

# Laser cooling of relativistic heavy ion beams

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The cooling of stored heavy ion beams to high phase space densities is of general importance when low momentum spread is required for precision spectroscopy or high luminosity for collision experiments. Ultimately, cooling the thermal energy far below the mutual Coulomb energy leads to a phase transition, a crystallization of the ion beam, into a regime where almost no further heating occurs and maximum brilliance is reached [1, 2]. Notably, electron cooling as the established tool in heavy ion storage rings cannot be used any more for highly relativistic beams [2]. Yet, laser cooling, up to now only applied to beams of singly charged ions, provides the possibility for an improvement of the beam quality of else uncooled beams by many orders of magnitude.

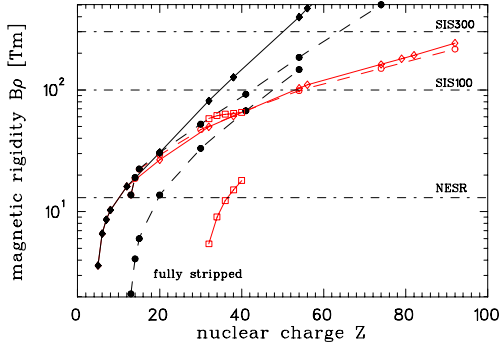


Figure 1: Magnetic rigidity required for the storage of the ions at an energy Doppler shifting the transition wavelength of the  $nS_{1/2} - nP_{1/2}$  (filled symbols) and  $nS_{1/2} - nP_{3/2}$  (open symbols) ground state transitions [4] to the sample laser wavelength of  $\lambda_{laser} = 257\text{nm}$  as a function of the nuclear charge  $Z$  (rhombs,  $n = 2$ , Li-like; circles,  $n = 3$ , Na-like; squares,  $n = 4$ , Cu-like). The horizontal lines denote the maximum rigidity of the future GSI storage rings.

For counterpropagating laser and ion beams with  $\gamma \gg 1$  the photon energy  $\hbar\omega_{in}$  is increased to about  $2\gamma\hbar\omega$  in the rest-frame of the ion. At SIS300 ( $\gamma_{max} < 35$ ) a fixed laser photon energy of the order of  $4.8\text{eV}$  [3] can thus be Doppler-tuned into resonance with the ground state transition of any Li-like systems of nuclear charge  $Z$ . In Fig. 1 the magnetic rigidity required for the storage of highly charged Alkaline-like ions at an energy providing the necessary Doppler shift is given. Moreover, after an extraction the remaining electrons could be stripped off leading to cold beams that could be transferred to the smaller rings like the NESR (lower squares in Fig. 1). A second advantage arises from the general increase of the laser cooling force with  $\gamma^3$  in the lab-frame. The momentum of the re-emitted photons is increased by  $4\gamma^2$  and the lifetime of the excited level is shortened roughly proportional to  $\gamma$ .

As an intermediate step between the anticipated laser cooling of highly relativistic heavy ion beams and the known field of electron cooled low energy beams we presently prepare an experiment for combined laser and electron cooling of Li-like  $C^{3+}$  ions ( $\beta = 0.47$ ) at the ESR. Encouraged by the low temperatures reached with electron cooling of highly charged ions at the ESR we are aiming for the generation of dense ion strings of  $C^{3+}$  ions.

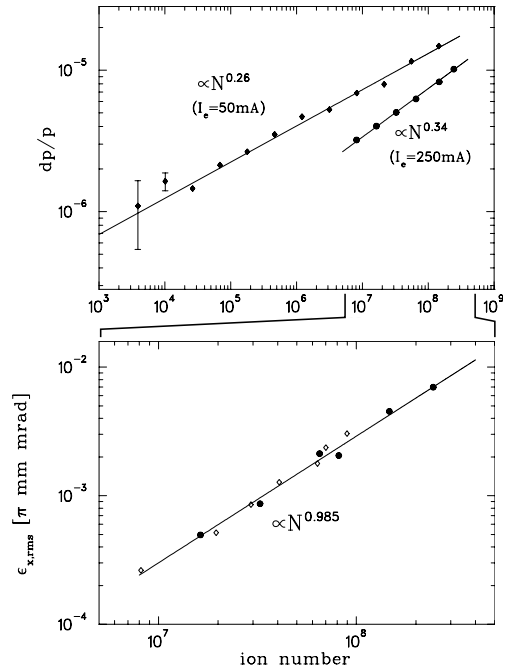


Figure 2: Development of the relative momentum spread and the horizontal emittance of a continuously electron cooled beam of  $^{12}C^{3+}$  beam at  $120\text{MeV/u}$  at the ESR.  $I_e$  indicates the electron current in the electron cooler.

A test experiment was recently performed. Electron cooling times down to the equilibrium between electron cooling and IBS heating of few seconds were reached compared to beam lifetimes of the order of half a minute. The development of the momentum spread of the continuously electron cooled coasting beam with decreasing particle number, measured via the relative spread of the Schottky noise signal, comes out to be typical for the emittance dominated regime as depicted in Fig. 2. For the lowest ion numbers a longitudinal temperature of about  $T_{\parallel} = 30\text{K}$  was reached, that would correspond to a plasma parameter of the order of unity ( $a_{ws} = 6.8\mu\text{m}$ ). The corresponding transverse temperature has not been measured, yet, scaling the given measurement similar values seem reasonable. The scaling of the transverse emittance  $\epsilon_{rms} \propto N$  corresponds to constant volume density and indicates an unexpected and unexplained influence of space charge. Summa-

	ESR	SIS 300
ion species	$^{12}\text{C}^{3+}$	$^{238}\text{U}^{89+}$
circumference [m]	108	1080
$\eta_{cooling}$ [%]	8	3
$\gamma$ ( $\gamma_{max}$ )	1.13	30 (35)
$\beta$	0.47	0.9994
$\hbar\omega_{in}$ [eV]	4.8	4.8 (4.0)
$\hbar\omega_0$ [eV]	7.9	280
$\hbar\omega_{out}(\Theta = 0^\circ)$ [eV]	13.3	19 600
lifetime $\tau_0 = 1/\Gamma_0$ [ns]	3.8	0.06
$I_{sat,0}$ [W/cm $^2$ ]	1.3	$4 \times 10^6$
$S = I_0/I_{sat,0}$	<10	<0.005
$F_{cool,out}$ [eV/m]	15	160
$\Gamma_0/\omega_0 \sim \Delta p/p$ [ $10^{-8}$ ]	2	4
$\tau'_{cooling,out}$ [s]	0.002	1
$\tau_{cooling,out}$ [s]	0.02-0.2	10-100
$\Delta p/p$ equil. ( $N = 10^8$ )	ecool: $< 10^{-5}$ laser: $< 10^{-6}$	not possible $\approx 5 \times 10^{-5}$
$T_D = \hbar\Gamma_{out}/(2k)$ [K]	0.001	1.9
$E_{Coul.}$ (10 $\mu\text{m}$ ) [K]	15	13000

Table 1: Parameters for laser cooling of relativistic Li-like heavy ion beams on the  $2S_{1/2}$ - $2P_{1/2}$  transition.  $\eta_{cooling}$  denotes the relative length of the individual cooling section. The saturation intensity is determined assuming an established power of the counterpropagating laser beam of 200 mW on 4 mm $^2$ . The Doppler-temperature  $T_D$  states the fundamental limit of this cooling scheme. The cooling time for a reduction of  $\Delta p/p \sim 10^{-4}$  in the lab-frame is estimated including the reduced interaction length ( $\eta_{cooling}$ ), the incomplete saturation ( $\rightarrow \tau'$ ), and the narrow linewidth of the transition as compared to the Doppler-width ( $\rightarrow \tau$ ).

rizing, beam parameters close to the range where the transition to the liquid-like regime is expected were reached, strongly motivating the application of laser cooling.

However, the favorable scaling of the laser cooling force  $\propto \gamma^3$  cannot be fully realized for the high  $Z$  ions due to the associated increase of the saturation intensities. The cooling time required for the reduction of the relative momentum spread of the highly relativistic ion beam  $\Delta\gamma/\gamma \approx \Delta p/p$  by four orders of magnitude can be estimated by dividing this relative spread by the relative energy change corresponding to one absorption-emission cycle  $\beta\hbar\omega_0/(m_0c^2)$  and multiplying the result with twice the lifetime of the excited state in the laboratory frame. This value has to be corrected for the incomplete saturation and the given spatial overlap of ion and laser beams. Promisingly, cooling times of the order of milli-seconds, respectively a second, result for the reduction of the relative momentum spread by  $10^{-4}$  when heating mechanisms are at first neglected.

The impact if the initial mismatch of the Doppler width and the line width of the transition is difficult to estimate. A conservative estimation of the relative width of the force in momentum space is given by the ratio  $\Gamma_0/\omega_0$  directly for the relativistic and by  $\Delta v/c = \Gamma_0/\omega_0$  for the non-relativistic case, where at least one order of magnitude

more has been demonstrated. For the method of bunched beam cooling, the ions perform synchrotron oscillations in the bucket and therefore only match the laser resonance in a fraction of the synchrotron motion. Depending on the bucket depth, this factor may vary between 0.1 and in worst case  $\approx 0.001$  at SIS 300. Thus, cooling times with and without this momentum overlap factor are given. The capture range and thus the cooling time especially for the initially broad distribution could be increased by the additional use of pulsed laser beams, having larger bandwidth due to the finite pulse length of the order of few times  $10^{-7}$  (and by far higher intensities), so that this restriction can be circumvented by the proper selection of a combination of different laser systems.

Furthermore, the intra-beam scattering (IBS) losses out of resonance yet not completely out of the bucket have to be considered. Simply regarding phase space arguments and neglecting the structure of the storage ring, equilibrium temperatures (for coasting beams) scale as  $T_{eq} \propto (NZ^4p^2/\Lambda_{cool})^{0.4}$ . From the equilibrium temperature or momentum spread  $kT_{eq} = mc^2\beta^2(\Delta p/p)^2$  measured at the ESR for the  $\text{C}^{3+}$  beams with electron cooling and the fact that the laser cooling outperforms electron cooling by a factor of 1000 in the rate, an improvement of roughly one order of magnitude in the momentum spread can be expected for  $\text{C}^{3+}$ . Regarding the momentum spread the exponent is changed to 0.2 and thus changes in the parameters have only moderate impact. Therefore, also for the highly charged relativistic  $\text{U}^{89+}$  beam a dramatic improvement of the equilibrium momentum spread as compared to the else uncooled beam can be expected.

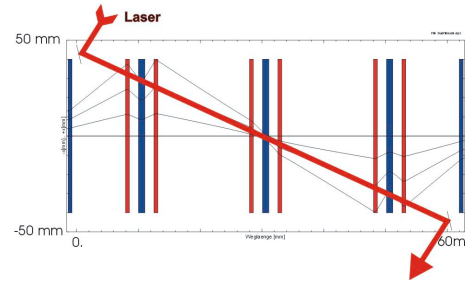


Figure 3: Possible preparation of a straight laser cooling section in SIS 100 and as well in SIS 300 by tilting the ion beam by 3 mrad over a section of 34 m.

For the realization of laser cooling at the SIS 300 a straight section has to be foreseen that might also serve for spectroscopy purposes as sketched in Fig. 3, as well as a guiding system and tunnel for the laser beams from a laser lab into the SIS ring tunnel.

## References

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