

PROGRESS IN FORMATION OF SINGLE-PULSE BEAMS BY A CHOPPING SYSTEM AT THE JAEA/TIARA FACILITY

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Abstract

The intervals of beam pulses from a cyclotron are generally tens of ns and they are too short for pulse radiolysis experiments which require beam pulses at intervals over 1 μ s (single-pulse beam). A chopping system, consisting of two types of high voltage kickers, is used at the JAEA AVF cyclotron to form single-pulse beam. However, we could not provide single-pulse beam stably over 30 min since the magnetic field of the cyclotron gradually decreased and the number of multi-turn extraction increased. The magnetic field is stabilized at present by keeping temperature of the cyclotron magnet constant. In addition, a new technique to measure and control an acceleration beam phase has enabled us to reduce the number of multi-turn extraction easier than before. The single-pulse beam of a 320 MeV $^{12}\text{C}^{6+}$ is successfully provided without retuning of the cyclotron over 4 h, as a result.

INTRODUCTION

A K110 AVF cyclotron at the JAEA/TIARA facility accelerates various kinds of heavy-ions up to 560 MeV mainly for research in biotechnology and materials science. The cyclotron has two RF resonators with a dee electrode whose span angle is 86° , and the acceleration harmonics h of 1, 2 and 3 are available. More than half of the heavy-ion beams are accelerated at $h = 2$. Beam pulses are extracted at intervals of 45.5 to 90.9 ns depending on an acceleration frequency ranging from 11 to 22 MHz. The ordinary intervals of beam pulses are too short for a pulse radiolysis experiment in radiation chemistry and for a time-of-flight measurement of secondary particles from a target. For example in a pulse radiolysis experiment [1], one cannot observe decay of a radical in a solution correctly since the following beam pulse hits the target before the radical, produced by the last beam pulse, goes out. We provide beam pulses spaced at intervals over 1 μ s (single-pulse beam) using a chopping system as shown in Fig. 1 for the experiments [2].

The ion beam is extracted by multi-turn extraction for all acceleration harmonics in the original design of the cyclotron. In order to form single pulse beam, the number of multi-turn extraction is less than 5 to 9 by the chopping system design. It is very effective to narrow a beam phase width using a phase slit for limitation of the number of multi-turn extraction. However, the beam phase width could not be practically less than 40° in the cyclotron using two pairs of original phase slits in the case of $h = 2$.

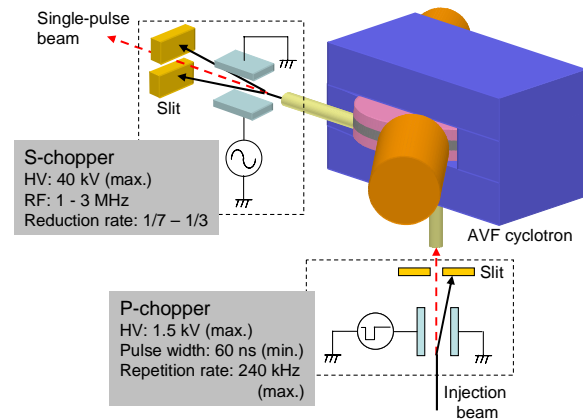


Figure 1: Layout of a chopping system consisting of two types of high voltage kickers: P-chopper and S-chopper.

The number of multi-turn extraction amounted over 30 when good isochronism was formed and the beam current was maximized at the exit of the cyclotron. The most effective way to reduce the number of multi-turn extraction was detuning the magnetic field from isochronism by changing coil current of the outermost trim coil. As a natural result, the beam current considerably decreased. We had formed single-pulse beam using the chopping system in this way. But the beam could not be provided for users stably over 30 min since the magnetic field gradually decreased by the order of 10^{-4} due to temperature rise of the cyclotron magnet, which led growth of the number of multi-turn extraction beyond the limitation.

The central region equipment was improved to precisely define the beam phase width [3], and the magnetic field was stabilized within $\Delta B/B = 1 \times 10^{-5}$ by keeping temperature of the magnet constant [4] mainly for reducing an energy spread of the ion beam using flat-top acceleration technique [5]. In addition, we have developed a new technique to measure and control an acceleration beam phase [6]. These improvements and technique greatly help us to form and provide single-pulse beam stably. In this paper, we describe the chopping system, control of the acceleration beam phase, and result of experiments for single-pulse beam formation of carbon ion.

CHOPPING SYSTEM

Figure 1 shows a layout of equipments of the chopping system consisting of two types of high voltage kickers. The first kicker (P-chopper) installed in the injection line generates beam pulses with repetition period of over 1 μ s.

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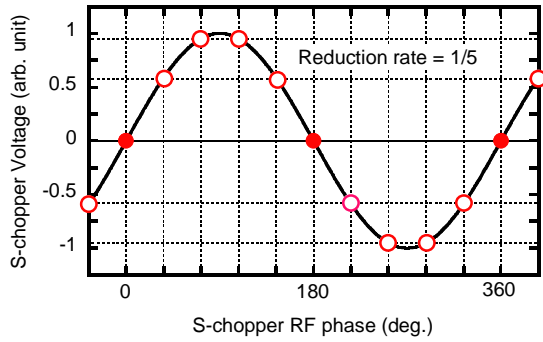


Figure 2: Distribution of beam bunches on the S-chopper RF phase for thinning out with reduction rate of 1/5. The beam bunches represented by open circles deflect from the beam transport axis, while ones represented by closed circles travel along the axis.

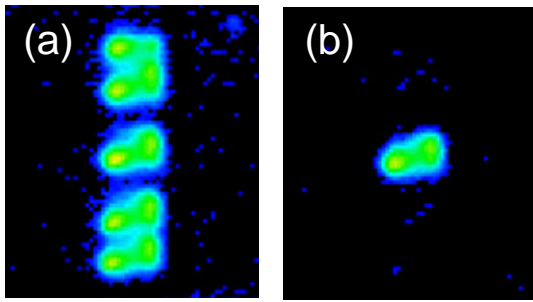


Figure 3: 2D deflection images of the 220 MeV $^{12}\text{C}^{5+}$ beam ($h = 2$) on the alumina scintillator obtained using the S-chopper with the reduction rate of 1/5: (a) no cutting beam, (b) cutting beam by the slit.

The pulse width is about a cycle length of acceleration frequency. A fast pulse generator (PVX-4150, Directed Energy, Inc.) is used as a main component of the P-chopper. The other kicker (S-chopper) in the transport line thins out needless beam pulses caused by multi-turn extraction. The S-chopper generates RF high-voltage ranging from 1 to 3 MHz, and vertically deflects most of the beam bunches. The deflected beam bunches are cut by a downstream slit. Reduction rate of the beam bunches is selectable from 1/7 to 1/3. When the reduction rate is 1/ N , the operational frequency of the S-chopper f_{SC} is given by

$$f_{\text{SC}} = \frac{f_{\text{RF}}}{2N},$$

where f_{RF} is the acceleration frequency of the cyclotron and N is an integer between 3 and 7. We mostly use 5 or 6 as N .

An optimal relation between the beam bunches and the S-chopper voltage waveform with the reduction rate of 1/5 is shown in Fig. 2. Figure 3 shows 2D deflection images of a 220 MeV $^{12}\text{C}^{5+}$ beam ($h = 2$) on an alumina scintillator obtained using the S-chopper with $N = 5$. An RF phase of the S-chopper voltage was fine-tuned to obtain the 2D image of Fig. 3 (a). The beam current measured by a Faraday cup reduced to about 1/5 with cutting beam by the slit. When the number of multi-turn extraction is limited less than 9, we can obtain single-

pulse beam using the P-chopper together with the S-chopper. In the case of $h = 1$, the number of multi-turn extraction is also allowed up to 9 when N equals to 5.

CONTROL OF ACCELERATION BEAM PHASE

A phase excursion, relative variation of the beam phase, is commonly measured by a phase probe to form the isochronous field. However, it is difficult to measure the acceleration beam phase θ which means the absolute value of the beam phase in an energy gain curve. The energy gain of the ion is the maximum at $\theta = 0^\circ$. In addition to defining the beam phase width, control of θ is also very effective to reduce the number of multi-turn extraction since radial spread of the beam bunch narrows due to reduction of the energy spread. Recently, we have developed an easy method to measure θ in the cyclotron. Beam current at a fixed radius before extraction is measured by a probe slightly varying the acceleration frequency within about $\Delta f_{\text{RF}}/f_{\text{RF}} = \pm 5 \times 10^{-4}$ to obtain a trapezoidal current pattern. The acceleration beam phase is obtained by analyzing symmetry of the beam current pattern; when θ equals to 0° , both absolute values of $\Delta f_{\text{RF}}/f_{\text{RF}}$ where the beam current disappears are the same. The beam phase width is also obtained by analyzing gradient of beam current decreasing part. Once θ is measured, we can control it by changing magnetic field of the central bump without breaking the isochronous field.

Figure 4 shows beam current distributions of the 220 MeV $^{12}\text{C}^{5+}$ measured by a deflector probe with a differential head. A clear turn pattern is seen when θ was estimated to be -3° (optimum condition). On the other hand, no clear turn pattern is seen when θ lagged by 15° by changing coil current of C2 trim coil which generates the central bump (C2 change). This result indicates that our method to control θ has enough reliability. The former instability of the magnetic field was simulated by changing coil current of the outermost trim coil (C12). The magnetic field reduction of 1×10^{-4} in the whole acceleration region lagged θ by about 20° at the extraction radius, and this operation also disappeared the clear turn pattern (C12 change). Compared with the

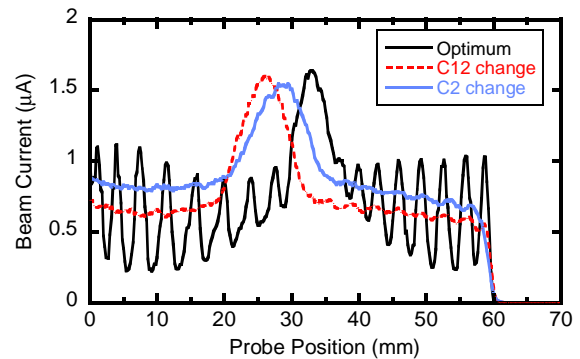


Figure 4: Beam current distributions of the 220 MeV $^{12}\text{C}^{5+}$ measured by the deflector probe for three conditions of acceleration.

optimum condition, the beam current at the exit of the cyclotron decreased to 58% and 18% for C2 and C12 trim coil current change, respectively. The beam phase width was estimated to be 6° in full width at half maximum in the cyclotron. This result, obtained without drastic beam cutting, indicates that the new central region has good performance for $h = 2$.

FORMATION OF SINGLE-PULSE BEAM

Experiments to form single-pulse beam were done with the reduction rate of the S-chopper of 5. First, we measured the number of multi-turn extraction by a plastic scintillation counter using only the P-chopper. Figure 5 shows beam pulse trains of the 220 MeV $^{12}\text{C}^{5+}$. Acceleration conditions are the same as those in Fig. 4. Quasi single-pulse beam was confirmed for the optimum condition of θ , and single-pulse beam has been formed easily using the two choppers. Although quasi single-pulse beam was obtained in the case of C12 change, the main pulse could not pass through the slit of the S-chopper because the beam bunch was extracted laggardly due to decrease of the energy gain. This change of the magnetic field must have made single-pulse beam lost on a user target. On the other hand, obvious multi-turn extraction was confirmed for C2 change, but the number of the beam bunches was less than 9. There is nothing difficult in forming single-pulse beam for the multi-turn extracted beam in this case.

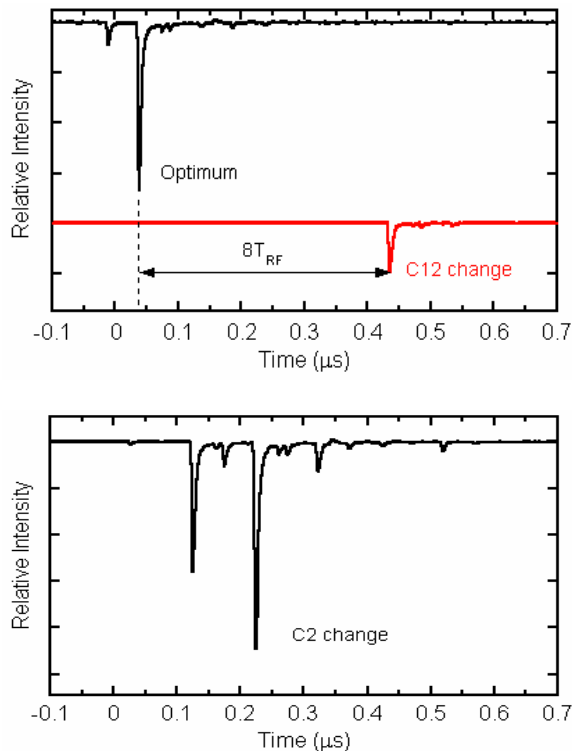


Figure 5: Beam pulse trains of the 220 MeV $^{12}\text{C}^{5+}$ ($h = 2$, $T_{\text{RF}} = 49.0$ ns) measured by the plastic scintillation counter. Beam pulses with duration of about a cycle length of the acceleration frequency were injected into the cyclotron using the P-chopper.

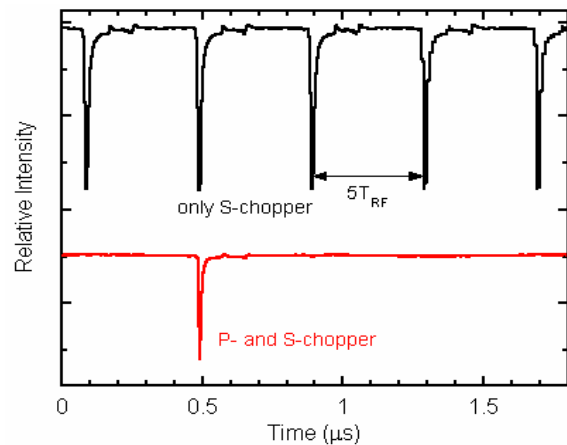


Figure 6: Beam pulse trains of the 320 MeV $^{12}\text{C}^{6+}$ ($h = 1$, $T_{\text{RF}} = 80.3$ ns) formed by the chopping system. The reduction rate of the S-chopper was 1/5.

Formation of single-pulse beam of a 320 MeV $^{12}\text{C}^{6+}$, a heavy-ion beam with the highest energy per nucleon at TIARA, was carried out at $h = 1$. Figure 6 shows pulse trains of the beam obtained using the chopping system. The S-chopper was operated with the reduction rate of 1/5, and the number of multi-turn extraction was limited to 7 by tuning the phase slit and the P-chopper. As a result, excellent single-pulse beam was obtained.

Main coil current of 900 A for the 320 MeV $^{12}\text{C}^{6+}$ is the highest value for all ion beams accelerated by the cyclotron. Therefore, the most serious magnetic field reduction arose before because temperature rise of the magnet originated from heat generation of the main coil. However, we have succeeded to provide single-pulse beam of heavy-ion with the highest energy stably over 4 h without retuning of the cyclotron.

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