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FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY

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Abstract

In the context of research on simultaneous heavy ion radiotherapy and radiography, a mixed carbon/helium ion beam has been successfully established and investigated at GSI for the first time to serve fundamental experiments on this new mode of image guidance. A beam with an adjustable ratio of $^{12}C^{3+}/^{4}He^{+}$ was provided by the 14.5 GHz CAPRICE ECR ion source for subsequent acceleration in the linear accelerator UNILAC and the synchrotron SIS18. Despite the mass difference between the $^{4}He^{+}$ and $^{12}C^{3+}$ ions, both could be slowly extracted simultaneously at 225 MeV/u using the transverse knock-out extraction scheme.

The ion beam has been finally characterised in the biophysics cave in terms of beam composition (particularly inter- and intra-spill He fraction), depth-dose-profiles, beam size, position and other parameters, all related to combined ion beam treatment and online monitoring. Utilising high-speed particle radiography techniques, a fast extracted mixed ion beam has also been characterised in the plasma physics cave under conditions favourable to FLASH therapy.

INTRODUCTION

Carbon ion beams containing a small fraction of helium ions have been proposed for simultaneous carbon ion radiotherapy and helium radiography [1–5], i.e. particularly for ion range verification and portal imaging as a new mode of treatment verification.

The almost identical mass-to-charge ratio of $^{12}C^{3+}$ and $^{4}He^{+}$ ions facilitates their simultaneous acceleration at the UNILAC and SIS18 up to the same energy per nucleon as required. At the same velocity the helium ions´ range in tissue is approximately three times higher than the range of carbon ions and thus carbon ions stop in the tumour volume while helium ions pass the patient's body and can be detected there. Previous investigations revealed that the additional dose from a small 10 %-fraction of helium arising from the plateau of the depth-dose-profile is sufficiently low [1–4]. This allows for simultaneous treatment and online monitoring.

The objective of this fundamental work conducted at GSI is the production of such a mixed beam at an energy of 225 MeV/u which is slowly extracted over a few seconds with a particle rate of roughly 10^{8} particles/second for beam characterisation in terms of this new method of image guidance. This paper briefly reviews the major steps of dual isotope beam production and of the important results achieved.

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MATERIALS AND METHODS

Ion Source Setup

The objective of the dedicated ion source development is to setup a constant carbon ion beam intensity of approximately 150 eμA ($^{12}C^{3+}$) containing a helium particle fraction of about 10 %, i.e. approximately 5 eμA ($^{4}He^{+}$) in front of the subsequent UNILAC-SIS18 accelerator chain. By this, the demands in terms of intensity are entirely met. The associated measurements were performed at the ECR ion source test bench which includes a low energy beam transport line (Fig. 1). The 14.5 GHz CAPRICE type ECR ion source was operated with methane and ^{4}He.

The C-to-He ratio was adjusted by stepwise adding Helium to the plasma while recording the optical emission spectrum (OES) with an optical spectrometer (Oceaninsight QE Pro [6]) covering approx. the visible light spectrum and the corresponding mass spectra. In the latter, it is impossible to distinguish between the $^{12}C^{3+}$ and $^{4}He^{+}$ ions, while the optical emission lines of carbon (wavelength 465 nm) and helium I (728 nm) allow for an estimate of the C-to-He ratio and its long term stability even during operation.

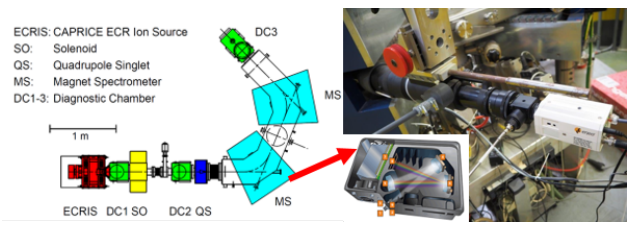

Figure 1: Scheme of the ion source and LEBT (left) including camera and optical spectrometer system (right).

SIS 18 and Beam Instrumentation at Biophysics Cave

A dual isotope beam with a constant carbon and helium ratio over time was requested. The sensitivity of the SIS18 to even small differences between the mass-to-charge ratios of the carbon and helium ions of r = 0.065 % is most challenging, in particular for slowly extracted ion beams. Both, the tune-sweep and transverse KO extraction schemes were

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investigated, while the horizontal chromaticity was adapted to minimize the effects of r [7].

In fact, it was impossible to discriminate the information of the beams´ constituents helium and carbon with the accelerators´ beam instrumentation. Therefore, the beam characteristics, in particular the particle rates were measured by the experimental setup in the biophysics cave with a stack of three ionisation chambers (IC): at the beam nozzle (IC1) and at the positions of the carbon (IC2) and helium (IC3) Bragg peak, respectively. The corresponding ion beam ranges were adjusted by an appropriate setup of range shifters (Fig. 2) allowing for a separate measurement of the helium and carbon ion beam.

Thus, IC2 was probing the carbon component while IC3 measured the helium content and light fragments created by nuclear interactions upstream. The fragment contribution to IC3 had been measured separately without any helium in the beam, in order to determine the helium contribution to the signal for mixed beam spills via subtracting the fragment signal.

Additionally, a dE-E telescope (particle composition), films (beam profiles), an IC array (dosimetry), and a camera/scintillator system were used to probe the carbon / helium mixed beam the results of which will be reported in future works.

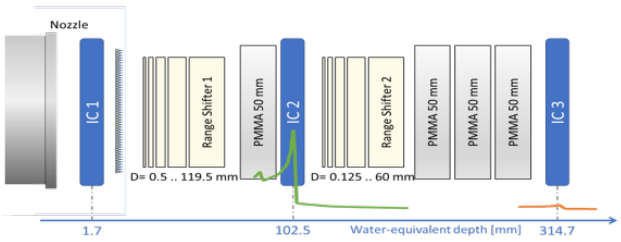

Figure 2: Scheme of the setup with an arrangement of range shifters and ICs; IC2 and IC3 are positioned at the carbon (green line) and helium (orange line) Bragg peaks.

EXPERIMENTAL RESULTS

The number of counts of an optical emission line of He I was read from an optical spectrum covering approx. the range of visible light (insert in Fig. 3). A distinct He I line over some background was taken at approx. 728 nm for probing the relative helium fraction in the plasma over time (Fig. 3). When adding helium to the plasma only the corresponding lines are increased (insert in Fig. 3: black curve) while the residue of the spectrum remains nearly unaffected.

These non-destructive measurements of the line intensities and, additionally, the analysed beam current measured with a current transformer (Fig. 4) were used for adjusting the relative helium fraction during operation. Figure 4 shows the extraordinary good stability during operation with a beam current of about 135 µA (estimated 9 µA $^4He^+$).

Prior to this, the charge state distributions (CSD) have been recorded for various helium fractions after setting up a

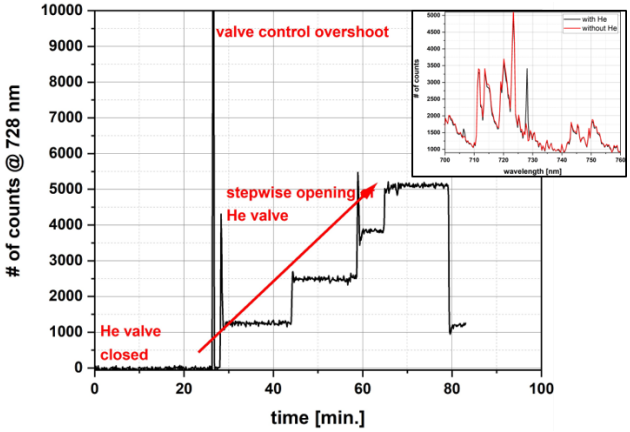

Figure 3: Number of counts at 728 nm wavelength (He I) for stepwise increase of He flow in a methane / helium plasma; insert: part of OES, number of counts over wavelength w/o He (red graph) and with He content (black graph).

C^{3+} beam of > 150 µA. Figure 5 shows five different CSDs containing different helium percentages. The CSDs are shifted on the momentum axis for comparison of the various graphs. With increasing inflow of He to the plasma only those combined peaks (C^{3+}/He^+, He^{2+}) are increasing at the same time while the rest of the beam composition, i.e. plasma properties, remains nearly unaffected by adding helium. Thus, this extra in current might be assigned to a helium current contribution, i.e. a correlation between the optical counts and analysed current and therefore the C-to-He ratio might be elaborated. The plasma and therefore the ion beam usually contains a small part of oxygen, which can be minimized by proper conditioning of the ion source over some days of operation. It cannot be eliminated completely so far. Thus, an O^{4+} part of less than 10 % is expected in the beam the amount of which can be roughly estimated by the height of the neighbouring peaks in the CSD.

However, the measured actual number of particles relies on the beam instrumentation in the biophysics cave.

Despite the small mass-to-charge difference r, both carbon and helium were successfully accelerated simultaneously at the UNILAC and SIS18 to its required beam energy of 225 MeV per nucleon. When using the tune-sweep extraction scheme with a fairly large horizontal chromaticity the carbon and helium constituents are well separated in time; the carbon being extracted before helium. This might be an interesting option for new treatment and verification modalities. Here, according to the objectives, a spill with a fairly constant ratio of helium to carbon was achieved by using the KO extraction scheme with adjusted, i.e. reduced chromaticity. Figure 6 summarises the results in arbitrary or relative units due to a missing calibration of the ICs:

The blue line in Fig. 6 (signal ratio of IC2 to IC3), measured with a pure carbon ion beam, is indicating the amount of fragments and its slight variation over the spill which contribute to the signal in IC3. The signal from IC3 has to be corrected by this in order to get the helium distribution

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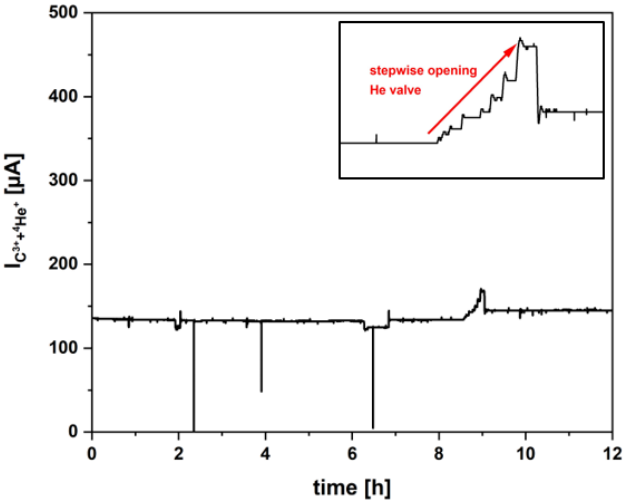

Figure 4: Ion source stability over time in terms of analysed beam current; current de- and increase for different He fraction (insert and at instant of about 2 h and 6.5 h).

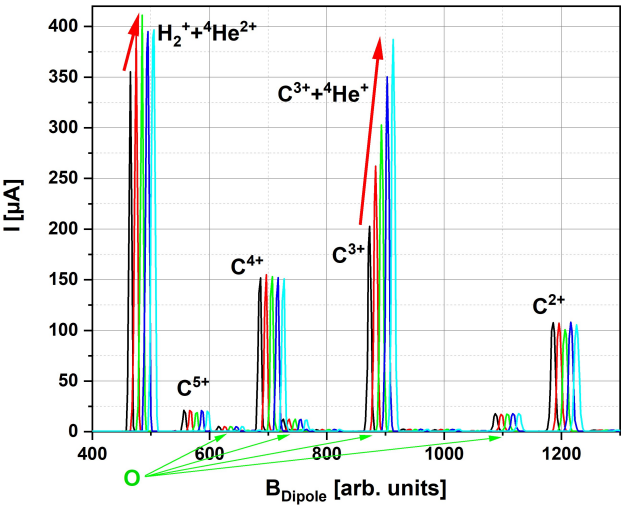

Figure 5: Charge state distributions (methane and 4He) as function of the He fraction; shifted on momentum axis for illustration; green: indicating oxygen part.

(orange line) while the carbon distribution is shown in green (IC2). The C-to-He-ratio (red line, ignoring small signals at the beginning of the spill) varies by +/- 30 %. It is, however, stable over many cycles and suitable for online monitoring in carbon ion beam therapy (see [7] for details).

Figure 7 shows the measured depth-dose-profile of the dual-isotope beam with adjusted helium part of 4.5 % and 20 % related to carbon and stable over time (signals normalised to IC1, setup see Fig. 2).

All peaks are clearly distinguished even showing the oxygen Bragg peak in front of the carbon Bragg peak (ruby) with a fraction of roughly 7 % related to carbon, but stable throughout. The light and dark green graphs are showing the helium profiles over a background of fragments. So finally this new method of imaging in radiotherapy could be successfully demonstrated.

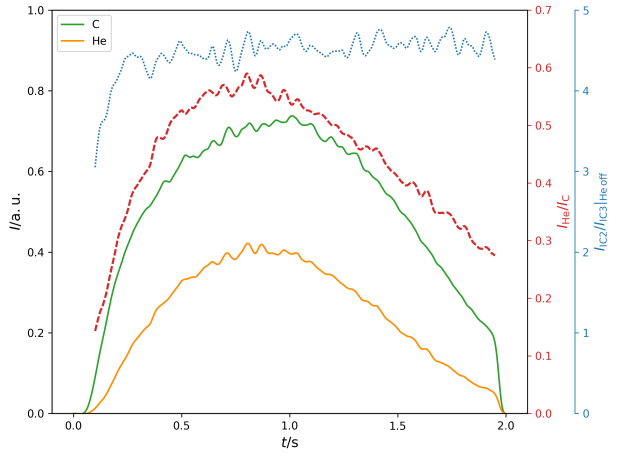

Figure 6: Carbon (green) and determined helium (orange) signals, helium to carbon ratio (red), and ratio of IC2 to IC3 signals (blue, without helium content) indicating the amount of light fragments in the signal.

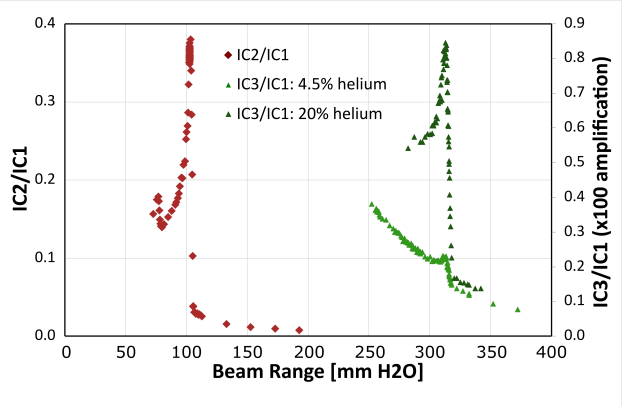

Figure 7: Depth-dose-profile of carbon and oxygen (ruby) and helium (light green: 4.5 %, dark green: 20 % helium fraction over fragment's background).

Many further experimental data were collected as mentioned above, the results of which will be reported elsewhere.

SUMMARY

A dual-isotope beam containing carbon and helium ions was produced, accelerated and extracted simultaneously for the first time using the transverse KO extraction scheme. The achieved stable conditions, i.e. the stable inter-spill He-to-C ratio, a fairly flat distribution over the spill (+/- 30 %), and apart from the unwanted, but stable oxygen fraction, permit to experimentally explore the potential of this new image guidance modality for carbon ion therapy. Further accelerator research is necessary; particularly to eliminate the oxygen contamination.

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