face by randomly adsorbed CO (or vacancies in the CO layer at high θ); heating to 100°K could permit rearrangement to a symmetric structure. The relaxation of surface symmetry might lead to orbital rearrangement of the surface atoms with a resultant change in the surface density of states, reflected in the TED.

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Plasma Heating by an Intense Electron Beam*

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An intense pulsed electron beam ($\nu/\gamma \sim 2$) was used to heat electrons in a target plasma in a magnetic field. A strong beam-plasma interaction was observed. Measured heating levels were found to be consistent with a two-stream instability calculation and return-current heating estimates. Energetic counter-streaming electrons were detected in the plasma during the beam pulse and possible sources of these electrons are suggested.

Experiments using intense pulsed relativistic electron beams to heat plasma electrons have been reported recently.[1-6] New results from an energetic beam-plasma experiment are reported here. A strong interaction between beam and plasma electrons has been observed. Both a two-stream beam-plasma instability and return-current heating were considered in the interpretation of our measurements.

A Nereus accelerator[7] produced a 350-kV, 60-nsec pulse of electrons with the current rising throughout the pulse to a peak of 50 kA. the 2.5-cm-diam beam was injected into a 10-cm-diam, 30-cm-long Pyrex tube. An 8-cm-diam Faraday cup collected beam current which was transported through the plasma. A hydrogen plasma was formed by first preionizing the gas by a spark between two electrodes spaced 1 mm apart and located 2 cm from the axis. This was followed by a pulsed longitudinal discharge which raised the degree of ionization substantially. The electron beam was then injected into the afterglow plasma after a preselected delay. The plasma column at beam injection time was ~3 cm in diameter; a lower-density background plasma was present near the walls. The electron density was measured with a 35-GHz interferometer; for densities below $\sim 10^{13}$ cm^{-3}, interferometer fringe measurements were used. Low backfill pressures ($\lesssim 2\times10^{-3}$ Torr) ensured that avalanche during the beam pulse was small. Bounds on densities above 10^{13} cm^{-3} were estimated from microwave cutoff behavior, avalanche considerations, and complete ionization limits on density. Backfill pressures up to 1.5 $\times10^{-2}$ Torr were used to obtain these plasmas. Upper limits to avalanche rates for electron impact ionization were calculated from published cross sections. A 0.15-T longitudinal magnetic field permeated the diode, plasma chamber, and Faraday cup.

Net plasma currents were measured with a Rogowski coil which surrounded the Pyrex pipe and a small glass-enclosed probe which was moved radially into the plasma. The plasma-formation technique dictated that no external return-current conductors be used; for this reason, plasma conductivity could not be inferred easily from the rate of change of the net current during the course of the beam pulse. Plasma energy was inferred from diamagnetic loops located 5 and 20 cm from the anode. Energetic backstreaming electrons in the plasma were measured on some shots with a small Faraday cup (~ 1 cm diam and Mylar window) located near the anode foil, at the edge of the beam channel, facing downstream.

Typically only 20% of the diode current was indicated by the main Faraday cup. The source of the beam loss is unknown; presumably it was due to space-charge blowup or a pinch near the anode foil where the plasma density was probably low and space charge and/or current neutralization were inadequate.

The diamagnetic loop signals were complex and varied considerably over the range of plasma electron densities employed (10^{12} to 10^{15} cm^{-3}). The two relatively closely spaced loops gave similar signals and no thermal wave[1] was identifiable. During the beam pulse, the signals indicated that the plasma energy increased following the general shape of the beam-current wave form. In the wake of the beam pulse, the signals decayed quickly at low densities (10^{12} to 10^{13} cm^{-3}), decayed more slowly (~ 1 μsec) at higher densities, and showed an initial increase (~ 1 μsec) followed by a slow decrease at the highest densities (10^{14} to 10^{15} cm^{-3}). See Fig. 1. At low densities a high-frequency signal was superimposed on the wave form during the beam pulse. This corresponded to calculated radial bouncing frequencies of the plasma column.[8] At low densities, plasma x-ray emission measured through a thin beryllium window with a collimated scintillator-photomultiplier combination displayed the same time dependence as the diamagnetic-loop signals, thus veryfying the existence of a hot-plasma component.

Inferring plasma-energy densities accurately solely from diamagnetic-loop signals is not possible in this experiment. We have estimated plasma-energy density from calculations which

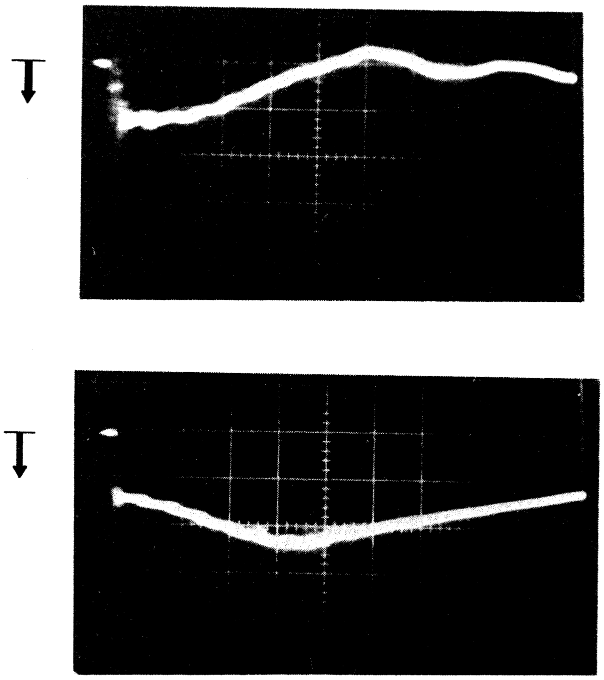

FIG. 1. Sample diamagnetic-loop signals. Vertical sensitivity $\sim 4\times 10^{16}$ eV cm^{-3}/division (see text). Time base, 200 nsec/division. Top, $n_p \sim 10^{13}/\mathrm{cm}^3$; bottom, $10^{14} < n_p < 10^{15}/\mathrm{cm}^3$.

equate plasma pressure (assumed isotropic) to pressure exerted by the difference between the applied longitudinal magnetic field in the plasma and in the un-ionized region. We have omitted corrections for pressure due to azimuthal magnetic fields from the beam and plasma currents because the measured azimuthal fields were always $\frac{1}{3}$ or less of the applied field. We also have omitted any corrections for forces due to radial electric fields which may arise because the plasma is heated in times comparable to or shorter than the time period for radial hydromagnetic oscillations.[8] The equilibrium assumption of the simple pressure-balance calculation is not satisfied in the experiment at high electron densities and the calculation may be substantially in error. We suggest that effects due to radial and azimuthal electric fields will be mitigated somewhat from the presence of conducting end walls which could short out these fields.

In Fig. 2 are indicated the results of measurements performed with the diamagnetic loops. The plasma energy density, W_p, measured at the end of the beam pulse is normalized to the peak instantaneous beam energy density W_b. The ab-

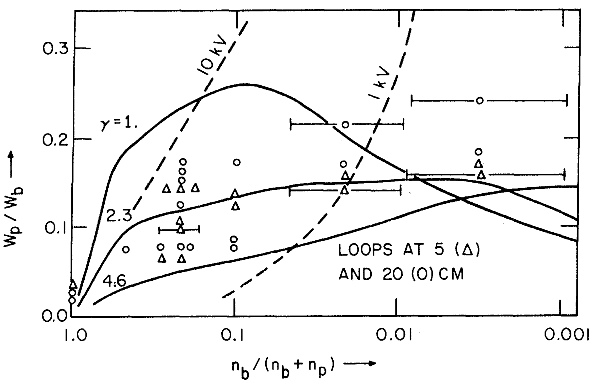

FIG. 2. Experimental and theoretical results for heating achieved by the end of the beam pulse. Data shown for two diamagnetic loops. $W_b \sim 3\times 10^{17}$ eV/cm^3, $n_b \sim 10^{12}$/cm^3. Dashed lines, plasma electron isotherms; solid lines, result from heating calculation (Refs. 9 and 10) for three beam energies.

scissa expresses the variable plasma electron density n_p in a form involving the beam density n_b. The peak (in time) beam density ($\sim 10^{12}$ cm^{-3}) is an average of the peak beam density at the anode and at the large Faraday cup; thus $W_b \sim 10^{17}$ eV cm^{-3}. The maximum of W_p approached 7×10^{16} eV cm^{-3}, which is indicative of a relatively inefficient coupling of total beam energy to our small-volume plasma. Also shown are the saturation levels predicted by Toepfer and Poukey[9,10] for the two-stream instability. Their theoretical analysis does not directly address the case of the continual injection of a beam into a plasma in which the temperature is rising; however, further work has shown that the energy-transfer rate from a cold beam to the plasma drops as the plasma energy approaches the predicted two-stream saturation levels.[11] Results for three beam energies are shown and the data are consistent with the calculations but do not necessarily confirm them. Because the parameters of this experiment violate some simplifying assumptions of the theory in Ref. 10, the details of the interactions which lead to heating may be different for the two cases. Further measurements discussed below show that another heating mechanism may be operative and that the agreement between theoretical and experimental heating levels could be fortuitous.

During the beam pulse, both the Rogowski coil and the small magnetic field probe indicated several kiloamperes ($\lesssim 5$) of net current under most plasma conditions. A lack of current neutralization has been noted before in a similar experiment.[2] These large net currents could not exist if the plasma conductivity were determined by electron-ion or electron-neutral collisions alone. Under most conditions however, the plasma electron drift velocity was high enough to satisfy the criteria for ion-acoustic or Buneman-type instabilities[12-14] and an enhanced plasma resistivity would be consistent with the measurements. In the wake of the beam pulse, the Rogowski coil indicated that no net plasma current was flowing, while the probe indicated several kiloamperes when it was inserted more than 2–3 cm into the tube. From this we infer that currents continue to circulate through the plasma long after the end of the beam pulse, flowing down the tube axis, across the conducting end walls, and returning close to or on the side walls. The time constant for the current decay was typically a few microseconds and too short to be explained by electron-ion collisions. The backfill pressures were too low to allow electron-neutral collisions to lower the conductivity unless substantial amounts of wall debris were present at these times.

The size of possible "anomalous" return-current heating[15,16] of the plasma can be estimated. Observed plasma current densities were ~ 1 kA cm^{-2} and greater, and plasma conductivities (both theoretical[12-14] values and values inferred from measurements) were ~ 10 mho/cm and less, so that resistive heating levels near 10^{18} eV cm^{-3} μsec^{-1} were expected as long as the plasma parameters satisfied the instability criteria.[12-14] These return-current heating rates were indeed large enough to account for all of the observed heating, even without invoking the two-stream beam-plasma instability. From this we conclude that both processes could be important and that the consideration of one without the other is an oversimplification of the problem.

The results of measurements performed with the small backward-facing Faraday cup are presented in Fig. 3. The indicated current densities are ~ 50 A cm^{-2} (a few percent of the total plasma current density) and the energies are $\gtrsim 25$ kV. Altyntsev *et al.*,[1] reported similar results and suggested that these energetic electrons were actually beam electrons which had been scattered by plasma waves through angles approaching 180 deg. We suggest that three more likely processes account for this observation:

(1) According to Monte Carlo calculations nearly 10% of the incident beam electrons should be back scattered from the end wall of the plasma container, with the majority of these electrons

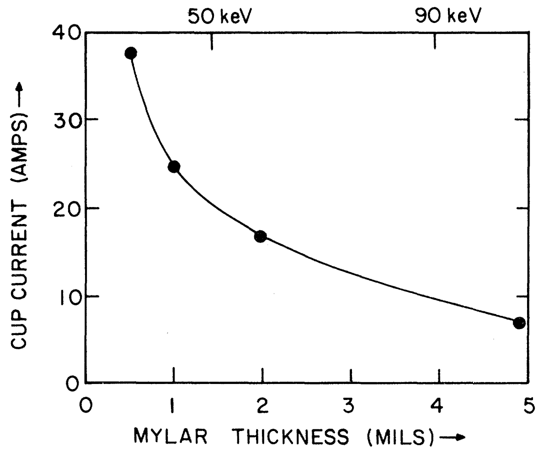

FIG. 3. Current to the small Faraday cup averaged over the beam pulse duration. Current wave forms were oscillitory with peaks exceeding twice the average values. Results shown for different window thicknesses. Top scale indicates electron energy at which window is 1 range thick.

retaining more than $\frac{1}{3}$ of their initial energy.

(2) The diamagnetic signals show that the hot plasma ($\beta \sim \frac{1}{2}$) created in this experiment causes a mirror configuration to form in the magnetic field at the ends of the tube where line typing occurs. These mirrors are capable of reflecting beam electrons which have high transverse velocities.

(3) There is substantial evidence that the plasma is highly resistive. Large steady longitudinal electric fields (~kilovolts/centimeter) which accompany the plasma current should thus be capable of accelerating plasma electrons to runaway conditions and very high energies.

The relative contributions of the three effects remain to be determined.

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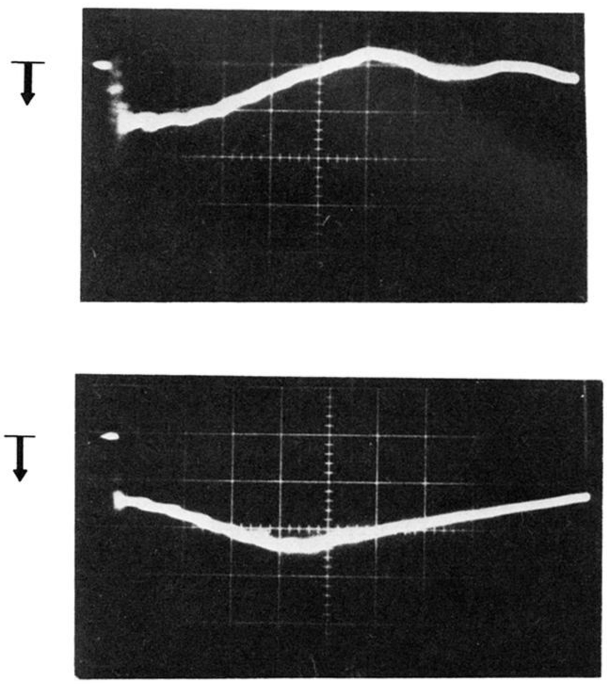

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