The compact electron cyclotron resonance ion source KeiGM for the carbon ion therapy facility at Gunma University


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A high-energy carbon-ion radiotherapy facility is under construction at Gunma University Heavy Ion Medical Centre (GHMC). Its design was based on a study of the heavy ion radiotherapy at the National Institute of Radiological Sciences (NIRS) in order to reduce the size and construction cost of the facility. A compact electron cyclotron resonance ion source (ECRIS) for Gunma University, called KeiGM, was installed in 2008. It is almost a copy of the prototype ECRIS Kei2 which was developed by NIRS; meanwhile this prototype produced over 1 e mA of C4+ using C2H2 gas (660 W and 40 kV). The beam intensity of C4+ was 600 e μA with CH4 gas (250 W and 30 kV). The beam intensity satisfies the required value of 300 e μA. © 2010 American Institute of Physics. [doi:10.1063/1.3273055]

I. INTRODUCTION

The heavy ion medical accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was the first heavy ion medical dedicated accelerator in the world. Its aim has been to verify the effectiveness and safety of heavy-ion radiotherapy. Carbon-ion radiotherapy (C-RT) started in 1994 and has mainly focused on the group of diseases in the whole body which are difficult to cure using conventional radiotherapy. The total number of patients enrolled by August 2009 was over 4800 and various types of tumors have been treated. These results have clearly demonstrated the advantages of C-RT.

The Japanese government approved the C-RT as a new treatment method in 2003, and promoted it to the development of new downsizing technologies under “the third comprehensive ten year strategy for cancer control (2004–2013).” NIRS carried out R&D studies for various components and designed a hospital-specified C-RT facility. The construction of the Gunma University Heavy Ion Medical Centre [GHMC (Ref. 4)] was funded by the Japanese government and Gunma prefecture beginning in 2006, and construction started in 2007 at the center site in Maebashi, Gunma. The technologies concerned were transferred from NIRS to Gunma University. GHMC will be a demonstration of the new C-RT facility. Gunma University plans to start a clinical trial in fiscal year 2009.

A compact electron cyclotron resonance ion source (ECRIS) for GHMC, the KeiGM, is also based on the development of the ECRIS at NIRS. This article presents an outline of the GHMC, a description of KeiGM, and current status of the beam commissioning.

II. CARBON ION THERAPY FACILITY AT GUNMA UNIVERSITY

In the design process, the following policies are considered to be important: (1) only high-energy carbon ions will be used in the facility to reduce the size and cost of the apparatus and (2) beam characteristics should cover the same clinical beam characteristics as the HIMAC. Major specifications of the facility were determined on the basis of the statistics of clinical data from HIMAC. The reliable and well-established wobbler method with the respiratory-gated irradiation system was adopted for the beam delivery system. It was decided to accelerate only carbon ions with a maximum energy established at 400 MeV/n. This energy ensures a 25 cm residual range in water and, for example, carbon ions can penetrate the human body and reach the prostate through a patient’s pelvis. Another important requirement of the new facility is to have two orthogonal beamlines directed toward the same isocenter. This beamline configuration is required in order to realize the sequential beam irradiation from different directions with single positioning of a patient. As a conclusion, GHMC consists of the following parts: an ECRIS, a radio-frequency-quadrupole (RFQ) linac, an interdigital-H mode drift tube linac (H-DTL), a synchrotron, and four treatment rooms. Of these the first room will have a horizontal beamline, the second will have a horizontal as well as a vertical beamline, and the third will have a vertical beamline. The fourth room will be used for developmental studies for advanced irradiation techniques. A fast beam course and energy switching are also required for the same purpose. The major specifications of
the facility are summarized in Table I. The main building of the facility is about $65 \times 45$ m$^2$, and it was completed at the end of October 2008.

C$^{4+}$ ions will be produced by the ECRIS and pass through a thin carbon foil installed downstream from the IH-DTL. The output energy of the linac is determined at 4 MeV/n so that more than 90% of the C$^{4+}$ ions are converted to fully stripped ions. An averaged diameter of the synchrotron is about 20 m and will accelerate C$^{6+}$ ions up to 400 MeV/n. The required beam intensity and emittance for the source are of the order of $300 \ e \mu \mathrm{A}$ and $0.67 \pi \ mm \ mmrad$ (normalized) for C$^{4+}$. Beam commissioning of the KeiGM at Gunma University has been done since December 2008. Beam acceleration tests started on 12 August 2009. The injector linac and synchrotron were already successful on 25 August, when a beam of 400 MeV/n carbon ions was produced with intensity of $10^8$ pps (particle per second). The carbon beam was sent to treatment room on 5 September 2009.

III. KeiGM

A. Description of the source

KeiGM has been manufactured by Sumitomo Heavy Industries. Figure 1 shows the schematic view of the KeiGM with high voltage platform. The general structure including the magnetic field was copied from Kei2. Based on experimental studies with a conventional 10 GHz electron cyclotron resonance source at HIMAC, the field distribution of the mirror magnet for compact source was designed so that a charge distribution of carbon ions was optimized at 4+. A microwave source with the traveling-wave tube (TWT) was adopted with a frequency range and maximum 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. The vacuum pressures of the gas injection side and beam extraction side are $1.5 \times 10^{-6}$ and $5.4 \times 10^{-5}$ Pa, respectively. Extraction voltage is 30 kV.

B. Beam tests of the KeiGM

The ion source is being operated at an injection line for the linac. The injection line consists of an analyzing magnet, three monitor boxes for Faraday cups, horizontal and vertical slits, beam attenuators and a vacuum pump (450 l/s turbo molecular pump). The analyzing magnet has a bending angle of 90$^\circ$ and a radius of curvature of 0.25 m. A pair of horizontal and vertical slits and a Faraday cup is installed downstream from the analyzing magnet (FC1) and just in front of the RFQ linac (FC2). A preliminary beam test at the factory of the Sumitomo Company was already finished in March 2008. In order to study the basis performance of the source, the beam test was conducted using CH$_4$ gas. At that time, the beam intensity of the C$^{4+}$ at FC1 and emittance at the injection line were measured. The maximum beam intensity of 4+ was $600 \ e \mu \mathrm{A}$ under the extraction voltage of 30 kV. The emittances for horizontal and vertical were 0.266 and 0.160 $\pi \ mm \ mmrad$ (normalized), respectively.

The KeiGM was installed to GHMC facility on December 2008. The beam commissioning of the source at the facility also started at the same time. Figure 2 gives the typical charge state distribution (CSD) of carbon ions under an extraction voltage of 30 kV. The ion source was optimized for C$^{4+}$ production. In order to know the basis performance of KeiGM, the dependence of the operation parameters was checked. The tuning parameters of the source are the gas flow, microwave power, microwave frequency, biased disk voltage, and its position. Three operation parameters (microwave power and frequency, extraction voltage) were examined to optimize the C$^{4+}$ yield under an extraction voltage of 30 kV. At first, the microwave power dependence of the beam intensity of C$^{4+}$ was checked under a fixed frequency of 9.955 GHz. Figure 3 shows the variation in the intensity of 9.955 GHz. Figure 3 shows the variation in the intensity...
of C^{4+} at Faraday cup versus the microwave power of the TWT amplifier. The C^{4+} intensity increased with increasing the microwave power. Second, the microwave frequency dependence was investigated. Figure 4 shows the variation intensity of C^{4+} versus the microwave frequency. We found that the optimal frequency for C^{4+} is around 10 GHz. Third, the extraction voltage dependence was studied under a fixed microwave power. Second, the microwave frequency dependence was investigated. Figure 4 shows the variation in C^{4+} intensity of C^{4+} versus the microwave frequency of 10 GHz. The result is shown in Fig. 5. Beam intensity of C^{4+} as a function of microwave power.

A major difference between the KeiGM and the Kei2 is the structure of extraction electrode. In order to reduce the cost of the extraction electrode, the electrode of KeiGM was simplified; however, the performance of water cooling was decreased from that of the Kei2. There was outgassing from the electrode due to heatup. Some slight sparking was observed during commissioning although the sparks did not interfere with the operation. The extraction electrode will be exchanged with another closer to the original electrode structure of Kei2.

IV. DEVELOPMENT FOR KeiGM

In order to operate the KeiGM with good performance, R&D studies have been performed at NIRS. In order to increase high intensity of 4+ carbon ions and other highly charged ions, we tested a gas mixing technique with the prototype Kei2 source. Moreover, the TWT amplifier with high output power was used for production of highly charged carbon. The maximum beam intensity of C^{4+} was 1017 e μA under the clean source condition with the extraction voltage of 40 kV. An isotopic gas 13C was used for analyzing C^{6+}. In this experiment, 13CH4 and 13C2H2 gases were used. Ion source parameters were optimized for C^{6+}. Extraction voltage was 30 kV. Repetition frequency and pulse width were 5 Hz and 50 ms, respectively. The beam intensity of C^{6+} was 7.8 e μA. The beam intensities of 4+ and 5+ were 781 and 159 e μA under the extraction voltage of 30 kV. Details of the gas mixing effect at this experiment are described in Ref. 8.