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Cooling rates and intensity limitations for laser-cooled ions at relativistic energies

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A B S T R A C T

The ability of laser cooling for relativistic ion beams is investigated. For this purpose, the excitation of relativistic ions with a continuous wave and a pulsed laser is analyzed, utilizing the optical Bloch equations. The laser cooling force is derived in detail and its scaling with the relativistic factor γ is discussed. The cooling processes with a continuous wave and a pulsed laser system are investigated. Optimized cooling scenarios and times are obtained in order to determine the required properties of the laser and the ion beam for the planed experiments. The impact of beam intensity effects, like intrabeam scattering and space charge are analyzed. Predictions from simplified models are compared to particle-in-cell simulations and are found to be in good agreement. Finally two realistic example cases of Carbon ions in the ESR and relativistic Titanium ions in SIS100 are compared in order to discuss prospects for future laser cooling experiments.

1. Introduction

The relative momentum spread of a particle ensemble can be strongly reduced by means of laser cooling [1]. This offers great perspectives for future facilities that will provide high-quality stored ion beams for precision experiments. Laser cooling of stored coasting and bunched ion beams has been demonstrated at the TSR in Heidelberg (Germany) [2,3], and at ASTRID in Aarhus (Denmark) [4]. At the Experimental Storage Ring (ESR) in Darmstadt (Germany), first laser cooling experiments at moderately relativistic energies were conducted [5]. Particle intensity limitations due to space charge effects and intrabeam scattering for low energy ion beams were investigated in ASTRID [6].

In the future, laser cooling of intense highly charged ion beams at relativistic energies will be attempted for the first time at the Facility for Antiproton and Ion Research (FAIR), which is presently under construction [7]. In the heavy ion synchrotron SIS100 only laser cooling will be available, because electron cooling becomes less effective at high relativistic factors ($\gamma \gg 1$) [8], and stochastic cooling works best at much lower intensities. In this paper the efficiency of laser cooling at high relativistic factors ($1.1 \lesssim \gamma \lesssim 12$) will be investigated using analytical as well as numerical models. The results are compared to laser cooling at moderately relativistic factors ($\gamma \lesssim 1.1$) which was experimentally studied in the ESR. The paper deals with laser cooling in the longitudinal direction and possible indirect coupling mechanisms to the transverse plane. Direct transverse cooling schemes were analyzed for example in Ref. [9]. This work concentrates on the effects during the cooling process and does not investigate the equilibrium state of ultra cold beams and strongly coupled ensembles (for more information see Ref. [10,11]).

The principle of laser cooling relies on the directional absorption of energy and momentum of resonant laser photons by an ion, and the subsequent random emission of fluorescence photons from the ion and the corresponding randomly distributed recoil momentum. For the laser light to be resonant with a fast atomic transition in the ion, the photon energy needs to be equal to the transition energy. This constraint demands a relationship between the ion type (element, charge state), the wavelength of the laser system and the speed of the ions, which is well described in Ref. [5]. Consequently, a change of the relativistic factor γ involves a change of the laser wavelength or the ion type. Due to practical reasons the laser wavelength is restricted to two values. The ion type can be changed over a broad range, of which we show two examples in this investigation. The $2s_{1/2} \rightarrow 2p_{1/2}$ transition in Li-like ions is chosen (values given in Ref. [12]), but the formulas can be applied to any other atomic transition with a lifetime that is short compared to the revolution time of the ion in the accelerator. The particle dynamics are studied for ion energies below the transition energy of the synchrotron ($\gamma < \gamma_t$). The structure of this paper is as

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follows: Firstly the expected laser forces for continuous wave (cw) and pulsed laser systems and the corresponding required laser intensities are calculated. In Section 3 the cooling process is discussed and the required cooling time is estimated. Then, the influences of intrabeam scattering (IBS) and space charge (SC) effects on laser cooling are discussed and the maximum particle intensities are given in Section 4. The paper is concluded with a comparison of two examples in Section 5 and an outlook in Section 6.

2. Laser force

Laser cooling is based on the repetitive resonant absorption of unidirectional laser photons, followed by the spontaneous and directionally random emission of fluorescence photons. The momentum change of the ion during the interaction is a combination of the momenta of the incoming and outgoing photons. Each scattering event changes the momentum of the ion by (for more information see Ref. [13])

$$\Delta p^{PF} = \Delta p^{PF}_{emit} - \Delta p^{PF}_{absorb} = -\frac{2\pi\hbar}{\lambda^{PF}} \cdot (1 + U_i), \tag{1}$$

where λ^{PF} is the photon wavelength in the rest frame of the ions (PF), that has to match to the atomic transition of the ion. U_i is a uniformly distributed random number in the interval $[-1, 1]$ and describes the projection of the spontaneously emitted photon on the longitudinal axis of the accelerator. Applying the Lorentz transformation to the incoming and outgoing photons, the momentum kick in the laboratory frame (LF) results in

$$\Delta p^{LF} = \frac{2\pi\hbar}{\lambda^{LF;in}} \cdot \gamma^2 \cdot (1 + \beta) \cdot (1 + U_i), \tag{2}$$

where $\lambda^{LF;in}$ describes the wavelength of the incoming laser photon in LF (see Ref. [14]). The frequency of occurrence of a scattering event is given by the spontaneous emission rate k^{PF}_{se}, that is calculated by (see Ref. [13])

$$k^{PF}_{se}(\delta, t) = \rho_{ee}(\delta, t) \cdot \frac{1}{\tau^{PF}_{se}} \tag{3}$$

where $\rho_{ee}(\delta, t)$ is the excitation probability (calculated in Sections 2.1 and 2.2) and τ^{PF}_{se} the lifetime of the excited state. The integration of the emission rate over a time interval $[t_1, t_2]$ results in the average number of scattered photons per ion

$$n_{scat}(\delta) = \int_{t_1}^{t_2} k^{PF}_{se}(\delta, t) dt. \tag{4}$$

Neglecting the statistical component, the strength of the ion laser interaction can be expressed by an averaged force acting on the ions:

$$\left\langle F^{LF}_L(\delta) \right\rangle = \left\langle \Delta p^{LF} \right\rangle \cdot \left\langle k^{LF}_{se}(t, \delta) \right\rangle \tag{5}$$

The averaged momentum change during one turn of the ions in the accelerator, is given by

$$\Delta p^{LF}_{turn}(\delta) = \int_0^{\Delta t} \left\langle F^{LF}_L(\delta) \right\rangle dt = \left\langle \Delta p^{LF} \right\rangle \cdot n_{scat}(\delta). \tag{6}$$

For a comparison of the laser force at different beam energies, the momentum kick is normalized to the initial momentum of the ion p_0.

$$\Delta \delta^{LF} = \frac{\Delta p^{LF}}{p_0} \tag{7}$$

For the $2s_{1/2} \rightarrow 2p_{1/2}$ transition in Li-like ions, the relative momentum kick of a single scattering event is very similar for different ions, as depicted in Fig. 1. The values of the atomic transitions are taken from Ref. [12]. The dependency of the magnetic rigidity ($B\rho = p_0/q$) on the transition of the ion and the applied laser system is discussed in Ref. [10]. The relative momentum kick is $\Delta\delta^{LF} \approx 10^{-9}$ and only increases slightly for very light ions, where $\beta < 1$. Therefore the impact on beam dynamics for a single scattering event is similar for ions at non-relativistic and relativistic beam energies. Transforming the momentum kicks of the absorbed (directional) and emitted (random) photons separately into the LF the ratio of these values is given by

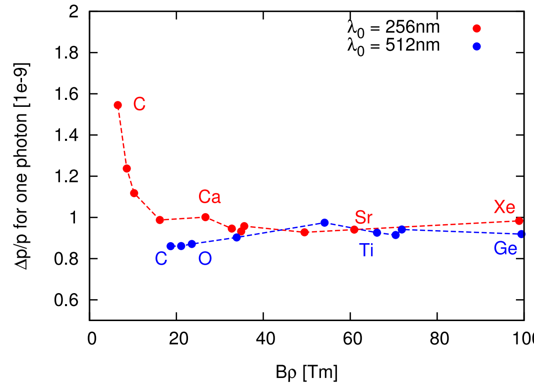

Fig. 1. Mean value of relative momentum kick for one scattering event, calculated for the $2s_{1/2} \rightarrow 2p_{1/2}$ transition in Li-like ions. The transferred momentum stays nearly constant for different magnetic rigidities. Different dots represent different ions, which are partly marked by their element name.

$$\frac{\left\langle \Delta p^{LF}_{emit} \right\rangle}{\Delta p^{LF}_{absorb}} = \gamma^2 (1 + \beta)^2 - 1. \tag{8}$$

This equation shows that for non-relativistic beams the transferred momentum of the emitted photons can be neglected, whereas for relativistic beams the transferred momentum of the emitted photons dominates the scattering event.

For the calculation of the laser force, the population density of the excited state (ρ_{ee} in Eq. (3)) is calculated by the optical Bloch equations (see Ref. [15]). The equations can be solved for arbitrary laser intensities $I(t)$. In the following the excitation probabilities for two different laser scenarios are discussed. For simplicity we assume that the transverse laser beam spot covers the whole particle beam equally.

2.1. *Continuous wave laser*

The ordinary solution for laser cooling experiments is to use a continuous wave (cw) laser system. The ions circulate in the accelerator and interact with the laser along a straight section with length $L_{interact}$. The ions see a rectangular laser pulse with length:

$$\Delta t^{PF}_{cw} = \frac{L_{interact}}{\gamma \beta c_0} \tag{9}$$

Usually the interaction section is long enough to approximate the excitation by a steady state solution ($\Delta t^{PF}_{cw} \gg \tau^{PF}_{se}$). For a constant excitation probability ($\dot{\rho}_{ee} = 0$) the optical Bloch equations can be solved analytically [13] and the number of scattering events per turn is given by:

$$n_{scat}(\delta) = \frac{L_{interact}}{\gamma \beta c_0} \cdot \frac{1}{2\tau^{PF}_{se}} \frac{S}{1 + S + (2\zeta(\delta - \delta_{LPos}) \cdot \tau^{PF}_{se})^2} \tag{10}$$

$$\zeta = \frac{d\omega}{d\delta} = \frac{2\pi c_0}{\lambda_{PF}} \beta\gamma(1 + \beta) \tag{11}$$

where $S = \frac{I^{PF}}{I^{PF}_s} = \frac{I^{LF}}{I^{LF}_s}$ describes the saturation parameter, δ the relative momentum deviation of a test particle and δ_{LPos} the position of the laser in units of relative momentum. The width of the function $n_{scat}(\delta)$ and consequently the width of the laser force in units of relative momentum is given by:

$$\Delta_{fwhm} = \frac{\sqrt{1 + S} \cdot \lambda^{LF}}{2\pi \tau^{PF}_{se} (1 + \beta) \beta \gamma c_0} \tag{12}$$

Assuming a saturated transition, the width of the laser force is very similar for different Li-like ions, $\Delta_{fwhm} \approx 4 \cdot 10^{-8}$ in units of relative momentum. Compared to the typical momentum spread of a heavy ion