Recent Developments on ECR Ion Sources at the medical accelerator HIMAC

A. KITAGAWA, M. MURAMATSU, S. YAMADA, NIRS, Japan;
K. JINCHO, T. OKADA, M. YAMAMOTO, AEC, Japan; S. BIRI, ATOMKI, Hungary;
R. BASKARAN, IGCAR, India; K. UNO, SHI, Japan; T. HATTORI, TIT, Japan

Abstract

In the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS), recent results of the development on two ECR ion sources named NIRS-ECR and NIRS-HEC are described. It was found that the elements of the gases used for producing a specific charge state of C ions affect the beam intensity. In the efforts for increasing the beam intensity at NIRS-HEC, it was shown that the ion-density distribution at the extraction slit should be matched with the extraction aperture. In order to optimize the ion-density distribution, three sextupole magnets with inner diameters of 46, 66, and 80mm were tested. Two-frequency heating of the plasma was tested by introducing an additional microwave power with variable-frequency. Generally, it enhances the beam intensity, but the additional microwave induces complicated effects on the behaviour of the source. The results suggest that the frequency of the additional microwave should be tuned finely in order to get a good performance.

1 INTRODUCTION

HIMAC[1] is dedicated to cancer therapy, and is also utilized with various ion species for basic experiments of biomedical science, physics, chemistry, material sciences, etc. For these requirements, three ion sources (one PIGIS and two ECRISs) are installed. The sources are required to produce ions with an energy of 8keV/u and a charge-to-mass ratio larger than 1/7. The sources are mainly operated with a pulsed mode and the pulse width is between two and several hundreds milli-seconds. The PIGIS[2] is mainly utilized to produce ions by sputtering the solid materials. The ECRISs are expected to produce highly charged intensive ions without maintenance.

2 PRODUCTION OF CARBON IONS

2.1 Operation experience of 10GHz NIRS-ECR

The 10GHz NIRS-ECR ion source has been mainly operated to produce C^{4+} or C^{2+} ions for the daily clinical treatment. Detailed specifications have been reported in Ref. [3]. In the case of the production of carbon ions, the plasma chamber and most of the other parts are covered with much carbon deposition. This causes the decreasing of the beam intensity or the breaking of the electric insulation, and finally stops the operation. To keep a long lifetime, the vacuum ceramic window should not face directly to the plasma. The pulsed operation is effective to reduce the deposition on the chamber wall, but the deposition is normally unavoidable. The beam intensity decreases just after the cleaning of the wall because of carbon deposition. The record of intensity reaches 430eμA for C^{4+} under the good condition just after the cleaning, whereas a typical intensity is 300eμA. Although the wall is completely covered by carbon deposition after the operation, the source can supply the beam for half a year without maintenance. NIRS-ECR realizes good reproducibility and reliability with easy operation.

2.2 Gas dependence of the charge-state distribution

We found the CH_4 gas was better for the production of C^{4+}, whereas CO_2 and CO gases was better for the C^{2+}[4]. The C_3H_8 gas was also tested, and the difference in the beam currents between CH_4 and C_3H_8 was little. The result by using CO was similar as CO_2. It seemed that the chemical form of the gases did not affect the beam intensity, but the elements were very effective.

Fig.1 shows typical charge-state distributions (CSD) which were optimized for C^{2+} and C^{4+} ions by using CH_4 and CO gases. Since C^{3+} were normally covered by other ion species, it was measured by using ^{13}C isotope gases with the same operation parameter. A gas-flow rate, a microwave power, a magnetic field, and other parameters were optimized to obtain the maximum beam current of ions with a desired charge state in each case. In the both cases, CSD by CH_4 was shifted to higher than CO. CSD seemed to depend on the amount of H or O ions, which play a role of a support gas[5].

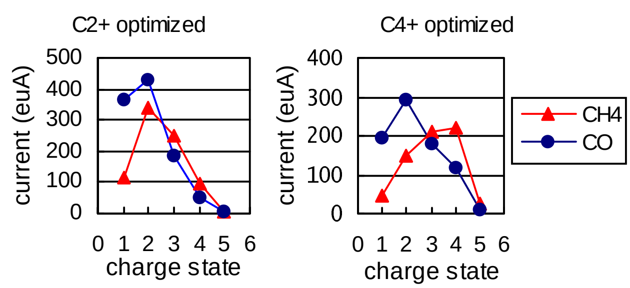


Fig.1. Charge state distributions at the production of C ions from CH_4 and CO gasses.

3 PRODUCTION OF HEAVIER IONS

3.1 Performance of 18GHz NIRS-HEC

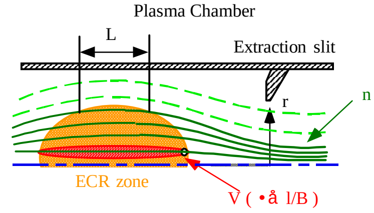
The purpose of NIRS-ECR has been focused on the stable operation for medical use. The 18GHz NIRS-HEC ion source was developed to obtain higher beam intensities of highly charged ions[3]. NIRS-HEC has two features. One is an extraction configuration with high voltage, and the other is a strong magnetic confinement. The maximum extraction voltage between the extraction slit and the extraction electrode reaches up to 60kV. The maximum axial mirror-field is 1.22T. The radial sextupole field is 1.1T on the chamber wall. The output currents of both sources are shown in Table I. Natural gases were used for the production of ^{84}Kr and ^{132}Xe, and the MIVOC technique[6] was used for Fe. The performance of NIRS-HEC, which is indicated in bold face, were improved especially in production of the highly charged ions than NIRS-ECR.

Table I. Beam currents of NIRS-ECR and NIRS-HEC (indicated in bold face). Currents are in eμA.

q+	C	Ar	Fe	^{84}Kr	^{132}Xe
2+	470				
4+	430	410			
5+	(50)	345			
6+		365			
7+		300 **650**			
8+		300 **1100**		160	
9+		105 **650**	**180**	125	
11+		7 **70**	**90**	55 **90**	15
13+		**4**	**15**	20 **150**	10
15+				**120**	
20+					**75**
21+					**65**

3.2 Optimization of the Radial Magnetic Field

The optimization of ion-density distribution around the extraction slit was the most effective for such improvement, as has been reported in Ref. [7]. The ion-density distribution cannot be observed, however we assume the highly charged ions are localized inside of the ECR zone and the ion trajectory from the ECR zone to the extraction slit is tightly bound the magnetic flux line. Therefore, the ion-density distribution depends on the magnetic trap configuration. The calculated ion-density distribution with a sextupole inner diameter of 46mm is shown in Fig.2. The calculation is made with the modified TrapCAD code[8] which calculates the ion



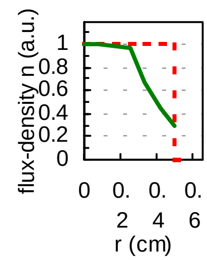


Fig.2. Calculated flux-density distribution at the extraction slit.

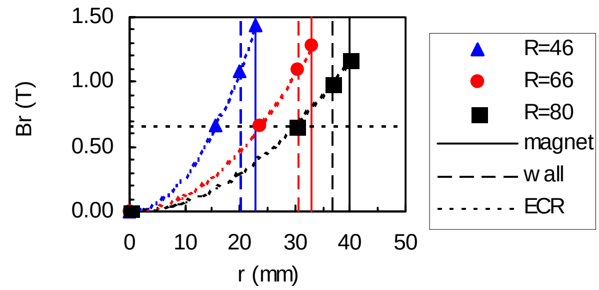


Fig.3. Radial magnetic fields at the sextupole inner diameter of 46, 66, and 80mm

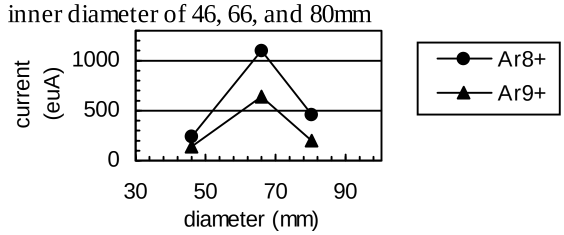


Fig.4. Various inner diameter of sextupole magnet and its currents of Ar8+ and 9+.

density n from the magnetic flux density B. Only the magnetic flux lines running through the ECR surface are taken into account to evaluate n. Since the concentrated ion-density distribution at the extraction slit of Fig.3 enhances the space charge effects, the extracted beam intensity is lower in this case than in the case with a uniform distribution. A diameter of the ECR zone was increased a sextupole magnets with large bore radius. A large ECR zone is expected to increase a number of magnetic flux lines running through the ECR zone and results in a uniform density distribution around the extraction slit.

In order to realize the uniform ion-density distribution at the extraction aperture, three sextupole magnets with inner diameters R of 46, 66, and 80mm were tested. Fig. 3 shows radial magnetic fields at each magnet. The solid and broken lines on the radius r indicate surface positions of magnets and chamber walls, respectively. The radial magnetic fields on the chamber wall are 1.1, 1.1, and 1.0T at R=46, 66, and 80mm. The dotted line also indicates the ECR condition, B_{ECR}=0.65T. Fig. 4 shows output currents for Ar^{8+} and Ar^{9+} at each magnet. The intensities increased by four times at 66mm than 46mm. Our experimental result was consistent with the calculation result which suggested the ion-density distribution at 66mm was more uniform than that at 46mm. On the other hand, the intensities at 80mm were smaller than that at 66mm. The current of Ar^{8+}

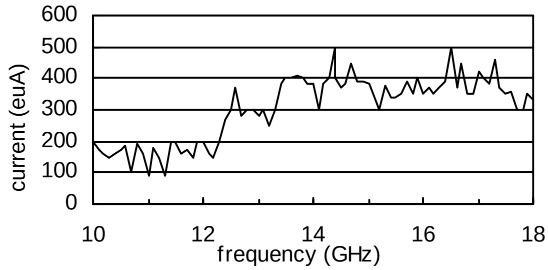


Fig.5. Output currents of Ar^{8+} as a function of the frequency of the additional microwave.

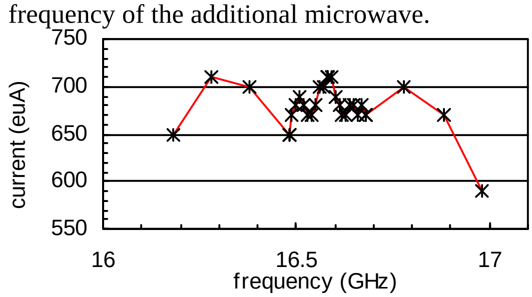


Fig.6. Output currents of Ar^{8+} as a function of the frequency of the additional microwave.

temporally reached to 800eμA, but was not stable. The magnetic field on the chamber wall and the distance between the ECR zone and the chamber wall were not so different at both of 66 and 88mm. We guess that too many ions impacted on the extraction slit and the unexpected gases evaporated from the heated slit gave a bad influence to the plasma.

3.3 Two-frequency heating

The relation between the surface area of the ECR region and the source performance has not been verified. However, several reports pointed out the possibility of improvement by increasing the amount of the ECR region, i.e., 2ω mode[9], volume ECR[10], two-frequency heating[11], and so on. We have also tested the two-frequency heating[12]. In order to investigate the effects of two-frequency heating, an additional microwave-injection system was added to NIRS-HEC which has a wide frequency range of 10 to 18GHz. The total reflection power of the wave-guide system is less than 3% between 10 and 18GHz. A maximum power is 250W. In addition, the power monitor can stabilize the forward power in all frequency range.

By using the two-frequency heating technique, the high beam intensities in the case of Xe production were obtained. The output currents reached 70 and 65eμA for Xe^{20+} and Xe^{21+}, respectively. However, the additional microwave induced complicated effects on the behaviour of the source. Fig.5 shows the output current of Ar^{8+} as a function of the frequency of the additional microwave. At first, we tuned all operation parameters to obtain the maximum output current. Then a frequency of the additional microwave was only swept between 10 and 18GHz. A power of the additional microwave was fixed in the measurement. A power of the main microwave with the frequency of 18GHz, a vacuum pressure, a magnetic confinement and other operation parameters were also fixed. The output currents had peaks at around 14.5 and 16.5GHz. On the other hand, the output currents lower than 12GHz were small and were almost same as the current with the main microwave only. Because the minimum B field was too high for the resonance of the frequency of the additional microwave between 10 and 12GHz. There was a fine structure in Fig.5. This structure strongly depended on the operation parameter.

We also found a very fine structure shown in Fig.6. The reason has not yet been cleared, but this 'hyperfine structure' is not negligible for the two frequency heating technique. Because it is important to adjust the frequency of the additional microwave strictly, but is difficult by using a normal krystron amplifier with a frequency band width of only 0.05GHz.

ACKNOWLEDGMENT

The current research was partly supported by a Hungarian-Japanese intergovernmental scientific-technological co-operation between the National Technical Development Committee (OMFB) and the Science and Technology Agency (STA). Reference number: OMFB-TET-J-6/98.

REFERENCES

[1] E. Takada *et al.*, "Present status of HIMAC", EPAC2000, Wien, June 2000 (these proceedings).
[2] T. Miyata *et al.*, "Status of the HIMAC pulsed Penning source", Rev. Sci. Instrum.**71**, 972, 2000.
[3] A. Kitagawa *et al.*, "Recent developments for ECRISs at HIMAC", Proc. of 14th Intnl. Workshop on ECRIS, Geneva, 1999, p.23.
[4] A. Kitagawa *et al.*, "Development of NIRS-ECRIS for HIMAC", Rev. Sci. Instrum.**65**, 1087, 1994.
[5] A.G. Drentje *et al.*, "Ion behavior and gas mixing in ECR plasmas as sources of highly charged ions", in Ref. 3, p.13.
[6] J. Arje *et al.*, "Status report of the JYFL-ECR ion source", Proc. of the 12th Intnl. Workshop on ECRIS, Wako, INS-J-182, 1995, p.136.
[7] A. Kitagawa *et al.*, "Optimization of the radial magnetic field of an 18GHz ECRIS at HIMAC", Rev. Sci. Instrum.**71**, 981, 2000.
[8] J. Vamosi and S. Biri, "TrapCAD – a program to model magnetic traps of charged particles", Comp. Phys. Comm., **98**, 215, 1996.
[9] B. Jacquot and R. Geller, "CAPRICE 10GHz – new $2\omega_{ce}$ radial B field", Proc. of the Intnl. Conf. on ECRIS and their Applications, East Lansing, NSCL #MSUCP-47, 1987, p.254.
[10] G. D. Alton and D.N. Smithe, "Design studies for an advanced ECR ion source", Rev. Sci. Instrum, **65**, 775, 1994.
[11] Z. Q. Xie and C. M. Lyneis, "Improvements on the LBL AECR source", in Ref. 6, p.24.
[12] A. Kitagawa *et al.*, "Status report on ECRISs at HIMAC", Rev. Sci. Instrum.**71**, 1061, 2000.