Anomalous Behaviour of a Laser Cooled $^9Be^+$ Ion Beam Observed at the Heidelberg TSR for Very Low Temperatures

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Aiming for the observation of ordering phenomena in cold ion beams, predicted to occur when the inter particle Coulomb energy exceeds the thermal energy [1], promising progress has been made in the technique of laser cooling of 7.3 MeV $^9Be^+$ ion beams at the TSR Heidelberg. On the one hand, direct transverse laser cooling independent of the particle density became possible via dispersive coupling [2,3] when the collinear laser beam was horizontally displaced with respect to the ion beam. On the other hand, the scheme of bunched beam laser cooling [4] has been extended, employing square-well buckets, as depicted in fig. 1. This novel scheme provides longitudinal confinement as well as an individually adjustable force necessary to counteract the laser acceleration. The longitudinal cooling efficiency inside the bucket is further improved by a capture range extension, relying on the weak but broad band optical excitation of the ion, when tuned over resonance in the fringe fields of a biased drift tube [5].

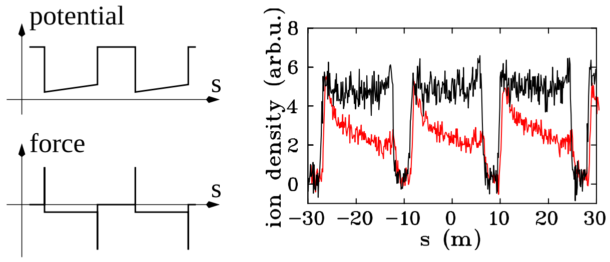

Fig. 1: Longitudinal density distribution of a bunched laser cooled ion beam. Bunching of the ion beam as well as the constant force counteracting the laser acceleration are provided by the potential sketched. For the black curve the synchronous velocity (determined by the bunching frequency) and the stable point velocity (reflecting the force equilibrium between the laser and the counteracting force) are perfectly matched resulting in a homogeneous distribution resembling the square-well potential (for a sufficiently dilute beam, the influence of space charge can be neglected). The grey curve shows the asymmetry resulting from a relative mismatch of the velocities of $3 \cdot 10^{-6}$, driving the ions to one side of the bucket.

Generally the dynamics of bunched beam laser cooling leads to a pronounced two-component velocity distribution, shown in the upper left of fig. 2 where a snapshot of the longitudinal velocity distribution is sketched. A fraction of the ions concentrates at the stable point (marked zero) where the accelerating laser force is exactly compensated by the decelerating auxiliary force and therefore experiences strong cooling. As a consequence of the resulting high phase space density these ions undergo hard Coulomb collisions. The corresponding momentum transfer from the transverse degrees of freedom then leads to the formation of a hot background fraction, still confined in the bucket.

The lower two curves in fig. 2 now represent the observed laser fluorescence rate of these two components as a function of time. Up to a time of about 60 s both signals show the exponential decrease of the ion current with a typical storage time of about 30 s and thus allow the observation of the beam behaviour as a function of the number of ions stored, respectively of the temperature expected to continuously decrease with phase space density. Then a sudden change in the behaviour is observed at a number of about 10^6 ions stored: The fluorescence yield from the cold fraction increases, where the yield from the hot background and thus intra-beam scattering totally vanishes, as also confirmed by the upper right sketch.

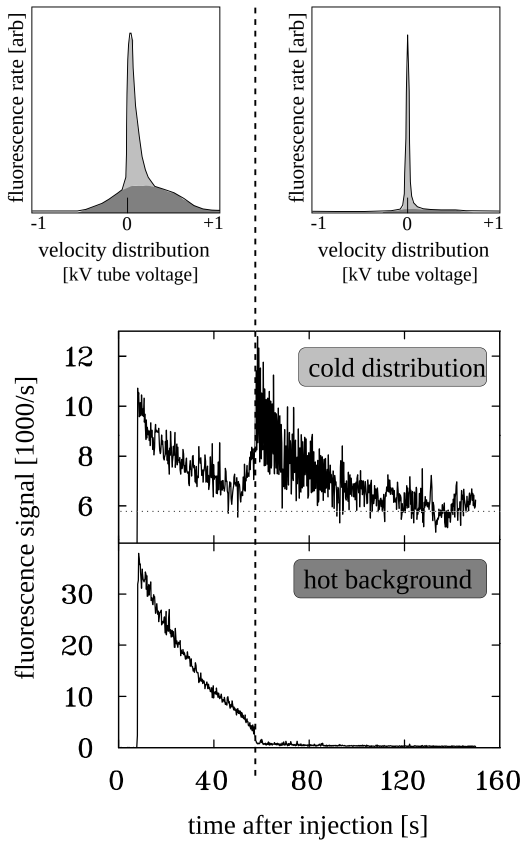

Fig. 2: Temporal behaviour of the fluorescence rate in the cooling and in the capture range region (lower graph). Velocity distribution before and after the transition (upper graph).

This signature, as well as the corresponding plasma parameter of $\Gamma > 1$ (for an inter particle distance of several 10 μm and a longitudinal temperature of below 200 mK) is consistent with the formation of a Coulomb-ordered structure [1]. However, especially the vanishing of the hard collisions could also be explained in terms of transverse beam instabilities, also irreversibly increasing the transverse phase space. Presently, neither of these possibilities can be definitely proven or ruled out.

References

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