SIMULATIONS OF VARIOUS DRIVING MECHANISMS FOR THE 3RD ORDER RESONANT EXTRACTION FROM THE MedAustron MEDICAL SYNCHROTRON

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Abstract

The MedAustron medical synchrotron is based on the CERN-PIMMS design and its technical implementation by CNAO [1]. This document elaborates on studies performed on the baseline betatron-core driven extraction method and investigates the feasibility of alternative resonance driving mechanisms like RF-knockout, RF-noise and the lattice tune. Single particle tracking results are presented, explained and compared to analytical results.

INTRODUCTION

MedAustron [2] is a synchrotron based cancer hadrontherapy and research center that is currently in its final design stage. While the building construction is advancing in Wiener Neustadt, Austria, the technical work is performed at/ in collaboration with CERN. Per spill, the accelerator complex will deliver $2 \cdot 10^{10}$ protons with an energy of up to 800 MeV (for-clinical irradiation only energies up of to 250 MeV are used) or $1 \cdot 10^9$ carbon ions of up to 400 MeV.

In order to allow for the foreseen active scanning of the beam over the tumor, a very stable, low intensity spill has to be delivered by the extraction from the synchrotron. For this reason the PIMMS study [3] proposed the use of a betatron-core to accelerate the beam into a third order resonance. While this is the baseline option for spill durations of 1 - 10 s which are required for clinical application, alternative extraction methods were studied in order to be able to deliver shorter spills down to 0.1 s for non-clinical purpose and to ensure flexibility to new irradiation strategies.

SIMULATION CODE

The studies were performed using the Python-based particle tracking-code TrackIt! [4]. For these tracking studies the option to use linear transfer matrices interleaved with individual non-linear sections (sextupole) was chosen. Furthermore, the code allows to change lattice element parameters as a function of time via a generic ramp function which was not only used for the extraction driving mechanisms but also to adiabatically ramp the resonance sextupole. Code benchmarking with WinAgile [5] was performed.

STUDY OF THE VARIOUS DRIVING MECHANISMS

The single particle's tune is made up from three contributions: The lattice tune Q_L, the chromatic tune shift Q_c and the amplitude dependent detuning Q_A.

The different extraction driving mechanisms change one or a combination of these, to drive the beam into the resonance (Figure 1).

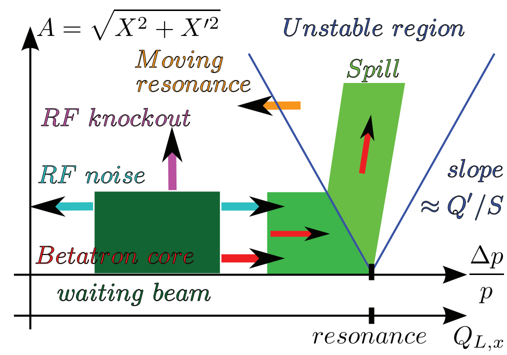

Figure 1: Steinbach diagram showing the various different driving mechanisms: a) betatron core (red), b) RF knockout (magenta), c) RF noise (cyan) and d) lattice tune adjustment (orange). The spill is indicated for case a and c.

Betatron Core

In betatron core driven extraction, induction acceleration is employed to alter the particle's tune via the chromaticity to fulfill the third order resonance condition.

The betatron core [6] itself is a closed magnetic circuit which is a highly inductive element with a large time constant in order to reduce the effect of current ripples. Additionally, RF-channeling [7] will be employed during the extraction to further decrease the impact of ripples on the extracted beam.

The beam is accelerated to an energy slightly below the targeted extraction energy and the momentum spread is intentionally blown up to $4 \cdot 10^{-3}$ identical for all energies. The extraction lattice is tuned such that on-axis particles reach the resonance tune right at the desired extraction energy (Figure 1).

Tracking studies (Figure 2) have shown that the betatron core method is able to deliver extracted beams as requested by the medical application. The horizontal extraction beam profile has a width of about 10 mm, which is in good agreement with analytic estimates. Furthermore, the Hardt condition is fulfilled, which implies that the extraction separatrices of different momenta are superimposed. Additionally, the particle distribution in the horizontal phase-space is aligned almost horizontally at the ESE.

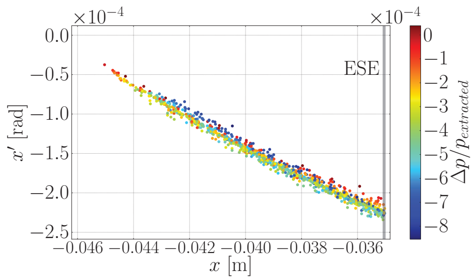

Figure 2: Phase space map (x-x') for betatron core method of extracted top energy carbon ions beam at ESE with the relative momentum deviation as color code. As expected, particles with high momentum exhibit the largest spiral step.

Particles with different amplitudes and momenta are extracted at the same time. Therefore the sensitivity to current ripples is reduced. As at the start and at the end of the extraction only selected regions of the x-$\Delta p/p$ phase space are extracted, the beam profile is subjected to changes (Figure 3). This part of the spill will thus be dumped in the HEBT [8] and not be directed onto the patient. Analytically it was found that these “losses” can be reduced by about a factor of five by using beams with a Gaussian energy distribution instead of a homogeneous one before the extraction.

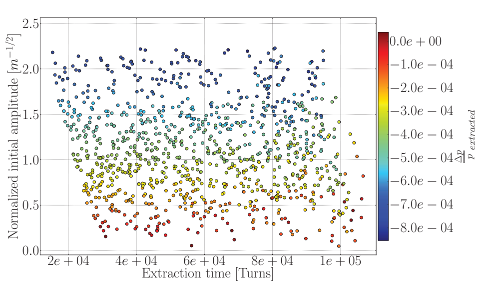

Figure 3: Correlation between initial normalized amplitude and extraction time for 400 MeV/u carbon ions with betatron core method, the extracted relative momentum deviation is color encoded

RF-knockout

Most other comparable facilities use RF-knockout extraction where a horizontal kicker is used to blow up the horizontal emittance of the stored beam (Figure 1).

In MedAustron no dedicated element is foreseen, but the horizontal Schottky monitor (SHH) will be used for this purpose. The SHH is designed to be capable to produce electric fields of up to E = 7 kV/m, corresponding to kicks of a few μrad per turn, which is sufficient to obtain spill durations below 0.1 s.

The frequency of the RF signal must be an integer multiple of the revolution frequency (a few MHz) times the fractional part of the horizontal tune to cause the desired emittance growth. Due to the non-zero tune spread in the beam (e.g. due to the non-zero chromaticity), the RF frequency has to be modulated. Furthermore, to achieve a constant extraction rate, the amplitude of the RF signal has to be increased over the spill duration [9].

As the particles momentum is maintained at a constant value during the extraction, in this case the beam has to be accelerated up to the targeted extraction energy before the extraction process. Consequently, the tune has to be adjusted via the quadrupole magnets such that before the RF excitation no particle fulfills the resonance condition.

While tracking simulations have confirmed that RF-knockout is feasible for MedAustron, several issues were identified.

- In order to extract a beam with similar properties like with the betatron core method, the relative momentum spread in the beam before extraction has to be adjusted to $\Delta p/p \approx 1.2 \cdot 10^{-3}$.
- It is not possible to reach the targeted spiral step of 10 mm. Even with twice the sextupole magnet strength (which seems to be an ideal strength for the RF-knockout extraction at MedAustron), only spiral steps less than 7 mm could be achieved.
- While a small chromaticity is favorable to minimize aperture problems with lower momentum particles in the beam, the Hardt condition cannot be fulfilled anymore.

While the beam size at the irradiation room's isocenter could still be adjusted in the High Energy Transfer Line (HEBT), this is not a convenient option as it is of interest to keep the extraction driving mechanism transparent to all other settings.

Longitudinal RF-noise

The stochastic longitudinal RF-noise extraction method is an acceleration driven extraction method which was successfully applied at LEAR [10]. Longitudinal noise is applied by the RF-cavity to cause the particles to carry out random walks in longitudinal phase space similar to Brownian motion, leading to a blow up of the momentum distribution (Figure 1). This extraction method promises to allow extraction of a low ripple beam with the same properties like the betatron core one. In addition, the change of driving mechanism is transparent to all other machine settings.

Using formulas given in [11], the minimal required voltage is 750 V with Δf = 5.5 kHz bandwidth in order to extract a 400 MeV/u carbon beam with $\Delta p/p = 4 \cdot 10^{-3}$ within 0.1 s. In this case, the lack of mixing would cause the extracted beam to be pulsed and it is therefore necessary to increase the bandwidth to e.g. 10 kHz with 3.1 kV. As for a constant voltage the extracted beam intensity would decay exponentially, the RF-voltage must be ramped up to this value.

First simulation results confirm an extraction almost identical to the betatron core one in terms of the extracted distribution in x-x'-phase space (Figure 4).

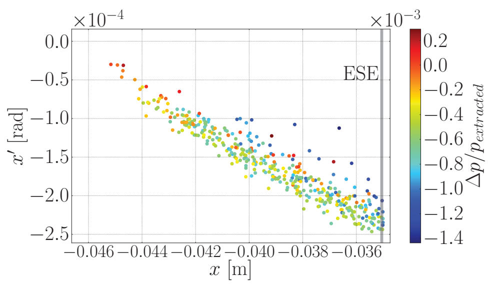

Figure 4: Phase space map (x-x') for RF-noise method of an extracted low energy proton beam at ESE with the relative momentum deviation as color code

Lattice Tune Adjustment

In this extraction scheme the resonance condition is met by adjusting the lattice tune via the focusing properties of the quadrupole magnets (Figure 1). The momentum of a particle stays constant during extraction and the momenta in the "waiting" beam are handed over to the extracted beam.

While this method convinces due to its simplicity, there are major disadvantages. As the necessary powering change of the quadrupoles are very small, it is difficulty to control the extraction duration and to obtain the targeted stable extracted intensity. Furthermore, due to changes in the lattice functions, the extracted beam profile is affected (Figure 5). Still it may be a suitable option for nonclinical irradiation with very short extraction durations.

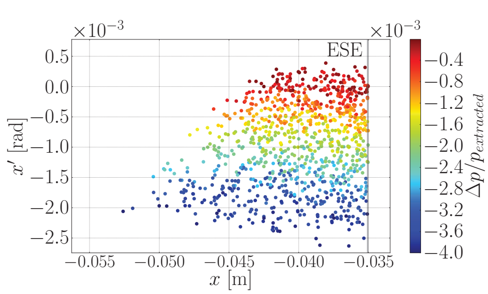

Figure 5: Phase space map (x-x') for lattice tune adjustment method of an extracted low energy proton beam at ESE with the relative momentum deviation color encoded

CONCLUSION

While all four presented extraction methods are feasible at the MedAustron synchrotron, not all are acceptable from the point of view of the quality of the extracted beam. The betatron core method works very fine in simulations and thus is still the primary option for medical use. The lattice tune method and RF-knockout both are not capable to deliver extracted beams for medical applications. Yet, both could be used at MedAustron for non-clinical irradiation. RF-noise seems to be the best alternative to the betatron core method, because it is able to produce almost identical extracted beams compared to the betatron core case, but offers shorter spill durations. Consequently, this scheme could be employed in medical applications as well as for non-clinical research.

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