Radiative Ion Cooling

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Abstract

Physics of the Radiative Ion Cooling (RIC) and possible applications of cooled ion beams are presented.

1 INTRODUCTION

Accelerated ion beams of the intermediate and high energies can be used in different fields of the science and technology. The quality of such beams is defined by the emittances of the beams. Different cooling methods are suggested to decrease the beam emittances. Among them: synchrotron radiation damping [1], electron cooling [2], stochastic cooling [3], one dimensional laser cooling [4]. In papers [5]-[8] the three-dimensional RIC method is proposed. The physics and applications of RIC are presented in this work.

2 RADIATIVE ION COOLING

RIC is the three-dimensional method of the ion beam cooling by laser light. This method is based on the backward Rayleigh scattering of the *broadband laser light* by ion beam when the radiofrequency system of the storage ring is switched on. Compared to the case of Thomson scattering on free electrons, the Rayleigh scattering cross-section of laser photons on bound electrons or complicated bare ions when the photon energy is at resonance with one of the transition energies of ions, is larger by many orders of magnitudes.

In the case of RIC the relativistic ions emit radiation mainly along the ion's velocity and that is why loose theirs both transverse and longitudinal components of the momenta. The losses of the transverse ion momenta will lead to damping of the transverse ion oscillations. The longitudinal momenta loss is compensated by the radiofrequency system of the storage ring. But the longitudinal damping will take place because the rate of the ion's energy loss depend on ion's energy. This dampings take place by analogy with synchrotron radiation damping [1]. Hence the RIC method is similar to an ordinary one dimensional laser cooling method by scheme [9] but it is similar to synchrotron radiation damping by physics.

Let a laser beam is directed against and scattered by an ion beam. Let $\hbar\omega_0$ be the transition energy in the ion's rest frame between two electronic states 1 and 2, and $\hbar\omega_r^L$ and $\hbar\omega_r^s$ be the corresponding energies of the incoming laser photons at resonance and the scattered photons in the laboratory frame, respectively. These quantities are related by

$$\hbar\omega_r^L = \frac{\hbar\omega_0}{\gamma(1-\beta\cos\psi)}, \qquad \hbar\omega_r^s = \frac{\hbar\omega_0}{\gamma(1-\beta\cos\theta)}, \quad (1)$$

where $\gamma = E/Mc^2$, E is the ion energy, M its mass $\beta = v/c$, v the ion velocity, c the speed of light, ψ the angle between the initial photon velocity and ion velocity, and θ the angle between final photon velocity and ion velocity. In this paper, we restrict to the case $\psi \simeq \pi$, $\beta \simeq 1$, $\gamma \gg 1$, in which case the above equations become $\hbar\omega_r^L \simeq \hbar\omega_0/2\gamma$, $\hbar\omega_r^s \simeq 2\gamma\hbar\omega_0/[1+(\gamma\theta)^2]$.

The frequency of the incoming laser photons and the scattered photons in the general case will be written as ω and ω^s respectively. Since we are considering the case near resonance, we have $\omega \simeq \omega_r^L$ and $\omega^s \simeq \omega_r^s$.

The maximum cross-section at exact resonance $\omega = \omega_r^L$ is $\sigma_{max} = g_2\lambda_0^2/2\pi g_1$, where $\lambda_0 = 2\pi c/\omega_0$ is the resonance wavelength corresponding to ω_0. The spontaneous linewidth is given by $\Gamma = \omega_0^2 r_e c f g_1/c g_2$, where r_e is the classical electron radius, g_1 and g_2 are respectively the degeneracy factors of the state 1 and state 2 between which the transition occurs, and $\beta_z = \beta\cos\psi \simeq 1$, f is the oscillator strength. The average cross-section of the photon scattering by ions is $\overline{\sigma} = (g_2/g_1)(\lambda_0^2/4)(\Gamma_{2,1}/\omega_0)(\omega//\Delta\omega = \pi r_e f\lambda_0\omega/\Delta\omega$, where $\Delta\omega$ is the bandwidth of the laser light. The enhancement of the resonant cross section over the Thomson cross section for a broad band laser is about a factor $(\lambda_0/r_e)(\omega/\Delta\omega)$, which is smaller than that in the case of exact resonance, but is still very large.

The number of scattered photons per ion is given by

$$\Delta n_\gamma = 2\frac{\overline{\sigma}}{(1+D)}[\frac{I}{\hbar\omega}][\frac{l_{eff}}{c}]. \quad (2)$$

The quantity $D = I/I_{sat}$ is the saturation parameter, $I_{sat} = (\pi c g_1\hbar\omega_0/\gamma^2 g_2\lambda_0^3)\ (\Delta\omega/\omega)$ and l_{eff} is the effective interaction length of the laser and ion beams, which is assumed to be much longer than the spontaneous decay length $c\tau_{spon} = c\gamma/2\Gamma$. If there are N_i number of ions in the pulse, the total number of γ-ray photons generated per ion pulse is given by $N_\gamma = \Delta n_\gamma N_i$.

The damping times of betatron and phase oscillations are determined by analogy with synchrotron radiation times by the power of the emitted (scattered) radiation [1]. In the case of the vertical betatron oscillations the damping time is

$$\tau_z = \frac{2m_i c^2\gamma}{\overline{P}^s} = \frac{SR(1+D)}{c n_{int}\lambda_0 l_{eff}\gamma f_{2,1}}\Big(\frac{\Delta\omega_{in}}{\omega_{in}}\Big)\Big(\frac{P_A}{P}\Big), \quad (3)$$

where $\overline{P}^s = \overline{\varepsilon}_\gamma \Delta n_\gamma n_{int} f$ is the mean scattered power, $\overline{\varepsilon}_\gamma = \hbar\omega_0\gamma$ is the mean photon energy, $f = c/2\pi R$ is the ion revolution frequency, $P_A = m_e m_i c^5/e^2$, M is the ion mass, $P = IS$ is the photon beam power, S is the cross-section area of the photon beam, n_{int} is the number of the interaction regions, and R is the mean radius of the storage ring orbit.

The damping times of radial betatron oscillations and phase oscillations are $\tau_x = \tau_z, \tau_s = \tau_z/(1+D)$.

Quantum nature of the photon scattering will lead to an equilibrium emittance and relative energy spread of the ion beam, when the Compton scattering takes place in the dispersion free straight section [6],

$$\epsilon_x = \frac{3}{20}\frac{\hbar\omega_0}{m_i c^2\gamma^2} < \beta_x >, \quad \frac{\sigma_\gamma}{\gamma} = \sqrt{\frac{1.4\hbar\omega_0(1+D)}{m_i c^2}}, \tag{4}$$

where β_x is the average horizontal beta function in the interaction region.

To shorten the damping times the broadband laser beam with sharp low frequency edge can be used as well. The frequency edge must be chosen of a such value that only ions with energies above γ_s will be exited equally effectively [10].

3 POSSIBLE APPLICATIONS OF COOLED ION BEAMS

3.1 Backward Rayleigh scattering sources

Spontaneous incoherent backward Rayleigh scattering sources based on resonance scattering of relativistic atoms, not fully stripped ions and bare nuclei were considered first in [11],[12]. Modern parameters of such sources presented in the papers [5]-[8]. Depending on the energy of storage ring and type of ions the energy of scattered monochromatic polarized photons can lie in wide range of energies of X-Ray to hard $\gamma-$Ray regions. The power of such sources cab be very high.

The scattered radiation will be polarized if we will use polarized initial laser radiation. It will be possible to change the kind of polarization of scattered radiation by changing the kind of polarization of initial radiation [13]. The backward Rayleigh scattering sources based on cooled ion beams are more effective and more monochromatic then backward Compton scattering sources and undulator radiation sources based on electron beams as the broadening of the Rayleigh radiation is much less when the monochromatic laser beam is used. It follows from the fact that the relative angular and energy spreads of the ion beam are essentially less and from selective interaction of laser and ion beams. Laser beam interact with ions of definite energies and all scattered radiation is emitted on the first harmonic of the laser frequency. Harmonic generation is possible in strong laser fields.

Backward Rayleigh scattering sources can find applications in the same fields of science and technology as synchrotron radiation sources and backward Compton radiation sources. Among them we should like to emphasize the applications of high intensity polarized monochromatic $\gamma-$rays of MeV and GeV regions in *nuclear and elementary particle physics.* Such beams can be produced on future storage rings like LHC.

3.2 Free-ion lasers

Under conditions of equal relativistic factors which define the hardness of the emitted radiation, ion beams possess many orders of magnitude higher stored energy and much less emittance then electron beams. For example, the electron beam of APS possess two orders higher emittance and five orders less stored energy then the proton beams of the LHC at nearly the same relativistic factors. The stored energy of the LHC will exceed 500 MJ. It follows that under conditions of optimal deflecting parameters of the undulators used in the free-particle lasers and equal efficiencies for both electron and ion beams the limiting power of Free Ion Lasers will be many orders higher then that of free electron lasers. Possible parameters of the FILs are presented in the paper [7].

3.3 Quantum generators on moving ion beams

The idea of quantum generators on moving ion beams was considered in [11] and developed in papers [14],[16]. The influence of the angular and energy spreads of the ion beams on broadening of the spectral lines and hence on the amplification is essential and three-dimensional cooling of stored beams is necessary for these generators.

3.4 Particle accelerators

Radiative ion cooling can be used for decreasing of the transverse and longitudinal emittances of the stored ion beams and for multiple injection of the ion beams in the free phase space of the storage rings. This process will permit to produce the high current and low emittance ion beams in storage rings and to increase the luminosity of the colliding beams. Stored and cooled not fully stripped heavy ion beams with a high charged state can be ionized without the lost of the beam by more hard laser light for a short time [17] in order to have the colliding beams of bare ions.

Cooled Super-high power high current ion beams of the energy $\sim$ 10 GeV or based on such beams cm-to mm FILs can be used for the excitation of the accelerator structures of the Linear Colliders [18].

3.5 Short period relativistic multilayer ion mirror

A scheme of short period relativistic multilayer ion mirror production was proposed in [18],[19]. In this scheme the ion beam can be produced in the form of a series of narrow flat layers transverse to the direction of beam propagation. This geometry is similar to that of a dielectric stack mirror. Such mirror can reflect both spontaneous incoherent and spontaneous coherent radiation with high efficiency and in a such a way to transform monochromatic IR or optical radiation to monochromatic X-ray radiation with low divergence.

3.6 Elementary particle physics

We mentioned in section 3.1 that $\gamma-$ray beam produced on cooled ion beam can be used in nuclear and elementary particle physics when working with the nuclear target at rest. A high energy ion-ion collider can be converted to a γ-γ or γ-ion collider with the photon energy in the GeV range [8], just as a high energy electron linear collider in TeV range can be converted to a TeV γ-γ collider. Experiments on excitation of electronic and nuclear transitions of cooled ions by ordinary lasers in storage rings like future collider LHC will permit to investigate the spectroscopy of all transitions in all ions of the periodical elements table (energy levels, probability transitions, branching ratios). In this case the laser light is equivalent to the beam of X-ray or γ-ray laser in the ion beam reference system. The photon energy of laser or more hard undulator radiation is enough for photodisintegration of cooled relativistic nuclei in storage rings and production of polarized, monochromatic relativistic neutron and nuclear beams with small divergence [20].

3.7 Ion fusion

Some accelerator developments in the field of accelerators and relevant to inertial fusion permit to store and compress a large amount of bismuth, lead, uranium or of similar heavy ions to reach high-likelihood conditions for inertial fusion [17],[21],[22]. With $\gamma \geq 100$ it becomes easier to design accelerators to produce high specific deposition power, although overall efficiency becomes poor. Beam cooling at full energy would be required in longitudinal degrees of freedom to produce pulse lengths down to 1 ns [22].

4 CONCLUSION

In this paper we have only considered the physics of radiative ion cooling and some possible applications. The backward Rayleigh scattering sources without doubt will be next generation of light sources of X-ray and γ-ray beams. K.-J.K. acknowledges the support of this work by the U.S. Department of Energy under Contract No DE-AC03-76SF00098.

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