Concept design of new compact electron cyclotron resonance ion source with permanent magnets for multi-ion radiotherapy

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Introduction

Carbon-ion radiotherapy using the Heavy Ion Medical Accelerator in Chiba (HIMAC) has been carried out at the National Institutes for Quantum and Radiological Science and Technology (QST-NIRS) since 1994. Over 11000 cancer patients have been treated with carbon beams having energies of between 56-430 MeV/u.

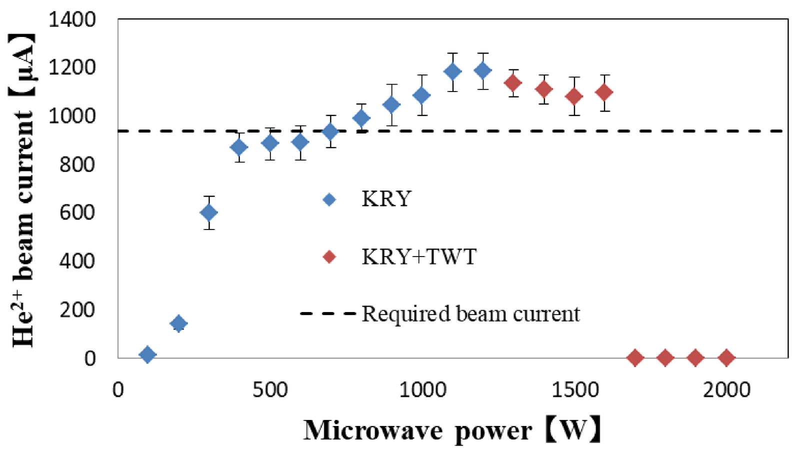
A compact ECRIS with all permanent magnets, named Kei2, was developed for the high-energy carbon-ion radiotherapy facility at QST-NIRS. The Kei2 source was designed for producing a sufficient current of carbon ions for medical treatments. In order to promote heavy ion radiotherapy in Japan, the Japanese government decided to develop a hospital-specified facility to be optimized for only carbon beams. In 2010, the Gunma University Heavy Ion Medical Center (GHMC) started operating as a carbon-dedicated demonstration facility. A compact ECR ion source for GHMC, the KeiGM, is also based on the development of compact ECR ion sources (Kei series) at NIRS. Kei series were installed at the GHMC, the Saga Heavy Ion Medical Accelerator in Tosu, the Ion-beam Radiation Oncology Center in Kanagawa, the Osaka Heavy Ion Therapy Center, and the East Japan Heavy Ion Center in the Yamagata University. These ECRISs have been developed for the production of C^{4+} ions for medical treatments.

The multi-ion radiotherapy with dose distribution and Liner Energy Transfer optimization is being studied at QST-NIRS. Helium, carbon, oxygen and neon ions are considered as ion species for multi-ion therapy. However, in the case of compact accelerator for high-energy heavy-ion radiotherapy facility, it is desirable to use with one ECR ion source with all permanent magnets from the viewpoint of cost, operation and maintenance. We considered the switching method with only one ion source for multi-ion radiotherapy. Ionization gases were helium, carbon dioxide and neon to produce He^{2+}, C^{4+}, O^{6+} and Ne^{7+} ions. Requirement values of beam current were 940 eμA correspond to He^{2+}, 290 eμA to C^{4+}, 330 eμA to O^{6+}, and 245 eμA to Ne^{7+}, estrictively. We did some beam tests for design of compact ECR ion source at existing the 18 GHz NIRS-HEC ion source.

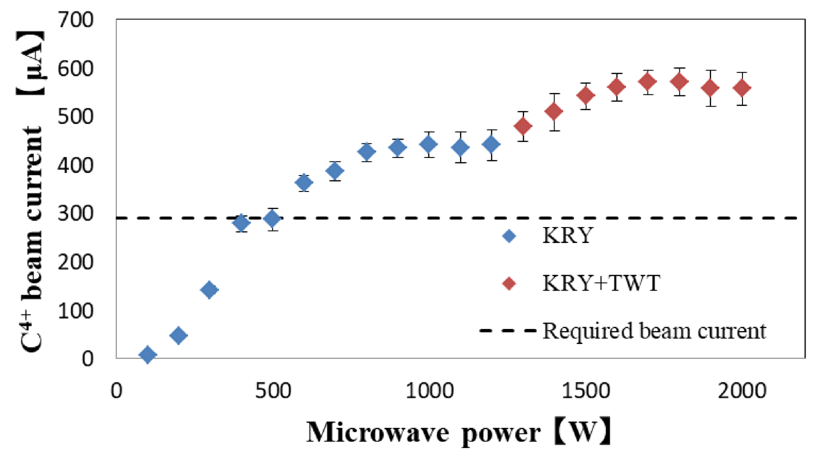
Beam test at the 18 GHz NIRS-HEC

First, we searched the maximum microwave power for production of these ions at the 18 GHz NIRS-HEC to determine the specification of the microwave amplifier. Second, optimal value of the mirror magnetic field for permanent magnets was checked.

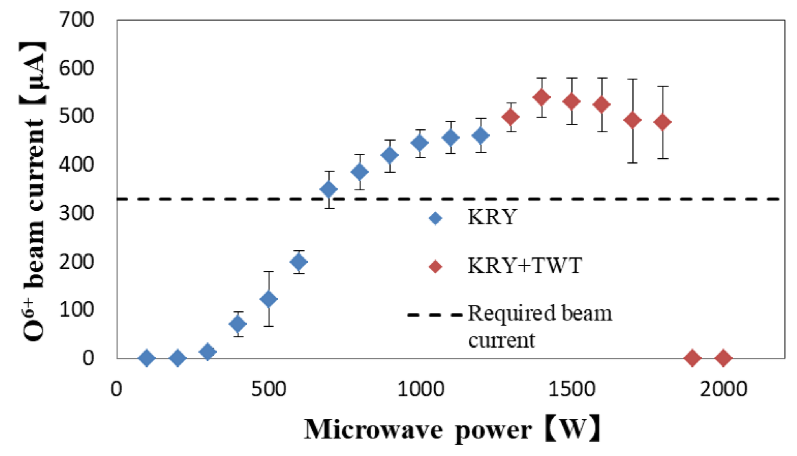
Helium, CH_4, O_2 and neon gases were used for production of each ion. There are two microwave amplifiers for two-frequency heating method, a klystron amplifier (KLY) and a traveling wave tube amplifier (TWT) in the NIRS-HEC. The microwave frequency and maximum output power of amplifiers are 18 GHz, 1200 W for KLY and 17.10-18.55GHz, 1200 W for TWT, respectively. The KLY was used daring output power of 0 to 1200 W (blue dot). Two frequency heating method 8 was used from 1300 to 2000 W (red dot). Dotted line shows requirement values.



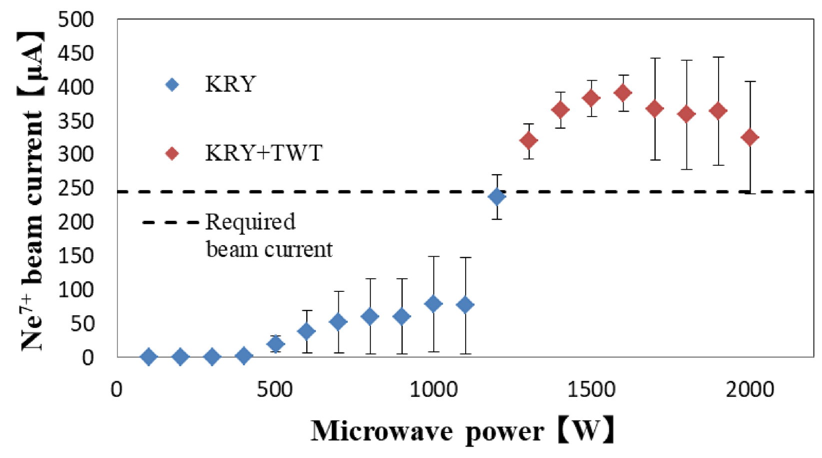
Dependence of He^{2+} beam current on microwave power. Microwave frequency of TWT was 17.32 GHz. Extraction voltage was 26.5 kV. Extraction gap was 15 mm. The current values of the upstream and downstream mirror coils were 820A and 500A.



Dependence of C^{4+} beam current on microwave power. Microwave frequency of TWT was 17.32 GHz. Extraction voltage was 30 kV. Extraction gap was 15 mm. The current values of the upstream and downstream mirror coils were 860A and 490A.

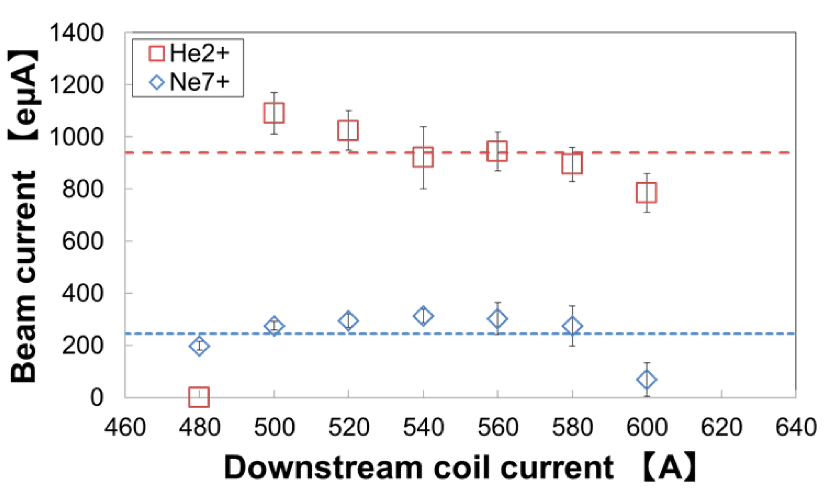


Dependence of O^{6+} beam current on microwave power. Microwave frequency of TWT was 17.32 GHz. Extraction voltage was 30 kV. Extraction gap was 15 mm. The current values of the upstream and downstream mirror coils were 840A and 500A.

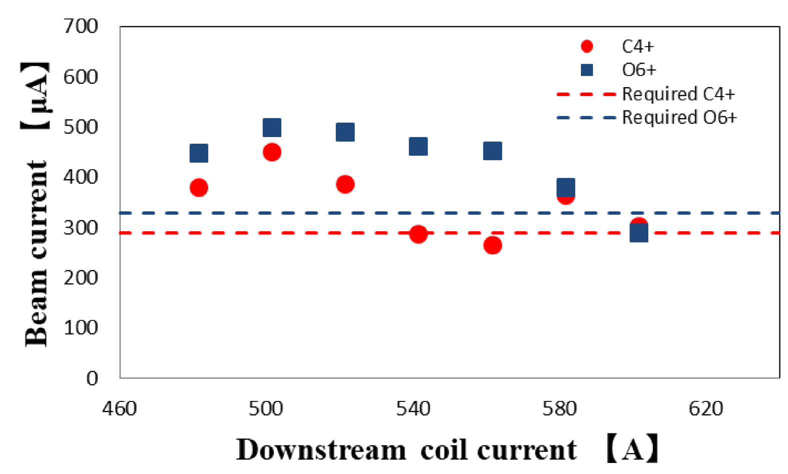


Dependence of Ne^{7+} beam current on microwave power. Microwave frequency of TWT was 17.32 GHz. Extraction voltage was 30 kV. Extraction gap was 16 mm. The current values of the upstream and downstream mirror coils were 860A and 540A.

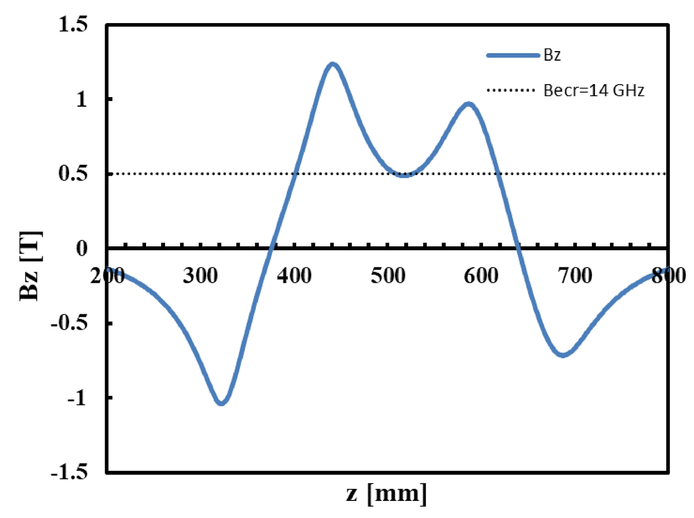
From the results of microwave power dependence, production of Ne^{7+} ion is difficult compared to production of other ions. The beam current of Ne^{7+} was sufficient when the combination of mirror coils with the current value of the upstream/downstream mirror coil was 860 A/540A, respectively. However, it is difficult to reproduce the magnetic field of 860 A with permanent magnets because of its structural problems. Therefore, the current value of the downstream coil was investigated by setting the upstream mirror coil current value to 840 A. Even in the cases of C^{4+} and O^{6+}, the required value of beam current could be exceeded when the coil current was 500 A and 520 A. From the result of the coil current dependence, we were decided to design the permanent magnet for the magnetic field corresponding to the current values of the upstream and downstream mirror coils of 860 A and 500 A.



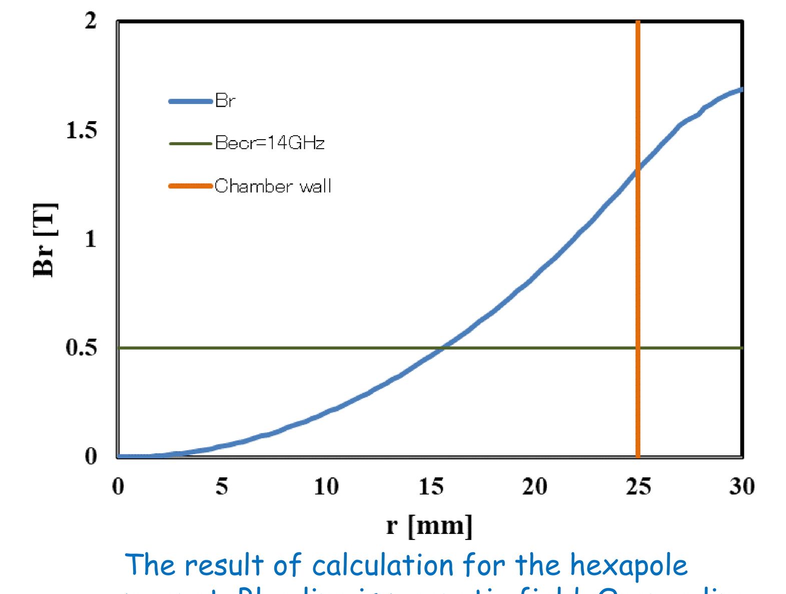
Comparison between He^{2+} and Ne^{7+} beam current at the dependence of downstream coil current under the upstream coil current of 840 A.



Comparison between C^{4+} and O^{6+} beam current at the dependence of downstream coil current under the upstream coil current of 840 A.



The result of calculation for the mirror magnetic field on the axis made by the five ring magnets (RM1-5).



The result of calculation for the hexapole magnet. Blue line is magnetic field. Orange line is the chamber wall (r=25 mm). Green line is Becr=0.500 T for 14 GHz.

Calculation of magnetic field

From the results of coil dependence, we estimate the mirror magnetic field of NIRS-HEC by using POISSON/SUPERFISH code. Then, the structure of the permanent magnet for new ECRIS is determined so as to reproduce the value of the upstream mirror peak (Binj), B minimum (Bmin) and the downstream mirror peak (Bext) at the NIRS-HEC. The magnetic fields of Binj, Bmin and Bext at NIRS-HEC were 1.14 T, 0.475 T and 0.9 T, respectively.

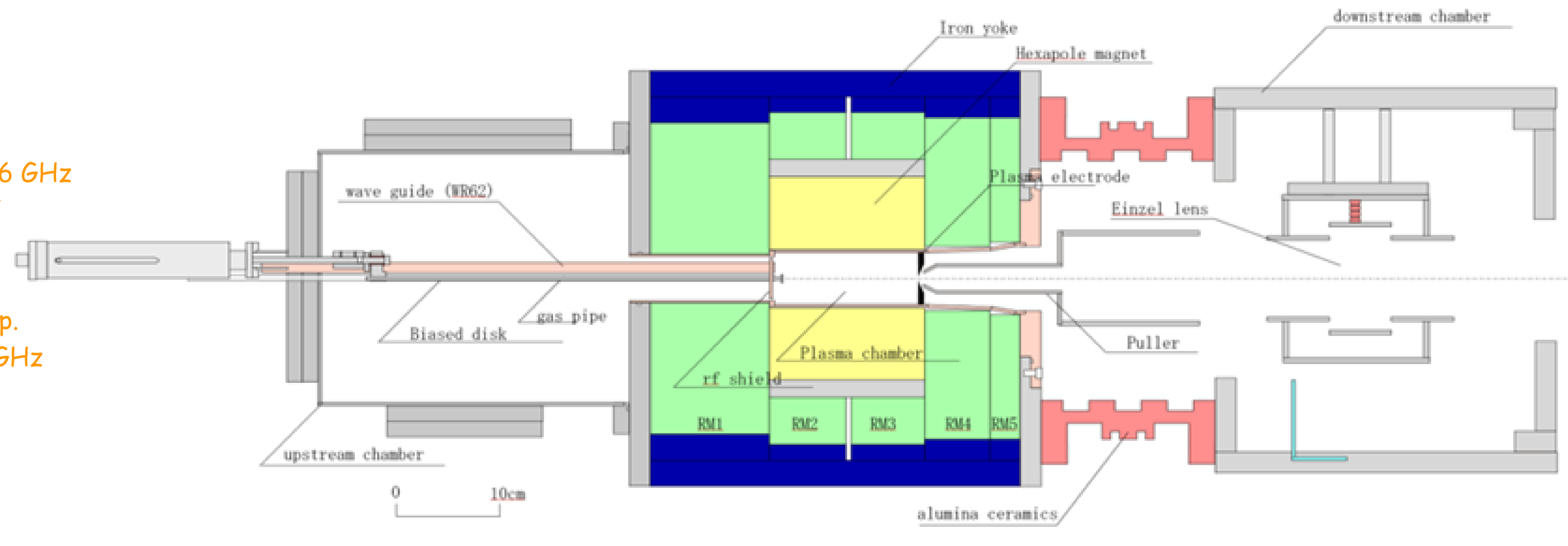
Design of new compact ECRIS

We design the structure of new compact ECRIS based on the result of the calculation and our experience of medical use. A rectangular waveguide, a gas pipe, and a biased disk are installed in the upstream vacuum box. An extraction electrode and an Einzel lens are installed in the downstream vacuum box. A high voltage for ion extraction is applied to the permanent magnet including the upstream vacuum chamber and the plasma chamber. A commercial model of N50H-MF (made by Shin-etsu) is used for the five ring magnets that forms the mirror magnetic field. A commercial model of N43TS (made by Shin-etsu) is used for the hexapole magnets that form the radial confinement magnetic field. The plasma chamber is made of copper with water cooling. The inner diameter of the plasma chamber is 50 mm. As a result of thermal calculation of the plasma chamber, this structure has sufficient cooling capacity. The calculation condition is that the heat input from the plasma is 100 W (microwave: pulsed operation, maximum power 2000 W, pulse width 50 msec, repetition frequency 1 Hz), and the discharge at the time of beam extraction is 30 W, total 130 W heat input. And the temperature rise of the cooling water was 3 degree. He, CH_4, O_2, and Ne gas are used to produce four kinds of ions, respectively. The gas lines merge outside the ion source and the gas is introduced into the plasma chamber with a single gas pipe. Gases are switched on and off using a solenoid valve for fast ion species switching. The aperture of extraction electrode is 10 mm. A plasma electrode made from molybdenum having a beam extraction hole of 8 mm is arranged on the plasma chamber side. The maximum extraction voltage is 30 kV.

Specifications

・Ion source	
Diameter	400 mm
Length	1500 mm
・Mirror magnets	
Material	NdFeB
Max. field strength (extraction side)	0.90 T
Max. field strength (gas injection side)	1.14 T
Minimum B strength	0.475 T
・Hexapole magnet	
Material	NdFeB
Maximum field strength on the chamber surface	1.31 T
Length	150 mm
Inner diameter	56 mm

・Microwave1	
Amplifier	SSA
Frequency	13.7-14.6 GHz
Maximum power	2000 W
Operation mode	pulse
・Microwave2	
Amplifier	TWTamp.
Frequency	10 - 18 GHz
Maximum power	100 W
Operation mode	pulse



New compact RCRIS