FIRST BEAM TEST RESULT OF RFQ ELECTRIC TUNE CONTROLLER AT HIMAC SYNCHROTRON

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Abstract

An equation of motion reduced to Mathieu's Equation was obtained by means of radio-frequency quadrupole(RFQ) electric field applied to the beam circulating in a synchrotron. An analytical solution newly developed [1] is a fairly good approximation to give the characteristic exponent for both a stable region and an unstable region depending on both the frequency and the field strength in a resonant manner. A betatron tune shift in a stable region is expected to compensate the space charge effect of a high-intensity beam. The performance in an unstable region would be adopted to the slow extraction because the beam is kicked-out from a separatrix. Performance test of RFQ device installed at HIMAC synchrotron [2] is being carried out both to control a vertical tune value at the injection energy and to extract beam using the transverse RFQ electric field resonated with a horizontal betatron tune.

1 PRINCIPLE OF RFQ PERTURBATION

When RFQ electric field is applied to the beam in a synchrotron, an equation of motion is reduced to Mathieu's Equation:

$$\frac{d^2y}{dz^2}+a\left\{1-\frac{2q}{a}\cos(2z)\right\}y=0$$

Where, (1)

$$\begin{cases} E_x(s,x,t)=G_0\frac{l}{L}x\cos(K\phi+\Phi_k) \\ y=\frac{x}{\sqrt{\beta_0}} \\ a=\frac{4}{K^2}\nu_0^2 \\ -\frac{2q}{a}=\frac{q_e}{m_0\gamma v^2}G_0\beta_0^2\frac{l}{L} \end{cases} ;\begin{cases} 2z=K\phi+\Phi_k \\ \phi=\frac{1}{\nu_0}\int_0^s\frac{ds}{\beta_0} \end{cases}$$

Here, K is a factor of phase ϕ of an electric field E_x, G_0 is a field gradient, l is an RFQ electrode length, L is a circumference of the ring, and ν_0 is a betatron tune which depends on beta function.

Taking conjugate momentum p to solve the Mathieu's equation, we transform y and p into r and θ, that means transformation into polar coordinates on the phase space. Thus, Q is expressed as a resultant frequency of oscillation.

Neglecting rapidly oscillating components which are averaged to zero, an approximate solution which gives a relation between parameters q, a and Q in stable region is obtained as given by:

$$-\frac{2q}{a}=4\frac{\sqrt{\left(\sqrt{a}-1\right)^2-(Q-1)^2}}{\sqrt{a}} \quad (2)$$

Where, $Q=2-\nu$, ν is a characteristic index number.

An expression in unstable region is also obtained as given by:

$$-\frac{2q}{a}=4\frac{\sqrt{\left(\sqrt{a}-1\right)^2-\left(\frac{1}{\pi}\ln S\right)^2}}{\sqrt{a}} \quad (3)$$

Where, $S=e^{i\nu\pi}$, ν is an imaginary number.

As a relation between rf voltage of RFQ and the parameters of analytical solution $-2q/a$ or a, $-2q/a$ is proportional to field gradient of RFQ G_0, on the basis of eq.(4), a relates to frequency of RFQ rf voltage f_{rfq} and revolution frequency f_{rev}.

$$f_{rfq}=f_{rev}\left(2\nu_0/\sqrt{a}-m\right) \quad ;m=0,\pm1,\pm2,\Lambda \quad (4)$$

The eq. (4) is derived from the relation between parameters in the eq. (1). From analytical solution in stable region of eq. (2), as a result, the original tune ν_0 is shifted to the resultant tune ν_r by tuning of both amplitude and frequency of rf voltage.

$$\nu_0\Rightarrow\nu_r=\frac{Q}{\sqrt{a}}\nu_0 \quad (5)$$

2 BEAM TEST AT HIMAC SYNCHROTRON

2.1 Application to tune controller

RFQ is designed to manipulate a vertical tune at the injection energy because a space charge effect is larger to vertical direction rather than horizontal one. It is derived from the relation of parameters in eq. (1) that tune shift caused by RFQ electric field depends on square of the beta function at RFQ device, RFQ device has been installed at the position of HIMAC synchrotron where vertical beta function is large. Therefore it is effective that we made experiment on application of RFQ to vertical tune controller under the condition that is given by: beam; $^{4}He^{2+}$ 6.1[MeV/u], revolution frequency f_{rev}; 0.2614[MHz], vertical (original) tune ν_0; 3.150.

By measurement of betatron sideband which the frequency spectrum contain, to which real-time spectrum analyser transfer the signal from position monitor, the variation of vertical tune value was measured at several frequencies in the range of f_{rfq}/f_{rev}=2.0~2.5. The dependence on rf voltage was also measured at each frequency by varying an rf power up to 1[kW]. As a consequence of this measurement, all the experimental data has the same tendency that vertical tune value increases from the original tune. We have found immediately that the beam intensity varies at every measuring time depending on frequency and voltage of RFQ. When the RFQ is turned-on, the unexpected beam loss occurs at all the measurements carried out so far. Thus we must correct the experimental data by the dependence of original tune value on the beam intensity for accurate investigation of performance of RFQ. Fig.1 shows an observation of tune value depending on beam intensity.

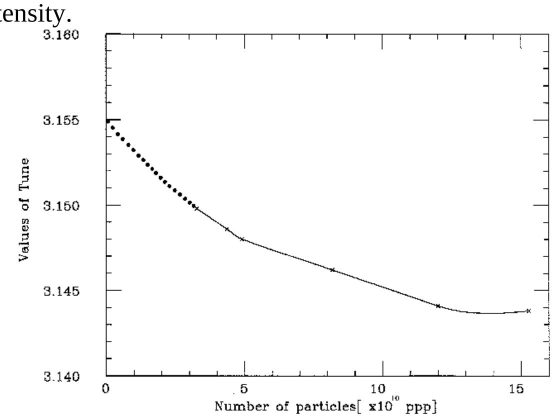

Figure 1: Dependence of original tune value on the beam intensity. As RFQ is turn-off, tune was measured in the process beam intensity is on a decrease. The tune was defined as original tune at several beam intensity.

Fig. 2 shows the comparison of tune shift between analytical expression and experimental data corrected by the dependence of original tune value on the beam intensity. The tune shift value was defined as a difference between shifted tune by RFQ and corrected original tune.

Except the data near the unstable region (about f_{rfq}/f_{rev}=2.28~2.32), the tendency -there is the distinguishable regions between where observed tune increase and decrease from original tune separated by center of unstable region (f_{rfq}/f_{rev}=2.3) - is comparable to that of analytical solution.

The reason why the tune shift value near the unstable region is smaller than expected one is that, the correction of original tune contains some errors because it was difficult to measure the dependence of original tune on beam intensity near the unstable region where the beam intensity is rather small.

Recently we experiment for investigation of the dependence of tune on low intensity of beam, a result was obtained that at lower intensity of beam, the dependence of tune is more sensitive to beam intensity. However this experimental condition is different from the data shown in Fig.1, the observed tune shift even near the unstable region is capable of being more comparable to that of analytical solution.

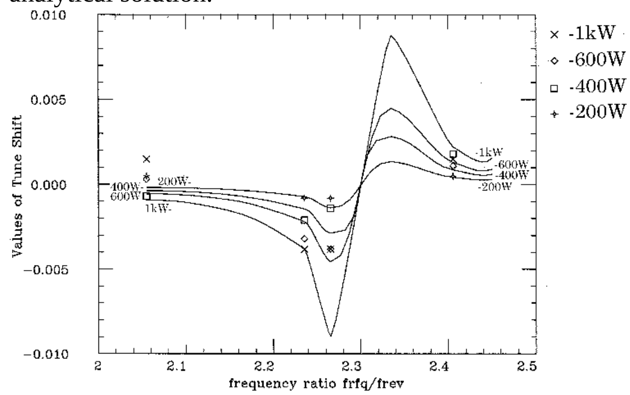

Figure 2: Comparison of tune shift between analytical expression (solid lines) and experimental data (plots) corrected by the beam intensity-dependence of original tune.

2.2 Application to slow extraction

As one of the beam extraction methods, beam extraction using a transverse rf dipole field resonated with a horizontal betatron tune (rf knockout slow extraction; abbreviated RF-KO-SE) has been investigated at HIMAC [3]. This attempt has resulted in success in the small emittance of extracted beam and the fast response of the extracted beam intensity to the applied transverse rf electric field.

We expect that it is capable of the applying of RFQ to slow extraction because the instability of beam is realized by resonance with a horizontal tune due to RFQ with an appropriate both amplitude and frequency of rf voltage. We made experiment on application of RFQ to slow extraction under the condition which is given by: beam; $^{12}C^{6+}$ 290[MeV/u], revolution frequency f_{rev}; 1.49787[MHz], horizontal tune ν_{x0}; 3.682, rf power; 100[W] (this is equivalent $-2q/a=3.292*10^{-6}$).

The condition of both rf frequency f_{rfq} of 0.545[MHz] and rf power of 100[W] belongs to unstable region as analytical solution, under this condition the circulating beam in synchrotron is unstabilized by RFQ electric field. Therefor under this condition, the dependence of the intensity of extracted beam on the rf frequency near 0.545[MHz] was measured. As a result, rf frequency of 0.544[MHz] maximized the extracted beam intensity. The intensity of the extracted beam was measured by using summing the output in each channel of a multi-wire proportional chamber type profile monitor. Fig. 3 shows the spill of the extracted beam at rf frequency of 0.544[MHz] and rf power of 100[W]. The spill of the extracted beam was monitored by a ripple monitor comprising a plastic scintillator with thickness of 0.2[mm] and a secondary electron ripple monitor [4]. On both Fig.3 and following Fig.4, these are shown that, from the bottom, beam spill by using secondary electron ripple monitor, beam spill by using scintillator ripple monitor, intensity of circulating beam and current of the sextupole magnet for separatrix production. As a noteworthy feature, although the intensity of extracted beam is lower than in the following case of using frequency modulated rf voltage, the ripple of extracted beam is small.

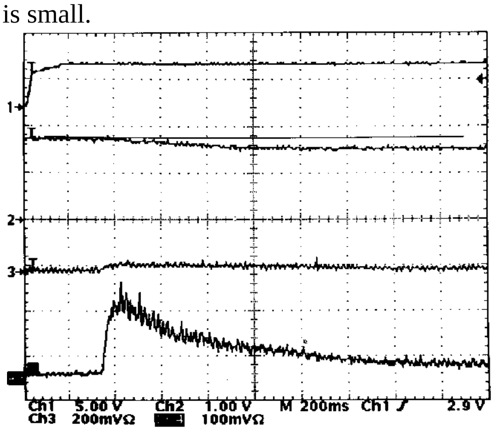

Figure 3: Extracted beam spill by the RFQ slow extraction.

As the adaptation for the spread of horizontal tune due to sextupole magnet for separatrix production, the frequency of rf voltage of RFQ was modulated by a saw-tooth wave, the dependence of extracted beam intensity on frequency band width as center frequency of 0.544[MHz] was measured. As the result, frequency band width of 26[kHz] maximized the extracted beam intensity. Fig. 4 shows the spill of the extracted beam at frequency band width of 26[kHz] as center frequency of 0.544[MHz] and rf power of 100[W]. In consequence of using modulated frequency, about 3.5 times the intense extracted beam of using not modulated frequency was obtained.

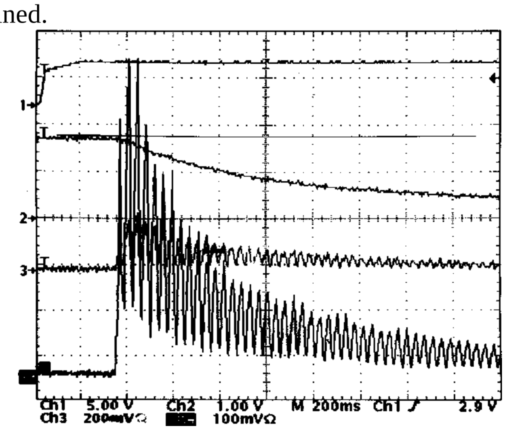

Figure 4: Extracted beam spill by the RFQ slow extraction with frequency modulated. Fig.3 and Fig.4 are same scale of axial.

As seen from Fig.3 and Fig.4, both beam spills exponentially decrease with time constant of 769[ms] or 714[ms], provided that the valuation of dependence about Fig.4 the points which were local maximums of beam spill referred. This time constant value is comparatively large with the span of flat top for extraction. To improve a control of extraction, explaining on what the value depends is necessary.

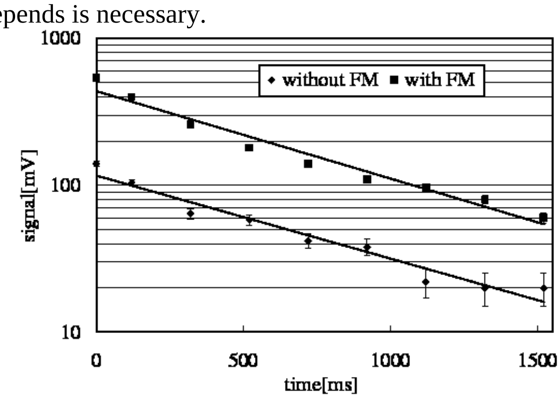

Figure 5: Dependence of the extracted beam spill on the passed time. Both spills exponentially decrease with time constant of about 740[ms].

3 CONCLUSION

Performance test of RFQ device installed at HIMAC synchrotron is being carried out both to control a vertical tune and to extract beam. The observation for tune control shows a tune shift, which is comparable to that of the approximate solution. However, as the application to tune controller, because the unexpected beam loss still occurs even now in most cases when the RFQ is turn-on, a further investigation is necessary. On the other hand, for the application to slow extraction, fundamental investigations, which contain an expounding of the process of extraction, are necessary.

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