Production of Quiescent Plasmas in a Magnetic Field by a Beam-Plasma Discharge*

D. Bollinger, D. Boyd, H. Liu, and M. Seidl
Stevens Institute of Technology, Hoboken, New Jersey 07030
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Very quiet, steady-state plasmas in axial magnetic fields with density fluctuations less than 0.1% may be produced in a beam-plasm discharge. The dependence of the density and electron temperature on the discharge parameters are in accordance with the predictions of a one-dimensional plasma model.

Extremely quiet steady-state plasma, with density fluctuations less than 0.1%, may be produced in uniform magnetic fields by a beam-plasma discharge when three conditions are met: (1) The anode must be close to the cathode which emits the electron beam; (2) the hot-cathode's emission must be temperature limited; and (3) the gas must be a mixture in which Penning ionization, ionization by metastable states, can occur. Beam-plasma discharges in a magnetic field are known to be quite noisy, usually with density fluctuations around 20%. Satisfying the first two of the above conditions reduces the density fluctuations somewhat, but only when all three conditions are met can we bring the plasma into the very low noise regime with high densities, up to 10^{13} cm^{-3}, and high magnetic fields, up to 2000 G. Earlier work has shown that putting the anode close to the cathode[1,2] and operating the cathode temperature limited[1] helps to stabilize the plasma. This is the first time, to our knowledge, that it has been shown that Penning gas mixtures can be used to very effectively suppress the density fluctuations in dense plasmas with large applied magnetic fields. The noise level is comparable to that quoted for quiescent plasmas produced without a magnetic field and at much lower densities.[3,4]

A schematic of the apparatus used is shown in Fig. 1. A uniform magnetic field of up to 2000 G has been applied along the plasma axis. The hot cathode is an indirectly heated, 2.5-cm-diam rhenium plate with the emitting surface coated with lanthanum boride. The cathode surface should emit evenly; otherwise at higher magnetic fields, density gradients occur within the plasma column which may result in noise which cannot be suppressed. Emission currents from the cathode are 20 mA to 1 A; cathode to anode accelerating voltages are 40 to 500 V. The anode disk has a 2.5-cm-diam hole concentric with the cathode and is 2.0 mm from the cathode. The end plate opposite the hot cathode is maintained at cathode potential. The anode disk at both the hot and cold cathode ends and the chamber walls are at ground potential. Always, the plasma potential is several volts above anode potential, and this potential is apparently fixed by the anode disk near the hot cathode. Removing the anode disk at the cold cathode end or varying the cold cathode potential has no substantial effect on the plasma potential, nor does it affect the conditions for a quiet plasma. If the anode disk near the hot cathode is removed, however, it is impossible to suppress the plasma noise. Plasma potentials and electron temperatures are measured using an emitting probe.[5,6] A microwave interferometer is used to measure the plasma density, and the density fluctuations are measured from the ion saturation current to a probe.

The effect of the hot cathode and the gas mixture in suppressing the plasma-density fluctuations is as follows. First, when the hot cathode is operating in the space-charge–limited regime, the plasma is always noisy with density fluctuations $\Delta n/n$ on the order of 20% at frequencies over the range of 0 to 100 kHz, whether or not the gas is a Penning gas mixture. Second, operating the cathode in the temperature-limited regime in a pure gas reduces the density fluctuations to about 10%; only the lower-frequency density fluctuations remain. These low-frequency fluctuations have been observed to occur on the

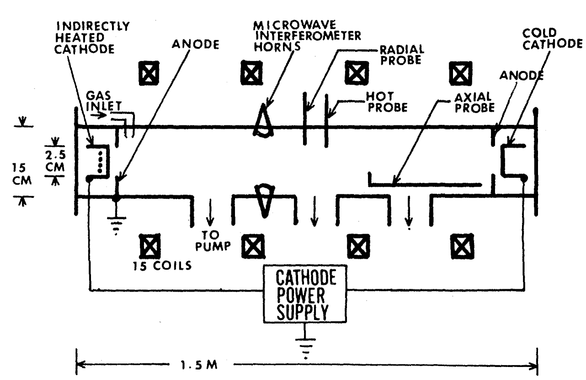

FIG. 1. Schematic of the experimental system.

density gradient of the plasma column and have frequencies on the order of those expected for drift waves. Third, using a gas mixture in which Penning ionization can occur, with the cathode temperature limited, the remaining low-frequency noise is suppressed so that the density fluctuations are less than 0.1%. In addition, for the same input power, the plasma density increases by more than an order of magnitude. A number of different gas combinations in which the Penning-ionization effect can occur were tried, and for each a certain mixture was found which gives very quiet plasma. Mixtures of gases in which the Penning effect does not occur would not give a quiet plasma. The exact proportion of the gases in a mixture to suppress the fluctuations is not critical, but certain approximate proportions give the most quiet plasmas. For the pressures at which we operate, $(4 \text{ to } 10)\times 10^{-4}$ Torr, we found the best mixtures of the gases we investigated to be helium with a trace or argon, 4 parts helium to 2 parts hydrogen, 50 parts helium to 1 part nitrogen, and 50 parts neon to 1 part argon. Penning-ionization cross sections for these gas mixtures may be found in a paper of Bolden *et al.*[7] Figure 2 shows for the case of a helium-argon gas that the plasma noise is very small only when the cathode is operating in the temperature-limited regime, for this example when the cathode heating power is less than 150 W. If the cathode-to-anode voltage is increased, the cathode becomes space-charge limited at a higher cathode heating power and, correspondingly, the onset of the plasma noise occurs at this higher power. Curves similar to Fig. 2 have been obtained for the other gas mixtures listed above.

Magnetic field strength usually has little effect on the density fluctuations for fields from 150 to 2000 G. Below 150 G the plasma is not well confined and the density decreases. Sometimes, above 1000 G the plasma density jumps between plasma densities differing by about 15%, but does not have any noise in the kHz range. These abrupt changes in plasma density appear to result from the formation of a plasma outside the main column. This behavior is reflected by the beam power required to produce a given plasma density as a function of field strength (see Fig. 3). The power is correlated to the plasma density fluctuations.

The details of the mechanism leading to a quiet plasma are not known. The primary reason for the stabilization may be the lowering of the electron temperature, for a given pressure, which occurs when the conditions for a quiet plasma are met. The fact that the plasma can be maintained at a lower electron temperature suggests an additional ionization mechanism. However, direct production of ions by Penning ionization cannot be of the same importance as it is in high-pressure discharges.[8] Assuming that ionization by direct electron impact and metastable excitation is dominated by the plasma electrons, we get the following relation for the ratio of the Penning ionization rate $R_{\rm P}$ to the direct electron ionization rate R_i:

$$R_{\rm P}/R_i = n_{02}\sigma_{\rm P} d\langle\sigma_{\rm exc} v_e\rangle/\langle\sigma_i v_e\rangle\,, \qquad (1)$$

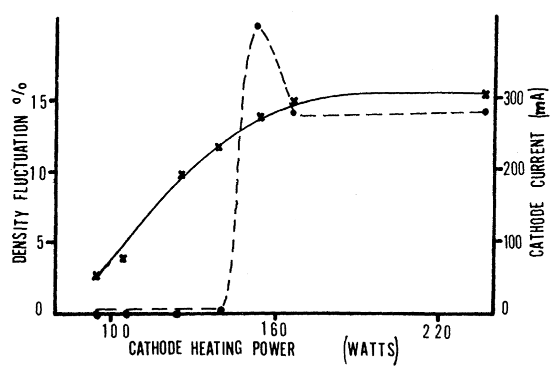

FIG. 2. Plasma-density fluctuations as a function of cathode heating power (dashed line), and cathode current as a function of heating power (solid line). Measurements at constant electron beam power of 7 W. Gas is helium with a trace of argon. Pressure is 6.5×10^{-4} Torr.

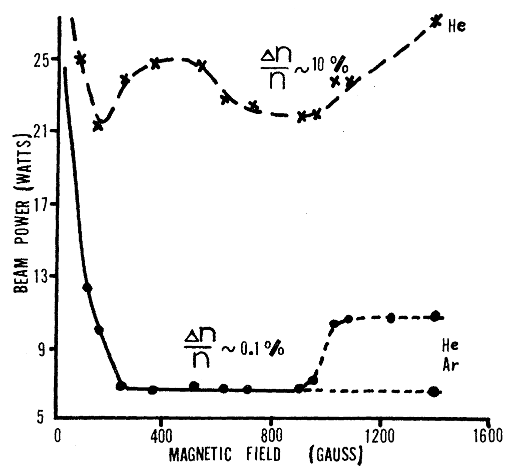

FIG. 3. Electron beam power required to produce a given density plasma, $n_e = 3\times 10^{11}$ cm^{-3}, as a function of magnetic field strength for helium gas with a trace of argon, and for pure helium gas. Gas pressure for each case, 6×10^{-4} Torr.

where n_{02} is the density of the neutral species which can be ionized by the Penning effect; d is the plasma diameter; v_e the electron thermal velocity; and σ_P, σ_{exc}, and σ_i are the cross sections for Penning ionization, metastable excitation, and direct electron ionization, respectively. For the parameters of our system and the low pressures at which we operate, R_P is 10^{-2} to at most 10^{-1} of R_i.

When the plasma is quiet, radial diffusion is measured to be very small so that the dominant particle losses are to the end walls. Using this assumption the main discharge parameters can be calculated and approximate agreement obtained with experiment. A particle balance between the rate of plasma production and diffusion to the end walls relates the electron temperature T_e to the gas pressure p.[9,10] Writing this equation in terms of parameters which are conventionally used to describe discharges gives

$$Lp = 4\times 10^{-23}(T_e/m_i)^{1/2}\langle\sigma v_e\rangle_{\text{eff}}^{-1}. \quad (2)$$

L is the length of the plasma column in cm, m_i is the ion mass in grams, $\langle\sigma v_e\rangle_{\text{eff}}$ the effective ionization rate coefficient in cm^3/sec; T_e is in eV and p is in Torr. An energy balance between the power in watts, W, transferred to the plasma by the beam and the rate of energy lost from the plasma, neglecting radiation, gives

$$W/An_e = 2\times 10^{-25}(T_e/m_i)^{1/2}(E_i + \tfrac{3}{2}T_e + \varphi_\omega). \quad (3)$$

A is the cross-sectional area of the plasma in cm^2, n_e is the plasma density in cm^{-3}, E_i the gas ionization energy in eV, φ_ω the plasma potential with respect to the anode in eV. Experimentally, W is estimated from W = (cathode current)$\times$(cathode to anode voltage)$\times\eta$, where η takes into account the ion current to the cathode and the efficiency of energy transfer from the electron beam to the plasma.

The dependence predicted by relations (2) and (3) are confirmed by our measurements. In Fig. 4, Eqs. (2) and (3) are plotted using the ionization rate coefficients for helium from the work of Lotz.[11] The points indicate different experimental beam powers and pressures and assume $\eta = 0.5$. It can be seen that the plasma electron temperature is determined by and varies inversely as the gas pressure. For a given gas pressure, the plasma density is linearly proportional to the beam power, but T_e is not affected by the beam power. Plasma density and electron temperature may then be varied independently; plasmas in the range of 10^{10} to 10^{13} cm^{-3} and temperatures of 1 to 10 eV are produced. Relations (2) and (3) can serve as a useful guide in estimating the power requirements and electron temperatures expected for given quiescent plasmas.

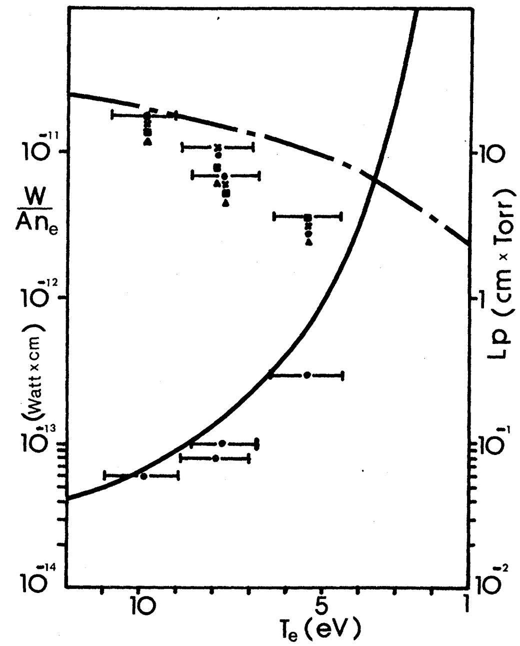

FIG. 4. Plots of Eq. (2) (solid line) and Eq. (3) (broken line). The lower set of points gives T_e as a function of Lp with $L = 100$ cm. For each T_e the various experimental W/An_e points correspond to values of W in the range of 5 to 150 W. Gas is helium with a trace of argon.

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Sound Absorption and Dispersion along the Critical Isochore in Xenon*

Don Eden,† Carl W. Garland, and Jan Thoen‡
Department of Chemistry and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 17 January 1972)

Ultrasonic and Brillouin absorption and velocity data along the critical isochore in xenon are reinterpreted in terms of modified theoretical expressions derived within the framework of the Fixman-Mistura theory. The new expressions mainly arise from avoiding the unjustified assumption of small dispersion near a liquid-gas critical point. Numerical analysis of the data shows quite satisfactory agreement between theory and experiment for both sound absorption and dispersion.

In this Letter we report a modification to the theory of critical sound propagation in pure simple fluids and present a reanalysis of some recent experimental data for absorption and dispersion along the critical isochore in xenon. Mode-mode coupling theory has been developed in considerable detail by Kawasaki[1] to describe acoustic absorption and dispersion near a liquid-gas critical point. Recently, Mistura[2] developed a modified version of Fixman's original approach[3] involving energy transfer between sound waves and density fluctuations and obtained results identical to those presented by Kawasaki. In both the Kawasaki and Mistura derivations, the velocity dispersion is assumed to be small. Although this is a good assumption for the closely related problem of critical phase separation in binary fluids, it is a poor approximation for pure fluids. The new expressions for absorption and dispersion presented below have been obtained without making this assumption.

In a previous Letter[4] new experimental results for sound absorption in xenon were reported in the frequency range between 0.4 and 5 MHz and interpreted in terms of the previously cited theories.[1,2] Hypersonic attenuation values from Brillouin linewidths[5] were also discussed. The essential result was that the critical sound absorption per wavelength (defined as the difference between the observed absorption and the classical absorption) depended only on a single reduced variable $\omega^* = \omega/\omega_D$, with the characteristic frequency for thermal diffusion defined by

$$\omega_D \equiv (2\Lambda/\rho C_p)\xi^{-2}, \qquad (1)$$

where Λ is the thermal conductivity coefficient, C_p is the specific heat at constant pressure, ρ is the density, and ξ is the correlation length. Good agreement between theory and experiment could, however, only be obtained for $\omega^* \lesssim 2$. For higher ω^*, the experimental α_λ values increased monotonically and then leveled off at a constant value independent of ω^*, whereas the theory predicted a decrease in α_λ with increasing ω^* values above $\omega^* \approx 8$. The behavior of α_λ as a function of ω^* in xenon was also in contrast with the experimental results for binary liquid systems where a decrease in α_λ has been observed at large ω^* values.[2,6]

In a simultaneously published Letter by Cummins and Swinney[7] an analysis of sound-dispersion data obtained from Brillouin and ultrasonic work was made in terms of the theoretical predictions of Kawasaki.[1] It was found that the dispersion in the Brillouin data and in the ultrasonic data could be separately described reasonably well with different sets of adjustable parameters, but the dispersion in the Brillouin velocities seem to be 2 to 3 times smaller than the theory predicted when values of the parameters obtained from the ultrasonic experiment were used.

The reanalysis of these experimental data in terms of our new expressions for α_λ and for the dispersion will show that the large discrepancies cited above and discussed in Refs. 2, 4, and 7 are artifacts which disappear when the correct theoretical expressions are used.

We will follow the Fixman-Mistura approach and introduce a complex sound velocity u^* which is related to a complex frequency-dependent excess specific heat Δ by

$$u^{*2} = u_T^2(C_p + \Delta)/(C_v + \Delta), \qquad (2)$$