 Tm in less than 1 s. A beam of 50-250 MeV protons and 85-430 MeV/u carbon ions can be slowly extracted during up to 10s. The intensity for protons and carbon ions will be well beyond the needs of scanning beam applications. The design and performance specifications of the synchrotron will be described in detail.

INTRODUCTION

Cancer therapy with protons and light ions has developed considerably during the last years, and the technique holds great promises in the fight against cancer. Several facilities have already been built or are under construction world-wide. The field has now matured to the extent that such facilities cannot only be built by large research accelerator laboratories but are now also offered by industry.

In the present contribution, we will describe the results of the efforts to design a relatively small synchrotron to form the major accelerator of the SIEMENS/DANFYSIK Particle Therapy system [1]. In addition to a description of the lattice, the operation of the synchrotron will be described together with some details of the hardware components.

The basis of the present design has been the design of the HICAT facility being built at the Universitätsklinikum in Heidelberg by GSI [2] and the experience obtained at the cancer therapy facility at GSI [3].

The accelerator facility will consist of two ion sources, a LEBT, an RFQ, a DT-LINAC, a MEBT, a synchrotron, and a modular system of beamlines [1].

*Particle Therapy is a work in progress and requires country-specific regulatory approval prior to clinical use.

THE SYNCHROTRON

General Layout

The lattice is a FODO lattice with 6-fold symmetry as shown in Fig. 1. Each super-period will contain a long straight section, a sextupole, a horizontally focusing quadrupole, a dipole magnet, a vertically focusing quadrupole, a vertical corrector magnet, a second dipole magnet, and a beam position monitor.

The long straight sections will contain, starting from the six o'clock location:

SS1: magnetic inflector magnet, electrostatic injection septum magnet
SS2; 1'st injection bumper, RF cavity
SS3: electrostatic extraction septum, diagnostics
SS4: two magnetic extraction septa
SS5: 2'nd injection bumper magnet
SS6: 3'rd injection bumper, Schottky diagnostics

Table 1: Parameters of synchrotron

Property	**Units**	**Lowest rigidity (7 MeV p)**	**Highest rigidity (430 MeV/u C^{6+})**
Magnetic rigidity	Tm	0.38	6.62
Dipole magnetic field	T	0.08	1.39
Circumference	m	64.8	
Revolution frequency	s^{-1}	0.56	3.37
Injected hor. beam emittance (multi-turn)	π mm·mrad	80	
Injected ver. beam emittance	π mm·mrad	8	
Maximum number extracted particles per cycle		$2 \cdot 10^{10}$ protons $1 \cdot 10^{9}$ C ions	

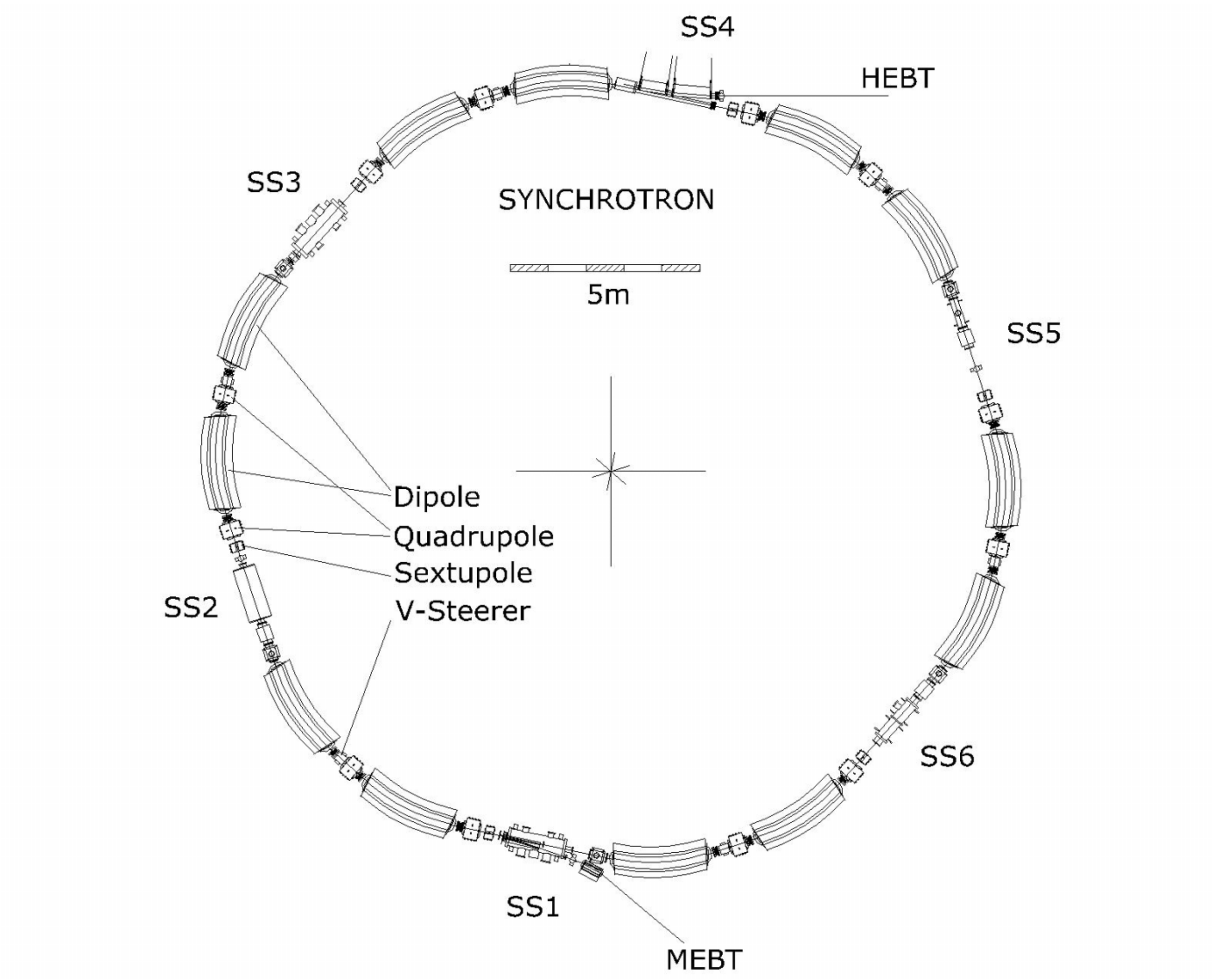

Figure 1: Detailed layout of the synchrotron with most major elements drawn.

Injection

A multi-turn injection of the beam from the LINAC will be performed at 7 MeV/u. The beam will enter the synchrotron through a 20.5° inflector magnet and a thin 7.5° wire septum. The synchrotron closed orbit is bumped into the electrostatic septum with the three bumper magnets and during the multi-turn injection, the bump is collapsed. The distance of the septum to the synchrotron axis will be 55 mm, and a voltage of 76 kV will produce the required field strength.

Simulations show that more than 10 turns can be accommodated within the aperture.

Magnets

The apertures and magnetic fields of the magnetic elements have been optimised to the required specifications, and the actual design has incorporated ease of production. The parameters for the main elements appear from Table 2.

For the dipoles, a simple design with a flat race-track coil has been chosen. The same magnet and profile is proposed for the HEBT [1]. Also the quadrupoles design for the HEBT will be re-used in the MEBT.

Table 2: Parameters of magnetic elements

Property	Dipole	Quadrupole	Sextupole
Magnetic field	1.43T	6 T/m	8.5 T/m^2
Magnetic length	2500mm	348mm	260mm
Aperture	160x65mm^2	Ø130mm	Ø130mm
Magnet weight	8t	0.6t	0.1t

For the magnet power supplies, individual supplies will be used for all elements apart from the two families of quadrupoles. For the main dipoles, each pair of nearby dipole magnets will be powered by its own supply. This will allow the main dipoles to be used as horizontal steerer magnets.

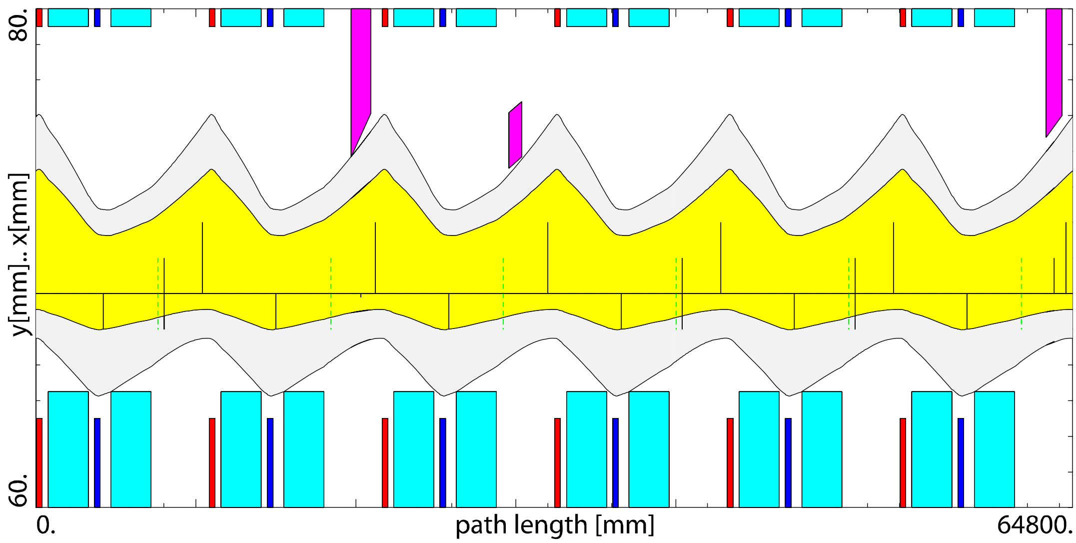

Figure 2: Beam envelopes of the injected beam (in yellow) and the acceptances (in grey) in the synchrotron. For details, see the text.

Synchrotron lattice

The beam envelopes for the injected horizontal and vertical emittances of 80 and 8 π mm·mrad, respectively, are shown in fig. 2. In addition, the horizontal and vertical acceptances of 166 and 56 π mm·mrad, respectively, are shown. The vertical acceptance is determined by the pole gap in the dipole magnets, whereas the horizontal acceptance is determined by the electrostatic extraction septum, the magnetic extraction septum and the electrostatic injection septum; these three elements are represented as the three purple bars in fig. 2. The rather smooth FODO structure is apparent. The main parameters of the lattice are given in Table 3.

Extraction

Slow extraction of the beam with a good duty cycle is one of the essential aspects of a synchrotron facility for particle therapy. The present system will be able to extract beams with a spill length of up to 10s.

Table 3: Lattice parameters of synchrotron

Property	**Units**	**Value**
Vacuum chamber aperture ×v	mm×mm	150×55
Transverse acceptance h×v	π mm·mrad	166×56
Max. amplitude function h×v	m×m	14×15.5
Min. amplitude function h×v	m×m	3.5×3.0
Max./min. dispersion function	m/m	5.2/2.6
Betatron tunes		~1.7/1.8
Natural chromaticity		-0.17/-0.86
Transition energy		1.7
Quadrupole strengths	T/m	5.6/3.6

The extraction will be performed using a third-order resonance extraction. A group of 6 sextupoles set up a stable separatrix. It will be possible, almost independently, to set (and adjust) 1) the Hardt condition (extraction angle independent of momentum error), 2) size of separatrix and spiral step, and 3) angular orientation of the extraction angle with respect to the angle of the electrostatic extraction septum.

The actual extraction is performed with a thin (0.1 mm) electrostatic extraction septum, which deflects the beam across the thickness of the two magnetic extraction septa in the proceeding straight section.

A radial step of around 6 mm is obtained leading to minimal losses on the septum.

CONCLUSIONS

- An optimised synchrotron has been designed for particle therapy.
- The third-order resonant extraction has been optimised for independent extraction parameters.
- The magnets have been designed for optimal production and operating costs.

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