ANALYSIS OF PHASE BUNCHING IN THE CENTRAL REGION OF THE JAEA AVF CYCLOTRON

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Abstract

Phase bunching generated in the central region of an AVF cyclotron was analysed by a simplified geometric trajectory model for particles travelling from the first to the second acceleration gap. The phase difference between particles and a reference particle at the second acceleration gap depends on combination of four parameters: the acceleration harmonic number (h), a span angle of the dee electrode, a span angle from the first to the second acceleration gap, a ratio between a peak dee-voltage and an extraction voltage of an ion source. In the JAEA AVF cyclotron, phase bunching was realized for $h = 2$ and 3. The geometric conditions of phase bunching for $h = 1$ were unrealistic for the case of the JAEA AVF cyclotron with an 86 degree dee electrode. The phase difference at the second acceleration gap for an initial particle phase width of 40 RF degrees, estimated by the geometric trajectory analysis, was reduced to 8.9 RF degrees for $h = 2$ and to 27.7 RF degrees for $h = 3$, but was expanded to 43.7 RF degrees for $h = 1$. The reduction of the phase width was consistent with the results obtained by orbit simulations. The practical phase bunching was demonstrated by the phase width measurement for an internal beam of the JAEA AVF cyclotron.

INTRODUCTION

The central region of the JAEA AVF cyclotron [1] had been remodelled [2] to improve the beam phase width reduction for production of a high-quality beam with an energy spread of the order of 10^{-4} which is required to reduce a chromatic aberration effect caused in the focusing lenses for microbeam formation [3]. In general, reduction of a phase width is controlled by a phase slit installed in the central region. An external buncher in an injection beam line is indispensable for improvement of beam intensity and quality under the condition of the phase defining. Further phase bunching effect is obtainable by optimizing configuration of the central region geometry. Feasibility of phase bunching generated in the central region with an internal ion source was explored by Reiser et al. [4] in the 1960's. In a design of the central region for external injection, the generation of phase bunching was reported by Aldea [5]. However, there was little discussion for phase bunching in recent years because phase bunching achieved by an external buncher was sufficient for usual operation. In a design process for remodelling the central region of the JAEA AVF cyclotron, we analysed the mechanism of phase bunching by a simplified geometric trajectory model [6] and realized the phase bunching effect in the central region [2].

In this paper, we described the mechanism of the phase bunching generation and its application to the central region of the JAEA AVF cyclotron.

MECHANISM OF PHASE BUNCHING

Phase bunching generated in the central region originates in energy gain modulation produced in the rising slope region of an acceleration voltage waveform at the first acceleration gap, and reduces phase difference between particles and a reference particle at the second acceleration gap. In general, a span angle θ_P from the first to the second acceleration gap is not always equal to a span angle θ_{Dee} of the dee electrode because the initial beam phase for acceleration to obtain maximum energy gain at the second acceleration gap depends on the position of a dee or a puller electrode. Consequently, the beam phase at the second acceleration gap can be changed by the electrode position and shape at the first acceleration gap. Moreover, the phase difference at the second acceleration gap is proportional to a bending angle from the first to the second acceleration gap. The bending angle is related to the energy gain at the first acceleration gap. The most effective phase bunching can be achievable at the first and second acceleration gaps, because the ratio of the energy gain to the total kinetic energy is largest.

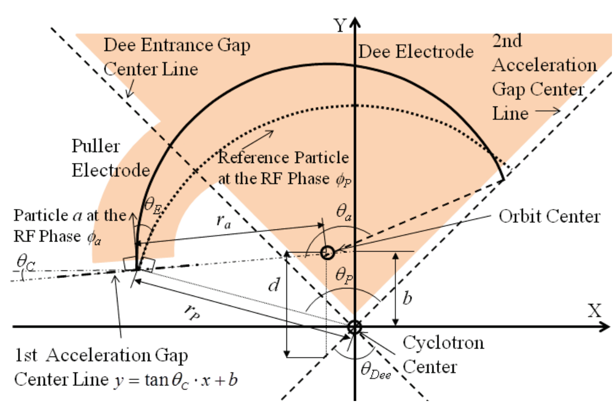

Figure 1: Layout of geometric analysis model.

The mechanism of phase bunching was investigated by the simplified geometric trajectory analysis model for particles travelling from the first to the second acceleration gap in homogeneous magnetic field. The layout of the geometric analysis model is shown in Fig. 1. In this model, the Y axis corresponds to the axis of the dee electrode. The center line of the first acceleration gap

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was expressed as $y = \tan(\theta_C)\cdot x + b$. The positions of the first and second acceleration gaps were given by the angle from the Y axis, $\theta_P - \theta_{Dee}/2$ and $\theta_{Dee}/2$, respectively. We assumed that the particle a was instantaneously accelerated perpendicular to the center line of the first acceleration gap. The reference particle was accelerated perpendicular to the line between the cyclotron center and the position at the first acceleration gap.

For simplicity, the orbit radius r_P of the reference particle after the first acceleration corresponds to the distance from the cyclotron center. According to a non-relativistic treatment, the orbit radius r_P is given by

$$r_P = \frac{\sqrt{2m_0c^2}}{300B}\sqrt{\frac{M}{Q}\left(V_{\mathrm{Ion}} - V_{\mathrm{Dee}}\sin\phi_P\right)}, \quad (1)$$

where m_0 (MeV/c^2) is the atomic mass unit, B (T) is the magnetic field, M/Q is the mass-to-charge ratio of the particle, ϕ_P is the initial RF phase of the reference particle at the first acceleration gap, and V_{Ion} and V_{Dee} are an acceleration voltage in MV of an ion source and a dee electrode at the first acceleration gap, respectively. The RF phase ϕ_P is defined to be 0 when the reference particle passes through the Y axis, and ϕ_P is given by

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

Since the orbit center of the reference particle corresponds to the cyclotron center, the RF phase from the first to the second acceleration gap is equal to the product of θ_P and h. The bending angle θ_a of the particle a was determined by an orbit radius r_a of the particle a after the first acceleration, given by

$$r_a = \frac{\sqrt{2m_0c^2}}{300B}\sqrt{\frac{M}{Q}\left[V_{\mathrm{Ion}} - V_{\mathrm{Dee}}\sin\left(\phi_P + \Delta\phi_a\right)\right]}, \quad (3)$$

where $\Delta\phi_a$ is the initial phase difference from the reference particle to the particle a at the first acceleration gap. The phase difference $\Delta\phi_S$ between the reference particle and the particle a at the second acceleration gap depends on the product of h and the bending angle difference between the first and second acceleration gaps, because the two particles started at the same position. The emission angle difference θ_E between the reference particle and the particle a at the first acceleration gap is

$$\theta_E = \theta_C - \theta_P + \frac{\pi + \theta_{Dee}}{2}. \quad (4)$$

The orbit center position of the particle a, which is on the first acceleration gap, is given by

$$\begin{aligned} x_a &= r_a\cos\theta_C - r_P\sin\left(\theta_P - \frac{\theta_{Dee}}{2}\right) \\ y_a &= r_a\sin\theta_C + r_P\cos\left(\theta_P - \frac{\theta_{Dee}}{2}\right) \end{aligned}. \quad (5)$$

In order to estimate θ_a, we consider the distance d in the Y direction between the orbit center of the particle a and the point at the intersection of the extended line of the second acceleration gap, as shown in Fig. 1. The distance d is given by

$$d = y_a - \tan\left(\frac{\pi - \theta_{Dee}}{2}\right)x_a. \quad (6)$$

The bending angle θ_a is obtained from the sine theorem as

$$\theta_a = \theta_E + \theta_P + \sin^{-1}\left[\frac{r_P}{r_a}\sin\theta_P - \sin\left(\theta_E + \theta_P\right)\right]. \quad (7)$$

Therefore the phase difference $\Delta\phi_S$ at the second acceleration gap is expressed as

$$\Delta\phi_S = \Delta\phi_a + h\cdot\theta_E + h\cdot\sin^{-1}\left[\frac{\sqrt{1 - V_R\sin\phi_P}}{\sqrt{1 - V_R\sin\left(\phi_P + \Delta\phi_a\right)}}\sin\theta_P - \sin\left(\theta_E + \theta_P\right)\right], \quad (8)$$

where $V_R = V_{\mathrm{Dee}}/V_{\mathrm{Ion}}$.

The phase difference $\Delta\phi_S$ determines phase bunching performance which mainly depends on combination of the four key parameters; θ_P, θ_{Dee}, h and V_R. The emission angle difference θ_E correlates closely to the RF phase offset of the all particles at the second acceleration gap. If $\theta_E = 0°$, the phase bunching condition is given by $|\Delta\phi_S| < |\Delta\phi_a|$. Phase bunching enhancement is expected for higher h as shown in the third term of Eq. (8).

APPLICATION TO CENTRAL REGION OF JAEA AVF CYCLOTRON

The geometric trajectory analysis model was applied for evaluation of phase bunching in the central region of the JAEA AVF cyclotron with two dee electrodes of θ_{Dee} = 86° and h = 1, 2 and 3. The V_R in practical conditions for the cyclotron was between two and four. For simplicity, we assumed V_R = 3 for phase difference estimation at the second acceleration gap. The remodelled central region of the cyclotron is shown in Fig. 2.

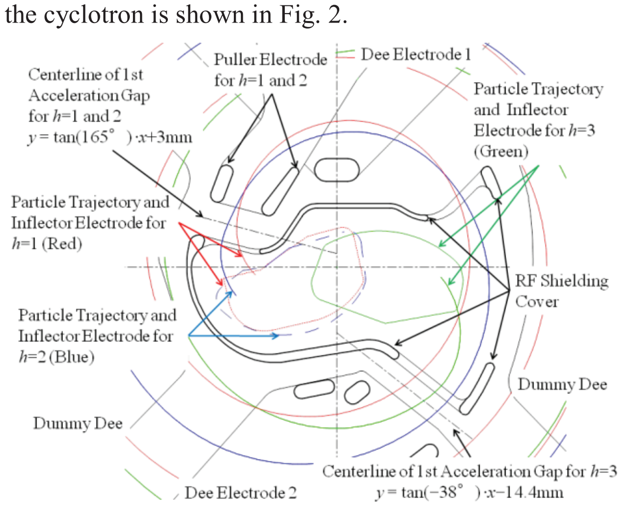

Figure 2: Layout of electrodes in the remodelled central region of the JAEA AVF cyclotron and typical simulated trajectories for h = 1, 2 and 3.

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An inflector electrode is exchanged when an acceleration harmonic mode is switched. The RF shielding cover is separated from the inflector electrode and fixed on an upper part of the dummy dee electrode. The first acceleration gap for h = 1 and 2 is located between the puller electrode of the dee electrode 1 and the RF shielding cover of the inflector. The first and second acceleration gaps for h = 3 are situated on the dee electrode 2 side. The center lines of the first acceleration gap were designed as $y = \tan(165°)\cdot x$ +3 mm for h = 1 and 2, and as $y = \tan(-38°)\cdot x$ −14.4 mm for h = 3. The centreline for h = 3 is located away from the cyclotron center compared to h = 1 and 2. In order to apply the geometric model to the central region for h = 3, the span angle θ_P was estimated to be 78° obtained from the simulated particle trajectory at the first acceleration gap. Consequently, the emission angle difference θ_E for h = 3 was equal to 17° from Eq. (4), and the RF phase offset $h\theta$ at the second acceleration gap was 51 RF degrees. On the other hand, the θ_P for h = 1 and 2 was approximated to be 118° since the centreline of the first acceleration gap was placed closely to the cyclotron center.

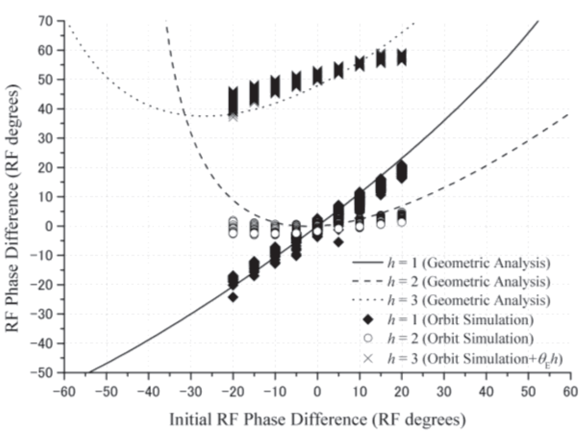

Figure 3: Correlations between $\Delta\phi_a$ and $\Delta\phi_S$ for h = 1, 2, and 3 estimated by the geometric analysis (solid, dashed and doted lines). Correlations of relative phase difference between the first acceleration gap and the dee gap after 100 turns obtained by orbit simulations.

The phase difference $\Delta\phi_S$ at the second acceleration gap was estimated from Eq. (8) for the parameters mentioned above. The correlation between $\Delta\phi_a$ and $\Delta\phi_S$ was shown in Fig. 3. Since the correlation curves for h = 2 and 3 had local minima, the phase bunching effect was maximized at $\Delta\phi_a$ = 0 RF degree for h = 2 and $\Delta\phi_a$ = −25 RF degrees for h = 3. From the correlation obtained by the geometric model, the initial phase width of $\Delta\phi_a$ = 0 ±20 RF degrees was reduced to 8.9 RF degrees for h = 2 and to 27.7 RF degrees for h = 3. The condition for h = 1 without local minima of the curves didn't generate any phase bunching effect. In this case, the initial phase width of $\Delta\phi_a$ = 0 ±20 RF degrees was expanded to 43.7 RF degrees. On the other hand, minimum $\Delta\phi_S$ for h = 3 was +38 RF degrees, originated from the condition that the orbit center of the particle a was different from the cyclotron center and the particle a at the second acceleration gap was delayed by 51 RF degrees.

The bunched phase after the second acceleration gap was investigated by an orbit simulation for the JAEA AVF cyclotron. The simulation was carried out for 1089 particles with different initial conditions at the inflector electrode exit; 9 initial phases from −20 to +20 RF degrees in 5 RF degree increments, 11 initial radial positions around the center of the inflector exit from −1 to +1 mm in 0.2 mm increments, and 11 initial radial divergences from −40 to +40 mrad in 8 mrad increments. The acceleration parameters for h = 1, 2 and 3 were 45 MeV H^+ (h = 1), 260 MeV $^{20}Ne^{7+}$ (h = 2) and 75 MeV $^{20}Ne^{4+}$ (h = 3), respectively. The simulation results were additionally plotted in Fig. 3 as the correlations between the initial phase difference and the phase difference after 100 turns.

The original simulation result for h = 3 after 100 turns showed a phase difference distribution around $\Delta\phi_S$ = 0 RF degree to obtain a maximum energy gain by optimizing trim coil currents for satisfying an isochronous condition. For comparison to the geometric analysis applied to the region between the first and second acceleration gaps, the offset $h\theta_E$ was added to the simulated phase difference data. The simulation results were consistent with the correlations based on the geometric analysis model. There was no phase bunching for h = 1. The initial particle phase width of 40 RF degrees for h = 2 with phase bunching was compressed to less than 10 RF degrees. The initial particle phase width for h = 3 was compressed to 22 RF degrees by phase bunching.

MEASUREMENT RESULTS

In order to verify phase bunching, RF phase distributions of accelerating particles in the cyclotron were measured by a fast plastic scintillator mounted at the head of a radial probe. The beam phase width under the injection beam condition without an external buncher and a phase slit was 26.5 RF degrees full width at half maximum (FWHM) for 45 MeV H^+ (h = 1) and 10.2 RF degrees FWHM for 260 MeV $^{20}Ne^{7+}$ (h = 2). The transmissions from the Faraday cup before injection to the radial probe before extraction were 0.152 and 0.137, respectively. Although these transmission difference was only 1.5 %, the beam phase width for h = 2 was reduced to less than a half of the phase width for h = 1. Therefore, the practical phase bunching was demonstrated by the measurement of the beam phase width in the JAEA AVF cyclotron.

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