Anomalous Schottky Signals from a Laser-Cooled Ion Beam

J. S. Hangst, A. Labrador, V. Lebedev, N. Madsen, J. S. Nielsen, O. Poulsen, and P. Shi
Institute of Physics and Astronomy, Aarhus University, Denmark

J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439
and The University of Chicago, Chicago, Illinois 60637

(Received 21 September 1994)

Longitudinal Schottky signals from a laser-cooled, spatially dense, ion beam have been studied in the ASTRID storage ring. The fluctuation signals are distorted by the effects of space charge, as is observed in electron cooling experiments. However, the spectra also exhibit previously unobserved coherent components. The ions' velocity distribution, measured by a laser fluorescence technique, suggests that the coherence is due to suppression of Landau damping. The observed behavior has important implications for the attainment of a crystalline ion beam in a storage ring.

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

In this Letter we describe measurements of longitudinal Schottky signals from a unique physical system, a spatially dense, very cold (i.e., having very small velocity spread) ion beam produced by laser cooling. This system has direct relevance to the understanding of the ultimate limits to the quality of a stored ion beam. In particular, the possibility of producing a crystalline ion beam [1] is usually associated with the technique of laser cooling.

Schottky signals [2] are used as a powerful diagnostic for characterizing stored ion beams. As in an electric circuit, a steady current in an ion storage ring is subject to small fluctuations due to the finite number of discrete charges comprising the current. These fluctuations can be sensed by a pickup electrode as temporal variations in the electric field produced by the beam. Analysis of such fluctuation signals induced in suitable pickups can provide a wealth of information on both the longitudinal and transverse dynamics of a stored beam.

A single fast ion circulating in a storage ring will induce delta-function-like voltage pulses in a pickup through which it passes. The frequency spectrum of this signal is also comprised of delta-function-like peaks, centered at harmonics of the ion's revolution frequency [3]. For a large number of *uncorrelated* particles having a spread in momentum, the spectrum will consist of frequency bands reflecting the momentum distribution of the stored beam. In practice, one cannot measure the response of a pickup electrode to individual particles, but only the power spectrum of the voltage fluctuations in the pickup, representing fluctuations in the linear charge density of the beam. For uncorrelated particles, this power spectrum is directly proportional to the momentum distribution of the beam, and the integrated fluctuation power around any harmonic is proportional to the number of particles in the beam [3].

In the case of a beam in which interactions between particles are not negligible, the Schottky spectrum may be distorted by the interaction. For example, if the beam spatial density is high enough and the momentum spread low enough, the spatial fluctuations in the beam may be suppressed by the effect of the beam's space charge force.

Schottky signals from cold and dense ion beams were first studied in the NAP-M ring in Novosibirsk [4]. Using the technique of electron cooling [5], the NAP-M group produced proton beams which exhibited Schottky spectra differing in two major respects from those of uncooled beams. First, the total noise power around a revolution harmonic was much smaller than expected for the number of particles in the beam. Secondly, the spectrum at a given harmonic did not have the Gaussian shape characteristic of the uncooled momentum distribution, but consisted of a symmetric, double-peaked distribution centered on the ideal revolution frequency [4].

The Novosibirsk researchers developed a model to explain these new features of the Schottky signal [3]. Using methods previously developed for plasma physics [6], they derived an expression for the spectral density function for a beam in which the space charge force is the dominant interaction. The model essentially consists of deriving a dielectric function for the beam plasma using the (assumed Gaussian) velocity distribution function of the ions. The fluctuation spectrum can then be calculated. The model (in the nonrelativistic limit) predicts suppression of the noise power when the rms velocity spread δv in the beam is less than a critical velocity v_s, given by

$$v_s = \left(\frac{N Z^2 e^2 g_0 (1 - \alpha)}{8 \pi^2 \epsilon_0 m R} \right)^{1/2}, \tag{1}$$

where N is the number of stored ions of charge Ze, $2\pi R$ is the orbit circumference, α is the momentum compaction factor $[\equiv (p/R)(\partial R/\partial p)]$, and g_0 is a geometric factor equal to $1 + 2\ln(b/a)$, where b and a are the vacuum chamber and beam radii, respectively.

The velocity v_s has a simple physical interpretation. It is the characteristic velocity of acoustic charge density waves propagating longitudinally in a cylindrical beam plasma surrounded by a conducting chamber. The model is one dimensional; the implicit assumption is that the transverse oscillation amplitudes (betatron motion) are large compared to the average interparticle distance. The double-peaked fluctuation spectrum was interpreted to represent copropagating and counterpropagating charge density waves in the beam. When the sound velocity lies within the beam's spread in relative velocity, these waves are strongly Landau damped. Cooling the beam so that $\delta v_{\parallel} < v_s$ implies that there are few particles having relative velocity $\pm v_s$, and therefore very little energy exchange with the charge density waves.

The Novosibirsk model has proven to be of great utility, since it allows one to extract a velocity width from a strongly distorted Schottky signal. The model is regularly employed in rings utilizing electron cooling [7]. Laser cooling [8], recently applied to low energy storage rings [9,10], has produced beams with extremely low longitudinal velocity spread, 1 to 2 orders of magnitude smaller than achieved by electron cooling. It is natural to apply Schottky analysis to these beams and to look for departures from previously observed behavior which may indicate the onset of ordering phenomena.

The ASTRID storage ring [11] was used to store 100 keV $^{24}\mathrm{Mg}^+$ ions. Copropagating and counterpropagating laser light, produced by frequency-doubling 560 nm light from two ring-dye lasers, overlaps the ion beam in two straight sections (8 m each) of the storage ring. The ultraviolet light, which can be frequency tuned over a range of 20 GHz, drives the $(3^2S_{1/2}) \leftrightarrow (3^2P_{3/2})$ electronic transition used for laser cooling. The lasers, developed specially for this experiment, produce up to 90 mW of cw radiation [12] at 280 nm. Laser and ion beam diameters vary between 2 and 4 mm in the cooling section.

Fluorescence photons emitted by the ions were detected by a photomultiplier tube, configured to view photons emitted perpendicular to the beam direction. A spectrometer is used to distinguish fluorescence photons from scattered laser light, the Doppler shift between these being about 0.8 nm. The section of beam observed by the photomultiplier passes through a cylindrical tube which can be excited with a dc voltage, thereby locally changing the ion's velocity and thus the Doppler-shifted resonant frequency of the optical transition. Recording the fluorescence intensity while scanning the voltage on this tube allows measurement of the ion velocity distribution. This optical technique is an important experimental tool, since it is not sensitive to the collective density fluctuations which distort the Schottky signal.

The Schottky diagnostic system consisted of a pickup and amplifier combination which is resonant at 514 kHz, the 23rd harmonic of the revolution frequency. In order to facilitate fast Fourier transform analysis, the signal was mixed down to about 15 kHz. A low-pass filter was used to eliminate aliasing from high frequency components of the signal.

The injected beam has a velocity spread of 10^{-5} FWHM, but rapidly (in several hundred ms) heats up to 10^{-3} FWHM due to intrabeam scattering. As observed in earlier experiments [10], this fast heating is too strong to be counteracted by laser cooling. A single intrabeam collision can transfer sufficient energy from the transverse to the longitudinal motion that an ion will jump out of the laser capture range. Thus, at injection, the cooling lasers are both detuned 4 GHz, defining a window, 2200 m/s wide, around the ideal ion velocity of 8.9×10^5 m/s.

A Schottky measurement of the uncooled beam (lasers detuned far from resonance) is shown in Fig. 1. Also shown is a fit to the spectrum using the model of Ref. [3]. Even for the uncooled beam, the spacecharge distortion is clearly seen in the Schottky signal. The number of stored ions for this measurement is 5.5×10^8, yielding a sound velocity v_s of about 730 m/s, compared to the rms velocity spread of the beam of 467 ± 13 m/s. A fit by the model for the Schottky noise yields a velocity spread of 488 ± 30 m/s. Several other measurements under varying conditions [13] yielded equally good agreement with theory. The laser induced fluorescence (LIF) technique thus provides an independent confirmation of the validity of the Novosibirsk model.

Cooling proceeds by scanning the lasers in frequency, accelerating slow ions, and decelerating fast ions to collect them into a narrow distribution. The velocity distribution can be measured during the cooling scan using

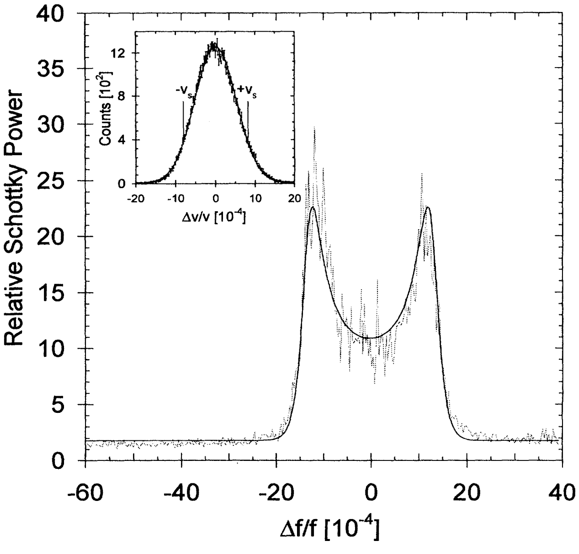

FIG. 1. Measured Schottky signal for the uncooled beam. The solid line is a fit to the theoretical model from Ref. [3]. The inset shows the Gaussian velocity distribution measured by laser fluorescence. The characteristic velocities $\pm v_s$ for charge density waves are indicated.

the LIF technique discussed previously. The resolution of the fluorescence diagnostic is limited by the homogeneous linewidth of the cooling transition to $\delta v/v \approx 1 \times 10^{-5}$. The Doppler temperature, characteristic of equilibrium between the laser cooling force and laser-induced diffusive heating, is about 1 mK, or $\delta v/v \approx 2 \times 10^{-6}$.

Measurement of the Schottky spectra during laser cooling yielded several surprises. The total Schottky power at the revolution harmonic rises by a factor of 10 when the lasers come into resonance with the tails of the beam [Fig. 2(a)]. As cooling proceeds, the total power first rises dramatically to a level 100 times higher than that of the uncooled beam before falling back almost to the uncooled level. This behavior is in sharp contrast to that expected from the theoretical model, which predicts only suppression of fluctuation power as the beam is cooled.

The shape of the Schottky spectra of the laser-cooled beam is also surprising. Figure 3(a) shows spectra measured for various laser detunings. Figure 3(b) shows the corresponding velocity distributions, measured by LIF. The spectrum is drastically altered by the presence of two large, coherent peaks. The rise and fall of the Schottky power in Fig. 2(a) is clearly associated with the coherent power in these peaks. Figure 2(b) depicts the frequency splitting between the peaks as a function of the laser detuning during cooling. The peaks move together as the lasers scan, but not at the same rate as the laser frequencies. The width of the velocity distribution follows the laser scan directly [Fig. 2(b)].

The dependence of the position of the coherent peaks on the beam's velocity spread is qualitatively very different from what is observed in electron-cooled beams. The Novosibirsk model contains a single characteristic velocity, which is dependent only on the beam density, leading to very little temperature dependence of the peak positions in the noise signal [3]. The maximum of Schottky power in Fig. 2(a) does, however, appear to coincide

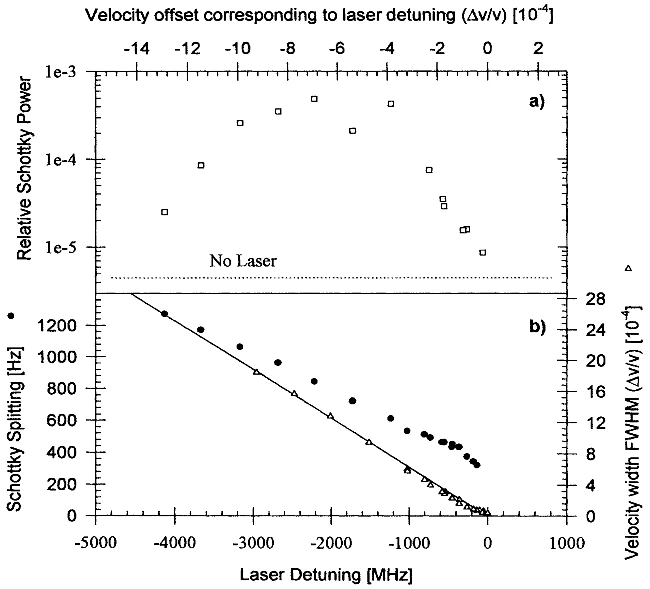

FIG. 2. (a) Integrated Schottky power versus laser detuning, measured during a cooling scan. The dashed line shows the power level with no laser cooling. (b) Schottky frequency splitting between coherent peaks (circles) and velocity width of the ion beam (triangles) as a function of laser detuning during laser cooling. The two vertical scales are equivalent. The solid line shows the splitting the peaks would have if they coincided with the velocities resonant with the lasers. The two horizontal scales apply to both parts [(a) and (b)] of the figure.

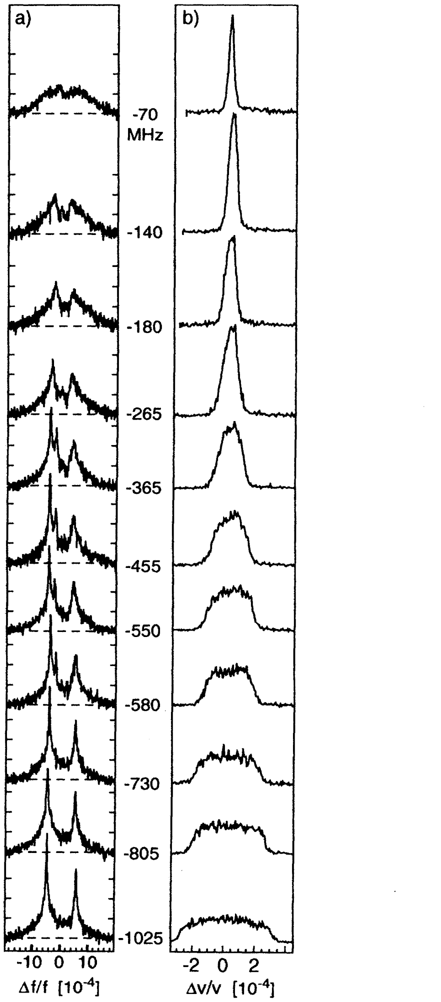

FIG. 3. (a) Schottky spectra measured at various detunings (shown between figures) during laser cooling. Dashed lines indicate the noise floor of the measurement; each vertical tick mark is one decade in relative power. The asymmetry in peak heights is probably due to a slight difference in laser powers, leading to larger diffusion past one laser. The nonzero resistivity of the vacuum chamber may also play a role. (b) The corresponding velocity distributions, measured by LIF. Each spectrum contains about 10^3 fluorescence counts.

approximately with the laser detuning (2300 MHz), corresponding to the sound velocity.

For the Schottky spectra exhibiting coherence, the velocity distributions measured by LIF [Fig. 3(b)] are not Gaussian. The radiation pressure force from each laser is very short ranged in velocity, resulting in the sharp-edged distributions observed. The shape of these distributions offers a possible explanation for some of the features observed in the Schottky spectra. The laser is extremely effective at depopulating the velocity distribution in a narrow range (~13 m/s) about the resonant velocity. A coherent disturbance at this velocity will therefore not be Landau damped, and can appear in the spectral density function if there are some residual particles in a tail beyond the sharp edge of the velocity distribution. Such a tail may be formed by particles which have diffused out of the laser capture range due to intrabeam Coulomb collisions. The coherent disturbance will appear in the fluctuation spectrum near the laser resonance velocity and will therefore shift as the laser scans. A model, based on calculating the dielectric function for the *measured* velocity distribution functions, is under development and quantitatively reproduces the peak splitting for large (compared to the transition linewidth) laser detunings [13]. For smaller detunings, the effect of the laser damping must be taken into account.

The LIF technique for characterizing the velocity distribution, in combination with high resolution Schottky analysis, has allowed direct confirmation of the validity of the accepted theoretical model for fluctuations in an intense beam. The combination of these two diagnostic methods and the flexibility of laser cooling at tailoring the velocity distribution function of the stored beam offer the potential for continued fundamental research into the collective behavior of very cold ion beams.

Schottky signals of cold and dense ion beams should be important for diagnosing the approach to condensation or crystallization. An ordered beam is expected to exhibit almost no fluctuation power at low frequencies. The present work shows that the short-ranged nature of the laser-cooling force can lead to a previously unexpected distortion of the noise signal by strong coherent signals. It is important to understand the physical origin of these signals and to learn to either extract information from them or to find a way to eliminate them so that the thermal fluctuations in laser-cooled beams can be studied.

Ion crystals have been produced, at rest, in an ion trap having storage ring geometry [14]. The present experiment highlights some major differences between the ion trap and a storage ring for fast ions. The larger initial temperatures (several thousand instead of a few hundred K) in the latter require a precooling phase in which lasers are frequency scanned to collect ions into a velocity distribution having a Doppler width comparable to the cooling transition's linewidth. The highly nonequilibrium distributions created during this precooling phase are seen to be susceptible to long-wavelength (several m) coherent disturbances which cannot exist in ion trap plasmas. The question of stability of these disturbances is of crucial importance in developing a strategy for obtaining a crystalline ion beam in a storage ring. The transverse temperature, inferred from the beam size, is, in the present experiment, more than 100 times larger than the longitudinal, and must be significantly reduced if the onset of order is to be observed. A new scheme utilizing dynamical coupling in conjunction with longitudinal laser cooling to cool all degrees of freedom [15] holds much promise, and will be experimentally evaluated shortly.

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 No. W-31-109-Eng-38.

[1] A. Rahman and J.P. Schiffer, Phys. Rev. Lett. **57**, 1133 (1986).
[2] S. Chattopadhyay, in *Physics of High Energy Particle Accelerators,* edited by Melvin Month, Per F. Dahl, and Margaret Dienes, AIP Conf. Proc. No. 127 (AIP, New York, 1985), p. 467.
[3] V. V. Parkhomchuk and D. V. Pestrikov, Sov. Phys. Tech. Phys. **25**, 818 (1980).
[4] E. N. Dementev *et al.,* Sov. Phys. Tech. Phys. **25**, 1001 (1980).
[5] G. I. Budker, At. Energ. **22**, 346 (1967).
[6] Yu. L. Klimontovich, *Statistical Theory of Nonequilibrium Processes in Plasmas* (Mosk. Gos. Univ., Moscow, 1964).
[7] For example, A. Wolf *et al.,* in *Proceedings of the European Particle Accelerator Conference* (World Scientific, Singapore, 1988), p. 204.
[8] T. Hänsch and A. Schawlow, Opt. Commun. **13**, 68 (1975).
[9] S. Schröder *et al.,* Phys. Rev. Lett. **64**, 2901 (1990).
[10] J. S. Hangst *et al.,* Phys. Rev. Lett. **67**, 1238 (1991).
[11] S. P. Møller, in *Proceedings of the 1991 IEEE Particle Accelerator Conference*, (IEEE, Piscataway, 1991), p. 2811.
[12] J. S. Nielsen (to be published).
[13] J. S. Hangst *et al.* (to be published).
[14] G. Birkl, S. Kassner, and H. Walther, Nature (London) **357**, 310 (1992).
[15] H. Okamoto, A. Sessler, and D. Möhl, Phys. Rev. Lett. **72**, 3977 (1994).