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SLOW EXTRACTION TECHNIQUES AT THE MARBURG ION-BEAM THERAPY CENTRE

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Abstract

The Marburg Ion-Beam Therapy Centre offers hadron therapy using proton and carbon beams. The accelerator is based on a 65-m ion synchrotron by Danfysik/Siemens Healthcare. Beam extraction from the synchrotron is driven by a transverse RF knock-out (KO) system featuring Dynamic Intensity Control (DIC) of the spill. DIC allows modulation of the extraction rate by factors up to 30 on millisecond time scales. A fast response of the system to the variable intensity set-point can be obtained by careful adjustment of the RF-KO spectrum relative to the machine tune. Tracking simulations of the extraction phase have been conducted to refine that behaviour. Presently, we investigate how fast machine tune shifts, induced by an air-core quadrupole lens, can be used as a way to further improve the spill quality.

INTRODUCTION

The Marburg Ion-Beam Therapy Centre (MIT) came into clinical operation in October 2015 [1]. Following its Heidelberg-based sister facility HIT, it is the second centre in Germany for precision hadron therapy using both proton and carbon beams [2].

The MIT accelerator was designed by Danfysik/Siemens Healthcare and consists of a compact injector followed by a light-ion synchrotron of 65 m circumference [3]. Two ECR ion sources produce precursor beams of H_3^+ and C^{4+}. The injector linac consists of an RFQ followed by an IH structure, both operating at 217 MHz. Foil-stripping after the linac yields pre-accelerated beams of protons or bare carbon ions ($^{12}C^{6+}$) that are accumulated in the synchrotron by multi-turn injection at a velocity equivalent to 7 MeV/u.

The synchrotron ramps the particle energies to maximum values of 221 MeV (for p) or 430 MeV/u (for $^{12}C^{6+}$), respectively, as required for 30 cm penetration depth in human tissue. Up to 2×10^{10} protons or 7×10^{8} $^{12}C^{6+}$ ions can be accelerated in one cycle. Depending on the particle type, energy, and number requested by the Safety and Therapy Control System (STCS), a specific synchrotron cycle is chosen automatically from a library of pre-defined accelerator settings.

After acceleration, the particles are extracted from the synchrotron via transverse RF knock-out (KO) excitation under control of the STCS (see below). The particle spill lasts from fractions of a second to a maximum of 8 s, depending on the dose requirement, before a fresh synchrotron cycle is started.

High-Energy Beam Transport (HEBT) lines guide the extracted particles to one of four treatment rooms. Three of the latter are equipped with horizontal beam outlets while, in the fourth, the beam enters the target volume at an angle of 45° from above. All beam outlets are equipped with pencil-beam scanning systems [4].

SYNCHROTRON EXTRACTION

The pencil-beam scanning method relies on active monitoring and control of the ion beam position at the beam outlet. Hence, it requires beam pulses of several seconds duration at stable intensity. During the extraction phase, the working point of the synchrotron is chosen near a 2/3 horizontal resonance. The stable horizontal phase-space is narrowed by amplification of the sextupole components, and particles are driven into resonance via horizontal RF-KO excitation.

The RF-KO exciter is equipped with a Dynamic Intensity Control (DIC) system, as first implemented at HIT [5]. DIC allows active control and variation (on millisecond time scales) of the instantaneous particle extraction rate by the STCS (cf. Fig. 1). The particle rate delivered to the treatment room is continuously measured by two ionisation chambers

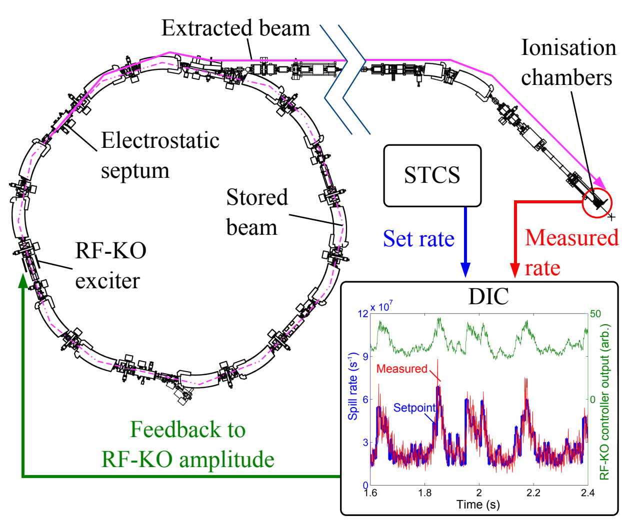

Figure 1: Working principle of the DIC: Ionisation chambers measure the instantaneous spill rate at the beam outlet. A feed-back loop continuously corrects the amplitude of the RF-KO signal such as to meet the intensity set-point of the STCS.

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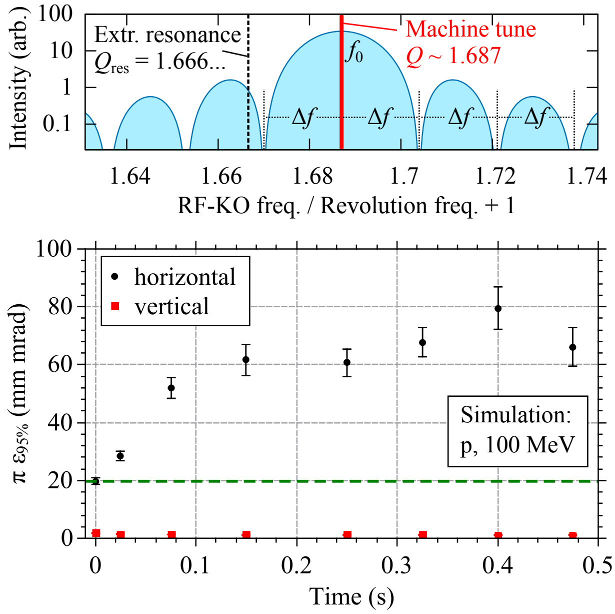

Figure 2: Results from a tracking simulation (p, 100 MeV) of the RF-KO process, optimised for highest extraction rate: The KO RF spectrum is centred on the small-amplitude tune (top). The horizontal emittance of the residual stored beam grows strongly during the extraction (bottom).

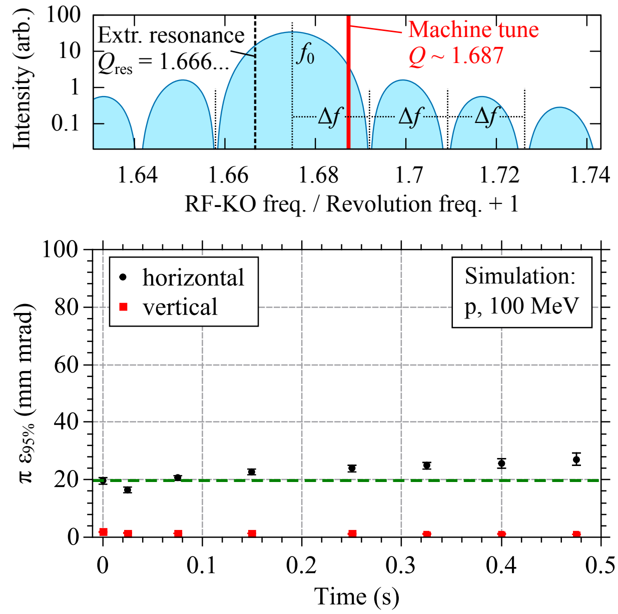

Figure 3: Results from a tracking simulation (p, 100 MeV) of the RF-KO process, optimised for DIC: The KO RF spectrum is shifted towards the extraction resonance (top). Higher RF power is required, but the horizontal emittance of the stored beam is almost unaffected by the extraction (bottom).

(ICs) at the beam outlet. A feed-back loop acts on the amplitude of the RF-KO exciter such that the intensity set-point requested by the STCS is reached.

The KO RF spectrum is generated by random 180° phase shift keying (PSK) of an oscillating electric field in a horizontal kicker electrode in the synchrotron. This yields a sinc^2-shaped noise power spectrum. Let f_0 be the mean oscillator frequency and Δf the random PSK frequency. The former defines the maximum of the sinc^2 distribution, the latter the distance between neighbouring orders of minima (cf. Figs. 2 and 3). f_0 and Δf can be chosen such that the central lobe of the KO RF power spectrum overlaps the expected distribution of horizontal betatron frequencies of the stored ions.

OPTIMAL RESPONSE TO DIC

A common technique of setting up the KO RF spectrum relative to the horizontal beam tune consists in optimising f_0 such as to obtain the highest average extraction rate at given total power of the RF. This usually results in f_0 being approximately aligned with the machine tune, as illustrated in Fig. 2 (top). In this situation, particles with small amplitudes are most strongly disturbed by the KO kicker, so that the entire beam is quickly destabilised.

However, such a setting yields suboptimal response of the extraction rate to variations of the DIC set-point within one spill (cf. Fig. 1). The intensity requested by the STCS may change on ~ ms time scales and by factors up to 30 and in both directions.

During clinical commissioning of the MIT accelerator in 2015, it was found that a much faster response of the extraction rate especially to a *falling* DIC set-point could be obtained when shifting the KO RF spectrum away from the small-amplitude tune towards the extraction resonance [1]. With this setting, particles at large horizontal amplitudes experience the greatest disturbance by the KO kicker and are quickly extracted once they leave the harmonic region of phase-space. The core of the beam is only weakly excited, which is why an overall greater RF power is necessary in order to reach the desired average spill rate.

Figures 2 and 3 show two tracking simulations, one for the case of f_0 aligned to the machine tune (Fig. 2), and one with f_0 shifted towards the extraction resonance (Fig. 3). The RF power was adjusted such that the average extraction rate was the same in both cases. Both calculations employed 10^4 protons at 100 MeV kinetic energy that were propagated over up to 10^6 turns. For the case of f_0 aligned to the machine tune (Fig. 2) one sees that the preferential excitation of small amplitudes leads to a strong blow-up of the horizontal stored beam emittance. Then, with many particles occupying the large-amplitude phase space, it is difficult for the DIC to stop the extraction, even when reducing the RF power to zero. In the case of f_0 shifted towards extraction (Fig. 3), the horizontal emittance of the stored beam is kept low as, at any given moment, only few particles occupy unstable phase-space. For the same reason, the DIC may quickly "switch off" the extraction by reduction of the RF power.

Further efforts to use particle tracking simulations as way to study and optimise RF-KO extraction are ongoing.

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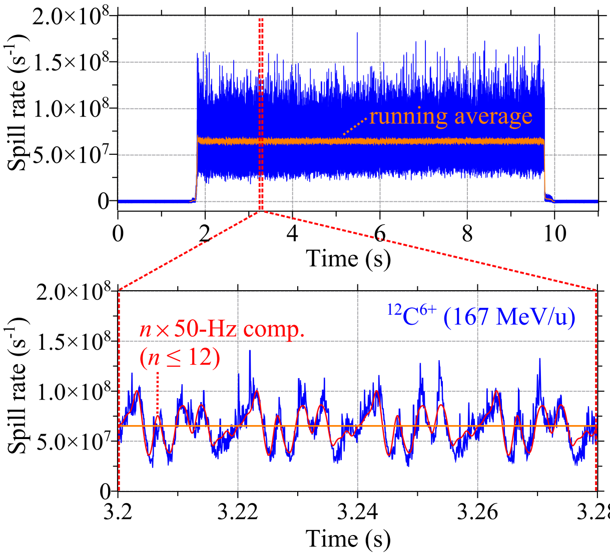

Figure 4: A spill of $^{12}C^{6+}$ delivered to a treatment room at constant average intensity (with DIC enabled), measured using the IC at the beam outlet. The approximating red curve is obtained by inverse Fourier transform of the 9 most prominent 50-Hz harmonics as shown in Fig. 5 (top).

SPILL TIME STRUCTURE

DIC stabilises the spill rate on time scales longer than a few 10 ms (cf. Fig. 4). Spikes in the extraction rate shorter than 50 µs are of minor importance as they are blurred by the time resolution of the ICs measuring the beam intensity. Disturbances in the frequency range from ~ 0.1 to ~ 10 kHz are presently not corrected for at either MIT or HIT and, if present, may lead to deterioration of the spill quality.

At MIT, significant contributions of power-grid harmonics to the spill time structure are observed at frequencies between 50 Hz and 1 kHz (cf. Fig. 4). The origin of this spill modulation is under investigation.

As a possible way to correct such machine-intrinsic ripple of the spill rate, an experimental air-core quadrupole (ACQ) magnet, compatible with the MIT and HIT synchrotrons, has been designed, following the example of previous work in this direction at CNAO [6]. In tests of the device at MIT, clear tune modulation signatures have been observed in the spill time structures at ACQ operating frequencies up to 10 kHz – limited only by the time resolution of the ICs.

Although development is at a very early stage, first experiments have shown that the ACQ can be used to partly cancel out the dominant 100-Hz component of the spill time structure, as shown in Fig. 5. Further experiments are in preparation to investigate whether the ACQ can lead to significant improvement of the spill quality by application of suitable fast corrections to the synchrotron tune.

SUMMARY

Techniques related to slow extraction of the synchrotron beam at MIT have been presented. RF-KO excitation and DIC are used to deliver beams of stable but variable intensity

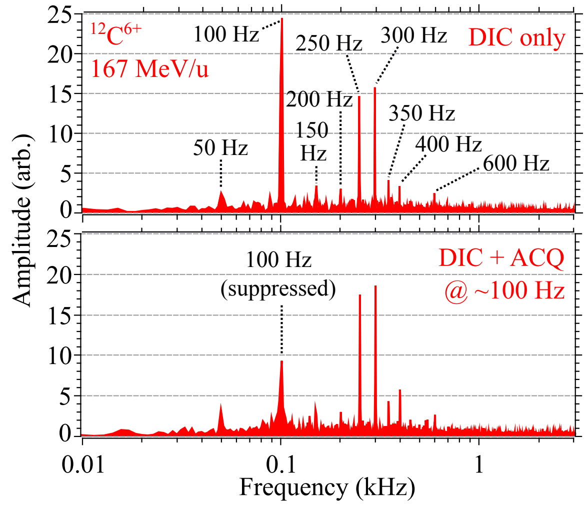

Figure 5: Discrete Fourier transforms (FFTs) of time structures of $^{12}C^{6+}$ spills. Top: FFT of the standard spill from Fig. 4, with the most important power-grid harmonics highlighted. Bottom: The otherwise same accelerator cycle, but with the ACQ magnet operating near 100 Hz such as to cancel out the machine-intrinsic modulation at that frequency.

to the therapy application. Tracking simulations can help in understanding and optimising the RF-KO technique. Experiments are ongoing to use an ACQ magnet as a potential way to further enhance the spill quality.

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