Slow beam extraction by RFQ electric field

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1.Introdaction

The circulating beam in a synchrotron ring oscillate on transverse surface by beam axis, called betatron oscillation (this frequency is called betatron tune), and stably circulate in the ring. To extract that beam from the ring, nonlinear force or sextupole magnetic field is applied to the beam. This method is called third resonance slow extraction. Thus, on the phase space of transverse motion of the beam, three boundaries, called separatrix, are built up. In the surrounded area by the separatrix, beam can circulate in the ring stably, but out of the area, betatron oscillation become resonantly unstable. Since this surrounded area is related to the tune or strength of sextupole magnetic field, a regulation of the either parameter makes the area contracted. Then beam is moved to out of separatrix, and extracted from ring. For this method, it has substituted in advance of the world at HIMAC synchrotron [1] that a fixed strength of sextupole magnetic field and a transverse rf dipole field resonated with a horizontal betatron tune is applied the beam for extraction (abbreviated RF-KO-SE) [2]. We are of the opinion that rf quadrupole (RFQ) electric field is applicable to extraction in place of this rf dipole field. Because, we have studied that the beam become unstable by RFQ field resonated with a tune [3][4]. And more over, as RFQ field device generates rf dipole field components which is due to a difference between beam and device axis, it is able to investigate that a comparison the RFQ with dipole field under the identical beam condition.

Then, we extracted beam using RFQ device, and had a chain of experiments to explain the process of extraction. In the result, the high quality beam, which has small ripple and long time constant, was acquired using mono frequency RFQ or dipole field. And it became known that on the extraction process using mono frequency resonated with a tune, the particles which are not only the tune but also the range from that to smaller tune have extracted, and it have no difference between using RFQ and dipole field.

2.Principle of slow extraction

When sextupole magnetic field is applied to the beam in a synchrotron, an equation of motion as given by:

$$\frac{d^2\eta}{d\phi^2}+\nu^2\eta=\nu S\eta^2\cos(N\phi)\ ,\ \begin{cases}\eta=x/\sqrt{\beta}\\ \phi=\frac{1}{\nu}\int_0^s\frac{ds}{\beta}\end{cases}$$

S is a strength parameter of sextupole magnetic field, ν is a betatron tune which depends on beta function β. Taking conjugate momentum $p=\frac{1}{\nu}\frac{d\eta}{d\phi}$, we transform η and *p* into *r* and θ as given by $\eta=r\cos(Q\phi\text{-}\theta)$ and $p=-r\cos(Q\phi\text{-}\theta)$.Where *Q* is resultant frequency of oscillation. Neglecting rapidly oscillating components, approximately a solution for separatrix as given by: $r^3\cos(3\theta)-\frac{3}{2}r_0r^2=-\frac{1}{2}r_0^3,\ \left(r_0=\frac{8(\nu-N/3)}{S}\right)$. Then the surrounded area by this separatrix is given by:

$$\frac{3\sqrt{3}}{4}\left(\frac{8(\nu-N/3)}{S}\right)^2$$

Since in this area beam can circulate in the ring stably with tune spread and out of this area can not, in the ordinary slow extraction method an increasing the strength of sextupole magnetic field *S* or a control of tune during extraction lead to shrink this area. Thus beam is moved to out of area and extracted. For this method, in the RF-KO-SE a fixed strength of sextupole magnetic field and a rf dipole field resonated with tune is applied.

$$\frac{d^2\eta}{d\phi^2}+\nu^2\eta=\nu S\eta^2\cos(N\phi)+\nu g\cos\left(\frac{f_{RFD}}{f_{rev}}\phi+\phi_0\right)\cos(m\phi)$$

In this equation of motion, *g* is strength of rf dipole field, f_{rev} is a revolution frequency of beam. When the frequency of rf dipole field satisfy $f_{RFD}=|\nu\pm m|\times f_{rev}$ (m=1,2,3…), resonantly beam is extracted. On the other hand, in the extraction using RFQ field an equation of motion is given by:

$$\frac{d^2\eta}{d\phi^2}+\nu^2\eta=\nu S\eta^2\cos(N\phi)+\nu g\eta\cos\left(\frac{f_{RFQ}}{f_{rev}}\phi+\phi_0\right)\cos(m\phi)$$

The force due to RFQ field is in proportion to η. When resonant frequency in this case satisfy $f_{RFQ}=|2\nu\pm m|\times f_{rev}$ (m=1,2,3…) in which a factor of ν is differ from resonant frequency of dipole field. When there is a difference between beam and RFQ device axis, it generates rf dipole components. Then beam is extracted by the resonant frequency, which satisfy preceding equation in the case of RF-KO-SE.

3.Experimental results and discussion

We installed RFQ device in HIMAC synchrotron ring, had a chain of experiments for extraction. Figure 1 shows the typical time structure of extracted beam (C^{6+}, 290[MeV/u], f_{rev} =1.49787[MHz]) to which a fixed strength of sextupole magnetic field and a RFQ field resonated with tune was applied.

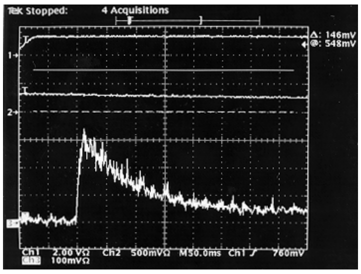

fig.1. Time structure of extracted beam. From bottom, beam spill, the intensity of the circulating beam and the current for sextupole magnet. The time scale is 50[msec/div]

The intensity of the extracted beam decays exponentially, and which had a time constant 150[msec]. Well, since the sextupole field spreads the tune, the spread of tune was measured by using the method of pick up the signal from beam position monitor. And then the extraction efficiency was measured with a changing the resonant frequency of RFQ field. In this result, there are the particles of tune that is not able to be made extracted, and at some resonant frequency the extraction efficiency exceeded the percentage of the single tune particles which is related to that resonant frequency. So it became clear that a certain range of tune was an object of extraction with mono frequency. Then the range from that to smaller tune was identified with this certain range. Figure 2 shows the comparison between extraction efficiency and integral value from inferior limit of tune spread. Both value are consistent in this fig.2, thus it turned out that the particles which are not only the tune but also the range from that to inferior limit of tune spread is extracted. Now It become known from figure 3, which shows the comparison of extraction efficiency by between using RFQ and dipole component, that there was no difference.

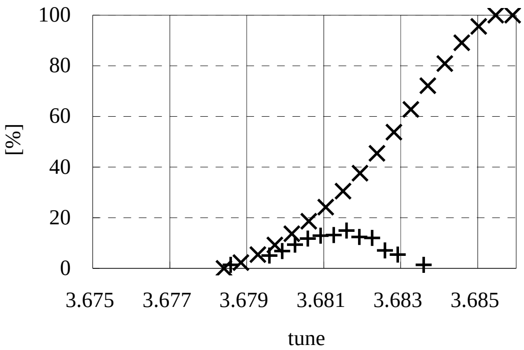

fig.2. Comparison between extraction efficiency and integral value. + means extraction efficiency, × means percentage of tune (integral value from inferior limit)

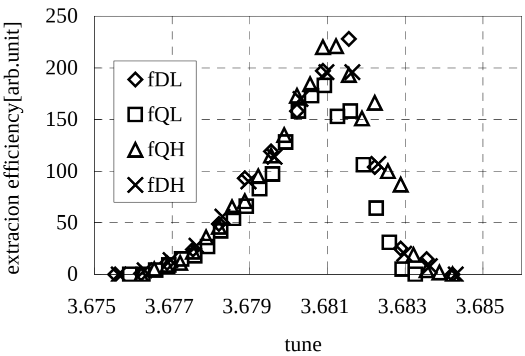

fig.3. Comparison of extraction efficiency by between using RFQ (fQL,fQH) and dipole component (fDL,fDH)

4.Conclusion

The beam is extracted by using either RFQ or rf dipole component field resonated with tune. Then we found that the high quality beam, which have small ripple and long time constant, is extracted. And from comparison between extraction efficiency and tune spread, it become known that this extraction process is not the forced oscillation effect which has a certain resonance. However, the investigations for explanation of dynamics with effect of sextupole field are necessary.

References

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