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MASS ANALYZER SYSTEM ORIENTED FOR SIMULTANEOUS CANCER TREATMENT WITH ^{11}C IMAGING

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Abstract

With the positron emission, ^{11}C can be utilized for OPENPET (PET system composed of separate double rings). With the projectile fragment scheme, ion beam intensities up to 10^5 / pulse and insufficient S/N ratio could be attained. In order to improve such situation, we have investigated a re-acceleration of the produced ^{11}C with a nuclear reaction. In the first step about 10^{11} ^{11}CO$_2^+$ ions are produced by irradiating a target with 18 MeV protons of 18 μA, delivered from a cyclotron. After the ^{11}C molecule production, the carbon dioxide is ionized to a single charge state (^{11}CO$_2^+$) and then mass analysed with the use of a magnet separator. With charge breeding (Isotope Separator On-Line (ISOL)) to ^{11}C$^{4+/5+}$ about 10^{10} ions can be provided. Currently we are considering a system consisting of a small size cyclotron combined with a ^{11}C molecule production/separation system (CMPS), a single charge ion source (SCIS) and a following analyser. Mass separation with a resolution better than 1/44, will be realized with a double focusing dipole magnet. In the present paper we describe the mass analyser for ^{11}CO$_2^+$ separation consisting of a single double focusing magnet with edge focusing.

INTRODUCTION

History of Heavy Ion Cancer Therapy

Following the splendid results for heavy ion cancer treatment at Lawrence Berkeley Laboratory using the BEVATRON mainly oriented for physics, the carbon ion radiotherapy was started at NIRS in June 1994 where several thousands of patients have been treated, as shown in Fig.1. Since 1994 the number of facilities which can provide such heavy ion radiotherapy has been increased to 5+2 and 6 (1)+10 for inside and outside of Japan, respectively, where the numbers after + indicate the ones which are in the design state or under construction and the one inside of parentheses indicates the terminated one. According to this growing number of facilities the importance of carbon ion radiotherapy has surely increased.

It should be noted that the heavy ion therapy has such merits as a high RBE (radio Biological Effectiveness) and a clear end cut shape of the irradiated area due to the heavier mass of the projectile. In order to extend the benefit of the heavy ion therapy to those who had not been able to be treated due to the closeness of an important organ to the tumour part, simultaneous imaging of the irradiated volume with the use of ^{11}C ion beam has been proposed, where the so-called "projectile fragment scheme" has been pursuit at first [1], but it was rather limited until now in the
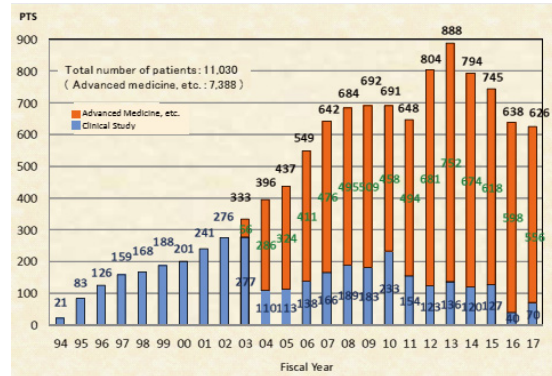

Figure 1: Annual number of patients treated with carbon ion radiotherapy at QST, NIRS from June 1994 to March 2018.

signal to noise ratio. "Target Fragment Scheme" has been proposed later [2]. In the present paper, we would like to describe a compact mass analyser scheme which leads to a new ^{11}C^{6+} ion beam therapy with sufficient beam intensity and simultaneous imaging by a "OPENPET" system [3].

Future Prospect

Numbers of treated patients and available facilities have been greatly increased, but there still exist such patients who are not be able to receive the benefit of heavy ion therapy due to closeness of the tumour part to an important organ. One of the important goals of NIRS, as a fundamental research institute, is to improve such a situation. Based on our research in these several years to enable simultaneous imaging of the irradiated region of the patient by a carbon ion beam, we would like to propose a plan to expand the HIMAC accelerator by a facility shown in Fig. 2, where an unstable β$^+$ emitter ^{11}C ion is produced and re-accelerated with HIMAC.

TOTAL SCHEME FOR ^{11}C ION BEAM RE-ACCELERATION

Fundamental Requirements

In this section the fundamental requirements for the new facility are shown. In order to realize good enough signal to noise (S/N) ratio by the OPENPET imaging, about 10^9 unstable ^{11}C^{6+} ion should be provided to each treating room in every acceleration cycle of the HIMAC synchrotron, which means 10^{10} charge bred unstable carbon ions are required [4]. Every 20 minutes (half life time of ^{11}C) about 10^{13} molecules of unstable ^{11}CO$_2$ will be produced at the target [5]. To separate ^{11}CO$_2$ from ^{12}CO$_2$ it is

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required to ionize CO_2 in the SCIS (singly-charged ion source). Its efficiency is estimated to be 0.1 (10%) [6]. The estimated value of $\varepsilon_{sep} \sim 1$ (separation efficiency of CMPS: ^{11}C molecule production/separation system) [6] requires a transport efficiency larger than 50 % for the present mass analyser if we assume the charge breeding efficiency of about 3 % for $^{11}C^{4+/5+}$ with the EBIS/EBIT type charge breeder [7]. In Table 1, the properties of the ion source to provide unstable $^{11}C^{4+/5+}$ ion beam to the HIMAC injector are given [6]. Based on these parameters, the design of the mass analyser system, used to connect the ion source with the charge breeder to provide the unstable beam is done. The proposed scheme of the unstable $^{11}C^{4+/5+}$ production and CO_2^+ separation is shown in Fig. 2(b), while Fig. 2 (a) is a total layout of the existing HIMAC facility.

MASS ANALYSER OF $^{11}CO_2^+$

In the scheme to provide $^{11}C^{4+/5+}$ for the HIMAC accelerator, $^{11}CO_2^+$ ions from the overwhelming background are to be separated. The background consists mainly of $^{12}CO_2^+$ coming from the contamination in the vacuum vessel. For

Table 1: Requirements for the Produced $^{11}CO_2^+$ Ion Beam

Ion Number	$\sim 10^{13}$
Beam Emittance (95%)	172 π mm・mrad
Beam Size (at the focus point)	$\sim$ +/- 10 mm
Momentum Spread (RMS)	0.1 %

the target material we plan to use B_2O_3 due to its higher collection efficiency ($\sim$76%) compared to a $NaBH_4$ target[5]. For the separation of $^{11}CO_2^+$ from $^{12}CO_2^+$, a mass resolution better than 1/44 is required. In order to attain this resolution, at first we assumed a scheme consisting of two dipole magnets and a quadrupole magnet triplet [8], which we recently intend to be replaced by a much compact single double focusing magnet with edge angles at both ends as shown in Fig. 3 and Table 2 [9]. With the present scheme, the beam distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ can be well
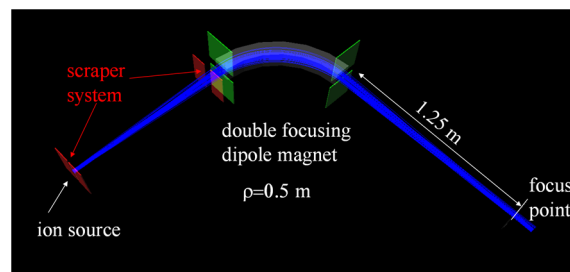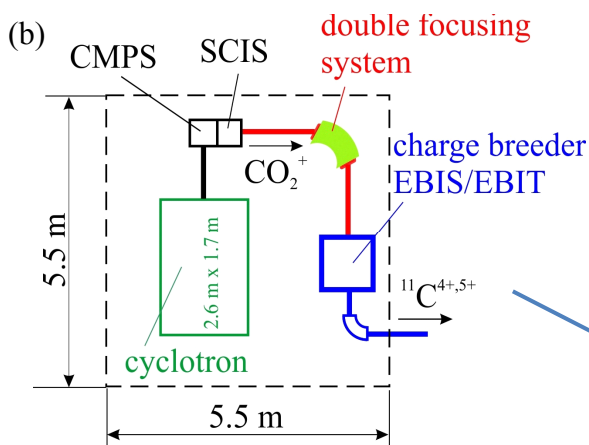

Figure 3: A mass analysing system composed of a single double focusing dipole magnet with edge focusing at both ends are shown together with a collimating system.
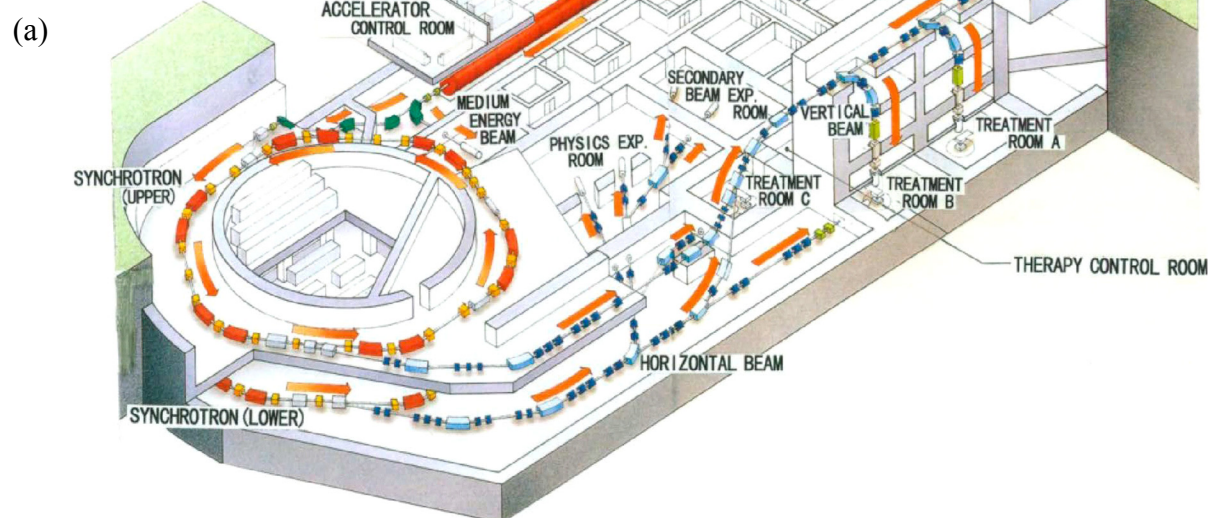

Figure 2: (a) Layout of the HIMAC. (b) Proposed provider of $^{11}C^{4+/5+}$ unstable ions for its re-acceleration with the use of existing HIMAC.
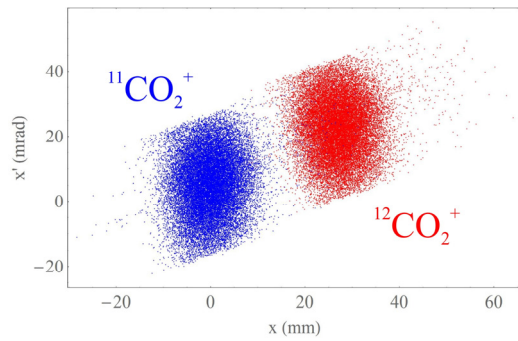
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Figure 4: Phase space distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ at the focusing point after the double focusing magnet calculated with g4 beamline.

separated at the beam slit in the focus point after the magnet as shown in Fig. 4 and Fig. 5 [9]. Due to the rather low required field of about 5 kG, the pole shape of the magnet is designed to have a sharp edge as shown in Fig.6 [9]. From Fig.5, the fraction of lost $^{11}CO_2^+$ ions by scraping out the $^{12}CO_2^+$ ions with the collimation slit seems less than a few percent. The required efficiency of higher than 50 % will be attained even if the real phase space distribution of $^{11}CO_2^+$ can be somewhat different from the tracking results. Therefore it is well expected that 10^{10} $^{11}C^{4+}$ ions are provided to the injector in a time interval of 100 μs.

The application of $^{11}C^{6+}$ ions for a real cancer therapy requires an accumulation of the unstable molecular ions in about 20 minutes. Progress in the tumour treatment using multi-energy operation with a single acceleration cycle, shown in Fig. 7, will efficiently use the accumulated unstable ions [10]. Recently patient treatments have been performed with 1 or 2 acceleration cycle [11]. By restricting the treatment to rather small tumours, a $^{11}C^{6+}$ ion beam therapy with simultaneous imaging by OPENPET can be well applied. Until now there are no experimental data of charge breeding process to $C^{4+/5+}$ from $^{11}CO_2^+$. In order to get this information, a charge breeder with EBIS/EBIT type has to be developed.

Table 2: Main Parameters of the Double Focusing Magnet

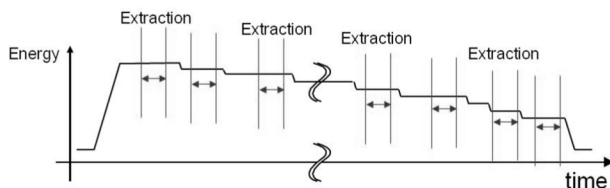| Magnetic Field	~5 kG
Magnet Gap	75 mm
Radius of Curvature	0.50 m
Deflection Angle	90°
Edge Angle	29.5°
End Cut Shape	Sharp Edge

Figure 7: Operation pattern of synchrotron that extracted ion beam while changing beam energy (from Ref. 11).
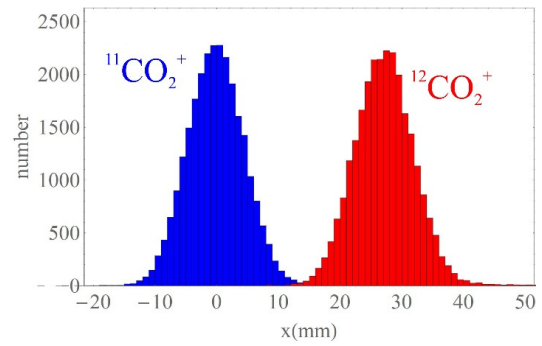

Figure 5: Horizontal ion beam distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ at the focus point after the double focusing magnet calculated with g4 beamline.

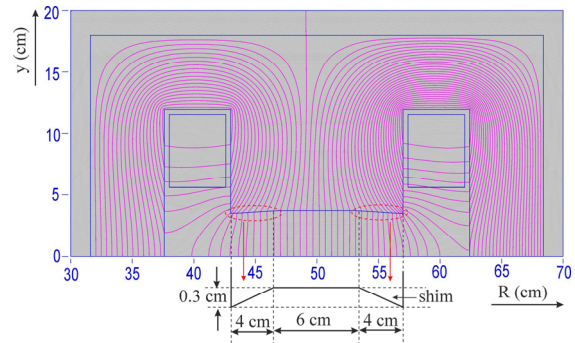Figure 6: Cross section of the double focusing dipole magnet.

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