SIMULATION STUDIES OF INTENSITY LIMITATIONS OF LASER COOLING AT HIGH ENERGY

L. Eidam*, TEMF, TU Darmstadt, Germany
O. Boine-Frankenheim, GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Germany
D. Winters, GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Germany

Abstract

Within the FAIR project, laser cooling of highly intense, ultra relativistic ion beams will be attempted for the first time, and in a large (circumference 1084 m) and strong (max. magnetic rigidity 100 Tm) synchrotron, called "SIS100".

Laser cooling of such ion beams should result in a further increase of the longitudinal phase space density and in non-Gaussian longitudinal beam profiles. For stable operation of such ion beams, and for optimization of the cooling process, both the laser force and the high-intensity effects have to be studied numerically in advance. The efficiency of laser cooling has been analyzed for different synchrotron frequency regimes. At high beam intensities, intra-beam scattering and space-charge effects have been found to counteract the laser cooling force. We will discuss how they influence the laser cooling efficiency and thus affect the cooling time.

INTRODUCTION

Laser cooling of stored coasting and bunched ion beams has been investigated experimentally at the TSR in Heidelberg (Germany) [1, 2], and at ASTRID in Aarhus (Denmark) [3,4]. At the ESR in Darmstadt (Germany), first laser cooling experiments with stored "bunched relativistic" ion beams were conducted [5]. In the future laser cooling will be applied to highly intense and ultra relativistic ion bunches within the FAIR project [6].

The principle of laser cooling is, especially after the Nobel Prize in 1997, very well known. Here, we consider an ion with a fast atomic transition, e.g. 2s - 2p (electric dipole), of a particular wavelength λ, and a well-defined velocity $v = \beta c$. When the ion moves towards a counter-propagating photon from a laser beam, both the energy and the momentum of the photon are absorbed in a single scattering event, see Fig. 1. This brings the ion in an excited state, which, however, de-excites almost instantaneously by fluorescence emission. The corresponding recoil then occurs in a random direction. After many scattering events, the random recoils average out to zero, but photon absorption always came from one direction, thus decelerating the ion. A pure deceleration force is highly unwanted here, but a strong reduction of the velocity spread of the ions is. Therefore, a counter-balancing force is required, which comes from bunching the ion beam: the rf-bucket force. The laser must thus address ions orbiting with relativistic velocities and performing synchrotron oscillating in the rf-bucket.

* L.Eidam@gsi.de

Since the Doppler-width of the transition is usually much smaller than the particle distribution, the laser light can only interact with a certain velocity class of ions in the beam. To address the full range of velocities, the laser must be scanned over a large range.

In this work, we analyze the dynamics of an ion beam during the laser cooling process, using a one dimensional particle-in-cell code. The transverse plain is assumed to be unaffected by the laser force. By using "macro particles" the modeling of direct coulomb interactions between single particles is not possible. The results at very low momentum spreads might therefore not be very exact, but the focus of this work lies on the cooling process and the intensity limitations of laser-cooled ion beams.

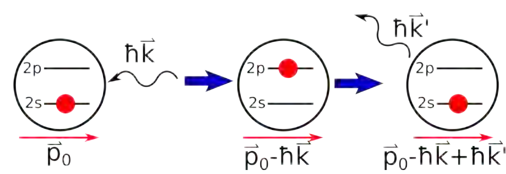

Figure 1: A single scattering event: The ion (traveling to the right) absorbs a photon from the laser beam (traveling to the left) followed by a spontaneous emission. After many scattering events, the momentum transfer of the random recoils average out to zero, but the momentum of the absorption always decelerate the ion.

The laser particle interaction is a statistical process. The probability of a spontaneous emission in a time interval Δt is given by

$$\rho_{emit} = \frac{\Delta t}{\tau} \cdot \rho_{ee} \qquad (1)$$

where τ is the lifetime of the exited state and ρ_{ee} is the excitation probability. For a saturated transition the excitation probability is given by (see ref. [7])

$$\rho_{ee} = \frac{1}{2} \frac{S}{1 + S + (2\Delta\nu \cdot \tau)^2} \qquad (2)$$

where S is the Saturation parameter and $\Delta\nu$ the detune between the frequency of the photon and the transition. For arbitrary excitations the optical Bloch equations have to be solved as described in [8]. The momentum kick of one spontaneous emission is given by

$$\Delta p_{lab} = \frac{\hbar\omega_{lab}}{c_0} \cdot \gamma^2 (1 + \beta) \cdot 2U_j \qquad (3)$$

where ω_{lab} is the frequency of the incoming photons in the laboratory frame and U_j a random number between 0 and 1, describing the projection of the randomly emitted photon.

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COOLING PROCESS

The cooling process of a particles distribution requires a stable point, where the sum of all forces cancels, surrounded by a friction force. In order to achieve a stable point for laser cooling process the laser force is counteracted by the RF voltage. The narrow laser force does not interact simultaneously with all particles. Therefore the position of the laser force is scanned from the position of the particle with the highest oscillation amplitude to the synchronous particle in order to damp the oscillation in the bucket of all particles like shown in Fig. 2.

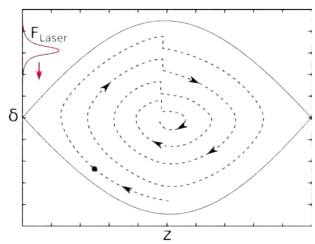

Figure 2: Sketch of the cooling process for a hot ion beam in a rf bucket. The laser force is scanned to damp continuously the synchrotron oscillation of all particles.

An example of the relative momentum rms during the cooling process is shown in Fig. 3. Up to a certain speed of the laser scan all particles are pushed in front of the laser force and the final momentum deviation reach the Doppler limit. Above this point the laser scan is too fast and particles get lost behind the narrow force. The lost particles do not interact with the laser light anymore and result in a much higher final momentum deviation as shown in Fig. 4. In the following this threshold is called 'minimal cooling time'.

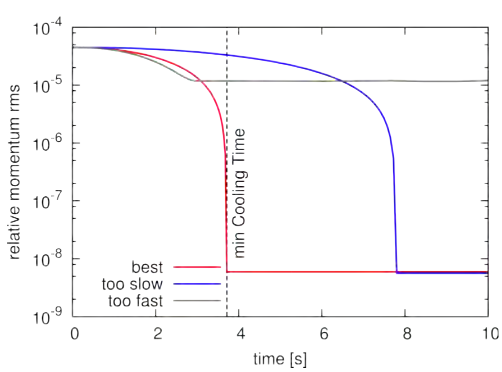

Figure 3: Relative momentum spread over time for three different speeds of the laser scan. The required time of the fastest successful cooling process is defined as minimal cooling time.

Beside the speed of the laser scan the speed of the synchrotron motion affects the efficiency of the cooling process. The synchrotron motion is characterized by the synchrotron tune, that describes the fraction of the synchrotron motion

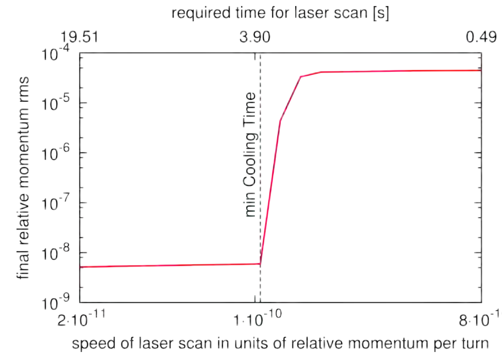

Figure 4: Minimal relative momentum deviation for different laser speeds. The required time of the fastest successful cooling process is defined as minimal cooling time.

for one turn in the synchrotron:

$$Q_s = -\frac{L\eta \cdot \hat{\delta}}{2\pi \hat{z}} \text{ with } \eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \quad (4)$$

where L is the circumference of the accelerator, γ_T the relativistic factor at transition energy and $\hat{\delta}$ and $\hat{z}$ are the amplitudes of the elliptic particle distribution in phase space. For high values of the relativistic factor ($\gamma < \gamma_T$) the speed of the synchrotron motion decreases. The synchrotron tune separates the cooling process into three different regimes. For high synchrotron tunes ($Q_s \approx 10^{-3}$) the spatial and relative momentum deviation is reduced simultaneously. Because of the high synchrotron frequency the particles are symmetrically pushed to the center of the bunch. This method was already tested in low energy storage rings as reported in ref. [9].

For medium synchrotron tunes ($Q_s \approx 10^{-4}$) the oscillation is too slow to keep the symmetry in phase space. The particles interact with the laser light for many turns and the circular motion is strongly perturbed.

For low synchrotron tunes ($Q_s \approx 10^{-5}$) the laser force becomes stronger than the kick of the RF cavities. This enables to position the laser force directly in the center of the bunch. All particles are rotated into the laser light and are captured in front of the laser force. The cooling of the bunch requires only one single synchrotron period. In contrast to the symmetric reduction in phase space the bunch length is only reduced by a factor of two. The particle motion in the bucket for these three different regimes of synchrotron tune are illustrated in detail in ref. [8].

The influence of the synchrotron tune on the required time for the cooling process is shown in Fig. 5. The spatial and relative momentum amplitudes of the initial elliptic distribution are $\hat{\delta} = 10^{-4}$ and $\hat{z} = 2.5m$. The FWHM of the laser force in units of relative momentum is $\Delta_{FWHM} = 10^{-7}$ and the interaction time of the laser light and the particle bunch is set to 40 lifetimes of the excited state. The results for three different values of relative momentum kick per scattering events are given. A detailed explanation of the analytic estimations illustrated by the dashed lines is given in ref. [8].

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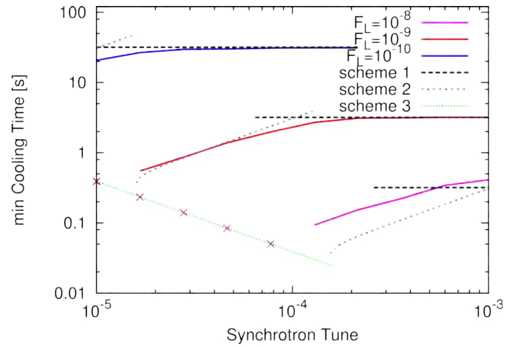

Figure 5: Required cooling time for different synchrotron tunes.

INTENSITY EFFECTS

For higher beam intensities heating processes counteract the cooling and limit the lowest attainable momentum deviation. In this section the influence of coulomb interactions of the particles is analyzed. The two effects Intra beam scattering (IBS) and space charge are discussed separately.

Intra Beam Scattering

Intra beam scattering describes the coupling of the three dimensions of motion by multiple small angle coulomb scattering events. For high energy beams the transverse oscillations are usually much stronger than the longitudinal motion and therefore heat is transfered to longitudinal oscillations. This effect can be described by the diffusion coefficient in the Vlasov-Fokker-Planck-equation. In simulations the random momentum kick for one particle is given by

$$\delta_{IBS} = Q_j \cdot \sqrt{2D_{zz}\frac{L_{acc}}{\beta c_0}} \qquad (5)$$

where Q_j is a Gaussian distributed random number and D_{zz} is the diffusion coefficient, that can be calculated for non-Gaussian distributions with the local diffusion model as described in ref. [10].

For the cooling process with a scanning laser the minimal relative momentum deviation and corresponding bunch length for different intensities is shown in Fig. 6.

The effect of IBS on the cooling process can be estimated by the rms rate equilibriums. The average of the laser force δ_L for one synchrotron motion is given by

$$\langle\Delta\delta_L\rangle_{syn} = \frac{1}{\pi}\int_0^{\pi}\cos(\phi)\cdot\Delta\delta_L(\delta_{pos}\cdot\cos(\phi))d\phi \qquad (6)$$

where δ_{pos} is the amplitude of a particle oscillation in units of relative momentum. For the final position of the laser force, close to the center of the bunch, the averaged force agrees with a linear friction force for small momentum deviations. The exponential cooling time in this region can be calculated by:

$$\tau^{-1}_{Laser} = \frac{1}{T_{rev}}\cdot\frac{\partial\langle\Delta\delta_L\rangle}{\partial\delta_{pos}} \qquad (7)$$

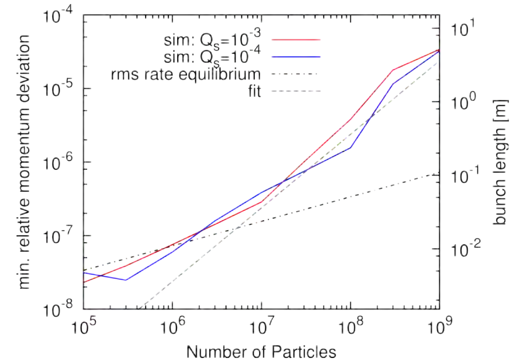

Figure 6: Influence of IBS on minimal relative momentum deviation for symmetric reduction of phase space. The rms equilibrium for low momentum deviations and the proportionality for higher momentum deviations agree with simulations.

The minimal relative momentum deviation is given by the equilibrium of the laser cooling rate and the intra beam scattering growth rate:

$$\tau^{-1}_{IBS} + \tau^{-1}_{Laser} = 0 \qquad (8)$$

This equilibrium only exist for relative momentum deviations in the linear region ($\delta_{pos} < 10^{-7}$) of equ. 6. For higher momentum deviations the rms rate equilibrium is not valid anymore. Instead the minimal relative momentum deviation is limited by a critical IBS kick, that pushes the particles behind the narrow laser force.

$$\langle\delta_{IBS}\rangle_{max} = const. \Rightarrow \frac{N}{\delta_{rms}} = const. \qquad (9)$$

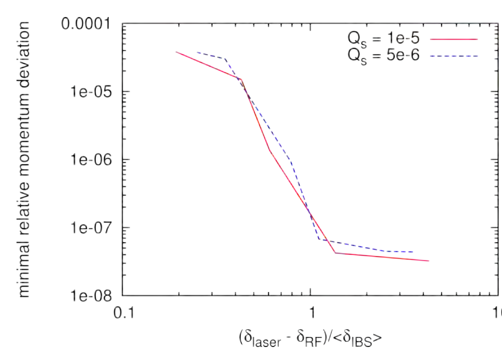

Figure 7: Influence of IBS on minimal relative momentum deviation for fixed laser scheme. The cooling is successful if the fraction of the cooling force and IBS kick is greater than one.

For the cooling process with the fixed laser position the relative momentum deviation is shown in Fig. 7. The results are plotted against the fraction of the cooling force, given by the difference of the laser force and the RF-kick, and the random IBS kick. Hence the condition for an efficient

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cooling process is given by:

$$\hat{\delta}_{Laser} - \hat{\delta}_{RF} > \sqrt{2D_{zz}\frac{L_{acc}}{\beta c_0}} \tag{10}$$

In case the beam intensity is too strong particles are kick beyond the barrier of the laser force.

Space Charge

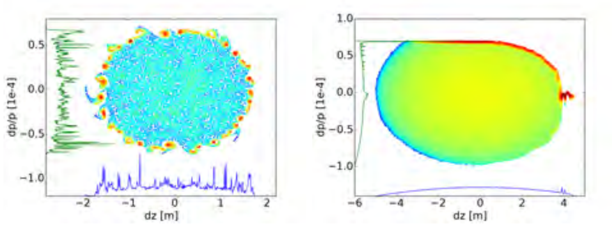

Figure 8: Longitudinal phase space of simulation with space charge. Instabilities for the two cases of high synchrotron tune left and medium synchrotron tune right.

Space charge describes the interaction of particles with the electric field of the bunch in a perfectly conducting pipe. In the longitudinal tracking code this effect is implemented by using the space charge impedance in frequency domain.

The effects of space charge on the particle bunch with scanning laser are shown in Fig. 8. For high synchrotron tune an intense, narrow ring of particles is formed in longitudinal phase space. Applying space charge this ring shows a kind of two stream instability. For high particle intensities the instability rise time is in the range of the cooling time and avoids further cooling of the particle distribution.

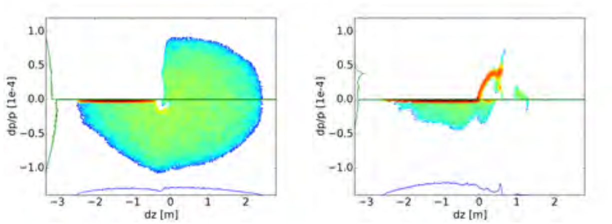

Figure 9: Longitudinal phase space of simulation with space charge of fixed laser scheme. Deformation of bunch for lower intensity (left). For higher intensities space charge kicks some particles beyond the laser force (right).

For lower synchrotron tunes the narrow peaks at the end of the bunch produce strong space charge fields (Fig. 8 right). For high particle intensities these strong space charge fields overcome the RF-kick and stop the synchrotron motion locally. Without the synchrotron motion the cooling process does not work anymore.

For the fixed laser configuration at low synchrotron tunes space charge strongly deforms the elliptic distribution. The success of the cooling process is limited by a certain intensity where the deformation is too strong and the arising space charge fields push particles beyond the laser force.

CONCLUSION AND OUTLOOK

The photon-ion interaction is successfully implemented in a longitudinal tracking code and can be analyzed for arbitrary excitation shapes. Neglecting intensity effects it was shown, that the cooling process depends strongly on the synchrotron tune. Three different regimes were separated and the required cooling times were compared. The effect of space charge and intra beam scattering were analyzed. Both effects limit the maximum intensity.

The exact limits of space charge induced instabilities have to be studied. Further intensity limiting effects like longitudinal coupling impedance has to be analyzed. Beside the effects of a current-wave laser the behavior of the particle beam interacting with a pulsed laser system has to be studied in detail.

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