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SIMULATION OF LASER COOLING OF HEAVY ION BEAMS AT HIGH INTENSITIES

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Abstract

In the past the principle of Doppler laser cooling was investigated and verified in storage rings in the low energy regime. Within the FAIR project the laser cooling will be applied to high intensity and high energy beams for the first time. The laser cooling results in a further increase of the longitudinal phase space density and in non-Gaussian longitudinal beam profiles. In order to ensure stable operation and optimize the cooling process the interplay of the laser force and high intensity effects has to be studied numerically. This contribution will identify constrains of the cooling scheme for an efficient reduction of momentum spread. For high beam energies the scattering of photons has to be treated stochastically instead of using averaged forces. The modeling of the laser force in a particle in cell tracking code will be discussed.

INTRODUCTION

Laser cooling produces ultra cold ion beams by intersecting laser light anti parallel with the particle beam. The momentum kick of the absorbed photon always points in direction of the laser beam, whereas the emission is isotropically distributed. For many scattering events the effect of the emission vanishes and the directional force of the absorption remains as shown in Fig. 1. Indeed this process requires a precise matching of the laser wavelength in the particle frame to the energy of the atomic transition. For available laser light sources this fact assigns a constrain on the beam velocity depending on the chosen transition as discussed in ref. [1].

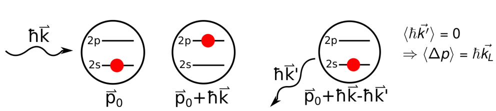

Figure 1: Sketch of a scattering event. Directional absorption and isotropic emission of photons leads to net force used for laser cooling.

The laser force requires a counteracting force to cool an ion beam. A second laser in opposite direction is the most efficient way for ion traps and low energy storage rings. For higher beam energies the best solution is given by capturing the particles in a rf bucket. The narrow laser force does not interact simultaneously with all ions in a hot particle bunch. Therefore the position of the laser force is scanned in order to damp continuously the synchrotron oscillation of all particles as shown in Fig. 2.

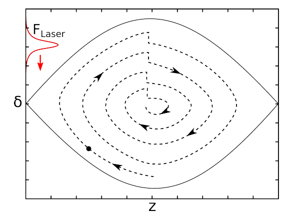

Figure 2: Sketch of the cooling process for a hot ion beam in a rf bucket. The laser force is scanned to damp continuously the synchrotron oscillation of all particles.

MODELING OF THE LASER FORCE

The influence of the laser force on the particle dynamic cannot be described by a cooling rate because of its strong non-linearity. In order to determine cooling equilibriums and optimize the general cooling process the longitudinal particle dynamics are solved numerically. For simplicity, the study contains only longitudinal dynamics assuming that the transverse motion is unaffected by the laser cooling.

The cooling force in the laboratory frame (LF) is given by the momentum change of one scattering event times the scattering rate.

$$F^{cool} = \Delta p^{LF} \cdot k \tag{1}$$

As shown in Fig. 1 the momentum change is given by the difference of the momentum of the incoming and outgoing photon:

$$\begin{aligned} \Delta p^{LF} &= \Delta p^{LF}_{in} - \Delta p^{LF}_{out} && (2)\\ &= -\frac{\hbar\omega^{LF}}{c_0} - \frac{\hbar\omega^{LF}}{c_0}\frac{U_i+\beta}{1-\beta} && (3)\\ &= -\frac{\hbar\omega^{LF}}{c_0}\gamma^2(1+\beta)\cdot(1+U_i) && (4)\end{aligned}$$

Where U_i is a random number between -1 and 1 that describes the projection of the isotropically radiated photon on the longitudinal axes. Note that the Lorentz boost of the outgoing photon provides a kick that is approximately $2\gamma^2$ higher than the incoming photon.

The scattering rate is given by the occupation of the excited state divided by its lifetime:

$$k = \frac{1}{\tau}\cdot\rho_{ee} \tag{5}$$

For simulations the ion-photon interaction is reduced to an atomic two level system in an electromagnetic mode and

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is described by a 2×2 density matrix. In general the time evolution of this density matrix can be calculated with:

$$\dot{\rho} = \frac{i}{\hbar} [H, \rho] \qquad \text{with } \rho = \begin{pmatrix} \rho_{ee} & \rho_{eg} \\ \rho_{ge} & \rho_{gg} \end{pmatrix} \tag{6}$$

The final set of four coupled differential equations for each element of the density matrix is called optical Bloch equations (see ref. [2]).

The optical Bloch equations can be solved numerically with a time dependent laser intensity. In case of a cw laser and a circulating ion beam the excitation intensity is given by a rectangular pulse with the length of the interaction section. The response of the ion ensemble is shown in Fig. 3 for three different laser intensities. In this case the excitation probability is already saturated and the finite pulse length does not lead to a noticeable broadening of the width of the laser force. The stationary solution of the optical Bloch equation is a proper approximation (see ref. [2]):

$$\rho_{ee} = \frac{1}{2} \frac{S}{1 + S + (2\Delta\omega \cdot \tau)^2} \tag{7}$$

Where S describes the ratio of the laser intensity to the saturation intensity of the atomic transition.

In simulations the momentum change of each scattering event has to be calculated successively, because the excitation probability changes after each scattering event due to the narrow laser force.

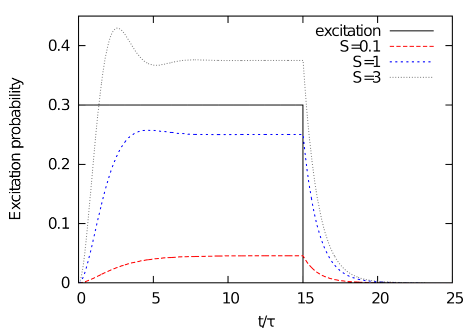

Figure 3: Excitation probability over time in units of the lifetime of the excited state for three different saturation parameters of the cw laser system.

COOLING SCHEMES

The success and efficiency of the cooling process depend strongly on the way the cw laser is moved through the particle distribution. The speed of the synchrotron motion separates three different techniques. As a first step, very low intensities are assumed to neglect intra beam scattering and space charge.

High Synchrotron Frequency

The conventional cooling scheme for high synchrotron frequencies scans the cw laser from the outside of the bunch to the synchronous particle. Because of the synchrotron motion the particles are pushed symmetrically to the center

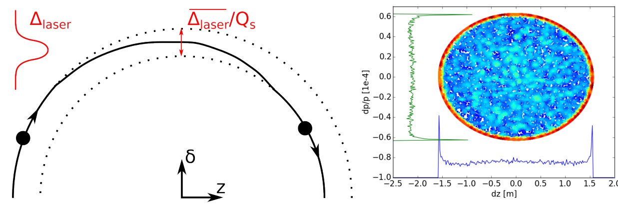

Figure 4: Sketch and snapshot of simulation of cooling scheme for high synchrotron frequencies. The synchrotron oscillation is smoothly damped.

of the bunch. The momentum and spatial deviations are reduced simultaneously. This method was already tested in storage rings as reported in ref. [3]. As shown in Fig. 4 the cooling reduces smoothly the size of the circular trajectory of the particles. For high synchrotron frequencies the particles couple to the laser light only for a few turns. The slightly disturbed motion can again be approximated by a circular motion. The relative momentum kick $\Delta_{laser}(\delta_{Pos})$ averaged over one synchrotron period for a particle with a relative momentum deviation of δ_{pPos} is given by:

$$\overline{\Delta_{laser}}(\delta_{pPos}) := \frac{1}{2\pi} \int_0^{2\pi} \Delta_{laser}(\delta_{pPos} \cdot \cos(\phi) - \delta_{laserPos}) \cdot \cos(\phi) d\phi \tag{8}$$

The maximum displacement of the laser position per turn d_{scan} is given by:

$$d_{scan} < max\left(\overline{\Delta_{laser}}(\delta_{pPos})\right) \tag{9}$$

In reality the statistical process of the laser force and the finite steps of the synchrotron motion lower this limit slightly. In order to compensate this an additional factor of approximately 0.8 is necessary. The required cooling time for a bunch with a maximum relative momentum deviation of δ_{max} is given by:

$$T_{cool}^{CS1} = \frac{\delta_{max}}{d_{scan}} \cdot T_{rev} \tag{10}$$

Low Synchrotron Frequency

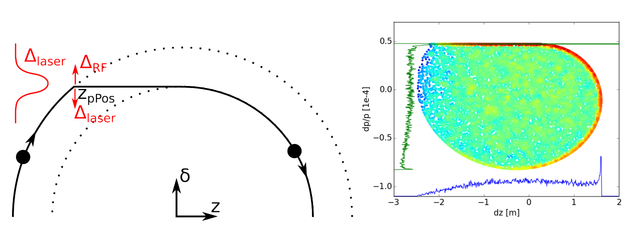

Figure 5: Sketch and snapshot of simulation of cooling scheme for low synchrotron frequencies. The particles are captured in front of the laser force.

For lower synchrotron frequencies the particles interact with the laser light for many turns. This leads to a strong perturbation of the circular motion in the rf bucket as illustrated

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in Fig. 5. The laser force catches the particles and keep them in resonance for a long time if the laser is stronger than the rf kick. The condition for this more efficient cooling of the particle at $z = z_{pPos}$ is:

$$\Delta_{rf}(z_{pPos}) \lesssim \Delta_{laser} \quad \text{with} \quad Q_s > 0 \tag{11}$$

Using geometrical constrains the condition results in the maximum scan per turn:

$$d_{scan} = Q_s \cdot \delta_{max} \cdot \left(1 - \sqrt{1 - \frac{z_{pPos}^2}{z_{max}^2}}\right) \tag{12}$$

Where Q_s is the synchrotron tune, z_{max} the maximum spatial size of the bunch and z_{pPos} fulfills the condition in equ. 11. The required cooling time contains an additional half synchrotron period in order to wait until all particles are rotated into the laser force at the final position of the laser:

$$T_{cool}^{CS2} = \frac{\delta_{max}}{d_{scan}} \cdot T_{rev} + \frac{1}{2Q_s} \cdot T_{rev} \tag{13}$$

The spatial size is only reduced to the final bunch length of:

$$L_f^{CS2} = \frac{3}{4Q_s} \cdot \frac{d_{scan}}{\delta_{max}} \cdot z_{max} \tag{14}$$

Very Low Synchrotron Frequency

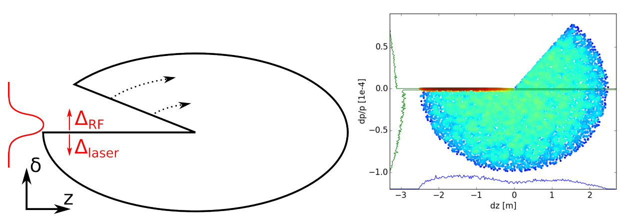

Figure 6: Sketch and snapshot of simulation of the third cooling scheme. The laser force is stronger than the rf kick for all particles. The whole bunch rotates into the laser force.

For even lower synchrotron frequencies equ. 11 is valid for the highest amplitude z_{max}. This gives the opportunity to set the position of the laser force directly to the center of the bunch. The rf kick is smaller than the laser kick for all particles and the bunch is rotated into the barrier of the laser force. The condition is given by:

$$\Delta_{rf}(z_{max}) < \Delta_{laser} \quad \text{with} \quad Q_s > 0 \tag{15}$$

The spatial bunch length is only reduced by a factor of 2 and the cooling time is given by one synchrotron period:

$$T_{cool}^{CS3} = \frac{1}{Q_s} \cdot T_{rev} \tag{16}$$

Cooling Times

In the following the three different cooling schemes are compared. As an example the transition $2p_{1/2} \Rightarrow 2s_{1/2}$ in Li-like ions in the SIS100 with $\gamma_t = 15$ is used. The lifetime elliptical bunch with a size of $\delta_{max} = 10^{-4}$ and $z_{max} = 2.5$ m is used. The laser wavelength is 256 nm, the laser interaction region is 26 m and the laser intensity is adjusted to three different values of the saturation parameter.

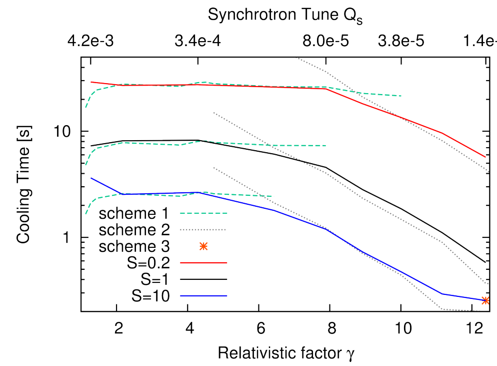

Figure 7: Cooling time for different Li-like Ions. Simulation results are compared to esimations of equ. 10 (green) and equ. 13 (gray) for three different saturation parameters S. The condition of the third cooling scheme is only satisfied for $\gamma = 12.4$ and $S = 10$.

Figure 7 shows the minimum cooling time for different Li-like ions. A further increase of the laser scan speed leads to loss of particles for the cooling process. The required cooling time varies for these examples between 30 s and 0.1 s. The analytic predictions represents the simulations nicely.

CONCLUSION AND OUTLOOK

The photon-ion interaction is successfully integrated in a longitudinal tracking code and can be analyzed for arbitrary laser pulse shapes. The dynamic of different ions under influence of the laser force was studied. For low intensities the bunch evolution separates into three different kinds of cooling mechanisms depending on the synchrotron frequency. The derived constrains agree with simulation results.

The next step is to analyze the interplay of the laser force and high intensity effects. The influence of space charge and intra beam scattering on the constrains of different cooling schemes and bunch profiles are very important. Finally the general stability of the generated non-Gaussian bunch forms has to be studied.

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