TECHNICAL OVERVIEW OF THE SIEMENS PARTICLE THERAPY* ACCELERATOR

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Abstract

Siemens has developed an accelerator system for particle therapy. It consists of an injector (7 MeV/u protons and light ions) and a compact synchrotron able to accelerate proton beams up to 250 MeV and carbon ions up to 430 MeV/u. These beams are extracted slowly from the synchrotron and delivered to a number of beam ports. The first accelerator system has been built and commissioned up to the first two beam outlets. An overview of the achieved performance of the system is presented.

INTRODUCTION

The Siemens particle-therapy accelerator system follows the lines of modern light-ion therapy accelerators like HIT (Heidelberg ion beam therapy center) built by GSI [1] or CNAO [2], designed for providing mainly proton and carbon ion beams with a penetration depth of about 30 cm in water-equivalent tissue. The system is comprised of an injector, where ions from one of two ion sources are pre-accelerated by a linear accelerator (LINAC), a synchrotron and a high-energy beam-transport (HEBT) system to deliver the beam to the various beam ports in the treatment rooms. Additional details on the design and layout of the accelerator system and the commissioning status at earlier stages can be found in [3-5].

BEAM PARAMETERS

The commissioning of the system up to the first two treatment rooms has been completed. The key design parameters have been reached (see Table 1). Particle therapy with a 3D scanning requires a large amount of beams ready for delivery upon a request. These beams are distinguished by ion species, energies, beam sizes at the iso-center, intensities and delivery channels (see Table 2). During the commissioning, the configuration data for more than 70000 beam combinations is established that can be loaded and executed on demand. To setup this variety of the beams, interpolation algorithms based on an accelerator machine model have been used. A special attention was put to have stable and robust settings so that small operational deviations of individual devices would not lead to significant effects.

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

Table 1: Main parameters of the PT facility

Parameter	Value
Proton energy range	48-221 MeV/u
Carbon energy range	88-430 MeV/u
Ramping time	< 1s
Extraction time	8 s
Max. number of p/C extracted	$2\cdot10^{10}/1\cdot10^{9}$
Intensity variation	0.01-1
Ion species	p, C^{6+}
Transverse field for scanning	200×200 mm²

Table 2: Number of ion beam combinations as presently commissioned

Parameter	Protons	Carbon ions
Energies	290	291
Beam sizes	4	5
No of intensity levels	12	15
Treatment rooms	2	2

SOURCES AND LEBT

The low-energy beam-transport system (LEBT) allows for the selection of beams from one of two ECR ion sources and delivers and matches the beam to the linear accelerator. An additional improvement of the output stability of the ECR sources was reached by exchanging the originally used thermal gas inlet valves with mass-flow controlled valves. The beam from the sources is momentum analyzed to select the required ion species (H_3^+ or C^{4+} for clinical use). Subsequently the beam from the source to be used is selected by means of a switching magnet.

The LEBT is also responsible for the variation of beam intensities. It has been set-up to achieve maximum transmission for the highest intensity. For standard operation, roughly 160 μA C^{4+} and 600 μA H_3^+ within the emittance of 180 π mm mrad are reproducibly delivered. If smaller intensities are requested, the settings of the quadrupole triplet after the analyzing magnet are changed and the emittance is cut at aperture screens. Figure 1 shows the number of extracted carbon ions for different intensity levels. For protons, the figure is similar, whereas the higher intensities within the tolerance band were preferred.

Though this method of intensity variation changes the emittance in the injector, no effect on the optics of the extracted beam in the HEBT was observed. The reason for that is the filamentation process of the beam in the LINAC, so that almost the complete LINAC acceptance is filled.

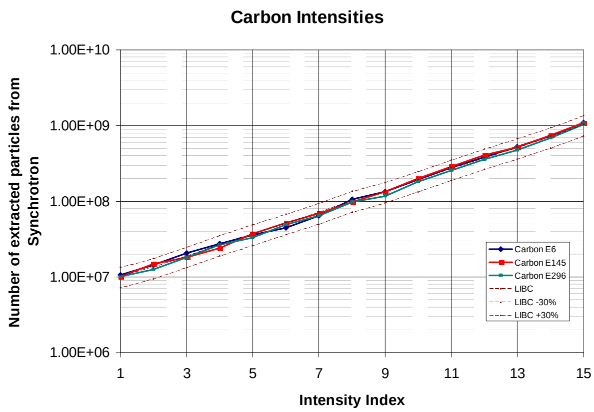

Figure 1: Number of extracted carbon ions per spill for different intensities.

LINAC

The linear accelerator consists of a radio frequency quadrupole (RFQ) and an IH-mode drift-tube LINAC (DTL). The RFQ accelerates the particles to 400 keV/u whereas the injection energy into the synchrotron of about 7 MeV/u is achieved by the DTL. After the LINAC, the beam is stripped by a thin carbon foil and guided by the medium energy beam transport (MEBT) to the synchrotron.

Currently, the LINAC is operating with a typical transmission of about 33%, whereas the majority of the losses are caused by the RFQ. The latest RFQ tests on an improved RFQ show that overall LINAC transmissions of larger than 50% are achievable.

SYNCHROTRON

The synchrotron has a modified design (described in more detail in [3] and [4]) as compared to the HIT facility, featuring an optics of 6-fold symmetry. Six straight sections host the injection and extraction septa, the accelerating RF-cavity, bumper magnets for the multi-turn injection and beam diagnostics. Extraction of the beam proceeds using a slow extraction scheme at a third order resonance.

The commissioning of the synchrotron has been finished. Presently about 9 effective turns for carbon ions and 7 turns for protons are accelerated over the full energy range. Figure 1 shows a typical operating cycle for synchrotron currents from MEBT injection through extraction.

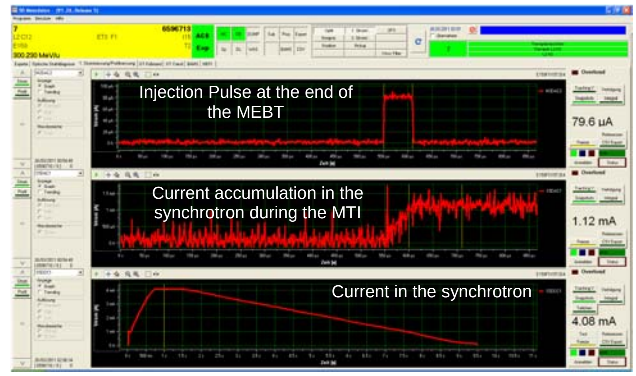

Figure 2: Standard synchrotron cycle for carbon ions of an energy of about 300 MeV/u.

In order to keep the same optics in the HEBT, the chromaticity was adjusted to -1 over the entire energy range and the average beam position in the synchrotron was set to be constant. Additionally, the horizontal emittancies of low energy beams were defined by cutting them at the resonance band. The combined extraction efficiencies yield about 75% for carbon ions and about 50 – 75% in case of protons. To get the same intensities over the complete energy range, the injection pulse for protons has been shortened for larger energies. This is sufficient to achieve the maximum requested beam intensities.

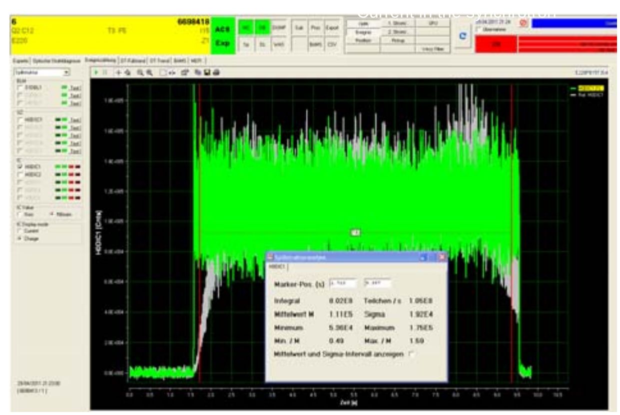

Figure 3: Spill shape for carbon beam with (green) and without (grey) feed back.

The ramping time of the synchrotron even to the highest carbon energy of 430 MeV/u is shorter than 1 s. However, the overall irradiation time depends also on other effects. They include the decay of the Eddy-currents to a negligible level in order to keep the energy of the extracted beam constant, duration of the synchrotron chimney (for reproducible hysteresis) and communication time of the control system.

The intensity of the extracted beam has been set to reach its maximum within a few 100 ms and is slowly reduced during the last second of the spill. The macroscopic shape of the spill can be made more rectangular with a feed back loop using the measurements from the Beam Application and Monitoring System (BAMS). On a microscopic level with a timing resolution of 1 ms the variations of the intensity do not exceed factor of 3 for the ratio of maximum intensity to the average level. Figure 3 shows the intensities of the extracted beam measured by an ionization chamber (at 1 ms integration time) with and without feed back for the carbon beam of 300 MeV/u.

For beam applications using raster scanning, spill pauses requested by the Therapy Control System represent one of the essential functionalities. If a spill pause is needed, the extraction can be stopped by switching off the driving force (see fig. 4). Additionally, for carbon ions the RF frequency is reduced slightly in order to move the beam further away from the resonance. The proton beam is only partly bunched and a tune shift by an RF frequency change is not efficient. Instead, the RF amplitude is reduced to slow down the synchrotron oscillation. After release of the spill pause, the beam properties remain unchanged.

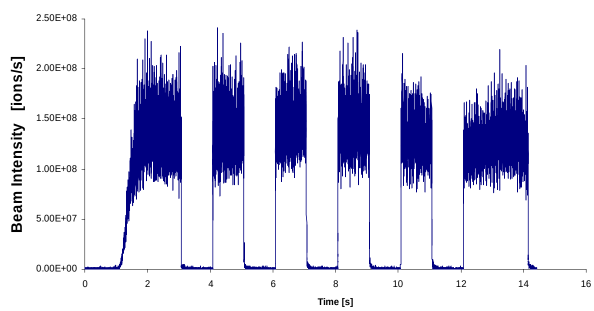

Figure 4: Five arbitrary spill pauses are applied to a carbon beam.

HEBT

The high-energy beam transport (HEBT) delivers the beam from the synchrotron to the different treatment locations. Currently, horizontal, vertical and semi-vertical, i.e. 45° vertically inclined, beam ports are installed (see [3-6]). Up to now, only horizontal beam ports have been commissioned.

In the HEBT, the optics are chosen to have dispersion and its derivative close to zero at the iso-center. The beam size is set with the last quadrupole doublet, and the beam scanning is performed with fast “scanner magnets”. To have “quasi-parallel” scanning, these scanner magnets are located in a distance of about 7 m from the isocenter.

In the HEBT, the final properties of the beam delivered to the iso-center are analyzed. This is done with internal destructive beam diagnostics during commissioning and maintenance. In the case of medical operation, the beam properties are monitored by the BAMS, which works independently from the accelerator system.

Due to scattering in the BAMS and in the air, the minimum achievable beam size at the iso-center is larger for lower energies, when the same optics is used. For patient treatment not only the smallest beam size is needed. In many cases wider beams are preferable and the beam has to be defocused. In Figure 5, the carbon beam sizes measured at the iso-center with a high-resolution viewing screen are presented for different energies and focus levels. This plot was produced by the Beam Quality Check procedure performed on a daily basis to monitor the reproducibility of the beam properties.

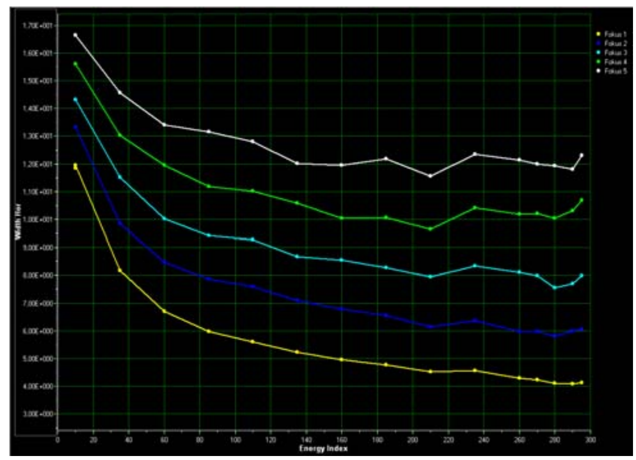

Figure 5: Measured horizontal beam sizes (FWHM) for a carbon beam of different energies at 5 focus steps.

CONCLUSION

An overview of the first accelerator system built for Siemens particle therapy has been given. The efficiencies of all steps involved in the ion beam acceleration have been described.

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