PROGRESS ON MIXED He/C BEAM SLOW EXTRACTION AT MedAustron

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Abstract

The recent availability of mixed $^{4}He^{2+}$ and $^{12}C^{6+}$ beams for research on online treatment monitoring in carbon ion therapy is introducing new challenges for slow extraction from synchrotrons. Ideally, the mixed beam should be extracted with a constant helium-to-carbon ratio over the entire spill. This is complicated by species-dependent dynamics: the two ion species feature an effective rigidity offset, which is 0.095 % to 0.135 % across the clinical energy range at MedAustron. Additionally, when generating the mixed beam via sequential synchrotron injection, helium and carbon ions occupy distinct regions in horizontal phase space. This paper summarizes the first experimental experience with dual-species RF knockout (RFKO) extraction at MedAustron.

INTRODUCTION

A recent proposal for online range monitoring in ion beam therapy is to irradiate patients with mixed helium ($^{4}He^{2+}$) and carbon ion ($^{12}C^{6+}$) beams. At the same $\frac{E}{m}$ $^{4}He^{2+}$ has an approximately three times larger range in matter than $^{12}C^{6+}$. The tumor can thus be treated with the $^{12}C^{6+}$ Bragg peak, while $^{4}He^{2+}$ ions are detected behind the patient for range verification. Since 2023, significant efforts have been made to provide such beams for research at the MedAustron center for ion beam therapy and research [1, 2], with first range probing experiments being carried out since late 2025. Similar studies have been performed at GSI since 2023 [3,4].

One key topic in this context is the simultaneous slow extraction of both ion species. To enable concurrent treatment and monitoring, the beam should ideally be extracted over the entire spill with approximately constant helium fraction

$$r(t) = \frac{N_{\mathrm{He}}(t)}{N_{\mathrm{C}}(t) + N_{\mathrm{He}}(t)} \approx \text{const.}\,,$$

where $N_{\mathrm{He}}(t)$ and $N_{\mathrm{C}}(t)$ are the extracted fluxes per species. However, this is not a trivial task, due to (a) energy-dependent differences in the magnetic beam rigidity $B\rho$ arising from the small relative offset in mass-to-charge ratio, $\frac{\Delta(m/q)}{(m/q)} = 0.065\,\%$, and (b), subject to the mixed beam generation scheme, differences in the horizontal phase space distribution. Adding to this complexity, the research field is still in an early stage, and users ideally want access to a variety of mixed beam configurations to explore detector technologies and treatment planning concepts, such as varying r, fluxes or extraction energies.

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Since 2025, first dedicated mixed-beam slow extraction experiments have been performed at the MedAustron synchrotron. While settings have been found empirically to provide “flat He/C” spills for specific energies and helium fractions r, enhanced understanding is desired to improve control and reduce tuning effort when new beam parameters are requested. Selected results are reported in this paper.

MIXED BEAM AND EXTRACTION SETUP

Mixed Beam Generation and Beam Characteristics

The general mixed-beam setup employed at MedAustron is described in Refs. [1, 2, 5–7]. The mixed beam is generated by sequentially injecting $^{4}He^{2+}$ and $^{12}C^{6+}$ into the synchrotron via two multiturn injections. The helium fraction r can be controlled by adjusting the amplitude of the second multiturn injection orbit bump. As a result, the two species are injected into distinct regions of horizontal phase space ($^{4}He^{2+}$ core, $^{12}C^{6+}$ annulus), which must be taken into account when specifying the initial distribution prior to slow extraction. To provide this input, the resulting beam distributions are currently being modeled in Xsuite simulations [8] and characterized experimentally using scraper-based profile measurements in the synchrotron [6].

When the RF system is turned on, both particle species must feature the same revolution frequency f_{rev}, despite their relative offset in m/q and resulting difference in closed-orbit length. Consequently, $^{4}He^{2+}$ is accelerated to slightly higher $\beta\gamma$. The offset $\hat{\delta} = \frac{\Delta(\beta\gamma)}{\beta\gamma}$ depends on the proximity to transition energy [5]. In a PIMMS-like synchrotron [9, 10], as installed at MedAustron, we obtain $\hat{\delta} \approx 3 \times 10^{-4}$ to 7×10^{-4} for clinical extraction energies of $E_{\mathrm{kin}} = 120\,\mathrm{MeV/u}$ to $400\,\mathrm{MeV/u}$. Combined, the offsets in m/q and $\beta\gamma$ yield a total effective rigidity offset of $\delta_{\mathrm{eff}} = \frac{\Delta(B\rho)}{(B\rho)} \approx 0.95 \times 10^{-3}$ to 1.35×10^{-3}, which is of the same order of magnitude as typical rms momentum spreads in our mixed-beam setups, $\delta_{\mathrm{rms}} \approx 3 \times 10^{-4}$ to 6×10^{-4}.

Setups for Slow Extraction and Helium-Fraction Detection

For mixed-beam extraction, we use radio frequency knockout (RFKO) slow extraction as the baseline approach. We employ a new experimental RFKO setup with a µTCA-crate-based RFKO signal generator [11], which allows us to flexibly apply a variety of RFKO signals and combinations thereof [12]. The clinically employed betatron core extraction cannot be used for mixed-beam extraction, as in the current configuration it is incompatible with the sequential injection setup. For some tasks, for which the spill structure is not of primary relevance, we also use phase displacement extraction (PDE), a momentum-driven slow extraction mechanism, as it does not require any hardware adaptations and is therefore more accessible than RFKO [12, 13]. However, due to its limited flexibility in tuning the extracted He:C ratio, it is not selected as our primary approach. This paper focuses exclusively on RFKO-based results.

In the research irradiation room, a two-stage ionization chamber (IC) telescope is used to quantify the extracted helium fraction $r(t)$, currently with 50 ms time resolution [5]. In this setup, r is obtained by comparing the currents measured in the two range-separated ionization chambers (below labeled IC1 and IC2), together with input from calibration measurements and Monte Carlo simulations.

FIRST EXTRACTION EXPERIENCE

Multi-second RFKO Frequency Sweep

The objective of one of the first experiments was to verify the assumed rigidity separation and identify the resulting betatron frequencies at which $^{4}He^{2+}$ and $^{12}C^{6+}$ are expected. For this, we swept the RFKO frequency f_{ko} over several seconds through a coasting mixed-beam with $r \approx 0.1$. We used different $\frac{df_{ko}}{dt}$, sweeping always from high frequencies towards the resonance. Machine and beam parameters are listed in Table 1.

Figure 1d shows a schematic Steinbach diagram of this setup. The central $^{12}C^{6+}$ frequency is computed as $f_{\beta,C} = (n \pm q_x) f_{rev}$, with harmonic $n = 0$ and measured values for f_{rev} and the fractional tune q_x. $f_{\beta,He}$ is derived analytically from the mentioned δ_{eff} estimate [5]. The opaque and shaded rectangles roughly indicate the expected rms and 95 % occupancy regions, respectively. These remain very approximate estimates, as a characterization of the mixed-beam distribution is challenging with the current diagnostics. More precise studies are ongoing [6].

Figures 1a and b show that the frequency dependence of the extracted helium and carbon flux is essentially indepen-

Table 1: Approximate Synchrotron and Beam Parameters for the Presented Mixed Beam Extraction Experiments

Param.	**Freq. Sweep**	**BPSK**
E_{kin} (MeV/u)	200	200
Q_x	1.672	1.672
n	0	1
ξ_x	−1.2	−1.2
α_c	0.257	0.257
f_{rev} (Hz)	2183440	2183440
Long. structure	coasting	bunched / coasting
δ_{rms}	6×10^{-4}	3×10^{-4} / 6×10^{-4}
$\delta_{eff,He/C}$	1×10^{-3}	1×10^{-3}
S_{mxr} ($m^{-1/2}$)	28	28

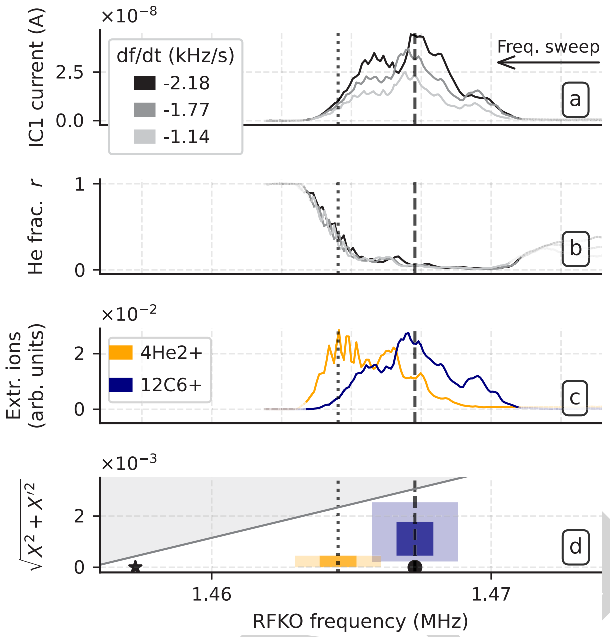

Figure 1: Helium and carbon flux measurements during multi-second RFKO sweeps: (a) Total current in IC1, (b) reconstructed $^{4}He^{2+}$ fraction, (c) reconstructed normalized $^{4}He^{2+}$ and $^{12}C^{6+}$ flux, (d) Steinbach diagram showing approximate expected distributions before RFKO excitation (neglecting amplitude detuning). • marks the center of a BPSK signal employed in subsequent studies, ⋆ the left null.

dent of sweep speed for the tested $\frac{df_{ko}}{dt}$ values: increasing $\frac{df_{ko}}{dt}$ primarily scales the IC1 current amplitude without altering the general characteristic. Figure 1c therefore shows only the $\frac{df_{ko}}{dt} = -1.77$ kHz/s case for clarity. Overall, f_{ko} at which the majority of $^{4}He^{2+}$ and $^{12}C^{6+}$ are extracted are well separated and agree to first order with the theoretical expectations indicated by the vertical lines, which is a valuable starting point for further studies. A detailed interpretation and comparison against simulations needs to be performed in future studies. The ripple structure visible in both the IC1 current and the reconstructed helium fraction r also needs further investigation to determine whether it is of physical origin or a measurement artifact. Follow-up experiments will also include sweeps from lower to higher frequencies.

First Operational Extraction Settings

With the first mixed-beam range probing experiments scheduled for autumn 2025, the main effort in 2025 had to be directed toward providing a reliable beam in time rather than pursuing in-depth slow-extraction studies. The main goal was to configure an extraction with $r \approx 0.1$, for which we set the amplitude of the $^{12}C^{6+}$ injection bump to ≈36.8 mm [5, 6]. Note that in practice we actually define a current to set the bump amplitude. The above-stated value is based on a preliminary current-amplitude calibration.

The extraction settings, Table 1, were kept close to those of the standard experimental RFKO setup at MedAustron [14]. The extraction efficiency is currently considered to be within

85 % to 92 %, based on preliminary data obtained with pure carbon beams. This value is expected to improve, as the strengths of the extraction septa and the High Energy Beam Transfer (HEBT) line elements were not optimized for RFKO and mixed beam operation. We further note that, unlike in the mixed-beam slow extraction studies at GSI [4], we kept nonzero horizontal chromaticity ξ_x. This was motivated by the fact that in our setup the two species occupy different regions of horizontal phase space. A separation in tune by $\Delta q_x = \xi_x \delta_{\mathrm{eff}}$ was intended to provide greater flexibility for applying different RFKO excitations to the two ion species and thereby support simultaneous extraction. The effect of alternative chromaticity settings is subject to future studies.

The RFKO signal parameters were tuned empirically to deliver $r \approx$ const., which turned out to be more efficient than expected. After testing a few broadband random binary phase-shift keying (BPSK) signals with different bandwidths (BW) and f_{ko}, we ended up using a signal with a null-to-null BW of 20 kHz, centered on $f_{\mathrm{ko}} = (q_{x,\mathrm{C}} + 1) f_{\mathrm{rev}}$. The BW corresponds to a span of $\Delta q_x = 0.009$, which should easily cover both species (•, ⋆ in Fig. 1d). This extraction setup was probed for bunched and coasting beams. In both cases, a polynomial amplitude modulation was empirically configured to produce an approximately flat spill. A fully flat spill and ripple minimization were not yet required and will be subject to future improvements.

This excitation was probed across varying helium fractions r. Figure 2 illustrates the extracted $r(t)$ (bottom) as well as the current measured in IC1 (top) for the different cases. Contrary to expectations from respective simulations, the extracted helium fraction remains remarkably constant throughout the spill. All settings feature a spike of extracted current at the start of the extraction, which is attributed to beam that happened to sit too close to the resonance and was therefore pre-extracted during the resonant sextupole ramp. In all settings, we further observe an initially elevated helium extraction during the first ≈0.5 s. Thereafter, for $r \lessapprox 0.2$ the extracted helium fraction remains remarkably constant, particularly for bunched beams. For coasting beams, bump amplitude 35.6 mm yields a similar helium fraction as 36.8 mm, suggesting that in this configuration more $^{4}\mathrm{He}^{2+}$ is being scraped in the HEBT than $^{12}\mathrm{C}^{6+}$. Species- and r-dependent extraction efficiency should, if possible, be quantified in a systematic follow-up measurement, also based on non-invasive determination of the helium fraction in the synchrotron [5]. This issue is not observed for bunched beams, for which we can also extract higher r (grey). However, the non-constant $r(t)$ in this case indicates that the RFKO excitation may need to be adjusted for large r. Further, compared to coasting beams, bunched beams yield reduced ripples in both intensity and r. Overall, we therefore employed the bunched setup for the first user experiments, and opened the HEBT chopper from 2 s to 8 s.

Finally, we note that while we kept f_{KO} = const. for all r, the RF radial loop actually slightly shifts f_{rev} for increasing r. For $r \approx 0.5$ (gray in Fig. 2) at 200 MeV/u this shift amounts to ≈ − 300 Hz [5]. However, in first order no significant impact is expected for the employed excitation, as the BW=20 kHz is significantly larger than these induced shifts.

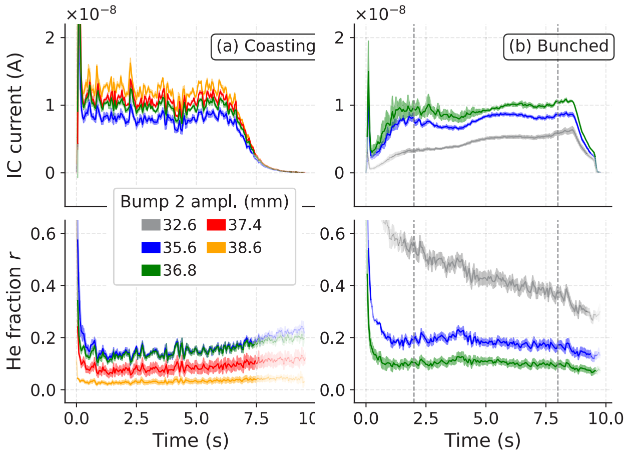

Figure 2: Extraction of (a) coasting and (b) bunched mixed beams with different helium fractions by means of a broadband BPSK RFKO excitation. Top: current in IC1, bottom: reconstructed helium fraction r, plotting $\overline{r(t)} \pm 1.5\sigma_r$.

Efforts are ongoing to reproduce the observed behavior in Xsuite simulations. At present, however, the simulations predict $^{4}\mathrm{He}^{2+}$ extraction later than observed in the measurements. We are therefore working to improve the characterization and modeling of the longitudinal and horizontal beam distributions of both $^{4}\mathrm{He}^{2+}$ and $^{12}\mathrm{C}^{6+}$ prior to RFKO excitation, as well as the optics model itself.

Additional tests beyond the scope of this paper aimed at probing the sensitivity of the extracted helium fraction $r(t)$ to different carrier frequencies f_{ko} of the broadband RFKO signal. As expected, $\Delta f_{\mathrm{ko}} = 2180$ Hz ($\Delta q = 0.001$) yielded a significantly delayed helium extraction with $\frac{\mathrm{d}r}{\mathrm{d}t} > 0$, and $\Delta f_{\mathrm{ko}} = -2180$ Hz the other way round.

SUMMARY AND OUTLOOK

We presented our first experimental experience with extracting mixed helium-carbon ion beams from a medical synchrotron, with the goal of maintaining a stable helium fraction throughout the spill. We empirically identified an RFKO setup to achieve such approximately constant mixing ratios, which is now used to provide mixed helium-carbon beams to research users. However, the detailed behavior observed is not yet fully understood. Future work will focus on resolving measurement-simulation discrepancies, finding a setup that can be re-tuned efficiently when changing helium fraction or extraction energy, studying He:C ripples, and designing RFKO signals for advanced He:C tailoring.

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