Present Status of NIRS ECR Ion Sources*

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Abstract Four ECR ion sources have been operated in National Institute of Radiological Sciences (NIRS). Two ECR ion sources supply various ion species for the Heavy Ion Medical Accelerator in Chiba (HIMAC). The 10GHz NIRS-ECR ion source mainly produces C^{2+} ions for the heavy-ion therapy. Ions of Si, Ar, Fe, Kr and Xe are usually produced by the 18GHz NIRS-HEC ion source for physical and biological experiments. The other two compact ECR ion sources with all permanent magnet configuration have been developed for the new generation carbon therapy facility. One of these, the Kei-source, is a prototype which has been installed to the NIRS-930 cyclotron for axial injection. The other source, Kei2-source, is a demonstration source and utilized for the new generation Linac. In addition, both Kei sources have been used to study fundamental properties. In this paper, present status of the ion sources and recent developments are reported.

Key words heavy ion therapy, ECR

1 Introduction

Heavy-ion cancer treatment is being carried out at the Heavy Ion Medical Accelerator in Chiba (HIMAC) with 140—400MeV/n carbon ion at National Institute of Radiological Sciences (NIRS). Over 2800 patients have been treated since 1994.

2 Status of NIRS ECR ion sources

There are four ECR ion sources in NIRS. The two ECRISs with water cooled coils supply various species for the HIMAC. The 10 GHz NIRS-ECR[1] ion source mainly produces C^{2+} ions for the heavy-ion therapy. The 18GHz NIRS-HEC[2] ion source supplies various heavy ions for physical and biological experiment. The two compact ECR ion sources have been developed for the next generation carbon therapy facility. Kei-source[3] has been installed to the NIRS-930 cyclotron for axial injection[4]. Kei2-source[5] produces the C^{4+} for new Linac[6]. The magnetic field profile of the Kei sources were copied from that of the 10GHz NIRS-ECR source, which has already been proven to be reliable and in particular suitable for production of medium charge states, like C^{4+}.

2.1 10GHz NIRS-ECR ion source

The 10GHz NIRS-ECR ion source was designed with a simple minimum B structure. Maximum mirror fields are 0.93 and 0.73T. Extraction voltage is

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applied to plasma chamber and hexapole magnet. Usually, this source produces the C^{2+} ion for medical treatment. Before 2004 Fe ions were made using MIVOC method for backup for the 18GHz NIRS-HEC source. Total operating time was 4936 hours. Fig. 1 shows a graph of troubles since 1994; the total number is 71. There were many accidents with microwave, high voltage and electronics until 2002. In 2003, there was one problem with microwave. In 2004, we change the microwave amplifier Klystron to Traveling Wave Tube. As can be seen, from that time the source was running extremely reliably.

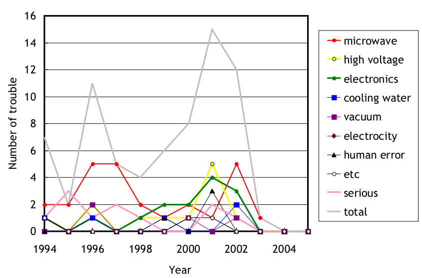

Fig. 1. Troubles in NIRS ECR source since 1994.

2.2 18GHz NIRS-HEC ion source

The 18GHz NIRS-HEC source was developed for production of heavy ion species for physical and biological experiments. NIRS-HEC is also designed with a simple minimum B structure. Maximum mirror fields are 1.29 and 1.22T. Maximum extraction voltage is 60kV. Fig. 2 shows operating time of NIRS-HEC during March 2005 to February 2006; total operating time was 2173 hours. NIRS-HEC was supplying mainly heavy ion species, for example Ar, iron, Kr Xe, and a few amount of special ions, ^{13}C, and ^{22}Ne. Fig. 3 shows charge state distribution of Si using Tetramethylsilane $Si(CH_3)_4$. We apply Si^{5+} beam to the Linac. Beam intensity of 220eμA for Si^{5+} is obtained, with good stability.

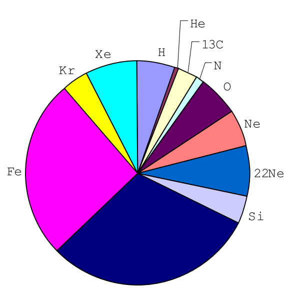

Fig. 2. Operating time of NIRS-HEC.

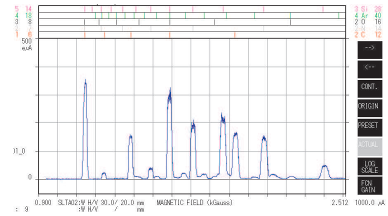

Fig. 3. Charge state distribution of Silicon using $Si(CH_3)_4$.

2.3 Compact ECR ion source (Kei-source)

Presently the Kei source is used as an external ion source for one of the NIRS-930 cyclotrons. For a future project of ^{11}C acceleration with HIMAC, ionization efficiency measurements of CO_2 are started. The project will be described below. Recently, at HIMAC, a ^{11}C has been utilized by the projectile fragmentation method. However, the intensity is not enough. A significant improvement is foreseen by injecting $^{11}C^{2+}$ ions into the HIMAC accelerator[7, 8].

A technical realization for a positron emitter ^{11}C-beam (R.I.) as an accelerating-beam has been studied at NIRS-HIMAC in order to apply for a heavy-ion therapy. In this study, we focused on the production of ^{11}C ($T_{1/2}$ = 20min), where ^{11}C is produced at the NIRS-Cyclotron-Facility, located about 150m from HIMAC. The system includes the production of radioactive isotopes (^{11}C), gas transport, gas separation, gas compression, gas pulsing and ionization, as well as reproducing residue $^{11}CO_2$-gas during the ionization process, as shown in Fig. 4, which sets the limit focused on this study. After the ionization process, as shown in the final stage of Fig. 4, a ^{11}C ion-beam is introduced to the HIMAC accelerator complex and extracted. In our test result, at this point, the ionization efficiency was about 1% or more for $^{12}C^{2+}$ beam extracted from the Kei-source[4] (Table 1).

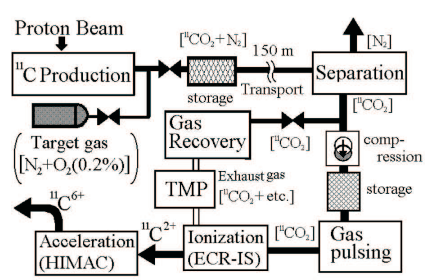

Fig. 4. Block diagram for process from production to acceleration of ^{11}C-activity.

Table 1. Ionization efficiency at Kei-source.

	gas flow rate	C^+	C^{2+}	C^{3+},O^{4+}	C^{4+}	C^{5+}
CH_4	0.70cc/min	1.1%	1.1%	1.7%	0.9%	0.1%
CO_2	0.36cc/min	2.2%	1.1%	1.0%	0.2%	0.01%

2.4 Compact ECR ion source (Kei2-source)

The injector is the most important point for the next generation heavy ion facility. We decided to test the performance of the prototype, consisting of compact ECR ion source, RFQ Linac, and IH-DTL (Interdigital H-mode Drift Tube Linac). Injection energy of RFQ Linac is 10keV/n and output energy is 600keV/n. Output energy of IH-DTL is 4MeV/n. Total length of prototype injector is less than 10m. For test in March 2006, the Kei2-source was operated with C_2H_2 gas giving about 500eμA C^{4+}, which was accelerated in the system. The intensity downstream of IH-DTL was 390eμA. Transmission efficiency between source to output of Linac was 79%. Fig. 5 shows result of the beam stability test. Beam intensity of 400eμA at stripped C^{6+} was obtained. Beam stability is better than 10% during 8 hour without any adjustment of parameters. From these results, new injector has acceptable performance for main accelerator synchrotron.

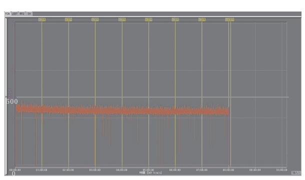

Fig. 5. Result of beam stability test at new injector.

In order to increase the intensity of C^{4+}, we employed gas mixing technique. Usually, carbon molecular gases e.g. CH_4 are used for production of C^{4+}. If CO_2 gas is used, highly charged ion of carbon become lower as compared to CH_4 gas. This phenomenon is gas mixing effect[9]. This means that oxygen is not a good mixing gas for highly charged carbon. The CH_4, C_4H_{10}, C_2H_2, CD_4, C_4D_{10} and C_2D_2 gases were tested in Kei2-source. Details of this experiment are described in Ref. [10]. Figs. 6 and 7 show dependence of chemical compounds. C_2H_2 was better than $CH_4$and C_4D_{10}.

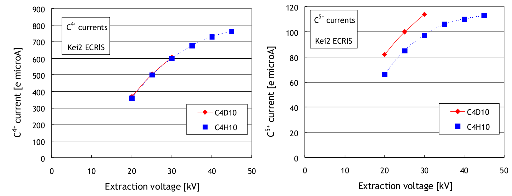

Fig. 6. Isotopic effect.

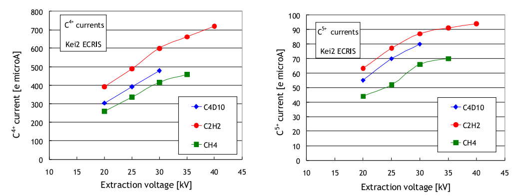

Fig. 7. Dependence of chemical compounds.

3 Conclusion

The two ECR ion sources supply various ions for the HIMAC. The 10GHz NIRS-ECR ion source mainly produces C^{2+} ions for the heavy-ion therapy with no trouble. The 18GHz NIRS-HEC ion source produce various ion for physical and biological experiments. The two compact ECR ion sources have been developed for the next generation carbon therapy facility. Kei-source has been installed to the NIRS-930 cyclotron for axial injection. Kei2-source, produce the C^{4+} for new Linac with successful acceleration.

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