Laser Cooling of Stored 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. Ultimatively, 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]. Unfortunately, electron cooling as the established tool in heavy ion storage rings cannot be applied for highly relativistic beams [2]. Yet, laser cooling, up to now only applied to beams of singly charged ions, seems promising.

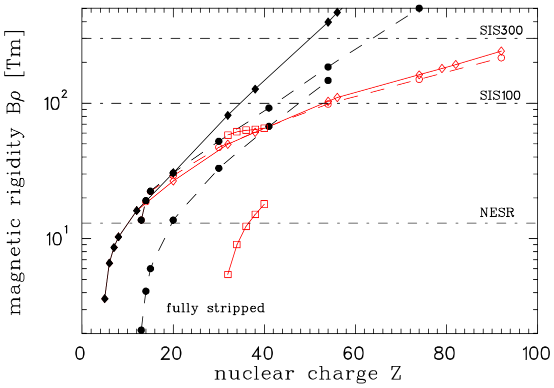

Fig. 1: Magnetic rigidity required for the storage of the ions at an energy Doppler shifting the transition wavelength of the $nS_{1/2} - nP_{1/2}$ (filled symbols) and $nS_{1/2} - nP_{3/2}$ (open symbols) ground state transitions [4] to the sample laser wavelength of $\lambda_{laser} = 257$ nm as a 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. As a result a fixed laser photon energy of the order of 4.8 eV [3] can be Doppler-tuned to any ground state transition in 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. With the planned accelerator complex at GSI these conditions can be fulfilled and thus laser cooling becomes possible. A second advantage arises from the principle increase of the laser cooling force with γ^3. 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 γ.

As an intermediate step between the anticipated laser cooling of highly relativistic heavy ion beams and the known field of 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 (GSI, Darmstadt). 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.

◇ supported by BMBF (06ML183)

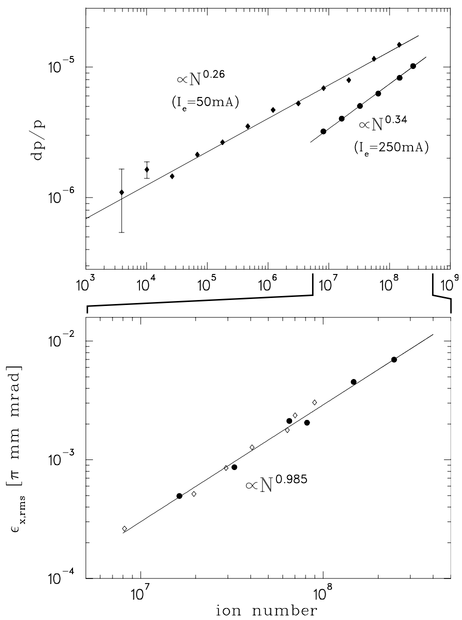

Fig. 2: Development of the relative momentum spread and the horizontal emittance of a continuously electron cooled beam of $^{12}C^{3+}$ beam at 120 MeV/u at the ESR. I_e indicates the electron current in the electron cooler.

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. Promisingly, the method of measuring and Fourier-analyzing the Schottky noise signal of the cooled beam works down to ion numbers of few thousand. 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 $T_{\parallel} = 30$ K was reached, that would correspond to a plasma parameter of the order of unity ($a_{ws} = 6.8\,\mu$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. Summarizing, already with electron cooling, 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.

References

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