

Energy Varying Resonant Beam Extraction from the Synchrotron

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Abstract

Two different operating schemes for the energy varying beam extraction from the synchrotron are presented based on the resonant extraction scheme in which the transverse RF perturbation is applied for increasing the amplitude of the betatron oscillations with keeping the separatrix of the resonance constant. The first operating scheme is that the primary acceleration is followed by the second acceleration, during which the beam is extracted by the above extraction scheme. In order to keep the separatrix constant during the extraction, the currents of the magnets are ramped with keeping the mutual ratio. In the other operating scheme, the currents of the magnets are ramped from the injection energy level to the maximum level and the beam is extracted with a constant energy at an intermediate stage. The ramping pattern can be commonly used for the beam extraction at the different energy level.

1. INTRODUCTION

A high energy ion beam has been considered to be very effective for the cancer therapy because it shows a relatively sharp Bragg peak in the patient body. Presently, sixteen dedicated ion accelerators is being operated worldwide[1].

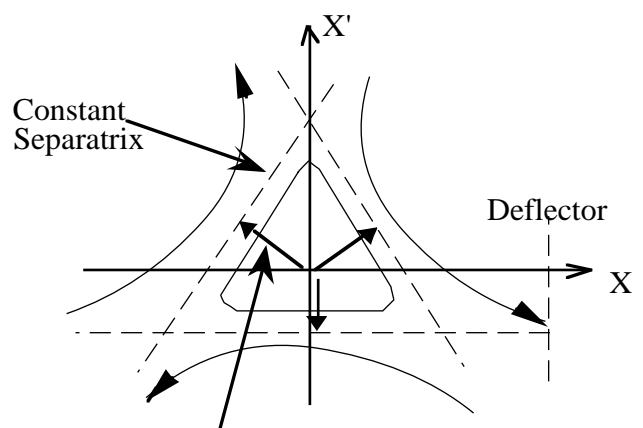
The depth of the Bragg peak depends on the energy of the ion beam. Accordingly, it is necessary to change the beam energy and its width when irradiating the different depth of the patient or treating the different patient. In most of the current ion accelerator systems for the cancer treatments, the beam is extracted at a fixed energy from the particle accelerator and, the beam energy and its width are controlled by the degrader and ridge filter installed at the end of the beam transport system. However, it has been pointed out that the degrader and ridge filter cause the beam loss of more than about 50% [2]. One of the reason why the degrader and ridge filter are applied is considered that practically it has not been so easy to change flexibly the extraction beam energy at the accelerator.

The synchrotron has a capability for accelerating and extracting the beam at several energy levels below the possible maximum beam energy. Then, for example, in GSI it is planned to use the energy variation of the synchrotron from pulse to pulse for the medical application[3]. For the energy variation, generally, it is necessary to prepare the several different and complex operating patterns of the magnets during the acceleration and extraction. Especially, in the conventional slow beam extraction scheme, the different current patterns of the several magnets are needed for each

extraction energy. In order to simplify the operation of the extraction, we have presented a new beam extraction scheme[4]- [7] in which the separatrix of the resonance is kept constant for an extraction energy by maintaining the constant magnet currents and the transverse RF perturbation is applied to the beam. Since the magnet currents are kept constant, the operation is quite simple. This extraction scheme has also other features that the low emittance beam can be extracted and the extracted current is not affected significantly by the ripple of the magnet current in the synchrotron. Then, by using the above extraction scheme, we present new operating schemes for varying the beam energy during an extraction operation or for each repetitive extraction.

2. BASIC RESONANT EXTRACTION SCHEME

For energy varying extraction, we apply the resonant extraction scheme in which the separatrix of the resonance of the betatron oscillations is kept constant and the transverse RF perturbation is applied to the beam to make the amplitude of the betatron oscillations increase and finally reach the separatrix.



Amplitude Growth of the Betatron Oscillations by the Transverse RF Perturbation

Fig.1 Phase Space of the Present Extraction Scheme

The phase space of the beam by the present extraction scheme is shown schematically in Fig. 1. When the particles reach the separatrix because of the transverse RF perturbation, the nonlinear resonance occurs and those particles are extracted from the deflector. Since the separatrix of the resonance of the betatron oscillations is kept constant, the orbit gradients of the

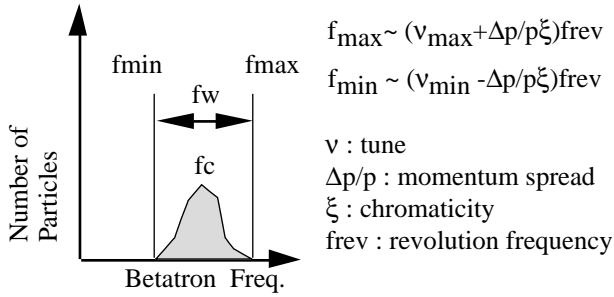


Fig.2(a) Frequency Spread of the Betatron Oscillations

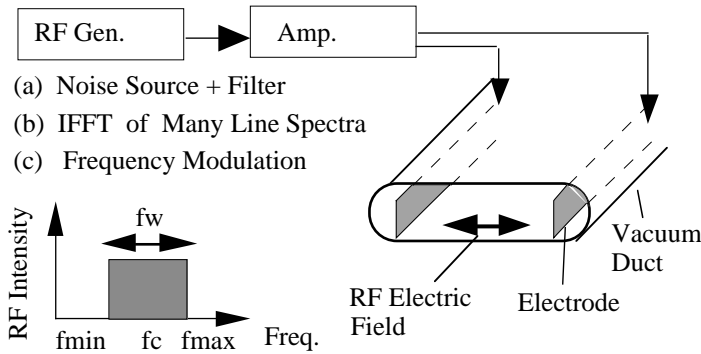


Fig.2(b) Transverse RF Perturbation applied to the Beam

extracted particles at the deflector position are kept almost constant. Therefore, the time integrated emittance can be reduced significantly.

Generally, the betatron tune varies with the betatron amplitude under the nonlinear magnetic field and the momentum of the particles because of the chromaticity. Then, the tune spectrum of the beam at the resonant extraction spreads, as shown in Fig.2(a). Therefore, in order to increase the amplitude of the betatron oscillations, it is effective to apply the transverse RF perturbation having a band width covering the spread betatron frequencies, as shown in Fig.2(b). The following methods can be applied to make the RF perturbation have an adequate central frequency f_c and frequency width f_w .

- (a) Filtering a random noise
- (b) Inverse Fourier transformation of many line frequency spectra with different random phases
- (c) Frequency modulation

The extraction using the above RF perturbation (c) has been already studied experimentally in HIMAC and the feature of the low emittance extraction has been confirmed[6].

Since the separatrix of the nonlinear resonance is determined by the magnet currents, these currents are kept constant during the extraction for a fixed energy. Furthermore, even in the case of changing the extraction energy, it is not necessary to alternate the ratio of the several magnet currents.

The intermittent structure of the extracted current can be also improved significantly even under the condition that the magnet current includes a low frequency ripple[6][7]. In the conventional extraction varying the separatrix size, the number of the extracted particles per unit time is expressed as NV where $N(1/\text{mm}\cdot\text{mrad})$ is the number of particles on the unit area near the separatrix and $V(\text{mm}\cdot\text{mrad}/\text{s})$ the speed of varying separatrix size. Since V is small in this scheme, its value is modulated by the ripple of the magnet currents. This results in

the intermittent extraction. In the present extraction, the number of the extracted particles per unit time is expressed as NV_{rf} where $V_{rf}(\text{mm}\cdot\text{mrad}/\text{s})$ is the outgoing speed of the particles on the separatrix. Since the value of N is small, a relatively large value of V_{rf} is needed to obtain a sufficient flux. As a result, the separatrix change due to the magnet current ripple does not make the extraction flux vary significantly. Furthermore, it has been also pointed out that this extraction scheme can be applied to the breath synchronized irradiation in the cancer treatments because the fast switching of the extraction is possible due to the RF perturbation[6].

3. OPERATING SCHEMES FOR VARYING BEAM EXTRACTION ENERGY

In order to make it simple to change the beam extraction energy, we present following two different schemes which employ the above resonant extraction scheme using the transverse RF perturbation under the constant separatrix.

(1) Energy Varying Extraction during One Pulse Operation

The operating patterns of the beam momentum and the magnet currents are schematically shown in Fig. 3. These operating patterns consist of the primary and secondary accelerations. Ψ_i and Ψ_{ei} ($i=1,2 \dots n$) shown in the figure

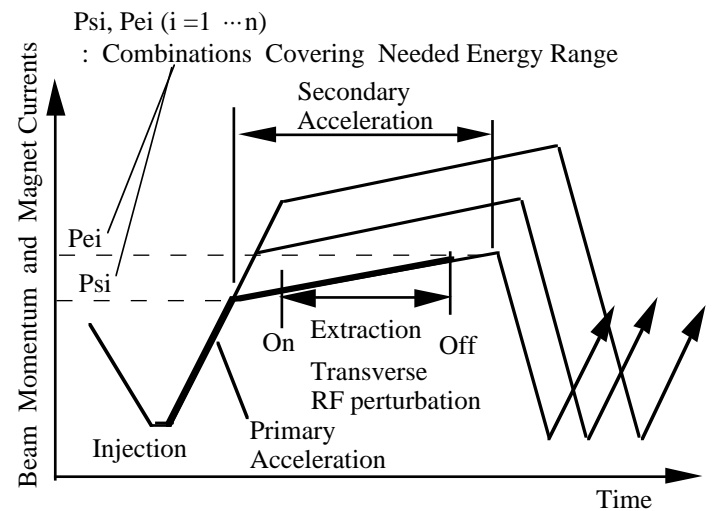


Fig. 3 Operating Pattern for Varying the Beam Energy during the Extraction

denote the beam momenta at the initiation and termination of the second acceleration. The beam extraction is done during the second acceleration. The separatrix of the resonance is generated by using the nonlinear magnet such as a sextupole magnet at the initiation of the second acceleration. If needed, the tune is varied after the primary acceleration by controlling the quadrupole magnets. The currents of the nonlinear magnets as the resonance exciter are increased with maintaining the ratio between the currents of the several magnets so as to keep the separatrix of the resonance constant during the second acceleration. It is necessary that the frequency spectrum of the transverse RF perturbation covers the spread frequency width due to the nonlinearity of the betatron oscillations and the momentum spread. On the other hand, it is

desirable that the transverse RF perturbation has a needed minimum frequency width because the needed RF power increases with the frequency width Δf . Since the frequency spectrum of the betatron oscillations varies with changing the beam energy, the central frequency f_c of the transverse RF perturbation should be shifted during the second acceleration with keeping a constant frequency width Δf . This can be realized easily by applying the recent RF or digital technique. If the energy changing width is narrow during the second acceleration, that is, the frequency spectra of the betatron oscillations does not vary significantly, it is possible that the transverse RF perturbation with a constant central frequency and wide frequency width is applied during the second acceleration.

The initiation and termination of the extraction can be controlled by turning on and off the RF perturbation. Accordingly, the momentum range of the extracted beam can be also selected between Ψ_i and Ψ_e . The combinations of the Ψ_i and Ψ_e ($i=1,2 \dots n$) are chosen between the minimum and maximum energy levels of the extraction. In the case of the medical use, generally, it may be useful to determine the combination of the Ψ_i and Ψ_e for each patient. On the other hand, if several combinations of the Ψ_i and Ψ_e ($i=1,2 \dots n$) covering the needed energy ranges are chosen and the machine tuning is performed in advance, it is possible to change the extraction beam energy more flexibly. Furthermore, the time of the machine tuning can be reduced by using the operating pattern of the primary acceleration commonly for the different combinations of the Ψ_i and Ψ_e ($i=1,2 \dots n$).

(2) Varying Energy Extraction per Pulse to Pulse Operation

In the following, the operating scheme for varying beam energy per pulse to pulse operation is presented. The operating patterns of the beam momentum and the magnet currents are

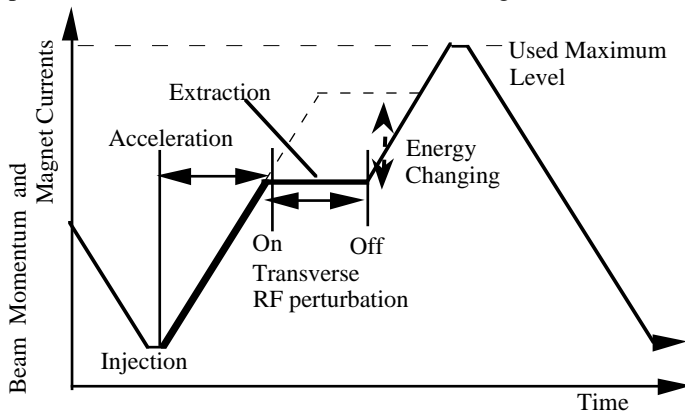


Fig. 4 Operating Pattern for Varying the Beam Energy per Pulse to Pulse Operation

schematically shown in Fig. 4. The beam is extracted at a constant energy after the acceleration. For the magnets used during the acceleration, the currents are also ramped up to the maximum beam energy level after the extraction. The operating patterns during the acceleration and after the extraction are used commonly when changing the extraction beam energy.

The extraction is initiated by turning on the transverse RF perturbation. In this operating scheme, in order to decrease the power of the transverse RF perturbation, it is also desirable that the transverse RF perturbation has a needed minimum

frequency width Δf and its central frequency f_c is alternated when changing the extraction energy. During the extraction, the separatrix for the resonance of the betatron oscillations is kept constant. As a result, the orbit gradient of the extracted beam is almost constant and the time averaged emittance can be very small. If the same separatrix size can be applied to the extraction at the different energy levels, the ratio between the currents of the magnets can be kept constant. Then, the machine tuning for changing the extraction energy becomes more flexible. Furthermore, this constant separatrix for the different extraction energy makes the energy dependence of the characteristics of the extracted beam vanish. As a result, the tuning of the electrostatic deflector and the magnets of the beam transport system can be significantly simplified.

4. CONCLUSIONS

In order to make it more flexible to change the beam extraction energy at the synchrotron for medical use, we presented the following different operating schemes using the resonant beam extraction scheme in which the transverse RF perturbation is applied for increasing the amplitude of the betatron oscillations while maintaining the constant separatrix.

In the first operating scheme, the primary acceleration is followed by the second acceleration. The separatrix of the resonance is kept constant by maintaining the ratio between the currents of the magnets during the second acceleration. Then, the beam is extracted by applying the transverse RF perturbation for reaching the betatron oscillations to the separatrix. The operating pattern of the primary acceleration is used commonly. By preparing about ten operating patterns for the second acceleration in advance, it is possible to select flexibly the extraction energy between the needed minimum and maximum energy.

In the other operating scheme, the beam is extracted with a constant energy after the acceleration. The magnet currents during the extraction are kept constant for the constant separatrix. After the extraction, the currents of the magnets for the acceleration are ramped to the maximum level. This ramping pattern before and after the extraction is used commonly for the extraction at the different energy levels.

5. REFERENCES

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