Two-dimensional Cooling of Ion Beams in Storage Rings
by Narrow Broad-Band Laser Beams

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Abstract

A new scheme for the two-dimensional cooling of ion beams in storage rings is suggested in which ions interact with a counterpropagating broad-band laser beam. The interaction region in the direction of the ion movement is much less then the wavelength of the ion betatron oscillations. The laser beam in the orbit plane has sharp flat edge directed to the ion beam and the width of the laser beam of the order of the ion beam width. Laser beam radial position is being displaced with some velocity at first from inside and then from outside to the ion beam and decreases both betatron and synchrotron oscillations.

1 Introduction

A series of the ion cooling methods are suggested to decrease the emittances of charged particle beams. Among them: synchrotron radiation damping \[1\], electron cooling \[2\], stochastic cooling \[3\], one dimensional laser cooling \[4\]. Laser cooling is highly efficient in the longitudinal direction, but difficult in the transverse direction unless a special coupling mechanism is introduced \[5\], \[6\]. In papers \[6\]-\[9\] the three-dimensional RIC method is proposed. Nevertheless the quest for new cooling schemes remains vital for the cooling of both not fully stripped and fully stripped high current proton and more heavy ion beams. In this Letter, a new scheme for two-dimensional cooling of ion beams in storage rings is suggested in which photons in a counterpropagating narrow broad-band laser beam interact with ions.

To explain the basic principle of the two-dimensional cooling of ion beams in storage rings consider the process of change of the amplitude of the betatron oscillations and the position of the instantaneous ion orbit in the process of the energy loss of the ions. We will consider the case when the RF accelerating system of the storage ring is switched off.

Let us the instantaneous orbits of ions are distributed in a region $\rho_0 \pm \sigma_{\rho\varepsilon}$ and the amplitudes of ion oscillations are distributed in a region $\sigma_{\varepsilon}$ relatively to the instantaneous orbits corresponding to the ion energy $\varepsilon$, where $\rho_0$ is the location of the middle instantaneous orbit, $\sigma_{\rho\varepsilon} > 0$ mean-root square deviation of the instantaneous orbits from the middle one which is determined by the initial energy spread $\sigma_{\varepsilon}$ (see Fig. 1). A broad-band laser beam $LB1$ is situated at the orbit region $(\rho_{ph}, \rho_{ph} - a)$, where $a$ is the laser beam width. The upper edge of the laser beam must have the form of the flat boundary and its lower part must have smooth decay of density or width. In such scheme the laser beam overlap only a part of the ion beam.
In this scheme the ions with the largest amplitudes of betatron oscillations will interact with the laser beam first. At that the interaction will take place only at the moment when the ion deviation caused by the betatron oscillations will have approximately the amplitude value and the deviation will be directed toward the laser beam. Immediately after the interaction the position of the ion will be the same (inside the laser beam LB1 and near to its edge) but the instantaneous orbit will be displaced inward in the direction of the laser beam. It means that after interaction both the position of the instantaneous orbit and the amplitude of the betatron oscillations will be changed at the same value. After every interaction the position of the instantaneous orbit will be nearer and nearer to the laser beam and the amplitude of the betatron oscillations will be smaller and smaller until it will reach zero. At the same time the instantaneous orbit will reach the edge of the laser beam. Up to that time the instantaneous orbit will go with some velocity $\dot{\rho} = d\rho/dt$ in the direction of the laser beam and will not get deeper into the laser beam.

![Diagram of ion cooling](image)

**Fig. 1:** The scheme of the two-dimensional ion cooling. The axis $y$ is the equilibrium orbit of the storage ring, 1-1, 2-2 ... the location of the instantaneous ion orbit after 0,1,2 ... events of the ion energy loss, LB1 and LB2 are the laser beams moving by turns with the velocity $v_{1,2}$ from outside to the equilibrium orbit.

At the moment when the instantaneous orbit will enter the laser beam the amplitude of the ion betatron oscillations will be small. After the instantaneous orbit will enter the laser beam then it will continue its movement but now it will move through the laser beam. Now the amplitude will be increasing proportionally to the root-mean-square of the number of the interactions of the ion with the laser beam that is slowly then the decreasing of the
amplitude in the previous case (proportionally to the number of the interactions). This is because of the ion will interact with the laser beam both with positive and negative deviation from the instantaneous orbit.

The ion beam has a set of amplitudes of betatron oscillations and instantaneous orbits. To cool all ions of the beam we must move the laser beam radial position with some velocity \( v_1 \) in the direction of the ion beam or move the instantaneous orbits by kick, phase displacement or eddy electric fields in the direction of the laser beam. This velocity must be much less then the velocity of the instantaneous orbit \( \dot{\rho} \). In this case the amplitudes of the betatron oscillations will be in time to decrease theirs amplitudes to small values before they enter the laser beam. After all ions of the ion beam will be in the state of interaction with the laser beam then the laser beam must be stopped. After the stop the ions will continue to move to the tapered edge of the laser beam with the decreasing velocity and will be gathered at this edge. The longer we will wait the less the energy spread will be obtained.

As the thickness of the laser beam will be the less the nearer the ion orbit to the remote edge of the laser beam then the damping time will be too high if we will wait for a small energy spread of the cooled ion beam. To shorten this damping time we can use the second laser beam from the opposite side of the ion beam (see Fig.1). At this stage the ion beam will have small amplitudes of betatron oscillations. The second laser beam radial position must be moved to the ion beam with the velocity slightly higher then the average velocity of movement of the instantaneous ion orbit which is determined by the intensity of the laser beam. In this case the ion orbits will be in time to enter into the laser beam at a distance higher then the residual amplitude of ion betatron oscillations and hence the amplitude of betatron oscillations at this stage will be increased slowly with the number of interactions (according to the root-mean-square law). High energy ions first of all and then ions with smaller energies will interact with the laser beam. This process will last until laser beam will reach the instantaneous orbit with the least energy and ions of this orbit will be cooled. Such a way we can repeat the cooling process and to reach the energy spread of the ion beam

\[
\frac{\Delta \varepsilon_i}{\varepsilon_i} \simeq \pm \frac{\varepsilon_{int}}{Mc^2\gamma},
\]

where \( \varepsilon_i = Mc^2\gamma \) is the ion energy, \( M \) ion rest mass, \( \varepsilon_{int} \) the average energy of the ion loss per one event of interaction, \( \gamma \) the relativistic factor of the ion.

The second laser beam can be monochromatic one with the sweeping frequency and overlap the ion beam as a whole. In this case the ordinary one-dimensional laser cooling will take place at the second stage of the laser cooling.

The two-step scheme will work in the case when the RF system of the storage ring is switched on as well. Some peculiarities will be in this case.

The number of interactions of one ion with the laser beam per one collision of the ion with a laser beam

\[
\Delta N_{int} = (1 + \beta) \frac{I_L}{h\omega_L} \frac{l_L}{c} \sigma,
\]

where \( \beta = v/c \), \( v \) is the ion velocity, \( I_L \) the laser intensity (power per unit area), \( h\omega_L \) the energy of the laser photon, \( l_L \) the length of the interaction region of the laser and ion beams, \( \sigma \) the cross section of the process of the laser photon-ion interaction.

The damping time of the ion beam in this scheme is \( \tau = \tau_s + \tau_b \), where

\[
\tau_s = \frac{\sigma_e}{k_1f\Delta N_{int}\varepsilon_{int}}, \quad \tau_b = \frac{\sigma_{eb}}{k_2f\Delta N_{int}\varepsilon_{int}},
\]
\(\tau_s\) is the ion cooling time for the longitudinal (energy - length) space, \(\tau_b\) the ion cooling time for the radial betatron oscillations, \(f\) the frequency of the ion beam revolution in the storage ring, \(\sigma_{ne} = \sigma_b \varepsilon / \alpha R\) the energy interval corresponding to one for the instantaneous orbits distributed through the interval of radii \(\sigma_b, R\) the average radius of the storage ring, \(k_1, k_2\) are the ratio of the velocity of movement of the first and second laser beam to the average velocity of movement of the ion instantaneous orbit caused by the interaction of the ions with the laser beam respectively, \(\alpha\) the momentum compaction function.

We now consider two examples of the two-dimensional ion cooling. First the hydrogen-like \(Pb\) ion beam in the CERN LHC, for which the relevant parameters are \(2\pi R = 27\) km, \(\gamma = 3000, Mc^2\gamma = 575\) TeV, \(Z = 82, \sigma_x = 1.2 \cdot 10^{-3}, \Delta\gamma / \gamma = 2 \cdot 10^{-4} (\sigma_\varepsilon = 1.15 \cdot 10^{11} \text{eV})\). Ion beam cooling occurs through the backward Rayleigh scattering of the laser photons. For the bandwidth of the laser beam \(\Delta\omega_L / \omega_L = 10^{-4}\), the transition between the IS ground state and the \(2P\) excited state of a hydrogenlike \(Pb\) ion, we obtain from the well-known formulas the value of the resonant transition energy \(\hbar\omega^* = 68.7\) keV, the cross section \(\sigma = 6.58 \cdot 10^{-18}\) cm\(^2\), average energy of the scattered photon \(\langle \hbar\omega \rangle = \varepsilon_{int} = 0.2\) GeV, and the required laser wavelength \(\lambda_L = 1080\) Å [7]. The laser cross section is larger than that of the ion beam as long as the Rayleigh length \(z_R = \pi \sigma z^2 / \lambda_L \geq 0.42\) cm. We will choose the value \(l_L = 2z_R = 15\) cm for the rms transverse laser beam size at its waist \(\sigma_L = 5.8 \cdot 10^{-3}\) cm and the power of the laser beam is \(P_L = 400\) W. In this case \(I_L = 4.94\) MW/cm\(^2\), \(\hbar\omega_L = 11.49\) eV, \(f = 1.11 \cdot 10^4\) Hz, \(\Delta N_{int} = 1.68 \cdot 10^{-2}\), the damping time \(\tau_{b|k_{1}=10} \approx 3.06\) sec. The damping time for the betatron oscillations \(\tau_{b|k_{2}=1,1} \approx 0.28\) sec when the value \(\sigma_{eb} = \sigma_\varepsilon\). The limiting relative energy spread (1) in this case \(\Delta\varepsilon_i / \varepsilon_i \approx 3.5 \cdot 10^{-7}\). A metal screen can be used to produce the laser beam with sharp edge.

In the second example the ion cooling of fully stripped \(Pb\) ion beam of LHC occurs through the electron-positron pair production [10], [11]. The parameters of the ion beam and the cross section of the laser beam are those of the previous example. In this case the threshold energy of the laser photon beam \(\hbar\omega_{L, thr} = 335\) eV. We choose the photon energy \(\hbar\omega_L = 670\) eV and the power \(P_L = 10^6\) W. In this case \(I_L = 1.23 \cdot 10^{10}\) W/cm\(^2\), \(\lambda_L = 18.5\) Å, \(z_R = 57\) cm, \(l_R = 115\) cm, \(\sigma = 8.1 \cdot 10^{-24}\) cm\(^2\), \(\varepsilon_{int} \approx 2mc^2 \approx 3.06\) GeV [11], \(\Delta N_{int} = 6.84 \cdot 10^{-6}\), \(\tau_{b|k_{1}=10} = 4.95 \cdot 10^3\) sec \(\approx 1.38\) h, \(\tau_{b|k_{2}=1,1} = 4.5 \cdot 10^2\) sec. The average power \(\overline{P}_L = 10^6\) W in 1 Å region is not real now. But if all particles of the ion beam will be gathered in one bunch of the length \(l_{ion} = l_L / 2 = z_R\) and the laser beam will consist of the wavepackets of the length \(l_L = 2z_R\) which follow with the frequency \(f\), then the average laser power can be decreased \(2\pi R / l_{ion} = 2.35 \cdot 10^4\) times that is to the value \(\overline{P} = 43\) W at the same damping time \(\tau_{s|k_{1}=10} \approx 1.38\) h. The limiting relative energy spread (1) in this case \(\Delta\varepsilon_i / \varepsilon_i \approx 2.7 \cdot 10^{-6}\).

We can get the part of the LHC trajectory with the average value of the \(\beta\)-function \(\overline{\beta} = 62\) m [12] to work with higher dimensions of the ion beam. Such interaction can take place in the banding magnet of the LHC and the laser beam with sharp edge can fall at some small angle to the plane of the ion orbit in order to the interaction took place at short distance \(l_L\) and the boundary of the laser beam was flat through the interaction region. The examples show that the suggested version of the two-dimensional cooling is more efficient then the three-dimensional radiative laser cooling scheme for the case of the resonant Rayleigh backscattering scheme [7]. The ion cooling through electron-positron pair production is possible in principle in this scheme. Some problems can arise for the heavy ion cooling in the last case because of strong \(Z\)-dependence of the probability of the electron capture by ion from the produced pair [12]. The scheme under consideration based on the backward Compton scattering can be used in the case of the electron cooling as well.
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