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SLOW EXTRACTION OPTIMIZATION AT THE MEDAUSTRON ION THERAPY CENTER: IMPLEMENTATION OF FRONT END ACCELERATION AND RF KNOCK OUT

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Abstract

MedAustron is a synchrotron-based quasi-discrete pencil beam scanning ion therapy center allowing tumor treatment with protons and other light ion species, in particular C6+. Commissioning of all fixed lines, two horizontal and one vertical, has been completed for protons and in parallel to the commissioning of a gantry and C6+, a facility upgrade study is progressing. The upgrade study encompasses the optimization of the slow extraction mechanism by employing the RF empty bucket channeling and RF Knock Out techniques. The former is a front end acceleration technique that suppresses spill ripples, fundamental to safely operate the machine at the highest intensities. The latter is an alternative extraction technique which opens up interesting possibilities for fast beam energy and intensity modulations. In this work, we quantify spill smoothening effects achieved with the first and report the results of a feasibility study of the second using a Schottky monitor as a transverse kicker.

RF-CHANNELING

Particles are extracted from the MedAustron [1] synchrotron in spills of few seconds (typically 5) with the third order resonant technique [2]. The machine is operated off momentum and the resonance is fed with a betatron core, which slowly accelerates the coasting beam until extraction. The process is very sensitive to current fluctuations in the power converters of the ring magnets, which are current regulated at a rate of 2 kHz. These ripples imprint into the particles extraction rate (also referred to as intensity). The characteristic time of this phenomenon is comparable to the minimum dwelling time in a voxel of the beam scanning system. This effect might result in an overdose in voxels which require a very low number of particles to be delivered. Without a feed forward mechanism that pre-emptively adapts the average intensity to the requested dose of the next voxel [3], the overall rate has to be reduced in order to mitigate risk of overdose.

On the other hand higher intensities translate into considerably faster treatment and ultimately to increased patient throughput [4]; for this reason it is of great importance to improve the quality of the time structure of the spill whenever possible.

It has been demonstrated [5] that the magnitude of the intensity ripples in the kHz range can be reduced with RF-channeling. This technique uses the synchrotron radiofrequency cavity (sRF) to position an empty stationary bucket at a frequency slightly higher (towards the resonance) than the average revolution frequency of the unbunched beam. The equipotential lines of the bucket close to the resonance condition provide an additional front end acceleration that "channels" the particles towards the resonance. The overall effect is to smoothen the spill in the kHz range, while increasing the component of the intensity ripples at frequencies comparable to the one the sRF is operated at (MHz), which do not affect the quality of the treatment (typical voxel dwelling time > 1ms).

Implementation tests of the RF-channeling technique have been successfully performed at MedAustron for the whole span of clinically available energies of proton beams, but in this work we refer for simplicity to 210.5 MeV only. Commissioning of Carbon beam [6] has not yet reached a phase adequate for spill ripples tuning.

Figure 1 shows the impact on beam losses and smoothening effect of the frequency offset Δf from the main particle revolution frequency, to which the sRF is operated. The peak-to-peak voltage applied is 4 kV.

The number of particles extracted is measured with a scintillating plate coupled to a photomultiplier installed in the High Energy Beam Transfer (HEBT) line. The electronic chain of this Quality Intensity Monitor (QIM) is operated with a data sampling rate of 50 kSample/s.

The beam efficiency is defined as the ratio between the numbers of extracted particles in a spill over the current measured before extraction by a DC current transformer installed in the synchrotron ring. The beam efficiency is normalized to 1 for the reference scenario without RF-channeling.

The intensity peak-to-mean is defined as the ratio of the number of particles extracted in a 500 µs integration time over the total number of particles extracted in the spill. 500 µs has been chosen because it is representative for the minimum dwelling time in a voxel.

As Figure 3 shows, an exponential modified Gaussian probability density function well describes the peak to mean distribution.

$$f(x;\lambda,\mu,\sigma) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)}\, erfc\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

with

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-t^2}dt$$

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We define *MaxPeak2Mean* as the peak to mean value for which cumulative probability of realization is 99.999. This can be roughly translated into: a voxel which requires to be irradiated for, or less than, 500 µs has an expectation of 1 in 100.000 to experience an intensity higher than *MaxPeak2Mean.*

Discussion of Results

The beam loss is negligible for $\Delta f \geq 15$ kHz. *MaxPeak2Mean* is significantly reduced for 10 kHz $\leq \Delta f \leq$ 35 kHz. For $\Delta f > 35$ kHz, the empty bucket is too far from the beam/resonance and its impact on the extraction process is negligible. For $\Delta f = 5$ kHz the spill is very smooth, but the overall spill structure is so distorted that the average intensity at the beginning of the spill (0 - 0.5 s) is roughly 3 times the one at the end (4.5 - 5 s). This slow distortion is very reproducible and could potentially be compensated by a non-constant contribution of the betatron induced acceleration. 10 kHz $\leq \Delta f \leq$ 20 kHz shows the best performance in terms of compromise between beam losses and smoothening of spill ripples. Fig. 2 shows the time structure of the extracted beam while using RF-channeling (Δf=15 kHz) compared to the reference operation.

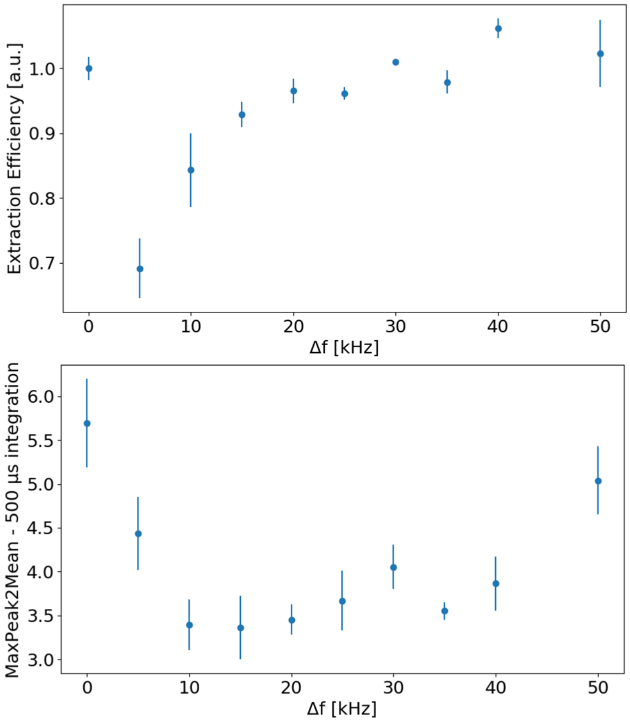

Figure 1: Impact of empty bucket Δf on proton beam (210.5 MeV) extraction efficiency (top) and *MaxPeak2Mean* (bottom). See text for definitions. Δf =‘0’ refers to extraction without RF-channeling.

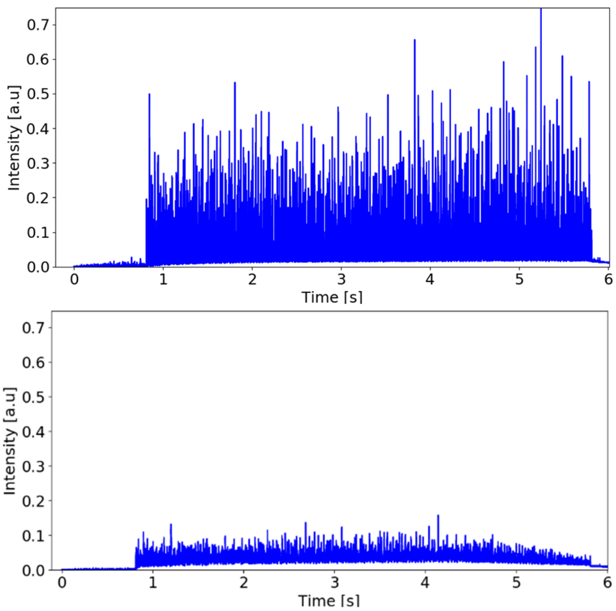

Figure 2: Time structure of extracted proton beam (210.5 MeV) sampled at 50 kSample/s. Reference (top) and using RF-channeling with Δf=15 kHz (bottom). Same integrated intensity, or comparable with shot-to-shot variations.

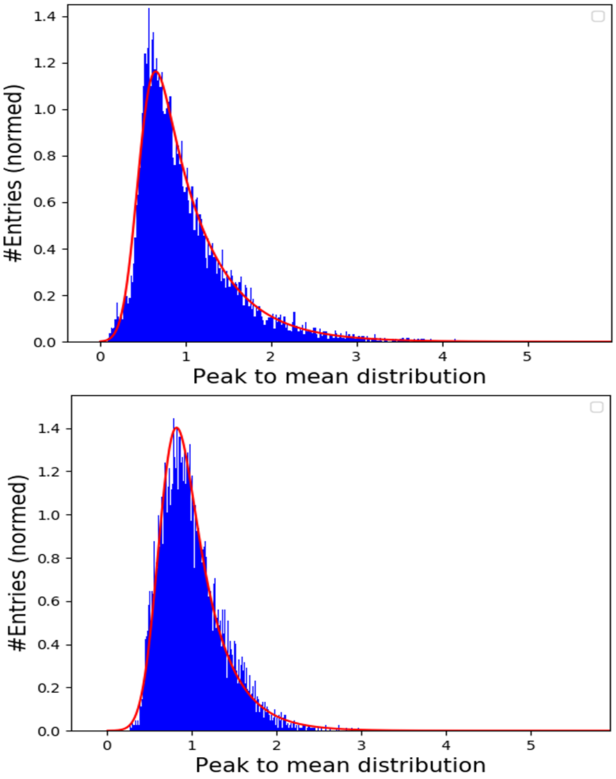

Figure 3: Peak to mean distribution of extracted proton beam (210.5 MeV). Reference (top) and using RF-channeling with Δf=15 kHz (bottom).

RF-KNOCK OUT

The energy of the beam delivered from cyclotron based hadron radiotherapy facilities can be changed in few tens of ms with the mechanical insertion of a well-defined thickness of material. Synchrotron based facilities suffer from longer dead-times between delivery of different energies, which require dumping, re-injection and acceleration (at the new target energy) of the beam. Changing the energy in a spill would greatly reduce the time necessary for a large set of patient prescriptions [4] and potentially enable treatment of moving lesions.

The extraction chosen in the design of MedAustron uses a debunched beam, which allows for front end acceleration techniques as seen in previous section, but in turns makes particle re-acceleration/deceleration very challenging.

Although the Betatron core is designed to accelerate a coasting beam, energy variations of more than few MeV/n would require supplying the magnet with currents of many thousands of Ampere.

The available options include

- Re-capture and deceleration with sRF
- Beam momentum distribution displacement with sweeping empty bucket [7]

Both are prone to beam losses, so a different extraction technique, RF-Knock Out (RF-KO) [8] , is under testing at MedAustron. RF-KO is widely used in other ion beam therapy centers [9] [10] , employs bunched beams and compatible with multi-energy spills operation [11] [12].

When using the RF-KO technique the machine is typically operated on-momentum, but the tune at extraction is set slightly off the third integer. A transverse horizontal kicker is used to grow the amplitude of the betatron oscillations until the amplitude dependent component of the tune compensates the tune shift from the resonance condition. With a constant kick the beam simply follows a different orbit; to grow the betatron amplitude the kick has to be sinusoidally varying in time, with a frequency f_k synchronized to the particle motion

$$f_k = f_{rev} \cdot (n \pm q); \qquad n \in \mathbb{N}$$

where f_{rev} is the particle revolution frequency and q the non-integer part of the tune. A chromaticity different from zero induces a momentum dependent tune shift, so f_k has to be swept in a bandwidth that covers the momentum distribution.

In the MedAustron synchrotron lattice there might not be space to add an additional dedicated kicker, but an already installed Schottky monitor could be converted into one.

The signal fed to the plate of the Schottky monitor is generated by the low level sRF system (LLRF) where a copy of the accelerating cavity signal is modified and routed to a spare output channel. The main frequency is moved to $q \cdot f_{rev}$ by setting a clock tuning word to q; a pseudo frequency sweeping is implemented by modulating the signal phase Φ whit a variable depth θ_{PM} and repetition period T_{PM}.

$$\Phi = \theta_{PM} \cdot \sin\left(\frac{2\pi t}{T_{PM}}\right)$$

Figure 4 shows the resulting frequency domain spectrum. A firmware timing enables the kicker signal with an extraction trigger provided by the main timing system of the facility.

RF-KO has been tested at MedAustron with Carbon ions first, because they are expected to pose the most restringing condition on the extraction. Fig. 5 shows an example time profile of the extracted Carbon (120 MeV/n) beam for $q = 0.685$; $\theta_{PM} = 60°$, $T_{PM} = 0.2$ ms. The extraction efficiency is 32%, *MaxPeak2Mean* is 8.1. As reported in literature [8], the intensity rapidly decreases if the kicker strength is kept constant. The LLRF offers the possibility to increase the amplitude of the signal fed to the Schottky monitors plates along an arbitrary curve. This function has been already tested in the lab, but not in the full system with beam.

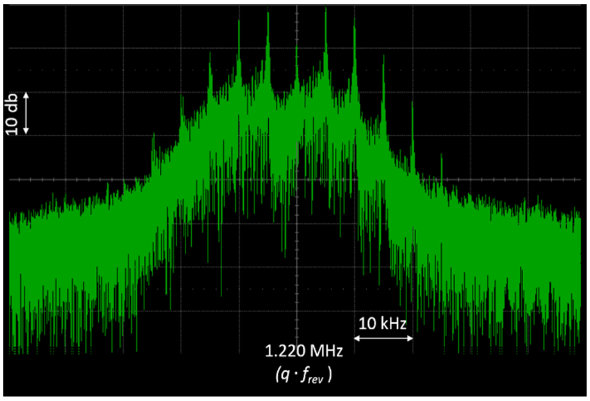

Figure 4: Frequency spectrum of the signal generated by the LLRF and fed to the horizontal kicker (Schottky monitor plates).

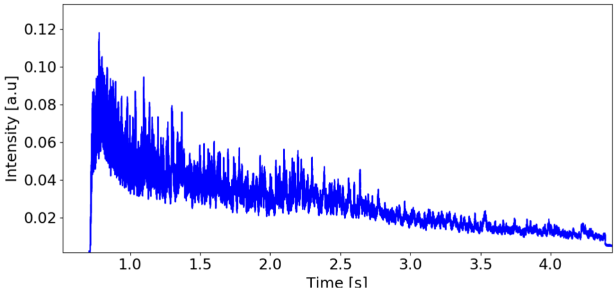

Figure 5: Time structure of Carbon beam (120 MeV/n) extracted with RF-KO. Data sampled at 50 kSample/s. $q = 0.685$; $\theta_{PM} = 60°$, $T_{PM} = 0.2$ ms.

CONCLUSION

RF-channeling provides a much smoother beam for almost negligible beam losses and will enable safe operation at higher intensities, leading to a patient throughput enhancement. For the implementation in the medical product is still necessary to tune the technique for the whole clinically available energy range, verify the impact on beam properties in the irradiation rooms, confirm the conformity to medical standards and performed associated risk management.

This work demonstrated the proof of principle for the implementation of RF-KO at MedAustron, without the need of major hardware installation.

The focus of further development is on optics optimization for beam loss reduction, adaptation of LLRF to provide constant intensity and even smoother spill, hazard and standard compliancy analysis.

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