COOLING STACKING EXPERIMENTS AT HIMAC

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Abstract

^{11}C beam acceleration has been studied in order to form and verify a three-dimensional irradiation field for cancer radiotherapy at HIMAC. In the project, the ^{11}C beam is generated in the ion source and injected to HIMAC synchrotron. The cooling stacking technique plays an important role because of the low intensity of ^{11}C (several 10^7 /injection). The numerical target of the stored ^{11}C is 10^9 in the ring, which is a sufficient number to irradiate a single slice in the 3D scanning irradiation method. We have preceded the cooling stacking experiments using ^{12}C. The issues of the cooling stacking at HIMAC are the cooling time and the coherent instability. The cooling time becomes 2 sec after the improvements of the ion trapping. The coherent instability can be suppressed by the digital beam feedback system. The stacking of 8×10^9 particles is achieved with the feedback.

INTRODUCTION

Since 1994, the carbon beam treatment has been continued at the Heavy Ion Medical Accelerator in Chiba (HIMAC) [1]. The total number of patients reaches more than 4000. Based on the experience of the treatment, we have constructed the new facility for the further therapeutic developments [2]. The research subjects are the fast 3D scanning system toward the adaptive therapy and a gantry system for the intensity modulated carbon therapy. Another future subject is the radioactive beam irradiation such as ^{11}C in order to confirm the dose distribution directly.

Figure 1 (a) shows the treatment plan for head phantom by the carbon beam irradiation [3]. The irradiation shape is concave. Figure 1 (b) shows the PET-CT image after 1 Gy irradiation of ^{12}C. The positron emitter is created along the beam track and the image shows the irradiation area. But it is difficult to compare it with the treatment plan quantitatively. On the other hand, Fig. 1 (c) shows the PET-CT image after 1 Gy irradiation of ^{11}C, which is the positron emitter beam. It was carried out in the secondary beam line at HIMAC. The image clearly shows the stop point of the ^{11}C beam. It is possible to compare with the treatment plan without model calculation. The event rate of PET is also higher than the ^{12}C irradiation. However, the fragment reaction is used for the present ^{11}C irradiation at HIMAC and the beam rate is less than 10^7 pps. It is too low for the normal treatment, because the particle number of 10^{10} is necessary even by the scanning irradiation.

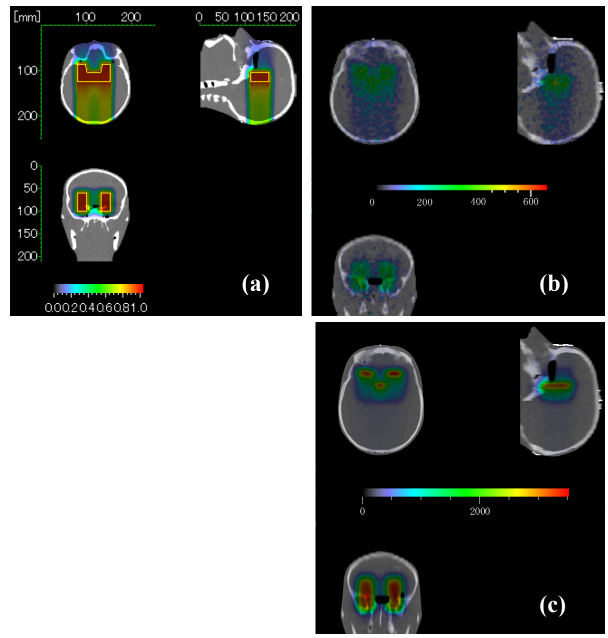

Figure 1: Dose distribution of the treatment planning for head phantom (a) and the measured image by PET-CT after the beam irradiation of ^{12}C , 1 Gy (b) and ^{11}C , 1 Gy (c) [3].

In order to increase the ^{11}C beam intensity for the treatment, we are planning to use the direct ^{11}C beam acceleration scheme from ion source to synchrotron [4]. Figure 2 shows the schematic diagram of the system. It is the application of the drug generation technique for PET. The separation of ^{11}C is carried out with liquid Ar using the difference of the melting point. The separation efficiency is around 50 % [4]. The atoms of ^{11}C are provided to ECR ion source.

Although the sufficient numbers of ^{11}C atoms are generated by the proton beam irradiation, the number of the injected ^{11}C to the synchrotron is rather limited due to the low efficiency of the compression and the ionization processes. The expected number of ^{11}C is less than 10^8 per one injection. Typically, the 10^{10} particles are necessary for the treatment but the ^{11}C particles are sufficient for one slice irradiation by the 3D scanning method. If we can irradiate a slice with the single injection, the non-uniformity of the dose distribution can be avoided. We

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have proposed to use the cooling stacking in order to increase the ^{11}C beam intensity from several 10^7 to 10^9.

The main specifications of HIMAC and the HIMAC electron cooler are shown in Table 1. We discuss here two issues for the cooling stacking at HIMAC, the cooling time and the coherent instability.

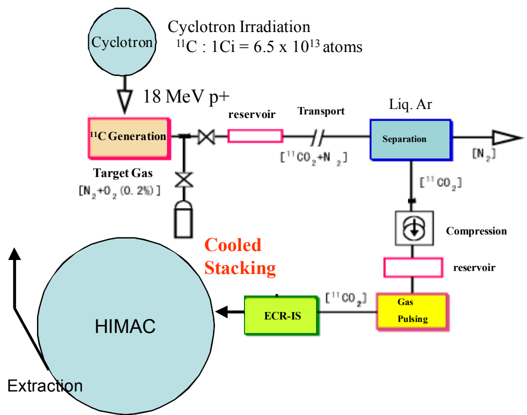

Figure 2: Schematic diagram of the ^{11}C beam acceleration system [4].

Table 1: HIMAC Parameters at Cooling Stacking

HIMAC Ring	
Circumference	129 m
Stack intensity	$10^9 \sim 10^{10}$
Ion Species, Energy	^{12}C, 6 MeV/n
Betatron tunes	3.73 / 3.11
Injection Repetition	3.3 sec
Electron Cooler	
Current	50 mA ~ 300 mA
Cathode Diameter	35 mm
Magnetic Field	500 Gauss
Magnetic Expansion Factor	3.3

COOLING TIME

The injection repetition rate at HIMAC is 3.3 sec and the beam lifetime at the injection energy is around 30 seconds. If the cooling time is less than 3.3 sec, the cooling stacking gain of 10 is expected. The calculated cooling time by BETACOOL [5] is almost consistent with the electron current of 50 mA. However, the cooling time was not shortened with the higher current in the past.

We have measured the cooling time with the various parameters of the ion clearing potential. The cooling time is measured by the sheet beam profile monitor [6]. The ion clearing electrode is a quadratic one and the location is shown in Fig.3. When the quadratic electric potential (+-+-) of +/-1 kV is applied, the cooling time becomes constant with the electron current of higher than 100 mA. It is improved with the dipole electric potential (++--). Figure 4 shows the relation between the electron current and the cathode voltage of the electron, when the ion velocity is kept constant. The ion clearing potential is dipole pattern and the voltage is -1 kV, 0 kV and +/-1 kV. With the voltage of -1 kV and 0 kV, the drop of the cathode voltage is observed, which shows the ion trapping. It is improved with the voltage of +/-1 kV.

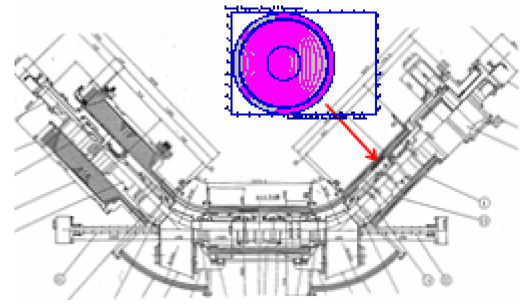

Figure 3: Cut view of the HIMAC electron cooler and the field distribution of the ion clearing electrode.

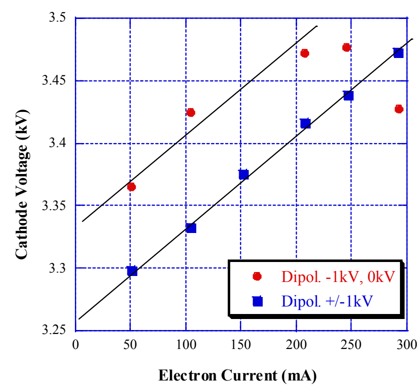

Figure 4: Relation between the electron current and the cathode voltage of the electron, when the ion velocity is kept constant.

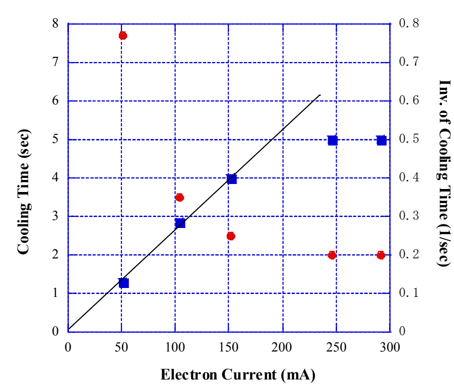

Figure 5: Cooling time and the reciprocal number as a function of the electron current. The clearing voltage is dipole pattern of +/-1 kV.

Figure 5 shows the cooling time and the reciprocal number of it as a function of the electron current. The ion clearing voltage is dipole pattern of +/-1 kV. The reciprocal of the cooling time is proportional to the electron current up to 150 mA, but it shows the plateau with the higher current. The improvements are still necessary to reach the cooling time of 1 sec, which corresponds to the maximum injection rate at HIMAC.

COHERENT BEAM INSTABILITY

Another issue of the cooling stacking is a coherent instability. Figure 6 (a) is the typical trend of the DC-CT signal. The maximum stored particle is 2×10^9 with the electron cooling. It corresponds to the ion current of 480 eμA. The source of the beam loss is the coherent vertical oscillation. Even below 10^9 particles, the oscillation is observed. The oscillation frequency is around 10 MHz with the revolution frequency of 0.25 MHz.

We applied the digital feedback system for the beam orbit [7]. The pickup signal is processed by the digital filtering and the delay and gain unit in FPGA box and applied to the electrostatic kicker through 10 W power amplifier. The processing cycle is 100 MHz and enough faster than the typical oscillation period. The digital feedback system has some advantages compared with the analogue one. It can suppress the horizontal and vertical oscillation from the single input and subtract the offset signal by the filter. Figure 6 (b) shows the DC-CT with the feedback. The maximum particle number is increased to 8×10^9 and the coherent oscillation is not observed below 10^9 particles.

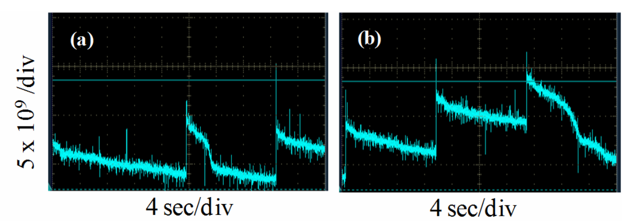

Figure 6: Trend of the DC-CT signal during the cooling stacking without feedback (a) and with feedback (b).

In the compact cooler ring, S-LSR at Kyoto University, the similar vertical coherent oscillation has been observed in the cooling stacking [8]. The maximum particle number without feedback is around 1.5×10^9 protons in the ring, which corresponds to 400 eμA. The oscillation frequency is around 90 MHz with the revolution frequency of 1.6 MHz. Table 2 shows the comparison of the results between HIMAC and S-LSR. The threshold current of the instability and the ratio between the oscillation and the revolution frequency are similar in the two rings. The ring size and the vacuum pressure are different but the cooler parameters are similar, such as the electron energy and the magnetic field.

Figure 7 shows the demonstration of the low current cooling stacking of ^{12}C. The injection beam current is 3×10^8 and after the 10 times injection, the beam current reaches 2.5×10^9. The maximum current is limited by the coherent oscillation.

Table 2: Comparison of the Coherent Oscillation Measurements between HIMAC and S-LSR

HIMAC Ring	HIMAC	S-LSR
Circumference	129 m	22.6 m
Ion Species, Energy	^{12}C, 6 MeV/n	p, 7 MeV
Betatron tunes	3.73 / 3.11	1.64 / 1.21
Threshold Number	2×10^9 $^{12}C^{6+}$	1.5×10^9 p^+
Threshold Current	480 μA	400 μA
Oscillation Frequency	10 MHz	90 MHz
Revolution Frequency	0.25 MHz	1.6 MHz
Vac. Pressure	10^{-6} Pa	10^{-8} Pa
Solenoid Field	500 Gauss	500 Gauss

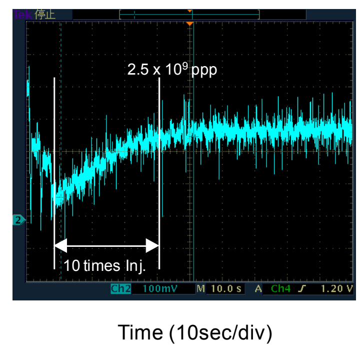

Figure 7: Trend of the DC-CT signal during the cooling stacking.

CONCLUSION

We have improved the ion trapping at HIMAC electron cooler and studied the cooling stacking of ^{12}C toward the future ^{11}C stacking. The cooling time is still longer than our target number of 1 sec but we can confirm the feasibility. We go forward the ^{11}C ion source development in parallel and will evaluate the actual particle number from the ECR ion source.

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