Density Limitations in a Stored Laser-Cooled Ion Beam

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We present a new technique for transverse beam profile diagnostics of a stored ion beam, imaging the fluorescence light from a laser-excited ion beam onto a high resolution charge-coupled device detector. This technique has much higher sensitivity and spatial resolution than conventional techniques. Using this method we have obtained evidence for space-charge-dominated behavior of a stored, laser-cooled beam of $^{24}Mg^{+}$ ions. However, the transverse size of the longitudinally cooled beam is larger than that expected for a space-charge limited beam. This seems to confirm expectations from molecular dynamics simulations, showing that to reach a crystalline beam, other techniques have to be applied.

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The creation and behavior of dense, cold ion beams in storage rings are of interest for many storage ring applications. The use of laser cooling, to reduce the momentum spread of a circulating ion beam, has been demonstrated [1] and, even though applicable to only a few ion species, the technique has raised much interest in the storage ring community due to its fast cooling rate [2]. Laser cooling is also often connected with the attainment of ion beam crystallization [3].

We have studied the transverse beam size and the longitudinal temperature of a stored, laser-cooled ion beam in the ASTRID storage ring. Earlier, longitudinally space-charge-limited beams have been produced in cooler rings [4,5]. (In the storage ring literature, the Coulomb interaction between the stored particles is often separated into two distinct effects: *space charge* is the smooth effect of Coulomb interactions between beam particles, *intrabeam scattering* is the component of the Coulomb interaction arising from charged particles having random relative velocities.) Transverse cooling through intrabeam scattering (IBS) in a longitudinally laser-cooled beam has been previously reported [6], and the limits of this process are of interest in determining the potential of laser cooling for producing a crystalline beam. In this Letter, we present the first direct evidence for strong space-charge effects in the transverse particle motion of a laser-cooled beam. However, the observed minimum sizes of the coldest beams do not comply with what would be expected for a space-charge limited beam, thus indicating important limitations to laser cooling as currently applied to circulating ions.

These observations have been made possible by use of a novel technique for studying the transverse beam profile of a stored ion beam. Imaging the fluorescent light from the laser-excited ion beam onto a high resolution charge-coupled device (CCD), we can directly monitor the beam profile, and that, with a much higher sensitivity and resolution than with conventional techniques.

Several techniques have been developed for nondestructive measurements of the transverse size or emittance in low-current, circulating ion beams. In some cases, the fluctuation (Schottky) noise spectrum of the beam, measured at the natural (betatron) oscillation frequency of the beam in the focusing lattice of the storage ring [7] provides useful information. This method, however, does not determine the beam's spatial profile and is, in our case, prohibited by the application of laser cooling, which can induce large distortions in the Schottky noise signal [8]. A residual-gas ionization beam-profile monitor detects the ionization products from collisions between beam particles and rest gas. This device has been employed very effectively at the TSR in Heidelberg [9]. However, the resolution is not sufficient for detailed study of the small beams studied here. We have therefore implemented a system to measure the beam profile by imaging the fluorescent light from the laser-excited ion beam onto a high-resolution, low-noise CCD camera (see also Ref. [10]).

Two separate cameras are used to observe the ion beam vertically and horizontally. In front of the CCD is a mechanical shutter which can be controlled externally, thereby making it possible to image the ion beam at different times after injection into the ring. Each CCD detector is a 1024×1024 pixel array; the pixels have a side length of 24 μm. Thus the limiting resolution is $\sim$24 μm with an optical magnification of 1, more than adequate for the observed beam sizes of 1 to 12 mm (FWHM). If higher resolution is desired, it suffices to increase the magnification (by moving the lenses)—thus the ultimate limit of the system is the diffraction limit. The CCDs are cooled with liquid nitrogen to reduce the thermal noise. In order to produce a spatially flat laser light distribution, the strongly focused (FWHM $\sim$1.0 mm) laser beam was actively swept (with a frequency of 100 Hz) in the desired plane. A spatially flat distribution means that all ions are illuminated evenly, thus no deconvolution of the laser beam profile is necessary, i.e., the charge distribution on the CCD reflects the ion beam density distribution directly (in the case of non-Gaussian beams, the laser beam profile in the nonimaged transverse plane needs to be considered [11]).

The sensitivity of the system depends on the available laser power. With the present camera system and available laser power, profiles of ion beams with linear densities down to $7 \times 10^2\ \mathrm{m}^{-1}$ (2.8×10^4 particles) have been measured. For comparison, the maximum linear density of a beam in the "string regime" (where the cold beam would collapse into a one-dimensional chain of particles), for a betatron tune Q of 2.5 (the betatron tune is the number of transverse oscillations a particle undergoes per revolution), is $1.7 \times 10^4\ \mathrm{m}^{-1}$ [12]. It should be noted that the sensitivity depends on the fluorescence intensity, and it is much easier to image cooled than uncooled beams, as the amount of fluorescence depends on the relation between the Doppler width of the ion beam (range 40–1200 m/s) and the optical transition line width (which is 42.7 MHz corresponding to $\sim$12 m/s). As is indicated in Fig. 1 the section of the beam observed by the camera passes through a cylindrical tube [called post acceleration tube (PAT)] which can be excited by a dc voltage, thereby locally changing the ions' velocity and thus the Doppler-shifted resonant frequency of the optical transition. Thus, in cases where the ion beam's Doppler width is much larger than the transition line width (i.e., "hot" beams), this system can independently and nondestructively probe the transverse dynamics of different velocity ranges of the same beam. We believe this capability to be unique to this technique. For example, the dispersion (dependence of orbit position on momentum) can be measured without changing the beam's average momentum [13]. The finite transition linewidth of 42.7 MHz and the dispersion of 2.7 m at the imaging position corresponds to a horizontal rms position spread of 20 μm, and has been ignored in the measurements presented.

We have used the ASTRID storage ring (Fig. 1 [14]) to store a beam of 100 keV $^{24}\mathrm{Mg}^+$ ions. Laser cooling is performed in one straight section, with co- and counterpropagating laser beams having radii of $\sim$3 mm overlapping the ion beam. For diagnostic purposes, copropagating laser light in a second ring section is focused strongly and overlaps the ion beam in the 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 while sweeping the voltage on the PAT [8].

At injection the beam is rather cold longitudinally, thus the co- and counterpropagating cooling lasers are initially detuned only slightly from resonance of the ideal particle. The strong cooling force of the lasers suppresses the usual longitudinal heating of the beam due to the transverse to longitudinal equilibration mediated by IBS. Thus, by changing the injected current or delaying the measurement to a later time after injection (up to 80 sec.), we can measure the transverse spatial profile of a longitudinally cold ion beam ($\Delta p/p \sim 5 \times 10^{-5}$) as a function of the number of circulating particles. Figure 2 shows examples of profiles of cooled beams. The well-defined profiles in this figure demonstrate the high resolution and sensitivity of the new method for transverse beam diagnostics. The background stems from scattered laser light in the vacuum chamber. The beam current at any time after injection could be extrapolated with an uncertainty of a few percent by using the signal induced from a bunched beam in a beam-current transformer together with the measured neutralization of the beam.

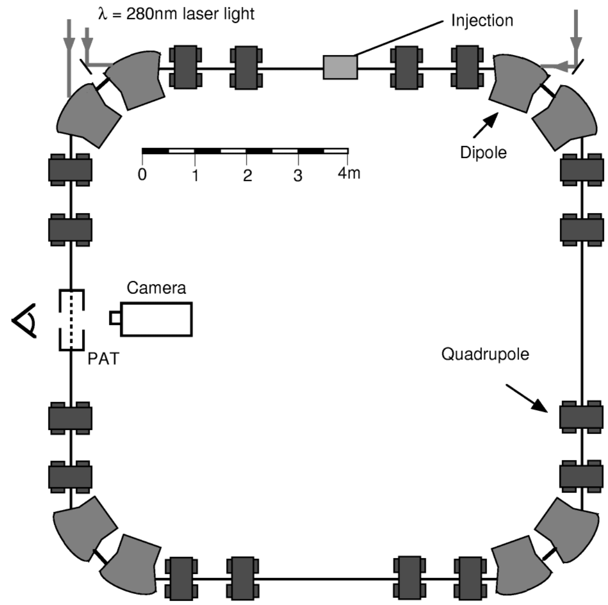

FIG. 1. The ASTRID storage ring.

In Fig. 3 the transverse beam sizes, extracted from Gaussian fits to the profiles of a beam cooled to a longitudinal temperature in the range of 2–5 K are shown as a function of the number of particles stored. (The minimum longitudinal temperature is chosen to limit the rate of particle loss by scattering out of the narrow velocity range covered by the laser force [15].) As illustrated, the dependence of beam transverse size on particle number fits very well to a square root function. It is this functional dependence which is intriguing, and which suggests that space charge is the determining factor for obtainable beam sizes.

Two extremes of beam behavior can be identified. For very hot, weakly coupled beams, the transverse size is determined by the transverse temperature (emittance), and is independent of particle number. For a beam with zero temperature, the transverse size is determined by the balance of the external confinement force and the space-charge repulsion. A harmonically confined Coulomb system at low temperature will tend towards constant charge density, until the onset of ordering or "crystallization." Constant charge density in a coasting beam implies that each transverse beam dimension will be proportional to the square root of the number of particles (for constant confining forces). Thus our observations scale in the way expected for a zero temperature beam. However, the *absolute* beam

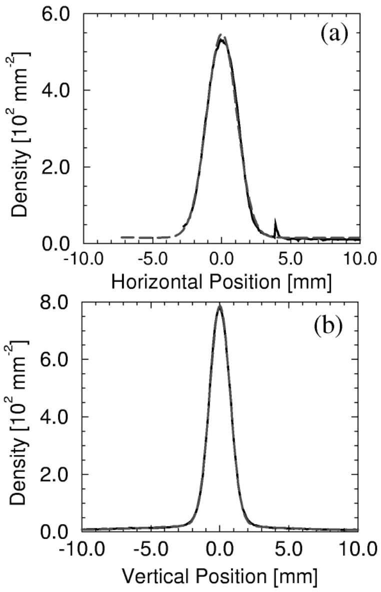

FIG. 2. (a) Horizontal and (b) vertical particle distributions for cooled beams of $\sim 5.8 \times 10^7$ particles. The distributions are normalized to an area equal to the linear density in the beam of $5.8 \times 10^7/(40\ \mathrm{m})$. The dashed lines are Gaussian fits.

sizes are larger than one would calculate for a zero temperature beam in ASTRID.

The ratio of horizontal to vertical beam size is ~ 2.2, which corresponds to the difference we would expect in a beam where space charge was negligible (a hot beam), due to the difference in the local horizontal and vertical confinement. However, in a hot, weakly coupled beam the size is given by transverse temperature alone. This is confirmed by calculations where we consider only IBS (i.e., neglecting space charge) using the code INTRABSC described in [16], and also used in [6]. These calculations show that for a constant longitudinal temperature, the beam size becomes much smaller than the size observed in the present measurements, and the size furthermore only depends on the chosen longitudinal temperature and not on the number of particles in the beam. Thus the thermal beam model does not explain why the beam sizes seem to scale like the square root of the particle number.

If we assume smooth, harmonic transverse confinement of the beam, with strength determined by the average transverse betatron tune Q, then the scaling of the size of a beam dominated entirely by the mutual repulsion of the beam particles (zero temperature) would be given by

$$r_{sc} = \sqrt{\frac{q^2 N}{2\pi \epsilon_0 m \omega^2 Q^2 C}}, \tag{1}$$

where q is the ion charge, N is the number of particles, m is the ion mass, ω is the revolution frequency in the ring, and C is the ring circumference.

As we in Fig. 3 observe a square root correlation we seem to have a space-charge limited and not a hot beam, but the beam size is far from what would be expected with the ASTRID average tune of 2.5. However, a square root scaling implies that the density of the beam is constant as a function of the number of particles. As the beam transverse profile is Gaussian, it is the peak density which is constant. The peak density is given by $n = N/(C 2\pi \sigma_x \sigma_y)$, where N is the stored number of particles, σ_x is the horizontal beam size, σ_y is the vertical beam size, and C is the ring circumference. For an absolute comparison (both of beam sizes and peak densities) we would need to compensate for the alternating focusing forces around the ring and calculate the average density. However, this is a nonlinear problem when space charge becomes important. We therefore plan to model the situation using molecular dynamics (MD) simulations [17]. If we instead assume that space charge is negligible, the problem is linear, and we can calculate a ring averaged density which is approximately 11% higher than the peak density at the camera position (caption of Fig. 3). This correction gives us an average peak density of $4.7 \times 10^5\ \mathrm{cm}^{-3}$, which is about 15% of $3.4 \times 10^6\ \mathrm{cm}^{-3}$ the density in a zero temperature beam.

Thus we observe that we cannot neglect space charge, which is in agreement with earlier studies, where strong coherent behavior in the form of longitudinal charge density waves in the beam [8] was observed. Furthermore, if we assume that the beam is moving with constant velocity, and that the transverse dimensions are in thermal equilibrium with the longitudinal, and we use the calculations in [18] to find the transverse profiles, we obtain non-Gaussian transverse profiles with peak densities of $3.4 \times 10^6\ \mathrm{cm}^{-3}$. As this is not the case, there must be an unaccounted for limitation to the transverse temperature.

In order to understand the transverse behavior of the cold beams, we consider the two extremes of density range, as discussed above. In the thin beam, where space-charge effects are a minor perturbation, we would expect the beam size to be determined only by the beam temperature, which is not the case in our experiment. In this regime we must take into account the physics of so-called resonances in the transverse oscillations of the particles. For instance, if a particle orbit closes on itself, a minor perturbation at one position in the ring can cause the particle's betatron amplitude to grow. For example, a half-integer tune would lead to the orbit closing on itself after two turns. When the density of the beam increases due to cooling, the tune shifts due to the defocusing effect of the space charge. If we calculate the first order space-charge tune shift for a density of $4.7 \times 10^5\ \mathrm{cm}^{-3}$ we get ~ 0.2, which brings the horizontal tune (2.27) close to an integer and the vertical (2.83) close to a half integer. As the first order space-charge tune shift depends on only the density, this is consistent with the limiting density being independent of the number of particles. Thus a possible explanation for the observed scaling is that the beam reaches an equilibrium between transverse cooling and transverse heating in the neighborhood of resonances. This explanation would be in agreement with observations done in MD simulations by Kihara *et al.* [19].

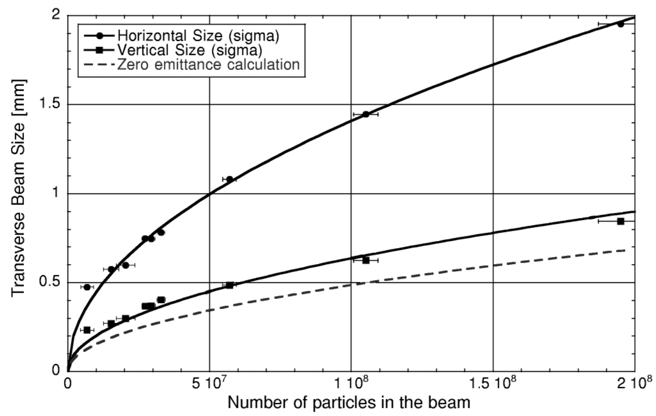

FIG. 3. Transverse beam dimensions for a laser-cooled ion beam, as a function of the number of particles. The beta functions at the camera position were $\beta_x = 12.1$ m and $\beta_y = 2.6$ m. The solid curves are fits to the data, assuming the beam size varies as the square root of the number of ions. The dashed curve is the size of a space-charge limited beam for a betatron tune of $Q = 2.5$. The peak density is constant and equal to 4.3×10^5 cm^{-3}. The deviation of the leftmost measurement is due to a slight misalignment of the cooling laser beam(s) which cause reduced transverse cooling for small beams. The density of the uncooled beam is constant, $\sim 5.5 \times 10^4$ cm^{-3}.

The other extreme in density is when space charge dominates the beam behavior. It has been known for some time [20] and reemphasized in a recent Letter by Wei *et al.* [21] that the ground state of a circulating beam is one where particles have a constant *angular* velocity, rather than the constant *linear* velocity that is imposed by laser (or electron) cooling. This implies a transverse gradient in the velocity of the ions, and the imposed constant linear velocity causes the beam to be heated through a form of enforced IBS when it is bent in the magnetic dipoles. In the present configuration of ASTRID the dispersion in the cooling section is approximately $D = 2.7$ m, which means that a particle with a position offset of 1 mm should have a velocity offset from the ideal particle of ~ 360 m/s, which should be compared to a laser-cooling induced longitudinal velocity spread of order 20 m/s. If one assumes that this deviation from the ideal velocity profile gets mixed into random motion this magnitude corresponds to a temperature of 380 K for a beam with a transverse size of 1 mm, which, assuming thermal equilibrium with the transverse dimensions, may explain the relatively low limiting density. However, since such a temperature will scale with the circulating beam current, one would expect this effect to diminish with decreasing beam size, as the longitudinal temperature in the moving frame would decrease with increasing beam size, but this dependence is not observed.

We have presented evidence for a space-charge dominated coasting beam of heavy ions in a storage ring, created by longitudinal laser cooling, and observed by means of a new technique for transverse diagnostics. The beam density seems to be limited by resonances in the beam caused by space charge tune shift. The results may have important implications for attaining densities high enough to be in the crystallization regime [3].

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