UPGRADE STUDY OF THE MedAustron ION BEAM CENTER

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Abstract

MedAustron is a synchrotron-based ion beam therapy center allowing the treatment of tumours with protons and other light ion species, in particular C^{6+}. Commissioning of the first irradiation room for clinical therapy with proton beams has been completed [1] and in parallel to the commissioning of the remaining two irradiation rooms [2], a facility upgrade study has started. Our analysis includes considerations for the possibility to introduce different extraction mechanisms, new diagnostic tools, optimization of the accelerator cycle time, ripples mitigation for more accurate active beam stabilization and other improvements for hardware reliability. We present the concept, the main benefits, also in terms of treatment time reduction, and the challenges for implementation. Each option will be investigated including a detailed assessment on resources demand, impact and risk analysis.

PERFORMANCE IMPROVEMENT PROJECT

The MedAustron accelerator is operated in cycles of roughly 10s during which a spill of particles at one energy is delivered in 5s via betatron core driven slow resonant extraction. The machine is able to accelerate an average of 1.8×10^{10} particles in a spill, but this is artificially degraded to roughly 20% to mitigate the effect of spill ripples. The developments presented in this work are summarized in Table 1 and detailed in the paragraphs below:

Table 1: Developments considered in this work and main motivation for their implementation. Spill smoothening also enables to run at higher intensities.

Upgrade	Motivation
Cycle Abort at EndOfSlice	Cycle shortening
Magnetic Field active Regulation	Cycle shortening
RF Channeling	Spill smoothening
Air core Quadrupole	Spill smoothening Intensity modulation
RF Empty Bucket Modulation	Spill smoothening
RF Knock Out	Multi Energy spills Intensity modulation
Phase Displacement Deceleration	Multi Energy spills
Schottky monitor	Beam diagnostic

Cycle Abort at EndOfSlice

A Dose Delivery System (DDS) [3] measures particle delivery and commands its interruption when sufficient dose has been reached for a particular iso-energy slice. The extraction continues until the end of the pre-programmed sequence of 5s, but a trajectory bump is deactivated to force the beam to a dump. In a typical treatment, most of the slices only require a few percent of the spill to be completed, thus a considerable amount of dead time can be avoided by quickly dumping the beam, invoking the necessary actions to end the cycle and trigger the next one. The control system [4] could accommodate for this feature, provided that the "EndOfSlice" signal is propagated from the DDS to the central timing system, from where it can be broadcasted to others components involved.

Magnetic Field Active Regulation

At the end of a cycle, a number of the magnets are "washed" by ramping up the current supplied to a maximum fixed value and consequently brought to a lower current set-point required for the injection of a second spill. This operation is performed in order to assure the reproducibility of the magnetic field. Other facilities [5] showed that is possible to avoid this procedure with an active magnetic field regulation for all dipoles and quadrupoles involved. The implementation of this feature would require a solid and precise measurement set-up (Hall/NMR probe + integrating coil) and development of Reference Signal Tracking control loop firmware for the current regulation board driving magnet power supplies.

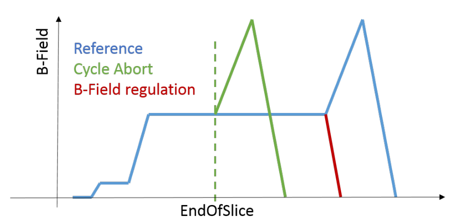

Figure 1: Magnetic cycle in the synchrotron. Blue: reference as implemented; Red: with magnetic field regulation; Green: example of Cycle Abort for a slice requiring delivering of roughly 30% of the particle accelerated in a cycle.

RF Channeling

During extraction, ripples on the power supplies of the main ring magnets lead to spikes in the time profile of the extracted beam. The synchrotron RF can be used to generate an empty bucket with frequency slightly higher that the main revolution frequency while a betatron core slowly accelerates the coasting beam into the resonance. The momentum of

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particles grows, and when they encounter the separatrix, they are shifted in phase to turn around, and finally cross, the bucket. This technique permits to extract a large group of particles with original different phases, at the same time and momentum. The overall effect is a smoothening of the spill structure as evident from Fig. 2. The feasibility of RF-Channeling and the impact on the quality of the spill at MedAustron has been demonstrated, but this feature will be pursued only after a detailed study to verify whether any possible fault scenario could impact on the medical beam properties.

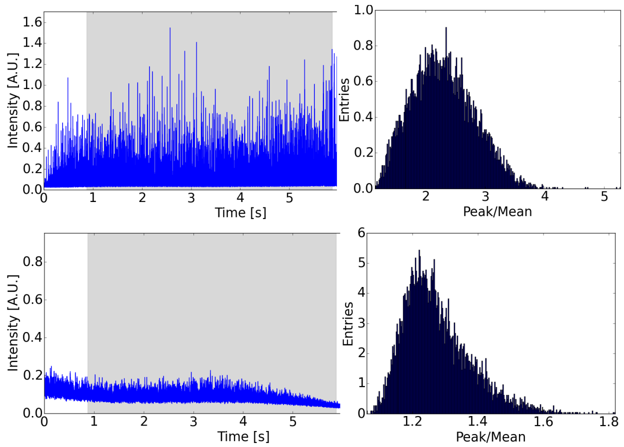

Figure 2: Left: spill structure of the extracted beam at 252MeV; right: peak to average intensity distribution. Top: reference; bottom: with RF-Channeling, empty bucket at 4kV and +10kHz offset respect to the revolution frequency.

Air Core Quadrupole

Another mean to smoothen the spill is described in [6] and involves the use of a quadrupole without a ferrite yoke, that could therefore be driven very fast. Such a device can be used to rapidly move the tune of the ring and thus changing the condition for the resonance. The spill ripples can be mitigated by either fast oscillations of the tune or its regulation via an extracted beam intensity feedback loop. In the former scenario the multi kHz tune oscillation simply "noise out" slower ripples of the main ring magnets power supplies. While in the latter a suitable non-interceptive high frequency intensity detector can be used to feedback the quadrupole current, or possibly even to feed-forward the power supplier to variate extraction speed between tumour regions. An air core quadrupole is foreseen in the accelerator design, but not installed yet. Furthermore, if a feed-back/forward loop is to be considered, a dedicated effort is to be undertaken to evaluate the proper electronics for the implementation.

RF Empty Bucket Modulation

A third viable way to mitigate spill ripples is the fast frequency modulation of empty buckets through the beam momentum distribution during extraction [6]. This method combines the phase displacement of RF-Channeling and the "noising out" effect mentioned for the Air core Quadrupole case. In this scenario the tune is fixed and the beam momentum distribution "wiggles" fast in the proximity of the resonance condition. The MedAustron RF system is able to implement this solution after minor changes to the control system, in particular to the RF front end controller.

RF Knock Out

Although the design of the MedAustron machine and its commissioning so far was based on betatron driven extraction [6], detailed studies were performed on alternative slow extraction techniques [7, 8]; among which RF knock out (RF-KO), a very widely employed solution in the community [9]. In this scheme, a transverse RF signal tuned to the betatron frequency, is used to grow amplitude of the beam oscillations, until extraction into a thin septum. The most suitable optics choice for the MedAustron machine, along with particle tracking simulations have been performed. Two components where the transverse RF signal could be applied were identified: a tune kicker and a horizontal Schottky monitor; with the latter as a favourite candidate, assuming it can provide a good field quality in the region interested by the beam. This technique could enable intensity modulation on a sub-milliseconds scale and multi energy spills, but a significant amount of components and systems would require re-commissioning. Furthermore a detailed system architecture review, with appropriate risk management study is necessary to pursue this option.

Phase Displacement Deceleration

Changing the energy of the beam in a spill is a very attractive feature, because it minimizes dead time between slices and it is a pre-requisite for tumour 3D re-scanning or tracking, both very sought after ways of treating by physicians. Other centers already implemented means for multi energy spills [10, 11]; mostly with extraction based, or involving RF-KO, but in case of MedAustron another option is viable. A betatron driven slow resonant extraction assumes coasting beam, which can be accelerated (or rather decelerated for medical purposes) with repeated adiabatic empty bucket scans that induce a phase displacement in the beam momentum distribution [12]. The subject was studied in Ref. [7] as an alternative drive for the slow extraction at MedAustron. In this work we propose to keep the betatron core to drive the extraction, change energy as above described (0.75-3MeV change) and repeat as long as the number of particles in the main ring allows for it.

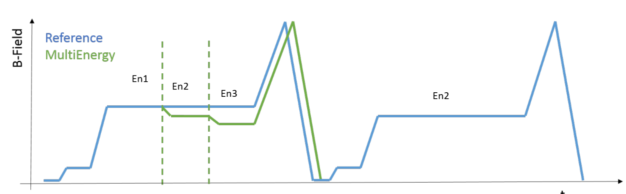

Figure 3: Magnetic cycle in the synchrotron. Blue: reference as implemented; Green: example of Multi energy spills.

Schottky Monitor

Schottky noise analysis is a powerful tool for non-interceptive beam diagnostic [13]. In the main ring, two monitors dedicated to perform this task are installed, one for each plane. Two 0.9m long parallel plates have each two electrode connections at their ends; one is left open (capacitive coupled to ground) and the other is used to measure the image current induced by the circulating beam. Each channel is amplified in a super low noise pre-amplifier[1] and provides one of the two inputs for an hybrid module, where the sum(Δ) and difference(Σ) of the two plates signal is generated. The spectrum of Δ and Σ is then measured with a signal analyser[2] for both planes. The momentum distribution $\frac{dp}{p}$ can be derived from the spectrum analysis of the Σ signal as shown in Fig. 4. Analysis of the Δ spectrum will be performed in the near future to measure transverse emittance, tune and chromaticity.

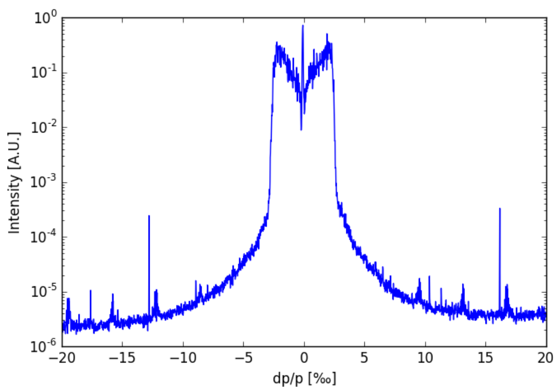

Figure 4: Beam $\frac{dp}{p}$ after the phase jump used to prepare the beam for extraction [14], as derived from measurement of the Σ spectrum of the horizontal Schottky monitor.

TREATMENT TIME REDUCTION

The developments above mentioned[3] would lead, directly or by enabling other features, to a reduction of the time necessary for treatment; thus less discomfort for the patient, higher therapy quality[4] and ultimately an enhancement of patient throughput of the facility. An estimate of the benefits in term of beam delivery time reduction is performed with an in-house simulation code against a set of therapy plans for patients treated since the beginning of start of operations. Behavioural aspects of the machine and its parameters, including spill-to-spill intensity fluctuations, are modeled according to the data provided by the daily beam quality assurance program [15]. Upgrade scenarios carry assumptions that will be explicitly expressed. The expected average time reduction for each scenario, and some combinations, is presented in Table 2. The dose accumulated during the treatment of deeper slices of tumour is significant, therefore typically only a reduced amount of particles is to be delivered at low energies. In this regime abortion of the cycle is a very effective feature. Energy variation in between spills is an even more efficient solution. In this work we presented two viable means to achieve this feature. Assumption: extraction intensities as for the reference scenario; 100ms to abort the cycle and proceed to magnet “washing”; 200ms and 15% particle loss for every energy change.

Table 2: Estimation of average beam delivery time, expressed as fraction of the time necessary with the reference model. Data elaborated for a set of already treated patient, therefore biased.

Upgrade	Beam delivery time
Higher intensity (HI)	98%
Magnetic field regulation (MF)	84%
Cycle Abort (CA)	61%
Multi energy spills (ME)	23%
MF + HI	82%
CA + HI	51%
CA + MF	45%
ME + MF	20%
ME + HI	7%

If the “washing” of the magnets at the end of each cycle is replaced with a simple ramp down of the ring components to injection level, roughly 16% of treatment time can be saved, independent to treatment field. Same ramp speed as acceleration is assumed.

In this work we presented a number of options to smoothen the extraction in order to allow clinical operation at 1.8×10^{10} particles per spill. A further increase of intensity, if not combined with other upgrades, does not lead to a significant reduction of treatment times for the currently treated patient population. This may somewhat change in the future with the advent of hypofractionation and larger treatment volumes.

CONCLUSION

MedAustron is fully committed to offer the best treatment options for its patient, and therefore operate at the cutting edge of the state-of-the-art of the ion beam therapy centers. In this work we presented an extensive set of possible facility upgrades. Detailed investigations on benefit, effort and risk assessment will follow in order to plan and structure a performance improvement project that will be run in parallel with the commissioning of other irradiation rooms and carbon ion beam.

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[1] Stahl-electronics, PR-E 3-SMA. 0.6nV/$\sqrt{Hz}$@1MHz
[2] Agilent Technologies, MXA N9020A
[3] besides the Schottky monitors
[4] less time for intra-fractional movements of the patient anatomy

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