An Electron-Positron Beam-Plasma Experiment

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Advances in positron trapping techniques have made it possible to perform the first electron-positron plasma experiments in a laboratory. An electron-positron beam-plasma system is studied by transmitting a low-energy electron beam through positron plasmas stored in cylindrical and quadrupole Penning traps. In the cylindrical trap, positron heating consistent with a two-stream instability is observed. In the quadrupole trap, a transit-time instability is excited, leading to a large amplitude oscillation of the positron plasma and ejection of positrons from the well.

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Electron-positron plasmas have been studied extensively using analytical models [1,2] and numerical simulations [3], motivated by their relevance to astrophysical plasmas such as pulsar magnetospheres. However, up until now, no laboratory studies have been carried out, because techniques for accumulating large numbers of positrons and combining them with electrons were not available, although various schemes for performing such experiments have been discussed in the literature [4–7].

The recent development of high-efficiency techniques for accumulating pure positron plasmas in Penning traps [4,5] now makes laboratory experiments on electron-positron plasmas possible. Other methods of creating pure positron plasmas are currently being pursued by several groups [7]. This Letter describes the first realization of such an experiment in the form of a beam-plasma system, created by transmitting an electron beam through positron plasmas stored in two different Penning trap geometries. In a cylindrical trap, we observe strong positron heating, consistent with the excitation of a two-stream instability. In a quadrupole trap, the system behaves like a transit-time oscillator, and the center-of-mass oscillation of the plasma is excited to very large amplitudes, leading to ejection of positrons from the trap.

The transmission of beams through plasmas in Penning traps is also a topic of current interest. For example, electron beams are now being investigated as a diagnostic for plasmas in Penning traps [8]. In another experiment, a spherically convergent electron beam in a Penning trap is being investigated to model an advanced concept for controlled fusion [9]. Other uses of beams in traps include the excitation of higher order modes using modulated beams. Such modes are of interest as remote diagnostics [10,11]. In such applications, it is important to understand the nature of the beam-plasma interactions that can occur.

The long-term goal is the study of electron-positron plasmas under conditions where the two populations are stationary relative to each other. Such an experiment might be accomplished in a magnetic mirror or in a Paul trap. As a first step, we have investigated the beam-plasma system, because it does not require the simultaneous confinement of both species.

The experiment was performed in the cylindrical and quadrupole traps shown in Figs. 1(a) and 1(b), respectively. Positrons from a ^{22}Na radioactive source are slowed to a few electron volts by a solid neon moderator and loaded into the trap by inelastic collisions with nitrogen buffer gas molecules [4,5]. After the positrons have been loaded and cooled to room temperature, the buffer gas feed is switched off, and the pressure falls to the base pressure of the device ($p \sim 5 \times 10^{-10}$ torr) in about 30 s. The positron lifetime at 5×10^{-10} torr is about half an hour. Axial confinement is provided by applying a negative potential to the central electrode and grounding the end electrodes. Radial confinement is provided by a magnetic field of 1260 G. Under these conditions, the axial bounce frequency of the center-of-mass motion of the plasma in the quadrupole trap is 4.4 MHz. The bounce frequency in the cylindrical trap depends on the amplitude of the oscillation.

An electron beam is transmitted through the positron plasma. After the beam has been gated on for an adjustable

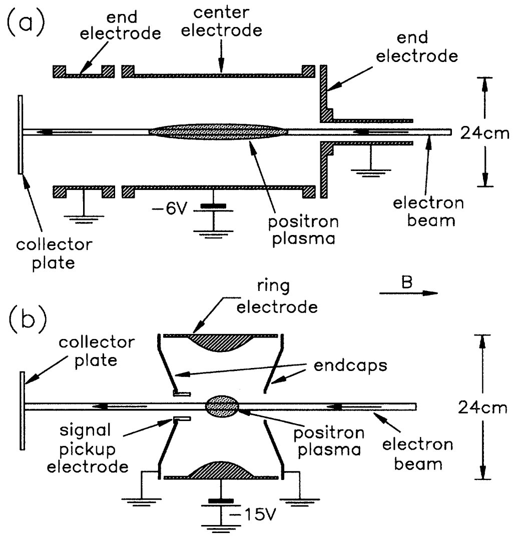

FIG. 1. Schematic diagram of the Penning traps: (a) cylindrical trap and (b) approximate quadrupole trap.

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time interval, the positrons are dumped onto a collector plate. The positrons are detected using a charge-sensitive preamplifier or by measuring the annihilation γ rays. By measuring the number of positrons collected as a function of the depth of the potential well during the dump cycle, the positron temperature is obtained [12]. Data obtained by scanning a movable beam stop are Abel inverted to obtain the radial profile of the electron beam and the axially integrated radial profile of the plasma. Oscillations excited in the plasma by the beam are detected using the signal pickup electrode attached to one of the conical end cap electrodes as shown in Fig. 1(b).

Plasmas containing up to 10^8 positrons can be obtained by accumulating positrons for several minutes. For the experiments described here, the plasmas contained about 2×10^7 positrons. The positron plasma parameters were obtained by measuring the axially integrated density profiles and using a Poisson-Boltzmann equilibrium code [13] to calculate the spatial distribution of the positrons in the trap.

Typical positron plasma parameters are total number of positrons $N_p \simeq 2.0 \times 10^7$, positron temperature $T_p \simeq 0.025$ eV, and plasma radius $r_p = 1.5$ cm. In the cylindrical trap, the plasma length $L_p \simeq 20$ cm, which gives a central positron plasma density $n_p = 3 \times 10^5$ cm^{-3}, an aspect ratio $\alpha = L_p/2r_p$ of 7, and a Debye length $\lambda_D = 2$ mm. In the quadrupole trap, $L_p \simeq 4$ cm, which gives $n_p = 1 \times 10^6$ cm^{-3}, $\alpha = 1.3$, and $\lambda_D = 1$ mm. Thus, in both traps we have $\lambda_D \ll L_p$, $\lambda_D \ll r_p$, and $N_D \gg 1$, where N_D is the number of positrons in a Debye sphere.

The electron beam has a diameter of about 0.7 cm at the location of the positron plasma. The energy spread ΔW_b of the electron beam (~ 1 eV full width at half maximum) is measured using a retarding-potential analyzer. The energy of the beam is about 10 eV before it enters the trap, where it slows down to a few electron volts. The electron beam energy within the positron plasma, which typically was a few electron volts, is determined by both the cathode bias and the depth of the well, modified by the positron space charge of several electron volts. The plasma potential is estimated by reducing the beam energy to the point where some of the electrons are reflected by the positron-confining well. The measured plasma potential agrees with the value calculated from the Poisson-Boltzmann code to within 0.3–0.4 eV.

Figure 2 shows a typical set of data illustrating the interaction of a low-energy electron beam with a positron plasma in the cylindrical trap. The inset to Fig. 2(a) shows the positron plasma temperature after the beam was gated on for various times and illustrates a strong heating effect. From the exponential part of these curves, we obtain the heating rate as a function of beam velocity, under conditions where the beam density is kept constant by adjusting the beam current. Figure 2(a) illustrates the range of beam velocities over which the interaction occurs.

For the energies considered here, one phenomenon of potential importance is the two-stream instability. For the infinite plasma case, the Doppler-shifted, slow Langmuir mode of the beam couples to the Langmuir mode of the plasma, and the usual two-stream dispersion relation for electron-ion plasmas is applicable [2]. This gives a maximum growth rate of $\omega_p/2$, which is substantially higher than that of the electron-ion case, for which the maximum growth rate is $(m_e/m_i)^{1/3}\omega_p$, where m_e and m_i are the electron and ion masses, respectively. The finite geometry of our experiment modifies the result, since the relevant modes are now the Trivelpiece-Gould modes of the beam and plasma. This leads to somewhat smaller growth rates than the infinite plasma dispersion relation predicts.

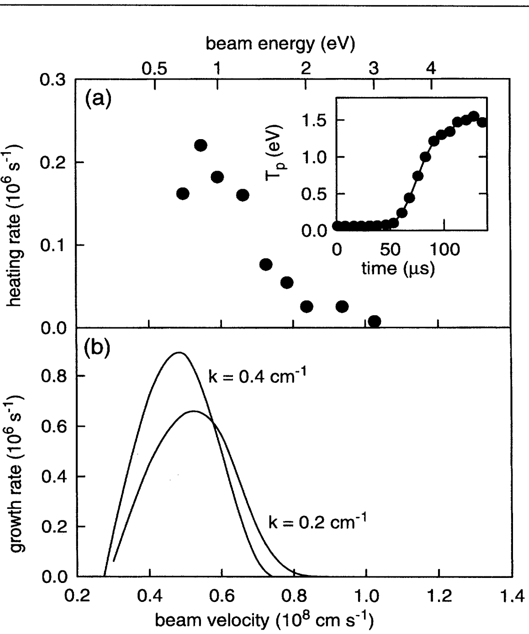

FIG. 2. Beam-plasma interaction in the cylindrical trap: (a) positron heating rates for $N_p = 1.2 \times 10^7$, $n_b = 3 \times 10^5$ cm^{-3} (inset: time-resolved positron heating following switch-on of the electron beam), and (b) calculated growth rates with $n_p = 3 \times 10^5$ cm^{-3}, $n_b = 3 \times 10^5$ cm^{-3}.

We interpret the heating as arising from the growth of unstable modes of the plasma which transfer energy to the particles. If the system obeys quasilinear theory, we expect the heating to scale with the growth of noise in the system, similar to the observations of Davidson *et al.* [14] in their numerical study of the two-stream instability in the electron-ion beam-plasma system.

For comparison with theory, we have investigated the system numerically using a drift-kinetic eigenvalue code, employing matrix shooting in a plasma column of infinite extent [15]. The model treats the system as two coaxial plasmas drifting relative to each other. The different radii for the two species are included in the model, but the radial profiles are assumed to be flat. Figure 2(b) compares the experimentally measured heating rates for a range of beam velocities with the growth rates calculated using the code.

In these calculations, the measured values of the beam and plasma radii and the density and temperature were used. The beam temperature T_b is obtained from the beam energy spread ΔW_b using the relation $T_b \simeq (\Delta W_b)^2/4W_b$, where W_b is the average beam energy. Typical values for T_b are in the range 0.05 to 0.1 eV.

The wave number k was treated as a fitted parameter, and solutions for two values of k are shown in Fig. 2(b). The best fit to the shape of the curve is obtained with $k \sim 0.2{-}0.4\ \mathrm{cm}^{-1}$, corresponding to $\lambda/2 \sim 7{-}15$ cm. Since the plasma length was 20 cm for this data set, this wavelength would correspond to a low-order axial mode.

In view of the simplifying assumptions of the model, the agreement between the theory and the experiment is reasonable, since the computations reproduce the major features of the data. The factor of 3 difference in the absolute values of the growth rates is reasonable, since the interaction is restricted to the short distance that the beam and plasma overlap. We conclude that the plasma heating is consistent with that expected for a two-stream instability. We cannot investigate experimentally the regime of beam velocities $<0.5 \times 10^8\ \mathrm{cm\,s}^{-1}$, because at such low beam energies the beam energy spread of $W_b \sim 0.5$ eV leads to beam reflection, which, in turn, sets up instabilities in the incident beam.

We have also obtained data for the interaction between the electron beam and positron plasmas stored in the quadrupole Penning trap shown in Fig. 1(b), and we observe some interesting differences from the behavior observed in the cylindrical trap. Unlike the cylindrical trap experiment, we are able to observe the unstable oscillation directly, using the signal pickup electrode shown in Fig. 1(b). A typical example of the detected signal is shown in Fig. 3(a). The transient at $t \sim 6\ \mu$s is caused by the image charge of the beam as it passes through the pickup electrode. For beam energies below some threshold value, a strong sinusoidal oscillation grows from the noise, with an initial exponential rise, and saturates after some overshoot at $t \simeq 50\ \mu$s. The frequency of the signal is 4.4 MHz in this case, which is close to the calculated center-of-mass frequency of the positron plasma. As shown in Fig. 3(b), the overshoot is accompanied by the ejection from the trap of some of the positrons, which were monitored by the γ-ray detector. In Fig. 4, we plot the measured growth rates as a function of beam energy for two values of beam density.

For the measured growth rates of the unstable mode in the quadrupole well, we find that we are not able to match the dependence on beam velocity using the eigenvalue code described above for the two-stream instability, unless we assume an unrealistically large value of beam temperature, $T_b \sim 0.5$ eV. In the quadrupole well, the system appears to behave like a transit-time oscillator [16], with the LC resonant circuit being replaced by the high Q oscillation of the center of mass of the positron plasma. An analytic, cold-fluid theory is being developed to describe this system [17]. Preliminary comparisons between the theory and experiment show good agreement for beam energies greater than about 1 eV. Theory and experiment diverge at lower beam energies, where the finite beam temperature is likely to be most important. A detailed comparison of theory and experiment will be published elsewhere.

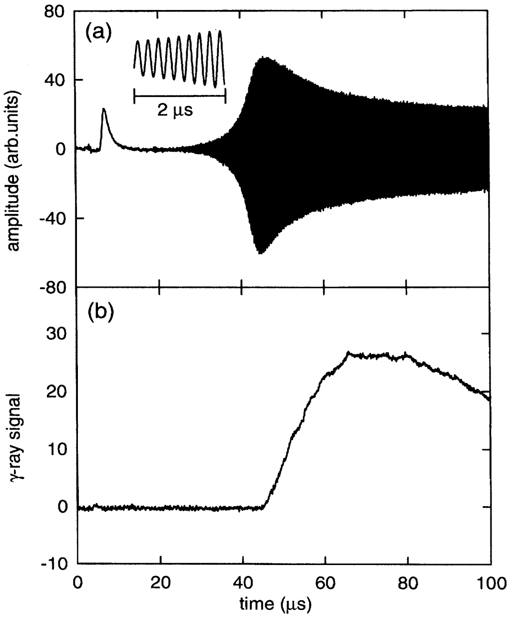

FIG. 3. Beam-plasma interaction in the quadrupole trap: (a) oscillation amplitude of the plasma during transmission of the electron beam, as measured on the pickup electrode (inset: 2 μs detail at $t = 40\ \mu$s) and (b) time-resolved γ-ray signal.

Unlike the quadrupole trap, we were not able to observe the unstable mode directly in the cylindrical trap. This appears to be due to qualitative differences between the modes in the two traps. In the cylindrical trap, the amplitude of excited modes is strongly dependent on the temperature of the plasma [18]. It appears that, in the anharmonic potential of the cylindrical trap, there is an efficient mechanism that couples wave energy into thermal energy. This phenomenon is not observed in the quadrupole trap. For the beam-plasma interaction, we interpret this as follows: In the cylindrical trap, plasma modes are driven unstable by the two-stream instability, but the energy is rapidly transferred to thermal energy, so a large-amplitude mode is not excited. In the quadrupole trap, on the other hand, there is no efficient mechanism for coupling wave energy into thermal energy, so the unstable mode grows to large amplitude. This is consistent with our observations on the external excitation of axial modes in cylindrical and quadrupole wells [18]. It is also consistent with the observation that the plasma is heated to a much higher temperature in the cylindrical well (typically > 1 eV), while the heating effect is less marked in the quadrupole well (~ 0.2 eV).

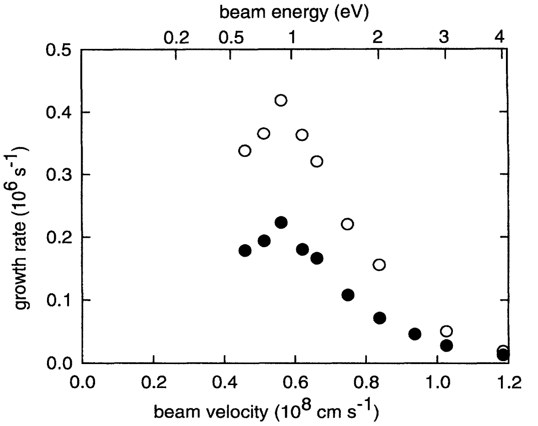

FIG. 4. Beam-plasma interaction in the quadrupole trap. Growth rates of the positron plasma oscillations for a selection of beam velocities at two values of beam density with $N_p = 2 \times 10^7$, $L_p = 4.4$ cm, and $r_p = 1.4$ cm; (○) $n_b = 1.1 \times 10^6$ cm^{-3} and (●) $n_b = 5 \times 10^5$ cm^{-3}.

The ejection of positrons from the quadrupole trap immediately after saturation of the unstable wave amplitude is of particular interest: The potential well is about 6.0 eV deep, but the electron beam energy is typically only about 1–2 eV, so that some particles must be accelerated to energies significantly larger than the relative drift. It appears that the amplitude of the plasma oscillations becomes comparable to the depth of the potential well. This is confirmed by a particle-in-cell simulation of the plasma, which shows large-amplitude growth of the center-of-mass oscillation on time scales similar to those that we observe [19].

Ejection of positrons from the trap is always observed in conjunction with overshoot of the wave amplitude at saturation. This overshoot is probably due simply to the reduction of the number of positrons in the well, and it is not likely to be related to the overshoot often associated with the nonlinear saturation of instabilities by particle trapping.

This paper describes one of many possible regimes of operation of the experiment. For example, by operating with higher beam velocities, a stable beam-plasma system can be studied. Such a system could be used to investigate some of the interesting nonlinear phenomena in electron-positron plasmas, where the most marked differences from electron-ion plasmas are predicted to occur [2,6]. Many of these phenomena, such as solitary wave structures and shocks, are directly relevant to astrophysical electron-positron plasmas.

In summary, we have investigated an electron-positron plasma experimentally for the first time by transmitting an electron beam through a positron plasma in two distinct Penning-trap geometries. In the cylindrical trap, we observe what appears to be a strong, two-stream instability with associated positron heating. In the quadrupole well, the center-of-mass oscillation of the positrons is excited to large amplitude, and positrons are accelerated out of the confining potential well. These experiments open up to laboratory investigation an important class of plasmas that are of interest in astrophysics and in other contexts.

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