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TOWARDS THE SLOW EXTRACTION OF MIXED He-2+ AND C-6+ BEAMS FOR ONLINE RANGE VERIFICATION

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Abstract

In recent years, mixed helium and carbon ion irradiation schemes have been proposed to facilitate in-vivo range verification in ion beam therapy. Such a scheme proposes to deliver both ion species simultaneously, with the idea of performing the treatment with carbon ions, while exploiting helium for online dosimetry downstream of the patient.

The center for ion beam therapy and research MedAustron supplies protons and carbon ions for clinical treatment. It is currently being commissioned to additionally provide helium ions for non-clinical research, opening the opportunity for exploring the feasibility of mixed beam irradiation. A key aspect in this context is the slow extraction of the ion mix, which is affected by the relative charge-to-mass ratio offset between the two ions of approximately 6e-4. This contribution analyses differences in the transverse phase space and tune distributions of the two ion species and subsequently discusses first simulation results of the extraction process.

INTRODUCTION

Ion beam therapy requires precise knowledge about the morphology of the irradiated volume. Inaccuracies in treatment planning, along with patient and organ movements, can contribute to range uncertainties in the administered dose distribution and thus affect the desired therapeutic outcome. Majorly contributing to these uncertainties are the challenges involved in converting X-ray attenuation from the planning CT into ion beam stopping powers [1]. Several novel approaches for monitoring the compliance between the ongoing and the prescribed dose distributions are being investigated, such as $^{11}C^{6+}$ irradiation combined with PET imaging [2] or ion-based imaging [3].

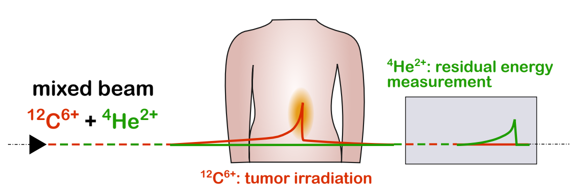

Figure 1: Schematic of a mixed beam irradiation.

Another proposal [4–6], specifically aimed at carbon ion therapy, is to simultaneously irradiate the patient with carbon ions for therapeutic and helium ions for dosimetry purposes (Fig. 1). Carbon and helium ions feature almost identical charge-to-mass ratios with a relative difference of $O(10^{-4})$. This makes simultaneous acceleration and delivery of both ion species to the irradiation room possible, as demonstrated for the first time in 2023 at SIS18, GSI [7], by extracting a mixture of 225 MeV/u $^{12}C^{3+}$ and $^{4}He^{+}$ ions.

Being extracted at almost the same energy per nucleon, $^{4}He^{2+}$ features approximately three times larger range in matter than $^{12}C^{6+}$. This opens the possibility to treat the tumor using the $^{12}C^{6+}$ Bragg peak, while the $^{4}He^{2+}$ traverses the patient and can be measured downstream for online range verification or radiography. Proof-of-concept studies published by Mazzucconi et. al [5] indicate, that extracting an intensity ratio of ≈He:C=1:10 would ensure that $^{4}He^{2+}$ does not account for more than $\lessapprox 1$ % of the total dose deposited in the patient, while still delivering sufficient $^{4}He^{2+}$ to distinguish it from $^{12}C^{6+}$ fragments in the detector.

Delivering such a beam in a clinical synchrotron has yet not been achieved and presents several challenges. Beyond the mixed beam generation, a key challenge will be to control the intra-spill particle fluence ratio

$$\xi(t) = \frac{(dN/dt)_{\mathrm{He}}}{(dN/dt)_{\mathrm{C}}}. \quad (1)$$

At this stage, due to the lack of more precise specifications, our goal is to maintain $\xi \approx 0.1$ throughout the entire spill.

The first part of this paper outlines considerations on the feasibility of providing a mixed beam at MedAustron for non-clinical research. The second part investigates the slow extraction of the ion mix in simulations.

Exploring Mixed Beam Generation at MedAustron

MedAustron is a centre for ion beam therapy and research located in Wr. Neustadt, Austria. It delivers 60-252 MeV proton and 120–400 MeV/u $^{12}C^{6+}$ beams for patient treatment. Additionally, it hosts a diverse user community for non-clinical research (NCR) studies, for which additional beam types, such as protons up to 800 MeV, are provided. To expand the capabilities for NCR, MedAustron is in the process of additionally commissioning $^{4}He^{2+}$ beams [8, 9]. This also sparked the interest in exploring the feasibility of delivering a mixed helium and carbon ion beam for NCR.

Currently, $^{12}C^{6+}$ and $^{4}He^{2+}$ are generated in separate ion sources. Required upgrades to generate the mixed beam in a single ion source are outlined by Kausel et. al [10]. Whereas the generation of the mixed beam in a single ion source is still considered the long-term baseline, recent efforts have focused on attempting to mix the two ion species during a proposed *double multi-turn injection* into the synchrotron [10]. This requires pulsing the injector twice, while ramping the synchrotron only once. In the first injector pulse,

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$^4He^{2+}$is injected into the synchrotron and kept at flat-bottom for ≈1 s. During this time, the injector is pulsed a second time to inject $^{12}C^{6+}$on top of $^4He^{2+}$, using a reduced injection bump amplitude in the synchrotron to preserve a small $^4He^{2+}$core in the circulating beam. The ion mix should then be accelerated and extracted simultaneously. The two generation schemes result in different initial horizontal emittance ratios. For the studies presented in this paper, we assume $\lambda := \epsilon_{x,\mathrm{He}}/\epsilon_{x,\mathrm{C}} \approx 1$ for generation in a single ion source and $\lambda \ll 1$ for the double multi-turn injection [10].

MOMENTUM AND TUNE DISTRIBUTIONS

$^4He^{2+}$and $^{12}C^{6+}$exhibit very similar q/m, with a ratio of

$$\chi = \frac{q_{\mathrm{He}}}{m_{\mathrm{He}}} / \frac{q_{\mathrm{C}}}{m_{\mathrm{C}}} = 0.99935. \quad (2)$$

However, the slightly lower q/m and hence higher rigidity of $^4He^{2+}$still causes a shift in the momentum and hence tune distribution, which is particularly relevant during the slow extraction process. In the following, $^{12}C^{6+}$is considered to be the reference particle, as the RF control loops are expected to act predominately on $^{12}C^{6+}$assuming the above-motivated intensity ratio of He:C=1:10 in the synchrotron.

It can be shown (see e. g. ref. [11]), that a particle of species B, with non-nominal charge-to-mass ratio, i. e. $\chi \neq 1$, and a relative momentum per mass offset

$$\delta = \frac{\beta_{\mathrm{B}}\gamma_{\mathrm{B}} - \beta_{\mathrm{A}}\gamma_{\mathrm{A}}}{\beta_{\mathrm{A}}\gamma_{\mathrm{A}}} \quad (3)$$

from a reference ion species A is deflected in a magnetic field identically to a particle with $\chi_{\mathrm{eff}}=1$, but an effective relative momentum per mass offset

$$\delta_{\mathrm{eff}} = \frac{1+\delta}{\chi} - 1. \quad (4)$$

Still, requiring the revolution frequency to match the RF frequency for both ion species, the rigidity difference causes a slight relative velocity offset (see e. g. ref. [12])

$$\frac{\beta_{\mathrm{He}} - \beta_{\mathrm{C}}}{\beta_{\mathrm{C}}} = \frac{1}{\gamma_{\mathrm{tr}}^2 - \gamma_{\mathrm{C}}^2} \cdot \left(\frac{1}{\chi} - 1\right), \quad (5)$$

which increases when approaching the transition energy γ_{tr}. The related real momentum per mass offset δ contributes to the effective δ_{eff}, which shifts the $^4He^{2+}$tune distribution by

$$\Delta Q_u = Q'_u \cdot \delta_{\mathrm{eff}} = Q'_u \cdot \left(\frac{1+\delta}{\chi} - 1\right), \quad u = x, y, \quad (6)$$

with Q'_u being the chromaticity. Note, that given the small circumference and hence transition energy, this tune separation is particularly apparent for compact, medical machines. In a PIMMS-like synchrotron [13, 14] as installed at MedAustron, with $\gamma_{\mathrm{tr}} \approx 2$ and an extraction energy of $\gamma_{\mathrm{C}} \approx 1.1$-$1.4$, this tune shift corresponds to ≈1-3 standard deviations (Fig. 2).

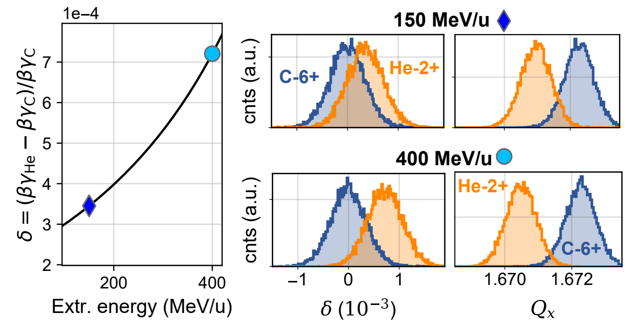

Figure 2: Relative momentum per mass offset (δ) and horiz. tune (Q_x) separation between the two ion species in a PIMMS-like synchrotron ($\gamma_{\mathrm{tr}} \approx 2$, here $Q'_x = -1.3$). Left: impact of the extraction energy on δ; right: distributions of δ and Q_x for the highest and lowest considered energy.

SLOW EXTRACTION SIMULATIONS

In summary, the two ion species feature an energy-dependant shift in the tune distributions (for $Q' \neq 0$) and, possibly, differences in the horizontal distributions (Fig. 3), but need to be extracted simultaneously with approximately constant fluence ratio $\xi(t) \approx$const. This section presents first proof-of-principle simulations of extracting this ion mix via 3rd-order resonant extraction. The simulations are performed using the particle tracking framework Xsuite [15], which enables 6D-tracking of ions with non-nominal q/m, for both bunched and coasting beams.

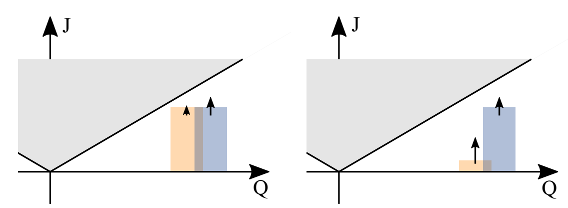

Figure 3: Schematic Steinbach diagram prior to the extraction, assuming the generation of the mixed beam in a single ion source (left) or via double multi-turn injection (right).

RFKO Extraction: Simulation Parameters

For now, the simulations focus on radio frequency knockout extraction (RFKO), which is an amplitude-selective extraction scheme that provides multiple knobs for controlling the fluence ratio $\xi(t)$ while adapting to different $\lambda := \epsilon_{x,\mathrm{He}}/\epsilon_{x,\mathrm{C}}$ or extraction energies. The available knobs include e. g. the chromaticity Q' to vary the tune separation, the virtual sextupole strength S to adapt the ratio of the stable areas or customizable, amplitude-modulated RFKO signals with different bandwidths to control the amplitude increase of $^4He^{2+}$and $^{12}C^{6+}$separately.

Below, proof-of-principle simulations for the extraction of a coasting beam at 400 MeV/u are presented. Table 1 lists the applied simulation parameters, which are based on parameter ranges presented in preceding studies for RFKO at MedAustron [16]. In this paper, the investigations are limited to varying the RFKO signals, with a broader investigation into the remaining parameters foreseen for the near future.

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Table 1: Simulation Parameters for RFKO Extraction of a Mixed Beam (C-6+/He-2+) in a PIMMS-Like Synchrotron

Parameter	Unit	Value
Q_x, Q'_x	-	1.672, -1.3
α_C	-	0.257
δ_{rms}	-	0.35e-3
$\epsilon_{n,\,rms,\,x/y}$	mm mrad	0.5 / 0.5
S	$m^{1/2}$	350

RFKO Extraction: Results and Discussion

Figure 4 illustrates the spill when extracting a 400 MeV/u mixed beam, in which $^4He^{2+}$and $^{12}C^{6+}$feature similar horizontal emittances prior to extraction, i. e. $\lambda\approx1$. As a first approach, a single binary phase shift keying (BPSK) signal with different bandwidths (BW), here 7 kHz and 10 KHz, is applied as excitation signal. The central frequency is chosen to match the central $Q_{x,0}$ of $^{12}C^{6+}$. It is evident that when starting the extraction, predominantly $^4He^{2+}$is extracted due to its smaller stable phase space area (I). In a clinical context, this behavior is manageable as transmission of excessive $^4He^{2+}$to the irradiation room can be prevented by closing the chopper during this period. Following this, both $^4He^{2+}$and $^{12}C^{6+}$are extracted with similar rate (II), with $^4He^{2+}$lagging slightly behind due to the RFKO signal predominantly spanning the frequency range of $^{12}C^{6+}$. When exciting with BW=10 kHz, we obtain a fluence ratio of ≈6-9 % (Fig. 4b, solid). This estimate assumes an initial intensity ratio of 1:10 and does not consider ripples. Note that the extracted fluence ratio is sensitive to the applied RFKO spectrum, including the location of side lobes. This is illustrated by the dashed lines in Fig. 4a and b, which feature the spill under the excitation with a BW=7 kHz signal. Future studies are encouraged to stabilize the fluence ratio $\xi(t)$ by adapting Q'_x and by combining multiple, amplitude-modulated RFKO signals with different central frequencies and BWs.

As mentioned above, when generating the ion mix using the double multi-turn injection scheme, we need to assume significantly different horizontal $^4He^{2+}$and $^{12}C^{6+}$emittances

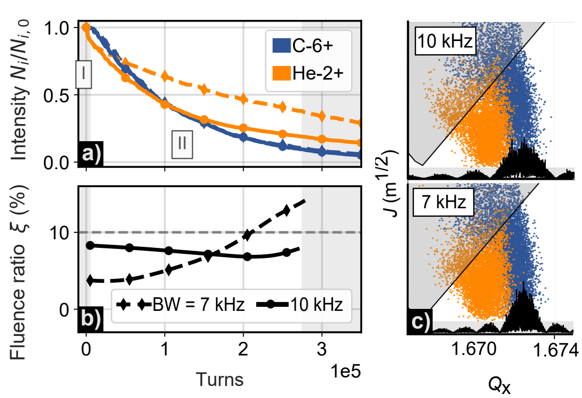

Figure 4: Extracting a mixed beam with similar initial horizontal emittances using BPSK signals signals with different bandwidths: a) Intensity evolution during extraction; b) Helium-to-carbon fluence ratio; c) Steinbach diagrams.

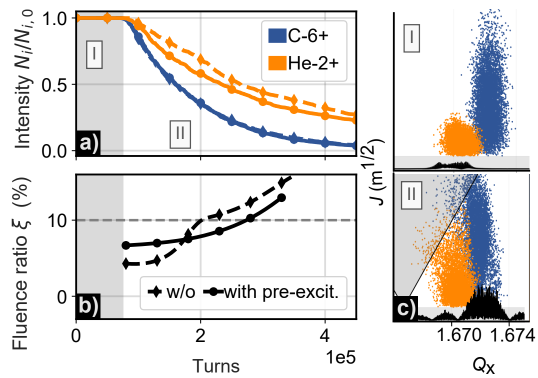

Figure 5: Extracting a mixed beam with strongly differing initial horiz. emittances: a) Intensity evolution during extraction; b) helium-to-carbon fluence ratio; c) Steinbach diagrams for the pre-heating (I) and extraction (II) phase.

prior to extraction [10]. In this case the described tune separation can be of advantage. Figure 5 illustrates the extraction of a beam with a small helium core, λ=0.05. It is evident that during the first half of the spill applying the same RFKO signal as before (BW=10 kHz, solid line in Fig. 5) would result in a higher extraction rate of $^{12}C^{6+}$than $^4He^{2+}$, as $^4He^{2+}$requires a larger amplitude increase for diffusing towards the separatrix. To stabilize $\xi(t)$, we thus propose '*preheating*' the helium emittance prior to extraction by applying a dedicated narrow-bandwidth signal which covers predominantly the $^4He^{2+}$rang (Fig. 5b, BW=1.5 kHz, frequency-modulation). This is done prior to ramping the resonant sextupole to prevent disturbing the $^{12}C^{6+}$distribution because of amplitude detuning causing additional overlap of the two tune distributions. The dashed lines in Fig. 5 qualitatively illustrate how this approach can help to stabilize ξ for $\lambda\ll1$.

CONCLUSION

This paper presented first proof-of-principle simulations for the slow extraction of a mixed $^{12}C^{6+}$and $^4He^{2+}$ion beam for online range verification. It highlighted that the small difference in q/m of around 6×10^{-4} results in an energy-dependant tune shift between the ion species. This shift is particularly apparent in compact medical machines with low transition energy and is, e. g. for a PIMMS-like synchrotron, in the order of 1-3 standard deviations of the tune spread. The extraction process must adjust for this tune separation, as well as possible horizontal emittance differences, which can occur depending on the proposed mixed beam generation scheme. By simulating an RFKO extraction of such an ion mix it was demonstrated how combining RFKO signals with different frequency, bandwidth and amplitude modulation can help reducing these effects to extract an approximately constant ratio of $^4He^{2+}$and $^{12}C^{6+}$throughout the spill.

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