ACCELERATION OF MULTIPLE-CHARGED IONS AT HIMAC

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Abstract

Ion species supplied from HIMAC accelerator complex have been increased in order to widen a scope of clinical, biological and physics study. The paper reports the preliminary results of acceleration test of hydrogen molecular ions and the multiple-charged ions such as Ar, Fe, Kr and Xe ions, which are not fully stripped.

1 INTRODUCTION

HIMAC accelerator complex has successfully supplied carbon beam for clinical study on the cancer treatment since June 1994, and 389 patients have been already completed in the treatment until this spring[1].

HIMAC accelerator complex has been required to supply heavier ions and a proton beam beyond both end of original design range from He to Ar. The need is not only for an ion therapy, but also for widening a scope of biological and physics experiment. Especially, Fe ions are strongly required, because it is important to simulate a radiation effect on human body in the space. Since the injector linac cascade is designed to accelerate ions with a charge-to-mass ratio from 1/2 to 1/7, an ion source should produce heavy ions with the charge-to-mass ratio above 1/7. The ion source has been required to obtain a peak intensity more than 1eμA for alignment of beam axis by multiwire profile monitors at the injection beam line, further, while beam tuning at the ring is not so difficult owing to a high sensitivity of an electrostatic pick-up monitor. Thus 18GHz-ECR (NIRS-HEC) has been developed for production of heavier than Ar ion including metallic ions with high charge-state and high intensity[2]. A fraction of fully stripped ion is decreased, however, when ions are heavier than oxygen ion of the energy at 6 MeV/n. In the original scheme, ions are passing through a carbon-stripper located just after the injector linac cascade, to supply fully stripped ions for synchrotron. Therefore, although vacuum pressure at the ring was designed to accelerate fully stripped ions from He to Ar, HIMAC synchrotron has been required to accelerate multiple-charged ions (partially stripped ions). In the case of Z=1, acceleration of H_2^+ ion was adopted as provisional solution to urgent need from medical physics research.

Hydrogen molecular ions and multiple-charged ions of Ar, Fe, Kr and Xe have been successfully accelerated at HIMAC accelerator complex. The preliminary experiment results are described on both the dependence of the lifetime on a vacuum pressure in the ring and the acceleration of the multiple-charged ions.

2 DEVELOPMENT OF ION SOURCE

NIRS-HEC as the third ion source at HIMAC accelerator complex has been developed for production of metallic and heavier ions than Ar. The features are high extraction voltage (60kV), movable extraction electrode, and strength of the axial mirror field and the radial sextupole field at the chamber wall (1.2T). Current of Ar and Kr ions from NIRS-HEC is shown in fig.1, after suppressing a charge up at Einzel lens by secondary electrons. As can be seen in fig. 1, current of Ar and Kr ions with higher charge-state were increased in comparison with that of 10GHz-ECR. Especially, an intensity of Kr^{15+} was dramatically increased to 12eμA by a factor of 6. The Metal Ion from Voltage compound (MIVOC) method[3] is adopted at NIRS-HEC in order to produce metallic ion. Fe^{9+} ions were produced by MIVOC method with $Fe(C_5H_5)_2$ and its intensity of 25eμA was obtained. The intensity of Ar^{9+} from NIRS-HEC is increased by a factor of 2 by optimising ECR zone, further, although all parameters have not yet optimised. Further, The after-grow method increases output-current, for example, that of Kr^{15+} was increased from 12 to 25eμA. The intensities of other heavier ions than Ar will be increased by about factor of 2.

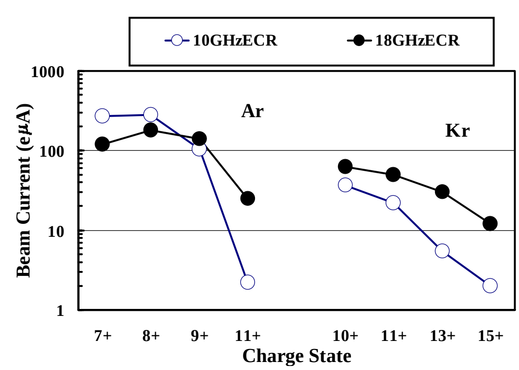

Fig. 1. Comparison between beam current of Ar and Kr from 18GHz-ECR and that from 10GHz-ECR.

3 VACUUM SYSTEM IN THE RING

Vacuum pressure and residual gas components determine mainly the efficiency in the acceleration of molecular ions and multiple-charged ions. In a design stage of a vacuum system of HIMAC synchrotron, lifetime (1/e) of ions in the ring due to charge-changing (τ_{CL}) and multiple scattering (τ_M) were estimated by the following formulas[4,5].

$$\tau_{CL}=1.04\text{x}10^{-27}/(\sigma_T\beta P) \text{ (sec)} \quad (1)$$
$$\sigma_T = \sigma_C + \sigma_L$$
$$\sigma_C=6.55\text{x}10^{-28}q^3\beta^{-6} \quad (\text{cm}^2) \quad (2)$$
$$\sigma_L = 5.22\text{x}10^{-23}(Z-q)\,\beta^{-2}\,(3.13\text{x}10^5q^{-2} - \beta^{-2})\,(\text{cm}^2) \quad (3)$$

where σ_C and σ_L are cross section of electron capture and loss, respectively, Z, q and β are atomic number, charge state and normalised velocity of projectile, respectively, and P is vacuum pressure in Torr. Above charge-changing cross section was obtained by fitting the data of Pb and Xe ions in N_2 in the velocities up to $4\text{x}10^9$cm/s.

$$\tau_M=0.85\text{x}(\beta^3\gamma^2QA_r/R)(A/Z)^2/P \text{ (sec)} \quad (4)$$

where Q is tune, A_r reduced acceptance and R mean radius of the ring.

A design pressure of HIMAC synchrotron was set to be below $5\text{x}10^{-9}$Torr in order to accelerate efficiently fully stripped ions up to Ar. Lifetime of C^{6+} and Ar^{18+} ions in injection energy of 6MeV/n were estimated at about 10 (τ_C=28s, τ_M=16s) and 1sec (τ_C=1s, τ_M=20s), respectively. The features of the vacuum system of the ring are as follows[6]. Vacuum pumping system consists of 8 turbo-molecular pumps (TMPs: 300*l*/sec), 22 sputter ion pumps (SIPs: 400*l*/sec), and 24 titanium getter pumps (TGPs: 800*l*/sec). Average achieved pressure at the pump heads is achieved at $6\text{x}10^{-10}$ Torr without operating TMPs and TGPs. Among reasons for better-than-designed vacuum are (1) low out gassing-rate of $4\text{x}10^{-14}$Torr l/sec/cm^2 at $3\text{x}10^{-8}$Torr in the dipole chambers and (2) several baking out at 200^{o}C. Pressure at pump head is monitored routinely by cold cathode gauge (CCG) calibrated by extractor gauges, because CCG is not so accurate generally in the pressure region below about $1\text{x}10^{-9}$Torr. Quadrupole mass analysers can measure residual gas components at the ring.

4 ACCELERATION TEST

4. 1 Hydrogen molecular ions

A proton beam is required for medical physics research such as the inter-comparison between dose monitors of ion therapy laboratories and proton therapy facilities. For the proton beam at HIMAC, accelerating hydrogen molecular ions at the injector linac cascade and the ring is the easiest way, because of the charge-to-mass ratio of 1/2 and high vacuum in the ring. A proton beam is supplied after dissociating the molecular ions by a plastic scintillator with 0.2mm thickness or vacuum window at the end of transport system after the extraction from the ring.

The dependence of the halflife of the molecular ions with the energy of 6MeV/n is measured on the vacuum pressure at the ring, in order to see effects of a small dissociation-energy of 2.8eV. The measurements are performed without operating rf-cavity. The result is shown in fig.2. The halflife calculated by using measured cross section[7] is larger by about factor of 3 compared with the measured values. The difference may be mainly caused by differences of estimated residual gas components and vacuum pressure. The halflife is also measured in 230MeV/n, and is about 1.8sec in an average pressure of $1\text{x}10^{-9}$Torr at pump heads. As the result, the dissociation cross-section is fairly consistent with the assumption of v^{-2}. The acceleration intensity of H_2^+ with the energy of 230 MeV/n is $1.5\text{x}10^{10}$ppp, and protons with the intensity of $1.9\text{x}10^{10}$ ppp are transported to the biological experiment room, when the injection peak-intensity of H_2^+ is 100μA. Survival rate until the end of the extraction is estimated at about 50% in the assumptions of injection and acceleration efficiency of 80% and the extraction efficiency of 85%.

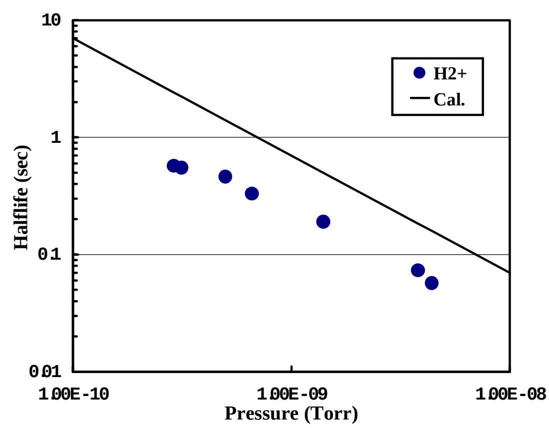

Fig.2. The dependence of the halflife of H_2^+ on the vacuum pressure. Closed circles and solid line indicate measured and calculated halflife, respectively.

4. 2 Ar^{17+}, Fe^{23+}, Fe^{24+}, Kr^{31+} and Xe^{42+}

Accelerations of heavier ions than Ar are tested. The injector linac cascade accelerates the ions, and a charge distribution is measured by analysing line after passing through a carbon stripper. The charge distribution cannot be measured accurately because the analysing line includes quadrupole magnets. However, the charge distributions are roughly consistent with the theoretical prediction[8]. Analysed ions are injected and accelerated in the ring.

The measured halflife of Ar^{17+} with the energy of 6 MeV/n is larger by about factor of 2 compared with the calculated value from eq. (1), as shown in fig. 3. A measured halflife is longer by about one order than that of hydrogen molecular ions, further, because of higher binding energy of 3.2keV. Ar^{17+} ions have already been supplied for atomic physics experiment[9].

The halflives of Fe^{23+} and Fe^{24+} with the energy of 6MeV/n are measured for investigating the difference of the binding energy of electron. As can be seen in fig. 4, the measured halflives are fairly consistent with calculated values by using eq.(1)-(3). The σ_C is comparable with σ_L in Fe^{23+} in the calculation, while σ_C is larger by factor about 2 than σ_L in Fe^{24+}. Fe^{23+} ions are accelerated up to 580MeV/n with the intensity of $4.3x10^8$ppp in the injection peak-current of 25eμA, and ions with the intensity of $3.0x10^8$ppp are transported to the experimental room after stripping all electrons by the plastic scintillator. From July 1998, Fe ions will be supplied to biomedical and physics experiments for study on the radiation effect.

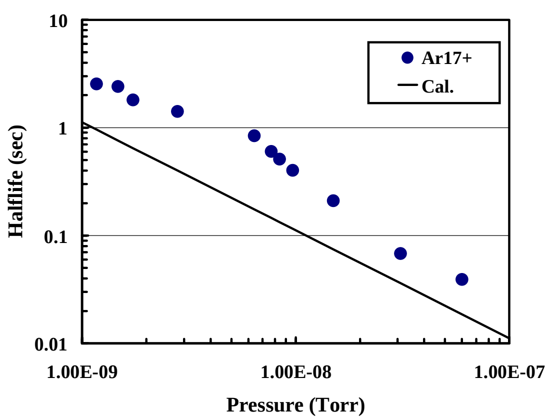

Fig.3. The dependence of the halflife of Ar^{17+} on the vacuum pressure. Closed circles indicate measured halflife and solid line is calculated one.

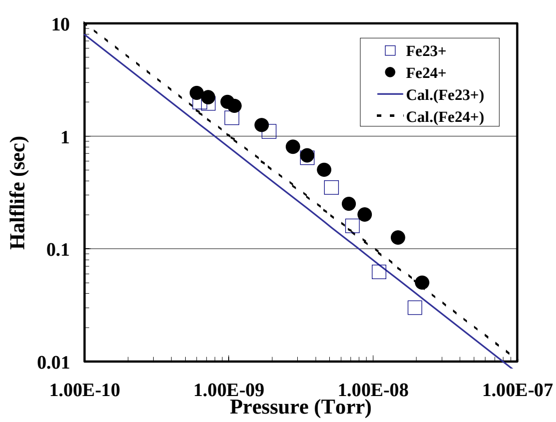

Fig.4. The dependence of the halflives of Fe^{23+} and Fe^{24+} on the vacuum pressure. Closed circles and open squares indicate measured halflives of Fe^{23+} and Fe^{24+}, respectively. Solid and broken lines indicate calculated ones of Fe^{23+} and Fe^{24+}, respectively.

Kr^{31+} has been accelerated. The acceleration intensity is $3.9x10^7$ppp at the energy of 290MeV/n, in the injection beam with the peak intensity of 12eμA. The halflives are 1.2s and 9.6s in the energy of 6 and 290MeV/n, respectively, in average pressure of $5x10^{-10}$ Torr at pump heads. The dependence of the measured halflife on β is roughly consistent with the calculated one.

$^{132}Xe^{42+}$ ions have also been accelerated. The acceleration intensity is $5x10^6$ ppp at the energy of 430MeV/n, in the injection beam with the peak current of 2.5eμA. The extraction intensity is $1.5x10^6$ppp. The halflives are 0.5s and 4.2s in the energy of 6 and 290MeV/n, respectively, in the average pressure of $8x10^{-10}$ Torr at pump heads.

5 SUMMARY

Ion species from HIMAC accelerator complex has been successfully increased for widening a scope of clinical, biological and physics study. Proton beams have already been supplied for producing irradiation field and inter-comparison between dose monitors. Fe ions will be supplied from July 1998. The supplied intensity will be increased further by improvement of NIRS-HEC.

6 ACKNOWLEGEMENTS

The authors would like to express their thanks to the crew of AEC for their skilful operation of HIMAC. This work has been carried out as a part of Research Project with Heavy Ions at NIRS-HIMAC.

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