UPDATE ON SLOW EXTRACTION STUDIES AT MEDAUSTRON

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Abstract

This contribution summarizes recent developments in slow extraction studies at the MedAustron center for ion beam therapy and research. In particular studies concerning radio frequency knock-out (RFKO) and phase displacement extraction (PDE) are presented. The experimental RFKO studies employ a new signal generator system based on a micro-telecommunication architecture. The experimental RFKO and PDE studies are supported by Xsuite particle tracking simulations.

INTRODUCTION

The main accelerator at the treatment and research center MedAustron is a synchrotron based on the proton ion medical machine study (PIMMS) [1, 2]. Proton and carbon ion beams for cancer treatment are extracted at 62 - 252 MeV (p^+) and 120 - 402 MeV u^{-1} ($^{12}C^{6+}$) using betatron core driven 3rd-order resonant slow extraction [3]. Other centers providing ion beams for medical applications, such as CNAO [4] and HIT [5], use radio frequency knock-out (RFKO) [6] as extraction mechanism. Both methods enable extraction of spills with stable beam position and width, as well as a steady particle rate, which is important for active scanning of tumor tissue. Table 1 lists the main differences of the two extraction mechanisms. For delivering spills with similar beam properties using betatron core or RFKO extraction a change in optics is necessary due the respective driving mechanism.

Table 1: Conceptual Comparison of Betatron Core and RFKO Extraction for Medical Applications

	Betatron core	RFKO
Driving mechanism	momentum	amplitude
Horizontal chromaticity	high	low
Longitudinal distribution	coasting	bunched[1]

RFKO is compatible with dynamic intensity regulation and facilitates multi-energy extraction operation, e.g. [7, 8]. Both features reduce beam-on time during treatment.

This proceeding presents the developments at MedAustron regarding preliminary tests for clinical implementation of RFKO and introduces first use cases for non-clinical research users enabled by the new RFKO setup.

This proceeding also shows the advances made in modeling phase displacement extraction (PDE) [9] with Xsuite [10]. Similar to slow extraction with the betatron core, PDE is a momentum-driven slow extraction mechanism, but enables gated application and great adaptability to user requests, similar to RFKO.

RFKO AT MEDAUSTRON

At MedAustron an experimental RFKO setup is used for system implementation tests, as well as for research projects of the non-clinical research user groups. The research topics include, among others, multi-energy extraction [11], mixed-species ion beam extraction [12] and the delivery of ultra-high dose rate (UHDR) beams [13, 14]. These studies are supported by Xsuite simulations.

Setup

In the experimental RFKO setup the signals for transverse excitement of the beam are applied via the horizontal plates of the Schottky monitor [15, 16]. The RF signal is generated using a micro-telecommunications architecture (µTCA-crate). Previously, a software defined radio was used for generating the RFKO signals. The low-level signal is amplified by a 1 kW amplifier and connected to the plates via an RF BalUN. The provisory setup can be controlled via a Python scripting interface.

µTCA-crate The µTCA-crate has been developed as a replacement for the injector and synchrotron low-level RF systems at MedAustron. It uses direct sampling and direct digital synthesis with high speed ADC/DACs (analog-digital converter/digital analog converter) and an internal sampling rate of 10 MS/s for cavity, beam phase and radial beam position regulation. The option to combine and modify signals enables the generation of suitable RFKO signals. Since the transverse motion of all particles has to be excited, the signals should cover the entire tune spread of the beam. Furthermore combining different signals proved to be advantageous, because unfavorable spill qualities, such as ripples, can be reduced [17]. At present, two operational modes are implemented for RFKO, one of which is binary phase shift keying (BPSK) and the other one is frequency modulation (FM). For both modes an amplitude modulation (AM) for the strength of the signals can be assigned. For the generation of a BPSK signal, the phase of a sinusoidal signal is randomly switched between $(0, \pi)$ every Δt_{flip}, typically in the order of 100 µs. The FM signal is generated as a linear frequency sweep over a specified bandwidth. The frequency signals resemble a staircase function, in which the applied

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[1] Both coasting and bunched beams can be extracted using RFKO. However the longitudinal motion of the bunched beam reduces the ripple factor significantly and is thus preferred for medical applications.

frequency is changed at most every 0.1 µs. To provide an example, Fig. 1 displays the Fourier transforms (FTs) of a programmed 20 kHz BPSK signal (orange), as well as the signal measured at the Schottky plates (blue). The signals show good agreement.

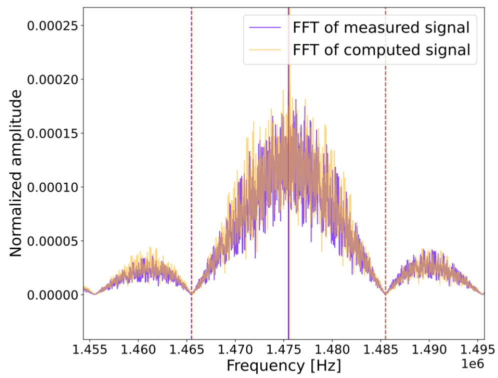


Figure 1: Fourier transforms (FTs) of the computed (orange) and measured (blue) signals are shown for a bandwidth of 20 kHz. The dashed vertical lines on either side mark the edges of the main lobe, which are used to determine the null-to-null bandwidth. The solid lines show the central frequency of the respective signal.

Current Applications

Tests for operational implementation Beam tests and beam-based optimizations have been conducted to evaluate RFKO as potential replacement for betatron core slow extraction in clinical operation, using both carbon ion and proton beams, in coasting and bunched mode. These activities included optimization of synchrotron optics and tuning of the RFKO excitation parameters to achieve acceptable spill quality [18]. Further, dedicated measurements were performed to verify that the delivered beam energy and associated beam parameters meet the required precision and reproducibility, supporting a robust energy verification workflow. In parallel, recent RFKO tests were carried out together with the implementation of B-field regulation for the synchrotron dipoles [19], demonstrating faster magnetic field stabilization at flattop compared to current-control mode and improved stability of beam conditions during extraction. With empirical AM functions flat spills were achieved for FM and BPSK signals, see exmaple in Fig. 2. In the course of the current FLASH-BPM project [20] direct beam control via a non-clinical hardware setup is being investigated with the goal of enabling fast dynamic intensity regulation and beam position scanning for research users.

Multi-energy extraction The current workflow for ion beam therapy at MedAustron, specific to the synchrotron, can be summarized as follows: injection, capture, acceleration to the energy requested by the treatment plan, extraction of the total dose for this energy slice as prescribed by the treatment plan. Subsequently, any unused beam left in the synchrotron is dumped, before preparing the synchrotron

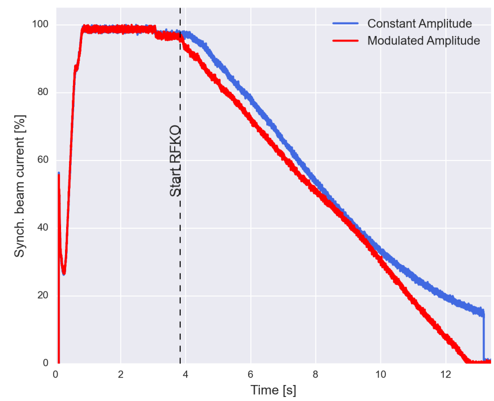


Figure 2: Signal of circulating beam during RFKO extraction using a broad-band BPSK signal, without (blue) and with AM (red).

for the next injection. The efficiency of treatments can be improved by re-acceleration or deceleration of the beam and extracting multiple energies within one cycle, multi-energy extraction (MEE). Currently, several approaches to implementing MEE with different energy steps and gated RFKO signals are under investigation, with a focus on minimizing the time required for the energy changes, while mitigating losses. Further information can be found in [11]. Within the scope of this project, suitable RFKO signals for bunched beams with discrete extraction stages are studied.

PDE AT MEDAUSTRON

Another momentum-driven slow extraction mechanism is phase displacement extraction (PDE). In PDE an RF bucket is swept through a coasting beam by ramping the RF frequency [9, 21]. The beam behaves like an incompressible fluid and moves through the channel around the non-stationary bucket. This front-end acceleration pushes the beam into the resonance. Due to its similarity to betatron core driven extraction, most elements can be kept at the commissioned clinical settings for first tests. Contrary to the RFKO setup, no additional installation is required. Thus PDE is a simple way to provide e.g. pulsed or UHDR beams to research users with the existing infrastructure. Additionally it proved to be very valuable for initial studies in the mixed beam project as a provisional extraction modality [22, 23]. In these studies the primary goal was quantification of the Helium content within the mixed beam and not the temporal structure of the spill, as in the current investigations using RFKO extraction [12]. While its experimental implementation at MedAustron has been established, we are currently improving the modeling of PDE in tracking simulations using the Xsuite framework.

Modeling in Xsuite

In simulations with an RF frequency unequal to a harmonic of the designed, on-momentum revolution frequency, $f_{RF} \neq h f_0$, as required by the PDE frequency sweep, the phase offset per turn is modeled as a shift in the longitudinal coordinate ζ of the particles in regard to the position of the reference particle. As defined in Xsuite the zero-crossing of the RF sine wave corresponds to the longitudinal position of the reference particle, per default $\zeta = 0$. The required shift in the longitudinal coordinate ζ can be calculated as

$$\Delta\zeta = -\beta_0 c \left(\frac{1}{f_{\mathrm{RF}}} - \frac{1}{f_0} \right), \tag{1}$$

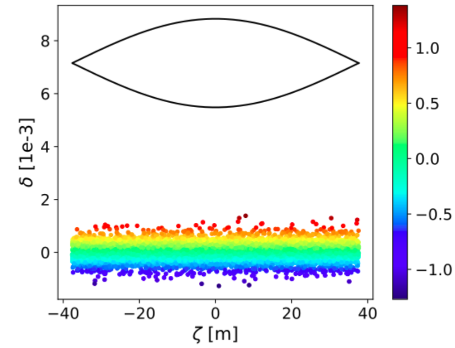
using the relativistic velocity β_0 and the speed of light c.

Figure 3 shows the evolution of such a time-dependent frequency offset in a tracking simulation using 5000 particles ($^{12}\mathrm{C}^{6+}$, $E_{\mathrm{kin}} = 402.8\,\mathrm{MeV\,u^{-1}}$). A coasting beam was initialized on-momentum with a Gaussian momentum distribution with $\delta_{\mathrm{rms}} = 3.5 \times 10^{-4}$. An RF bucket with a voltage of 1.4 kV passed through the beam in 12.6 ms with $\frac{\mathrm{d}f}{\mathrm{d}t} = 140\,\mathrm{Hz\,ms^{-1}}$. *Xtrack* version 0.89.4 was used for the simulation. Benchmarking of this and similar PDE simulations with measurements is ongoing.

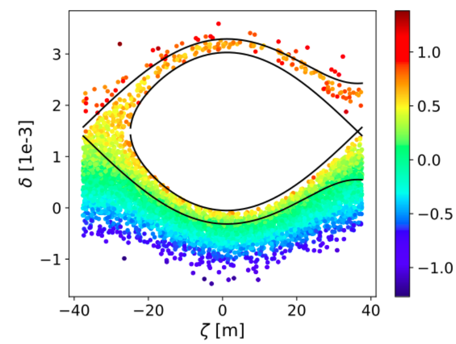
EXPERIMENTAL BEAM MODALITIES

Non-clinical research user groups at MedAustron further explore strategies for delivering various novel ion beam modalities. These include, among others, mixed helium/carbon beams for online monitoring in carbon ion therapy and ultra-high dose rate beams for research on the FLASH effect as well as detector development. Within the mixed beam project at MedAustron, mixed He/C beams, can be provided for first range probing experiments. While the mixing ratio is variable, a typical value is $\frac{N_{\mathrm{He}}}{N_{\mathrm{C}}} \approx 0.1$. RFKO is a suitable extraction method to simultaneously extract these dual-species beams with approximately constant mixing ratio over the entire spill, even in the presence of slight differences in beam rigidity and phase space distributions [12]. In the current setup, the dual-species beams are extracted using a broad-band BPSK signal with a null-to-null bandwidth of 20 kHz, with the center frequency tailored to achieve an approximately flat He/C ratio.

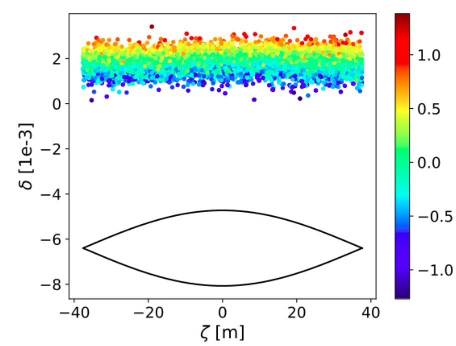
Additionally, different methods for delivering ultra-high dose rate (UHDR) beams for non-clinical research applications, e.g. research on the FLASH effect, are under investigation [13, 14]. At MedAustron proof-of-principle tests with both RFKO and PDE demonstrated the successful UHDR beam delivery of both continuous and pulsed beams with arbitrary pulse lengths down to < 1 ms. In the last years, such beams have been provided to first research users on an experimental basis. With the new µTCA-based RFKO signal generator, gated RFKO applications and AM for subsequent pulses have become feasible and reproducible allowing for a stable accelerator setup. This enabled MedAustron and non-clinical research partners to trigger the prototyping of a silicon carbide based detector solution [24] to monitor UHDR pulses and potentially enable pre-clinical intensity control for research applications.



(a) Initial state: Stationary bucket initialized above the coasting beam.



(b) During sweep: Particles travel through the channel.



(c) Final state: The RF bucket stops moving.

Figure 3: Example of PDE tracking simulation using Xsuite. The simulation used 5000 particles ($^{12}\mathrm{C}^{6+}$) with $E_{\mathrm{kin}} = 402.8\,\mathrm{MeV\,u^{-1}}$. Please note that the vertical scale (δ) is adapted for each plot. The colorbar on the right side shows the relative momentum offset of each particle at the start of the simulation.

SUMMARY

This proceeding provides an update on recent slow extraction developments at MedAustron. The new signal generator of the experimental RFKO setup and various application of its capability are described. These applications include the extraction of mixed ion beams with nearly constant mixing ratio, pulsed extraction and multi-energy extraction studies. Furthermore advances in the simulation of PDE are presented.

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