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MIXED CARBON AND HELIUM ION BEAMS FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY: AN ION SOURCE PERSPECTIVE

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Abstract

Within the framework of research on simultaneous heavy ion radiotherapy and radiography, a mixed carbon/helium ion beam with a variable He percentage has been successfully established and investigated at GSI for the first time in order to study this new mode of image guidance for carbon ion beam therapy. The mixed C / He ion beam was provided by the 14.5 GHz CAPRICE ECR ion source for the subsequent linac-synchrotron accelerator systems at GSI. Prior to that experiment, different ion combinations ($^{12}C^{3+}$/ $^{4}He^{+}$ or $^{12}C^{4+}$/ $^{3}He^{+}$) out of CH_4 or CO_2 have been investigated at the ECR test bench in terms of ion beam currents, stability, and C-to-He-fraction quantified by optical spectral lines and mass spectra. From an ion source perspective, it turned out that each of the different combinations comply with all the requirements of the experiments which successfully took place utilizing a $^{12}C^{3+}$/ $^{4}He^{+}$- ion beam with an energy of 225 MeV/u. Finally, both ions were simultaneously accelerated, extracted and characterised in the biophysics cave. This paper briefly outlines some of the measurements obtained at the test bench and during the beam time from an ion source perspective.

INTRODUCTION

Particle therapy, as a Bragg peak method of irradiation, is subject to even small range uncertainties in especially for anatomical changes like moving tumours. Mixed carbon and helium on beams have been proposed for simultaneous therapy and online monitoring [1–6].

Due to the similar mass-to-charge-ratio C^{3+} and $^{4}He^{+}$ (or C^{4+} and $^{3}He^{+}$) ions can be accelerated to the same energy per nucleon. At this same velocity the penetration depth of He in water is three times the one of carbon ions. Therefore, carbon ions stop in the tumour volume applying the dose there while helium ions exit the patient and can be detected and used for range verification and imaging. Previous works revealed that the additional dose from a small, 10 % helium percentage in the plateau of the depth-dose-profile of helium is sufficiently low [1–4].

Most recent simulation works analysed the injection and extraction process at a medical facility while the experimental exploration is still ongoing [7, 8]. Recently, such a mixed beam has been produced at GSI with an energy of 225 MeV/u, slowly extracted with a particle rate of about 10^8 particles/second [9, 10]. This paper briefly reviews the major steps of the dual isotope beam production and some of the important results achieved with an emphasis on ion source development.

MATERIALS AND METHODS

Ion Source Set Ups

In order to meet the requirement of 10^8 particles/second at the experiment an ion beam of circa 150 µA ($^{12}C^{3+}$ or $^{12}C^{4+}$) with a helium fraction of approx. 10 %, i.e. circa 5 µA ($^{4}He^{+}$ or $^{3}He^{+}$) has to be provided upstream the subsequent linac-sychrotron system UNILAC-SIS18 at GSI. The 14.5 GHz CAPRICE type ECR ion source was utilised for this purpose meeting all the requirements given.

The preliminary measurements were conducted at the ECR ion source test bench which includes a low energy beam transport line (Fig. 1). Different reasonable combinations of methane/carbon dioxide and $^{4}He^{+}$/ $^{3}He^{+}$ were checked in terms of feasibility.

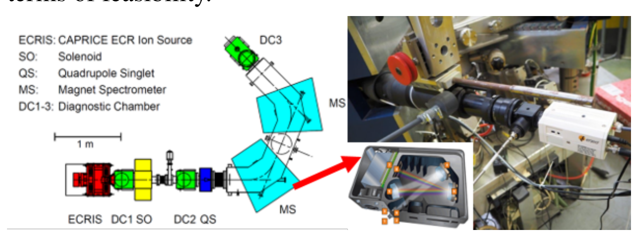

Figure 1: Sketch of the test bench: ion source and LEBT (left), camera and optical spectrometer system (right).

The helium percentage was controlled by stepwise altering the helium inflow to the plasma and by measuring a) the optical emission spectrum (OES) with an optical spectrometer (Oceaninsight QE Pro [11]) covering approx. the visible light spectrum, b) the analysed ion beam current in a Faraday cup, and c) the corresponding mass spectra. In the two latter cases, it is impossible to distinguish between the $^{12}C^{3+}$/ $^{4}He^{+}$ or $^{12}C^{4+}$/ $^{3}He^{+}$ ions, but the C-to-He ratio and its long term stability also during operation can be estimated by the optical emission lines of carbon (wavelength 465 nm) and helium I (728 nm).

Finally, a mixed ion beam of $^{12}C^{3+}$ and $^{4}He^{+}$ was provided from the high charge state injector (HLI) to the experiment (smaller deviation of the mass-to-charge ratios compared to $^{12}C^{4+}$ and $^{3}He^{+}$). After setting up the ion source, the C-to-He ratio was adjusted and constantly monitored by measuring the analysed ion beam current in a current transformer and by measuring the optical emission lines that is by non-destructive beam instrumentation.

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Unfortunately, the oxygen emission lines, and therefore the evolution of the oxygen contamination of the plasma and hence, the ion beam, were not recorded in both cases.

SIS18 and Beam Instrumentation at Biophysics Cave

The sensitivity of the SIS18 even to the small difference between the mass-to-charge ratio of carbon and helium (^{4}He) ions of 0.065 % is most challenging, in especially for slowly extracted ion beams. The transverse RF Knock-Out (RFKO) extraction scheme was used with reduced horizontal chromaticity minimising the effects of r in order to get an ion beam with a constant carbon-to-helium ratio over a spill as requested [9].

Since it was impossible to obtain information of the different ion beam species helium and carbon with the accelerators´ beam instrumentation, the beam properties were measured by different set ups in the biophysics cave. The particle rates, for instance, were recorded by 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 set by a set up of range shifters (Fig. 2) allowing for a separate measurement of the carbon and helium ion beam.

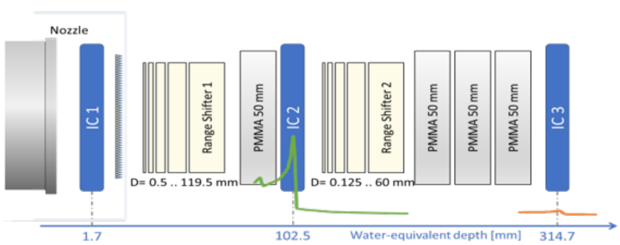

Figure 2: Scheme of the set up with an arrangement of range shifters and ICs; IC2 and IC3 are positioned at the carbon (green line) and helium (orange line) Bragg peaks.

EXPERIMENTAL RESULTS

Prior to the ion beam production at the injector beam line and accelerator, different combinations of ions have been checked at the ECR test bench (EIS) for their suitability. Those were CH_4 / ^{4}He (C^{3+}/ $^4He^+$), CH_4 / ^{3}He (C^{4+}/ $^3He^+$), and CO_2 / ^{3}He (C^{4+}/ $^3He^+$).

The charge state distributions (CSD) have been recorded for various helium fractions after setting up a C^{3+} or C^{4+} beam of approximately 150 µA out of CH_4 or CO_2. Figures 3 and 4 show 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+}/ $^4He^+$, $^4He^{2+}$ (methane) or C^{4+}/ $^3He^+$, $^3He^{2+}$ (carbon dioxide)) are increasing at the same time while the rest of the beam composition remains nearly unaffected by adding helium. A similar result for the system C^{4+}/ $^3He^+$, $^3He^{2+}$ (methane) is reported in [12].

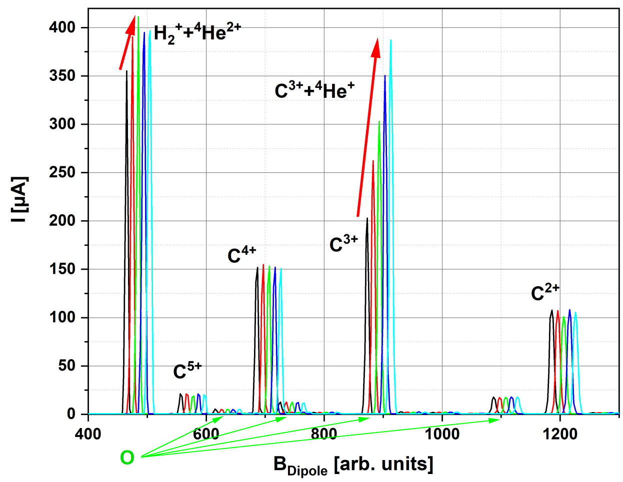

Figure 3: Charge state distributions (methane and ^{4}He) as function of the He fraction; shifted on momentum axis for illustration; green: indicating oxygen part.

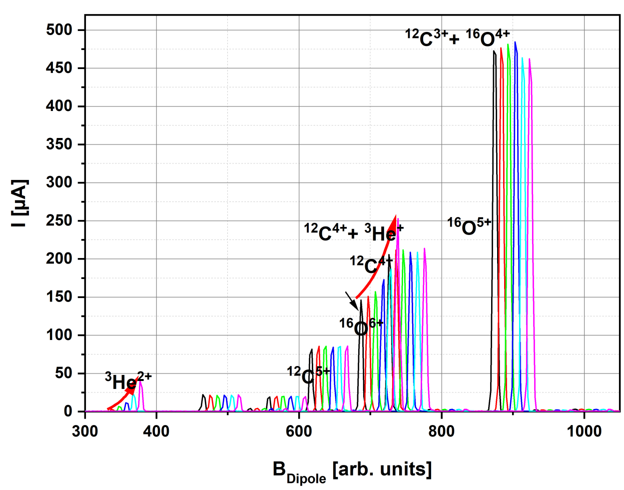

Figure 4: Charge state distributions (carbon dioxide and ^{3}He) as function of the He fraction; shifted on momentum axis for illustration.

Additionally, the number of counts of an optical emission line of He I at approximately 728 nm wavelength was read from the overall optical spectrum (see Fig. 5). This distinct He I line over some background was taken for probing the relative helium fraction in the plasma over time. By controlling the helium inflow to the plasma to different extents only the corresponding helium lines alter (insert in Fig. 5: black curve) while the residue of the spectrum remains almost unchanged. Thus, one can correlate the optical counts to the analysed current and therefore the C-to-He ratio can be elaborated (Figs. 6 and 7) while the actual particle rates of the beams' constituents helium and carbon cannot be discriminated with the accelerator's beam instrumentation; the measured actual number of particles relies on the beam instrumentation in the biophysics cave.

Finally a C^{3+}/ $^4He^+$ (methane) ion beam has been provided by the ion source (smaller mass-to-charge-ratio of ^{4}He to C).

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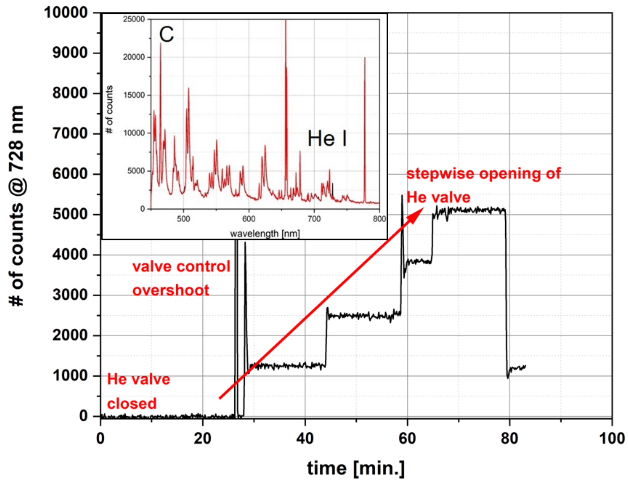

Figure 5: Number of counts at 728 nm wavelength (He I) for stepwise increase of He flow in a methane / helium plasma; insert: part of OES, number of counts over wavelength w/o He (red graph) and with He content (black graph) [10].

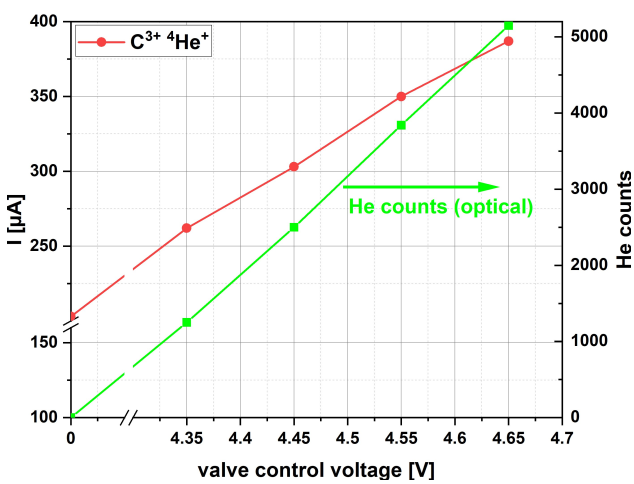

Figure 6: Correlation between current and counts; system CH_4 and ^4He.

The analysed beam current measured with a current transformer and the optical emission lines were used to adjust the relative helium fraction during operation at the injector and to monitor the overall stability of operation (Fig. 8). It shows the good stability during the whole duration of the experiment which lasted for about four days. There are two main sources of fluctuating current measurement, that is HV drops due to plasma fluctuations and partly a lack of timing of the beam instrumentation devices; none of them being of concern for the experiment.

The plasma and therefore the ion beam still contained a small part of oxygen the amount of which could be reduced (not eliminated completely) by conditioning of the ion source over weeks of operation. Thus, an O^{4+} part of less than 10 % was expected in the beam the amount of which can be roughly estimated by the height of the neighbouring peaks in the CSD. This was quantitatively confirmed by the experiments' instrumentation (see below).

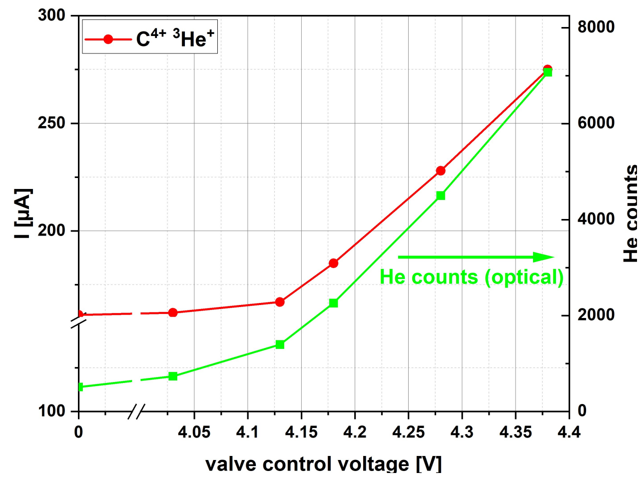

Figure 7: Correlation between current and counts; system CO_2 and ^3He.

Despite the small mass-to-charge difference, both C^{3+} and $^4He^+$ were successfully accelerated simultaneously at the UNILAC and SIS18 to the required beam energy of 225 MeV per nucleon. According to the objectives, a spill with a fairly constant ratio of helium to carbon was achieved by using the RFKO extraction scheme with adjusted, i.e. reduced chromaticity. The C-to-He-ratio varied by ±30 %, but it was, however, stable over many cycles and suitable for the exploration of this particular method of online monitoring in carbon ion beam therapy (see [9] for details).

Figure 9 shows the depth-dose profile of the dual- isotope beam with a helium fraction of 4.5 % and 20 % (related to carbon) and stable over time. The signals are normalised to IC1: the ruby graph shows the carbon Bragg peak and the oxygen Bragg peak in front (percentage of 7 % related to carbon); the light and dark green graphs show the helium Bragg peaks also containing a background of fragments. Thus, this new method of imaging was successfully investigated. Many further experimental data (utilising a dE-E telescope (particle composition), films (beam profiles), an IC array (dosimetry), and a camera/scintillator system) were collected, the results of which have yet been and will be reported elsewhere (see for instance [13, 14]).

SUMMARY

A mixed carbon-helium ion beam was produced successfully with the CAPRICE ECRIS using methane, carbon dioxide and ^3He and ^4He. C^{3+} and $^4He^+$ were accelerated and extracted simultaneously for the first time by using the transverse RFKO extraction scheme. The achieved stable conditions (inter-spill He-to-C ratio, fairly flat distribution over the spill (±30 %), and unwanted, but stable oxygen fraction) permitted to experimentally explore the potential of this new image guidance modality for carbon ion beam therapy. To further reduce the oxygen content in the plasma the ion source conditioning phase will be revised.

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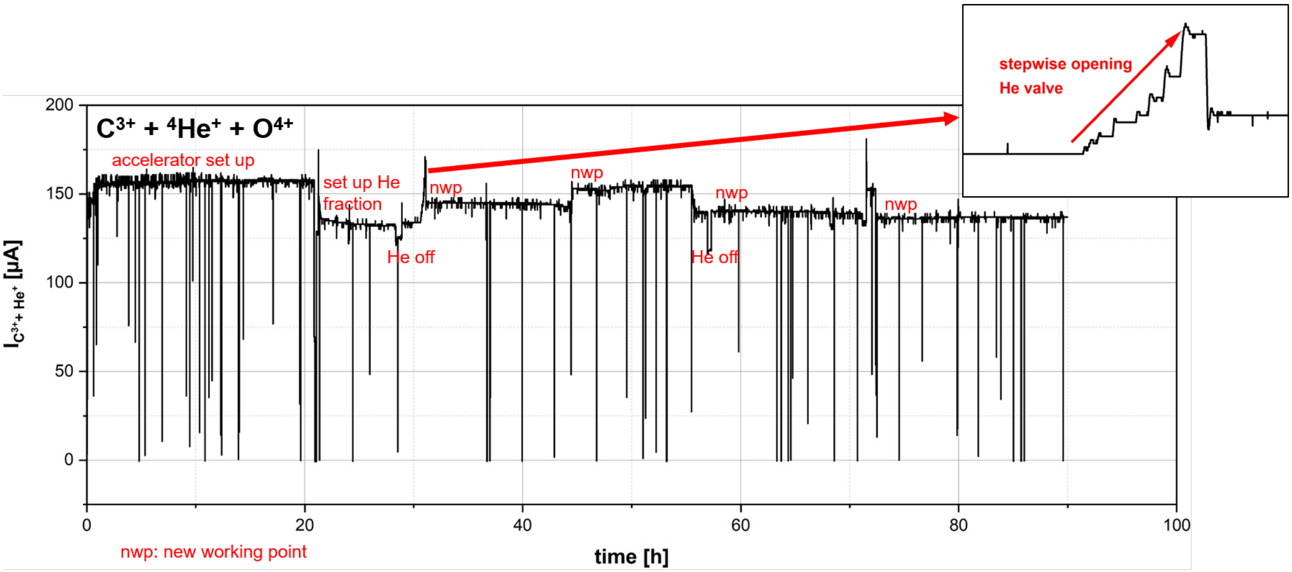

Figure 8: Ion source stability over 4 days in terms of analysed beam current; current de- and increase for different He fraction (insert).

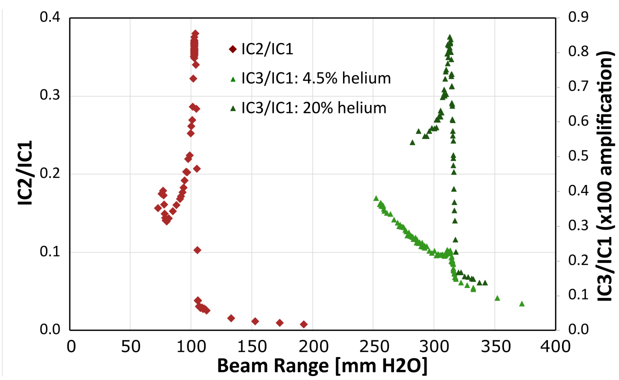

Figure 9: Depth-dose profile of carbon and oxygen (ruby) and helium (light green: 4.5 %, dark green: 20 % helium fraction over fragment's background).

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