# SLOW EXTRACTION OF PARTICLES USING A THIN TARGET FOR DRIVING FOR RESONANCE

Yu.Severgin, W.Belov, A.Makarov, M.Tarovik
The D.V.Efremov Scientific Research Institute of Electrophysical Apparatus 189631, St.-Petersburg, Russia

Abstract

The slow extraction of particles from the accelerator using parametric resonance of betatron oscillations is investigated. A special feature of the parametric resonance is the absence of separatrix on a phase plane. Therefore frequencies of betatron oscillations of the particles to be extracted at each revolution are to change abruptly. A value of this jump is need to be sufficient to transfer the frequencies of betatron oscillations of these particles inside the band of parametric resonance from the region outside and to ensure the increase of the oscillation amplitude in two revolutions, which is required to throw the particles in a gap of the extraction septum-magnet. It can be achieved through the energy losses of the particles, as ones passes through the thin target, and the use of sextupole lenses. Suggested techniques of the slow extraction can be applied for resonance of the higher order as well.

## I.

The resonance slow extraction is based on existence of both stability region for oscillations with small amplitudes and resonance growth of amplitudes on asymptotes of separatrix outside the region. For linear parametrical resonance such region is not available. Close to a band of parametrical resonance the oscillation amplitude has beats, with swing growing as the boundary of the band is approached. The amplitude grows linearly at the boundary and exponentially within the band. Therefore the slow driving for resonance involves an increase of oscillation amplitude of particles not only in the beam part being extracted but in the whole beam as well. It is necessary to have a mechanism allowing the betatron oscillation frequency for a some share of particles to be moved abruptly in the resonance band from the region outside the band, in which the beats swing is reasonably small, and to act only on this share by resonance. It is necessary also, that this mechanism acts at all times for long. The mechanism is available: the use of both thin target for a part of the beam and sextupole lenses. The target releases a jet of particles with a pulse different from that of the main beam and imparts coherent betatron oscillations to the jet. Sextupoles under certain conditions excite the parametrical resonance only for this jet. The slow extraction is performed as follows. At the close of acceleration, using bump-magnets, the beam displaces inward (or outward) of the synchrotron ring so that its edge passes through a thin wire target. The target is positioned in that part of the ring, where dispersion $\psi$ function is distinct from zero. The thickness of target is selected so that the change in pulse $|\delta p/p|$, in its only passage through the target, to be several times greater than pulse dispersion $|\Delta p/p|$ in beam. For this share of particles the equilibrium orbit displaces inward ($\psi \gg 0$) the ring by magnitude

$$X = -\psi \left|\frac{\delta p}{p}\right|$$

and the coherent betatron oscillations about the orbit are excited with initial amplitude

$$X_0 = \sqrt{(x_0 - \psi_t \left|\frac{\delta p}{p}\right|)^2 + (x_0' - \psi_t' \left|\frac{\delta p}{p}\right|)^2 R_0^2}$$

and angle

$$X_0' = x_0' - \psi_t' \left|\frac{\delta p}{p}\right|,$$

where $x_0' = \psi_t' \Delta p/p + \alpha_t \sqrt{\varepsilon/\beta_t}$, $x_0 = \sqrt{\varepsilon\beta_t} + \psi_t \Delta p/p$, $\varepsilon$—emittance of the beam at the close of acceleration, $\alpha_t, \beta_t, \psi_t, \psi_t'$—characteristic function of synchrotron in the site of target. Sextupole lenses should be installed, where the $\psi$ function is maximum ($\psi_S \gg \psi_t$) and

$$\psi_s \left|\frac{\delta p}{p}\right| > X_s$$

$X_s = X_0\sqrt{\beta_s/\beta_t}(\cos(\mu_s - \mu_t) + \alpha_t \sin(\mu_s - \mu_t)) + X_0'\sqrt{\beta_s\beta_t}\sin(\mu_s - \mu_t)$—amplitude of coherent betatron oscillation of particles, passed through the target, on azimuth of sextupole. Then in the sextupole they move about the orbit, shifted from the axis of chamber by value $\delta X_s = -\psi_s|\delta p/p|$ and sextupole lens field can be presented as

$$H_s = \frac{1}{2}\frac{\partial^2 H_z}{\partial x^2}\left(\left(\psi_s \frac{\delta p}{p}\right)^2 - 2\psi_s \left|\frac{\delta p}{p}\right| x + x^2\right) \quad .$$

Quadrupole component of the field $H_s$ causes displacement of the betatron oscillation frequency for these particles by value

$$\Delta Q_x = \frac{1}{2\pi R_0}\int_0^{2\pi R_0} \frac{1}{HR}\frac{\partial^2 H_z}{\partial x^2}\psi\beta_x ds \left|\frac{\delta p}{p}\right|$$

and excitation of parametrical resonance $2Q_x = k - \delta$ with half-width $|P_k|$

$$P_k = -\frac{1}{2\pi R_0}\int_0^{2\pi R_0} \frac{1}{HR}\frac{\partial^2 H_z}{\partial x^2}\psi\beta_x \exp(-2i\chi - \frac{iks}{R_0}) ds \left|\frac{\delta p}{p}\right|$$

($\Delta Q_x$ and $|P_k|$ for particles of main part of the beam, that has not passed through the target is several times less, on the strength of condition $|\delta p/p| \gg |\Delta p/p|$). Gradients of sextupole lenses should be chosen so that

$$\Delta Q_x = \delta - \kappa_x \frac{\delta p}{p} \quad , \tag{1}$$

where $\delta$—detuning from resonance, and $\kappa_x$— self-chromaticity of synchrotron (without sextupole lenses). Then the exponential growth of amplitude of coherent betatron oscillations takes place only for the share of particles, that passed through the targets, with maximum increment $|P_k|$:

$$X = X_0 \exp(|P_k|s)$$

on azimuth of synchrotron, where the phase shift of betatron oscillations from the sextupole makes $\pi/2$. In this case the oscillation amplitude of particles, which have not passed through the target, essentially does not increase if $|\Delta p/P| \ll |\delta p/p|$. When slowly driving the beam on the target, it is possible to expand the extraction greatly. The risk of the repeat passing through the target is run. At half-integer frequency of betatron oscillations this can to be obviated by setting several sextupole lenses with the gradients and shifts of phases between them, so that the condition (1) would be met and increment $|P_k|$ would be sufficient to get around the target at the second revolution. Driving of the beam on target during the extraction results in change of amplitude of coherent betatron oscillations, so to keep the same throw throughout the whole time of extraction is necessary to change $|P_k|$ at constant value of $\Delta Q_x$. Emittance of extracted beam is defined by the radial width of the target $s$, angular divergence of the beam, hitting in the target $(2/\beta_t)\sqrt{(2\sqrt{\varepsilon\beta_t} - s)s}$, root-mean square angle of divergence on passing through the target $\langle\theta^2\rangle^{1/2}$ and can be made small

$$\varepsilon_{extr} = \frac{\pi s}{2}\left(\frac{\sqrt{(2\sqrt{\varepsilon\beta_t} - s)s}}{\beta_t} + \frac{1}{2}\langle\theta^2\rangle^{1/2}\right) \quad .$$

It is advisable to position the target in the interval, where $\alpha_t = 0$.

## II.

Let us use the synchrotron K4, [1], to illustrate the method of slow extraction. It produces electronic cooling of the beam on accumulation, and final $\Delta p/p = \pm 10^{-4}$. Magnetic structure includes intervals with large 7.3 m and small ∼0 m values of $\psi$ function. The working point $Q_x = 2.4$. The self-chromaticity $\kappa_x = -2.13$. The perimeter $P = 82.97$ m, magnetic rigidity $HR = 4$ T-m. Frequency $Q_x$ is shifted to the working magnitude $Q_x = 2.48$ by using structural quadrupole lenses, $\delta = 0.04$, and $Q_z = 2.64$. The target is installed within small straight at values of $\beta_x = 2.5$ m, $\psi = 1.0$ m. Its thickness is selected so that $\delta p/p = -2 \cdot 10^{-3}$. At energy of protons $W = 585$ MeV the thickness of carbon target makes $s = 4.4$ mm, $\Delta p/p = 10^{-4}$, $\langle\theta^2\rangle^{1/2} = 2.4 \cdot 10^{-3}$, [2]. A single sextupole lens of length $l = 0.25$ m is used. It is installed within a long straight at values of $\psi_s = 6.91$ m, $\beta_s = 12.2$ m. From the condition (1) it is found $\partial^2 H_z/\partial x^2 = 26.8$ T/m$^2$. Increment $|P_k| = 3.4 \cdot 10^{-3}$ m$^{-1}$. The initial amplitude of coherent betatron oscillations $X_0 = 1.0$ cm, $X_0 = 0.6$ cm when positioning the target outside and inside the closed orbit, accordingly. The value $|P_k|$ is enough to get around the target at the second revolution (amplitude increase ∼32%). At the local displacement of orbit to the septum-magnet for a distance 1.5 cm, knife thickness of 0.2 cm and target positioned outside, extraction begins at 4-th revolution. Emittance of extracted beam $\varepsilon = 1.4\pi$ mm-mrad.

The most complicated problem is an investigation of interaction of particles and a target when slow (several microns per revolution) driving the latter on a beam. The numerical simulation [2] has shown, that the incomplete passing of particles through a target causes the repassing with the greater amplitude of a throw and increase of effective emittance of extracted beam. The efficiency of slow extraction is basically determined by losses on a target resulted from the nuclear reactions (makes ∼3%, [2]). Due to resonance nature of a swing amplitude of betatron oscillations the efficiency of extraction is higher, than that in the Piccioni method [3,4]. In the work [2] the extension of the Piccioni method is proposed for the case of strongly focusing accelerators, where is the large difference of values of $\psi$ function. That is not required for the method put forward here, that can be, in principle, used for accelerators with the weak focusing. This method is applicable providing the decrease of pulse dispersion for the beam at the close of acceleration is realizable through the performance of high-frequency stations. We have considered the slow extraction at parametrical resonance for reasons of its features noted above. However, the mechanism of extraction being suggested can be applied for resonances of higher orders as well.

## III. ACKNOWLEDGEMENTS

We are grateful to I.Shukeilo for discussion.

## References

[1] The storage complex for heavy ions K4-K10. Technical proposal. Report of group K4-K10, edited by G.M.Ter-Akopian. R9-92-15. JINR ,Dubna, 1992.

[2] N.D.Malitsky, Yu.P.Severgin, I.A.Shukeilo. The beam slow extraction from a magnetic ring, based on particle-target interaction. EPAC-88, v.1, p.565, Rome 1988.

[3] B.T.Wright. Rev.Sci.Instr.,25, p.429, (1954)

[4] W.A.Wenzel.Proc.of the Inter.Conf.on High Energy Acceler.p.698, Dubna, (1963)