Resonant Beam Extraction with Constant Separatrix

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Abstract

A new scheme for slow beam extraction using nonlinear resonance is presented to realize small emittance. In the scheme, the amplitude of the betatron oscillations is increased by perturbations, while keeping the separatrix constant. As a measure of perturbation, the transverse filtered noise is studied in computer simulations. It is shown that the emittance of the extracted beam is vanishngly small. It is also shown that the time structure of the extracted current is not affected by the ripple in the magnet current.

I. INTRODUCTION

In a circular accelerator such as a synchrotron for physical experiments or medical use, a charged particle beam is slowly extracted by using nonlinear resonance of the betatron oscillations[1][2]. The separatrix of the nonlinear resonance of the betatron oscillations is defined as the boundary in the phase space between stable and unstable betatron oscillations. In order to excite the nonlinear resonance to the beam having not only large betatron amplitudes but also small ones, conventional slow extraction methods gradually make the separatrix shrink and finally vanish by varying the betatron tune, defined as the number of the betatron oscillations per one revolution. This tune change is realized by controlling the quadrupole magnets or the radio frequency of the acceleration.

Changing of the separatrix size generally varies the orbit gradient and turn separation of the extracted beam at the deflector position. As a result, it is expected that the position and size of the extracted beam change, that is, the emittance of the extracted beam becomes larger. Some countermeasures have been taken to keep the beam characteristics constant during the extraction[3][4]. These countermeasures, however, require rather complicated design and control. Then, we have proposed a new, simpler nonlinear resonant extraction scheme[5] in which the beam is ejected with a constant orbit gradient and turn separation by perturbing only the beam to increase the betatron amplitudes while maintainig steady operation of other components. In the paper, we showed that the tranverse filtered noise and monochromatic perturbation are potentially good measures of the increase in the betatron amplitudes.

Another concern in the slow beam extraction is preventing an intermittent time structure of the extracted beam current due to current ripple of the magnet power supply. In the present scheme using the transverse filtered noise, it is expected that the intermittent extraction can be prevented by the effect of random motion due to the applied noise[6]. Then, the time structure of the extracted current is evaluated for the scheme applying the filtered noise and compared with that by the conventional scheme.

II. EXTRACTION SCHEME

The present extraction scheme is characterized by keeping the separatrix constant for nonlinear resonance of the betatron oscillations and increasing the amplitude of the beatatron oscillations to excite the resonance (Fig.1). Since the separatrix is kept constant, the orbit gradient and turn separation at the deflector position are almost constant. Therefore, the emittance of the extracted beam can be reduced to a negligibly small value. The following methods can be used to increase the amplitude of the betatron oscillations:

(1) transverse perturbation by a high frequency electromagnetic field,
(2)longitudinal perturbation by a high frequency electromagnetic field, from the position of a non-zero dispersion function, and
(3) scattering of the beam by other neutral or charged particles.

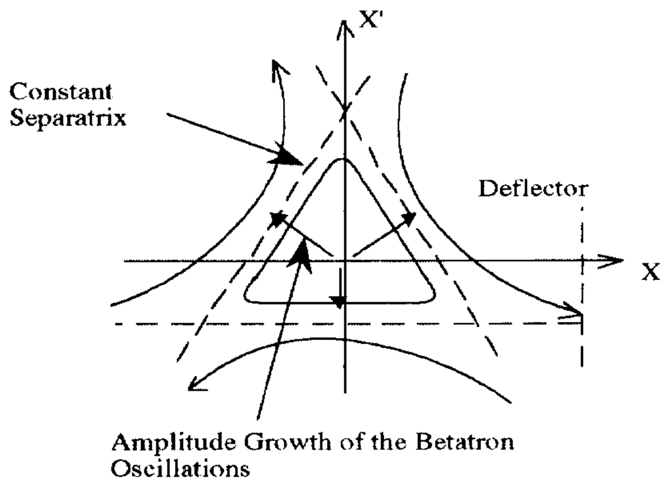

Fig.1 Phase Space of the Extraction Scheme with Constant Separatrix

Generally, the betatron tune varies with the betatron amplitude under the nonlinear magnetic field. Then, the tune spectrum of the beam at the resonant extraction spreads. Therefore, in order to eject the beam having the spread tune spectrum, it is effective for the transverse perturbation in method (1) to have wide band frequency components synchronous with the spread betatron tunes. A single frequency perurbation for the same purpose was also proposed[5][7].

The applied tranverse noise is expected to cause the circulating beam to diffuse in the transverse phase space. This diffusion makes the amplitude of the betatron oscillations increase slowly with relatively fast, but small fluctuations. Because of the fluctuations, the effect of the low frequency ripple of the magnet currents is expected to be overcome. This effect for longitudinal diffusion has been confirmed in the

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ultra slow extraction scheme developed in CERN[6]. In the following section, the wide band perturbation with filtered noise is studied through computer simulations.

III. COMPUTER SIMULATION METHOD

In the computer simulations, a coasting beam is assumed with the design momentum. The coasting beam is divided into N_s bins having an equal size along the circulating direction. It is assumed that the beam in each bin has an equal emittance and consists of N_p super particles. The initial particle distributions in the normalized phase space are assumed to be Gaussian with an rms value of σ for both X and X' directions. The emittance is defined as the phase space area including 3σ for both X and X'. The betatron oscillations and nonlinear resonance of the beam are analyzed in the normalized phase space with one degree of freedom. Thin lens approximations are applied to the treatments of the effects of the nonlinear magnetic field and the high frequency perturbation field:

$$\begin{pmatrix} X_{i,j,new} \\ X'_{i,j,new} \end{pmatrix} = \begin{pmatrix} \cos\phi, -\sin\phi \\ \sin\phi, \cos\phi \end{pmatrix} \begin{pmatrix} X_{i,j,old} \\ X'_{i,j,old} + f(X_{i,j,old}) \end{pmatrix} + \begin{pmatrix} C_1\delta_i \\ C_2\delta_i \end{pmatrix} \quad (1)$$

where X and X' are the position and orbit gradient normalized by the Twiss parameters: i $(=1,\cdots N_s)$, the bin number in the s direction; j $(=1,\cdots N_p)$, the particle number in the i-th bin; ϕ, the phase advance of the betatron oscillations per one revolution in the accelerator; $f(X_{i,j,old})$, the transverse kick by the nonlinear magnetic field with thin lens approximation; δ_i, the transverse perturbation for an increase of the betatron amplitude; and C_1 and C_2 are constants determined by the lattice elements between the nonlinear magnetic field f(x) and the transverse perturbation δ_i. Then, the nonlinear resonance can be analyzed by successive calculation of Eq.(1) for each particle. δ_i by the filtered noise is approximated by superposing perturbation signals of multi frequency components having respective random phases. In the following, the perturbation intensity $\overline{A}$ is defined by rms value of δ_i.

For comparison, the conventional scheme varying the tune is analyzed with the assumption that the phase advance of the betatron oscillations per one revolution is decreased monotonically from the initial value of ϕ_{init} to the final value of ϕ_{end}:

$$\phi = \phi_{init} + (\phi_{end} - \phi_{init}) N_{rev}/N_{tot}, \quad (2)$$

where N_{rev} is the revolution number after initiation of the extraction and N_{tot} is the total revolution number during the extraction. For both the present extraction scheme and the conventional one, the effect of the ripple of the magnet current is considered through the following relationship:

$$\phi = \phi_0 + \Delta\phi \sin(N_{rev} / N_{rip}) \quad (3)$$

where ϕ_0 is the phase advance without the ripple, $\Delta\phi$ is the ripple amplitude of the phase advance, and N_{rip} is the ripple period in a unit of the revolution number.

IV. SIMULATION RESULTS

The above computer simulation technique was applied to analysis of the second order resonant extraction by the present scheme. The fractional part of the betatron tune was assumed to be 0.505. The beam was divided into 20 bins, each of which consisted of 1000 super particles. The beam emittance was assumed to be 10 πmm·mrad. The nonlinear magnetic field was defined to make the separatrix larger than the beam emittance of 10 πmm·mrad. For simplicity, it was assumed that the filtered noise and the nonlinear magnetic field were applied to the beam at the same position. It was assumed that the filtered noise has spread frequency components equivalent to the tune range from 0.495 to 0.505 and the power of each frequency component was equal. The deflector for the extraction is assumed to be at Xd = 10 x10^{-3}.

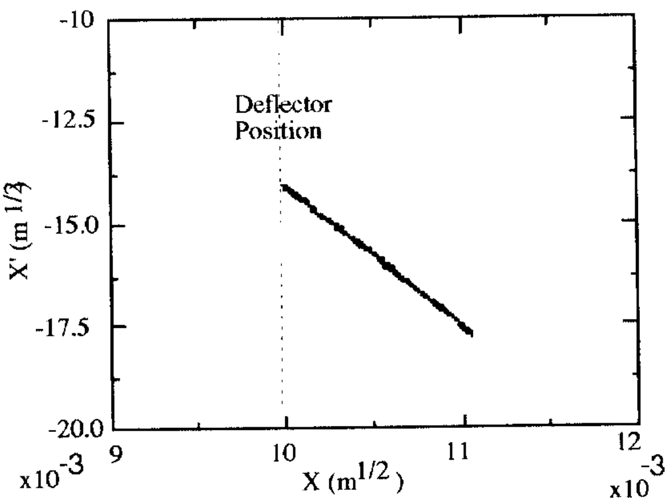

Fig.2 Phase Space Positions of the Extracted Particles

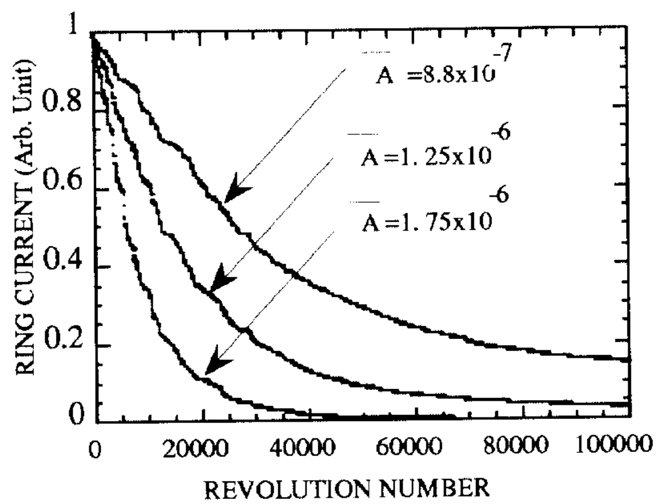

Fig.3 Relationship between Revolution Number and Ring Current

Figure 2 shows the phase space plots for the particle inside the separatrix. The rms value of the perturbation $\overline{A}$ was assumed to be 1.25×10^{-6}. It was confirmed in the simulations that the orbit gradient is kept constant and the emittance of the extracted beam is smaller than 0.5 πmm·mrad. For comparison, the resonant extraction was analyzed next by varying the separatrix size. The betatron tune was reduced linearly from 0.505 to 0.500 so that the separatrix shrank and finally vanished. The results showed that the orbit gradient changes significantly in comparison with the present scheme.

The change in the fraction of super particles in the separatrix, i.e. the accelerator ring current, is shown in Fig.3. Results for three perturbation intensities of $\overline{A}$ = 8.8 x10^{-7}, 1.25x 10^{-6} and 1.76 x10^{-6} are shown. The ring currents decrease more rapidly when increasing the noise intensity. The behavior of the particles in the phase space under transverse noise can be written by a diffusion equation and the diffusion constant is proportional to the square of the perturbation intensity $\overline{A}$. In a typical slow extraction, it is necessary to eject the beam during about 10^6revolutions. Since the required diffusion coefficient is inversely proportional to the extraction period, the necessary noise intensity $\overline{A}$ is reduced to about 5.0x10^{-7} for the above extraction time. Assuming that the beam is a proton beam of 250 MeV and the tranverse perturbation is added by a kicker of 0.5 m length at a point where the betatron function is 10 m , the necessary noise voltage is lower than about 50 V.

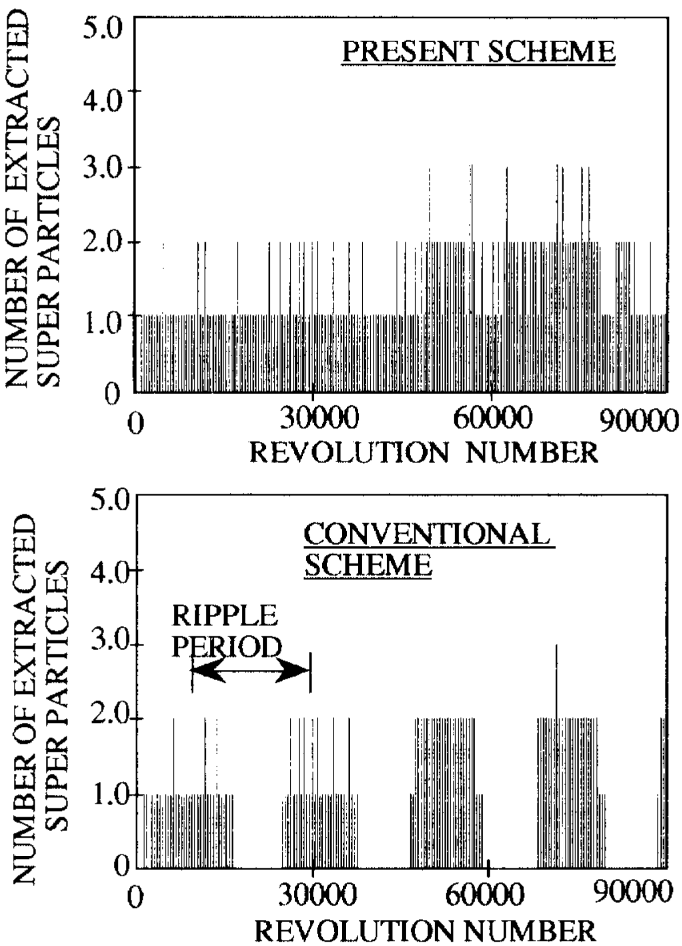

Fig.4 Number of Extracted Super Particles

Figure 4 shows the time (revolution number) dependences of number of the extracted super particles for the present and conventional extraction schemes. It was assumed for both schemes that the ripple of the phase advance, that is, $\Delta\phi/\phi_0$ was 10^{-4} and N_{rip}, the period of the ripple was the revolutin number of 20000. For the present extraction scheme, the rms intensity of tht pertubation noise was 5.0x10^{-7}. It is seen that extraction by the conventional scheme occurs intermittently. The time structure of the extraction by the present scheme is less affected by the ripple because of the random motion of the particles due to the applied filtered noise.

V. CONCLUSIONS

A new scheme for resonant extraction was presented to realize beam extraction with small emittance and constant characteristics of the position and size. The present extraction scheme is characterized by keeping the separatrix constant and increasing the amplitude of the beatatron oscillations to excite the resonance. This scheme was studied for a second order resonant extraction by computer simulations. As a measure for the perturbation, the transverse filtered noise were studied. It was shown that the emittance of the extracted beam could be reduced to a negligibly small value. It was also shown that the time structure of the extracted current was less affected by the ripple of the magnet current in comparison with that by the scheme varying the separatrix size.

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