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# PRODUCTION OF VARIOUS ION SPECIES BY GAS PULSING TECHNIQUE FOR MULTI-ION IRRADIATION AT NIRS-HEC ION SOURCE

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*Abstract*

High-energy carbon-ion radiotherapy is being carried out at Heavy Ion Medical Accelerator in Chiba (HIMAC). Over 11000 cancer patients have been treated with carbon beams having energies of between 56-430 MeV/u since 1994. At present, multi-ion irradiation method by various ion species is being studied for optimization of LET and dose distribution. An ion source has to produce the helium, carbon, oxygen and neon at pulse by pulse for this method. Requirement currents for $He^{2+}$, $C^{2+}$, $O^{3+}$ and $Ne^{4+}$ are 500, 150, 230 and 300 eμA, respectively. We obtained beam current of 482, 151, and 270 eμA for $He^{2+}$, $C^{2+}$ and $O^{3+}$ with mixed helium and $CO_2$ gases under the extraction voltage of 27 kV. Beam current of 27 and 15 eμA for $C^{5+}$ and $O^{7+}$ ions were also obtained in this time. $He^{2+}$ beam include full striped ion such as $C^{6+}$, $N^{7+}$ and $O^{8+}$. We have to increase the purity of $He^{2+}$ beam. The gas feed system was modified for making pulsed gas by using a solenoid valve for switching different gas.

## INTRODUCTION

Four ion sources produce various ions for medical use, biological and physical experiment in HIMAC at the National Institute of Radiological Sciences (NIRS). The multi-ion irradiation with dose distribution and Liner Energy Transfer (LET) optimization is being studied at NIRS [1, 2]. Helium, carbon, oxygen and neon ions are considered as ion species for multi-ion irradiation. When we use more than one ion sources, it is possible to switch different ion species easily. However, we considered the switching method with only one ion source. Ionization gases were helium, $CO_2$ and neon to produce $He^{2+}$, $C^{2+}$, $O^{3+}$ and $Ne^{4+}$ ions. These set points of intensity were 500 eμA correspond to $He^{2+}$, 150 eμA to $C^{2+}$, 230 eμA to $O^{3+}$, and 300 eμA to $Ne^{4+}$. At first, we tested production of the $He^{2+}$, $C^{2+}$ and $O^{3+}$ with mixing the gases of helium and $CO_2$ at 18 GHz NIRS-HEC [3]. Next, we measured the switching time of different ion species with gas pulsing technique.

## GAS MIXING EXPERIMENT

The $CO_2$ and helium gases were introduced at the same time to the plasma chamber for production of $He^{2+}$, $C^{2+}$, $O^{3+}$ at this experiment. Dependences of the microwave power and the mirror field were measured under the same parameters. The microwave frequency was 18.0 GHz. The gas flow of helium was 0.075 cc/min. The extraction voltage was 27.0 kV. The downstream coil current was 500 A. Figure 1 shows microwave power dependence of $He^{2+}$, $C^{2+}$, $O^{3+}$. The gas flow of $CO_2$ and upstream coil current were 0.016 cc/min and 840 A, respectively. When microwave power was increases, $He^{2+}$ was increased, but $O^{3+}$, $C^{2+}$ was decreases. The microwave power of 800 W was good for production of $He^{2+}$. Figure 2 shows dependence of the upstream coil current. The ion source parameters were same as the microwave power dependence. The respective ions became highest when coil current was 790 A. We obtained the beam current of 482, 151, and 270 eμA for $He^{2+}$, $C^{2+}$ and $O^{3+}$ with microwave power of 800 W and upstream coil current of 790 A. However, the beam current of $He^{2+}$ is not yet reach the requirement value due to the gas mixing effect. If more neon gas is added, it is difficult to reach the requirement value of helium ion.

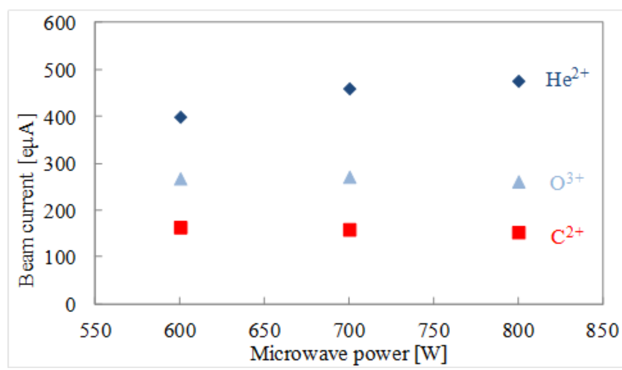


Figure 1: Dependence of microwave power.

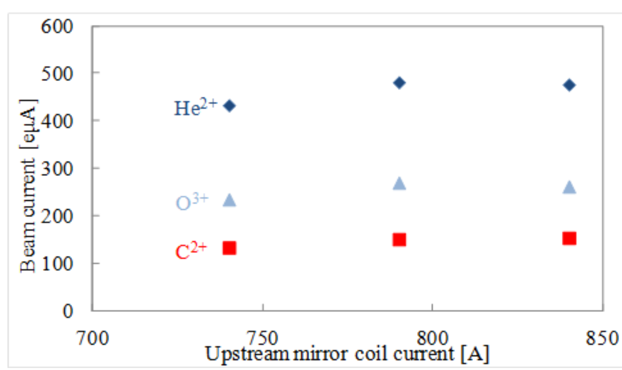


Figure 2: Dependence of upstream mirror magnetic field.

## GAS SWITCHING EXPERIMENT

We try to produce $He^{2+}$, $C^{2+}$, $O^{3+}$ and $Ne^{4+}$ ions by using helium, $CO_2$ and neon gases. The high speed solenoid valve (Parker, Series 9) and controller (Parker, Iota One)

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were used for $CO_2$ gas line. Figure 3 shows gas piping diagram for NIRS-HEC with gas pulsing technique. The solenoid valve was set in $CO_2$ line. The helium and neon gases were regulated by a piezo valve (Mass Flow Control valve: MFC).

Figure 4 shows switching time of $O^{3+}$ to $He^{2+}$ comparison between MFC and solenoid valve. We have to wait about 10 minutes for stable beam current of $He^{2+}$ by using MFC. There were residual $CO_2$ gas in the gas line and vacuum chamber. In the case of solenoid valve, wait time is about 3 minutes. Pulse width was 0.22 msec. The solenoid valve opens 120 msec before the microwave ignition. The influence of residual $CO_2$ gas is big to the production of $He^{2+}$ ion. The gas pulsing method is effective in a changing ion species.

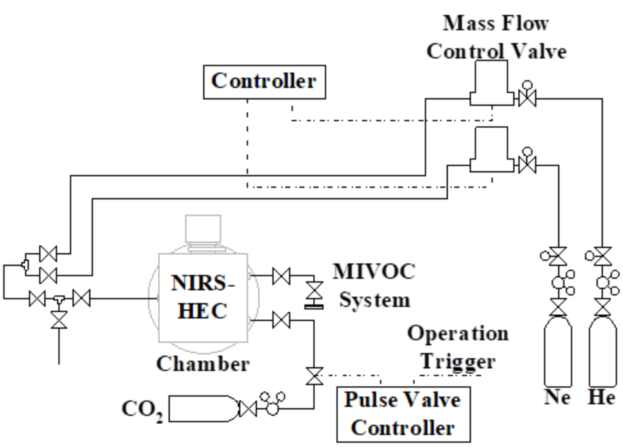


Figure 3: The diagram of gas piping with gas pulsing technique.

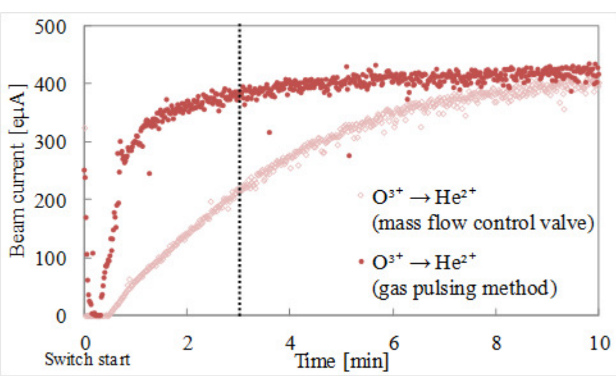


Figure 4: Reproducibility of $He^{2+}$ at the switching of $O^{3+}$ with mass flow control valve and gas pulsing method.

## *Ion Separation Experiment*

Figures 5, 6, 7, 8 shows beam switching time of $He^{2+}$, $C^{2+}$, $O^{3+}$ and $Ne^{4+}$. From Fig. 5, switching time for stable the beam current from $He^{2+}$ to other ion species were about 2 or 3 minutes. The helium gas was not affect for production of $C^{2+}$, $O^{3+}$ and $Ne^{4+}$ ions. From the Fig. 6 and Fig. 7, switching time of carbon and oxygen was less than 1 minute, because, there was no change the gas. In the switching time from carbon and oxygen to $He^{2+}$ and $Ne^{4+}$ were about 2 or 3 minutes. From Fig. 8, the switching time from $Ne^{4+}$ to $He^{2+}$, $C^{2+}$ and $O^{3+}$ions were 4 or 5 minutes. There was the neon gas affect to production of helium, carbon and oxygen ions.

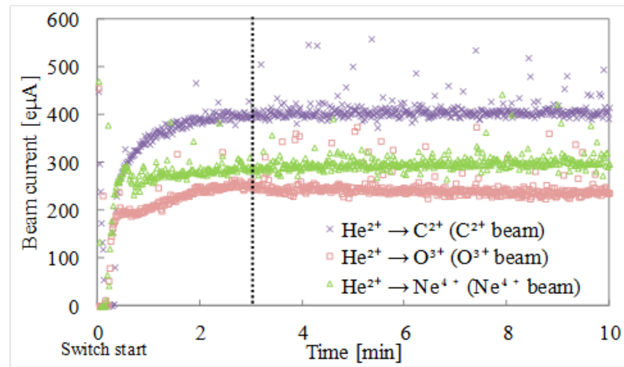


Figure 5: Switching time of $C^{2+}$, $O^{3+}$ and $Ne^{4+}$ from $He^{2+}$.

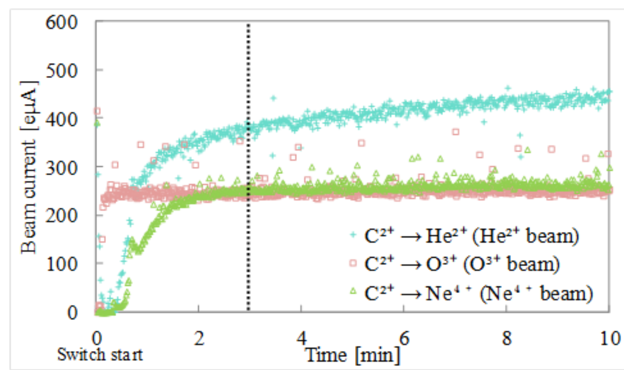


Figure 6: Switching time of $He^{2+}$, $O^{3+}$ and $Ne^{4+}$ from $C^{2+}$.

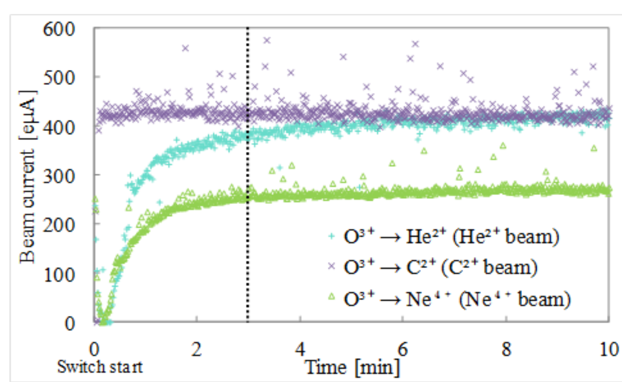


Figure 7: Switching of $He^{2+}$, $C^{2+}$ and $Ne^{4+}$ from $O^{3+}$.

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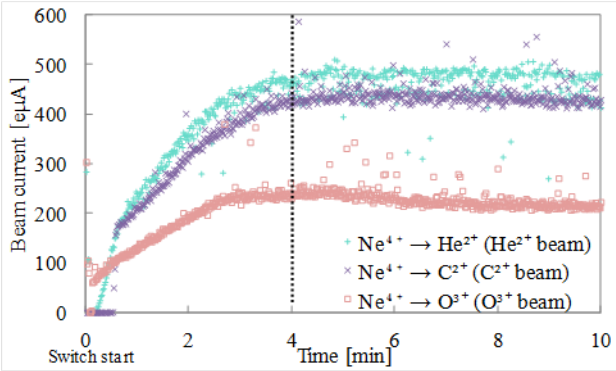


Figure 8: Switching of $He^{2+}$, $C^{2+}$ and $O^{3+}$ from $Ne^{4+}$.

### *Ion Separation Experiment*

$He^{2+}$ beam include full striped ion such as $C^{6+}$, $N^{7+}$ and $O^{8+}$ (A/Z=2). We checked impurity of accelerated $He^{2+}$ beam at HIMAC injector. An ion is separated using dif-ferences in an energy loss on ion species when an ion passes a thin foil. Figure 9 shows beam current as a func-tion of magnetic field of bending magnet. Blue line is A/Z=4 beam. The energy of accelerated ions was 6 MeV/n. Thickness of Al foil was 5 μm. The NIRS-HEC produced $He^{+}$ ion using helium and $CO_2$ gases. $He^{+}$ beam including $C^{3+}$ and $O^{4+}$ is changed to $He^{2+}$, $C^{6+}$ and $O^{8+}$ by carbon foil after the LINAC. There were two peaks from $He^{+}$ beam. Left side peak consists of $C^{6+}$ and $O^{8+}$ ions. Right side peak is $He^{2+}$ ion. Red line is $He^{2+}$ beam with gas pulsing method. There was no $C^{6+}$ and $O^{8+}$ ions. We could optimize the condition for production of $He^{2+}$ ion at NIRS-HEC.

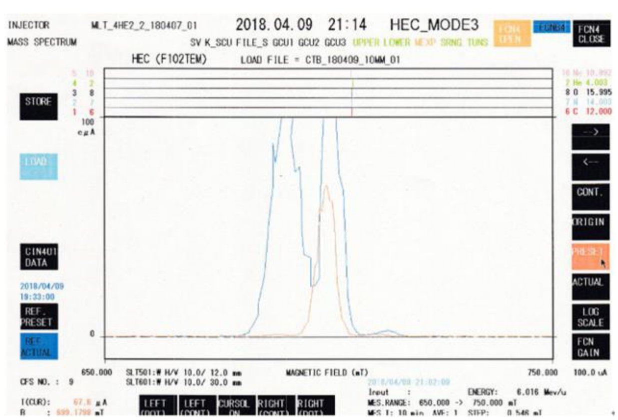


Figure 9: The beam spectrum from $He^{+}$ and $He^{2+}$ at after the HIMAC injector.

## CONCLUSION FOR THE NEXT STEP

The result of the gas mixing experiment, we obtained beam current of 482, 151, and 270 eμA for $He^{2+}$, $C^{2+}$ and $O^{3+}$ with mixed helium and $CO_2$ gases. The optimal mi-crowave power and upstream coil current were 800 W and 790 A, respectively. From the results of gas pulsing experiment, the switching time from $He^{2+}$, $C^{2+}$ and $O^{3+}$ to other ions were 2 or 3 minutes, however, from $Ne^{4+}$ to other were 4 or 5 minutes. We will set the solenoid valve to all of gas line.

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