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NON-DELIVERY TIME REDUCTION AT MEDAUSTRON*

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Abstract

MedAustron is a cancer treatment center in Austria, providing proton and carbon ion beams to three clinical and one non-clinical research beam lines. The slow extraction of particles from the synchrotron follows a third order resonance extraction scheme. Currently, for every change of extraction energy a new spill needs to be generated. In addition to the beam-on time of the particle delivery, every spill is also comprised of non-delivery time components e.g. the multiturn injection, acceleration or magnet conditioning. For small tumor target volumes, this non-delivery time is the major contribution to the overall treatment time. A dedicated performance improvement project (supported with a grant from the state of lower Austria) was undertaken with the goal to reduce non-delivery times without affecting important clinical beam parameters such as the beam size or penetration depth. The implemented reduction of the non-delivery time >50% could be achieved, resulting in treatment time reductions for reference treatment plans between 25% (largest proton PTV (planning target volume)) and 58% (smallest carbon PTV). Results of commissioning efforts, technical details and achieved optimizations will be presented.

INTRODUCTION

MedAustron is a synchrotron based ion therapy and research center located in Wr. Neustadt, Austria. Its design as shown in Fig. 1 is based on the PIMMS [1] and CNAO [2]. It features three ECR ion sources, a 400 keV/n RFQ and a 7 MeV/n IH Drift tube LINAC feeding the beam into a synchrotron with 77 m circumference. Currently patient treatments are delivered with extracted proton beams from 62.4 MeV to 252.7 MeV and carbon ions from 120 MeV/n to 402.8 MeV/n. The beam is delivered between one dedicated research horizontal fixed beam line (IR1), two irradiation rooms featuring a fixed horizontal and vertical beam line (IR2) and a fixed horizontal (IR3) beam line as well as the present commissioning of a proton gantry (IR4).

The beam is extracted using a betatron core driven 3rd order resonance in the horizontal plane, which is generated using lattice quadrupoles and a dedicated sextupole magnet in a dispersion free region of the ring. The current implementation of the extraction scheme requires a new cycle to be generated for every change of extraction energy. Besides the beam-on time, during which particles are actively delivered to the patient, every cycle is also comprised of the following non-delivery time components:

- multiturn injection
- capture of the beam in the synchrotron
- acceleration
- extraction preparation
- chopping of medically not used part of the spill
- field stabilization and magnet conditioning times

This non-delivery time is the major contributor to the overall treatment duration, frequently accounting for >90% of the treatment time for small tumor target volumes. To reduce the treatment times, a dedicated performance improvement project was successfully executed in 2020 with the aim to shorten the time required for delivery of a certain number of particles without changing the beam-on time (and therefore the particle flux), by reducing the non-delivery time of each cycle. An additional constraint was to not affect important clinical beam parameters such as the beam size or penetration depth in all irradiation rooms.

COMMISSIONING TASKS

HEBT Dipole Recommissioning

The main obstacle in reducing the non-delivery time components is the stabilization of magnetic fields, especially of the bending and switching dipoles in the high energy beam transfer line (HEBT), highlighted in Fig. 1. Since the initial commissioning, these dipoles were following the same current curve as the synchrotron dipoles, resulting in the introduction of artificial waiting times at flat top before the magnetic field in the extraction line was stable enough for beam transport. Due to new control system capabilities, it is possible to change the operation mode of the HEBT dipoles, resulting in much smaller current steps (and therefore magnetic field changes) between cycles. This drastically reduced the magnetic field stabilization times and allowed various timing optimizations.

After changing the operation mode of the HEBT dipoles, their current set point needed to be recommissioned. Special care was taken to reproduce the beam trajectory in the extraction line as closely as possible.

The change in operation mode of the HEBT dipoles uncovered an intra-spill movement of the horizontal beam position of up to 1 mm, which was previously partially compensated by the dipole magnetic field stabilization. Extensive investigations into the origin of this intra-spill movement were undertaken and while the exact root cause could not be determined, it was confirmed, that the movement is caused by neither any variation in the set point of accelerator components nor potentially by a no longer closed dispersion.

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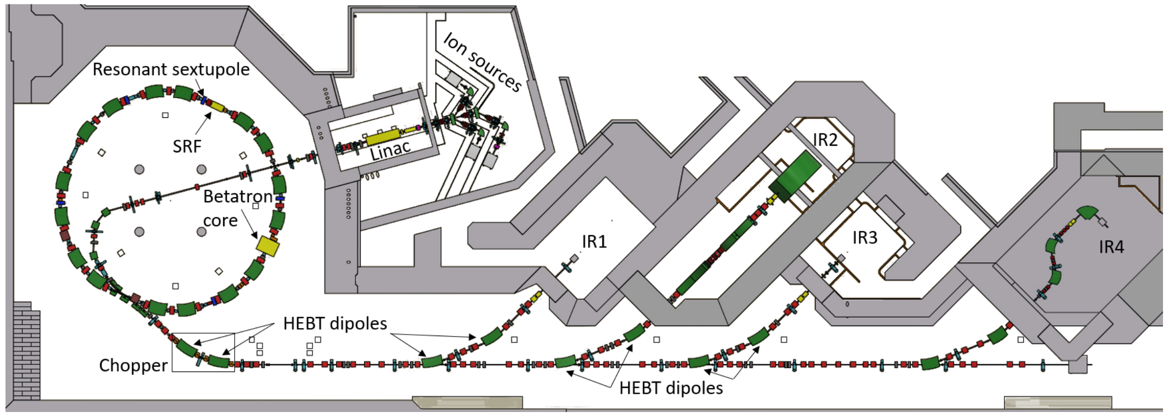

Figure 1: Layout of the MedAustron accelerator complex.

Injection Timing Optimization

The heartbeat of the MedAustron accelerator is set by the 10 Hz repetition rate of its IH drift tube LINAC. The time of the injection into the synchrotron can therefore be optimized in steps of 100 ms and was originally set to be 300 ms after the start of the cycle. During the performance improvement project, this time was optimized to be 100 ms after the start of the cycle, resulting in the need to increase the ramp rate of the synchrotron dipoles to reach the flatbottom current within 98 ms as opposed to the previous 250 ms as can be seen in Fig. 2. The resulting slight change of the final magnetic field at flatbottom required an adaptation of the fixed synchrotron RF injection frequency.

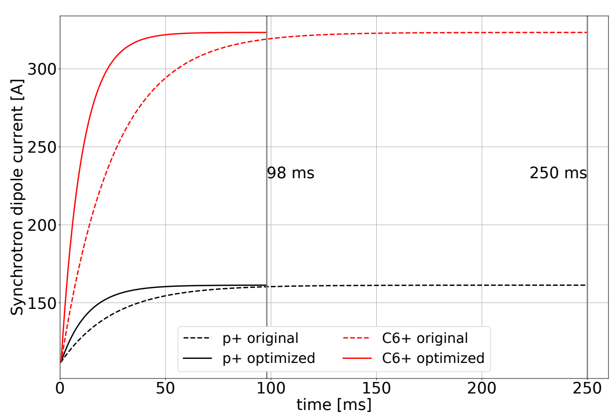

Figure 2: Current ramp of the synchrotron dipoles for protons and carbon ions before and after the injection timing optimization.

Capture Timing Optimization

Originally, the time during which the synchrotron RF captures the particles after the injection was chosen rather conservatively to reduce particle losses [3]. It could be shown, that the capture time could be reduced from 125 ms for protons and 199 ms for carbon ions to 42 ms and 50 ms without noticeable losses.

Extraction Preparation Optimization

After the acceleration, the so called RF jump is performed where the RF phase is shifted quickly to the unstable fixed point allowing the bunch to elongate along the separatrix [4]. The goal is to produce a uniform momentum distribution after debunching the beam [5]. Originally the beam was given 30 ms to completely filament between the RF jump and the start of the ramp of the resonant sextupole. After the resonant sextupole finished its 25 ms ramp, the beam had an additional 145 ms before the betatron core would start the extraction. In addition the carbon ion beam had an extra 1.5 s of waiting time for the field stabilization of the HEBT dipoles.

The head and tail[1] of the spill are not usable for clinical treatment, as the average momentum and therefore range is different from the rest of the spill [6]. The first part of the spill is therefore dumped in the chopper beam dump [7] and not delivered to the irradiation room. This opened up the possibility to parallelize the debunching after the RF jump, the ramp of the resonant sextupole and the start of the slow extraction. A reduction in non-delivery time of 198 ms for protons and together with the no longer needed field stabilization time 1.698 s for carbon ions could be achieved.

Dynamic Betatron Core Extraction

The not clinically used head of the beam can in principle be extracted with a higher betatron voltage than the clinically used part, resulting in a higher flux and therefore shorter extraction times.

The intra-spill movement of the horizontal beam position uncovered by the change in operation mode of the HEBT dipoles showed a stronger change in position at the beginning of the spill. The increased position movement was therefore compensated by dumping a larger part of the beam head into the chopper dump. As the no longer needed field stabilization waiting times allowed the extraction to be performed earlier with respect to the end of the acceleration, the clinically unused part of the beam can now be extracted faster, resulting in a reduction in non-delivery time between 350 ms

[1] The first and last part in time of the extracted spill respectively.

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and 700 ms for protons and between 70 ms and 414 ms for carbon ions, depending on the extracted beam energy.

Magnet Conditioning Times

After the end of the extraction the synchrotron dipoles perform a current loop to close the hysteresis and provide reproducible fields for the next cycle. In this case waiting times after the current loop finished needed to be introduced for magnetic field stabilization. Due to the $B\rho$ dependent starting points of the current loop, the duration of the loop is particle species and extraction energy dependent. Recently implemented control system settings allowed an adaptation of the waiting times resulting in a reduction in non-delivery time of 1 s for protons and 1.2 s for carbon ions.

Re-Steering

The recommissioning of the HEBT dipole set-points as well as the timing optimizations influenced the position of the beam in the extraction line. After all timing optimizations were implemented the beam was re-steered in the IR1, IR2 and IR3 beam lines.

ACHIEVED NON-DELIVERY TIME REDUCTION

Overall, a reduction in non-delivery time of between 48 % and 63 % with respect to the initial non-delivery time per cycle could be achieved. The detailed results are summarized in Table 1 for the lowest and highest clinically used proton and carbon ion extraction energies.

Table 1: Non-Delivery Time (NDT) Before and After All Implemented Optimizations

Beam [MeV/n]	Initial NDT [s]	Optimized NDT [s]	Rel. change
p+ 62.4	3.97	2.04	-48 %
p+ 252.7	4.49	2.21	-50 %
C6+ 120	5.25	1.95	-59 %
C6+ 402.8	5.58	2.28	-63 %

For the extreme cases of very small and very large proton and carbon treatment plans, the clinically relevant reduction in overall treatment time is shown in Table 2. With the achieved non-delivery time optimization, significant reductions in treatment time of several minutes per patient could be achieved. This not only saves several hours of beam time per treatment day, ultimately allowing the treatment of additional patients, but also increases the quality of the treatment, as movement artifacts are possibly reduced, as the time where patients have to stay in potentially uncomfortable positions is shortened.

Table 2: Overall Treatment Time and Share of Non-Delivery Time (NDT) for Reference Treatment Plans

	Head aden.	Prostate carzin.	H&N carzin.	Pelvis chord.
Particle species	p+	p+	C6+	C6+
PTV [cm^3]	36.21	1074.6	57.68	3019.37
Treatm. time initial [s]	255.7	1011.7	556.6	3551.8
Treatm. time optim. [s]	142.4	755.1	237.0	2196.2
Change in treatm. time	-44 %	-25 %	-57 %	-38 %
Share of NDT initial	92 %	57 %	95 %	64 %
Share of NDT optim.	84 %	39 %	88 %	41 %

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