DEVELOPMENT OF ELECTRON CYCLOTRON RESONANCE ION SOURCES FOR CARBON-ION RADIOTHERAPY

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Abstract

Compact Electron Cyclotron Resonance (ECR) ion sources have been developed for high energy carbon-ion radiotherapy (C-ion RT). Three compact ECR ion sources have been developed as the prototype at National Institute of Radiological Sciences (NIRS). The first ion source was used the microwave of 2.45 GHz to reduce the construction cost of the source as much as possible. It was required to produce 150 μA for C^{2+}. This ion source could not obtain enough intensity of C^{2+} because there were problems in microwave injection and beam extraction system. The second and third ion sources, named Kei and Kei2, solved these problems and set a target of 200 μA for C^{4+}. The structure of Kei and Kei2 were similar, however Kei2 improved on the magnetic field configuration and the beam extraction system. The beam intensity of 260 μA and 780 μA for C^{4+} were obtained by Kei and by Kei2, respectively. Kei2 was modified to connect with an injector linac for C-ion RT facility.

All of later C-ion RT facilities in Japan, the Gunma University Heavy Ion Medical Center, the Saga Heavy Ion Medical Accelerator in Tosu, and the Ion-beam Radiation Oncology Center in Kanagawa, installed copies of Kei2 and named them KeiGM, KeiSA, and KeiGM3. On the other hand, the original Kei2 have been installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at NIRS and produces carbon beams for experimental use. Kei2 is still improving and is utilized for the development of ion sources at present.

KEI SERIES

The NIRS-ECR ion source [1] with normal conducting coil has been supplied the carbon ion for medical use with good stability. However, NIRS-ECR has large electric power supply (maximum current and voltage are 600 A and 60 V) for mirror magnet in same high voltage platform. Therefore, the size of high voltage platform include ion source, electric power supplies, vacuum system and controllers is large with 5.3 m length and 6.9 m width. Case of the NIRS-ECR, there is a fault that the running cost increases by occasion of three of the following. 1) A large amount of water is needed to cooling the electromagnet and power supply. 2) From the operating experience with about ten years, the klystron power amplifier (KPA) for microwave source had many troubles. 3) The breakdowns in the control system for power supply etc. by the aged deterioration has increased from there are a lot of numbers of parts that compose the ion source, too.

In order to solve these problems, a compact ECR ion source for the carbon ion production with all permanent magnet has been developed. The electric power and cooling water can be decreased by using a permanent magnet. Therefore, size of ion source with utility such as water cooling can be reduced. Moreover, a permanent magnet is given maintain easy because the number of parts is less than that of the electromagnet. However, it is difficult to obtain an optimal magnetic field for production of target ion under the uncontrollable magnet.

Three compact ECR ion sources have been developed as the prototype. The first prototype ion source is used the microwave frequency of 2.45 GHz aiming to reduce the cost of the source as much as possible. It was required to produce the C^{2+} by 150 μA in this ion source [2]. Figure 1 shows schematic view and magnetic field of the first prototype ion source. An enough performance was not obtained in this ion source because there were problems in microwave injection and beam extraction system [3]. In the microwave injection, the introduced microwave reflected almost from the plasma chamber, and was not absorbed to plasma. The production of the highly charged ion was difficult as the result. In the beam extraction, the puller was made by iron because increasing the mirror field at extraction side. However, distance between puller and plasma electrode could not be optimize for beam extraction. From this problem, the beam defocuses immediately extraction, and was not able to transport the beam to the downstream side. And the cost and size of the accelerator is increased because target ion was C^{2+}.

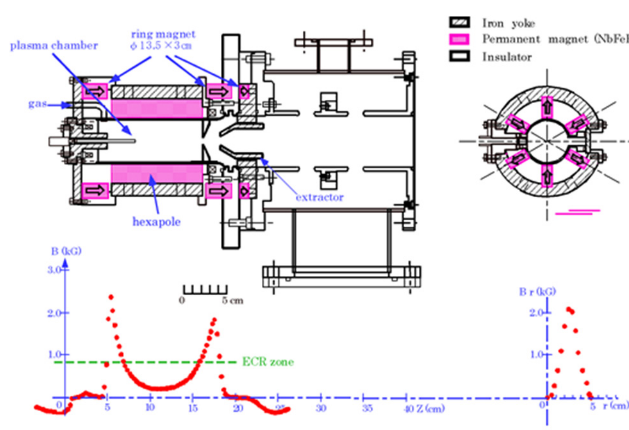

Figure 1: Schematic drawing of 2.45 GHz compact ECR ion source.

The second and third prototype ECR sources (Kei and Kei2), these were developed for solution of problem of the 2.45 GHz compact ECR ion source. The target is change to 200 μA for C^{4+}. Figure 2 shows schematic drawing of Kei source. The fixed magnetic field of the Kei and the Kei2 are copied from that of the 10 GHz NIRS-ECR source at HIMAC, which has already been proven to be reliable

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and stable for the production of C^{4+}. This particular field profile seems to be suitable for the production of C^{4+}, but not for C^{5+} or C^{6+}.

The upstream-chamber is placed upstream from ion source for installation of waveguide, gas pipe and biased disk. A Traveling-Wave-Tube (TWT) amplifier is used in the Kei and Kei2, in order to find the optimum frequency under a fixed and uncontrollable magnetic field. The TWT amplifier operated at a frequency of 8-10 GHz, and can be driven both in cw and pulse modes with a maximum output power of 300 W. Microwave power is fed into the plasma chamber through a rectangular wave guide from the axial direction. An rf window is used for vacuum. The diameter of the biased disk is 8 mm, and is made of molybdenum. The disk position is movable between 7 mm upstream and 25 mm downstream in the direction from the peak of the mirror field (gas injection side). From our experience, this method seems to be suitable for such a compact ECRIS, since the disk does not need a large space for installation. Extraction electrode is installing in down stream from ion source. Einzel lens is set up on the downstream side of the extraction electrode. The Turbo Molecular Pump (TMP) (150 l/sec and 500 l/sec) are installed respectively with the upstream vacuum chamber and under the einzel lens The beam intensity of 260 μA at C^{4+} was obtained in the Kei source [4-6].

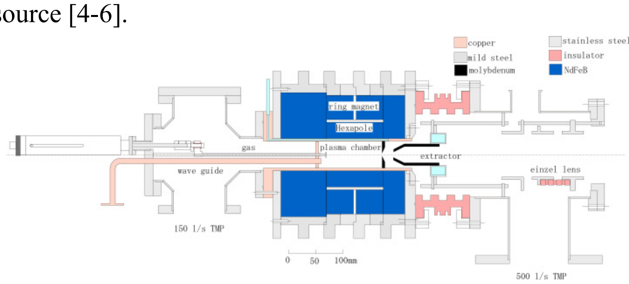

Figure 2: Schematic drawing of Kei source.

The structure of Kei and Kei2 were similar, however Kei2 improved on the magnetic field configuration and the beam extraction system. Figure 3 shows schematic drawing of Kei2 source. Mirror field of Kei2 was increased from Kei source about 13.8% and 13.6% at injection side and extraction side, respectively [7,8]. The extraction electrode is cooled directly by water. This is very effective to reduce any outgassing from the electrode and to keep a good vacuum at the extraction region. The disk was installed in the extraction electrode so that the carbon ion is not adhering to the insulator.

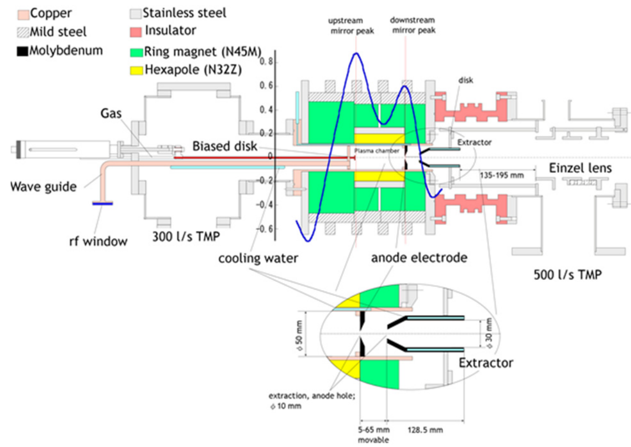

Figure 3: Schematic drawing of Kei2 source.

In order to increase the intensity of C^{4+}, we test gas mixing technique. Gas mixing technique is suitable for all-permanent-magnet ion source Kei2, because, this technique don't need big modification and complicated structure parts. Figure 4 shows charge distribution of carbon with CH_4, C_4H_{10} and C_2H_2. Beam intensity of C^{4+} was reached to 600 μA using C_2H_2 gas.

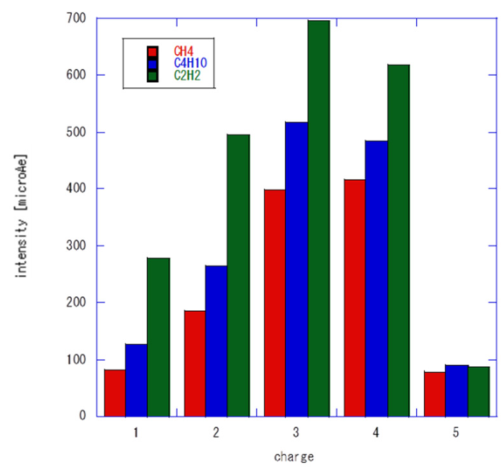

Figure 4: Charge state distribution of carbon.

Moreover, the TWTA with high output power is used for production of highly charged carbon. We change the TWT amplifier. Microwave frequency and output power are 9.75-10.25 GHz and 750 W, respectively. The maximum beam intensity of C^{4+} under the extraction voltage of 30 kV and 40 kV were 760 and 1017 μA, respectively. Figure 5 shows dependence of extraction voltage.

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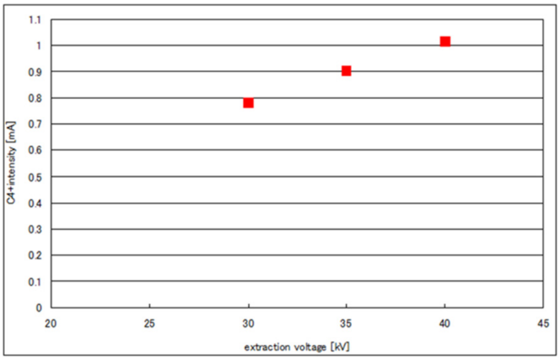

Figure 5: Dependence of extraction voltage.

All of later C-ion RT facilities in Japan, the Gunma University Heavy Ion Medical Center, the Saga Heavy Ion Medical Accelerator in Tosu, and the Ion-beam Radiation Oncology Center in Kanagawa, installed copies of Kei2 and named them KeiGM, KeiSA, and KeiGM3. These ion sources have been manufactured by Sumitomo Heavy Industries. The general structure including the magnetic field was copied from Kei2. A microwave source with the TWT was adopted, with a frequency range and maximum output power of 9.75 - 10.25 GHz and 750 W, respectively. Microwave power is fed into the plasma chamber through a rectangular wave guide from the axial direction. A biased disk is also used for optimizing. The plasma chamber is made of copper for a good cooling efficiency, in order to avoid a decrease in the magnetic field due to high temperature. The plasma chamber has an inner diameter of 50 mm. Extraction voltage is 30 kV. The CH_4 gas was chosen for production of carbon ions. There are two reason for choose the CH_4 gas, (1) enough beam intensity of C^{4+} is obtained for medical use under the CH_4 operation. (2) There is experience of long operation of the source used the CH_4 gas at HIMAC.

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