PHASE BUNCHING IN THE CENTRAL REGION OF THE JAEA AVF CYCLOTRON FOR HEAVY-ION ACCELERATION IN THE THIRD-HARMONIC MODE

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Abstract

Phase bunching realized in the central region of the JAEA AVF cyclotron for heavy ion acceleration in the third-harmonic mode (h = 3) was evaluated using both calculations with a simplified geometric trajectory model and measurements of internal beam phase distributions. The phase bunching effect for h = 3 was compared with that for h = 2, where the geometric condition of the central region differs from that for the former. Both of the measurements of internal beam phase distributions without the buncher and the calculations with the model have shown that the phase bunching effect for h = 3 was equivalent to that for h = 2 when a beam buncher was not used before the acceleration. In the measurement using the buncher, the phase width in the case of h = 3 was larger than that of h = 2. In order to enhance of the phase bunching for h = 3, it is necessary to modify the geometric condition of the central region and to increase the ratio of a peak dee-voltage to an extraction voltage of an ion source, which is one of the parameters determining the phase bunching performance, with a suitable injected beam distribution in the radial phase space.

INTRODUCTION

The azimuthally varying field (AVF) cyclotron with a K number of 110 MeV at the Japan Atomic Energy Agency (JAEA) is widely utilized for research in radiochemistry, biotechnology and materials science as well as nuclear physics and the production of radioisotopes [1]. In order to produce a variety of heavy ion beams in a wide range of energy, the cyclotron is operated with three acceleration harmonic modes of h = 1, 2 and 3, which is defined as f_{rf} / f_{particle}, a ratio of the rf frequency to the orbital one. Heavy ions up to osmium ions are produced by four normal conducting electron cyclotron resonance (ECR) ion sources.

Recently, the cyclotron was upgraded for the advanced ion beam applications using a microbeam [2] and a single-pulse beam [3]. In the microbeam formation, an energy spread of the order of 10−4 is required to reduce the influence of chromatic aberrations caused in the focusing lenses. A flat-top acceleration system was developed to minimize energy spread of an ion beam [4], and the central region of the cyclotron was remodelled to minimize the beam phase width [5]. For production of the single-pulse beam, specific techniques to optimize the acceleration phase [6] and to stabilize the magnetic field [7] are needed to enhance the controllability of the beam pules number extracted from the cyclotron [3].

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The remodelled central region generates the phase bunching effects in the acceleration harmonic mode of h = 2 and 3. Phase bunching originates in energy-gain modulation produced in a rising-slope region of an acceleration-voltage waveform at the first acceleration gap, and minimizes the beam phase width at the second acceleration gap. We elucidated the mechanism of phase bunching by a simplified geometric trajectory model [8]. The beam phase correlations between the first and the second acceleration gap obtained by the geometric trajectory model for three acceleration harmonics in the JAEA AVF cyclotron were consistent with the correlations between the initial beam phase and the beam phase at 100 turns analysed by the orbit simulation [9]. Moreover, the phase bunching performance in the central region of the cyclotron was evaluated by measurement of the beam phase distributions. The correlations between the buncher phase and the measured internal phase distribution for h = 1 and 2 were consistent with the calculated results obtained by the geometric trajectory model [10]. However, the phase bunching effect for h = 3 in the central region, where the geometric condition of h = 2 is different, was not evaluated yet.

In this paper, we described the calculation and the measurement of the phase bunching for h = 3 in the JAEA AVF cyclotron, and the comparison of the phase bunching effect for h = 3 with that for h = 2.

CALCULATION OF PHASE BUNCHING BY GEOMETRIC TRAJECTORY MODEL

The phase bunching performance was evaluated with the correlation between the initial phase difference $\Delta\phi$ and the phase difference $\Delta\phi$S at the second acceleration gap by the geometric trajectory model in homogeneous magnetic field, as indicated by the following equation,

$$\Delta\phi_S = \Delta\phi + h\left(\theta_E + \Delta r'\right) + h\cdot\sin^{-1}\left[\begin{array}{l}\dfrac{\sqrt{1-V_R\sin\phi_P}+\Delta r}{\sqrt{1-V_R\sin\left(\phi_P+\Delta\phi\right)}}\sin\theta_P \\ -\sin\left(\theta_E+\Delta r'+\theta_P\right)\end{array}\right], \quad (1)$$

where θ_P is a span angle from the first to the second acceleration gap, θ_E is the angle between the straight line of the acceleration gap passing through the cyclotron center and the line perpendicular to the particle emitting direction, V_R is the ratio of a peak dee-voltage to an extraction voltage of an ion source in units of MV, Δr and Δr' are the position difference and emission angle difference from the reference particle, respectively and ϕ_P

ISBN 978-3-95450-131-1

is the initial RF phase of the reference particle at the first acceleration gap. When the reference particle passes through the center of the dee electrode, the RF phase ϕ_P is defined to be 0, and ϕ_P is indicated by the following equation,

$$\phi_P = -h\left(\theta_P - \frac{\theta_{Dee}}{2}\right) \qquad (2),$$

where θ_{Dee} is a span angle of a dee electrode. When both Δr and $\Delta r'$ are 0, the phase bunching performance mainly depends on the combination of the four key parameters; θ_P, θ_{Dee}, h and V_R [8]. The phase difference $\Delta\phi_S$ is susceptible to higher h as shown in the third term of Eq. (1). The higher harmonic mode is typically needed to accelerate the heavier ion within upper limit of the magnetic field in a cyclotron. Therefore, the phase bunching effect is easily obtainable in the acceleration condition of heavy ions.

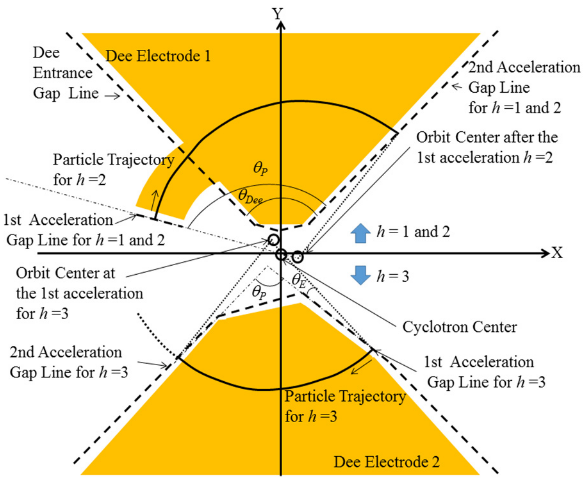

Figure 1: Layout of the geometric trajectory analysis model for the remodelled central region in the JAEA AVF cyclotron.

The geometric trajectory model was applied to the remodelled central region the JAEA AVF cyclotron with two dee electrodes of $\theta_{Dee} = 86°$, as shown in Fig. 1. In h = 1 and 2, the span angle θ_P is equal to 118° since the first acceleration gap is located in front of the puller electrode of the dee electrode 1. The initial phase width of 40 RF degrees for reference particle centered at ϕ_P was reduced to 7.8 RF degrees for h = 2. The span angle θ_P for h = 3 is equal to 78° since a tip of the dee electrode 2 is deformed. The angle difference θ_E from θ_{Dee} is equal to 17°. Then, the phase offset $h\theta_E$ of 51 RF degrees at the second acceleration gap results from the second term of Eq. (1). Moreover, the optimum initial phase, at which the phase bunching effect is maximized, is changed by the phase offset in the third term. The initial phase width of 40 RF degrees for reference particle centered at the initial phase of −22 RF degrees was minimized to 7.8 RF degrees. The phase bunching performance of h = 3 was equal to h = 2.

MEASURMENT OF BEAM PHASE DISTRIBUTION IN THE CYCLOTRON

The beam phase distributions were measured to compare the effect of phase bunching on the beam phase width between the acceleration modes in the JAEA AVF cyclotron. The measurement of the beam phase without the buncher was carried out by the radial probe with a plastic scintillator (BC400, Saint-Gobain) in the cyclotron since the buncher restricts the initial beam phase. In order to enhance the accuracy of the measurement, the deviation from an isochronous field was decreased within ±3 RF degrees and a phase shift from the top of the sinusoidal dee-voltage waveform was reduced within 3 RF degrees by changing the currents of the trim coils. The measured beam phase distributions for a 107 MeV $^{4}He^{2+}$ beam of h = 1 (black), a 260 MeV $^{20}Ne^{7+}$ beam of h = 2 (red) and a 120 MeV $^{20}Ne^{6+}$ beam of h = 3 (blue) are shown in Fig. 2. The beam phase distributions of h = 2 and 3 were narrower than that of h = 1 because of phase bunching. There is little difference on the beam phase width between h = 2 and 3 after phase bunching. These results were consistent with the calculation results. The phase offset had no effect on phase bunching, because the beam phase after phase bunching was adjusted to the top of the waveform by changing the currents of the trim coils.

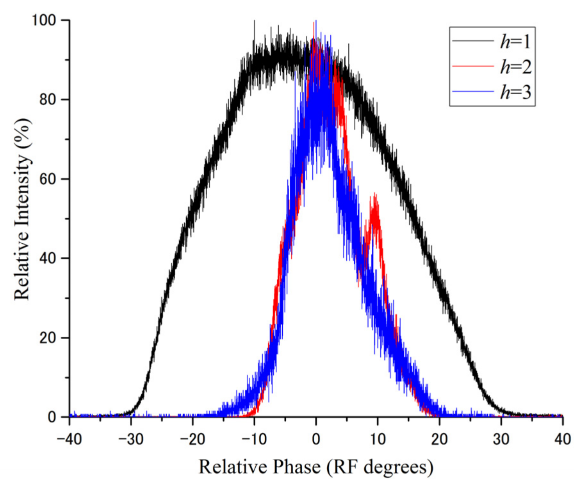

Figure 2: Measured phase distributions by the radial probe without the buncher for a 107 MeV $^{4}He^{2+}$ beam of h = 1, a 260 MeV $^{20}Ne^{7+}$ beam of h = 2 and a 120 MeV $^{20}Ne^{6+}$ beam of h = 3 in the JAEA AVF cyclotron.

The effect of the initial phase on phase bunching was investigated by the measurement of the beam phase distribution with changing the buncher phase. The initial phase at the first acceleration gap can be relatively determined by adjusting the buncher phase with a resolution of less than 0.367 RF degrees. The measurement results for a 260 MeV $^{20}Ne^{7+}$ beam of h = 2 and a 120 MeV $^{20}Ne^{6+}$ beam of h = 3 are shown in Fig. 3 and 4, respectively. These contour maps (black line) were formed by merging larger than 50% regions of particle density distributions measured in 1% relative buncher phase

ISBN 978-3-95450-131-1

increments from −8% to 8%, which correspond to the initial RF phase region from −29.4 to 29.4 RF degrees. Moreover, in order to investigate the shape of the measured contour map, the phase correlations for h = 2 and 3 calculated by the model with Δr and $\Delta r'$ were also shown in Fig. 3 and 4, respectively. The calculation was carried out for 9 particles with different initial conditions: $\Delta r = -2$ (red), 0 (green), 2 mm (blue), and $\Delta r' = -20$ (broken line), 0 (solid line), 20 mrad (dotted line). We assumed that the center of the initial phase of distributions in the measured contour map corresponded to the initial phase in the calculated correlations which the slope at the center of the distributions in the measured contour map is consistent with the slope of the calculated correlation.

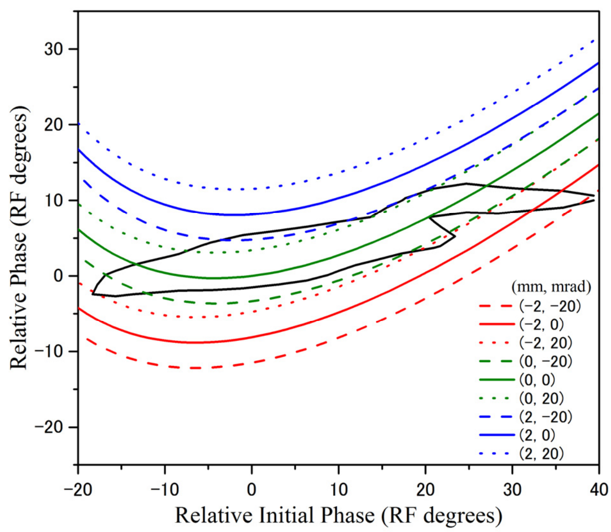

Figure 3: Contour map formed by merging larger than 50% regions in measured particle density distribution for a 260 MeV $^{20}Ne^{7+}$ beam and the calculation result for h = 2.

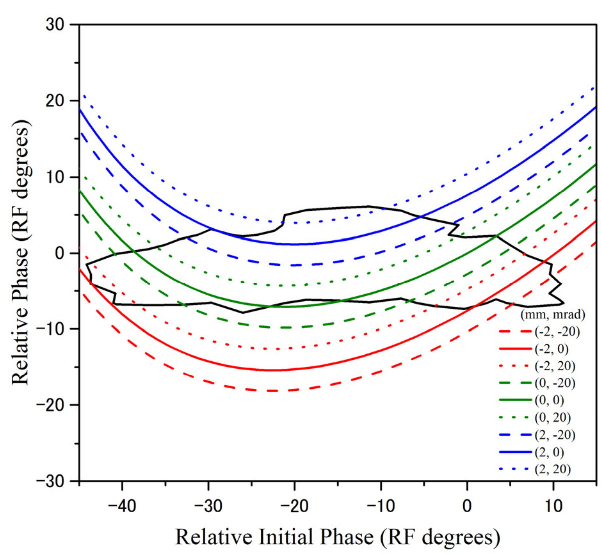

Figure 4: Contour map formed by merging larger than 50% regions in measured particle density distribution for a 120 MeV $^{20}Ne^{6+}$ beam and the calculation result for h = 3.

Both distributions in the contour maps clearly show the phase bunching effect; the initial phase difference larger than 55 RF degrees was compressed to the measured phase difference less than 15 RF degrees. The measured total phase width for the whole initial phase of h = 2 was nearly equal to that of h = 3. However, the measured local phase width of h = 2 for each initial phase was the smaller than that of h = 3.

The center of the initial phase in the measured contour map for h = 2 and 3 were estimated at 11 and −16 RF degrees, respectively. The difference of the center of the initial phase between h = 2 and 3 was consistent with the initial phase difference caused by the phase offset. The distribution in the contour maps depends on the phase offset in the geometric condition. On the other hand, the calculation indicated that the interval between the correlation lines narrowed in an upward-sloping region of the lagged initial phase. The interval between the correlation lines depended on V_R which is one of the parameters determining the phase bunching performance. Moreover, the interval between the correlation lines also depended on the particle distribution in radial phase space, because the calculated correlations with (Δr, $\Delta r'$) = (0, -20) and (0, 20) were proximate to (-2, 20) and (2, -20), respectively. The distribution in the measured contour map for h = 2 overlapped with the upward-sloping region, but the distribution for h = 3 was away from the region. Therefore, the local beam phase width for h = 2 was narrower than that for h = 3.

Enhancement of the phase bunching effect for h = 3 needs to modify the geometric condition with a decrease in θ_E and to optimum V_R with a suitable injected beam distribution in the radial phase space. Further empirical studies are needed to obtain optimum conditions in radial phase space for enhancement of the phase bunching effect.

REFERENCES

[1] K. Arakawa et al., in: Proceedings of the 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada, 1992, p. 119.
[2] M. Oikawa et al., Nucl. Instr. and Meth. B 260 (2007) 85.
[3] S. Kurashima et al., Rev. Sci. Instrum. 86 (2015) 073311.
[4] M. Fukuda et al., Rev. Sci. Instrum. 74 (2003) 2293.
[5] N. Miyawaki et al., Nucl. Instr. Meth. A 636 (2011) 41.
[6] S. Kurashima et al., Rev. Sci. Instrum. 81 (2010) 033306.
[7] S. Okumura et al., Rev. Sci. Instrum. 76 (2005) 033301.
[8] N. Miyawaki et al., Nucl. Instr. Meth. A 715 (2013) 126.
[9] N. Miyawaki et al., in: Proceedings of the 20th International Conference on Cyclotrons and their Applications, Vancouver, Canada, 2013, p. 350.
[10] N. Miyawaki et al., Nucl. Instr. Meth. A 767 (2014) 372.

ISBN 978-3-95450-131-1