3D-Laser-Cooling of a Bunched $^9Be^+$ Ion Beam at the Heidelberg TSR

U. Schramm, M. Grieser [a], R. Grimm [a], D. Habs, I. Lauer [a], V. Luger [a], P. Merz [b], H.-J. Miesner [a], A. Peters, D. Schwalm [a], and M. Stößel [a]
[a] MPI für Kernphysik, 69029 Heidelberg, Germany
[b] Inst. für Physik, Universität Mainz, 55099 Mainz, Germany

Laser–cooling of ion beams [1] has proven to produce beams with exceptionally high phase space densities [2] opening access to a regime where the influence of space charge effects becomes important and possible ordering phenomena may drastically affect the beam dynamics.

Here we report on the first observation of the indirect transverse laser–cooling effect in a RF bunched $^9Be^+$ ion beam subject to direct longitudinal laser–cooling. In this scheme the spontaneous laser force is used to efficiently damp the synchrotron oscillations in the longitudinal RF potential [3], already leading to a longitudinally space charge dominated beam. As for a coasting beam [2] intrabeam Coulomb–scattering leads to a relaxation process between all degrees of freedom where the major dissipation of thermal energy, responsible for the indirect transverse cooling, is assumed to be due to rare close collisions. The confinement of all ions in the RF buckets now allows rapid re–cooling of these longitudinally heated particles which tend to get lost in a coasting beam scheme.

For the experiment performed at the TSR Heidelberg [4] about $2 \cdot 10^6$ $^9Be^+$ ions were injected into the storage ring at an energy of 7.3 MeV and electron pre–cooled resulting in a beam diameter of less than 1 mm. The storage time is limited to about 25 s due to collisions with the residual gas ($p < 3 \cdot 10^{-11}$ mbar). The beam is permanently bunched at the 15^{th} harmonic (3.38 MHz) of the revolution frequency by modulating the electric field of a longitudinal kicker with a voltage amplitude of only $\hat{U} = 4.1$ V. These parameters are chosen to optimize bunched–beam laser cooling in a way that the maximum energy transfer per turn in the RF field corresponds to the one caused by the resonant laser force ($e \cdot \hat{U} = F_{laser} \cdot l \approx 4$ eV, l being the interaction length of ~ 5 m). For the voltage $\hat{U}$ fixed the harmonic number h should first be low enough to provide sufficient energy acceptance $\Delta E \propto 1/h$ to prevent ions from escaping out of the bucket after a close intra beam collision. On the other hand it should be as high as possible since the synchrotron frequency $\nu_{sync} \propto h$ defines the time scale for the ion to come into resonance with the cooling laser, resulting in $\Delta E = \pm 1.7$ keV and $\nu_{syn} = 175$ Hz. The bunching frequency is tuned so that the synchronous velocity lies about 100 m/s above the velocity at which the ions come into resonance with the Doppler–shifted fixed–frequency laser light, leading to a moderate longitudinal laser–cooling rate of roughly 100 s^{-1}.

The indirect transverse laser–cooling effect is demonstrated in fig. 1 where the temporal evolution of the ring–averaged transverse temperature, extracted from the measured transverse beam profile, is presented. For the first 12 s the ion beam is electron pre-cooled, the data points showing stable equilibrium conditions with electron cooling balancing the heating due to intra–beam scattering at temperatures in the horizontal and vertical planes of $T_h = 2100$ K and $T_v = 700$ K respectively. Shutting off the electron cooling device after 12 s then leads to the well known "blow up" of the ion beam (open circles) where the filled triangles represent the same scenario with longitudinal laser cooling switched on after 22 s, almost instantaneously reducing the longitudinal beam temperature to about $T_{\parallel} = 15$ K. Simultaneously the transverse beam temperatures drop to significantly lower equilibrium values of $T_h = 1400$ K and $T_v = 500$ K which are reached within less than 5 s. Thus even under the present conditions laser cooling provides a phase–space density ten times higher than reached with standard electron cooling.

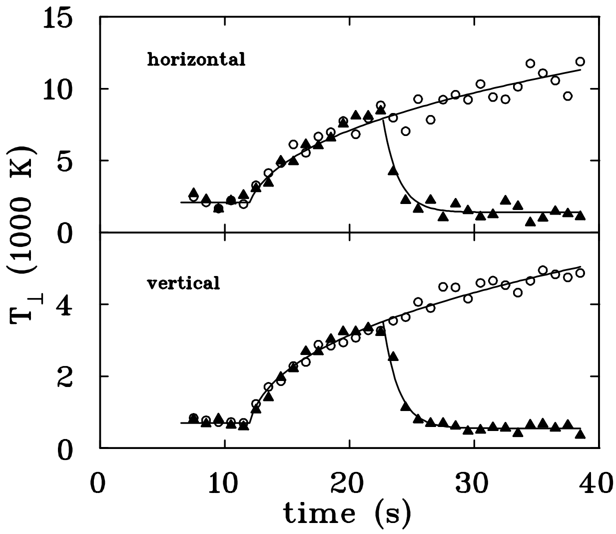

Fig. 1: Temporal evolution of the transverse beam temperatures after 12 s of electron pre-cooling with (filled triangles) and without (open circles) longitudinal laser cooling applied 22 s after injection. The solid lines are shown to guide the eye.

A great potential of the method described originates from the possibility to increase the longitudinal cooling rate up to $\sim 10^6$ s^{-1}. Since additionally recent TSR experiments [5] show a critical dependence of the indirect cooling efficiency on the lattice conditions, not understood so far, further experiments are on their way at TSR and ESR (GSI Darmstadt) [6] to explore the possibilities and the criteria for ultimate three dimensional laser–cooling under extreme longitudinal cooling.

References

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