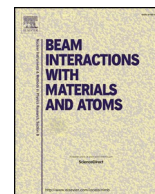




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journal homepage: www.elsevier.com/locate/nimbChallenges in ^{11}C charge breedingJ. Pitters^a, M. Breitenfeldt^b, H. Pahl^{a,c}, A. Pikin^{a,d}, F. Wenander^{a,*}^a CERN, BE Department, 1211 Geneva 23, Switzerland^b ADAM SA, Rue de Veyrot 11, 1217 Meyrin, Switzerland^c Heidelberg Graduate School of Fundamental Physics, Heidelberg University, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany^d School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, United Kingdom

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ABSTRACT

In this paper we discuss the possibilities of using a charge breeding scheme based on an Electron Beam Ion Source for beam preparation of a radioactive ^{11}C beam for hadron therapy. Test measurements under extreme operating conditions were conducted at the REX-ISOLDE facility to explore the limitations of the charge breeder for high-intensity, low-repetition-rate, molecular CO^+ beams. Based on our findings, we discuss different possible scenarios of coupling a charge breeder with either a medical synchrotron or linear accelerator. This paper is a highly condensed version of an exhaustive report on the topic [1], which we would like to refer to for further details.

1. Introduction

When using ^{11}C (β^+ emitter, $t_{1/2} = 20.4$ min) as the primary treatment beam in hadron therapy, one can benefit from its excellent properties for both on-line and off-line PET imaging, which can be used for dose verification [2]. While ions are produced abundantly in conventional hadron therapy with stable carbon, it is highly challenging to provide a radioactive beam of adequate intensity for treatment [3]. In this paper it is assumed that the radioactive treatment ions are produced by the Isotope Separation On-Line (ISOL) technique. Previous experience with carbon ion beams at the nuclear physics facility ISOLDE at CERN has shown that the ^{11}C output with the highest yield from the ISOL-production stage is typically a singly charged, molecular $^{11}\text{CO}^+$ beam [4]. The main challenge of this work lies in coupling the production of a continuous, molecular CO^+ beam from an ISOL-target with a medical accelerator (see Fig. 1). The concept of accumulation, breeding and post-acceleration of radioactive carbon beams was tested at REX-ISOLDE [5], which consists of a Penning trap coupled to an Electron Beam Ion Source (EBIS). The Penning trap, REXTRAP, cools and bunches the quasi-continuous beam from ISOLDE. The bunched beam is transported via an electrostatic transfer section and injected into REXEBIS, where the initial ions' charge of 1^+ is increased for an efficient post acceleration. After separation by A/Q in a spectrometer, the selected beam is accelerated in a linac.

For the tests presented here, the REX-ISOLDE charge breeder stage was operated well outside the normal regime (2–50 Hz repetition rate

and $< 10^7$ ions/bunch) to determine its limitations in the context of hadron therapy. In a scheme where we match the quasi-continuous 1^+ ion beam from the target ion-source to a synchrotron, the low repetition rate of the synchrotron (< 1 Hz) imposes a challenge on the design of the charge breeder system. The output of the charge breeder should ideally be a pulse of carbon ions of charge state 4^+ or higher, with a pulse length that can be accepted for injection into the synchrotron, i.e. some tens of μs . The required intensity of extracted beam is $1 \cdot 10^{10} \text{ C}^{4+}$ ions per pulse, which would be sufficient to complete a treatment session in one single synchrotron spill.

2. Measurements at REX-ISOLDE

All measurements were performed with stable beams, mainly $^{13}\text{CO}^+$, as radioactive $^{11}\text{CO}^+$ beams with sufficient intensities cannot be provided with the present ISOL-system. As the radioactive half-life of ^{11}C is much longer than the trapping time, it is assumed that the qualitative behavior of the radioactive ions is similar to that of the stable beam.

2.1. Molecular breakup

As a first step, the injection of CO^+ into the Penning trap was studied for different trap configurations and buffer gases in order to understand the molecular breakup. It was found that for normal trapping condition, i.e. with Ne buffer gas and approximately 200 eV injection

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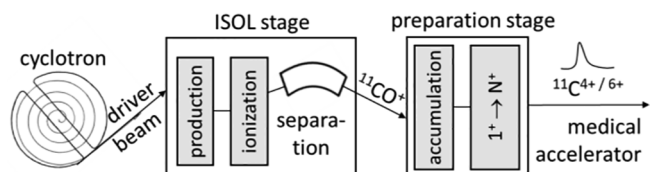


Fig. 1. Schematic layout of production and preparation stage for $^{11}\text{C}^+$ to be used as treatment beam in a synchrotron-based facility.

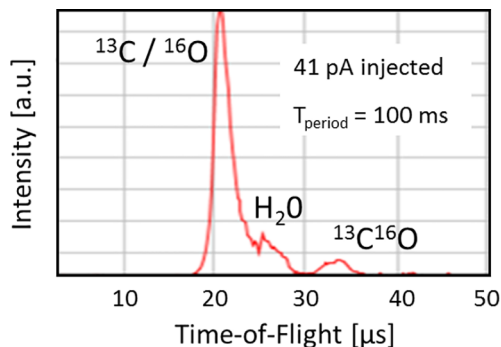


Fig. 2. Time-of-flight spectrum after REXTRAP with Ne as buffer gas. A $^{13}\text{C}^{16}\text{O}^+$ beam is injected into a normal trap configuration and RF cooling tuned for $A = 13$.

energy relative to the trap center, almost all of the molecules are broken up at injection into the Penning trap (see Fig. 2). A larger fraction of the molecules could be preserved when lowering the injection energy, particularly in combination with a He buffer gas, however this was dismissed as the over-all transmission through the consequently more shallow trapping potential was lower.

2.2. Holding-time dependent losses in the Penning trap

In the next step the storage capability for long holding times inside the Penning trap was investigated. The loss behavior of molecular CO^+ was compared to that of an atomic K^+ beam. Ions were collected during the first 100 ms of each cycle in the Penning trap (normal trapping potential configuration) and their holding time was changed systematically. Thereafter, the ions were extracted in the normal way and sent to the EBIS for charge breeding. Fig. 3 shows the normalized intensity after the EBIS and separator, as function of the period time. K^+ ions can be stored in the trap for up to 900 ms period time without measurable losses.

The CO^+ beam is lost exponentially with a half-life of around

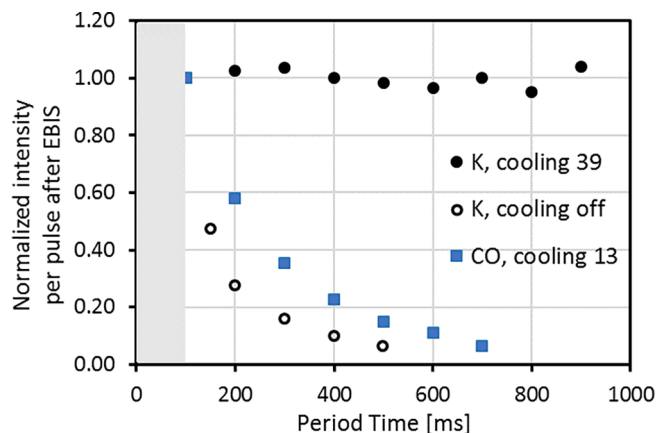


Fig. 3. Ion loss measurement with beam gate open during the first 100 ms of each cycle, indicated by the gray bar.

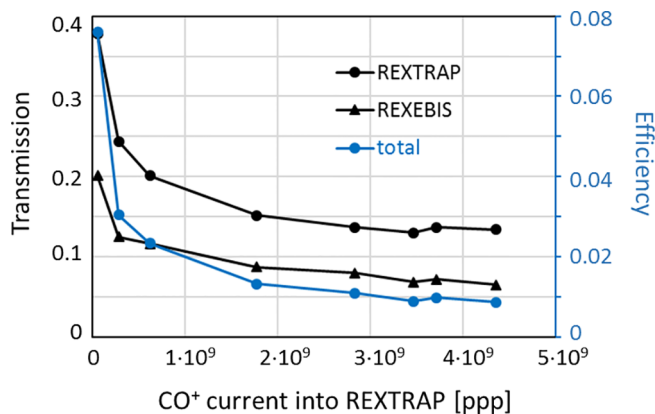


Fig. 4. Current dependent transmission through the Penning trap, from the trap exit through the EBIS (including BTS and separator); and total efficiency from the Penning trap entrance to after the REX separator.

100 ms. Measurements with K^+ and CO^+ were taken over a wide intensity range (10^7 – 10^9 particles injected per pulse into the Penning trap), which had no systematic effect on the loss rate. It is important to remember that CO^+ breaks up at injection into the Penning trap, thus we were actually measuring losses of carbon ions. Injection of atomic C^+ showed an identical loss rate. The mechanism behind the losses, however, could not be fully explained within this study.

2.3. Space charge limitations in the Penning trap

In the next step, the practical space charge limit in REXTRAP was determined. In order to assess the actual cooling capability, and not only the transmission through the Penning trap, the extracted beams were injected into the EBIS for charge breeding. Fig. 4 presents the transmission through REXTRAP, the combined transmission of beam transfer section (BTS), REXEBIS and the REX separator, and the total transmission through the charge breeder system. All of them decrease for an increasing input current, the trap transmission from initially 38% ($6 \cdot 10^7$ $^{13}\text{CO}^+$ injected) to only 13% when injecting $4 \cdot 10^9$ $^{13}\text{CO}^+$ ions per cycle. From Fig. 4 it can be concluded, that saturation effects in the Penning trap are present almost throughout the measurement range, latest at $7 \cdot 10^7$ charges extracted from REXTRAP, corresponding to the second measurement point in the data series. As will be shown below, the space charge capacity of the EBIS is higher, and did therefore not affect the result.

2.4. Space charge limitations in the EBIS

In order to establish a limit for the EBIS space charge neutralization, the ion current saturation was measured after the EBIS without prior cooling of the beam in the Penning trap, to exclude a possible current limitation from the trap. To mimic the timing of a pulsed injection into REXEBIS, a fast solid-state switch (50 ns switching time) was connected to an electrostatic deflector. For intensity reasons, an Ar^+ beam was used. At approximately $7.5 \cdot 10^8$ ions/pulse being injected into the EBIS, the extracted charge bred Ar^{11+} showed signs of saturation. This corresponds to an electron beam neutralization factor of 25%. A higher neutralization degree is not attainable due to the relatively high energy of the injected $1+$ ions, which leads to losses after ion thermalization. Translating this to the CO^+ case, and assuming the same neutralization degree, would result in saturation starting at $5.2 \cdot 10^8$ C^{6+} ions/pulse being injected into REXEBIS. This is significantly higher than the limit given by the Penning trap.

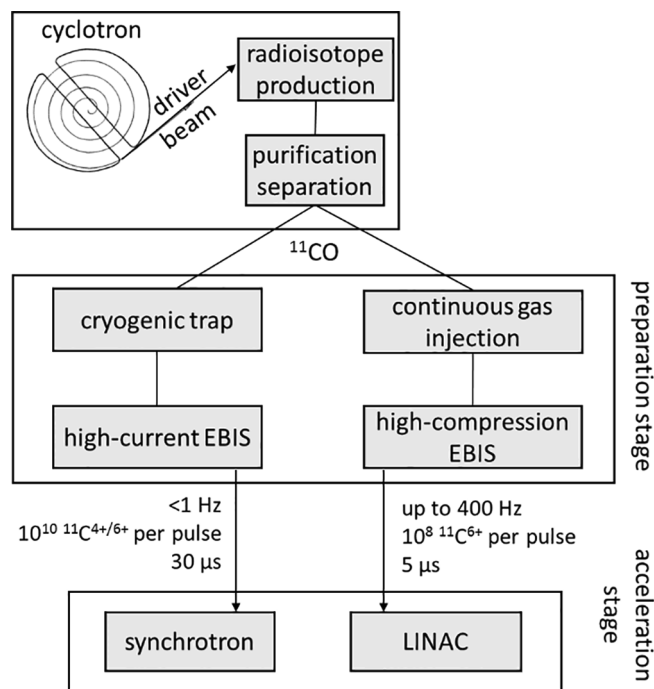


Fig. 5. Summary of most promising approaches to ^{11}C acceleration [1].

2.5. Continuous ion injection into REXEBIS

Continuous ion injection into the EBIS was examined as a method of circumventing bunching in the trap. For this operational mode of the EBIS, the outer barrier of the axial trapping potential – which is usually low during the injection and high during breeding – is constantly at an intermediate voltage, and ions are injected with a certain residual energy above the barrier. It was found that only a small fraction, approximately 1%, of the electron space charge could be occupied by the charge bred ions. This is understandable as the energy of the injected ions is even higher than for pulsed injection, and with an outer trap barrier at only 120–150 V above the trapping region, optimized on the charge breeding efficiency, the ion boil-off is severe. We conclude that in the continuous injection mode it is not possible to fill the EBIS properly, while maintaining a reasonable efficiency, as we do in the pulsed injection mode with a beam pulse length $< 30 \mu\text{s}$. In addition, the breeding efficiency of around 1% is lower compared to bunched ion injection.

3. Conclusions and outlook

Injection into a medical synchrotron requires the EBIS to deliver a pulse of 10^{10} carbon ions within a pulse length of few $10 \mu\text{s}$. While it is straightforward to achieve a sufficiently short pulse length from an

EBIS, the intensity requirement is very demanding. In combination with a medical synchrotron, it necessitates an EBIS with high electron beam current, which is, however, within reach of state-of-the-art technology. The challenge is to efficiently store and introduce the radioactive ^{11}C into the electron beam. It should be pointed out that, although an Electron Cyclotron Resonance ion source has a sufficient space charge capacity, the extracted pulse length is long compared to the synchrotron acceptance window even in afterglow mode (1–2 ms).

The tests have shown that a continuous injection into the EBIS can be excluded due to low efficiency and low output, as the EBIS cannot be filled properly to more than a fraction of its potential capacity. The Penning trap can be ruled out as well due to its low capacity and inability to store molecular CO beam. A scheme with a Radio Frequency Quadrupole (RFQ) ion beam cooler as buncher coupled to an EBIS should be investigated.

To increase the neutralization factor and better exploit the space charge potential of the EBIS, the presently advocated solution is neutral gas injection via a cryogenic trap into the EBIS [6]. In order not to fill the EBIS with background ion species, the target output could be purified either in a gas separation system or in an electromagnetic spectrometer after 1^+ ionization of the target gas, if required.

In case of the synchrotron, a high-capacity EBIS with $1.3 \cdot 10^{12}$ electron charges is required, which is technically possible. For an all-linac accelerator, operating with a high repetition rate (several 100 Hz), an EBIS equipped with a high-compression electron gun is more suitable. In this case a smaller electron space-charge capacity is sufficient due to the relaxed per-pulse intensity-requirements. In addition, it does not require the cryogenic trap as gas can be injected continuously due to the high repetition rate, making this the most favorable approach. Fig. 5 summarizes the here listed viable scenarios.

Acknowledgement

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