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DEVELOPMENT OF He^{2+} 10GHz ECR ION SOURCE FOR ASTATINE GENERATION ACCELERATOR

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Abstract

At Tokyo Institute of Technology, we are proposing to construct a linac facility for producing ^{211}At, an isotope for α-emitter cancer therapy. To produce ^{211}At, we aim to bombard a bismuth target with helium ion beam of sufficient intensity at 29 MeV. Unlike a cyclotron, this facility will be able to accelerate a milliampere class high intensity helium ion beam. In addition, the subsequent accelerator system can be made compact by providing fully stripped helium ions. For this purpose, an ECR ion source is best suited. Multiply charged ions are generated by resonant absorption of microwaves by electrons orbiting in a magnetic field and can supply high-intensity beams can be delivered. The planned ECR ion source will use an RF frequency of 10 GHz, and a suitable magnetic field distribution will be designed to confine the plasma by a composite magnetic field consisting of a mirror field using two solenoid coils and a sextupole magnetic field generated by a permanent magnet to increase the charge states of the ions in the chamber. The final goal is to extract He^{2+} at 15 mA.

INTRODUCTION

Nuclear medicine therapy is a treatment using a radiopharmaceutical which contains radioisotope (RI). The drugs home in on cancer cells and bombard them mainly with α radiations, causing them to stop growing or die. The mass of the α-rays is approximately 8000 times heavier than that of the β-rays, thus they have short range in the body and a high linear energy transfer (LET) when passing through the tissue. Therefore, treatment with α-rays can kill only cancer cells and minimize radiation effects on surrounding normal cells and tissues.

There are two methods of producing α-ray-emitting nuclides for nuclear medicine therapy: one is to obtain them by separating them from the parent nuclide, which has a long half-life, and the other is to produce them using an accelerator. In Japan, domestic supply of parent nuclides with long half-lives is very limited, thus accelerator-based RI production is an important method.

The α-ray emitting nuclide ^{211}At has shown high efficacy in the nuclear medicine treatment of cancers such as thyroid cancer and pheochromocytoma, and its early commercialisation is strongly desired [1-2]. The main characteristics of ^{211}At are as follows. ^{211}At decays to ^{207}Bi emitting a 5.87 MeV α particle by α-decay or ^{211}Po by electron capture with probabilities of 41.8% and 58.2%, respectively, with a relatively short half-life of 7.21 hours. ^{211}Po has an extremely short half-life of 516 ms compared to the half-life of ^{211}At, and has a 100% probability of α-decay emitting a 7.45 MeV α particle. Therefore, ^{211}At effectively emits 7.45 MeV α-rays from the moment of production until it decays with its half-life.

The most common method of ^{211}At production using accelerators is the use of ^{209}Bi(α, 2n)^{211}At reaction. ^{211}At is produced by irradiating a ^{209}Bi target with a He beam above 20 MeV. ^{209}Bi has a 100% natural abundance ratio. Thus, it is easy to handle.

There are five ^{211}At production sites in Japan [3], where the He beam is accelerated by using cyclotrons. In cyclotrons, the amount of beam current that can be accelerated is limited to a few μA to a few hundred μA. Therefore, the production yield of ^{211}At is also restricted by the beam current limitation [3]. The short half-life of ^{211}At is favourable in terms of nuclear medicine therapy, but it is one of the problems in terms of separation and purification of ^{211}At by chemical processing. In the production of ^{211}At using an accelerator, increasing the beam current intensity is one of the solutions to shorten the production time including beam irradiation period, which is very important.

At Tokyo Institute of Technology, a conceptual design of a compact He beam accelerator for ^{211}At production is proposed based on a linear accelerator technology, which is more compact and has a higher intensity than the existing one and is for installation on the University's campus.

ACCELERATOR SYSTEM

A conceptual view of the proposed He beam accelerator system is shown in Fig. 1. The accelerator system mainly consists of the Electron Cyclotron Resonance (ECR) ion source, the Radio Frequency Quadrupole linear accelerator (RFQ), and two Drift Tube Linear accelerators (DTL). The accelerator system is designed to accelerate He^{2+} beams up to 4 MeV in the RFQ, 17 MeV in the first DTL and 29 MeV in the second DTL. The final beam current to be delivered to the target is designed at 10 mA, and the production of several hundred GBq of ^{211}At is considered at continuous-wave (CW) operation. In this accelerator system, the ECR ion source is the first component and is important in the production of high-intensity beams.

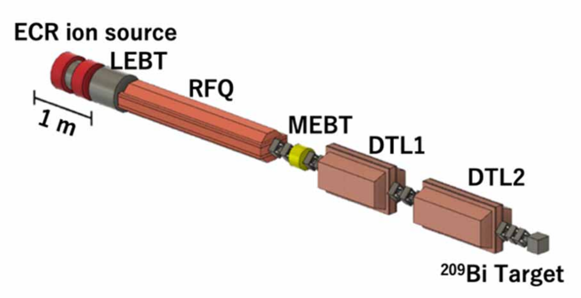

Figure 1: Structure design of the proposed He beam accelerator system.

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DESIGN OF ECR ION SOURCE

The requirements for the ion source to be designed are as follows. The He^{2+} beam must be extracted to design a compact overall accelerator system. To have beam current of 10 mA to irradiate the ^{209}Bi target, more than 15 mA of He^{2+} beam from the ion source is preferred. To meet the criteria, we adopted an ECR ion source operated with DC mode operation.

As examples of successful development of He^{2+} beams with the ECR ion source, the beam currents of 2 mA and 4.4 mA were achieved at a microwave frequency of 10 GHz at National Institute of Radiological Sciences (NIRS) [4] and that of 2.5 GHz at Peking University (PKU) [5-6], respectively. The inner diameters of the plasma chambers of ion sources developed at the NIRS and PKU are 50 mm and 40 mm, respectively [4-6]. Because the beam intensity depends on the plasma frequency and the size of the plasma volume [7], Then we choose 10 GHz and a larger size diameter of the chamber which is 100 mm. The schematic drawing of proposed ECR ion source is shown in Fig. 2. Plasma confinement is provided by two solenoids in the axial direction of the beam and by a radial magnetic field of a sextupole permanent magnet.

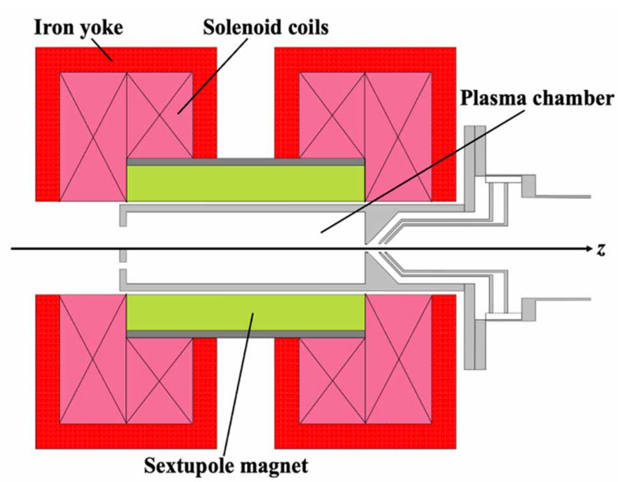

Figure 2: The schematic drawing of proposed ECR ion source.

The magnetic field of the ECR, B_{ecr}, is 0.357 T at 10 GHz. Because the ionization energy of He^{2+} is relatively low (54.4 eV) among the fully stripped ions produced by a typical ECR ion source, a long confinement time is not necessary. The maximum magnetic field strength was set to about 1 T for the proposed ECR ion source. Table 1 shows the target value of magnetic field.

Table 1: Target Value Magnetic Field Strength

Parameter	Value
・ B_{ecr} (10 GHz)	0.357 T
・ Mirror magnets	
Injection peak B_{inj}	0.9 T
Extraction peak B_{ext}	0.64 T
Minimum B B_{min}	0.28 T
・ Sextupole magnet	
the plasma chamber wall B_r	0.71 T

The ratio of each magnetic field to the resonant magnetic field Becr is as follows. This ratio is the semiempirical optimum field ratio for ECR ion sources intended for highly-charged heavy-ion production, except on the injection side [8-11].

$$\frac{B_{inj}}{B_{ecr}} \sim 2.5, \frac{B_{ext}}{B_{ecr}} \sim 1.8\,, \frac{B_{min}}{B_{ecr}} \sim 0.8, \frac{B_r}{B_{ecr}} \sim 2 \qquad (1)$$

SIMULATIONS

Calculation of Magnetic Field

The magnetic field distributions of the mirror and radial magnetic fields were designed using the electromagnetic simulation code CST studio suite [12]. The model used in CST is shown in Fig. 3.

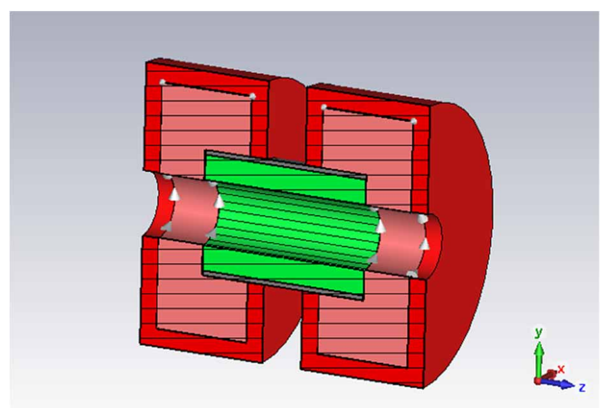

Figure 3: The model used in CST.

Mirror Confinement Field

The magnetic field distribution on the central axis of the ion source in this calculation is shown in Fig. 4. The distance between the mirror solenoids was 83 mm, and the outer diameter including the iron yoke was 560 mm and the total length was 607 mm. The inner diameter and the length of the chamber were set as 100 mm and 345 mm, respectively. The magnetic field strengths of the mirrors were calculated to be B_{inj} = 0.91 T, B_{ext} = 0.69 T, and B_{min} = 0.28 T.

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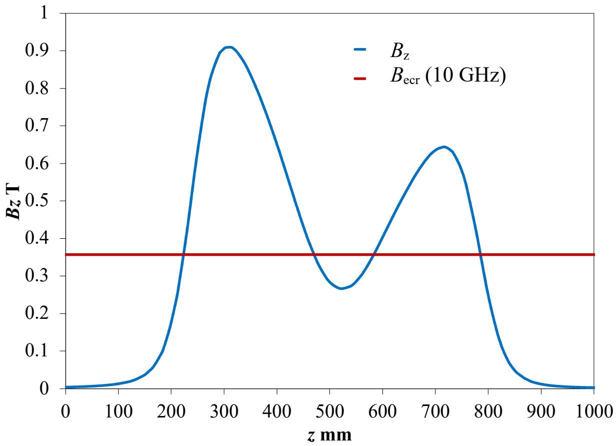

Figure 4: Mirror confinement field.

Radial Confinement Field

The inner diameter and the outer diameter of the sextupole magnet was set as 130 mm and 250 mm including the fixture, respectively. The sextupole magnets were arranged in a 24-segment Halbach array, and the remanent flux of each magnet is 1.3 T. The calculated magnetic field distribution in the radial direction of the ion source is shown in Fig. 5. The magnetic field strength in the radial direction is $B_r = 0.73$ T at the plasma chamber wall.

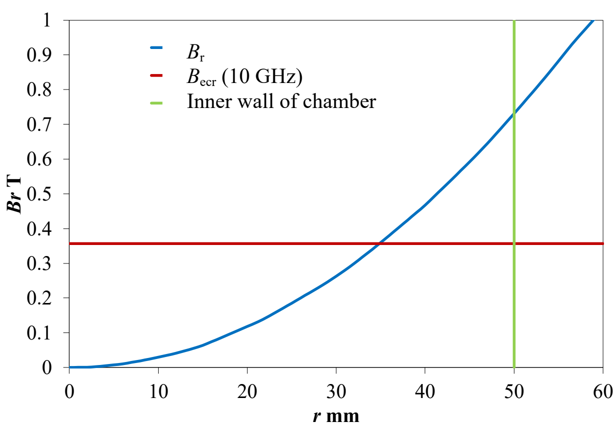

Figure 5: Radial confinement field.

FUTURE PROSPECTS

To produce the proposed ion source, it is necessary to design the extraction electrode and the Low Energy Beam Transport (LEBT) by beam-transport simulations. Beam extraction from ion source considering plasma conditions and beam transport to the RFQ is performed using the IBSimu code [13].

Figure 6 shows an example of the results obtained when a beam with a beam current of 34 mA is extracted from the ion source. The diameters of the extraction hole of the plasma electrode, the middle electrode, and the electron repulsive electrode are 5 mm, 6 mm and 6 mm, respectively, and their voltages are 30 kV, 12 kV, and -5 kV. The distance between the plasma electrode and the middle electrode is 10 mm. The normalized RMS emittance is 0.25 πmm mrad at $x = 0.3$ m in the IBSimu coordinates, where the effect of the magnetic field in the beam axis direction due to the mirror coil is almost eliminated. This is a subject that needs to be continued to be studied since the initial plasma conditions have not yet been set up using the real machine. The same IBSimu code [13] is ongoing used simulate the beam transport to the RFQ to design the LEBT.

In addition, the designed magnetic field is based on the optimum field ratio for heavy-ion sources. the effect of too much electron confinement for He^{2+} and the practical applicability of a similar field ratio need to be studied.

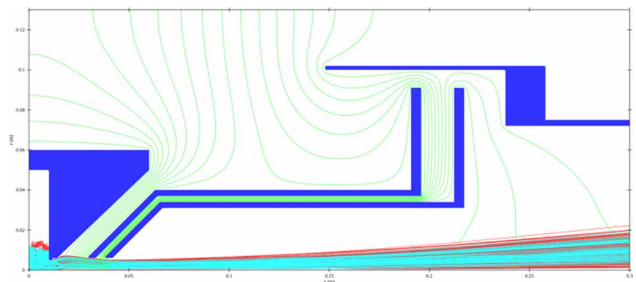

Figure 6: An example of the results using IBSimu.

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