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FAST COOLING OF HEAVY IONS IN A STORAGE RING

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Abstract

Peculiarities of the optical stochastic cooling of ion beams in storage rings are discussed.

The rate of the energy losses in magnetic field for proton and ion is many orders of magnitude less than for electron due to the mass ratio. From the other hand, the number of the photons emitted by particles in undulators at the first harmonic has an optimum, corresponding to the optimal undulator field, which depends on the period of undulator, the charge and mass of particles and on type of undulator (plane, helical) [1]. The number of photons emitted by particles in undulators in this case does not depend on the energy of this particles and theirs mass. Based on this observation, the effective sources of both incoherent and coherent undulator radiation were suggested [2].

So the hardness of the radiation emitted by different particles having the same relativistic factors might be the same if trajectory and relativistic factor are the same. The only difference might occur due to limitations in maximum magnetic field achievable (~10^5 G) so period of undulator must be adjusted also.

One of important parameters of undulators is the deflecting parameter

$$K = \frac{qH\lambda_0}{2\pi m_i c^2}, \tag{1}$$

where q, m_i are the particle's charge and mass respectively, λ_0 is period of the undulator, H is the value of magnetic field in the undulator. At the optimum fields the deflecting parameter is about unit.

The number of photons emitted by a particle on the first harmonic in the energy interval $\Delta\varepsilon_\gamma / \varepsilon_\gamma \cong 1/M$, where M is the number of periods, can be found as [1]

$$\Delta N_\gamma \cong 4\frac{q^2}{\hbar c}\frac{K^2}{1+K^2}. \tag{2}$$

The last formula (2) for multi charged ions becomes

$$\Delta N_\gamma \cong 4\frac{Z^2 e^2}{\hbar c}\frac{K^2}{1+K^2} \equiv 4Z^2\alpha\frac{K^2}{1+K^2}, \tag{3}$$

where $\alpha = e^2/\hbar c$ is the fine structure constant, and $q = Ze$ is the charge of ion.

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In its turn the energy exchange between the particle and the electromagnetic wave in the planar undulator now determined by the following equation

$$\Delta\varepsilon = \int q\vec{E}_L\vec{v}dt \cong \frac{ZeE_L M\lambda_0 K}{2\gamma} Cos\varphi, \tag{4}$$

where φ is the phase location of the particle in the electromagnetic wave, $\gamma = \varepsilon / m_i c^2$.

The fact that the number of the photons radiated by multi charged particle is about Z^2 times higher, than for single charged particle drastically improves performance of the optical stochastic cooling [3]. Really, the number of the photons in the bandwidth, emitted in the first undulator is proportional to

$$N_\gamma \cong \alpha Z^2 N_u = \alpha Z^2 N \frac{M\lambda_u}{l_b} \cong \alpha Z^2 N \frac{M\lambda_0}{l_b 2\gamma^2} = \alpha Z^2 N \frac{L}{l_b 2\gamma^2}, \tag{5}$$

where *N* is total number of particles in the bunch, l_b is the length of the bunch, $L = M\lambda_0$ is the length of the undulator, $\lambda_u = \frac{1}{2}\lambda_0 / \gamma^2$ is the wavelength of radiation.

This number must overwhelm the number of the photons associated with the noise of amplifier. The last one can be made as low as a single photon in the coherence volume [4].

One can see that the multi charge ions have advantage $\sim Z^2$, if compared with single charged particles such as protons, electrons or muons. With other words, multi charged particle radiates Z^2 more photons under the same conditions such as the same gamma factor and the same trajectory. Together with (4) following calculations done in [3] one can obtain the formula for amplification coefficient required for laser amplifier becomes the same

$$\kappa \cong \frac{\varepsilon_\parallel}{r_i} \frac{1}{NM}, \tag{6}$$

where $r_i = Z^2 e^2 / m_i c^2$ is the classical ion radius, $\varepsilon_\parallel = \gamma l_b \times (\Delta\varepsilon / \varepsilon)$ is the normalized longitudinal emittance. Last formula gives for amplification required a factor $\sim 1/Z^2$ in favor of multi charged ions.

In addition, the emittance reduction during the cooling [3]

$$\frac{\varepsilon_f}{\varepsilon_i} \cong \frac{1}{Z^2 \alpha N_u}, \tag{7}$$

where $\varepsilon_i, \varepsilon_f$ are initial and final emittances respectively, becomes significantly lower in this case also. In the last formula (7) we neglected the number of noise photons *n* referred to the exit of first undulator as $Z^2 \alpha N_u \geq n$.

All this opens a possibility for *fast cooling of ions in a storage ring*, as the number of the turns, required for decrease of betatron amplitudes and/or energy spread is equal to the number of the particles in the bandwidth N_u [5].

For single charged particles, limitation on the number particles in the bandwidth is restricted by requirement, that the number of radiated photons in the bandwidth must be at least one. So the minimal number of the particles in the bandwidth must be at least $N_u \sim 1/\alpha$.

So for multi charged particles the possibility for a *single turn* cooling becomes open as the number of the photons radiated must be of order of one can be satisfied for multi charged particles easily, as $Z^2\alpha \geq 1$ for ions having $Z \geq \sqrt{137} \cong 12$.

In original publication [3] it was mentioned, that the method considered could be applied to any charged particle.

Examples of applications of optical stochastic cooling for heavy ions considered in [6,7] missed this peculiarity of interaction of multi charged particles with electromagnetic wave, however.

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