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SLOW EXTRACTION OF A DUAL-ISOTOPE BEAM FROM SIS18

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Abstract

Recently, the heavy ion synchrotron SIS18 at GSI was for the first time operated with a dual-isotope beam, made up of $^{12}C^{3+}$ and $^{4}He^{+}$. Such a beam can be used to improve carbon radiotherapy by providing online information on dose deposition, where the helium ions serve as a probe beam traversing the patient while depositing a negligible dose. For this, the accelerator has to deliver a slowly extracted beam with a fixed fraction of helium over the spill. The difference in mass-to-charge ratio of ^{4}He compared to ^{12}C is small enough to permit simultaneous acceleration and to make the two isotopes practically indistinguishable for the accelerator instrumentation. Yet, it may cause a temporal shift between the two components in the spill owing to the sensitivity of slow extraction to tiny tune variations. We investigated different extraction methods, and examined the time-wise stability of the dual-isotope beam with a monitoring setup installed in the GSI biophysics experiment room. A reasonably constant helium fraction was obtained using transverse knock-out extraction with adjusted chromaticity.

INTRODUCTION

Range uncertainty is a major challenge in ion therapy [1], especially for moving tumors [2]. It has been proposed that ^{4}He can be accelerated in a synchrotron together with ^{12}C to the same velocity due to their similar mass-to-charge ratio [3]. Upon simultaneous extraction, carbon ions deliver the treatment, while helium ions, having a much larger range, exit the patient and enable range monitoring and portal imaging. Recently, such a beam was for the first time created and investigated at GSI.

The versatility of GSI's accelerator complex with its synchrotron SIS18 makes it an ideal place to study such a scheme. Carbon therapy with 3D raster scanning was invented there, with patients treated from 1997 to 2008 [4, 5]. Rid of the strong constraints on modifications to the accelerator during therapy, scientists at GSI are now free to utilize the availabe options. Thus, a beam consisting of $^{12}C^{3+}$ and $^{4}He^{+}$ could be created in an ECR ion source operated with methane using helium as support gas [6]. The helium fraction was varied by controlling the inflow of helium gas, even though there was no observable indicating its abolute concentration. The choice of charge states lead to a small contamination of the beam with $^{16}O^{4+}$, which did not interfere, however, with the investigations of helium and carbon.

Owing to the small difference in mass-to-charge ratio of $\mu = 0.65 \cdot 10^{-3}$, the mixed beam containing about 10^8 carbon ions per spill could be accelerated simultaneously in the linear accelerator UNILAC and SIS18 to a final energy of 225 MeV/u, where the beam was debunched. The biggest challenge for achieving a spill with approximately constant helium fraction over time was the sensitivity of slow extraction to the magnetic rigidity $B\rho = m/q\,\gamma\,\beta c$ of the circulating particles. Since SIS18 allows both tune-sweep extraction and transverse KO extraction, both schemes were investigated. Horizontal chromaticity ξ_h was adjusted to reduce the influence of μ. A spill with reasonably flat ratio of helium to carbon was finally obtained using KO extraction with $\xi_h = -2.5$. A summary of the relevant machine parameters is given in Table 1. Results on the dependence of the helium distribution over the spill on the choice of extraction scheme and horizontal chromaticity are reported below.

Table 1: SIS18 Machine Parameters for KO Extraction

Parameter	Symbol	Value
Working point	Q_h, Q_v	4.33, 3.28
Virt. sext. strength	S	23.1 $m^{-1/2}$
Nat. chromaticities	$\bar{\xi}_h, \bar{\xi}_v$	-6.5, -4.1
Adj. chromaticities	ξ_h, ξ_v	-2.5, -4.1
Mom. compaction	α_c	0.032
Hor. emittance (norm.)	ε_x	16 mm*mrad
BPSK center tune	$Q_{h,\mathrm{KO}}$	0.321
BPSK tune bandwidth	$\Delta Q_{h,\mathrm{KO}}$	0.026

DESCRIPTION OF EXPERIMENT

Generally, it was nearly impossible to obtain independent information about the helium and carbon components in the beam with the accelerators' instrumentation. The small deviations created by μ simply do not result in useful signals, even if measurements with and without a helium are compared: With sensors relying on electromagnetic fields, a helium fraction in the order of $f = 0.2$ contributes about $f \cdot 1/3 \lesssim 0.1$ to a coherent signal and about $f \cdot (1/3)^2 \lesssim 0.02$ to an incoherent signal, e.g. the spectral power of a Schottky signal. Visible differences could only be seen when measuring the spill on (destructive) particle counters during tune-sweep extraction with sufficiently large horizontal chromaticity. In this case, the helium was actually separated from the carbon in time (see below).

The helium fraction over the spill was therefore investigated utilizing the experimental setup installed in the GSI biophysics cave (see Fig. 1). Particle rates over time were recorded by three ionization chambers (ICs) at a sampling rate of 50 kHz. The ICs were located at the nozzle, where the beam exits the vacuum pipe, and at the locations of the carbon and helium Bragg peak, respectively. The range of the ions was tuned by controlling energy loss selecting the appropriate combination of range shifters.

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While this setup allows the separation of carbon and helium due to the range difference, care must be taken when interpreting the signals. In general, the particles create a signal proportional to the square of their nuclear charge Z^2.

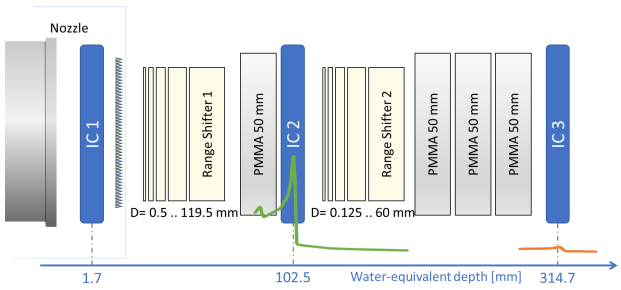

Figure 1: Sketch of the experimental setup, with IC2 and IC3 being located at the carbon (green) and helium (orange) Bragg peaks. As common in ion therapy applications, the range of the ions is given in water-equivalent depth.

Thus, as long as IC2 is located at the Bragg peak for ^{12}C, its signal will be dominated to very good approximation by the carbon component. IC3, however, records both the helium component and light fragments created by nuclear interactions of carbon particles passing through matter upstream IC2. Therefore, the helium signal must be reconstructed from the signal of IC3 by subtracting the fragment contribution during the data analysis.

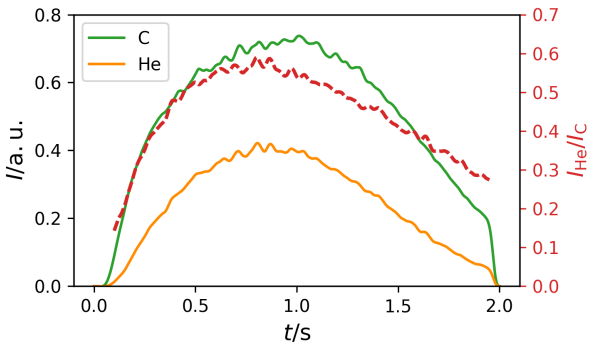

Figure 2: Carbon (green solid) and reconstructed helium (orange solid) signal as well as the ratio of helium to carbon (red dashed) for a KO extracted spill.

Figure 2 shows the result of such a decomposition for the case of KO extraction using single-band BPSK noise with $\xi_h = -2.5$. Apart from the very beginning, the ratio of helium to carbon varies within ±30% over the spill. A smaller ratio at the start of the spill is actually compatible with the fact that the slow extraction separatrix is larger for helium. The origin of the apparent correlation with intensity is unclear, however. The ratio was stable and reproducible over many cycles, even though the actual helium concentration in fraction of particles is not known due to a missing calibration of the ICs. This spill demonstrates the feasibility of a dual-isotope beam satisfying the requirements for online range verification in carbon ion therapy, at least under the extraction conditions applied in SIS18.

From the accelerator point of view it is, in addition, interesting to study how the distribution of helium over the spill can be influenced by changing machine parameters. In fact, having the option of shifting helium relative to carbon in time in a controlled way may even pave the way towards new treatment and verification modalities. Therefore, the distribution of helium over the spill was also studied for tune-sweep extraction as function of horizontal chromaticity. For each choice of scheme and chromaticity, the data from all ionization chambers were recorded for about ten to twenty spills. Due to lack of time, it was not possible to achieve a uniform macroscopic spill shape for all conditions.

DATA ANALYSIS AND RESULTS

The raw spill data showed the strong intensity fluctuations caused by power converter ripple typical for slow extraction. In addition, the signals from the ICs had a small offset and, in particular in the case of IC3, a significant 50 Hz ripple. The raw spill data were therefore averaged over all spills and then low-pass filtered using a fourth-order Butterworth filter with a bandwidth of 15 Hz, removing both the inherent high-frequency fluctuations and the artificial 50 Hz ripple. Afterwards, the offset was subtracted. A typical result can be seen in Fig. 3, where the spill signal is diplayed in units of the voltage U measured by the IC. When comparing spills for different settings, the data were normalized to the integral of the carbon signal from IC2. We will denote the signals calculated this way by $I(t) = U(t)/\int U_C dt$. Both U and I are proportional to the instantaneous particle rate, even though the calibration factor is unknown.

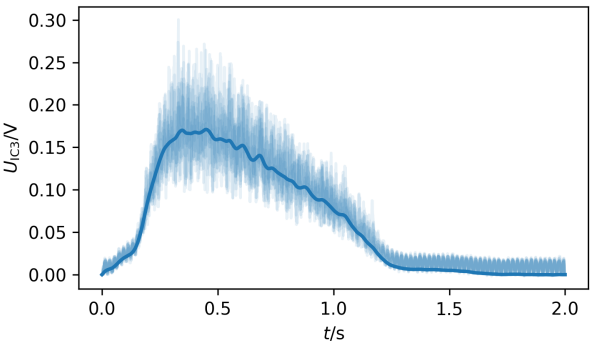

Figure 3: Raw spills on IC3 (lighter shade) and corrected average spill (solid line) for tune-sweep extraction with helium turned off. Note the 50 Hz ripple when there is no beam.

In order to analyze the helium distribution over the spill, the signal from IC3 must be corrected for the fragment contribution. The original assumption was that the fragment contribution to the signal of IC3 would be proportional to the signal of IC2, owing to the statistical nature of the nuclear fragmentation process. In order to determine the constant of proportionality, two machine settings (KO extraction with

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$\xi_h = -2.5$ and tune-sweep extraction with $\xi_h = \bar{\xi}_h$) were recorded with helium turned on and off. Contrary to expectations, analysis of the data with helium off revealed that the ratio of the carbon signal to the fragment signal varies moderately over time, even if sections of the spill with low intensity are ignored, as shown in Fig. 4. The variation is a bit stronger for tune-sweep extraction, but otherwise no clear correlation with beam properties can be derived. The origin of this effect is not yet understood and requires further investigation.

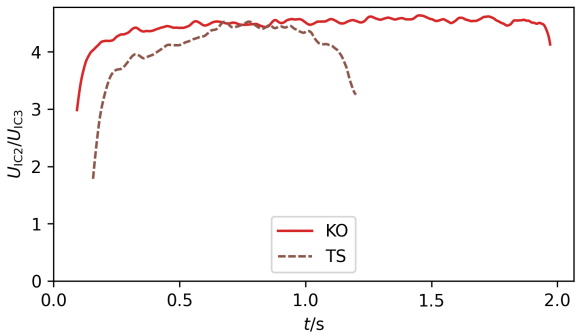

Figure 4: Ratio of IC2 to IC3 for KO and tune-sweep (TS) extraction with helium turned off, ignoring sections of the spill for which the IC2 signal drops below 10 per cent of its maximum. Contrary to expectations, this ratio of ^{12}C to fragments is not constant over the spill.

Despite this unexpected effect, the helium contribution could be analyzed with a high degree of certainty in the mentioned cases where data had been recorded with helium on and off by normalizing the data from IC3 with the carbon signal (IC2) and subtracting them (see Fig. 2 for the case of KO extraction). This was not possible for the two machine settings with tune-sweep extraction and ξ_h tuned to -2.5 and -0.5, for which only data with helium on were recorded. In those cases, the fragment contribution was simply estimated as $1/4$ of the carbon signal.

Figure 5 shows carbon and helium spill for tune-sweep extraction with different values of ξ_h, where $\xi_h = -6.5$ corresponds to natural chromaticity $\bar{\xi}_h$. The spills are displayed as function of the tune change ΔQ_h during extraction. Since the tune ramp $Q_h(t)$ is nonlinear, this way of presentation is better suited for a comparison to the underlying beam properties. First, we note that the separation between carbon and helium corresponds quite well to the expected value $|\xi_h \mu|$.[1] Next, we observe that the width of the spills in tune units is approximately independent of ξ_h. From this we infer that the beam had a very small momentum spread, such that the spill width is dominated by the comparatively large horizontal emittance. Lastly, the integral helium signal is significantly smaller for natural chromaticity. This effect may have a simple explanation in terms of non-optimal extraction settings for $\xi_h = \bar{\xi}_h$, caused by the difficulties in obtaining quantitative data on the helium contribution online. In any event, it requires further investigation.

[1] More precisely, the expected tune offset is $\xi_h \delta B\rho/B\rho = \xi_h(1 + \alpha_c/\eta)\mu$. However, under the given conditions, $\alpha_c/\eta \approx 0.05$ is negligible in SIS18.

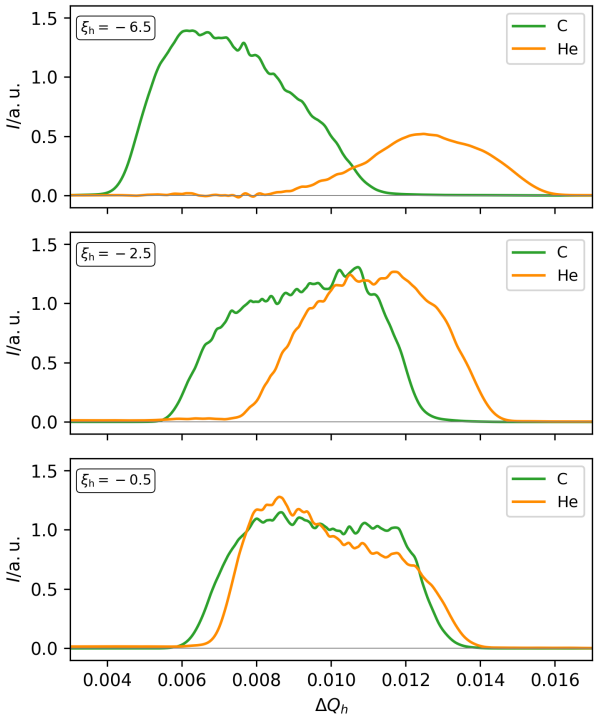

Figure 5: Carbon and reconstructed helium signal for tune-sweep extraction displayed as function of the tune change ΔQ_h during extraction. The different plots correspond to different values of the horizontal chromaticity ξ_h.

Finally, we want to mention that the horizontal position of the helium beam measured at the isocenter was offset compared to the carbon beam by about 1 mm to 2 mm. This offset cannot be explained through dispersion caused by the scanning magnets alone. Most likely, it is related to dispersion created in the synchtron and the beam transport line. Future studies are necessary to mitigate this effect.

CONCLUSION

A dual-isotope beam composed of carbon and helium was extracted from a synchrotron for the first time. Apart from a small contamination with oxygen, the properties of the mixed spill satisfied the requirements for online range monitoring in carbon ion therapy when employing KO extraction. In this case, the ratio of helium to carbon varied within about $\pm 30\%$ over the spill. When employing tune-sweep extraction, the relative position of the carbon and helium spills could be varied by adjusting horizontal chromaticity. Generally, the He/C ratio was very stable over many cycles.

Further studies will be performed within the ERC grant program PROMISE. They aim at gaining more quantitative knowledge and control over the distribution of helium in the spill. Also, the origin of few so far unexplained effects will be explored.

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