The Slow Extraction of Electrons from Synchrotrons and Storage Ring using Synchrotron Radiation.

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A new resonance extraction method is proposed for slow ejection of electrons from circular machines. Betatron tunes are chosen so that the separatrix is greater than the beam phase space. Due to synchrotron radiation in case of positive radial increment the separatrix is open with slots in the corners. Under action of radiation electrons go out of the separatrix through the slots and move along the asymptotes. The increment of betatron oscillation can be changed by wigglers, that make it possible to provide the desired extraction time, uniformity and emittance of the extracted beam.

Nonlinear resonance is common for slow extraction of particles from synchrotrons. It leads to appearance of a stable region for oscillations with the finite amplitudes and unabated growth of amplidude for oscillation out of this region. At the start of slow extraction, when tune shift is $\delta = \delta_{st}$, the beam fills the stable region. Switching on the quadrupole magnets reduces the tune shift δ from the resonance tune. In this case the stable region is shrinked down and a portion of particles goes out of this region, amplitudes of the particles oscillations increase, then particles thrown into the septum-magnet and ejected outside. Ejection of a new portion requires further shrinking of the stable region. Angular particle deviation x', radial separatrix at the septum entrance, and accordingly, the amplitude at the septum, the ejected beam intensity and the effective emittance of the beam are changed continuously during the extraction time.

However in electron machines the synchrotron radiation in bending-magnets influences the particles motion essentially [1]. It can cause the growth of radial betatron oscillations amplitudes and this natural effect can be used to transfer particles from the stable region to the unstable region [2]. The separatrix size will be constant in this case. It is allow to decrease the ejecting beam emittance, to keep the constant angular deviation of the particle beam at the septum entrance during extraction time and to control the uniformity of beam.

We have considered the influence of radiation on the exciting of resonance in [3]. By way of example let us consider the 3-order resonance $3\nu_x = m + \delta$, the tune shift is $\delta \ll 1$.

Parameters (the amplitude and the angle) of the betatron motion of electrons in synchrotron nearby the resonance $k\nu_x = m + \delta$ are given by equations [3]:

$$\begin{aligned} x &= \sqrt{\varepsilon_x \beta_x} \cos\phi_x \ , \\ x' &= \sqrt{\varepsilon_x \beta_x}(\alpha_x \cos\phi_x + \sin\phi_x) \ , \end{aligned} \tag{1}$$

where α_x and β_x are Twiss parameters. The emittance ε_x and the phase ϕ_x fit shortcut equations

$$\begin{aligned} \tfrac{d\varepsilon_x}{ds} &= A - \langle \xi_x \rangle \varepsilon_x - \tfrac{1}{2}|F_m|\varepsilon_x^{3/2} \sin(3\phi_x - \arg F_m) \ , \\ \tfrac{d\phi_x}{ds} &= \tfrac{\delta}{R_o} - |F_m|\varepsilon_x^{1/2} \cos(3\phi_x - \arg F_m) \ , \end{aligned} \tag{2}$$

where

$$\begin{aligned} A &= \tfrac{55}{24\sqrt{3}} \tfrac{r_o \Lambda K \gamma^5}{R_o \beta_{x\,\max}} \ , \\ K &= R_o \beta_{x\,\max} \langle \tfrac{\beta_x \psi'^2 + 2\alpha_x \psi\psi' + \gamma_x \psi^2}{R^3} \rangle \ , \\ \langle \xi_x \rangle &= \tfrac{2}{R_o} \langle \Gamma \tfrac{1-(1-2n)\psi}{R_o} \rangle \ , \\ F_m &= \tfrac{1}{2} \langle \tfrac{1}{H_o R} \tfrac{\partial^2 H_z}{\partial x^2} \beta_x^{3/2} e^{-3i\lambda - ims/R_o} \rangle \ , \\ \tfrac{\Gamma}{R} &= \tfrac{2}{3} \tfrac{r_o R_o \gamma^3}{R^2} \ , \\ r_o &= \tfrac{e^2}{mc^2} \ , \ \ \Lambda = \tfrac{\hbar}{mc} \ , \\ \langle f \rangle &= \langle f(s) \rangle = \tfrac{1}{2\pi R_o} \int_o^{2\pi R_o} f(s) ds \ , \end{aligned} \tag{3}$$

λ is the periodic part of the Floquet function phase.

The system of equations (1) takes into consideration the joint influence of regular quadric nonlinearity of the magnetic field exciting the resonance $3\nu_x = m + \delta$ and the synchrotron radiation. In first equation item A determines the growth of the radial oscillation amplitude under the action of quantum fluctuations. The second item corresponding classical part of the synchrotron radiation determines the damping of radial oscillation with the decrement $\tau = 2/(c\langle \xi_x \rangle)$ if it is positive or the antidamping if it is negative. In the absence of the radiation ($A = 0$, $\langle \xi_x \rangle = 0$), the system of equations (1) describes the resonance $3\nu_x = m$. In this case the phase space can be split into a stable inner region and unstable external region separated by separatrix.

The inclusion of radiation influence causes the unstable motion over the phase space including the region of finite amplitudes on retention of characteristic resonance structure. If $\langle \xi_x \rangle < 0$ the centre of the phase space should be the fixed point of unstable focus type. The separatrix is disappear, quasiseparatrix is formed. Slots appear in angles of the characteristic triangular, fig 1. Particles are kept in constant flow from the inner region outward if $\langle \xi_x \rangle < 0$ or inward from the external region if $\langle \xi_x \rangle > 0$. The coefficient A is always positive, and quantum effects lead to the amplitude growth of betatron oscillations. If the energy of particles is low this influence is insignificant. The radiation growth is commonly attempted to damp by changing $\langle \zeta_x \rangle$ value by means of special damper machines (wigglers or ondulators), so that the amplitude of radial oscillations will not increase and even decrease. However, the radiation growth may be used for ejection of particles tuning damper machines properly or switching them off. Then at constant tune shift δ the particles will flow through the slots in quasiseparatrix from inner region out to the region of fast amplitude growth, be catched up by the resonance and ejected. Ejection takes place at constant quasiseparatrix. Thus the ejected beam passes into septum at constant angle. The width of slot is determined by A and $\langle \xi_x \rangle$ values may be made small. In this case the ejected beam emittance will be modest. Nonlinear resonance is required to form the stable region of small amplitudes and to provide fast increase of oscillations on amplitude of particle caught in the unstable region.

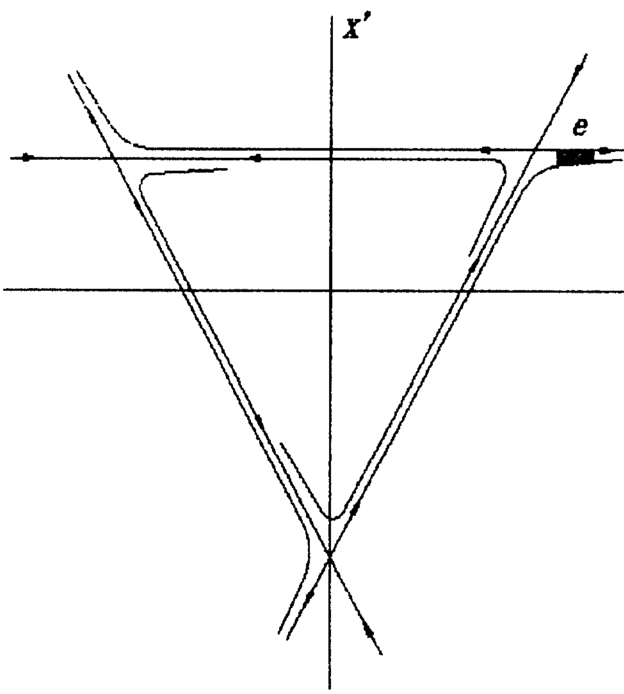

Fig.1. The quasiseparatrix of the resonance $3\nu_x = m$. e is the ejected beam.

A practical realization of the method of slow extraction is carried out as follows. Damper machines prevent beam particles from being excited with the high amplitude at the all time of the acceleration. The resonance, for example $3\nu_r = m$, is excited by sextupole lenses, and tune shift is chosen so that all particles are in the stable region. For the higher-order resonance the lenses of greater multipolarity are required. To provide slow extraction damper machines are switched off or powered in such a way as to achieve an amplitude growth of oscillations. As a result, particles are kept in constant flow through the slots in the quasiseparatrix in the region of the fast amplitudes growth. The tune shift δ, the size and orientation of quasiseparatrix are held because of the fixed operating mode because of sextupoles and quadrupoles throughout the slow extraction.

The offered method of the slow extraction can be realized for any electron synchrotron or storage ring. We can use it most efficiently when energy of electrons is most higher.

The scattering of particles (for example, protons) from residual gas of accelerator is also the statistical process, and, with resonance, betatron oscillations of particles are to be described by equations which are similar to equations (1). Therefore, in this case, too, there is the quasiseparatrix. Particles will flow through the slots in the region of the fast amplitudes growth and can be ejected.

In conclusion it may be note that slow extraction with constant separatrix having another mechanism of particles ejection from stable region to unstable region considered in [4].

1 REFERENCES

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