DESIGN OF THE DOUBLE FOCUSING MAGNET FOR MASS SEPARATION OF A $^{11}C^{+}$ RADIOACTIVE ION BEAM*

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Abstract

At NIRS, re-acceleration of unstable ^{11}C ion beam with the synchrotron for cancer therapy, HIMAC has been pursuit in order to enable the real-time imaging of irradiation distribution of carbon ion into malignant tumour. Up to now $^{11}C^{6+}$ ion beam has been tried with very limited intensities of ~10^5 per pulse created with the use of a nuclear reaction of accelerated $^{12}C^{6+}$ ion beams by the HIMAC (so-called "Projectile Fragment Separation Scheme"). It was not possible to attain good enough signal to noise ratio to obtain a diagnosable imaging. Recently, the usage of ^{11}C ion beams, produced by irradiation of a high intensity proton beam coming from a cyclotron has been investigated. For this purpose, we have studied the separation of the molecular $^{11}CO_2^{+}$ ion beam from the overwhelming $^{12}CO_2^{+}$ ion beam with the use of a double focusing magnet. The design of the double focusing magnet to supply $^{11}C^{4+}$ radioactive ion beam to the HIMAC injector to re-accelerate the ions for the cancer therapy will be presented.

INTRODUCTION

History of Heavy Ion Cancer Therapy

Ion beam therapy was first applied at LBNL in 1970's with the use of the BEVALAC. The accelerator was mainly used for fundamental physics and partly for the heavy ion therapy [1]. The first accelerator oriented for heavy ion cancer therapy was constructed at National Institute of Radiological Sciences (NIRS) in Chiba, Japan starting the first cancer treatment in 1994 [2,3]. Carbon ions were chosen for the cancer therapy because these ions had a high RBE around the Bragg Peak, avoiding a too much fragmentation behind the Bragg Peak which was anticipated for the heavier ions like Ne or Ar, which were utilized at the BEVALAC. The delivered dose distribution is required to be within a variation of ±2%, which has been attained by the "Wobbler System", utilizing a broad ion beam strictly cut with a collimator and a range shifter or the dual-ring double scatterer method [4], in the first stage. To avoid an unnecessary irradiation into the normal tissue located in front of the tumour part, a spot scanning scheme has been pursuit.

APPROACH TO UNSTABLE ION ($^{11}C^{6+}$) IRRADIATION

At first, the so-called "Projectile Fragment Scheme" has been tried, which, however, was limited in the deliverable $^{11}C^{6+}$ ion beam intensity which was under 10^5 ions per pulse [5,6] and therefore a good signal to noise ratio could not be realized to enable a simultaneous imaging of the irradiated dose distribution with the use of "OPEN PET" [7]. To attain the required intensity of the $^{11}C^{6+}$ ion beam delivered from HIMAC, it is proposed to produce the unstable ^{11}C by irradiation of a target with a high intensity proton beam coming from a cyclotron and then re-accelerate it with the HIMAC complex (so called "Target Fragment Scheme") as shown in Fig.1. Such a scheme was first proposed by using a gas target [8]. To avoid the difficulties caused by the overwhelming background from the $^{12}CO_2$

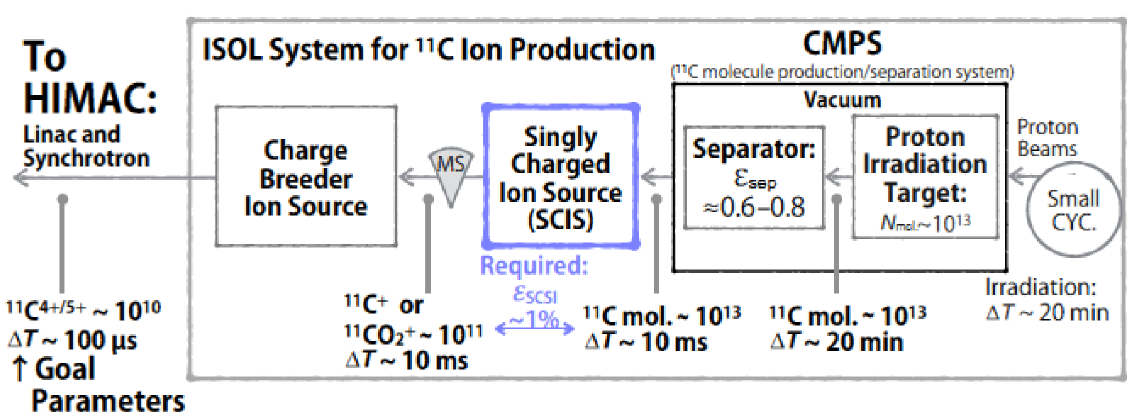

Figure 1: A possible scheme of ^{11}C ion production.

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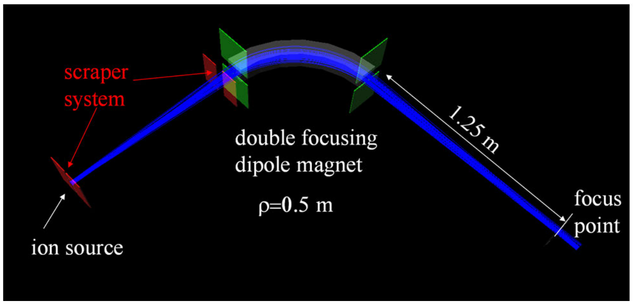

Figure 2: Newly proposed mass analysing system composed of a single double focusing dipole magnet and a collimating system.

gas molecule in the residual gas, we recently investigate the possibility of utilizing a solid target [9, 10]. At first, we investigated the scheme to ionize $^{11}CH_4^+$, which, however, was found to have difficulties in the discrimination of $^{12}CH_3^+$ therefore we consider now an ionization scheme where $^{11}CO_2$ gas is produced in a nuclear reaction.

Compared with the case of using $^{11}CH_4^+$ ions (<1/16) [11] a much better mass resolution below 1/44 is required for the case of the $^{11}CO_2^+$. In Table 1, the assumed parameters of $^{11}CO_2^+$ ion production/separation system (CMPS) required to separate $^{11}CO_2^+$ ions from the various background molecules, are listed up. Last year, we proposed a scheme composed of two dipole magnets with a central quadrupole triplet in between [12], which we could simplify by using only a single double focusing magnet together with a collimating system, as shown in Fig. 2. In the present paper the newly proposed mass analysing scheme will be described.

Table 1: Parameters of the Produced $^{11}CO_2^+$ Ion Beam

Ion Number	~10^{13} (in ΔT~10 ms)
Beam Emittance (95%)	172 π mm・mrad
Beam Size (at the focus point)	~ +/- 10 mm

NEW MASS ANALYZER SYSTEM

The separation capability of $^{11}CO_2^+$ from $^{12}CO_2^+$ with the system shown in Fig. 2, has been investigated. The simulation has been performed with MAD8 [13]. In Fig. 3,

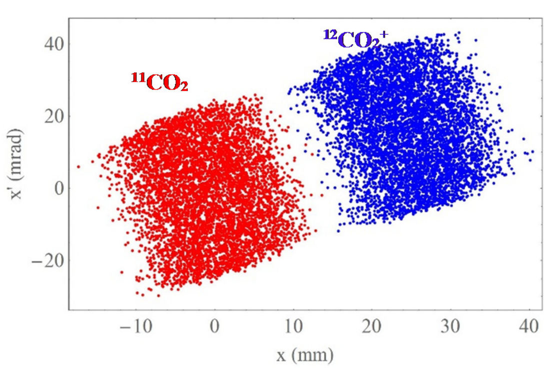

Figure 3: Phase space distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ at the focusing point after the double focusing magnet calculated with MAD8.

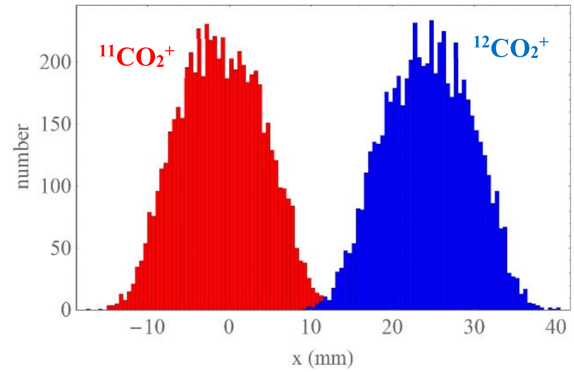

Figure 4: Horizontal ion beam distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ at the focus point after the double focusing magnet calculated with MAD8.

phase space distributions of $^{11}CO_2^+$ and $^{12}CO_2^+$ at the position close to the second focus point after the double focusing magnet are shown. The horizontal distributions of these ion beams at the same place are given in Fig. 4. It is shown that a small tail of $^{12}CO_2^+$ ion beam overlaps with that of $^{11}CO_2^+$. To ensure the separation of $^{11}CO_2^+$ ion beam from the overwhelming $^{12}CO_2^+$ ions, we started at first the design of a double focusing magnet by using the POISSON [14] code to optimize the flatness of the magnetic field in the dipole gap. Because in these 2D calculations, no edge

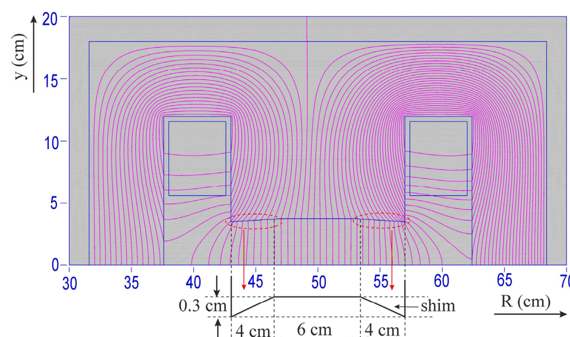

Figure 5: Cross section of the double focusing dipole magnet. At both sides, shims with the dimension illustrated above have been added.

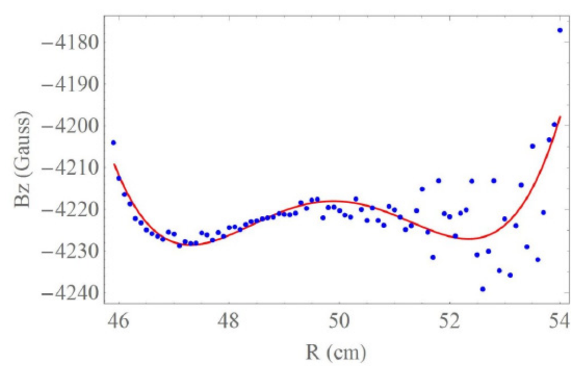

Figure 6: Calculated magnetic field distribution with the 2dimension code POISSON for the pole shape shown in Fig. 5.

angles at the both sides of the magnet are included further tracking calculations with the optimized magnetic field, has to be done with the 3D TOSCA code [15]. This 3D calculations are in preparation to get a three dimension field table for the G4 beamline tracking calculation [16] used to guarantee the separation performance of the system.

For the double focusing dipole magnet shown in Fig.2, we adopted a H-shape magnet. The cross section is shown in Fig. 5, where on both sides of the magnet gap shims, to improve the field quality, are attached. After the optimization of the magnetic field structure with the POISSON code, using cylinder coordinates, we have obtained a magnetic field flatness as shown in Fig. 6. The calculated magnetic field in the symmetry plane as a function of the radial position is indicated by blue dots together with a fitted polynomial curve (red). From the figure, it can be seen that a flatness of $\Delta B_z/B_z = \pm 0.003$ could be obtained in the range from R=-46 cm to R=54 cm.

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

DISCUSSION

To provide the needed intensity of $^{11}C^{6+}$ ions for the carbon ion therapy with simultaneous imaging of the radiation distribution using positron emitter every 20 minutes 10^9 ions are required. Considering the beam loss during multiturn injection into HIMAC from its injector and its slow beam extraction, it is needed to provide 10^{10} ions to the injector of the HIMAC every 20 minutes. Concerning recent studies of the singly charged ion source (SCIS) [17] it might be possible to attain an ion-production efficiency (IPE) of 0.075 (7.5%) for the $^{11}CO_2^+$ case.

However the field quality of the real magnet might be somewhat worse, in comparison to an ideal dipole field assumed in the MAD8 calculations, which can result in a suboptimal mass resolution. To study mass resolution effects coming from the non-ideal dipole field further G4 beamline tracking calculation using a real dipole field has to be carried out. In these further studies also the effects of the fringing fields at both ends of the magnet are to be taken into account. For the end cut shape we are now considering a sharp edge magnet without using a Rogowski profile [18] because the magnet is used at a fixed level around 5 kG. Our magnetic field with about 5 kG is rather low which is the reason why we have adopted a pole shim structure with sharp edges at both sides of the magnet as shown in Fig. 5 without using round shapes.

In the calculation described above, the space charge effect has not been taken into account, which we expect not to be important because the ion beam intensity is not so high and the ion beam size is larger than ~+/- 10 mm even at the focus point as shown in Fig. 4.

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