AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTIPROTON STORAGE RINGS

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UDC. 621.384.60

A method is proposed for the damping of synchrotron and betatron oscillations of heavy particles, which makes use of the sharp increase in the cross section for the interaction of these particles with electrons at small relative velocity. It is shown that it is possible by this method to compress strongly the proton and antiproton bunches in storage rings, and also to achieve multiple storage of these particles.

As it is known, radiation in a magnetic field (synchrotron radiation) leads to a damping of the betatron and synchrotron oscillations of particles in accelerators. This phenomenon laid the basis for the creation of devices with opposing electron and positron beams inasmuch as it makes it possible to accumulate particles in a magnetic track and also to compress the bunches strongly. Unfortunately, the synchrotron radiation of heavy particles (protons and antiprotons) is vanishingly small up to the highest particle energies and magnetic fields applicable in contemporary accelerator technology, and therefore it cannot be used in devices with opposing beams of heavy particles.

Thus all the designs of devices with opposing proton beams were based on collisions of the beams with the inherent accelerator density (CERN storage ring design, and the Novosibirsk design of iron-free accelerator with opposing proton beams [1]). Opposing proton–antiproton beams were not considered practically feasible.

It should be possible to attempt to damp the particle oscillations in a storage ring by passing the beam through a stream of gas. Ionization losses as well as synchrotron radiation lead to a continuous decrease in the total energy of the particles, but the system restores only the longitudinal component, the result of which is the damping of the transverse velocity components in a time equal to the time of the total energy loss. Unfortunately, multiple scattering and dispersion losses increase the transverse beam dimensions such that some equilibrium beam dimension is established for which the angular spread of the particles is of the order of $(mZ/\gamma M^{\frac{1}{2}})$, where Z is the nuclear charge of the gas jet; m and M are the electron and proton masses; and $\varepsilon = (E/Mc^2)$. Even for $Z = 1$ these angles are too large to be useful in present day accelerators, and more so in storage devices. The angle decreases in the extreme relativistic case, but for these energies the nuclear interaction is very much larger than the Coulomb interaction, and the damping effect completely disappears. It might be possible to try to circumvent this difficulty by using an electron cloud instead of a gas jet. However, without ion compensation it is practically impossible to produce an electron density which would somehow influence the motion of the high-energy protons.

Nevertheless, it is possible to achieve the result by a specific method. Let us send a sufficiently dense electron beam along the ion beam with the same (or similar) average velocity. In such a case the relative proton and electron velocities are determined only by the velocity spread in the proton and electron beams, which in contemporary synchrotrons amounts to less than one percent. Since the cross section for Coulomb interaction is inversely proportional to the fourth power of the velocity, the effect increases by more than 10^8, which allows damping to be achieved rather quickly.

Damping by a tracking electron beam is qualitatively different from other damping methods in that the heavy particles lose only the velocity spread without losing the average velocity. The damping of phase and betatron oscillations takes place without energy losses. Moreover, under specific conditions the electron beam may also accelerate the protons.

Translated from Atomnaya Énergiya, Vol. 22, No. 5, pp. 346–348, May, 1967. Original article submitted December 2, 1966.

The picture becomes particularly clear if we transform to the coordinate system in which the average particle velocity is zero. There are two gases in this system: the electron gas and the proton (antiproton) gas. Since their velocity spread is of the same order, their "temperature" is in this system proportional to their masses. Due to the Coulomb collisions the proton gas is cooled by the electrons. To keep the temperature of the electron gas from rising, it is necessary to replace it by a cool one, i.e., in place of the broadened electron beam a new one has to be injected with a small velocity spread. The cooling of the electron gas (pinching of the electron beam) may be realized at sufficiently high energies at the expense of synchrotron radiation.

To evaluate the damping constant we consider the case when the spread in the radial, vertical, and longitudinal velocities in the moving system is of the same order. Since in the Lorentz transformation the longitudinal momentum is contracted, the average particle energy in the moving coordinate system is

$$T=\frac{p_{\perp}^{2}}{2M}=\frac{p^{2}\theta^{2}}{2M},$$

where p is the momentum of the particle in the laboratory system: and θ is the angular spread (for $\gamma\theta \ll 1$ the gas is nonrelativistic in the moving system).

The energy transfer time for Coulomb interaction was obtained by G. I. Budker and S. T. Belyaev [2]. The portion of the curve to the right of the peak in the figure corresponds to the case when the average proton velocity v_p' is larger than the electron velocity v_e' (in the moving system).

In this case the damping time is

$$\tau' \approx 5\cdot 10^{-2}\frac{M}{m}\cdot\frac{(\gamma\beta\theta_p)^3}{Lr_0^2N'c\eta}; \quad (1)$$

$$\tau \approx 5\cdot 10^{-2}\frac{M}{m}\cdot\frac{\gamma^5(\beta\theta_p)^3}{Lr_0^2Nc\eta}, \quad (2)$$

where τ' and τ are the damping times in the moving and laboratory frames, respectively; $\beta^2=\frac{v^2}{c^2}=1-\frac{1}{\gamma^2}$; L is the Coulomb logarithm; $r_0=(e^2/mc^2)$; N' and N are the electron beam densities in the moving and laboratory frames, respectively; c is the speed of light; and η is the fraction of the proton orbit occupied by the electron beam. The factor γ^2 in Eq. (2) is a consequence of the Lorentz transformation of time and density. The portion of the curve to the left of the peak corresponds to the case when $v_p' < v_e'$, but $T_p > T_e$. In this case we obtain the well-known formula in plasma theory for the temperature equalization time defined by $\frac{dT_p}{dt}=-\frac{T_p-T_e}{\tau}$:

$$\tau' \approx 5\cdot 10^{-2}\frac{M}{m}\cdot\frac{(\gamma\beta\theta_e)^3}{Lr_0^2N'c\eta}; \quad (3)$$

$$\tau \approx 5\cdot 10^{-2}\frac{M}{m}\cdot\frac{\gamma^5(\beta\theta_e)^3}{Lr_0^2Nc\eta}. \quad (4)$$

The energy transfer goes to zero in the case of equal temperatures which is of no interest to us. The rate of energy transfer is a maximum at $v_p' \sim v_e'$. Then

$$\left|\frac{d\theta_p^2}{dt}\right|_{\max} \approx 7\eta\frac{m}{M}\cdot\frac{Lr_0^2Nc}{\gamma^5\beta^3\theta_e}. \quad (5)$$

If there exists some process which broadens the proton beam (e.g., residual gas scattering), then there are two equilibrium temperatures (stable beam dimensions): one is T_1, stable to the left of the peak where the friction characteristic is positive, and the second is T_2, unstable to the right of the peak where the friction characteristic is negative. All particles with energies larger than T_2 leave the beam, and all others accumulate in the temperature range T_1.

Let us consider the case when the only cause of beam broadening is scattering by the residual gas. Here

$$\frac{d\theta_p^2}{dt}=\frac{8\pi Z^2r_0^2L_ZN_0c}{\gamma^2\beta^3}\left(\frac{m}{M}\right)^2,$$

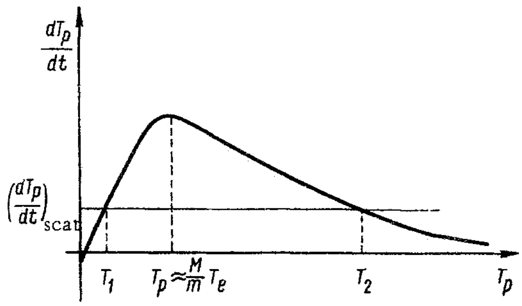

Fig. 1. Rate of change of the proton temperature during interaction with electrons.

where Z is the nuclear charge of the residual gas; N_0 is the gas density; and L_Z is the appropriate logarithm. Comparing this expression with (5), we obtain the ratio of the electron gas density to the residual gas density for a given angular spread of the electrons which corresponds to the beginning of the ion beam damping:

$$\frac{N_{\text{crit.}}}{N_0} \approx 3\gamma^3 Z^2 \frac{m}{M} \cdot \frac{L_Z}{L} \cdot \frac{\theta_e}{\eta}. \qquad (6)$$

For $N \gg N_{\text{crit}}$ the angular spread settles to

$$(\theta_p)_s \approx \sqrt{0.4 \frac{N_{\text{crit}}}{N_0}}\, \theta_e. \qquad (7)$$

We note that $(\theta_p)_s$ is not smaller than $\sqrt{\frac{m}{M}}\,\theta_e$, corresponding to equal temperatures.

Let us consider a practical interesting numerical example. We take $\theta_e = 3 \times 10^{-3}$, $\gamma = 2$ (proton energy 1 BeV), and $\eta = 0.1$. Then $N_{\text{crit}} = 10^{-2}\, N_0$.

With the cross-sectional radius of the electron beam of 1 cm and N_0 of the order of 10^8 ($p = 10^{-9}$ torr) the critical electron current is 15 mA. With an injected electron energy of 500 keV ($\gamma = 2$) it is technically possible to obtain a closed electron beam with the above parameters and with a current of the order of 1 A; also $(\theta_p)_s = 3 \times 10^{-4}$. For a 3-m focal length of the magnetic system of the storage ring the stable proton (antiproton) beam radius is $r_s = 1$ mm. Finally, the damping time (starting from an amplitude of 1 cm) is $\tau = 60$ sec while the lifetime of the particles in the beam against losses due to single scattering is of the order of 10^7 sec.

The damping time is sufficiently short to achieve multiple accumulation of antiprotons and protons. The beam density is increased by two orders of magnitude by the damping.

In view of the fact that the orbit is closed the damping process in storage rings and accelerators naturally appears more complex than was described above due to the interconnection between the oscillations in the damping process and the particle scattering (effects which are similar to radiation antidamping of radial oscillations in strong focusing electron accelerators, AdA-effects, and others). However, the consideration of all these questions is beyond the scope of this paper.

LITERATURE CITED

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