INVESTIGATING ALTERNATIVE EXTRACTION METHODS AT MEDAUSTRON

F. Kühteubl[*], E. Renner, Vienna University of Technology, Vienna, Austria
L. Adler, L. Fischl, X. German, G. Guidoboni, K. Holzfeind, C. Kurfürst, C. Maderböck,
M. T. F. Pivi, F. Plassard, D. A. Prokopovich, V. Rizzoglio, I. Strasik, C. Schmitzer, A. Wastl,
EBG MedAustron GmbH, Wiener Neustadt, Austria
P. A. Arrutia Sota, M. A. Fraser, CERN, Geneva, Switzerland

Abstract

MedAustron is an ion therapy facility for protons and carbon ions located in Wiener Neustadt, Austria. The beam is presently extracted for clinical operation from the synchrotron with third-order resonant slow extraction via acceleration with a betatron core. However, due to the flexibility of the synchrotron operation for Non Clinical Research (NCR) purposes, other extraction methods can be investigated for potential improvement of the machine performance as presented in this work.

Radio-Frequency Knock Out (RFKO) extraction was investigated by applying an RF signal voltage across the horizontal Schottky plates in the synchrotron. Different excitation signals were evaluated with the required transverse excitation frequency band applied.

Investigation of the synchronous ramping of all synchrotron magnets for extraction via Constant Optics Slow Extraction operation (COSE) was undertaken for a bunched beam in order to extend the implementation of COSE with possible Multi Energy Extraction (MEE).

The last extraction method presented here is via longitudinal RF manipulation in order to extract the beam by sweeping a properly configured empty bucket through the beam stack. This method is known as Phase Displacement Extraction (PDE).

Extraction rates with these methods were observed which meet the clinical requirements and might also be considered compatible with FLASH.

INTRODUCTION

MedAustron is a PIMMS-based facility which employs third-order resonant extraction with a betatron core [1]. Throughout the acceleration process, the beam is maintained off-momentum. A dedicated resonant sextupole is used to excite a third-order resonance at a horizontal tune of $Q_x = \frac{5}{3}$. The beam is slowly extracted via acceleration in energy with the betatron core into resonance. As the beam approaches the resonance, the transverse amplitude of the particles within the unstable region increases every third turn. Particles that have a sufficiently large horizontal displacement enter an electrostatic septum which deflects the particles into the extraction channel [2, 3].

RADIO-FREQUENCY KNOCKOUT

With Radio-Frequency Knockout (RFKO), the amplitude of the circulating particles is gradually increased by applying a horizontal kick on the particles via a horizontal RF electric field application. The excitation frequency f_β required to excite the particles is given by:

$$f_\beta = (n \pm q_x) \cdot f_{\text{rev}} \tag{1}$$

In Eq. (1), q_x is the fractional part of the horizontal particle tune, n is an integer and f_{rev} is the revolution frequency of the particles. In order to cover the entire momentum spread of the beam and to account for amplitude-dependent tune shifting, the excitation frequency must be extended over a specific bandwidth. This frequency spread can be achieved by employing different RF modulation methods such as Frequency Modulation and Phase Shift Keying variants [6].

Simulation

To identify the optimal parameters for RFKO, a multidimensional scan was simulated for horizontal beam parameters encompassing tune Q_x, chromaticity Q'_x, and momentum offset of the beam $\frac{\Delta p}{p}$. Simulation of the extraction process was performed with MAD-X [4] with evaluation of the extraction efficiency and distribution parameters of the extracted beam at the electrostatic septum (ESE). Promising RFKO candidates with the parameter ranges summarised in Table 1 were identified. A comprehensive simulation of the different excitation patterns with these settings was subsequently performed with Xsuite [5].

Table 1: Settings for RFKO

Parameter	Value
Hor. Tune Q_x	[1.6707, 1.6717]
Ver. Tune Q_y	1.79
Hor. Chromaticity Q'_x	[-1.5, -0.6]
Ver. Chromaticity Q'_y	-3
Momentum offset $\frac{\Delta p}{p}$	$[-2.5 \cdot 10^{-3}, 0]$

Setup

In the absence of a dedicated RFKO exciter at MedAustron, the horizontal Schottky plates (l = 0.95 m) are used for this purpose. The excitation signal is generated using a Ettus USRP X310 Software Defined Radio (SDR). The

---

[*] florian.kuehteubl@medaustron.at

revolution frequency, horizontal tune, and excitation pattern parameters are input to a GNU Radio script, which computes and produces the required excitation waveform. This output is fed through a 1 kW amplifier before connection to the Schottky plates via an RF BalUn. An RF switch, toggled via the control system, is between the SDR and the amplifier for extraction control. Figure 1 presents a schematic depiction of the current RFKO setup implemented at MedAustron.

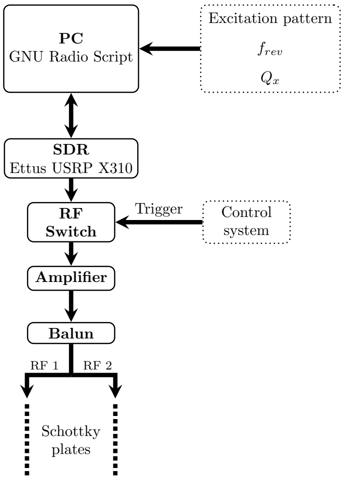


Figure 1: RFKO setup at MedAustron.

Measurements

Using the aforementioned setup, the beam could be extracted with a high efficiency of up to 95% and transmitted to the treatment room with a nearly constant particle flux. The use of the SDR in generating the RF excitation signal has allowed for a wide variety of signals to be evaluated with minimal effort.

CONSTANT OPTICS SLOW EXTRACTION

Constant Optics Slow Extraction (COSE) is an extraction technique that involves the synchronous ramping of all synchrotron magnets to move the resonance into the stationary beam. Unlike the Tune Sweep extraction method, in which only the quadrupoles are ramped, COSE ensures that the on-resonance separatrix remains constant throughout the extraction process. This leads to a superposition of the separatrices for different momenta, preventing angular sorting by momentum as observed for Tune Sweep extraction [7]. COSE is compatible with bunched beam operation, allowing the magnets to be ramped while the beam is still kept bunched. However, in bunched COSE, it is crucial to synchronously decrease the mean radial position of the beam relative to the resonance in synchronisation with the magnet ramping. This adjustment of the relative beam position ensures that the beam remains stationary while the resonance approaches. To achieve this, we use the radial loop feedback in such a way that it induces a momentum change of the beam precisely equal to the momentum shift caused by the COSE dipole ramping.

Multi Energy Extraction

In bunched COSE, the energy of the beam can be altered during the spill, allowing for Multi Energy Extraction (MEE). For MEE, multiple COSE ramps are executed consecutively, separated by segments where no extraction takes place. During these non-extraction segments, the dipole strengths are adjusted while the feedback loops are active, forcing a relative change in beam energy. The schematic configuration for MEE using bunched COSE is illustrated in Figure 2.

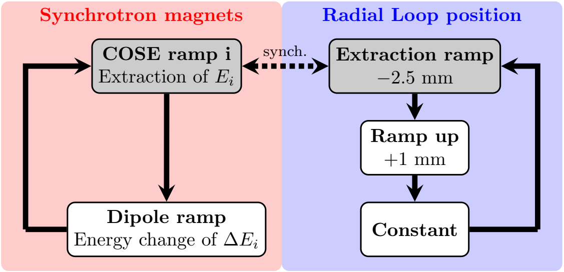


Figure 2: MEE with bunched COSE at MedAustron. The extraction phase is depicted with grey nodes, the energy change phase with white nodes.

By moving the beam away from the resonance during the energy change, the likelihood of particles being extracted due to ripples from the power supply of the synchrotron magnets is minimised.

Measurements

For MEE, measurements have revealed that adjusting the radial loop position during the energy change phase by 1 mm from the position after the last extraction phase proves effective. For the extraction phase, the radial loop position is ramped down by $\delta x = 2.5$ mm at a maximum horizontal dispersion of $D_x = 8.6$ m for each sub-spill, which corresponds to a relative momentum change given by Eq. (2):

$$\delta\left(\frac{\Delta p}{p}\right) = \frac{\delta x}{D_x} = \frac{-2.5\,\text{mm}}{-8600\,\text{mm}} = 2.91 \cdot 10^{-4} \tag{2}$$

Consequently, to achieve synchronisation between both ramps, the current of all synchrotron magnets must also be ramped down by the relative change specified in Eq. (2). The energy change in between the sub-spills ΔE_i can be adjusted by the ramp rate of the intermittent dipole ramps. The overall energy change is constrained by the energy acceptance of the High Energy Beam Transfer Line (HEBT), as the HEBT magnets are not capable of being ramped during the spill and thus need to be set to a specific energy value. However, by carefully optimising these HEBT setpoints, we were able to to increase the total energy acceptance of the HEBT to 3 MeV with the current configuration.

Figure 3 presents the extraction of ten energies, each with an energy difference ΔE_i of 300 keV, utilising bunched COSE. The upper plot displays the measured mean radial position of the beam, while the lower plot shows the extracted intensity. The extraction phases are highlighted in

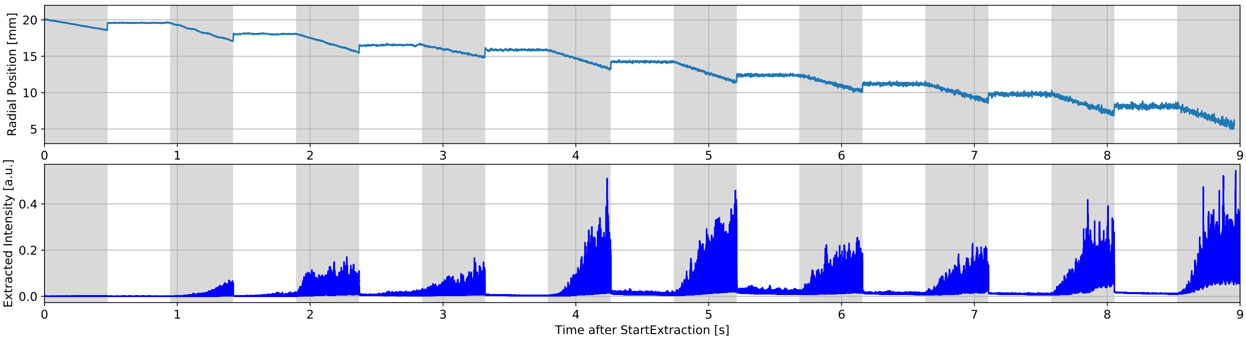


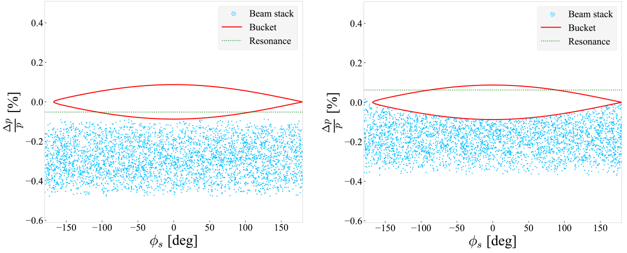
Figure 3: 10 energies MEE with bunched COSE.

grey, while the energy change phases are depicted in white. During the energy change phases, the extraction is almost completely suppressed. The first sub-spill tends to be relatively empty, primarily due to the limited number of particles within this first momentum slice. To homogenise the intensity of the sub-spills, the respective COSE ramp rates can be adjusted accordingly.

PHASE DISPLACEMENT EXTRACTION

Phase Displacement Extraction (PDE) was simulated for the MedAustron synchrotron in [8] and analysed as possible technique for FLASH in [9].

PDE involves sweeping an empty bucket through the beam stack by altering the frequency offset of the cavity. The bucket configuration is set up to overlap with both the resonance and the waiting beam, so that the particles that are following the separatrix are accelerated into resonance as the bucket traverses the beam. Figure 4 shows the BLonD [10] simulation of the bucket configuration in longitudinal phase space for PDE with a frequency offset ramp from 2.5 kHz to 1.5 kHz with a bucket voltage of 200 V.



(a) $t = 0$

(b) $t = t_{\mathrm{sweep}}$

Figure 4: Longitudinal phase space for PDE at the start and the end of the bucket sweep.

The speed of the sweep can be controlled by adjusting the ramp rate of the frequency offset. Multiple sweeps can also be combined for pulsed extraction. In this case, when the frequency is ramped back to the starting point, we set the bucket voltage (and hence the bucket height) to zero to prevent any extraction. Once back at the starting point, the voltage is increased again, and the sweep can be repeated.

PDE was successfully tested at MedAustron, demonstrating the capability of the RF system of the synchrotron to perform multiple bucket sweeps. However, further refinements are necessary regarding the frequency sweeps and bucket voltage to ensure a constant intensity and effective extraction.

CONCLUSION

Successful testing of alternative extraction methods, namely Radio-Frequency Knockout (RFKO), Constant Optics Slow Extraction (COSE), and Phase Displacement Extraction (PDE), was carried out at MedAustron. The proof of concept was demonstrated for each method by extracting the circulating beam into the treatment room. However, further optimisation is required to establish these techniques as viable alternatives to the default betatron core extraction method at MedAustron.

Table 2 provides a summary of the advantages and disadvantages of each tested technique for possible clinical usage. RFKO and COSE are both compatible with bunched beams, making them suitable for MEE. On the other hand, PDE requires an empty bucket and is thus not compatible with bunched beams for the current setup at MedAustron. All three techniques could achieve extraction rates compatible with FLASH. For RFKO, the extraction speed is limited by the maximum kick strength, while for COSE, the ramping speed of the dipoles is the limiting factor.

Table 2: Summary of alternative extraction methods

	Extraction method		
	RFKO	COSE	PDE
Bunched beam	✓	✓	✗
MEE	✓	✓	✗
FLASH	(✓)	(✓)	✓

ACKNOWLEDGEMENTS

This work has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

REFERENCES

[1] P. J. Bryant *et al.*, "Proton-Ion Medical Machine Study (PIMMS) Part I", CERN/PS 99-010 (DI)

[2] M. G. Pullia *et al.*, "Betatron Core driven Slow Extraction at CNAO and MedAustron", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016. pp. 1330-1333. `doi:10.18429/JACoW-IPAC2016-TUPMR037`

[3] M. T. F. Pivi *et al.*, "Overview and Status of the MedAustron Ion Therapy Center Accelerator", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017. pp. 4627-4630. `doi:10.18429/JACoW-IPAC2017-THPVA076`

[4] MAD - Methodical Accelerator Design, `http://mad.web.cern.ch/mad/`

[5] Xsuite, `https://xsuite.readthedocs.io/en/latest/`

[6] E. Feldmeier *et al.*, "Upgrade of the Slow Extraction System of the Heidelberg Ion-Beam Therapy Centre's Synchrotron", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, June 2022. pp. 2509-2512. `doi:10.18429/JACoW-IPAC2022-THPOST029`

[7] P. A. Arrutia Sota, "Implementation of a Tune Sweep Slow Extraction with Constant Optics at MedAustron", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, June 2022. pp. 567-569. `doi:10.18429/JACoW-IPAC2022-WEPOST015`

[8] U. Dorda, A. Wastl, H. Schonauer, M. Benedikt, "Simulation studies of longitudinal RF-noise and phase-displacement acceleration as driving mechanism for the MedAustron synchrotron slow extraction", in: *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013. pp. 2501-2503.

[9] P. A. Arrutia Sota *et al.*, "Millisecond burst extractions from synchrotrons using RF phase displacement acceleration", in *Nuclear Inst. and Methods in Physics Research, A 1039* (2022) 167007. `doi:10.1016/j.nima.2022.167007`

[10] BLonD - Beam Longitudinal Dynamics simulator, `https://blond.web.cern.ch/`