STATUS OF THE PARTICLE THERAPY ACCELERATOR SYSTEMS BUILT BY DANFYSIK A/S

S.P. Møller, T. Andersen, F. Bødker, A. Baurichter, M. Budde, P.A. Elkjaer, C.E. Hansen, N. Hauge, T. Holst, M. Jensen, L. Kruse, S. Madsen, and M. Schmidt, Danfysik A/S, Jyllinge, Denmark
K. Blasche and B. Franczak, BTE Heidelberg, Ingenieurbüro, Schriesheim, Germany

Abstract

Danfysik and Siemens have entered a cooperation to market and build Particle Therapy* systems for cancer therapy. Two accelerator systems are presently under construction. The accelerators consist of a LINAC injector and a compact synchrotron. The beams can be slowly extracted over a period of up to 10s and delivered to treatment rooms through a choice of fixed-angle horizontal and semi-vertical beamlines. The intensity for protons and carbon ions is sufficient for the needs of scanning beam applications. The detailed layout of a particular system with three horizontal beamlines and one semi-vertical (45º) beamline will be presented, together with some of the components and their performance.

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

Table 1: Main parameters of the PT facility

Proton energy range	50-250 MeV/u
Carbon energy range	85-430 MeV/u
Ramping time	< 1s
Extraction time	< 10s
Max. number of p/C extracted	$2\cdot10^{10}/1\cdot10^{9}$
Intensity variation	0.001-1
Ion species	p, He, C, O
Transverse field for scanning	200×200 mm^2

As the present design will be used in several future accelerator systems, already during the design phase considerations have been given to aspects of series production, power consumption and easy maintenance. Also the number of different components has been minimised by use of the same components in various parts of the machine.

Finally, small apertures are used still providing large transverse acceptances. In addition, the multi-turn injection and resonance extraction have been redesigned to reduce beam losses.

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

LEBT, RFQ, LINAC AND MEBT

The injection system into the synchrotron consists 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 and improvements.

A test beamline, including one ion source and the associated LEBT has been built and is presently being operated at Danfysik. The same LEBT also provides the ion beams for the tuning of the RFQ accelerator.

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.

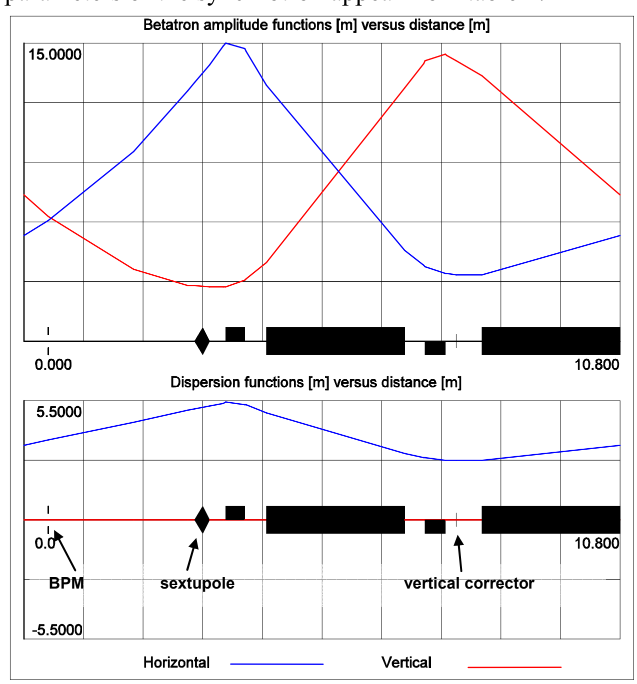

Figure 1: Lattice functions in one period of the synchrotron.

Injection

The beam is multi-turn injected into the synchrotron using a thin electrostatic septum and an injection bump with three bumper magnets. The bumpers are of a novel design with window-frame ferrite magnets in vacuum.

This design with three overlapping turns, as seen in figure 2, provides a good homogeneity. Each magnet has an impedance of 7.5 µH. A simple tailored bumper supply has been built creating an exponentially decaying current with adjustable parameters: amplitude, decay time and zero crossing. Simulations show that with this exponential decay over ~20 µs, effectively more than 10 turns can be injected.

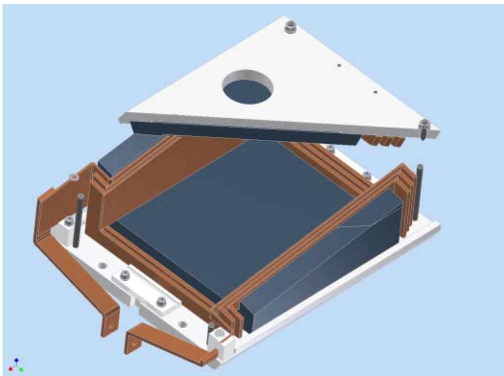

Figure 2: Cut through the bumper magnet indicating the three-turn coil and the ferrite.

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.

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
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. The acceleration time will be less than 1 s.

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

Strict tolerances of the magnetic fields are required inside the aperture for the circulating beam. The specifications call for a field integral homogeneity of less than $\pm 2.5 \cdot 10^{-4}$ within the good field area of 100 x 55 mm at low excitations and 70 x 40 mm at higher excitations, where the beam size is reduced. All the synchrotron dipole magnets are built within this requirement, as exemplified in figure 3. The measured relative field integral strength is for all 12 synchrotron dipole magnets within $\pm 3.5 \cdot 10^{-4}$.

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, whereas individual MPS are used for the 6 sextupoles and the 6 correctors. The MPS are designed for small tracking errors (< 10 ppm).

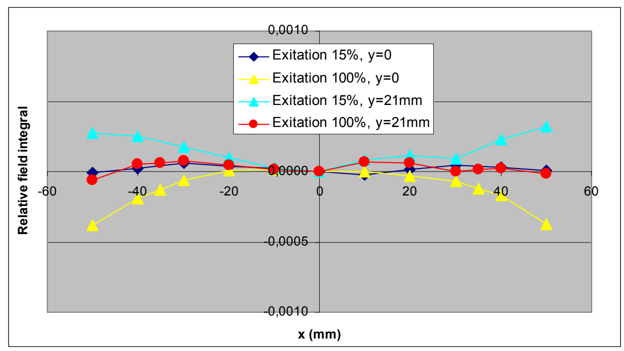

Figure 3: Relative field integral for one main dipole.

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 for Synchrotron

The synchrotron RF system is designed for an operating frequency of 1-7 MHz and a maximum acceleration voltage of 2.5 kV.

The RF system consists of a ferrite loaded RF cavity, a solid-state RF power amplifier, and the associated low-level RF control system. Two ferrite sub-assemblies each consisting of 12 ferrite rings are excited by bias windings and cooled with forced air flow avoiding the complication of water-cooled discs. The total length of the cavity is 1.4 m.

Two control/feedback loops control the RF power amplifier and the ferrite bias supply. The system has recently been tested at full power, providing a bandwidth in excess of 1 kHz for the tuning loop.

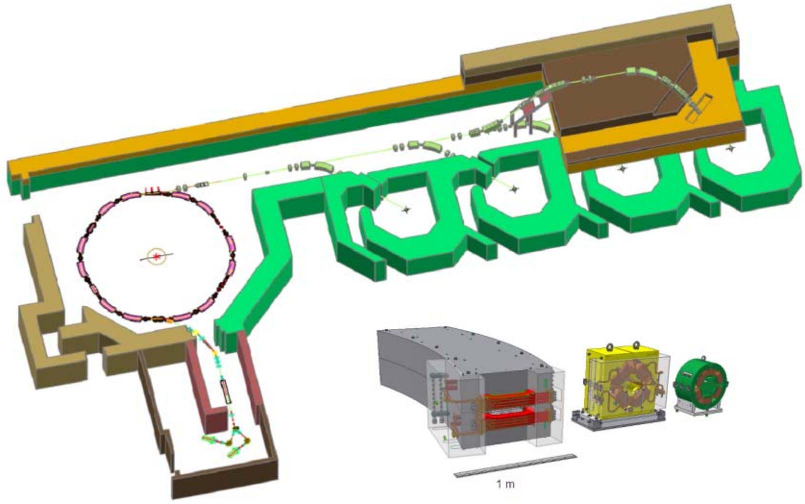

Figure 4: Layout of PT facility. The main synchrotron magnets are shown in the foreground with an enlarged scale.

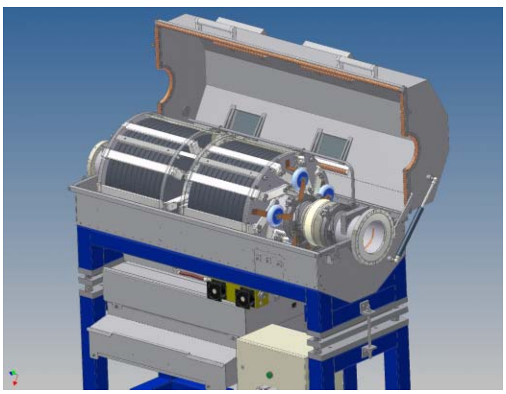

Figure 5: The RF cavity with the ceramic gap at the front.

Extraction System

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 $5\cdot10^{-9}$ mbar is required here. In the LEBT and MEBT, a pressure around 10^{-8} mbar is sufficient, and in the HEBT a very moderate pressure of 10^{-6} mbar suffice.

The vacuum system is built according to normal UHV practice, and the synchrotron vacuum system is baked ex-situ before installation. The vacuum system has been designed for quick repair following a vacuum failure with an evacuation time of less than 10 hours.

A new design has been made of the thin-walled vacuum chamber in the synchrotron dipoles. It has a thickness of 1 mm and ribs are point-welded onto the chamber to counteract the forced from the ambient pressure.

HEBT

The high-energy particles extracted from the synchrotron are transported to the treatment rooms with a number of beamlines. The ion-optical layout allows by use of the last quadrupole doublet to change the beam size at the iso-center between 4 and 10mm not including any multiple scattering in vacuum windows, detectors and air. In addition, by design the dispersion vanishes at this location. In addition to the above requirements, the optics is designed to minimize the aperture of the magnets.

Steering of the beam through the beamlines is performed with a number of steering magnets and downstream beam position and profile detectors (Multi Wire Proportional Counters). 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 is also used in the MEBT and LEBT.

CONCLUSIONS

We have described an accelerator system being built for cancer particle therapy.

Two systems are being manufactured, the first to be installed starting august 2008.

REFERENCES

[1] H. Eickhoff et al., Proc. EPAC 2004, p. 290, and D. Ondreka, this conference.

[2] S.P. Møller et al., Proc. PAC 2007, p. 2714.