An Experimental Study of Slow Extraction by Kicks of Rf Quadrupole and Rf Dipole Electric Fields

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Abstract

An RFQ electric device was installed at HIMAC synchrotron in order to investigate beam physics of slow extraction process cooperated with RFQ or rf dipole electric fields. During beam experiments in a mono-frequency operation of the RFQ electric device, we encountered a unique result of a new fact. Beam spill shows a very low ripple together with a long time constant of 150 ms minimum in an exponential decay with time although a total amount of the extracted beam is 15 % maximum which is a part of the circulating beam. A beam performance for an rf dipole electric field results in the same as that for the RFQ electric field.

Observations show that a tune distribution of the extracted beam is a part which is a lower side of a tune distribution of the circulating beam. This fact implies that the operating frequency of rf electric fields is an important factor for the extraction; so that an amplitude of rf voltages is considered to be a secondary factor because the extraction efficiency saturates with the amplitude although the time constant becomes short with the amplitude gradually.

There seems to be no theoretical explanation for particle motions for the present findings. But the extraction process seems to relate with chaotic particle motions due to non-linear forces because of the existence of stochastic areas around separatix.

1 Introduction

When an rf quadrupole(RFQ) electric field is applied to the beam circulating in a synchrotron, an equation of motion is reduced to Mathieu's equation. We developed an analytical solution of the equation approximately[1] and the solution was translated to provide a betatron tune shift in a resonant manner depending on both of the frequency and the amplitude of RFQ voltage. The strictest resonance occurs independently of the amplitude in a relation

$$f_{RFQ} = |2\nu \pm m| \times f_{rev} \quad (m = 1, 2, 3, \cdots) \qquad (1)$$

where f_{rev} is a revolution frequency of the beam, f_{RFQ} a frequnecy of RFQ electric field, ν a betatron tune, and m an adequate integer.

We installed an RFQ electric device in HIMAC synchrotron and carried out beam experiments for a fast tune control. A tune shift was observed surely as expected but a considerable amount of beam loss was observed at the same time as an undesirable performance. As for particle motion, a large tune shift might result in a large growth of betatron oscillation because a large tune shift results in a large beam loss in experiments.

A slow extraction by a kick due to an rf dipole electric field has been developed at HIMAC synchrotrons of National Institute of Radiological Sciences(NIRS) successfully. This unique method[2], which is abbreviated to RF-KO-SE, utilizes a transverse rf electric field resonating to horizontal betatron tune under the condition that a sextupole magnetic field forms a separatrix due to the 3rd integer resonance.

In a sense, the extraction process is considered to be a kind of the beam loss process. Because of the observed beam loss, the RFQ electric field resonating to horizonatl betatron tune is expected to be applicable to the slow extraction in the same way as the rf dipole electric field of the RF-KO-SE method.

On the other hand, an RFQ electric device can generate an rf dipole electric field for the off-axis beam effectively. When the device is operated at a resonant freqeuncy for the rf dipole field, the RFQ field is generated at the frequency actually but does not affect particle motions because of off-resonance although the rf dipole field affects motion of the off-axis particles because of resonance. This resonance for the rf dipole electric field occurs in a relation

$$f_{RFD} = |\nu \pm m| \times f_{rev} \quad (m = 1, 2, 3, \cdots) \qquad (2)$$

where f_{RFD} is a frequency of rf dipole electric fields and others are the same as those for the RFQ electric fields. In order to compare the beam perfomances between RFQ and rf dipole electric fields, the RFQ electric device is useful because of quick change of operation mode due to simple frequency change.

A purpose of the present study is to investigate beam physics of a fundamental process of slow extraction by kicks due to RFQ and rf dipole electric fields. Although the RF-KO-SE method is being used extensively in daily operation, we do not know yet what really happens by kicks due to rf electric fields.

Preceding to beam experiments, we started a theoretical investigation of the slow extraction process by kicks of rf electric fields. A strength of a sextupole magnetic field is fixed at a given value during extraction period and an rf electric field is added. An equation of motion is a non-linear differential equation and thus is solved approximately in a similar way to the ordinary slow extraction. A solution showed a shrinkage of a size of a stable phase space area surrouded by separatrix but did not show a resonance characteristics which corresponds to a solution of Mathieu's equation. The reason of this solution of a non-resonant type seems to be because a non-linear force is stronger than an rf electric force at a large amplitude in betatron oscillation; so that the frequency is not an important factor for the extraction. As a result, it is very difficult to explain the experimental result quantitatively because a shrinkage is too small. Therefore, we abandoned this theoretical approach so as to need another approach.

2 Experimental Results

Beam experiments of slow extraction by a kick due to the RFQ electric field were started at a mono-frequency around a resonant frequency although a daily operation of the RF-KO-SE method at HIMAC synchrotron is being carried out by a kick due to the rf dipole electric field at a so-called colored rf noise which is a band-limited rf noise around a resonant frequency.

During the beam experiments due to the RFQ voltage at a mono-frequency, we encountered a unique result of a new fact as shown in Fig. 1 which is a typical time structure of the extracted beam. It is worthy of notice that a beam spill shows a very low ripple together with a long time constant in an exponetial decay with time.

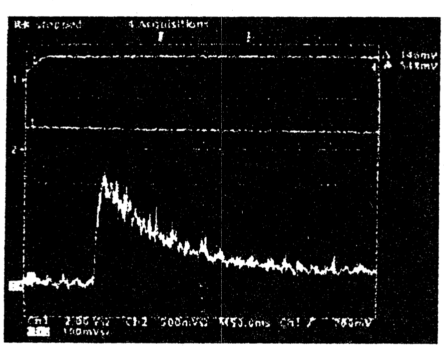

Figure 1: Typical time structure of the extracted beam. The lower shows a beam spill of a very low ripple and a long time constant, the middle the intensity of the circulating beam, and the upper the coil current of sextupole magnet for slow extraction.

In order to investigate the effect of the frequency and the amplitude of the RFQ voltage at a mono-frequency, various combinations of them were tested around a resonant frequency. The frequency can be reduced to a betatron tune value on the basis of Equation (1) equivalently and the dependence of the extraction efficiency on a tune value are then shown in Fig. 2 by plus marks.

On the other hand, a tune distribution of the circulating beam was observed by a spectrum analyzer from a position signal of the beam circulating in the synchrotron ring. The distribution is then integrated with a tune value numerically from the lowest tune value to the highest. A ratio of the extracted beam intensity at a tune value to the integrated intensity is then plotted in Fig. 2 by cross marks.

It is apparent from Fig. 2 that a part of the circulating beam which is a lower side of the tune distribution is extracted in comparison between the extraction efficiency and the integrated distribution.

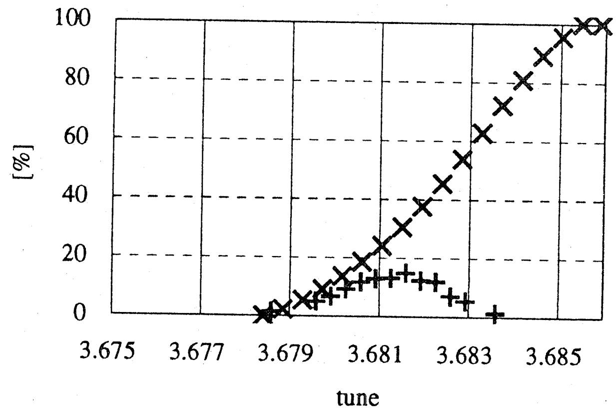

Figure 2: Comparison of experimental data for the tune value between the extraction efficiency and the integrated distribution of the circulating beam.

The amplitude dependence of the extraction efficiency and the time constant are shown in Figs. 3 and 4, respectively. The observation showed that the efficiency seemed to saturate with the amplitude although the time constant becomes short with the amplitude gradually.

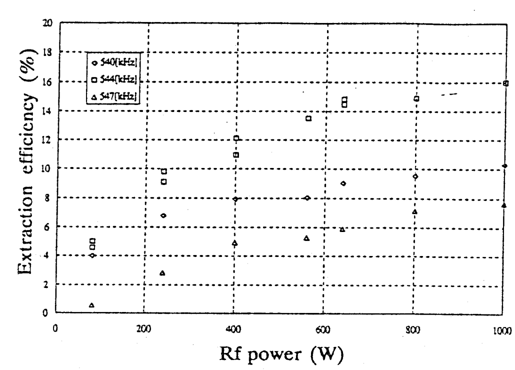

Figure 3: Amplitude dependence of the extraction efficiency.

In order to confirm the fact described above, we carried out beam experiments at RFQ and rf dipole electric fields at different frequencies.

Based on Equations (1) and (2), the RFQ electric device can be operated at a different mono-frequency corresponding to the same tune value to kick the circulating beam. We set the higher side band frequency, fQH, although the lower side band frequency, fQL, was chosen for Fig. 1. Similarly we set a frequency of the RFQ electric device at a mono-frequency of lower and higher side band frequencies, fDL and fDH, respectively, around a resonant frequency for rf dipole electric field for a given

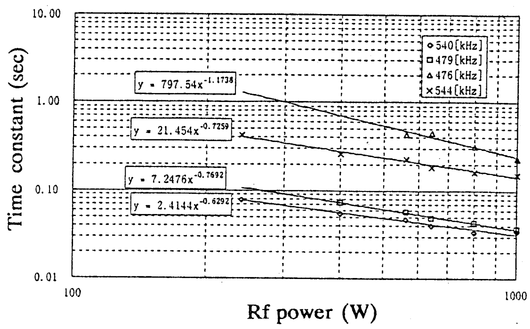

Figure 4: Amplitude dependence of the time constant.

tune value. Observations of the extraction efficiency were summarized in Fig. 5. It is seen from the figure that both RFQ and rf dipole electric fields give the same effect for slow extraction.

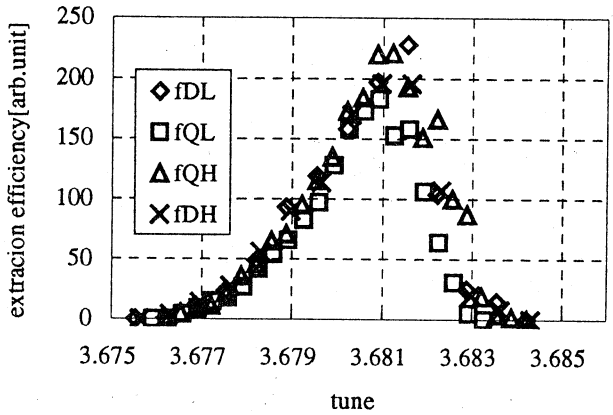

Figure 5: Comparison of the tune dependence of the extraction efficiency between RFQ (fQL and fQH) and rf dipole(fDL and fDH) electric fields.

The present unique results are summarized from the experimental data shown in the figures quantitatively as follows; a beam spill shows a very low ripple together with a long time constant of 150 ms minimum and the extraction efficiency of 15 % maximum.

3 Discussion

The present unique results are summarized qualitatively as follows. A tune distribution of the extracted beam by kicks due to RFQ and rf dipole electric fields is a part which is a lower side of the tune distribution of the circulating beam. The operating frequencies of rf electric fields is an important factor to dominate an extraction efficiency although the amplitude of rf electric fields is considered to be a secondary factor for the extraction efficieny because the extraction efficiency seems to saturate with the amplitude although the time constant becomes short with the amplitude gradually.

Because a usual formalism of slow extraction process due to shrinkage of a stable area in a phase space may provide the amplitude dependence of the extraction efficiency which does not saturate with the amplitude, it is difficult to explain the experimental results.

In this respect, a new aspect of slow extraction process due to rf electric fields is required. A candidate for such a process seems to relate to chaotic particle motions near a stochastic area around a separatrix which is generated by non-linear forces. In addition, such a stochastic area may disappear by kicks due to rf electric fields although the very stable area inside the separatrix remains despite rf electric fields being operated around the resonant frequencies.

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References

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