Transverse Laser Cooling of a Fast Stored Ion Beam through Dispersive Coupling

I. Lauer,[1] U. Eisenbarth,[1] M. Grieser,[1] R. Grimm,[1] P. Lenisa,[1] V. Luger,[1] T. Schätz,[2] U. Schramm,[2] D. Schwalm,[1] and M. Weidemüller[1]

[1]*Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*

[2]*Ludwig-Maximilians-Universität München, Sektion Physik, 85748 Garching, Germany*

(Received 16 March 1998)

Transverse laser cooling of a fast stored $^9Be^+$ ion beam based on a single-particle force independent of the ion density is demonstrated at the Heidelberg Test Storage Ring. The cooling scheme exploits longitudinal-horizontal coupling through ring dispersion and the transverse intensity profile of the longitudinally merged laser beam. By linear betatron coupling the horizontal force is extended to the vertical degree of freedom resulting in true 3D laser cooling. The observed transverse-cooling mechanism represents an important step towards crystalline ion beams. [S0031-9007(98)07024-0]

PACS numbers: 29.20.Dh, 32.80.Pj, 42.50.Vk, 52.25.Wz

Cooling of energetic ion beams to high phase-space densities represents a challenging issue with great importance for present and future experiments performed at storage rings [1]. The ultimate goal in beam cooling experiments is the observation of Coulomb ordering in a space-charge dominated beam [2–4]. An ion crystal circulating in a storage ring at great speed uniquely combines high-energy beam physics with the physics of strongly coupled plasmas. Besides the understanding of fundamental intrinsic properties, crystalline ion beams may find applications as high-luminosity sources for, e.g., high-resolution nuclear physics experiments, colliders, and inertial confinement fusion.

With the introduction of electron and laser cooling to ion storage rings the field has developed rapidly [4]. Laser cooling, in particular, reaches extremely high longitudinal cooling rates adequate for the formation of an ion crystal, but it does not directly affect the transverse degrees of freedom. At high phase-space densities relaxation due to intrabeam Coulomb collisions leads to efficient indirect cooling of the transverse motion [5]. As the beam approaches an ordered state, however, heat exchange due to Coulomb interaction becomes insufficient to reach crystallization [6,7].

Different schemes have been proposed to provide a transverse damping force independent of the mutual particle interaction [8–10], but none of them was realized so far. In this Letter, we experimentally demonstrate transverse cooling solely based on *single-particle* interaction of the ions with laser light. The cooling scheme [8] exploits longitudinal-horizontal coupling of the particle motion arising from storage ring dispersion, i.e., the dependence of the ion's horizontal position on the longitudinal momentum, in combination with a transverse gradient of the light force ("dispersive cooling"). Thus, damping of the longitudinal momentum fluctuations is transferred to the horizontal degree of freedom. True 3D cooling is demonstrated by additionally mixing horizontal and vertical motion through betatron coupling.

To understand how a longitudinally acting force can affect the horizontal betatron motion consider a stored ion resonantly absorbing photons from a collinearly merged laser beam. In combination with an appropriate mechanism counteracting the light pressure [11], the momentum change in the cooling region can be approximated by $\Delta p \simeq -f_z(p - p_0) + K_{xz}x$ with the momentum deviation $|p - p_0| \ll p_0$. The friction coefficient f_z determines the longitudinal cooling rate and reflects the momentum dependence of the light force resulting from the Doppler effect. The horizontal-longitudinal coupling coefficient K_{xz} stems from the intensity gradient along the horizontal direction x of the Gaussian laser beam [12].

Through dispersion the longitudinal momentum change leads to a horizontal shift Δx of the closed orbit as schematically depicted in Fig. 1. The shift depends on the specific ring lattice, and is given by $\Delta x = D\Delta p/p_0$, where D is the local dispersion function [13]. The phase of the ion's horizontal betatron motion determines whether the longitudinal momentum transfer leads to a decrease [Fig. 1(a)] or an increase [Fig. 1(b)] of the horizontal betatron amplitude. If Δp is constant across the horizontal

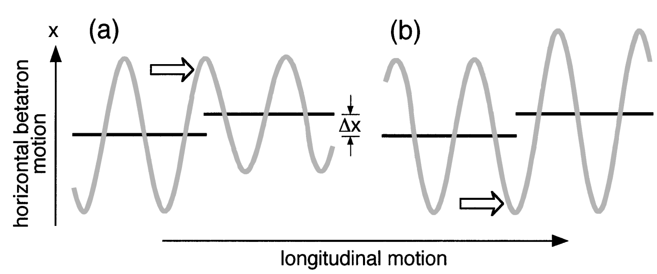

FIG. 1. Longitudinal-horizontal coupling through dispersion. Depicted is the horizontal betatron motion of a stored ion experiencing a longitudinal momentum change Δp indicated by the arrow. Through dispersion the closed orbit is shifted by Δx. (a) The longitudinal momentum transfer happens at $x > 0$ leading to a decrease of the betatron amplitude. (b) Momentum is transferred at $x < 0$ yielding an increase of the betatron amplitude.

 0031-9007/98/81(10)/2052(4)$15.00

extension of the ion beam ($K_{xz} = 0$), averaging over all betatron phases will have no net effect on the betatron amplitude. If, on the other hand, one creates a horizontal gradient in Δp by, e.g., horizontally displacing the laser beam from maximum overlap ($K_{xz} \neq 0$), the betatron amplitude on average changes. Depending on the sign of K_{xz} the horizontal betatron amplitude decreases or increases which corresponds to horizontal cooling or heating, respectively. By linearizing the equations of horizontal motion for stored ions one finds that the horizontal emittance ε_h changes with a rate coefficient [14]

$$\Lambda_h \equiv \frac{1}{\varepsilon_h}\frac{d\varepsilon_h}{dt} = -\nu_{\text{rev}}\frac{DK_{xz}}{p_0}, \tag{1}$$

where ν_{rev} denotes the revolution frequency.

Our experiments are performed at the Test Storage Ring (TSR) with a beam of typically 10^7 $^9\text{Be}^+$ ions injected at an energy of 7.3 MeV corresponding to about 4.2% of the speed of light. The residual pressure of the ring chamber (3×10^{-11} mbar) limits the $1/e$ storage time to about 25 s. Electron cooling is applied to precool the ion beam, thus reducing the ion beam diameter from several cm after injection to less than 1 mm. The ion beam is bunched at 3.38 MHz, corresponding to the 15th harmonics of the revolution frequency which has been demonstrated to eliminate losses due to close binary Coulomb collisions during laser cooling [5,15].

The laser beam copropagates with the ion beam over a length of about 5 m in one of the straight TSR sections. In this section the ring lattice yields a dispersion of $D \approx +2$ m. The laser is resonant with the D_2 transition of the alkali-like $^9\text{Be}^+$ ion at a wavelength of 300.35 nm in the laboratory frame. The laser beam of 70 mW is focused to a $1/e$ radius of 1.5 mm in the center of the interaction region. Overlap between ion and laser beam is precisely controlled by an active system for stabilization of the laser beam described in Ref. [16]. The stabilization scheme allows parallel displacement of the laser beam relative to the ion beam to better 10 μm, and adjustment of the relative angle to better 1 μrad. The main cause for the uncertainties are fluctuations in the ion beam steering. Maximum overlap between laser and ion beam to within an absolute displacement and angle uncertainty of 250 μm and 200 μrad, respectively, is achieved by optimizing the fluorescence signal on two photomultiplier tubes separated by 1.2 m.

Transverse emittances are measured by a beam profile monitor (BPM) which spatially resolves ions produced by collisions of the ion beam with residual gas [17]. From the (Gaussian) spatial distribution of the ion beam at the BPM position one can deduce the emittances by taking into account the ring lattice functions of the TSR [18]. The longitudinal velocity distribution is monitored by ramping a bias voltage applied to a drift tube installed in the laser-cooling section and detecting the fluorescence intensity induced by the cooling laser inside the tube [18].

In a first series of measurements, horizontal and vertical tune ($Q_x = 2.83, Q_y = 2.79$) are chosen well separated from low-order coupling resonances [13]. In the vicinity of a coupling resonance, the magnetic guiding field of the electron cooler represents the main source for mixing of horizontal and vertical betatron motion. To exclude such residual coupling, the magnetic field was adjusted to a comparably low value of 20 mT.

Figure 2 shows the temporal evolution of the transverse emittances for different laser beam displacements. The measurement cycle starts with the beam injection at $t = 0$. After 6 s of electron precooling the beam reaches transverse equilibrium. Electron cooling is stopped at $t = 10$ s. Without external cooling the beam steadily heats up in all degrees of freedom (triangles in Fig. 2) as a result of intrabeam Coulomb scattering (IBS) [5]. The heating rate goes down as the phase-space density decreases. At $t = 15$ s, we start laser cooling by opening a shutter which blocked the laser beam. The laser frequency is detuned 200 MHz below the resonance frequency of ions moving at the synchronous velocity.

At maximum overlap between the laser and the ion beam (squares in Fig. 2) no longitudinal-horizontal coupling is present since the gradient of the transverse laser beam profile vanishes. The longitudinal light force leads to rapid cooling of the longitudinal degree of freedom to a few tens of degrees Kelvin within milliseconds. One observes damping of both transverse emittances simultaneously at a cooling rate of about -1 s^{-1} due to IBS which has extensively been analyzed in former experiments [5].

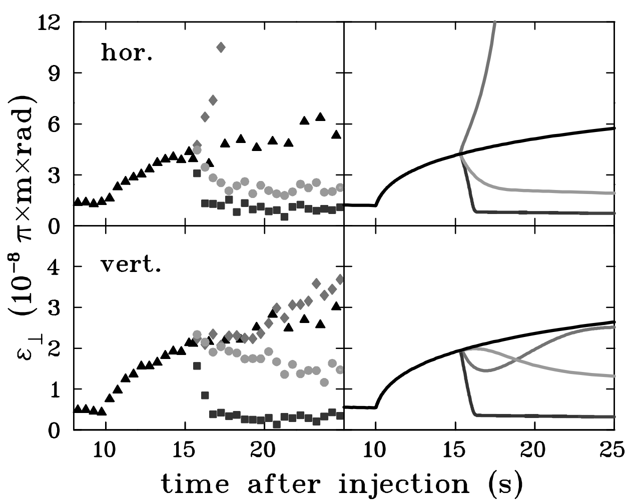

FIG. 2. Temporal evolution of horizontal (upper graphs) and vertical (lower graphs) emittance for various displacements of the laser beam at the absence of betatron coupling. The left graphs present the measured data; on the right the results of numerical simulations are shown. During the first 10 s the ions are electron cooled. For the next 5 s no cooling is present. At $t = 15$ s laser cooling starts. Triangles: without laser interaction; squares: maximum overlap between laser and ion beam ($x = 0$); diamonds: laser beam displaced towards the ring center ($x = -2.0$ mm); circles: laser beam horizontally displaced away from the ring center ($x = +2.5$ mm).

To experimentally separate the dispersive force from effects induced by IBS we first horizontally heat the ions. Horizontal heating rapidly decreases the phase-space density and thus leads to a disappearance of IBS cooling. For dispersive heating the laser beam has to be displaced towards the ring center ($x < 0$); see Eq. (1). The observed result is shown by the diamonds in Fig. 2. The horizontal emittance rapidly increases, but no effect on the vertical emittance can be identified. The observed decoupling of horizontal and vertical dynamics indicates the expected disappearance of IBS. Horizontal heating is thus purely governed by the dispersive force.

In contrast to heating, dispersive cooling is more difficult to be demonstrated since it is always superposed by IBS cooling. Optimum dispersive cooling is reached at a displacement where the transverse intensity gradient of the laser beam reaches its maximum ($x \approx 1$ mm). By choosing a much larger displacement ($x = +2.5$ mm, circles in Fig. 2) longitudinal cooling is strongly reduced due to the smaller laser intensity at the ion beam. Consequently, dispersive cooling becomes more efficient than indirect horizontal cooling by IBS. As shown in Fig. 2 the observed dynamics of the vertical and the horizontal degree of freedom differs significantly. While the horizontal emittance is damped in within some seconds, the vertical emittance decreases much slower. Obviously, the vertical time scale is determined by the weak IBS cooling while dispersive cooling dominates the dynamics of the horizontal degree of freedom.

The above observations provide conclusive evidence for the existence of a horizontal force which influences the motion of the individual ion independent of the ion beam density. To check whether this force is indeed mediated by dispersion, which only exists horizontally, we displace the laser beam vertically from the position of maximum overlap. The transverse cooling rate decreases as one displaces the laser beam, in full accordance with indirect IBS cooling since the laser intensity at the ion beam becomes smaller. Neither a difference on the temporal evolution between vertical and horizontal emittance is found nor do we observe the transition from cooling to heating which appeared at horizontal displacement of the laser beam (Fig. 2). For vertical displacement we can therefore exclude transverse effects of the laser interaction besides indirect cooling through IBS.

Our experimental results are in good agreement with numerical simulations shown in the right part of Fig. 2. The calculations are based on IBS theory [19] as incorporated in the computer code INTRABS by Giannini and Möhl [20]. With the specific lattice functions of the TSR the program calculates the temporal evolution of the beam emittances under the assumption of complete horizontal-vertical decoupling of betatron motion. A fit to the data points without laser interaction (triangles in Fig. 2) is consistent with a number of 10^7 stored ions.

The light force is introduced into the program by longitudinal and horizontal damping coefficients $\Lambda_\parallel$ and Λ_h which we use as adjustable parameters to reproduce the experimental data. At maximum overlap between laser beam and ion beam ($x = 0$, $\Lambda_h = 0$) we find $\Lambda_\parallel \approx -50\ \mathrm{s}^{-1}$. The coefficient decreases as the laser beam is displaced horizontally mainly because the laser intensity at the ion beam position becomes much smaller. From the evolution of the vertical emittance at $x = 2.5$ mm we deduce $\Lambda_\parallel \approx -0.5\ \mathrm{s}^{-1}$. The temporal behavior of the horizontal emittance yields the rate for dispersive cooling $\Lambda_h \approx -0.3\ \mathrm{s}^{-1}$. We have compared these damping rates with a model describing the longitudinal dynamics of stored ions in a rf bucket, which we will discuss elsewhere. To predict an effective longitudinal cooling rate under our experimental conditions the model explicitly includes binary collisions and the Lorentzian velocity dependence of the light force. The collision probability is adjusted by comparing the resulting two-component velocity distributions with the measured ones [21]. The horizontal rate for dispersive cooling is determined by integrating Eq. (1) over the measured longitudinal velocity distribution. The results of the model give reasonable quantitative agreement within a factor of 2 with the rate coefficients deduced from the IBS program.

In a second series of experiments we show that the dispersive force can simultaneously act on the vertical degree of freedom. This is accomplished by adjusting the ring to equal horizontal and vertical tune ($Q_x = Q_y = 2.81$), and by coupling both degrees of freedom by a 40 mT longitudinal field of the electron cooler solenoid [13]. The resulting betatron coupling becomes apparent by equal horizontal and vertical emittances as shown by the data points without light interaction (triangles) in Fig. 3). As before we displace the laser beam parallel with respect to the ion beam in order to vary the dispersive light force. As presented in Fig. 3 the transition from dispersive cooling to heating again appears as the laser beam is displaced towards the ring center. Vertical and horizontal emittances are now evolving identically. By betatron coupling, the dispersive light force has thus been fully extended to the vertical degree of freedom.

In conclusion, our observations show that, in contrast to IBS cooling, dispersive cooling acts as a single-particle effect independent of the ion density. Transverse cooling rates on the order of $1\ \mathrm{s}^{-1}$ have been reached comparable to the maximum rates achieved by IBS cooling, but these rates are still far below typical longitudinal cooling rates. The coupling coefficient K_{xz} is limited mainly by the maximum intensity gradient attainable in a Gaussian beam. However, dispersive cooling may be enhanced by, e.g., including specially devoted high-dispersion sections in the storage ring.

To stabilize crystalline order against shear and other destructive effects induced by the ring lattice, the longitudinal momentum should be a function of the transverse displacement [6,22]. In the ideal case, all particles independent of their radial position would be cooled to the same average angular velocity ("tapered cooling"). Tapered cooling

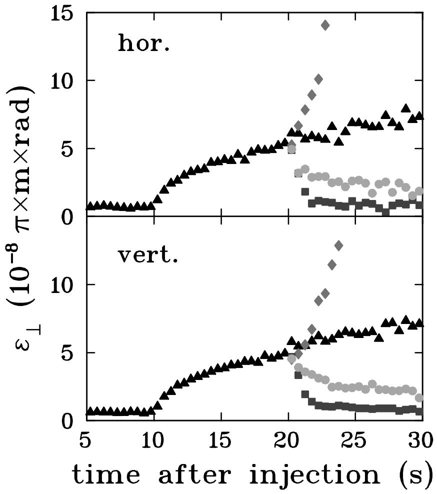

FIG. 3. Temporal evolution of horizontal (upper graph) and vertical (lower graph) emittance for various diplacements of the laser beam with full betatron coupling. The emittances now evolve identically. After 10 s of electron cooling no cooling is present for 10 s. At $t = 20$ s laser cooling starts. The laser beam displacements are chosen as in Fig. 2 and are indicated by the same symbols and gray scales.

poses severe constraints on the coupling coefficient K_{xz}. Under our present experimental conditions it seems unrealistic to attain coupling coefficients sufficient for 3D ion crystals. Nevertheless, recent molecular dynamics simulations [6] show that today's achievable laser cooling rates may suffice to generate a linear Coulomb chain (1D crystal). For this purpose, the number of stored particles, and thus the linear density, has to be kept low in order to ensure that the 1D structure represents the ground state at low temperatures. Dispersive cooling then serves two important purposes, both necessary to attain a crystalline beam [6]. First, even before crystallization it transversely cools the beam at the required low densities where IBS cooling becomes too slow. Second, it provides a small but finite coefficient K_{xz} necessary to stabilize the 1D crystal (see Fig. 3 in Ref. [6]).

Cooling through dispersive coupling is not restricted to light forces acting on singly charged ions. Following Eq. (1), any longitudinal friction force showing a horizontal gradient will allow for dispersive cooling. This can be realized by an electron cooler with a slightly displaced electron beam [23]. Dispersive electron cooling might be of significance to attain and stabilize Coulomb ordering phenomena with highly charged heavy ion beams [24].

Stimulating discussions with A. Wolf are gratefully acknowledged, as well as invaluable technical contributions by H. Krieger.

[1] *Beam Cooling and Related Topics*, edited by J. Bosser, CERN 94-03 (European Organization for Nuclear Research, Geneva, 1994).

[2] A. Rahman and J.P. Schiffer, Phys. Rev. Lett. **57**, 1133 (1986).

[3] D. Habs and R. Grimm, Annu. Rev. Nucl. Part. Sci. **45**, 391 (1995), and references therein.

[4] For a recent overview see *Crystalline Beams and Related Issues*, edited by D.M. Maletic and A.G. Ruggiero (World Scientific, Singapore, 1996).

[5] H.-J. Miesner *et al.*, Phys. Rev. Lett. **77**, 623 (1996); H.-J. Miesner *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **383**, 634 (1996).

[6] J. Wei, H. Okamoto, and A.M. Sessler, Phys. Rev. Lett. **80**, 2606 (1998); see also J. Wei *et al.*, in Ref. [4].

[7] Q. Spreiter, M. Seurer, and C. Toepffer, Nucl. Instrum. Methods Phys. Res., Sect. A **364**, 239 (1995).

[8] A. Wolf, in Book of Contributions of the 2nd Workshop on Diagnostics of Laser Cooled Beams, Sandbjerk, 1991 (unpublished).

[9] P.J. Channel, J. Appl. Phys. **52**, 3791 (1981); L. De Salvo, R. Bonifacio, and W. Barletta, Opt. Commun. **116**, 374 (1995); R. Calabrese *et al.*, Opt. Commun. **123**, 530 (1996).

[10] H. Okamoto, M. Sessler, and D. Möhl, Phys. Rev. Lett. **72**, 3977 (1994); H. Okamoto, Phys. Rev. E **50**, 4982 (1994).

[11] For a coasting beam the restoring mechanism may be provided by an induction accelerator [5] or an additional counterpropagating laser beam; for a bunched beam the counteracting force is exerted by the rf bunching cavity. When averaged over many revolution cycles, stationary conditions are established such that the average restoring force equals the average light pressure, i.e., $\langle \Delta p \rangle = 0$.

[12] Note that the momentum at force equilibrium ($\Delta p = 0$) not only depends on the laser frequency, but also on the laser intensity (see R. Grimm *et al.*, in Ref. [1]).

[13] P.J. Bryant and K. Johnson, *The Principles of Circular Accelerators and Storage Rings* (Cambridge University Press, Cambridge, England, 1993).

[14] Strictly speaking, Λ_h^{-1} describes the time constant of longitudinal-horizontal coupling. If, as in our experiments, the longitudinal momentum spread is damped at a rate much larger than Λ_h, i.e., $f_z \gg DK_{xz}/p_0$, the horizontal cooling rate becomes equal to Λ_h.

[15] J.S. Hangst *et al.*, Phys. Rev. Lett. **74**, 4432 (1995).

[16] H. Wernøe, Report No. MPI H-V08-93, MPI für Kernphysik, Heidelberg, 1993.

[17] B. Hochadel *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **343**, 401 (1994).

[18] W. Petrich *et al.*, Phys. Rev. A **48**, 2127 (1993).

[19] A. Piwinsky, in *Proceedings of the CERN Accelerator School*, edited by S. Turner, CERN 87-03 (European Organization for Nuclear Research, Geneva, 1987), p. 402.

[20] R. Giannini and D. Möhl (private communication).

[21] S.N. Atutov *et al.*, Phys. Rev. Lett. **80**, 2129 (1998).

[22] J.P. Schiffer, in Ref. [4], and references therein.

[23] Note that the longitudinal electron velocity in an electron cooler is a function of the transverse position due to space-charge effects.

[24] M. Steck *et al.*, Phys. Rev. Lett. **77**, 3803 (1996).