Laser Cooling of a Bunched Beam in a Synchrotron Storage Ring

J. S. Hangst, J. S. Nielsen, O. Poulsen, and P. Shi
Institute of Physics and Astronomy, Aarhus University, Aarhus, Denmark

J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439
and The University of Chicago, Chicago, Illinois 60637
(Received 31 January 1995)

We have demonstrated, for the first time, laser cooling of a bunched ion beam in a synchrotron storage ring. Using a single cooling laser and a radio-frequency cavity, we have obtained a steady state in which the minimum bunch lengths are limited by the longitudinal space-charge force. Space-charge suppression of the synchrotron oscillations is indicated by direct measurement of the bunch lengths and velocity spread.

PACS numbers: 41.75.Ak, 29.20.Dh, 29.27.Bd, 52.25.Wz

Laser cooling [1] has recently emerged as a powerful tool for manipulating the longitudinal phase space distribution of ion beams in synchrotron storage rings. Although not applicable to all ions, the laser cooling technique is of physical interest because of the very low momentum spreads and very high cooling rates which are attainable. The possibility of obtaining a crystalline beam [2], a spatially ordered state in which the interion Coulomb potential energy is much larger than the ion thermal energy, is often closely linked to the strength and speed of the laser cooling process.

The minimum temperature obtainable in laser cooling is determined by the energy width of the electronic transition. This temperature, known as the Doppler limit [3], is of order 1 mK for the ions used in storage ring experiments. Two storage rings, the TSR at Heidelberg and ASTRID at our institute, have been used for investigations of laser cooling [4,5]. Several species of ions have been cooled. Longitudinal temperatures close to the Doppler limit have been obtained [5,6], and the dynamics of these cold systems has been studied [6–10]. Several experimental configurations, involving the use of two counterpropagating lasers, a single laser and an induction accelerator, or a single frequency-scanned laser have been developed [5–10].

In the current work we present a new method of laser cooling which takes advantage of the spatial bunching produced by a radio-frequency (RF) cavity. (Bunched, electron cooled beams have previously been investigated [11] and exhibit unique behavior which is discussed below.) The RF cavity, which provides a periodic, longitudinal electric field at a harmonic h of the revolution frequency in the storage ring, spatially bunches an initially uniform circulating beam into h bunches. Particles initially having energy or phase different from the ideal ("synchronous") particle within the bunch undergo oscillations (synchrotron oscillations) in energy and in phase (or spatial position) relative to this particle. For small amplitudes these oscillations are harmonic. Seen from the rest frame of this ideal ion, the situation is analogous to that of ions confined in an ion trap having a large aspect ratio. The storage ring's quadrupole magnets provide transverse confinement, and the RF cavity provides longitudinal confinement within the bunch. Laser cooling provides damping of the longitudinal oscillations.

Figure 1 schematically illustrates the principle of bunched-beam laser cooling. The phase space trajectory of a single particle is shown. Each point represents the velocity and position deviations (at the RF cavity) for a single turn in the storage ring. The particle initially undergoes large synchrotron oscillations (thus the

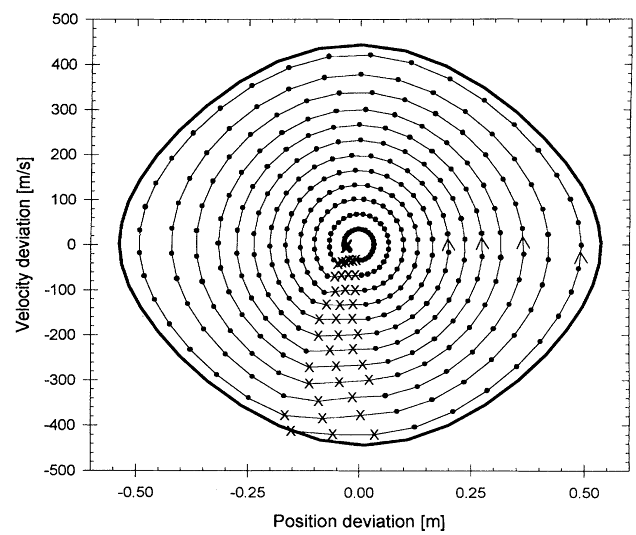

FIG. 1. Simulation of a single ion in a bunch being laser cooled. The outermost, heavy solid line indicates the phase space trajectory the ion would follow in the absence of cooling. During cooling, every fifth turn in the machine is indicated by a dot. The $\times$'s indicate turns during which the particle is in resonance with the laser. The arrows indicate the direction of time. For the purposes of illustration, the actual cooling rate has been exaggerated by a factor of 100.

 0031-9007/95/74(17)/4432(4)$06.00

distorted trajectory, which would be elliptical for a smaller amplitude). A copropagating laser beam is frequency detuned to be in resonance with the ion when it has its maximum negative energy deviation. The ion will then scatter photons from the laser beam and be accelerated to a trajectory having a smaller synchrotron oscillation amplitude. The ion will continue to scatter photons until it Doppler shifts out of resonance with the laser. However, if the laser frequency is scanned to keep the laser in resonance with the ion, the synchrotron oscillation can be damped, as illustrated. An ensemble of particles can be cooled in the same fashion; the initial laser detuning must be large enough to efficiently cool the ion having the largest synchrotron amplitude in the bunch.

In the physically observable projections of the phase space distribution in the bunch, i.e., the velocity spread and the bunch length, the signature of the process illustrated in Fig. 1 is a bunch that shrinks symmetrically, even though the cooling is applied to only the low-velocity side. The width of the velocity distribution at any time should be approximately twice the velocity detuning of the laser from the synchronous velocity (if the distribution is broad enough that the transition linewidth can be ignored). In the absence of diffusive heating such as intrabeam scattering, the final beam energy spread will be determined by the laser detuning at the completion of the cooling scan. In a dense beam, particles experiencing energy-changing collisions which push them to a higher synchrotron amplitude will continue to occasionally encounter the cooling laser, as their synchrotron oscillations take them periodically back into resonance. Stated another way, the laser has a much-improved capture range when used together with RF confinement.

We have experimentally demonstrated such bunched-beam laser cooling in the ASTRID storage ring [12]. ASTRID (circumference 40 m) was used to store 100 keV $^{24}Mg^+$ ions. A specially developed, frequency-doubling system for a ring-dye laser was used to produce the necessary UV light (up to 90 mW, cw) at about 280 nm [13]. The laser radiation, which drives the $(3\,^2S_{1/2}) \leftrightarrow (3\,^2P_{3/2})$ electronic transition used for laser cooling, overlapped the ion beam in one straight section (length $\sim$8 m) of the storage ring. The laser frequency can be continuously scanned over a range of 20 GHz, covering a velocity range of $\delta v/v \approx 6 \times 10^{-3}$. The RF cavity was operated at the 26th harmonic (580 kHz) of the ion revolution frequency. The low longitudinal emittance of the injected beam (energy spread $\sim$1 eV) requires only a few (7–70) volts of potential on the RF cavity for bunching.

The cooling laser is also the key component in an important diagnostic method for monitoring the cooling. Laser-induced fluorescence light from the ions is detected by a photomultiplier tube configured to view photons emitted perpendicular to the beam direction. The beam observed by the phototube passes through a postacceleration tube which is isolated from the vacuum chamber and upon which can be placed a voltage. This voltage locally alters the kinetic energy of the ions and can therefore be used to choose a particular velocity class of ions to be *locally* in resonance with the laser. Scanning the voltage on this tube while monitoring the fluorescence light from the beam thus allows direct measurement of the ions' velocity distribution during the cooling process.

In a typical measurement, the beam, initially unbunched, is injected and bunched by ramping the RF voltage. Since the spatial bunching is accompanied by a corresponding increase in momentum spread, the laser is initially detuned about 4 GHz, corresponding to $\delta v/v \approx 1 \times 10^{-3}$. The laser is then scanned linearly in time to damp the synchrotron oscillations. The time development of the measured velocity distribution of a bunched beam during laser cooling is illustrated in Fig. 2. The figure shows the last 2 GHz of a 4 GHz cooling scan. The beam momentum spread is reduced from 1×10^{-3} to 3×10^{-5} FWHM, corresponding to a reduction in longitudinal temperature from about 500 to 0.5 K.

The other phase space coordinate was monitored by measuring the physical length of the bunch using an electrostatically coupled beam pickup. The wave form for a single revolution in the storage ring (26 individual bunches) was digitized at various times during the cooling scan and analyzed off-line. The comparatively slow (8.9×10^{-5} m/s) speed of the beam places no great demands on the measurement electronics. The ultimate spatial resolution is determined by the length (10 cm) of the pickup electrode. Typical bunch lengths were 0.2 to 1 m FWHM. Initial measurements of the bunch lengths during cooling revealed that the bunch length decreases initially as the beam velocity spread is reduced, but then remains at a constant value though the velocity spread is seen to decrease further by a substantial amount [14]. This result is illustrated in Fig. 3. This observation

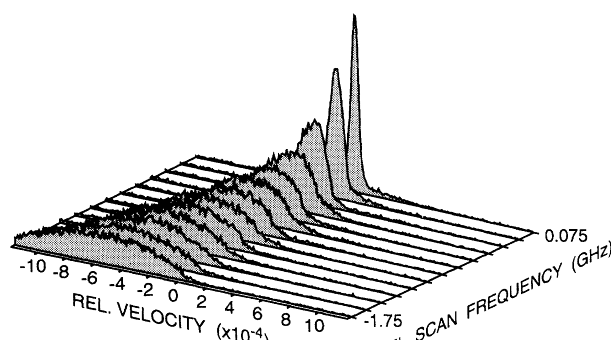

FIG. 2. Velocity distributions measured by laser-induced fluorescence at various times during bunched-beam laser cooling. The interval between measurements is 50 ms. The center of each distribution is offset for clarity.

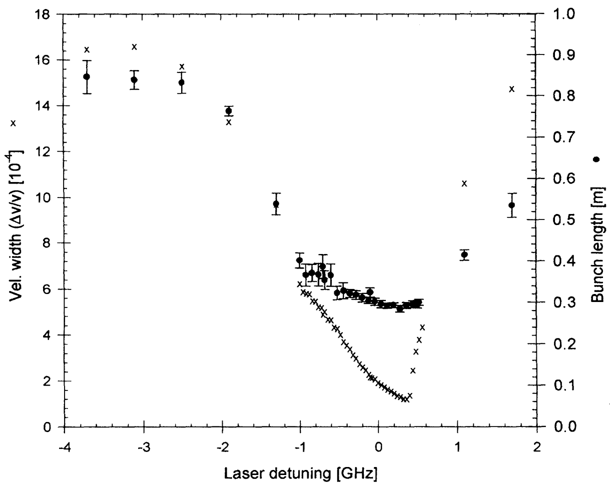

FIG. 3. Longitudinal velocity spread (×'s, left ordinate) and bunch length (dots, right ordinate) versus laser detuning, measured during a cooling scan. The laser is scanned *past* the optimum detuning, leading to the rise in temperature and bunch length at the right of the figure.

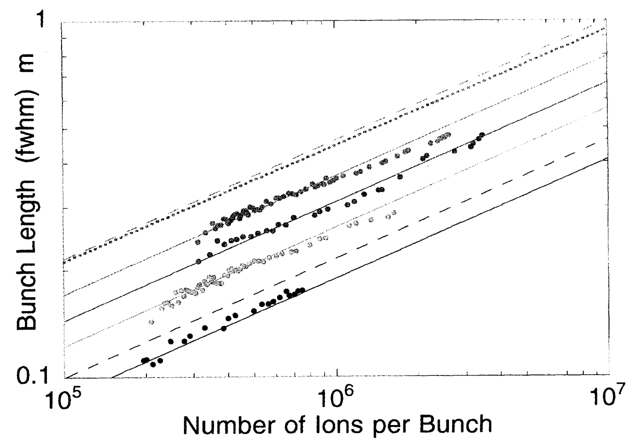

FIG. 4. Bunch length versus number of ions in the bunch, measured for four different RF voltages: 7 V (red), 13 V (green), 22 V (blue), and 66 V (black). Each point is the average of ten bunches. The systematic errors in these measurements are believed to be on the order of 30%. The solid lines are calculated from Eq. (1). The dashed lines (for 7 and 66 V) are for the fluid model of Refs. [15] and [16]. The dotted line (for 7 V) includes a correction for shielding due to the vacuum chamber.

indicates that the single particle synchrotron oscillations are suppressed and that the bunch length is limited by space-charge repulsion. The bunch length is thus not a measure of the beam's velocity spread.

In studies with an electron cooled beam [11] the bunch length was observed to vary as the cube root of the number of ions in the bunch, and parabolic linear charge distributions were observed. In ASTRID, to measure the bunch length as a function of the number of ions in the bunch, the beam was first injected and bunched. The laser was then scanned to cool the beam, and, with the laser held at fixed frequency, the beam current was allowed to decay with the storage lifetime (about 10 s). At various times after the cooling scan, the bunch lengths were measured. A fitting function was derived to simulate the response of the pickup electrode to a parabolic bunch, permitting the length and the relative number of ions for the bunch to be extracted from a fit. The agreement of the more detailed shape of the profile with the measurement was excellent, indicating that the bunch shape is indeed parabolic. The absolute number of ions was determined from the area of the fit to the signal from the pickup, which has been calibrated with respect to a Faraday cup in the injection beam line. The systematic errors in these measurements are believed to be on the order of 30%. The results are shown in Fig. 4 for several values of the RF voltage. The data follow the cube-root scaling observed previously [11].

We have considered two models for describing the equilibrium shape of such dense and cold bunches. The first has been developed for ions in an asymmetric ion trap [15,16]. In this model, the ion cloud is treated as a harmonically confined, cold Coulomb fluid, in thermal equilibrium in all dimensions. The bunches take on the shape of a very eccentric spheroid; the eccentricity of the bunch is determined by the aspect ratio of the confining fields $\alpha \equiv (\omega_s/\omega_\beta)^2$, where ω_s and ω_β are the synchrotron and betatron frequencies, respectively. (In ASTRID α is between 10^{-5} and 10^{-4}; the synchrotron period ranges between 1 and 4 ms.) The length and radius of the spheroidal cloud are uniquely determined by the strengths of focusing forces and the number of ions, with no additional parameters. This model, for the experimental parameters in ASTRID, also predicts a cube root scaling between bunch length and ion number, as well as a parabolic *linear* charge density. (The cloud has constant volume charge density and spheroidal shape.) Shielding of the ions' electric field by the beam pipe is not considered.

The second model, described in Ref. [11], treats the beam as a cylinder of charge in a cylindrical, conducting beam pipe. In this model, transverse to longitudinal equilibration is not assumed; the beam radius is treated as an experimentally determined parameter. A parabolic linear charge distribution $\lambda_0[1 - (S/L_b)^2]$ in the longitudinal coordinate S is expected. In particular, in the nonrelativistic limit, the relationship between bunch length and number of ions should be

$$L_b = \left(\frac{3Neg_0R^2}{4h\epsilon_0 V}\right)^{1/3}, \tag{1}$$

where N is the number of ions in the bunch, e is the electron charge, R is the storage ring radius, V is the RF voltage, and g_0 is equal to $1 + 2\ln(\frac{b}{a})$, where a and b are the radii of the beam and vacuum chamber, respectively. (We depart from Ref. [11] in using the on-axis value of the electric field in the force balance, instead of the field at the beam radius. The magnetic field is neglected.)

Figure 4 also displays the predictions of the above models. The beam radii to be used in the cylindrical model were estimated by scraping the beam, yielding values (perhaps upper limits) of between 1 and 2 mm. The RF voltage was measured by a pickup loop in the cavity. The agreement between this model and the experimental data is very good, perhaps deceptively so. (Had we used the convention for g_0 from Ref. [11], the agreement would not be as good.) The spheroidal model predicts bunch lengths for a cold beam which are uniformly greater than in the data, or, conversely, the number of ions for a given length is uniformly lower, but this difference is within the estimated systematic errors. The spheroidal model should be modified to properly include the shielding of the beam pipe. We have estimated this effect. For the purposes of calculating the image charge distribution, the bunch is taken to be a parabolic line charge distribution, i.e., the transverse bunch size is neglected with respect to the size of the vacuum chamber. The space-charge field for a bunch is calculated using Ref. [16]. Treating the image field as a linear perturbation to the RF force, the relationship between the bunch length and the number of ions is then determined by self-consistently solving the force balance at the bunch end. The shielding effect is found to be small for the parameters of the experiment, as indicated in Fig. 4.

The intriguing question then is whether the longitudinally cold beam may also be simultaneously transversely cold, leading to a suppression of betatron oscillations. Molecular dynamics simulations suggest that the Coulomb coupling within the beam bunch, between the longitudinal and transverse modes for a beam of the measured size, would be strong enough to bring about equilibrium within a few hundred turns. Such coupling seems inconsistent with the observed stability (against longitudinal blowup) of the cold beam, if the beam were transversely as hot as would be implied by a beam radius of 1–2 mm (on the order of several hundred K, compared to the 0.5 K measured for the longitudinal temperature). At present, therefore, the data are not sufficient to conclude anything definitive about the transverse temperature of the beam. A new class of measurements will be needed to determine, with greater reliability than the scraping measurements, the transverse size (and thus the transverse temperature) of the laser cooled beam. More detailed models for the longitudinal particle distribution function in a bunched beam [17] also need to be examined.

The experiments described in this Letter represent both a new method of exploiting laser cooling and a new way to cool and study bunched beams in synchrotrons. The experience with ASTRID demonstrates that such a laser cooled bunched beam is a unique new physical system for investigating the dynamics of strongly coupled ion plasmas in storage rings. The combination of laser cooling and laser Doppler velocimetry opens new possibilities for creating and characterizing cold and dense beams. The ability to directly measure the ion velocity distribution at the same time as the physical length of the bunch is a feature particular to these experiments and offers a distinct advantage over similar bunched-beam experiments with electron cooled beams. In view of the much higher cooling rates obtainable with laser cooling, the ASTRID facility provides the opportunity to extend the understanding obtained in the previous, seminal works [11,17]. Finally, we note that a laser cooled, bunched beam is the basis for a recently proposed scheme to achieve transverse cooling by *resonantly* coupling the synchrotron and betatron motions [18]. This technique can be applied, with little modification, to ASTRID, should the coupling between the degrees of freedom be weaker than our present estimates.

The authors would like to thank Dr. V. A. Lebedev and Professor D. H. E. Dubin for useful discussions. This work was supported by the Danish National Research Foundation through the Aarhus Center for Advanced Physics, and by the U.S. Department of Energy, Nuclear Physics Division, under Contract W-31-109-Eng-38.

[1] T. Hänsch and A. Schawlow, Opt. Commun. **13**, 68 (1975).
[2] A. Rahman and J. P. Schiffer, Phys. Rev. Lett. **57**, 1133 (1986).
[3] W. D. Phillips and H. Metcalf, Phys. Rev. Lett. **48**, 596 (1982).
[4] S. Schröder *et al.,* Phys. Rev. Lett. **64**, 2901 (1990).
[5] J. S. Hangst *et al.,* Phys. Rev. Lett. **67**, 1238 (1991).
[6] W. Pietrich *et al.,* Phys. Rev. A **48**, 2127 (1993).
[7] J. S. Hangst, Ph.D. thesis, The University of Chicago, 1992 [Argonne Report No. ANL/PHY-93/1].
[8] J. S. Hangst *et al.,* Phys. Rev. Lett. **74**, 86 (1995).
[9] H.-J. Miesner *et al.,* in *Proceedings of the Workshop on Beam Cooling and Related Topics* (CERN Report No. CERN 94-03 1994).
[10] J. S. Nielsen *et al.,* in *Proceedings of the Workshop on Beam Cooling and Related Topics,* Ref. [9].
[11] T. J. P. Ellison *et al.,* Phys. Rev. Lett. **70**, 790 (1993).
[12] S. P. Møller, in *Proceedings of the 1991 IEEE Particle Accelerator Conference* (IEEE Report No. IEEE 91CH3038-7, 2811, 1991).
[13] J. S. Nielsen (to be published).
[14] J. S. Hangst *et al.,* in *Proceedings of the Workshop on Beam Cooling and Related Topics,* Ref. [9].
[15] L. Turner, Phys. Fluids **30**, 3196 (1987).
[16] D. H. E. Dubin, Phys. Rev. Lett. **71**, 2753 (1993).
[17] S. S. Nagaitsev *et al.,* in *Proceedings of the Workshop on Beam Cooling and Related Topics,* Ref. [9].
[18] H. Okamoto, A. Sessler, and D. Möhl, Phys. Rev. Lett. **72**, 3977 (1994).

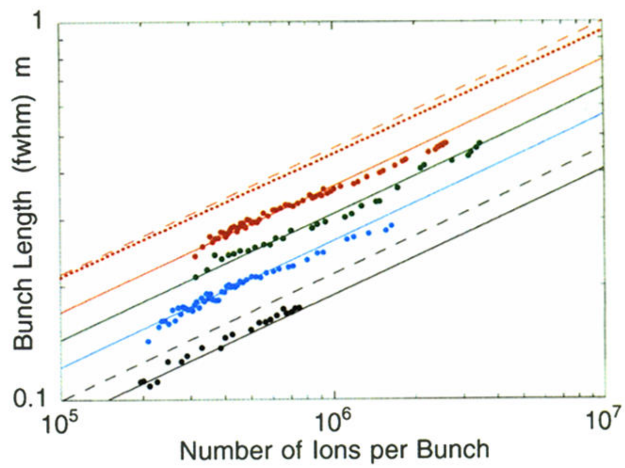

FIG. 4. Bunch length versus number of ions in the bunch, measured for four different RF voltages: 7 V (red), 13 V (green), 22 V (blue), and 66 V (black). Each point is the average of ten bunches. The systematic errors in these measurements are believed to be on the order of 30%. The solid lines are calculated from Eq. (1). The dashed lines (for 7 and 66 V) are for the fluid model of Refs. [15] and [16]. The dotted line (for 7 V) includes a correction for shielding due to the vacuum chamber.