EXTRACTION COMMISSIONING FOR MEDAUSTRON PROTON OPERATION

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Abstract

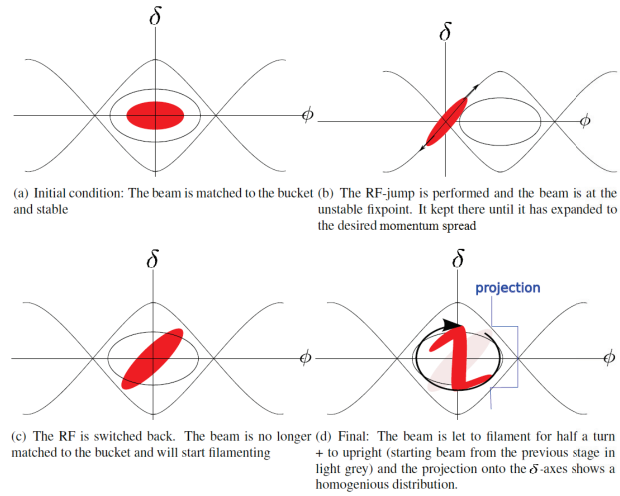
MedAustron is a synchrotron based ion beam therapy center for proton (62-250 MeV) and carbon ion(120-400 MeV/n) treatments. The MedAustron synchrotron uses a betatron core driven slow extraction scheme based on a third order resonance. The commissioning of the extraction from the synchrotron involved the setup of the correct orbit and optics at flattop. In order to maximize the momentum spread before extraction and optimize spill structure the RF system enforces a so called RF-phase jump to the unstable phase. Different scenarios were simulated using MADX-PTC [1] in combination with Python to overcome the static nature of PTC. Simulations have shown that the initial phase of the beam and a finite time to jump to the unstable fix point have a strong impact on the performance. Using a high frequency intensity monitor in the extraction channel (QIM), the spill structure was analysed and used for optimization. Simulation and measurements of the procedure are presented.

INTRODUCTION

In the extraction scheme of MedAustron a betatron core slowly accelerates the beam onto a 3rd order resonance in the horizontal plane which is generated via lattice quadrupoles and a dedicated sextupole magnet in a dispersion free region. Naturally the momentum distribution in the ring has a high impact on the time and energy structure of the extracted beam. For medical and research purposes low and slow intensity variations are of importance. Also the energy variation should be minimized as this directly maps to aberrations in the penetration depth in tissue. To flatten the momentum distribution whilst maintaining high intensities a phase jump scheme was introduced [2].

EXTRACTION SCHEME

Since the synchrotron cannot be operated close to the resonance during the entire cycle, the tune needs to be adapted before extraction can occur. To always stay on the same side of the hysteresis curve, the change of optics (see Figure 2) happens during acceleration, finishing when the maximum energy is reached. In addition to an adaptation of the tune, also the chromaticity gets adapted to satisfy the Hardt condition [3]. After reaching the maximum energy, manipulating the momentum distribution is the next step for extraction. At MedAustron, this is performed via a jump of the RF phase to the unstable fix point in longitudinal phase space and filamentation. The scheme is outlined in Figure 1.



(a) Initial condition: The beam is matched to the bucket and stable

(b) The RF-jump is performed and the beam is at the unstable fixpoint. It kept there until it has expanded to the desired momentum spread

(c) The RF is switched back. The beam is no longer matched to the bucket and will start filamenting

(d) Final: The beam is let to filament for half a turn + to upright (starting beam from the previous stage in light grey) and the projection onto the δ-axes shows a homogenious distribution.

Figure 1: General scheme of a phase jump [2].

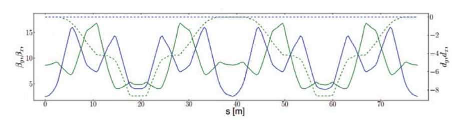


Figure 2: Lattice functions at flat top [2].

Once the desired momentum distribution has been reached, the RF system is switched off and the beam debunches. At this point in time, a strong sextupole magnet in a dispersion free region is ramped to excite the 3rd order resonance and enlarge the stopband [4]. As soon as the magnet has reached its full strength, the betatron core slowly begins to accelerate the beam into the resonance thus extracting the beam in a controlled way. The betatron core is a magnet which is used to induce a voltage onto the circulating beam at each turn there for accelerating. Unstable particles will pass an electrostatic septum which gives an additional kick. After 60 deg phase advance, the resulting horizontal orbit gap between the particles in the waiting stack and the extracted particles enables the beam extraction through a thin magnetic septum [5]. Criteria for a good extraction are:

- provide high intensity beams to the high energy beam transfer line [5]
- small intraspill extracted beam energy variation
- constant extracted beam flux over the spill
- minimal ripples on the extracted beam instensity

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Machine Requirements

During an iterative process, the offsets between the measurement and MAD-X were obtained and used for accurately matching the machine to the desired lattice properties.

- Dispersion at electrostatic septum
- Horizontal tune at resonance position and horizontal Chromaticity satisfying the Hardt condition
- closed orbit errors lower than ($\pm 1\ mm$)
- correct placement of the beam in longitudinal phase space
- a very stable beamphase before the phase jump

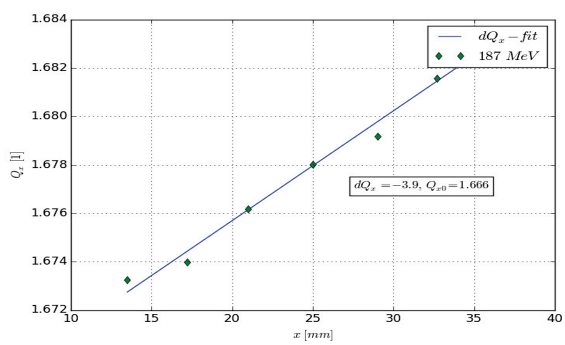

Figure 3: Horizontal chromaticity measurement for 187 MeV, vertical axis shows the measured horizontal tune and the horizontal axis shows the beam position at the maximum dispersion position.

Orbit correction was performed at flattop after measurement of the dispersion. The normalized corrector strengths were found to scale perfectly with energy and closed orbit errors lower than $\pm 1mm$ were thus obtained for all energies. Figure 3 shows a horizontal chromaticity measurement for 187 MeV after careful rematching. The tune at resonance was extrapolated to be 1.666. Rematching was performed for the lowest, highest, and two intermediate energies. All other configurations of the normalized quadrupole and sextupole strengths were obtained via interpolation.

MEASUREMENTS

Set Up

For a successful measurement series on phase jump performance it was necessary to reduce any phase oscillation to a minimum, ensuring reproducible results. In addition empty bucket measurements on the coasting beam were performed to measure the momentum spread for different energies.

Beforehand the correct strength of the sextupole needed to be set to obtain the correct spiral step. Measurement (Figure 4) has shown that the most intensity measured in the extraction channel is at the normalized setupole strength of $2.2\ 1/m^2$ which is consistent with design.

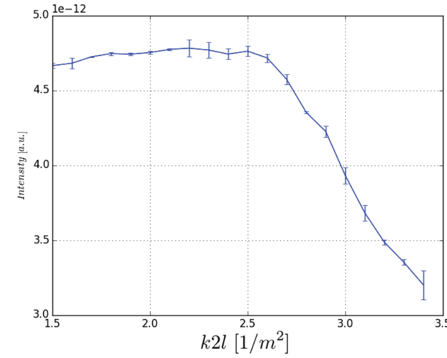

Figure 4: Extracted intensity normalized to the number of particles at the extraction energy.

Naturally the momentum spread is smaller for higher energies. To achieve similar conditions for different energies, for each energy the voltage was increased before the phase jump. An example voltage waveform can be seen in Figure 5. Note that the phase jump is not performed at the maximum voltage necessary for momentum spread increase, but rather at around 650 V for all energies which showed best results. A scintillator with 50 kHz readout rate served as the measurement device for judging spill quality.

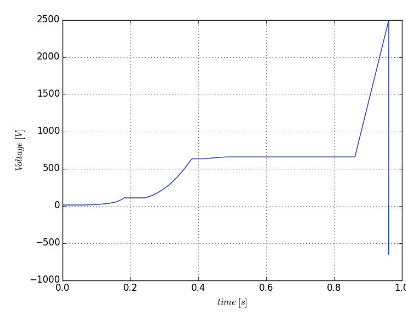

Figure 5: Voltage waveform for phase jump at 136 MeV.

Establishing Correct Timings

The timings for which the best performance could be determined were found experimentally via the use of dedicated commissioning applications [6]. For all energies the best performance was found at 76° in respect to synchrotron frequency for t_{ufp} (time at the unstable fix point). What was surprising is, that filamentation (t_{fil}) did not create a more rectangular distribution, but rather introduced unwanted low frequency oscillations within the spill. To determine the quality of the spill, it was necessary to heavily downsample the data provided by the QIM, and then additionally smoothen using a moving average. Only then the low frequency structure became visible to the naked eye as in Figure 6.

Figure 6 shows the overall spill as it was measured on the QIM. With filamentation the flanks could be slightly steepened, but low frequency ripples were introduced, so it was decided not to implement filamentation. The measurement shown is for 253 MeV, but shows typical behaviour

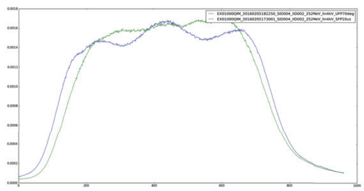

Figure 6: Overall spill for 253 Me downsampled and further smoothed. The green curve represents the intensity without the implementation of filamentation, whilst the blue curve uses filamentation.

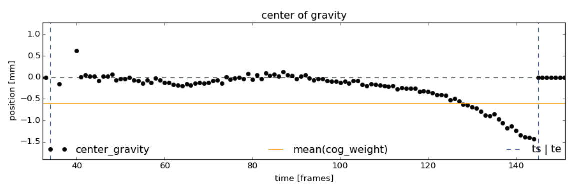

Figure 7: horizontal position position measurement in a region of the HEBT with $D \neq 0$.

for all energies. That a very flat momentum distribution was achieved can also be seen when looking at a position measurement (SFX) in a region with non zero dispersion in the HEBT. Figure 7 shows such a measurement in which positional variation can be reduced below 0.5 mm for most parts of the spill.

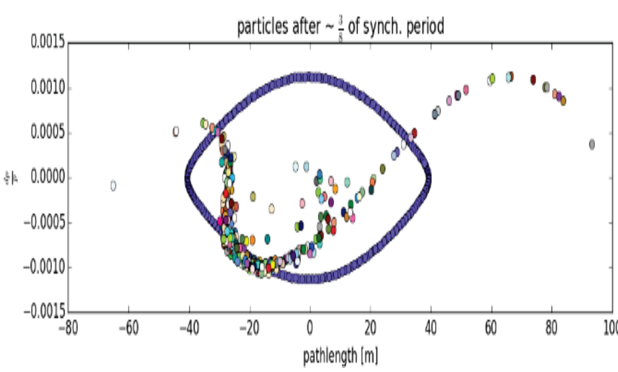

Figure 8: Particle distribution in longitudinal phase space when a phase offset was present before the phase jump.

Limiting Factors

When using a phase jump scheme on extraction level the parameters such as t_{ufp} and t_{fil} obviously have a large impact on the performance and spill quality, but the real limiting factors are machine inherent. Namely the phase stability of the beam and how quick the voltage loops are able to react to a sudden change in phase. The phase jump is performed via directly inverting the voltage on the cavity. Depending on the servo loop set up, this can range between $50\mu s$ and $300\mu s$. If the loop is slow, the phase jump occurs in a less controlled way. If the beam phase in non-zero when jumping to the unstable fix point, the results become unusable as can be seen in Figure 8 which shows the performance of a phase jump at bad conditions. Simulations on the phase jump were performed using a combination of cpymad [7] and MADX-PTC [1], allowing the simulation of quasi dynamic processes in the otherwise static PTC environment. Simulation and measurement showed that very careful set up of the phase and voltage regulation loops was necessary to achieve satisfying performance. In the future, the performance of the phase jump can be further increased via enhancements on the front end controller of the sRF.

CONCLUSION AND FUTURE OUTLOOK

The performance of the current phase jump implementation provides very satisfying and reproducible spills. In theory, a phase jump is a very elegant tool to control the momentum distribution. Simulations have shown that with an ideal set up (instantaneous phase flip and no phase oscillations), the particle distribution can indeed be manipulated in such a way, that rectangular distributions can be achieved. In practice however, the scheme requires very precise and careful work until reproducible results can be obtained. With this in mind, other schemes like voltage jumps may be the easier and more robust implementation. Future upgrades on the control system will enable improved features of the synchrotron LLRF [8] which could potentially heighten the performance.

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