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BEAM PROPERTIES BEYOND THE THERAPEUTIC RANGE AT HIT

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Abstract

The Heidelberg ion beam therapy facility HIT has more than ten years experience in patient treatment. More than 8000 patients have been treated with protons and heavy ions, about 700 patients are treated every year.

In addition to the beam time dedicated to therapy and quality assurance (QA), we provide beam time for a large spectrum of preclinical experiments in physics, biology and medicine which make use of various ion beam settings apart from therapeutic beam settings and application.

By slow extraction the HIT synchrotron produces a wide range of spill lengths between a few ms and more than 10 s. The intensity can be varied accordingly: For FLASH-irradiation studies we provide more than $2 \cdot 10^9$ carbon ions/s, still applying the high-quality raster-scanning beam delivery method. On the other hand, we deliver very stable low intensity beams in the order of 1000 ions/s if sensitive detector equipment is mounted.

The design of the facility was made for therapeutic carbon ion beams with a maximum beam energy that corresponds to a penetration depth of ≈ 30 cm in water and tissue accordingly. Especially for developments in ion beam radiography we now commissioned beams with higher energies for the light ions available at HIT (p, He).

This paper summarizes the large variety of beam properties for the experimental activities at HIT.

INTRODUCTION

Although it is the main purpose of the HIT accelerator to provide ion beams for therapy, there is also a comprehensive preclinical experimental programme taking place in the fields of physics, biology, and medicine. In most instances those experiments make use of the range of ion beam settings which is commonly used in therapy and is also provided and maintained at the experimental area. Additionally, the HIT accelerator and its underlying flexible control system are capable of customising dedicated ion beam parameters on user request which might be completely different from the therapy settings, but without affecting the latter.

These particular abilities and flexibility of beam settings are similar to the situation at research accelerators, but quite exceptional at a medical facility.

MATERIALS AND METHODS

HIT-Accelerator for Therapy Purposes

HIT uses intensity-controlled raster scanning of pencil beams [1]. A linac-synchrotron system (Fig. 1) accelerates ions to energies up to 430 MeV/u corresponding to ion penetration depths of approx. 30 cm in tissue [2–5]. The slow extraction is performed via transverse RF-knock-out excitation [6, 7] giving spill lenghts in the order of seconds.

The facility has three treatment rooms to allow for a dense patient scheduling, one being equipped with a heavy-ion gantry [8]. The beams can be further delivered to two additional, non-therapeutic beam targets: the beam dump and the experimental room.

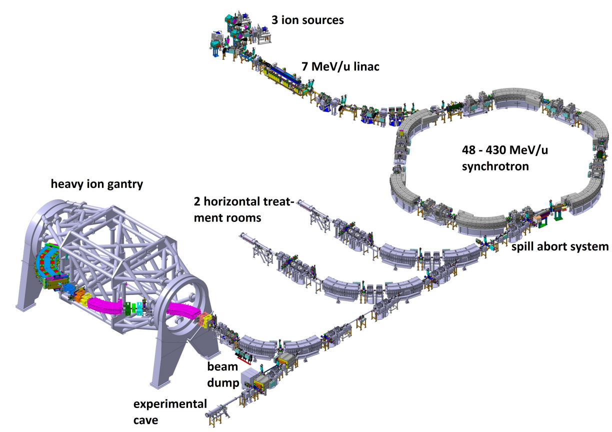

Figure 1: The HIT accelerator: three ECR ion sources, a 7 MeV/u injector LINAC, the synchrotron for carbon ions up to 430 MeV/u. Two horizontal treatment rooms, one gantry, an experimental room for R&D and the beam dump.

Experimental Room and Beam Dump

Experimental Room The equipment of the experimental room (Fig. 2) is widely identical to the one in the horizontal treatment rooms, e.g. it comprises

- the raster scanning system
- the beam application and monitoring system (BAMS)
- the in-room laser positioning system
- the same dynamic intensity control abilities (DIC).

It has even more flexibility concerning the following aspects:

- Beam parameters can be set according to the specific requirements of the experiment.
- Interlocks of the therapy control system can be masked, to allow for non therapeutic beams.
- Settings concerning the BAMS can be altered, e.g. the gas supply for the monitoring chambers.

The room has recently been equipped with a 0.25 T device for magnetic resonance imaging (MRI) and with a big bore 60 cm Helmholtz coil which has a maximum flux density of 100 mT to study MR guided ion beam therapy (Fig. 3).

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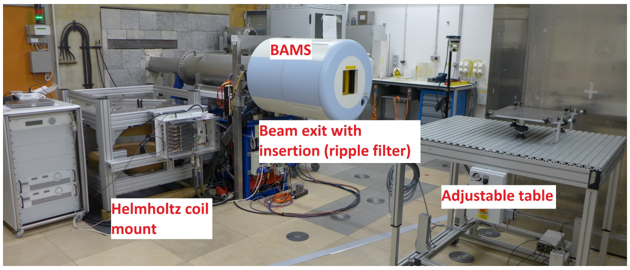

Figure 2: HIT's experimental irradiation facility.

Figure 3: MRI installation on its rail system.

Beam Dump The beam line to the beam dump is quite limited in its beam manipulation abilities and instrumentation (e. g. no beam scanning) but it is used as target for long-term experiments. The gap between the beam exit window and the beam dump can be used to mount samples, e.g. to investigate their radiation hardness. During parts of the standard accelerator quality assurance or in periods without any other beam usage, the samples accumulate dose.

RESULTS AND DISCUSSION

Ion Beams Commissioned for Therapy

From the very beginning of operation at HIT, most of the experiments have taken advantage of the same ion beams in the whole range of characteristics available for therapy.

These beam characteristics can be used for experiments without further preparation, since the beam quality is routinely checked and maintained.

Particle Rate

At HIT the 3rd order resonant RF-knockout extraction is performed. The extraction, i.e. beam-on time, can be set to arbitrary values between a few ms up to 12 s, but being typically a few seconds for therapy.

To keep the intensity on a predefined level, an intensity control system has already been implemented at HIT in 2013 [9]. For certain experiments, however, the therapeutic intensity range is not suitable.

Low Intensities One reason for low intensity requirements can be sensitive detector equipment (saturation effects or risk of damage). A low total dose is another one. Ion beam radiography [10] is an example for both.

This dynamic intensity control system works well, as long as the ionisation chambers deliver a sufficient signal ($\approx 10^5$ carbon ions/s and $\approx 10^6$ protons/s).

For lower rates the raster scanning system and the RF-knock-out extraction are operated in a feed-forward, time-triggered mode. The number of particles injected into the synchrotron is reduced. Therefore, intended particle losses are produced in the LEBT with a quadrupole-triplet and – if additionally needed – by detuning the first bending magnet behind the ion source.

For these very low intensities in the order of $\approx$ 1000 ions/s the accelerator team uses scintillators in the HEBT-line for the tuning or the intensity relies on the experimenter's equipment. A profile monitor for this low intensity range to allow for scanning is currently under development at HIT [11].

High Intensities, FLASH-irradiation The HIT-accelerator can also produce higher intensities than typically used in therapy. A recent application which is intensively discussed in the field of radio therapy are ultra high dose rates or FLASH-irradiations [12].

Higher dose rates are realised at HIT with the intensity control system, too. The achievable intensity for a set of optical parameters is limited by the maximum amplitude of the RF-knockout exciter.

For the ions with rather low rigidity (proton, helium) the dose rates are sufficient using the standard optics. For carbon and oxygen, we use special control data for FLASH-experiments. In order to extract particles more easily, the extraction tune is shifted closer to the resonance and the sextupole strength is increased.

Table 1 shows the achieved intensities for FLASH conditions for the different ions at HIT. These correspond to dose rates up to 200 Gy/s. An example for a spill prepared for FLASH-irradiations is shown in Fig. 4.

Table 1: Intensities for therapy (except oxygen) and under FLASH conditions. Each number is the result of an optimisation for a particular experiment. They do not show the technical limitation.

Ion	Therapeutic intensity (ions/s)	spill duration (ms)	FLASH-intensity (ions/s)
Protons	$3.2 \cdot 10^9$	200	$5 \cdot 10^{10}$
^{4}Helium^{2+}	$8 \cdot 10^8$	90	$3.9 \cdot 10^{10}$
^{12}Carbon^{6+}	$8 \cdot 10^7$	200	$2.1 \cdot 10^9$
^{16}Oxygen^{8+}	$4 \cdot 10^7$	180	$1.1 \cdot 10^9$

The raster scanning and the intensity control system are working well even with these very high intensity ion beams.

In order not to exceed the measurement range of the ionisation chambers in FLASH-mode, they are operated with He-CO_2 gas instead of the standard Argon-CO_2 mixture.

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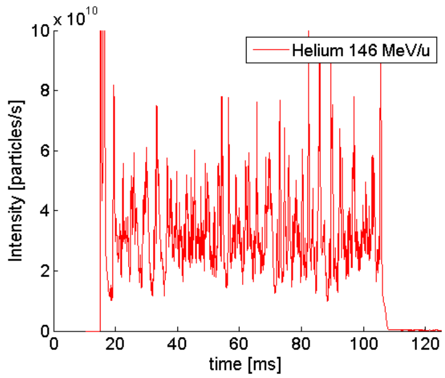

Figure 4: Helium spill prepared for FLASH-irradiations. $3.0 \cdot 10^9$ ions are extracted within 90 ms ($\approx 3.3 \cdot 10^{10}$ ions/s). Recorded with helium flushed BAMS-IC, resolution 50 µs.

This reduces the accuracy in the low intensity regime but allows for higher ion beam currents without saturation effects [13].

Timing Patterns of the Extracted Beam

The HIT accelerator can provide different beam extraction patterns with alternating beam-on / beam-off phases which range from approximately 10 s down to tens of milliseconds of beam-on time. One recent example of such a user request is the measurement of short lived beta+ emitters in positron emission tomography [14]. The beam-on-target time is used as a production phase for the desired radioisotopes, the beam-off phase is used to measure their decay. Depending on the time scale there are two different mechanisms which are used to create these timing patterns.

Beam-on / Beam-off Pattern in the Order of Seconds The beam-on time can be set to arbitrary values between a few ms up to 12 s. The extraction phase is followed by $\approx$ 3 s without beam availability at the beam target, e.g. for beam-injection and -acceleration.

If a periodical pattern is requested, including a defined minimal period between beam-on times, a delay between synchrotron cycles can be defined in a beam sequence.

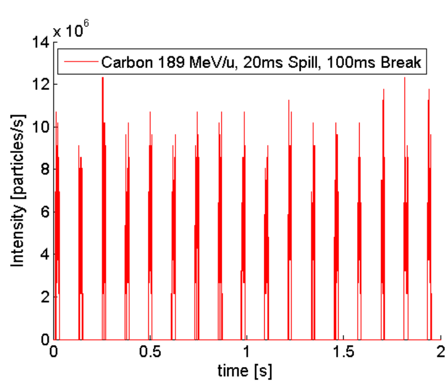

Figure 5: One spill, 20 ms beam-on, 100 ms spill-pauses.

Beam-on / Beam-off Pattern in the Order of Tens of ms By using RF-knockout, it is possible to pause and resume the beam extraction several times within one synchrotron cycle by turning off and on the RF-exciter amplitude [15]. This has intentionally been developed to interrupt the beam delivery to mitigate organ motion (via *gating*, [16]) or to move the scanned beam without delivering dose.

For beam-on times << 5 s, we make use of the this spill-pause mechanism. With the HIT control system it is possible to programme regular gates within specific front-end controllers. This signal can be fed into the central accelerator timing system as spill-pause signal, the result is a beam-on / beam-off sequences as shown in Fig. 5.

High Energies

Experiments in the field of ion beam radiography [10, 17] requested higher energies than therapeutically used. The particle energy is technically limited by the maximum magnetic rigidity of about 6.6 Tm, and the maximum RF frequency of 7 MHz usually operated at 2^{nd} harmonics (maximum revolution frequency is thus 3.5 MHz). The currently available and commissioned maximum energies at HIT, approved by the authorities, are given in Table 2. In the case of carbon, helium, and oxygen ion beams (mass-to-charge ratio close to 2) the energy is thus limited to approximately 430 MeV/u by the magnetic rigidity, while the energy limit of the proton beams of approximately 480 MeV/u is given by the maximum RF-frequency. A further increase of the energy up to $\approx$ 1.3 GeV/u is possible with modifications of the RF operational scheme and the control system's data supply.

Table 2: The therapeutic (except oxygen) energy range at HIT. The last column gives the maximum available energies restricted by regulations, and not by the accelerator itself.

Ion	therapeutic E (MeV/u)	max. available E (MeV/u)
Protons	48.12 – 221.05	480
^{4}Helium^{2+}	50.57 – 220.51	430
^{12}Carbon^{6+}	88.83 – 430.10	430.10
^{16}Oxygen^{8+}	103.77 – 430.32	430.32

CONCLUSION AND OUTLOOK

The HIT accelerator facility is not only serving a dose delivery system for therapy by its linac-synchrotron-system, but also serves as a research accelerator for basic and applied research mainly in the field of ion beam radiotherapy and related topics.

Many studies have been conducted making use of the preset therapeutic beam characteristics, but – as reviewed here – even with customised beams with beam properties beyond those default settings.

Furthermore, due to the high flexibility of the HIT medical accelerator with its different components and its underlying control system, there might be many more options in customising the beam parameters for beam time applicants.

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