RADIATIVE METHOD OF ION COOLING IN STORAGE RINGS

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Abstract

A three-dimensional Radiative Ion Cooling (RIC) method of a non-fully stripped relativistic ion beams in storage rings is investigated when the process of resonance Reyleygh scattering of the laser light by ions is used.

1 INTRODUCTION

By analogy with the synchrotron radiation, a cooling method of non-fully stripped ion beams in storage rings of arbitrary energy can be used at a top energy of the rings which is based on the process of resonance Rayleigh scattering of a laser light by relativistic ions [1]. It will give a chance to store the ultimately achievable high current, and low-emittance ion beams using multiple injection of ions in storage rings.

2 RADIATIVE ION COOLING

The following scheme of RIC will be considered. In a straight section of a storage ring, a laser photon beam is directed towards the ion beam and is scattered by the ions. The photon energy is of such a value that in the coordinate system connected with the average ion velocity it was close to the transition energy between definite electron states in the ions. Since the scattered radiation is directed mainly along the direction of the ion velocity, it will be decelerating and will lead to a damping of betatron and phase oscillations of ions in the storage ring.

In the moving coordinate system, the scattered radiation is spherically symmetrical and the energies of incident and scattered photons are about the same. In the laboratory coordinate system, the scattered radiation will be directed mainly in the ion velocity direction in the narrow interval of angles, $\Delta\theta \sim 1/\gamma$, where γ is the ion relativistic factor. The energy of the scattered photons will be Doppler shifted. Their maximum energy is $\hbar\omega_{max} \simeq (1+\beta)^2\gamma^2\hbar\omega_l$, where $\hbar\omega_l$ is the energy of laser photons, $\beta = v/c$, and v is the ion velocity. The average energy of the scattered photons $\hbar\overline{\omega} \simeq \hbar\omega_{max}/(1+\beta)$.

In the coordinate system connected with the moving ion, the cross-section of laser photon scattering by ions has the form

$$\sigma_{\omega l} = \frac{g_2}{g_1}\frac{\pi^2 c^2}{\omega_0'^2}\Gamma_{2,1}' g(\omega_0', \omega_l'), \tag{1}$$

where $g_{1,2}$ are the statistical weights of the states 1 and 2, $\Gamma_{2,1}' = 2r_e\omega_0'^2 f_{1,2}g_1/cg_2 \ll \omega_0'$ is the probability of the spontaneous photon emission of the excited ion or the natural linewidth, $g(\omega_0', \omega_l') = (\Gamma_{2,1}'/2\pi)/[(\omega_l' - \omega_0')^2 + \Gamma_{2,1}'^2/4]$ is the Lorentzian ($\int g(\omega)d\omega = 1$), $r_e = e^2/m_ec^2$ is the classical electron radius, e and m_e are its charge and mass, ω_0' is the transition frequency between the states 1 and 2, ω_l' is the frequency of the scattered laser wave, and $f_{1,2}$ is the transition strength [2].

The cross-section has a maximum $\sigma_{max} = \sigma|_{\omega_l'=\omega_0'} = g_2\lambda_0'^2/2\pi g_1$, where $\lambda_0' = 2\pi c/\omega_0'$ is the resonance wavelength in the ion coordinate system. The transition from the first excited level to the ground state of sodium-like ions corresponds to $f_{1,2} = 0,42$, $g_2/g_1 = 4$, $\lambda_0' = 4/3Z_{eff}^2 R'$, where $R' = e^4m_e/4\pi c\hbar^3 = 109678$ cm^{-1} is the Rydberg constant, $Z_{eff} = n^+ + 1 \leq Z$, n^+ is the ion charge state, and eZ is the nuclear charge.

When the ion beam has a high angular spread, θ_b, and energy spread, $(\Delta\gamma)_b$, then, for effective interaction of all ions with the photon beam, the bandwidth of the spectral line should exceed the value

$$\frac{\Delta\omega_l}{\omega_l} > \frac{\theta_b^2}{4} + \frac{(\Delta\gamma)_b}{\gamma}. \tag{2}$$

If condition (2) is satisfied, and with the assumption that the spectral intensity of the laser beam $I_{\omega l}$ is distributed homogeneously in the frequency range, $\Delta\omega_l$, we can denote the relative probabilities (populations) of the atomic states belonging to the levels $|1>$ and $<2|$ through n_1 and n_2, accordingly, and write down the system of equations for them:

$$\begin{cases} \dfrac{dn_2}{dz} = \dfrac{(1+\beta)\dot{n}_\gamma\overline{\sigma}}{\beta c}(n_1 - n_2) - \dfrac{n_2}{\beta c\tau_{2,1}}, \\ n_1 + n_2 = 1, \end{cases} \quad (3)$$

where $\dot{n}_\gamma = I/\hbar\omega_l$ is the photon flow density, $I = \int I_{\omega_l} d\omega_l$ is the total intensity of the laser beam, $\overline{\sigma} = (1/I) \int \sigma_{\omega_l} I_{\omega_l} d\omega_l = \pi r_e \lambda_0' f_{2,1}\omega_l/\Delta\omega_l$ and $\tau_{2,1} = \gamma/\Gamma_{2,1}'$ is the decay time. The solution of the system in the case of $n_2|_{z=0} = 0$ is:

$$n_2(z) = \begin{cases} n_{2m}(1 - e^{-z(1+D)/l_e}), \\ 0 \le z \le l_{eff} \\ n_{2m}(1 - e^{-l_{eff}(1+D)/l_e})e^{-(z-l_{eff})(1+D)/l_e}, \\ l_{eff} \le z \le \infty, \end{cases} \quad (4)$$

where $n_{2m} = 0.5D/(1+D) < 0.5$, $l_e = \beta c\tau_{2,1}$ is the length of the ion relaxation, $D = 2(1+\beta)\dot{n}_\gamma\overline{\sigma}\tau_{2,1} = I/I_c$ is the saturation parameter, $I_c = (\pi c g_1 \hbar\omega_0'/\gamma^2 g_2 \lambda_0'^3)(\Delta\omega_l/\omega_l)$.

The number of photons scattered by an ion in one straight section is

$$\Delta n_\gamma = \int \frac{n_2(z)}{l_e} dz =$$

$$\frac{n_{2m}}{l_e}[l_{eff} + \frac{Dl_e}{1+D}(1 - e^{-(1+D)l_{eff}/l_e})]. \quad (5)$$

where l_{eff} is the effective interaction length of the laser and photon beams.

The power of the scattered radiation can be presented in the form

$$\overline{P}^s = \frac{\hbar\overline{\omega}\Delta n_\gamma c}{2\pi R}|_{l_{eff} \gg l_e} = \frac{c\gamma\hbar\omega_0' n_{int} l_{eff} D}{4\pi R l_e(1+D)}. \quad (6)$$

where n_{int} is the number of interaction regions, R is the mean radius of the storage ring orbit.

The energy emitted by ion per one turn is

$$eV = \frac{2\pi R\overline{P}^s}{c} = \frac{\gamma\hbar\omega_0' n_{int} l_{eff} D}{2l_e(1+D)}. \quad (7)$$

In the case of the radial and longitudinal movement it is important to know the dependence of the power P^s emitted by a particle on a radial displacement x, and on the energy deviation $\Delta\gamma/\gamma$. In our case

$$P^s = P_s^s(1 + \frac{1}{I}\frac{\partial I}{\partial x}\frac{x}{1+D} + \frac{2}{1+D}\frac{\Delta\gamma}{\gamma}), \quad (8)$$

where P_s^s is the power emitted by the equilibrium particle. This dependence coincides with the dependence that determined by synchrotron radiation, if we substitute the magnetic field index of the storage ring n by $n_l = -[\rho/2(1+D)](\partial \ln I/\partial x))$, ρ is the instantaneous radius of the storage ring orbit [3,4].

The rate of the increase of the square amplitudes of radial and vertical oscillations $A_{x,z}$ is defined by the expression

$$\frac{dA_{x,z}^2}{dt} = \int \frac{\partial n_\gamma}{\partial\omega\partial t}(\Delta A_{x,z})^2 d\omega, \quad (9)$$

where $\partial n_\gamma/\partial\omega\partial t = P_\omega^s/\hbar\omega$, $P_\omega^s = 3P^s\xi(1 - 2\xi + 2\xi^2)\omega_{max}^{-1}$ is the spectral distribution of the emitted photons, $\xi = \omega/\omega_{max}$. The increase of the square amplitudes of radial (both betatron and phase) and vertical oscillations after emission of one photon are equal, respectively to: $\Delta(A_x)^2 = (\alpha R\hbar\omega/m_i c^2\gamma)^2$, $\Delta(A_z)^2 = \beta_z(\hbar\omega)^2/8\gamma^2(m_i\ c\gamma)^2$ where m_i is the ion mass [3,4]. The equilibrium values $A_{eq}^2 = (\partial A^2/\partial t)\tau$. The equilibrium dimensions of the ion beam $\sigma_{x,z} = \sqrt{A_{eq\,x,z}^2/2}$. The radial dimension of the ion beam defined by the energy spread σ_γ is equal to $\sigma_s = \sigma_x = R\alpha\sigma_\gamma/\gamma$, where $\alpha \simeq \nu_x^{-2}$ and ν_x are the momentum compaction factor and radial betatron oscillation tune of the storage ring, accordingly.

From the above there follow the damping times for both the vertical betatron oscillations

$$\tau_z' = \frac{2m_i c^2\gamma}{\overline{P}^s} = \tau_{zmin}'\frac{2\pi R}{n_{int} l_{eff}}\frac{1+D}{D} \quad (10)$$

and radial betatron oscillations and phase oscillations

$$\tau_x' = R/c\zeta_x = \tau_z', \quad \tau'_s = R/c\zeta'_s = \tau'_z/2. \quad (11)$$

where $\tau_{zmin}' = g_2\gamma\lambda_0'^2 P_A/2\pi^2 c^2 g_1 f_{1,2}\hbar\omega_0'$, $P_A = m_e m_i c^5/e^2$, $\zeta_x = < (RP^s/2m_i c^3\gamma)[1 - (1-2n_l)R\psi/\rho] >$, $\zeta_s = < (RP^s/2m_i c^3\gamma)[2 + (1 - 2n_l)R\psi/\rho] >$ and ψ is the momentum compaction function [4]. For sodium-like ions $\hbar\omega_0' = 3\alpha^2 m_e c^2 Z_{eff}^2/8 \simeq 10.19 Z_{eff}^2$ [eV], $\tau_{zmin}' = (8^4/3^3\ f_{1,2}\alpha^7)(m_i/m_e)(\gamma\Lambda_e/cZ_{eff}^6) \simeq 0.775 A\gamma/Z_{eff}^6$ [s], where $\alpha = e^2/\hbar c \simeq 1/137$, $\Lambda_e = \hbar/m_e c \simeq 3.8610^{-11}$ cm, A is the atomic number of the ion. For helium ions ${}_3^2He^+$, the power $P_A \simeq 4.8 \cdot 10^{13} W$, $I_c = 873 W$, $\hbar\omega_0' = 40.6 eV$, $\lambda_0' = 3.03 \cdot 10^{-6}$ cm, $\Gamma_{2,1} = 7.57 \cdot 10^9 sec^{-1}$, $l_e/\gamma = 3.96$cm, $\tau_{zmin}'/\gamma = 36$ms.

The laser power $P_l = I_l S$, where S is the cross-section area of the laser beam. The cross-section area of the laser beam must exceed that of the ion beam. The length l_{eff} is determined as the minimum of the straight section length and double Rayleigh length $l_R = S/\lambda_l$, where $\lambda_l = 2\pi c/\omega_l$ is the laser wavelength (within the limits of this length, the laser area exceeds the minimum area by less than two times).

Quantum nature of the photon scattering will lead to an equilibrium radial dimension and energy spread of the ion beam

$$\sigma_x = \alpha R\sqrt{\frac{1.4\hbar\omega_0'}{m_i c^2}}, \qquad \frac{\sigma_\gamma}{\gamma} = \sqrt{\frac{0.7\hbar\omega_0'}{m_i c^2}}, \qquad (12)$$

An equilibrium vertical dimension of the ion beam $\sigma_z = \sigma_x/\alpha\gamma\nu_z$. The equilibrium radial angular spread and emittance of the ion beam in this case are

$$\sigma_{\theta x} = \frac{1}{\nu_x}\sqrt{\frac{1.4\hbar\omega_0'}{m_i c^2}}, \qquad \epsilon_x = \frac{1.4\pi R}{\nu_x^3}\frac{\hbar\omega_0'}{m_i c^2}. \qquad (13)$$

The Eqs. (10)-(13) are valid when the bandwidth of the laser spectral line exceeds the value (2). In the process of damping of the betatron and phase oscillations the bandwidth of the laser spectral line can be decreased.

We have considered the simplest version of the three-dimensional RIC method using the wide spectrum laser beam, which overlap the ion beam. The damping times (10),(11) are close to minimum at the laser intensity $I_l \simeq I_c(D \simeq 1)$. The damping time τ_s can be decreased to the value

$$\tau_s'' = \frac{m_i c^2(\Delta\gamma)_b}{\overline{P^s}} = \tau_z'\frac{(\Delta\gamma)_b}{2\gamma} \qquad (14)$$

when a high-degree monochromatic laser beam and sweeping of the laser frequency are used. In this case the laser bandwidth (2) can be done $\Delta\omega_l/\omega_l \geq \theta_b^2/4$ and the radiofrequency resonators can be switched off. After damping of phase oscillations the damping times of betatron oscillations will be shortened in accordance with a shortening of the laser bandwidth. The synchrotron-betatron resonance can be used to decrease the vertical and horizontal damping times. In the later case the transformation of the betatron oscillations to phase ones and cooling through the last way must be done.

3 BEAM LIFE TIMES

For nearly fully stripped ions at high energy a beam loss due to a residual gas interaction at pressures $\leq 10^{-10}$ mbar is negligible compared to that caused by a high current inelastic intrabeam interaction processes with ion charge-exchange and ionization [5-7]. But these are a threshold processes. The energy threshold can be estimated as follows. The minimum distance which can be reached between two similar ions of the kinetic energy $\Delta T'$ is $r_{min} = n^{+2}e^2/2\Delta T'$. In order to elastic process took place the value r_{min} must be more then a value $a \simeq a_0/Z_{eff}$, where $a_0 = \hbar^2/m_e e^2$ is the Bohr radius of the ion. Hence, the threshold energy $\Delta T_{thr}' \simeq n^{+2}Z_{eff}e^2/2a_0 = \alpha^2 m_e c^2 n^{+2}Z_{eff}/2$, where $\alpha = e^2/\hbar c$. As the transverse momentum is an invariant, then the value $p_\perp' = \beta_\perp'\gamma' = \beta_\perp\gamma \simeq \theta_b\gamma$ and hence the mean kinetic energy of the beam ions is $< \Delta T_\perp' > \simeq m_i c^2 p_\perp'^2/2 = m_i c^2(\theta_b\gamma)^2/2$. The value $< \Delta T_\perp' > |_{\theta_b=\sigma_{\theta x}} \simeq 0.26\alpha^2\gamma^2 m_e c^2 Z_{eff}^2/\nu_x^2$ can be done less then $\Delta T_{thr}'$ when the energy of the ions $\gamma < \gamma_{thr} = 1.38n^+\nu_x/\sqrt{Z_{eff}}$. The losses of the ions through the inelastic beam interactions are absent in this case. The value $\Delta T_\parallel' = m_i c^2(\Delta\gamma/\gamma)_b^2/2$ determined by the energy spread of the beam can be neglected when $(\Delta\gamma)_b \simeq \sigma_\gamma$.

4 CONCLUSION

Non-fully stripped heavy ion beams of rather high current and excellent brilliance can be obtained in storage rings by means of radio frequency stacking and radiative cooling of the relativistic ion beams. Such beams can be used in high energy physic, heavy ion fusion, spectroscopy, high-power free-ion lasers, etc.

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