VOLUME 87, NUMBER 27 PHYSICAL REVIEW LETTERS 31 DECEMBER 2001

Low-Current, Vertical Blowup in a Stored Laser-Cooled Ion Beam

N. Madsen,[1] P. Bowe,[2] J. S. Nielsen,[3] L. E. Siegfried,[2] and J. S. Hangst[2]
[1]*CERN, Geneva, Switzerland*
[2]*Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus C, Denmark*
[3]*ISA, University of Aarhus, 8000 Aarhus C, Denmark*

(Received 4 April 2001; published 10 December 2001)

Using a novel technique for real-time transverse beam profile diagnostics of a stored ion beam, we have observed the transverse size of a stored laser-cooled ion beam. Earlier we observed that the density of the beam is independent of the beam current. At very low currents, we observe an abrupt change in this behavior: The vertical beam size increases suddenly by about an order of magnitude. This observation implies a sudden change in the indirect vertical cooling mediated by intrabeam scattering. Our results have serious implications for the ultimate beam quality attainable by laser cooling.

DOI: 10.1103/PhysRevLett.87.274801 PACS numbers: 29.20.Dh, 29.27.Bd, 42.50.Vk, 52.27.Jt

Laser cooling in a storage ring [1] has been demonstrated to be a powerful tool for creating ultracold and dense stored ion beams [2]. Cold and dense beams are of interest for many storage ring applications, and the ultimate state for such beams is the attainment of ion beam crystallization [3].

Using a novel technique for transverse beam profile diagnostics, we have studied the development of the transverse beam size of a stored, laser-cooled, low-current coasting ion beam in the ASTRID storage ring. Earlier we observed that the maximum density of a stored laser-cooled ion beam is limited by the space charge tune shift [2]. In this Letter, we present experimental evidence of a deviation from this behavior at very low ion beam currents. During continuous observation of the transverse beam size of the stored beam, we observe how the beam size is reduced as the beam current decays due to charge exchange with the residual gas in the storage ring. At a certain point in time (and thus beam current), we observe that the vertical beam size increases dramatically, while at the same time the horizontal beam size decreases. The current at which this happens depends on the cooling power, the laser detuning, and the laser polarization. The circulating beam current at the time of this observation is below the maximum current at which a "string" (a one-dimensional ordered beam [3]) may exist in the machine. We argue that this low-current vertical blowup of the beam arises due to a sudden reduction of the indirect transverse cooling mediated by intrabeam scattering (IBS), which thus no longer compensates the diffusive heating caused by the spontaneous emission of photons during laser cooling. The horizontal dimension, however, is cooled by the dispersive coupling between the horizontal and the longitudinal dimensions [4] and thus does not blow up. Our results indicate that there may be serious limitations to the possibility of using laser cooling in the creation of a crystalline beam.

These observations have been made possible by the use of a novel technique for studying the transverse beam profile of a stored ion beam. By imaging the fluorescent light from the laser-excited ion beam onto a high resolution, image intensified, charge-coupled device (CCD) camera, we can directly monitor the beam profile in real time, and that with a much higher sensitivity and resolution than with conventional techniques. We have previously observed the beam profile using an integrating CCD, a system that did not allow for the dynamics studies reported here [2].

A single high speed CCD camera with an image intensifier is used to continuously monitor the transverse beam profiles (typical integration time used ~0.3 s). We observe one dimension at a time. A simple lens system images the light from the laser-excited ion beam onto the image intensifier. The spatial resolution of our system is approximately 20 μm. In order to produce a spatially flat laser light distribution, the focused (FWHM ~ 1.0 mm) laser beam is actively swept in the desired plane, at a frequency of ~100 Hz. A spatially flat distribution means that all ions are illuminated evenly; thus the charge distribution on the CCD reflects the ion beam density distribution directly [2].

We have used the ASTRID storage ring (Fig. 1 [5]) in Aarhus to store a beam of 100 keV $^{24}\mathrm{Mg}^{+}$ ions. Laser cooling is performed in one straight section, with copropagating and counterpropagating laser beams, having radii of ~3 mm, overlapping the ion beam. The overlap between the laser beams and the ion beam is carefully optimized for optimum longitudinal and transverse cooling [2,4]. For diagnostic purposes, copropagating laser light in a second ring section is focused and overlaps the ion beam in the post acceleration tube (PAT) in front of the transverse imaging system. We measure the longitudinal velocity distribution by monitoring the laser-induced fluorescence from the ion beam inside the PAT using a photomultiplier while sweeping the voltage on the PAT [6].

The beam current at any time after injection could be extrapolated with an uncertainty of a few percent by monitoring the injected current and the neutralization of the beam.

In Fig. 2 the transverse beam sizes, extracted from Gaussian fits to the measured distributions, are shown as a function of the time after injection. The longitudinal

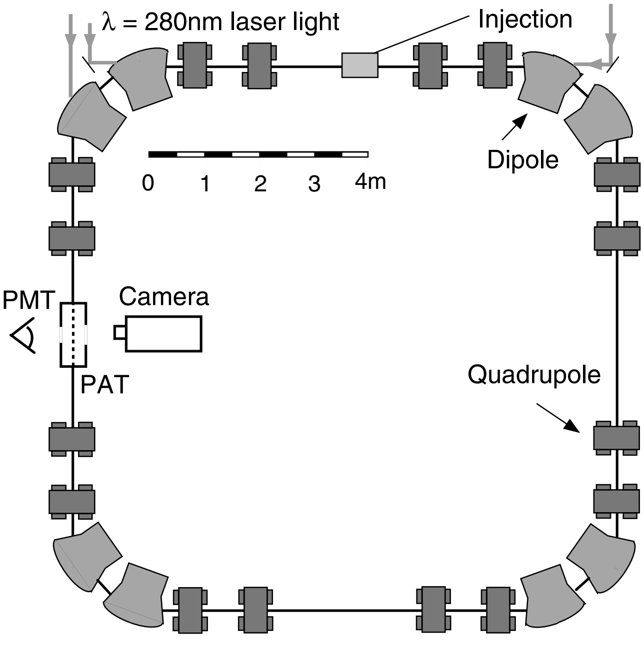

FIG. 1. The ASTRID storage ring.

temperature is <1 K. We observe that at 68 s after injection the vertical beam size increases dramatically. The beam lifetime was 26.6 s ± 1 s. $(5.0 \pm 0.3) \times 10^6$ particles were injected. There were thus $(3.8 \pm 0.2) \times 10^5$ circulating particles at the start of the blowup. One also observes that the beam size does not shrink below about 0.18 mm. Calculations of the orbit response based on the stability of the dipole-corrector power supplies of ASTRID ($\pm 3 \times 10^{-4}$) indicate that this limitation is due to fluctuations in the beam position in ASTRID.

In considering possible heating sources, we performed a simple IBS calculation based on binary collisions using the program INTRABTC [7] with the ASTRID magnetic lattice and the measured beam parameters right before the blowup. This calculation indicates that the vertical degree of freedom should be cooled with a characteristic time of 94 ms; thus IBS is not the heating source. The horizontal degree of freedom on the other hand should be heated with a characteristic time of 27 ms (the IBS calculation does not include the direct horizontal cooling through dispersion).

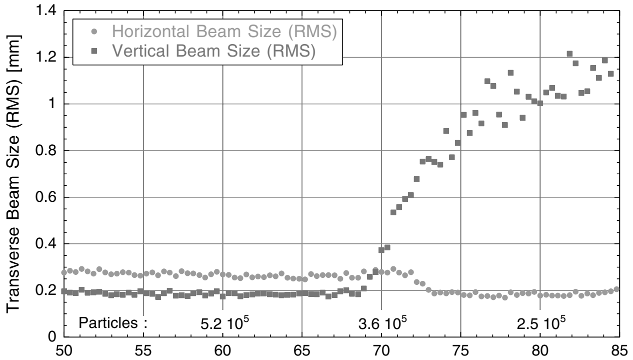

FIG. 2. Transverse beam sizes as a function of the time after injection. About 5.0×10^6 particles were injected. Cooling laser powers ~9 mW. Longitudinal temperature ~1 K.

A possibly important and generally overlooked source is the heating due to the spontaneous emission of photons during laser cooling. Laser cooling is based on the scattering of photons, and the lowest temperature for Doppler cooling (the Doppler limit) is given by the equilibrium between the cooling force from the lasers and the diffusive heating due to the recoil of the ions when the excited electronic states decay spontaneously. As the laser-cooling force is very strong, the Doppler limit is, in spite of the laser-induced diffusion, very low, for Mg^{24+} about 1.0 mK. However, in the transverse dimensions the compensating cooling does not originate from the laser, as the laser-cooling force acts directly only in the longitudinal dimension. Thus, we have a potentially significant heating source in the transverse degrees of freedom.

In order to investigate whether the laser-induced diffusion is the source of the heating, we can exploit the fact that the spontaneous emission from the decay of the $(3^2\mathrm{S}_{1/2}) \leftrightarrow (3^2\mathrm{P}_{3/2})$ transition is spatially nonisotropic. It turns out that the intensity of light emitted perpendicular to the polarization of the cooling laser is a factor 2.5 higher than that emitted parallel to the polarization. Thus, by investigating the dependence of the blowup on the polarization of the cooling lasers, we may clarify the source of the heating.

Figure 3 shows two sets of measurements of the transverse beam sizes as a function of the time after injection. The top plot 3(a) is for both cooling lasers polarized horizontally and the lower plot 3(b) is for both polarized vertically. We observe that the blowup occurs significantly earlier for the horizontal polarization, i.e., at a higher current. Horizontally polarized cooling lasers will cause more spontaneous photons to be emitted vertically and thus more heating vertically. This observation supports the hypothesis that the spontaneous emission is a significant heating source.

In order to quantify the effect, it is of interest to estimate the diffusion caused by the spontaneous emission of photons. The velocity diffusion induced in each spatial dimension (assuming isotropic photon emission) by the scattering of photons is approximately [8]

$$D_{\mathrm{laser}} = \tfrac{1}{2}\Gamma_{\mathrm{phot}} v_{\mathrm{recoil}}^2 , \qquad (1)$$

where Γ_{phot} is the photon scattering rate, $v_{\mathrm{recoil}} = \hbar k/m$ is the recoil velocity of the $^{24}\mathrm{Mg}^+$ ion, k is the wave number, and m is the ion mass. The total rate of photon scattering is given by

$$\Gamma_{\mathrm{phot}} = \frac{1}{2} S\Gamma \frac{(\Gamma/2)^2}{\delta^2 + (\Gamma/2)^2(1 + S)} , \qquad (2)$$

where Γ is the transition linewidth, $S = I/I_s$ is the saturation parameter, I is the laser intensity, I_s is the saturation intensity of the transition, and δ is the frequency detuning from resonance [8]. Using the values from the experiment,

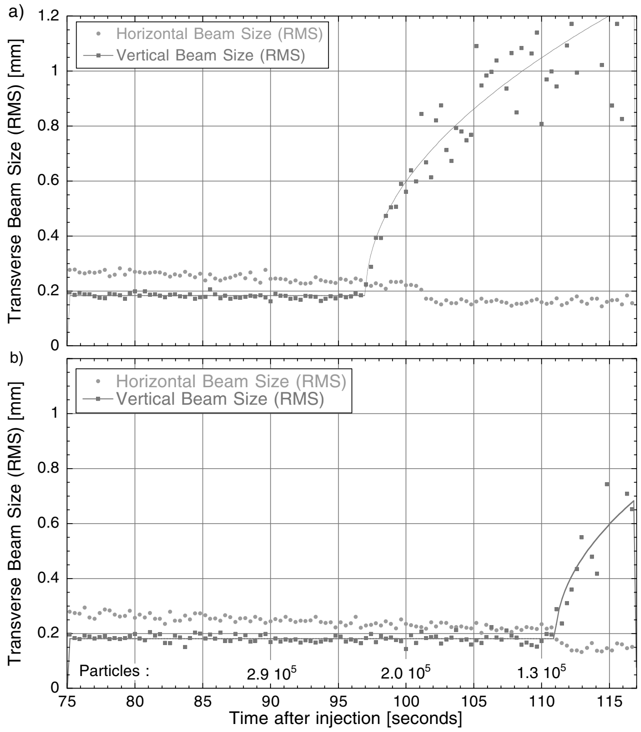

FIG. 3. Transverse beam sizes as a function of the time after injection. About 8.4×10^6 particles were injected. Cooling laser powers ~7 mW. (a) Both cooling lasers were horizontally polarized. (b) Both cooling lasers vertically polarized.

we find that for zero detuning the diffusion coefficient equals $3 \times 10^4\ \mathrm{m^2/s^3}$.

With constant diffusion the square of the velocity spread increases linearly with time [8]. The measured diffusion coefficient can therefore be extracted from a square root fit to the blowup, as indicated by the lines in Fig. 3. We find the measured diffusion coefficients given in Table I.

The diffusion coefficients in Table I were measured with a longitudinal temperature of 1 K, which corresponds to a detuning of about 70 MHz. Inserting in Eqs. (1) and (2), we find a diffusion coefficient of $3.6 \times 10^3\ \mathrm{m^2/s^3}$ in fair agreement with the measurements. The determination of the absolute detuning of the laser with respect to the transition is limited by the beam energy spread at injection, and is not better than about 50 MHz.

The calculation above shows that the diffusion rate depends strongly on the laser detuning (for small detunings). We therefore expect the time of the blowup to be very sensitive to the laser detuning. The measurements shown in Fig. 4 confirm this hypothesis. Figure 4 shows the vertical beam size as a function of time after injection for three different laser detunings of a beam with a longitudinal temperature of order 1.5 K. We observe a strong variation in the blowup time for detuning changes equal to only half of the linewidth of the cooling transition. The uncertainty in the measured diffusion coefficients is unfortunately too large for this information to be quantitatively decisive. We have also observed a tendency of the blowup rate to scale with the cooling laser power. More detailed quantitative investigations of the blowup are unfortunately hampered by the long term frequency stability of the laser system.

The experimental evidence presented supports the hypothesis that the heating source which drives the vertical blowup is the laser-induced diffusion. However, the binary IBS calculation indicates that the vertical motion should be cooled at a rate much faster than the measured blowup. This contradiction implies that some feature of the dynamics is overlooked by the binary IBS model.

It is suggestive that the regime of interest in this experiment involves linear charge densities for which the beam's ground state would be a one-dimensional ordered structure, or "string." For a cold beam, correlations between particles can be important. These correlations are not included in a binary scattering model. An important effect, observed in electron cooled beams [9,10], is a type of quasiordering in which the particles no longer drift past one another longitudinally. One signature of this effect is that the longitudinal beam temperature, measured by observing charge density fluctuations known as Schottky noise, drops suddenly at the onset of ordering. Both electron- and laser-cooled ion beams have nonisotropic distribution functions, because the cooling is much stronger longitudinally than transversely. There is thus energy transfer (through Coulomb interaction) from the transverse to the longitudinal motion, which competes with the longitudinal cooling. It is in fact this energy transfer which provides the indirect transverse (sympathetic) cooling in a longitudinally laser-cooled beam.

The above-mentioned drop in longitudinal temperature of electron cooled beams has been interpreted as a kind of decoupling between the transverse and the longitudinal degrees of freedom at the onset of the quasiordering. The higher transverse temperature no longer perturbs the longitudinal one, since the ions stop drifting past one another longitudinally. If this decoupling happens in a laser-cooled ion beam, the transverse sympathetic cooling of the beam

TABLE I. Particle numbers and densities at the blowup time and diffusion coefficients extracted from the measurements shown in Figs. 2 and 3.

Measurement	N $[10^5]$	Density n $[\mathrm{cm^{-3}}]$	D_{vertical} $[\mathrm{m^2/s^3}]$
Fig. 2	3.8 ± 0.2	$(3.0 \pm 0.2) \times 10^5$	$(3.9 \pm 0.9) \times 10^3$
Fig. 3(a)	2.2 ± 0.1	$(2.1 \pm 0.2) \times 10^5$	$(3.4 \pm 0.4) \times 10^3$
Fig. 3(b)	1.3 ± 0.1	$(1.3 \pm 0.1) \times 10^5$	$(2.5 \pm 0.9) \times 10^3$

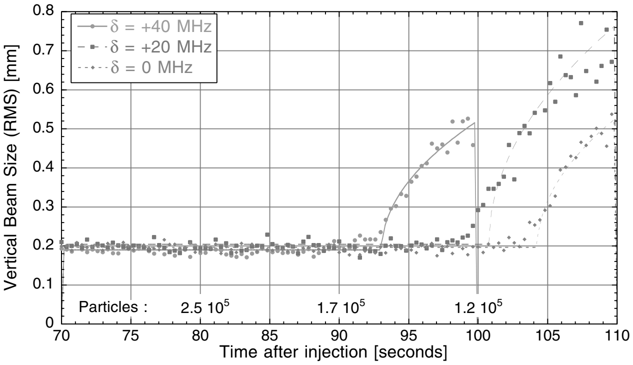

FIG. 4. Transverse beam sizes versus time after injection for three different laser detunings. The given detunings are relative. About 5.0×10^6 particles were injected. Cooling laser powers ~5 mW. Longitudinal temperature ~1.0–1.6 K.

would be strongly suppressed, and the beam heating by laser-induced diffusion could become dominant. The loss of transverse cooling would be more critical vertically, since the horizontal motion would still be cooled by dispersive cooling [4]. The observed decrease of the horizontal beam size after the blowup starts supports this hypothesis as the IBS calculation indicated heating (which before the blowup is countered by the dispersive cooling). The size reduction can thus be interpreted as a reduction in the IBS mediated heating compared to the dispersive cooling. This hypothesis was further strengthened in a measurement carried out with a setup in which the vertical and horizontal tune were identical ($Q = 2.277$). In this measurement the blowup was not observed, indicating that the introduction of dispersive cooling of the vertical degree of freedom compensates for the loss of sympathetic cooling. Thus, a possible interpretation of our results is that the beam has become quasiordered longitudinally, leading to an undesired loss of sympathetic transverse cooling. A parameter of interest in this regard is the linear charge density of the beam. For the sake of comparison between different machines, the linear charge density can be expressed in dimensionless form by using the Wigner-Seitz radius as a length scale. The Wigner-Seitz radius is the average interparticle spacing for a zero-temperature beam. The Wigner-Seitz radius for a uniform storage ring plasma can be defined as

$$a_{\mathrm{WS}} = \left(\frac{3q^2}{8\pi\epsilon_0 m \omega_\perp^2} \right)^{1/3}, \tag{3}$$

where q is the ion charge, m is the ion mass, and $\omega_\perp$ is the betatron frequency, which characterizes the transverse focusing. The dimensionless linear charge density is then defined to be $\lambda = a_{\mathrm{WS}}/d$, where d is the average longitudinal distance between ions in the ring. For ASTRID, the Wigner-Seitz radius is about 41 μm, and the circumference of the machine is 40 m. Thus, the λ parameter at the onset of blowup (Fig. 2) is about 0.4. The transition between one- and two-dimensional ordered structures occurs for $\lambda = 0.709$ [11], so we are well into the linear regime. We note that our longitudinal temperature measurement is an upper limit, the resolution being determined by the inherent width of the cooling transition.

If the above interpretation is correct, laser cooling as implemented in ASTRID may not be suitable for obtaining true one-dimensional order in a storage ring. Schottky diagnostics of the beam could help to clarify the experimental situation, but our earlier experience indicates that the longitudinal Schottky signals are strongly distorted by the effect of the laser [6]. Whether this behavior persists in the regime of one-dimensional beams remains to be determined.

Using a novel technique for real-time, transverse, beam profile diagnostics, we have observed an unexpected, low-current vertical blowup in a laser-cooled ion beam. One possible interpretation of the beam's behavior is that the beam is quasiordered longitudinally, leading to decoupling of the transverse and longitudinal motions. The heating mechanism leading to the blowup is the diffusion induced by spontaneously emitted photons from the cooling process. Such behavior would pose a major obstacle to attainment of a strongly coupled, one-dimensional, ordered beam, unless some way can be found to counteract the laser-induced diffusion. We are confident that the new diagnostic method described here will shed much light on the behavior of cold and dense beams at the onset of ordering.

This work was supported by the Aarhus Center for Atomic Physics.

[1] S. Schröder *et al.,* Phys. Rev. Lett. **64**, 2901 (1990); J. S. Hangst *et al.,* Phys. Rev. Lett. **67**, 1238 (1991).
[2] N. Madsen *et al.,* Phys. Rev. Lett. **83**, 4301 (1999).
[3] A. Rahman and J. P. Schiffer, Phys. Rev. Lett. **57**, 1133 (1986).
[4] I. Lauer *et al.,* Phys. Rev. Lett. **81**, 2052 (1998).
[5] S. P. Møller, in *Proceedings of the 1991 IEEE Particle Accelerator Conference, San Francisco, 1991,* edited by L. Lizama and J. Chew (IEEE, New York, 1991), p. 2811.
[6] J. S. Hangst *et al.,* Phys. Rev. Lett. **74**, 86 (1995).
[7] R. Giannini and D. Möhl, PS/AR/Note 96-19, CERN, Geneva, 1996.
[8] S. Stenholm, Rev. Mod. Phys. **58**, 699 (1986).
[9] M. Steck *et al.,* Phys. Rev. Lett. **77**, 3803 (1996).
[10] R. W. Hasse, Phys. Rev. Lett. **83**, 3430 (1999).
[11] R. W. Hasse and J. P. Schiffer, Ann. Phys. (N.Y.) **203**, 419 (1990).