SPILL STRUCTURE MEASUREMENTS AT THE HEIDELBERG ION THERAPY CENTRE

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Abstract

A specially designed accelerator facility for tumour irradiation located at the Heidelberg University Hospital was built up, the commissioning is still ongoing. Technically the Heidelberg Ion Therapy Centre (HIT) fully relies on the three dimensional intensity-controlled raster scan technique developed at GSI. This method demands for smoothly extracted ion beams (from protons to oxygen) from the HIT synchrotron. For this purpose a RF knock-out system is routinely used. To characterize the extracted beams ionization chambers are installed in the high energy transport lines and directly in front of the patient. Full spills are recorded with a resolution up to 100 μs. Typical raw data are shown as well as derived statistics like Fourier spectra and maximum-to-average ratios, which give good information about the quality of the beam and its applicability for the scanning dose delivery method. In addition, the performance of the flexible spill interrupt procedure will be demonstrated with measured data.

HIT ACCELERATOR FACILITY

The Heidelberg Ion Therapy Centre (HIT) is a dedicated hadron accelerator facility for radio-therapeutical treatment of tumour patients [1]. The advantage of using hadron beams in cancer therapy is their characteristic energy loss profile in irradiated materials. When applied to tumor tissue this leads to a DNA destructive maximum at the Bragg peak immediately before the particles come to rest, while the beam loses very little energy in the entrance channel. To reach penetration depths of 20-300 mm in water, charged particles like protons or carbon ions with energies in the range from 48 up to 430 MeV/u are required; see the following table with the implemented **L**ist of **I**on **B**eam **C**haracteristics (LIBC) at HIT:

Parameter	Steps	Protons	Carbon
Energy	255	48-221 MeV/u	88-430 MeV/u
Focus	4 [6]	8 – 20 mm	4 – 12 mm
Intensity	10 [15]	$4\cdot10^{8}$-$1\cdot10^{10}$ 1/s	$1\cdot10^{7}$-$4\cdot10^{8}$ 1/s
Places	5	5	5

The values in brackets are options, which will be realized after the linac upgrade program [2], which should lead to an intensity increase of a factor 4 for protons and 2.5 for carbon ions. In addition, helium and oxygen beams will be available at a later commissioning stage.

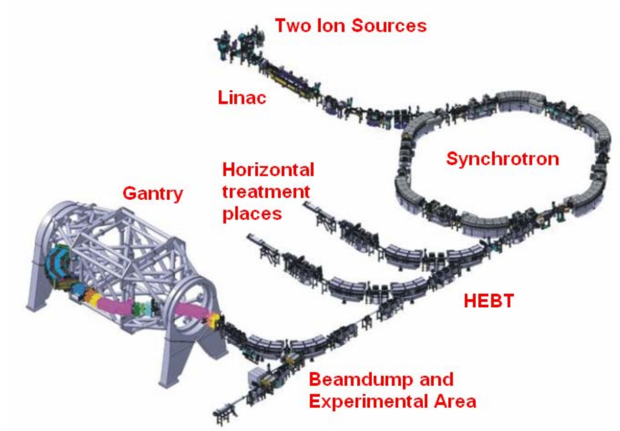

Figure 1: Isometric drawing of the HIT accelerator facility.

Presently the HIT accelerator facility (Fig. 1) is in an advanced phase of its commissioning [3]. The two horizontally fixed treatment places as well as the experimenttal area can be served with proton and carbon beams, first steps have been done for the Gantry launch. The first patient treatments are scheduled for Q4/2008.

SPILL STRUCTURE PARAMETERS

At HIT tumours will be irradiated in slice-by-slice mode (iso-energy-layers) by means of cycle-to-cycle energy variation. Within such a layer the intensity controlled raster-scan method applies a pencil beam which is moved from voxel to voxel (3D-pixel) by two fast scanner-magnets [4]. Due to this technique some accelerator characteristics have to be taken into account. For the spill structure the following intensity stability criteria should be fulfilled:

Integral number of particles per spill	Tolerance band concerning LIBC values: –50% / +30%
Spill form	symmetric plateau
Maximum/average ratio	< 3 (5 ms integration window)

In addition spill-pause and abort functionalities were implemented in the HIT control and irradiation treatment system. During raster-scan operation within a synchrotron cycle the spill-pause functionality spares healthy tissue in cases where irradiation areas are spatially separated. Secondly the spill-pause is an important tool to optimize treatment planning, and machine efficiency.

For this purpose combined functions of the RF exciter, the synchrotron RF (amplitude and frequency), a beam chicane consisting of two steerers and a fast ramped dipole (called SPAM: **Sp**ill **A**bort **M**agnet) as well as a beam scraper were implemented, see [3] for details. With this system the following requirements have to be fulfilled:

Spill abort time after error recognition	≤ 50 μs
Turn-off-time of SPAM (max. operation value down to zero)	≤ 200 μs
Max. dose during spill pause	< 10% of the last voxel dose

DETECTOR SYSTEM AND DATA ACQUISITION

To proof the specified beam parameters several ionization chambers (ICs) are used, which are built in the high energy beam transport line. The effective length of these ICs is 2 × 3.3 mm, the active area 70 × 70 mm^2, the supplied voltage 1000 V. These detectors are part of the HIT beam diagnostic devices, which were categorized into separate device classes linked to the measured beam parameter such as current, energy, beam profile, position, phase and others [5]. One of these classes is the "event counting" class. It combines all particle counting devices such as plastic scintillators, ionization chambers with I/f converters [6], and beam loss monitors, which all can be used to investigate the spill-structure beneath the standard usage for intensity, transmission and beam loss measurements. The analogue signals of the scintillators are shaped and converted by standard NIM modules. All signals are finally fed into the data acquisition system (DAQ).

The DAQ consists of a PXI front-end system running LabViewRT using four eight-channel PXI-6602 scalers from National Instruments, which are installed for the "event counting" class together with digital I/Os for control purposes. In default mode the scalers sample and deliver data of all 32 channels with 1 kSa/s. In addition, data of three selected channels may be acquired with a sample rate of 10 kSa/s using the DMA mode.

MEASURED INTENSITY STABILITY

Since February 2008, the beam performance is recorded daily through the HIT operating staff by measuring beam parameters at the synchrotron exit and at the treatment places for a representative sample of the parameter space. Fig. 2 shows an example of the intensity measurements for carbon, which demonstrates, that the –50%/+30% limits are kept excellently for the integral particle numbers per spill. No changes of significant beam parameters of the synchrotron have been observed so far. Only the settings for the ion sources and the intensity variation quadrupoles in the LEBT have to be tuned sometimes, mostly in intervals of weeks.

MACRO- AND MICROSTRUCTURE OF THE SPILL

Figure 3 (top box) displays the time structure of a 200.3 MeV/u carbon spill. Red and black curves represent particle numbers measured in 100 μs intervals and in a 5 ms binning mode. The nearly rectangular macroscopic shape is produced without feedback loop and fulfils the above listed criteria. The superb spill microstructure, see bottom box of Fig. 3, is demonstrated in a maximum over average evaluation using the 5 ms binning window – only the bad statistics at the beginning and end of the spill leads to values greater than 3 whereas most of the spill shows a value round 2. This high-quality structure is achieved by keeping the synchrotron RF voltage on during extraction, which was formerly studied in the slow extraction mode of the SIS18 synchrotron at GSI [7].

To further evaluate the spill microstructure the data is passed to a Fast Fourier Transformation (FFT) algorithm to discover interfering ripples of machine parts such as the mains or the power supplies. Fig. 4 shows 10 averaged FFTs for synchrotron cycles at 88.83 MeV (top) and 430.10 MeV (bottom). At both energies no dominant lines appear, but the harmonics of the 50 Hz mains are

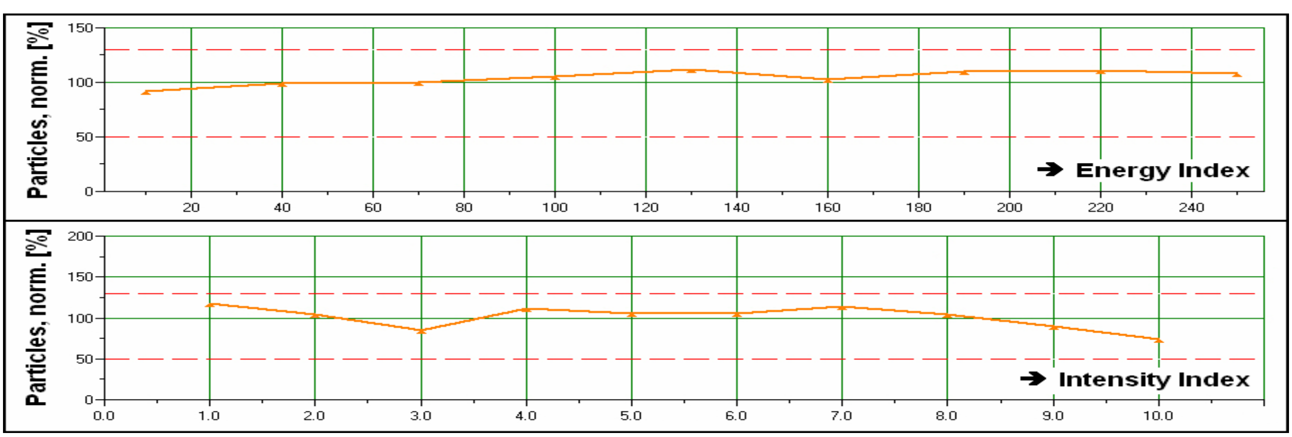

Figure 2: Example for the daily spill intensity checks at HIT; extract from the HIT logbook at 12th June 2008 for carbon measurements; upper diagram: integral spill intensity vs. energy index, lower diagram: integral spill intensity vs. intensity index, both diagrams normalised to LIBC values, the dashed red lines mark the tolerance bands.

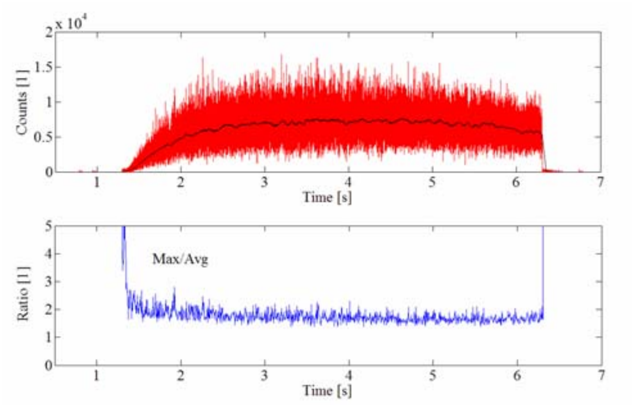

Figure 3: Measurement of a $_{12}C_{6+}$ beam at 200.3 MeV/u and $8{\cdot}10^7$ particles; top: single spill measurement; bottom: max/average evaluation of the spill.

visible and - for unknown reasons - only at the lower energy the 50 Hz itself is present. The influence of the synchrotron frequency of 2 kHz at 88.83 MeV and of 456 Hz at 430.10 MeV is clearly visible. The noticeable peaks at 165 and 262 Hz give a hint to minor ripple influence of the synchrotron equipment and are subject of further investigations.

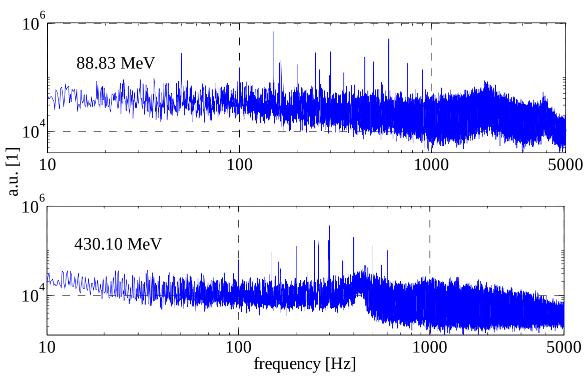

Figure 4: Averaged FFTs of 10 spills at 88.83 MeV (top) and 430.10 MeV (bottom).

SPILL PAUSE AND SPILL ABORT

Figure 5 shows a spill with an interruption of 1 s (same beam parameters as in Fig. 3), measured with an ionization chamber directly in front of the scanner system at the horizontal treatment place 2. The interruption is generated by switching off the KO exciter and manipulating the frequency of the synchrotron RF, see [3, 8] for more details. The extracted intensity directly behind the synchrotron can be reduced during the interruptions below $5{\cdot}10^{-4}$ of the nominal intensity that way. To deplete the spill pauses entirely, the SPAM (see above) in the common part of the high energy beam transport (HEBT) line has to be used. As can be seen in Fig. 5 this procedure works perfectly, the extracted particles during ramping down the SPAM only amount to about 8 % of the last 5 ms before the spill pause, which fulfills completely the requirements. Additional calibrated measurements will be done in the next weeks with the BAMS (**B**eam **A**pplication and **M**onitoring **S**ystem), which is the final part of the scanning dose delivery system provided by Siemens Medical Solutions.

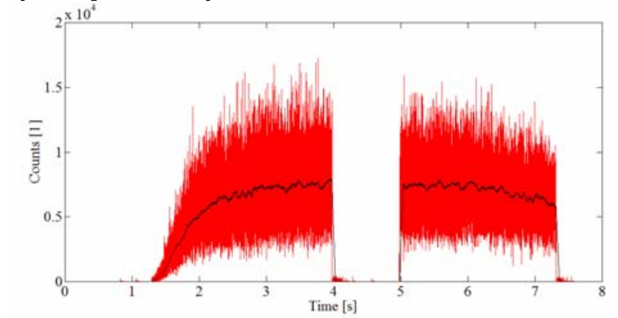

Figure 5: Measurement with spill pause.

CONCLUSION

The measured data show that all spill specifications are completely fulfilled from the accelerator side to optimally support the beam scanning system, which is still under commissioning. But there is yet some potential for further improvements of the spill, which will need additional machine tuning time in the near future.

ACKNOWLEDGEMENTS

The authors would like to thank P.Forck, D.Liakin, D.Ondreka and B.Voss (all GSI) for supplying valuable information, help on data evaluation and many fruitful discussions.

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