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INVESTIGATING PULSED SLOW EXTRACTION SCHEMES AT THE MedAustron SYNCHROTRON

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Abstract

The temporal characteristics of ultra-high dose rate beams delivered for FLASH research are often dictated by machine constraints, making it challenging to compare the outcomes across studies performed at different facilities. To broaden the opportunities for systematic, non-clinical FLASH research, this study explores methods to deliver beams with customizable time structures from a medical synchrotron. The studies are being performed at the center for ion beam therapy and research MedAustron and aim at extracting ultra-high dose rate proton beams in a series of pulses with adjustable dose per pulse, pulse length and pulse separation down to sub-ms levels. This contribution describes the implementation of the extraction methods explored for this application, phase displacement and radio frequency knockout extraction, and presents first measurement results. The measurement setup employs a silicon carbide detector in conjunction with a 20 MHz bandwidth amplifier, enabling intensity measurements with a resolution exceeding the synchrotron revolution period.

INTRODUCTION

Radiotherapy with ultra-high dose rates (UHDR) has recently gained significant attention due to its ability to reduce radiation-induced toxicity in healthy tissue without compromising its effect on the tumor. The required beam parameters for achieving this so-called FLASH effect are often characterized by average dose rates exceeding $\gtrsim$40 Gy/s [1]. However, it is essential to note that the occurrence of the FLASH effect potentially also depends on the time structure of the dose, which is at some facilities delivered in quasi-continuous mode, at others in the form of pulsed beams with sub-millisecond to millisecond (macro-)pulse separation [2–4]. It can be difficult to compare experimental studies reporting on both observed and non-observed instances of the FLASH effect, as they are often conducted on different machines and hence are based on different time structures. Thus, to move forward, studies are required that not only focus on the average dose rate but also systematically examine the impact of the time structure on the FLASH effect [3, 4].

Motivated by this requirement, we explore methods to extract UHDR proton beams from a synchrotron in a series of pulses with inter- and intra-spill adjustable dose per pulse, pulse length and pulse separation down to a sub-ms level. The proposed methods include radio frequency knockout (RFKO) and phase displacement extraction (PDE). Although the investigations are currently focused on proton beams only, the techniques being developed can be adapted for extracting ions or also pulsed beams at conventional dose rates.

This contribution describes the proposed methods for extracting and measuring the pulsed UHDR beams, showcases the technical implementation, and highlights initial findings. The presented setups pave the way for a more systematic evaluation of the potential and limitations of PDE and RFKO for delivering such customized pulsed beams in further studies. It is important to note, that as the current focus is on investigating deliverable time structures, further challenges concerning FLASH-compatible beams such as total dose, irradiation of larger volumes, or the impact of transverse beam profiles are not directly addressed within this paper.

MATERIALS AND METHODS

The presented measurements were performed at the synchrotron of the MedAustron facility located in Wiener Neustadt, Austria. The accelerator is based on the proton-ion medical machine study (PIMMS) [5], delivers proton and carbon beams for research and clinical irradiation, and is currently being commissioned to even provide helium beams for research applications [6]. The facility hosts a diverse non-clinical research community and, among others, provides an infrastructure for biological and pre-clinical studies. The beam is extracted using third-order resonant extraction, which is driven by a betatron core. However, ongoing research [7] also explores alternative extraction methods at MedAustron, such as the here-employed RFKO and PDE.

The provisional machine settings and beam parameters used in the presented measurements are summarized in Table 1, with the settings for RFKO being motivated by ref. [7]. All measurements were performed for coasting 250 MeV proton beams. The momentum distribution of the coasting beam is Gaussian in case of the RFKO tests, but flattened in case of the PDE measurements due to a phase jump being performed prior to extraction [8]. Beyond assessing the attainable pulse length, separation and dose, this study aims at exploring the structure within a single pulse, which requires a dosimetry set-up with sufficient bandwidth.

Phase Displacement Extraction Setup

One of the explored methods for extracting the targeted customizable pulsed beams is PDE. In this extraction scheme, particles within a coasting beam are accelerated (or decelerated) by an empty bucket that sweeps through the

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Table 1: Machine and Beam Parameters. †Momentum Dist.: Gaussian for RFKO; Quasi-Homogeneous for PDE.

Parameter	**Unit**	**Value PDE**	**Value RFKO**
Particle	-	protons	protons
E_{kin}	MeV	≈250	≈250
$N_{\mathrm{p+}}$	10^{10} p+	≈1.5	≈1.5
$\epsilon_{\mathrm{n,\,rms},x}$	mm mrad	0.6	0.6
f_{rev}	MHz	2.370	2.371
Q_x	-	1.679	1.672
Q'_x	-	-4	-1.3
$\delta_{\mathrm{rms}}{}^{\dagger}$	10^{-3}	1.6	0.35
S	$\mathrm{m}^{1/2}$	280	350

coasting beam stack, to be progressively pushed into resonance. PDE has been previously studied for the MedAustron synchrotron in proof-of-principle simulations and measurements [7, 9], mostly focusing on spills with conventional dose rate and spill duration. Additionally, the extraction of FLASH-compatible dose rates in pulses lasting $\approx 10^4$-10^5 turns has been described in simulations [10] based on the PS, the SPS and PIMMS-like machines as examples.

In the measurements presented here, the empty bucket is initialized with V_{on}=1 kV at a relative frequency offset of $\Delta f_{\mathrm{st}}/f$=8.5 × 10^{-3} and linearly swept to $\Delta f_{\mathrm{end}}/f$ = -8.5×10^{-3} within t_{sweep}=0.4 to 100 ms. This corresponds to ≈1000 to 3 × 10^5 turns for 250 MeV protons. After each sweep, at $\Delta f_{\mathrm{end}}/f$, the RF voltage is set to V_{off}=0 kV to allow for resetting the frequency to $\Delta f_{\mathrm{st}}/f$ without disturbing the remaining beam. This frequency sweep can be repeated multiple times, which enables to extract the beam in multiple pulses. The initial offset of $\Delta f_{\mathrm{st}}/f$ is chosen to provide sufficient distance from the waiting beam stack when switching the RF voltage on (the beam has a rms momentum spread of $\delta_{\mathrm{rms}} \approx 1.6 \times 10^{-3}$; the empty bucket has a height of $\hat{\delta}=2\times 10^{-3}$ and an initial frequency offset $\Delta f_{\mathrm{st}}/f$, which corresponds to a relative momentum offset of $\Delta p_{\mathrm{st}}/p \approx 0.02$).

To achieve flexible pulse characteristics, one can modulate the extracted dose by adjusting the bucket voltage and sweep time. Additionally, pulse separations can be fine-tuned by adjusting the time in between sweeps. With the low level RF (LLRF) control offering adjustments with 100 kHz time resolution [11], the frequency sweep and bucket voltage could even be varied within a single sweep, thus also allowing for nonlinear sweeps.

Radio Frequency Knockout Extraction Setup

An alternative method for pulsed slow extraction is RFKO. This method employs a horizontal RF field to increase the horizontal amplitude of the particles toward the separatrix, driving the extraction through amplitude selection. The RFKO field oscillates with $f_\beta = f_{\mathrm{rev}} \cdot (n \pm q_x)$. Here n is an integer, f_{rev} the revolution frequency, and q_x the fractional horizontal tune. At the MedAustron synchrotron RFKO was already explored for conventional extractions [12], optimized for ripple reduction [7] and tested for high dose rate extractions [13]. Concerning pulsed beams, we add that a gated RFKO extraction is employed at the Heidelberg Ion Beam Therapy Center HIT to deliver conventional dose rates with on/off patterns in the order of tens of ms [14].

As the current accelerator layout at MedAustron does not include a dedicated RFKO exciter cavity the horizontal Schottky monitor is used as a provisional RF kicker. The excitation signal is generated using the synchrotron LLRF system and amplified using a custom-built 1 kW amplifier. The amplified signal is fed to the Schottky plate via a matched RF BalUn. To obtain a synchronized RFKO signal the DSP code of the existing LLRF [11] is slightly adapted to allow for direct amplitude control of a phase-locked signal with a different frequency tuning word adapted to the resonant frequency. Considering the limited excitation time within a single pulse, i. e. sub-ms to ms, we do not use an excitation signal with finite bandwidth, but rather a sinusoidal excitation signal with a frequency $f_\beta \approx f_{\mathrm{rev}} \cdot q_x$. Modulating the amplitude of the established excitation signal is possible with a 100 kHz time resolution. This enables flexible adjustments of pulse on/off times and amplitudes within tens of µs, which corresponds to tens of turns for 250 MeV protons. It should be noted, that these numbers refer to the time scale at which the excitation signal can be switched on or off. For evaluating the width of the extracted pulse, also the finite time the particles need to increase in amplitude and reach the extraction septum needs to be considered [15].

Dosimetry Setup

Given that ionization chambers normally used for online dosimetry are expected to saturate at high dose rates, we employ a silicon carbide (SiC) sensor for dosimetry. SiC is known to allow for extremely high fluence measurements without saturating [16]. Besides working at high fluences, SiC sensors are radiation hard, promising a useful life-span up to radiation doses of $10^{16}\ n_{\mathrm{eq}}\mathrm{cm}^{-2}$ [17]. Leakage currents are extremely low even when exposed to radiation doses up to $10^{16}\ n_{\mathrm{eq}}\mathrm{cm}^{-2}$ and operated at room temperatures [18]. Thus, in contrast to silicon, no cooling of the sensors is required, and sensors can operate in DC coupled mode without dark current compensation. Also, SiC sensor costs are falling and wafers with a diameter of up to 8 inches are becoming available due to the semiconductor industry's adoption of the material, making it an interesting alternative to ionization chambers in online dosimetry.

The employed sensor is provided by the Instituto de Microelectronica de Barcelona, IMB-CNM-CSIC, Spain [19]. The active area is round with a diameter of 1 mm and an active thickness of 50 µm. The sensor is biased at 400 V in order to fully deplete the active volume. The signal is amplified using a custom-built transimpedance amplifier with a gain of 66 dB Ω. The bandwidth of the sensor and amplifier combination is determined to be 20.7 MHz and the oscilloscope was configured to sample at a rate of 50 MHz with 16 bit resolution.

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RESULTS AND DISCUSSION

For PDE, Fig. 1a features first measurements to demonstrate that the extracted pulse length and dose per pulse are adjustable by adapting the sweep time. When the sweep time approaches ≲1-2 ms, corresponding to a beam stack transit time of ≲0.5 ms or ≈1000 turns, respectively, the pulses start to blend together with a decreased yet non-zero dose in between them. Figure 1b illustrates the capability of modulating the pulse amplitude by varying the bucket voltage, here for t_{sweep}=2 ms. It is important to note that the amplitude modulation function (black in Fig. 1b) was not optimized in this experiment. The goal would be to adapt it in order to extract multiple pulses with harmonized dose per pulse. Note, that these results should be regarded in a relative context, particularly considering their dependency on the provisional machine parameters.

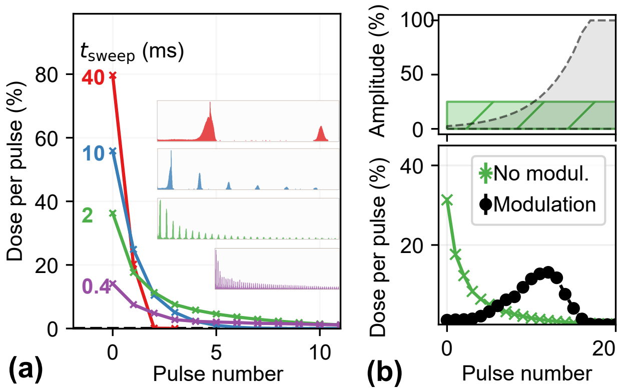

Figure 1: Pulsed extraction via PDE; a) relative dose per pulse for varying sweep times (V=1 kV); b) amplitude modulation through variation of the bucket voltage (t_{sweep}=2 ms).

For RFKO, Fig. 2 demonstrates the efficacy of modulating the extracted dose pulse-per-pulse by adjusting the excitation voltage. When applying an RFKO signal with constant amplitude, the dose per pulse decreases significantly within the first pulses (red curves). Applying a manually optimized amplitude-modulation function, however, enables emptying the synchrotron within ≈80-100 pulses of similar amplitudes (black). Building upon the amplitude modulation function established above, the robustness of the extracted dose per pulse to variations in pulse-off times is assessed in Fig. 3. The gray-shaded curve indicates the dose per pulse when extracting with a constant pulse-off time of 1 ms and serves as a reference. In contrast, in sets 1-3, we randomly varied the pulse-off times between 0.1-10 ms, while maintaining the pulse-on time of 1 ms. A systematic difference in dose is observed for the first pulses, which are extracted using the smallest RFKO amplitudes. This difference diminishes for the later pulses. The results are promising for flexibly providing pulses with similar doses and duration but different spacing, which can also be non-periodic.

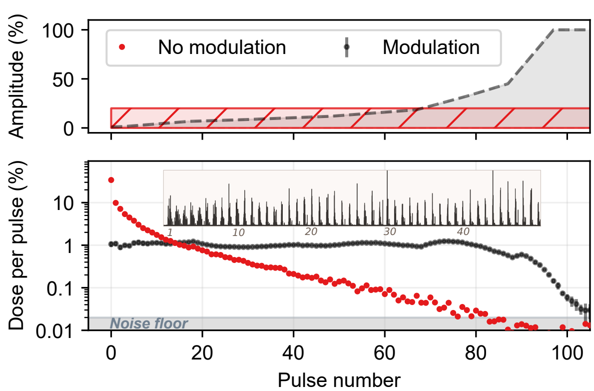

Figure 2: Pulsed RFKO excitation with constant (red) and modulated amplitude (black). Top: excitation amplitude relative to the maximum configurable kick without saturation; bottom: relative dose per pulse. t_{on}=t_{off}=1 ms.

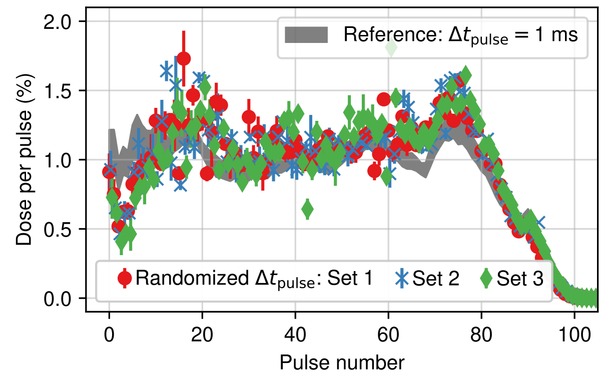

Figure 3: Measured relative dose per pulse for constant (t_{off}=1 ms, gray-shaded) and randomized pulse separations ($t_{off,i}$ ∈ [0.1, 10 ms], set 1-3). 1σ error bars, t_{on}=1 ms.

SUMMARY AND OUTLOOK

Two extraction methods, phase displacement and radio frequency knockout, are currently being explored for their potential to extract pulsed ultra-high dose rate beams with tailored pulse length, separation, and dose per pulse. Such customized beams would facilitate systemic research on the sensitivity of the FLASH effect to the time structure of the delivered dose. Initial measurements show promise for both techniques. Moving forward, the limits of these methods will be explored in simulations and measurements, considering factors such as minimal pulse length, reproducibility, and structure within a pulse. It should be noted that providing such a beam for research purposes also necessitates establishing a viable dosimetry setup. The translation of the applied setup into a beam monitoring system is another aspect that needs to be addressed separately.

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