ACCELERATION SCHEME OF RADIOACTIVE ION BEAM WITH HIMAC AND ITS INJECTOR LINAC

Akira Noda#, Satoru Hojo, Ken Katagiri, Masao Nakao, Etsuo Noda, Koji Noda, Akinori Sugiura, Kazutoshi Suzuki, Takashi Wakui , NIRS, Inage, Chiba, 263-8555, Japan
Manfred Grieser, MPI-K, 69117, Heidelberg, Germany

Abstract

At the National Institute of Sciences (NIRS), cancer therapy with the use of a carbon beam has been successfully applied since 1994 by using 'HIMAC' (Heavy Ion Medical Accelerator in Chiba). Recently the number of treated patients has been increased to nearly 1000 per year. For the purpose of real-time verification of the irradiation distribution in the patient's body during a heavy ion cancer treatment, the capability of the so-called "Open PET" with a radioactive $^{11}C^{6+}$ ion beam has been proposed[1] and projectile fragment ^{11}C ion beams, already has been tried to be applied[2], but the beam intensity was rather poor, about 10^5 pps, and a good S/N ratio had not been attained[1]. Therefore to remedy this situation, the acceleration of radioactive ions created by the "Target Fragment" scheme, where beams from the cyclotron irradiate a target, has been proposed[3]. In the present paper, in connection with recent developments[4], an acceleration scheme of secondary produced radioactive ^{11}C ion beams with HIMAC and its injector is investigated.

INTRODUCTION

Radiation cancer therapy utilizing heavy ions has increased its importance by a steady increase of the treatment numbers in addition to the fact that it is improving the "Quality of Life" of the patients. Up to now the irradiated region by heavy ion beams has been estimated with a preparatory irradiation into a water phantom and by using computer simulation. However, recent innovations of imaging technology might enable a direct detection of the irradiation area during the real therapy treatment with the use of an "OPEN PET"[1]. For such purpose, it is inevitable to provide enough ions (>10^7 pps) to the irradiation port of HIMAC for attaining a good S/N ratio.

Up to now, radioactive ion beams of ^{11}C, produced by projectile fragmentation of stable ^{12}C ion beams have been created[2] and transferred to the secondary beam port of HIMAC for the purpose of visualization of the beam stopping point. Its intensity, however, was rather limitted (less than 10^5 pps) and it is not strong enough for real clinical usage.

In order to attain enough intensity of a radioactive ^{11}C ion beam, a scheme utilizing target fragments, produced by high intensity proton beam irradiation with the use of the cyclotron; NIRS HM18, has been considered[3], which is a similar scheme used at ISOLDE of CERN[5] , although the energy region of the primary proton beam is much lower. Originally a N_2 gas target has been proposed using a $^{14}N(p, \alpha)^{11}C$ reaction[6]. The collection efficiency of molecules containing radioactive ^{11}C ions, however, is rather limited with the use of a N_2 gas target, because separation of the huge amount of the impurity N_2 gas is a serious problem to provide the ^{11}C molecules to the 1+ ion source under vacuum condition, which is different from radioactive drug generation case. Therefore a new scheme using a solid $NaBH_4$ target for $^{11}B(p,n)$ ^{11}C reaction is utilized where the ^{11}C gas can be ionized and efficiently collected[4].

#a_noda@nirs.go.jo

RADIOACTIVE ISOTOPE PRODUCTION

Radionuclide Production with Cyclotrons at NIRS

At NIRS since its establishment, various knowledge and experiences have been accumulated concerning treatment and imaging with the use of radioactivity. Recently more than 200 radiopharmaceuticals have been developed and been globally utilized for diagnostic imaging. Reflecting the rapid progress of imaging and medical treatment utilizing radio-pharmaceuticals, Targeted Radionuclide Therapy (TRT) has been also investigated and basic experiments with animals have been applied using α-particle with high LET (Linear Energy Transfer) or radioisotopes with Auger electron emission. In table 1 and table 2, lists of radionuclides produced by

Table 1: Ion Beams from the NIRS930 Cyclotron and their Created Radionuclides

Beam Particle	Radionuclide
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: Ion Beams from HM-18 Cyclotron and their Created Radionuclides

Beam Particle	Radionuclide
Proton	^{11}C
	^{13}N
	^{18}F
Deuteron	^{15}O

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the irradiation with a beam from cyclotron, NIRS-930 and a small HM-18 cyclotron, respectively, are shown. Based on such an activity, a new project to extend the TRT has been proposed.

Radioactive ^{11}C Ion Production at NIRS930 Beam Line

At the beam line of NIRS930 used for neutron therapy just after construction about 40 years ago, a modification utilizing wobblers to enlarge the beam size for various radiopharmaceuticals production is being applied[7]. With this beam line, the scheme above mentioned to create $^{11}C^{+}$ beams will also be tested experimentally using proton beams from NIRS-930 as a preparatory study before the beams are further accelerated.

At NIRS, on the basis of such an activity as described before, ^{11}C of the amount of about 10^{13} are produced in 20 minutes with the $^{11}B(p, n)^{11}C$ reaction by irradiation with 18 MeV proton beams onto a solid $NaBH_4$ target. A ^{11}C beam with an intensity of 10^8 pps can be provided in each 20 minute cycle. Recent scheme utilizes irradiation onto a solid target under the vacuum condition[8].

ACCELRERATION SCHEME OF ^{11}C BEAMS WITH HIMAC

Injector Linac System of HIMAC

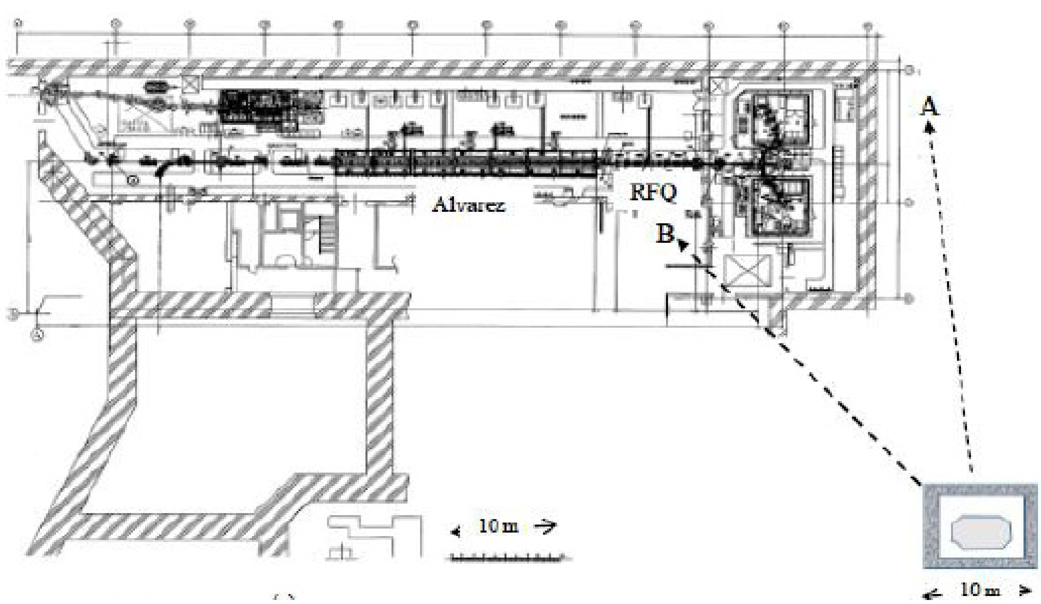
The beams from the ion source are accelerated by the RFQ and the drift tube linac of Alvarez type, both with the operation RF frequency of 100 MHz, before the beam is injected into the HIMAC synchrotron. In table 3, the main acceleration performance parameters of the injector linac are listed up[9]. Ions with charge to mass ratio (q/M) larger than 1/7 times e/m_0 (e and m_0 are unit charge and atomic mass unit, respectively) can be accelerated. The normalized emittance (90 %) of the injector linac is 0.7 πmm・mrad and the momentum spread is ±0.1%.

Acceleration of Radioactive ^{11}C Ion with HIMAC and its Injector

For the purpose of acceleration of a radioactive ^{11}C ion with a life time of about 20min by the injector linac of HIMAC as shown in Fig. 1, the CMPS (^{11}C molecule production and separation system) has to be followed with a singly charged ion source and a charge breeder (shown in Fig. 2). The ISOL system for ^{11}C ion production has to be close to the linac, for example at the position A or B shown in Fig. 1. We are now considering the construction of a small cyclotron, HM-20[10] with an irradiation room for the unsealed radiation. The final decision of the position of HM-20 and CMPS depends on the usage of the area next to the RFQ.

Table 3: Main Parameters of the Injector Linacs (Borrowed from Ref.[9])

Injection Energy	8 keV/u
Output Energy	800 keV/u(RFQ), 6 MeV/u (DTL)
Input Current	140eμA(C^{4+}), 300eμA(C^{2+})
Transport Efficiency	
LEBT	93%(C^{4+}), 80%(C^{2+})
RFQ	92%(C^{4+}), 92%(C^{2+})
Alvarez	96%(C^{4+}), 86%(C^{2+})
Stripping Efficiency	93%
MEBT Transmission	95%(C^{4+}),84%(C^{4+})
Normalized emittance (90%)	0.7 πmm・mrad
Momentum Spread	±0.1%



(a) (b)

Figure 1: (a) Layout of the injector linac system of HIMAC, (b) Rough scale of HM20 (with shielding).

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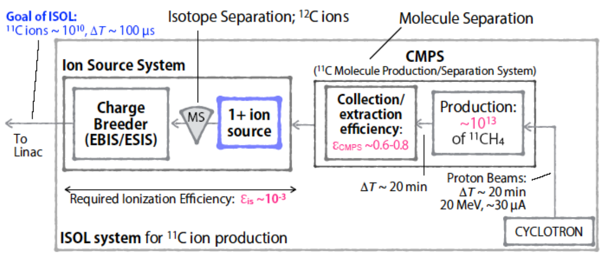

Figure 2: A scheme to provide ^{11}C ion beam (borrowed from Ref. [8]).

The performance of the above scheme composed of CMPS and 1+ ion source followed by a charge breeder has to be experimentally investigated. The studies will start early next year. The beam emittance and momentum spread of the ^{11}C ion beam will be measured as soon as the irradiation system becomes available.

Beam Dynamics Evaluation

Because the initial parameters of the radioative ^{11}C ion beam from the ISOL system for ^{11}C ion production shown in Fig.2, are not yet known so far, beam dynamics simulations of the ^{11}C ion beam has to be carried out with a computer simulation code such as PARMTEQ[11], assuming similar beam parameters (emittance and momentum spread) of a usual ^{12}C ion source. It is expected that by modification of the intervene voltage according to the difference of the charge to mass ratio, similar beam behaviour as shown in Fig.3 can be obtained.

CONCLUSION

Using the above scheme, we expect to be able to provide totally about 10^9 ^{11}C ions every 20 minutes. If the beam extraction from HIMAC and the beam supply to the treatment room is performed during 10 seconds, beam rates of about 10^8 pps will be realized for a limited part (10 sec.) of the 20 minutes period, which is around 10^3 times larger compared with the already applied scheme utilizing the

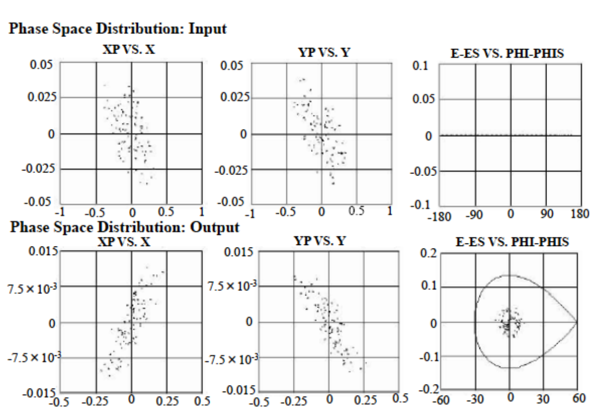

Figure 3: Example of beam distribution at the input and output of the RFQ calculated by PARMTEQ.

"Projectile Fragment" scheme and the S/N ratio for online PET imaging is expected to be well enhanced.

Possibility of Acceleration of Other Ions

As shown in table 2, the small cyclotron can produce other ions like ^{13}N, ^{18}F and ^{15}O. ^{15}O ions with a rather short life time (2 minutes) needs a deuteron beam for the production and is not usable for further acceleration. The available accelerated radioactive ion beams are rather limited due to the required charge to mass ratio larger than 1/7 (e/m_0) by the injector linac. However the combination with HIMAC might give us a possibility of unique higher energy radioactive ion beams and seems to require further deep discussions for the future.

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