Direct Transverse Laser Cooling of a Fast $^9Be^+$ Ion Beam at the Heidelberg TSR via Dispersive Coupling

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Laser cooling of bunched ion beams in storage rings [1] has up to now been restricted to extreme longitudinal cooling, leading to a pronounced imbalance between longitudinal and transverse beam temperatures. Additionally collisional relaxation processes, "intra beam scattering" (IBS), could be exploited to indirectly cool the transverse degrees of freedom with cooling rates comparable to standard electron cooling. Nevertheless the aspired observation of ordering phenomena [2] requires direct three dimensional laser cooling since IBS coupling will be negligible for thin or ultra-cold beams.

Direct horizontal cooling in a collinear beams arrangement has now been achieved [3] making use of the positive storage ring dispersion $D(s)$, describing the horizontal displacement $\Delta x = D(s) \cdot \Delta p/p$ of an ion from the reference orbit $x(s) = 0$ as a function of its momentum deviation Δp: Assuming a positive momentum kick Δp by the laser on a particle at an arbitrary horizontal position $x(s)$ during its betatron oscillation, its closed orbit will be changed by Δx thus reducing respectively increasing the particles betatron amplitude depending on its initial displacement having been positive (outside the ring) or negative. Transverse cooling (heating) results from the asymmetry $\Delta p(x)$ introduced by a horizontal displacement Δ of the Gaussian laser beam relative to the reference orbit. In a linearized description the cooling rate is proportional to the slope of the longitudinal force $\partial F/\partial x$ and predicts a maximum cooling rate of about 1/s for typical TSR conditions [1] independent from the particle density.

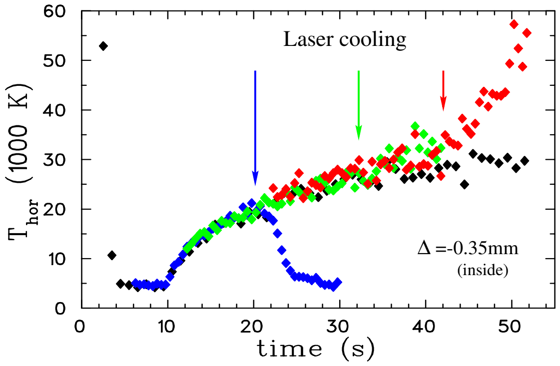

Fig. 1: Temporal evolution of the horizontal beam temperature applying 10 s of electron pre-cooling after injection for different delay times before starting longitudinal laser cooling.

Since indirect transverse cooling rates due to IBS are comparable to the expected dispersive cooling rate the unambiguous demonstration of the effect was performed for dispersive heating. The temporal evolution of the horizontal temperature shown in fig. 1 clearly shows the expected transition from indirect IBS cooling to weak dispersive horizontal heating for the IBS coupling strength decreasing with the phase space density respectively the prolonged "blow up" time before starting laser cooling.

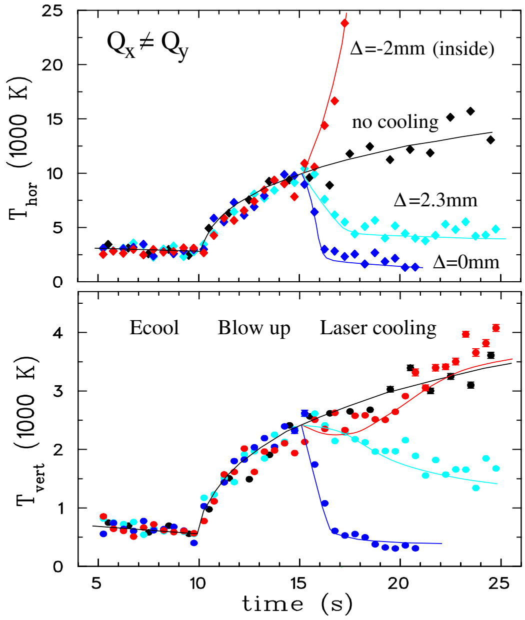

Fig. 2: Temporal evolution of the transverse beam temperatures for different horizontal displacements Δ of the laser beam with respect to the ion beam. In agreement with the standard IBS model [3] including the corresponding linearized dispersive cooling rate (solid lines) the transition from dispersive heating to cooling is obvious in the horizontal plane, where in the vertical only IBS cooling is visible.

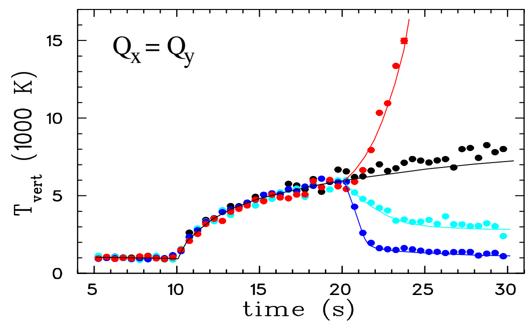

Fig. 3: Similar timing and displacement as above for $Q_x = Q_y$, where also dispersive cooling in the vertical plane becomes possible.

The dependence of the dispersive force on the displacement Δ can be studied in fig. 2. Starting with $\Delta = -2\,$mm, a strong horizontal heating is clearly dominating indirect IBS cooling at zero displacement. Also notice that for $\Delta = 2.3\,$mm (beam waist (FWHM) 2.1 mm) horizontal cooling is still visible although longitudinal cooling is strongly weakened. Furthermore fig. 3 proves that with the storage ring operated on a betatron coupling resonance ($Q_x = Q_y \approx 2.81$) dispersive horizontal cooling can be efficiently transfered also to the vertical plane thus allowing true three dimensional laser cooling.

References

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[3] I. Lauer *et al.*, submitted to Phys. Rev. Lett.