LASER-COOLING FOR LIGHT ION ACCUMULATION

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Abstract

The ALICE experiment to be installed at the Large Hadron Collider (LHC) will initially look at Pb^{82+} - Pb^{82+} collisions. In a later stage, collisions of lighter ions are also foreseen. For lead ions, fast electron cooling will be used in the accumulation process at low energy to reach the beam brightness necessary for the experiment. For lighter ions, electron cooling becomes less efficient as the ratio Q^2/A decreases (Q and A are respectively charge state and mass number of the ion). For this reason, a study has been made of the possibility to use the maturing technology of laser-cooling of fast ion beams to reach the desired emittances for lighter ions. The main problems encountered are the availability of useful ion species, the availability of corresponding laser systems, and the efficiency with which the transverse emittance can be reduced by the laser-cooling mechanism (which works mainly in the longitudinal plane).

1 INTRODUCTION

For the ALICE experiment at the LHC a scheme for accumulation of Pb^{54+} ions in the Low Energy Ion Ring (LEIR)[1] has been proposed [1, 2]. The purpose of the scheme is to provide lead ion beams of high luminosity for the experiment. The scheme, tests of which have been published [3], has two goals. First of all it is an accumulation scheme, since present ion sources cannot deliver the desired ion currents, and secondly it is an emittance reduction scheme to reduce the emittances to the nominal values of 1.5 π mm mrad (1 sigma) normalized emittance in the LHC.

However, it would be possible to increase the luminosity in the experiment if lighter ions with lower charges could be delivered. For this, and also for particle physics reasons, schemes for accumulating lighter ions are being investigated.

In this article the possibility of using laser-cooling for accumulation is being investigated [4].

2 ACCUMULATING WITH ELECTRON-COOLING

The scheme for accumulating lead ions is discussed in Ref. [3]. However, some aspects are similar to those for lighter ions, and will be briefly discussed here.

The accumulation of Pb^{54+} ions is done by a mixed horizontal/longitudinal multi-turn injection. The linac produces ions at 4.2 MeV/amu. The lead ion production is optimized for Pb^{28+} production, and the ions are stripped at 4.2 MeV/amu to charge state 54+. One batch of approximately 10^8 ions is injected every 0.4 s in about 200μs (about 30 effective turns in the machine). Electron cooling is used to cool the particles to the stack momentum. Right after the injection, the beam has a horizontal emittance (2σ) of about 50 π mm mrad, a vertical emittance of 10 π mm mrad and a relatively uniform $\Delta p/p$ of $\pm 3\times 10^{-3}$.

For the accumulation of light ions in LEIR, the scheme to be used for lead ions cannot be used directly. Table 1 summarizes values for some of the ions considered for accumulation in LEIR.

Table 1: Parameters of various ions in LEIR [1]. In the top part of the table $\bar{Q}$ is the most abundant charge state after stripping at 4.2 MeV/amu. In the bottom part Q is the proposed charge states for accumulation. The transverse electron cooling time (e-folding of emittance) τ_{ec} is obtained by scaling the experimental results with Pb^{54+} with Q^2/A. The intrabeam scattering (IBS) growth rate τ_{ibs} is the longitudinal growth rate, calculated with the program INTRABTC [5]. $\Delta\hat{Q}_v$ is the maximum tune shift calculated in the worst case in the scheme, which is right after cooling and rebunching in LEIR [1].

Ion	$\bar{Q}$	N_{LEIR}	$\bar{Q}^2/A$	τ_{ec}	τ_{ibs}	$\Delta\hat{Q}_v$
$^{208}_{82}$Pb	54	1.2×10^9	14	0.2s	2.2s	0.084
$^{40}_{20}$Ca	17	3.2×10^{10}	7.2	0.4s	0.3s	1.2
$^{16}_{8}$O	8	1.2×10^{11}	4	0.7 s	0.3s	2.4
Ion	Q	N_{LEIR}	Q^2/A	τ_{ec}	τ_{ibs}	$\Delta\hat{Q}_v$
$^{40}_{20}$Ca	10	3.2×10^{10}	2.5	1.1s	2.4s	0.40
$^{40}_{20}$Ca	8	3.2×10^{10}	1.6	1.7s	5.8s	0.26
$^{16}_{8}$O	4	1.2×10^{11}	1	2.8 s	3.8s	0.6
$^{16}_{8}$O	2	1.2×10^{11}	0.25	11s	57s	0.15

From Table 1, it can be concluded that the main problem with the lighter ions is the tune shift, as the longitudinal intrabeam scattering (IBS) growth times in all cases are small compared to longitudinal electron cooling times (10s of milliseconds). To deliver increased luminosity it is necessary to accumulate the extra particles desired in a reasonable time, such that the integrated luminosity is actually increased. Furthermore, as reducing Q^2/A slows electron cooling, and reducing the number of particles per injection increases the accumulation time, it would be desirable to find an alternative scheme. As laser-cooling is suited to relatively low charge states it might be suitable for exactly this purpose.

[1] LEIR is the former Low Energy Antiproton Ring (LEAR).

3 THE LASER FORCE

Laser-cooling is based on the fact that photons carry momentum. When an ion absorbs a photon, the ions momentum is thus changed by an amount equivalent to the momentum of the photon. If the ion then decays spontaneously, a photon is emitted. The spatial distribution of spontaneously emitted photons is symmetric; thus, if a condition can be achieved where an ion is continuously excited by photons coming from one direction, and then decays spontaneously, a net average force in the direction of the incoming photons is exerted on the ion. As the force is based on resonance with the transition, it is velocity dependent due to the Doppler shift. The Doppler shift cause the velocity range of the force to be short (typically $\sim$ 20 m/s).

Table 2 lists some lighter ions with suitable transitions for laser-cooling. There are at least 11 ion species which have been cooled to date, all of them singly charged. Table 2 lists the three which have been cooled in a storage ring.

Table 2: Parameters of light ion species which may be laser-cooled. Only Li^+, Be^+ and Mg^+ have been cooled in a storage ring. A laser intensity of 12.7 W/cm^2 has been assumed. λ_{air} is the wavelength of the transition, τ_{up} the lifetime of the upper level, F^{res}_{las} is the maximum laser-force and I_s is the saturation intensity [6].

Species	λ_{air} [nm]	τ_{up} [ns]	I_s [mW/cm^2]	F^{res}_{las} [MeV/c/s]
$^{6,7}_{3}Li^+$	548.5	43.9	8.61	25.7
$^{9}_{4}Be^+$	313.0	8.70	234	224
$^{24}_{12}Mg^+$	279.6	3.8	751	551
$^{40}_{20}Ca^+$	396.8	7.1	141	218
$^{11}_{5}B^{2+}$	206.6	5.24	1.3×10^3	517

In the lead ion accumulation scheme, the initial momentum spread was $\pm3\times10^{-3}$, which, with a relativistic β of 9.43% corresponds to a Doppler shift of order $\pm$ 400 GHz.

4 LASERS

Continuous wave (CW) lasers for generating visible or ultra-violet light come in many varieties. The parameters of interest for accumulation of particles are the laser power which gives the available force, the frequency tunability, and the system stability, which for LEIR purposes should be measured in days.

With such stability requirements, the main interest would be in ion-lasers or solid state (diode) lasers. As ion-lasers are based on specific transitions in the laser medium, these are fixed frequency lasers. Diode lasers can be tuned 10's of GHz (and at times more), but deliver frequencies in the red to infra red region, which means that frequency doubling will be necessary. The matching conditions for frequency doubling cause the available *online* tuning range to be of order 20 GHz or less (i.e. the tuning range which will be feasible to carry out in the short time during accumulation) [7]. Even if dye laser systems would be considered, the *online* tuning range would only increase in the best of circumstances to about 50 GHz.

In terms of wavelength and power, it is not practical to obtain CW laser light below 200 nm, as light below this limit is absorbed heavily by air. In the range 200 nm - 400 nm power up to about 0.5 W will be possible at specific wavelengths, decreasing as the desired wavelength approaches 200 nm. Above 400 nm, several watts are possible, again depending very much on the desired wavelength, as well as the financial investment.

If laser-cooling is desired, it will be necessary to study the specific case at hand, as it is not possible to obtain the power levels mentioned above at all wavelengths. Being able to tune the energy of the particles to a given Doppler shift is therefore highly desirable.

5 LASER COOLING

It was noted above that the momentum spread of the multi-turn injected beam corresponded to a Doppler shift of hundreds of GHz. This is much larger than the *online* tuning range of existing laser systems. Therefore, only cooling with a fixed frequency laser will be considered.

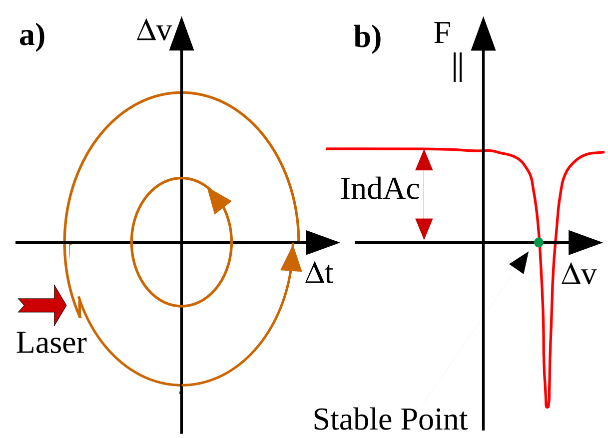

Figure 1: See text for explanation. a) Longitudinal Phase Space during bunched beam laser-cooling. b) Cooling with a single fixed laser and an induction accelerator.

Two methods have been demonstrated which accomplish laser-cooling in a storage ring with a fixed frequency laser (Figure 1). The first is to do laser-cooling of a bunched beam, where the periodic synchrotron oscillations of the particles may cause them all to experience the laser force, and thus with correct tuning of the laser, the synchrotron oscillations can be damped [8]. The second is to use an induction accelerator to accelerate the ion beam into resonance with the laser. As the laser force is very large it will counteract this force for ions which are within resonance range, and thus a stable point in velocity around which the ions are cooled longitudinally is achieved [9]. The RF method has the advantage that once cooled, the beam can in principle be kept cooled for ever [8]. The RF can furthermore be used to accelerate the particles into resonance with the laser, and thus improve the longitudinal cooling time for large $\Delta p/p$.

For efficient and fast accumulation in LEIR it is necessary also to be able to stack in the transverse degrees of freedom. Transverse laser-cooling is accomplished indirectly, either through IBS or dispersive coupling [10, 11]. IBS is not efficient for accumulation, as the initial injected beam is not very dense and therefore the IBS rates will be low. However, in the final state after cooling, intra beam scattering may well be an important factor [11].

Transverse laser-cooling through dispersion has been demonstrated [10]. When an ion scatters a laser photon, its momentum and thus the closed orbit about which it oscillates are changed. If this happens in a dispersive section of the storage ring, the amplitude of the betatron oscillation is changed, and by suitable arrangement of the laser position, cooling can be accomplished [12]. By introducing coupling of the vertical and horizontal motion in the ring, cooling can be accomplished in both dimensions.

Table 3 shows the horizontal cooling times from a simulation of bunched beam laser-cooling of a single particle in a dispersive section of LEIR. For the calculation B^{2+} has been used as this is the most promising species for LEIR (many of the ions available for laser-cooling have too high rigidity to be stored in LEIR). The laser position relative to the beam center Δx_{las} and the frequency offset Δf_{las} have been optimized in each case.

Table 3: Horizontal emittance cooling times (e-folding) from a simulation of bunched beam laser-cooling of a single particle of $^{11}B^{2+}$ at 4.2 MeV/amu in LEIR. A counter-propagating laser of 200 mW power with a size of 0.5 mm (sigma) and a wavelength of 227.1 nm was used. The lattice used is Machine 97-2 from Ref. [3], where β_h = 2.2 m and D = 9.5 m in the cooling sections, and Q_h = 1.59. The RF is set to the second harmonic and the voltage to 6.5 kV.

	Single Part. Emit. [mm mrad]			
$\Delta p/p$	2.1 π	10 π	50 π	Δf_{las}
2×10^{-5}	0.01s	0.09s	0.5s	-0.2 GHz
2×10^{-4}	0.4s	0.6s	3.0s	-17 GHz
2×10^{-3}	2.2s	3.3s	7.3s	-200 GHz
Δx_{las}	-1 mm	-4 mm	- 10 mm	

The cooling times given in Table 3 for the large emittances and momentum spreads are the initial cooling times; in most cases the cooling would stop after a time, as the particle moves out of the range of the laser force (both in frequency and physical overlap). Therefore it will be necessary to move the laser both in frequency and position.

Changing the position of the laser can be accomplished with a simple piezzo-based mirror system. However, as discussed before, the laser frequency cannot be changed by the large amounts necessary. At least two solutions are possible to remedy this. One is to refrain from momentum stacking. This would however increase accumulation time. Another option is to accelerate the ion beam into resonance with the laser and thereby cool it longitudinally. Acceleration can be done either with an induction accelerator [9] or using RF acceleration. In any case, Table 3 shows that the cooling times for the full beam are an order of magnitude longer than the requirements (about 0.2 - 0.5s). Thus unless significantly more laser-power can be supplied it will not be practical to use laser-cooling for accumulation in LEIR.

6 CONCLUSIONS

A preliminary study of the feasibility of using laser-cooling for accumulation of light ions in LEIR has been described. The study shows that the main hurdles in using laser-cooling in a storage ring are the velocity range of the laser-force, combined with the relatively feeble laser intensities available at the wavelengths necessary. These hurdles can to some extent be overcome by using RF or induction acceleration and a dedicated storage ring lattice. A simulation of laser-cooling in LEIR shows that the accumulation time compared to present day electron-cooling is about an order of magnitude longer. Thus in the case of LEIR, the option does not look promising for the moment.

However, the study also indicates that if some effort is put into a storage ring with a lattice specially optimized for laser-cooling, and if, furthermore, external acceleration (RF or induction) is used to reduce the initial momentum spread, or only transverse filling is used, and if enough laser power could be obtained, then laser-cooling would be possible. The purpose of doing this rather than electron-cooling, is that once comparatively small emittances have been reached, laser-cooling is orders of magnitude stronger than electron cooling, and has been demonstrated to sustain rather large tune shifts [11]. Thus if high luminosity beams are needed, laser-cooling may be a candidate, perhaps in combination with electron-cooling initially.

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