DEVELOPMENT OF $^{11}C^{+}$ ION SOURCE FOR REACCELERATION WITH HIMAC FOR REAL-TIME OBSERVATION OF DOSE DISTRIBUTION

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Abstract

In order to improve the precision of dose distribution in a patient's body in the case of carbon therapy, real time measurement of the dose distribution with the use of the so called OpenPET is desirable. For the realization of such a treatment, the usage of an isotope separator online scheme based on target fragment might be inevitable to keep the needed S/N ratio. To fulfil the above requirement, 1+ ion source (SCIS: singly charged ion source) of positron emitting $^{11}C^{+}$ ions is under development. Charge breeding to higher charge state of 4+ is applied before injection into the injector LINAC of HIMAC. $^{11}C^{+}$ ions are to be produced by a high intensity proton beam coming from a cyclotron. In a real treatment process, a small cyclotron like HM20 will provide the proton beam, but in the present development stage, we are utilizing a proton beam from the existing AVF cyclotron at NIRS with K-number of 110.

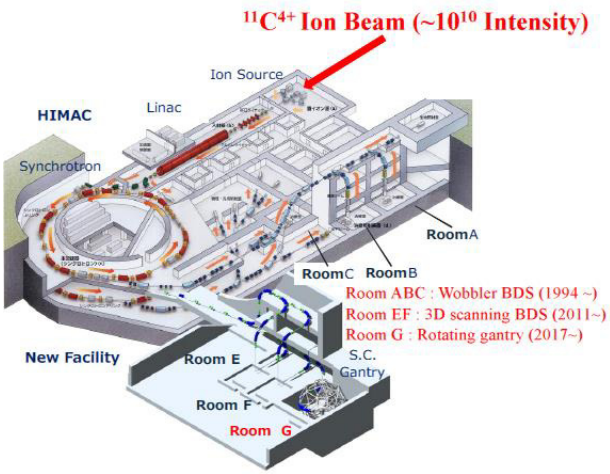

Figure 1: Bird's eye view of the present HIMAC Facility (borrowed from Ref. [2]).

INTRODUCTION

At NIRS, QST in Chiba, almost 10,000 cancer patients have been treated up to now by carbon ion irradiation therapy since the start of the facility, HIMAC in 1994 [1]. The total layout of the HIMAC facility is shown in Fig. 1, where the proposed injection possibility of $^{11}C^{4+}$ ion beam should be applied. Nowadays, the number of heavy ion cancer therapy facilities have increased around ten in the world and its wide spread use with much less expense of the patient by reducing its size and construction cost, has become an urgent object [2]. In parallel, the approach to treat special tumours, which have not yet been treated because of their clinical difficulties is one of the main research items of NIRS as a research institute. For this purpose, NIRS is proposing TRT (Targeted Radiation Therapy) [3]. Together with such an approach, more efficient irradiation therapy with the use of multi-ion beams has been studied [4,5], for which the precision of dose distribution has essential importance. Irradiation for treatment with the use of radioactive ^{11}C beam combined with the so-called "OpenPET" [6], might enable real time measurement of the dose distribution in the patient's body. In the present paper, the goal to achieve re-acceleration of radioactive ^{11}C ion beam by HIMAC is presented.

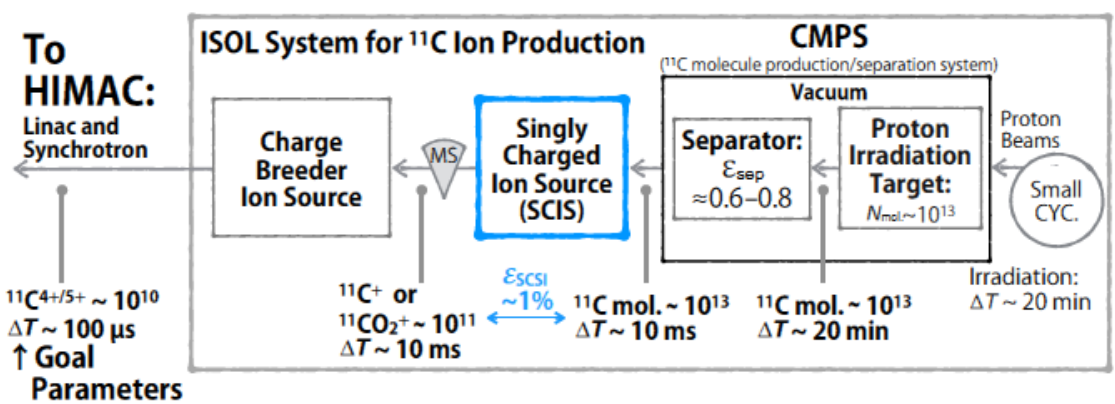

Figure 2: Possible scheme for ^{11}C ion production [12].

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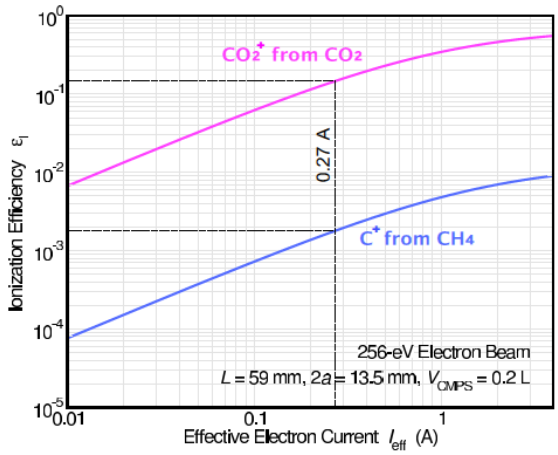

Figure 3: Ionization efficiency for CO_2^+ production from CO_2 and C^+ production from CH_4 molecules [12].

PRODUCTION OF ^{11}C IONS

At first, ^{11}C ion beam for PET measurement has been provided with the projectile fragment scheme, which, however, was limited in intensity under ~10^5 ppp due to the rather poor beam qualities such as large momentum spread and transverse emittance [7,8]. In order to overcome these limitations, ISOTOPE SEPARATION ONLINE: ISOL, scheme based on a target fragment scheme has been proposed to provide ^{11}C ion beams, produced by irradiation of the high intensity proton beam from a cyclotron [9]. With the existing cyclotrons at NIRS, NIRS930 and HM-18, radioactive nuclides as shown in tables 1 and 2, respectively, can be produced and we developed a scheme to provide a positively charged radioactive ^{11}C beams [10,11].

ISOL SCHEME

The schematic layout of the proposed system for providing radioactive ^{11}C ion beam is shown in Fig. 2. High intensity proton beams from a cyclotron are irradiated on a solid target. In a former publication, we have proposed the gas collection scheme by using $^{11}CH_4$ molecule produced in a $NaBH_4$ solid target [10,11]. A separation of $^{11}CH_4^+$ from $^{12}CH_3^+$ at the succeeding Mass Separation (MS) process is impossible, therefore we are forced to use $^{11}C^+$ instead of $^{11}CH_4^+$, which resulted in rather low ionization efficiency as ~0.2 %. Higher ionization efficiencies have been investigated with the use of $^{11}CO_2^+$ production with CO_2 molecules and an ionization efficiency, of ~11% is expected by the 3-D computer simulation with PIC code as shown in Fig.3 [12] based on the previously reported data and trials [13,14]. Although experimental data taking under the vacuum condition without using a carrier gas utilizing radioactive $^{11}CO_2$ molecule has been left to be obtained from now on, we have estimated the collectable number of $^{11}CO_2^+$ molecular ion beam to be ~10^{11} assuming conservative overall efficiency, ε_{SCIS} to be 1% [12].

Table 1: Radioactive nuclides created by ion beams from the NIRS930 AVF cyclotron.

Beam Particle	Radio-Nuclide
Proton	^{89}Zr
	^{11}C
	^{62}Zn/^{62}Cu
	^{68}Ge
	^{67}Cu
H_2^+	^{64}Cu
	^{124}I
Deuteron	^{177}Lu
Helium	^{67}Cu
	^{43}Sc
	^{47}Sc
	^{74}As
	^{155}Tb
	^{186}Re
	^{211}At
	^{28}Mg

Table 2: Radioactive nuclides created by ion beams from the HM-18 cyclotron.

Beam Particle	Radio-Nuclide
Proton	^{11}C
	^{13}N
	^{18}F
Deuteron	^{15}O

Singly Charged Ion Source (SCIS)

In the previous approach utilizing analytical calculation, the inner radius of the drift tube was assumed to be constant as shown in Fig. 4, which was found to reduce the effective electron current by the new PIC simulation. Modification of the drift tube shape as shown in Fig. 5, expects increase of the effective electron current and hence a higher $^{11}CO_2^+$ ion number [12].

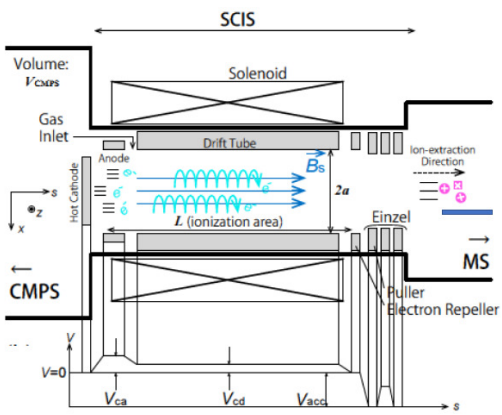

Figure. 4: Layout of the proposed 1+ ion source (SCIS) before modification [12].

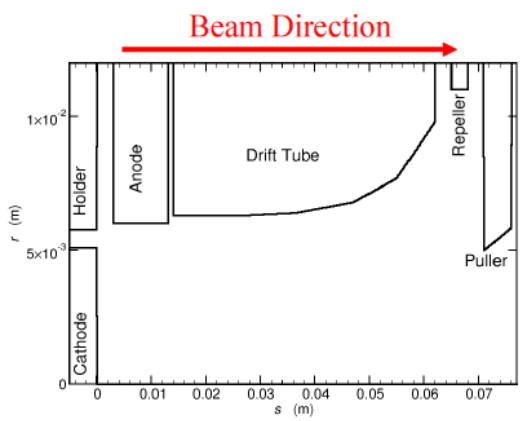

Figure 5: Proposed modified drift tube shape [12].

ISBN 978-3-95450-182-3

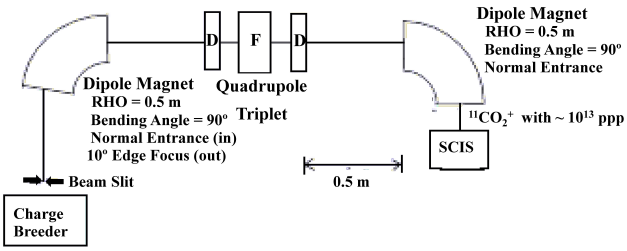

Figure 6: Proposed mass separator system consisting of two dipole magnets and quadrupole triplet in between, which is separable $^{11}CO_2^+$ from $^{12}CO_2^+$.

MASS SEPARATION SYSTEM

With the use of $^{11}CO_2^+$ molecular ion beam instead of $^{11}C^+$ ion beam, almost two orders of magnitude larger ionization efficiency is expected as shown in Fig. 3. However, the following mass separator is required to separate $^{11}CO_2^+$ molecular ion beam from $^{12}CO_2^+$ with a mass difference of 1/44, which is much smaller compared to 1/11 for the case at $^{11}C^+$ and $^{12}C^+$. In order to remedy this situation, we put the previously described CMPS and SCIS systems on a high voltage terminal of 20 kV and put kinetic energy of 20 keV to these molecular ion beams, which reduced the relative momentum spread ($\Delta p/p$) almost 1 order of magnitude compared with the previous scheme dealing with 2 keV ion beams. With this energy, the unnormalized 95% beam emittance becomes to be 172 mm • mrad. But, the previously proposed separation system consisting of a single dipole magnet of 90 degree deflection with edge focusing at both sides [15] was found to be unable to separate these molecular ion beams. So as to improve this situation, two dipole magnets including a focusing and defocusing quadrupole magnets triplet in between as shown in Fig. 6, is proposed. In table 3, the main parameters of this separator are given. With this scheme, these molecular ion beams can be separated as shown in Fig. 7.

SUMMARY

Assuming the modified scheme of SCIS, we have investigated the attainable beam intensity which can be reaccelerated with HIMAC and its injector after charge breeding. Although the charge breeder composed of EBIS/EBIT has to be developed, we assume a rather conservative value of transition and charge breeding efficiency of ~10%. From the above consideration, an output intensity of ~10^{11} $^{11}CO_2^+$ molecular ion beam has to be provided and $^{11}C^{4+}$ beam with an intensity of ~10^{10} ions after charge breeding will be expected to be injected into the HIMAC Linac. As the carbon ion beam intensity is anticipated to be reduced almost 1 order of magnitude due to multi-turn injection into HIMAC synchrotron ring and slow beam extraction processes [16], we expect ~10^9 ppp $^{11}C^{6+}$ ion beam to the irradiation port every 20 minutes, which might be tolerable for the real-time usage of patient treatment owing to the recent development of variable energy operation during a single acceleration cycle of HIMAC [2].

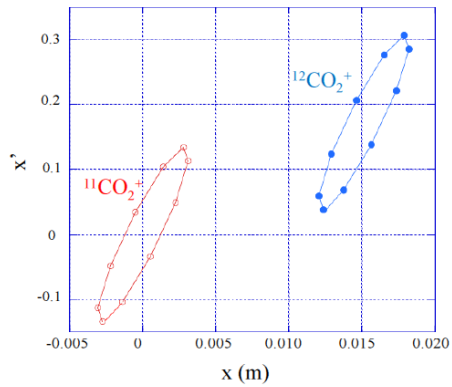

Figure 7: Distributions of the molecular ion beams in the horizontal phase space at the beam slit position shown in Fig.6.

Table 3: Main Parameters of the Mass Separator

Dipole Radius of Curvature	0.5 m
Dipole Bending Angle	90 Degree
Edge Angle	0 Degree 10 Degrees only for output of the second dipole
Quadrupole Length	0.2 m (QF), 0.1 m(QD)
Quadrupole Strength (n/ρ^2)	50 m^{-2}(QF), 30 m^{-2} (QD)

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