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Heating of a Fully Ionized Plasma Column by a Relativistic Electron Beam*

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A magnetized plasma column ($n_p \leq 6\times10^{13}$ cm^{-3}) is heated by the injection of an intense relativistic electron beam along the magnetic field. The energy per electron-ion pair transferred to the plasma increases linearly with the beam-to-plasma density ratio n_b/n_p. The electron heating is attributed to the electron-electron beam-plasma interaction while the energetic ions are produced by an electrostatic acceleration. After heating, the plasma column oscillates radially at a frequency proportional to $B/n_p^{1/2}$.

Advances in electron-beam technology have made possible the production of very intense relativistic electron beams with power levels as high as 10^{13} W. With the capability of delivering several megajoules of energy in a time less than 100 nsec, these beams have several applications in fusion research. One of the more promising is in their use for rapid heating of plasma to thermonuclear termperatures. The coupling between relativistic electron beams and plasmas of thermonuclear interest via Coulomb collisions is rather weak, but collective interactions can result in very significant energy transfer. Two collective interactions are expected, the electron-electron two-stream instability[1] involving the high-energy beam electrons streaming through the plasma, and the electron-ion streaming instability driven by the induced return currents flowing within the beam.[2] There have been several experimental studies of plasma heating by relativistic electron beams in which significant heating has been observed,[3-7] but as yet the dominant heating mechanism has not been positively identified. Most of the experiments were complicated by the presence of wall effects, un-ionized gas, or uncertainties in beam or plasma parameters which made comparison with theory difficult.

In the experiments described here, the plasma column is fully ionized and confined in a hard vacuum ($p \leq 2\times10^{-6}$ Torr) away from the vacuum chamber walls. The relativistic electron beam is produced in a diode having a foil anode which isolates the diode from the plasma, thus decoupling the beam parameters from those of the plasma. The latter feature eliminates the ambiguity that existed in earlier experiments using foilless diodes.[6] Recent observations of very weak x-ray production and paramagnetic signals indicate that only a weak beam, if any, was present in the foilless diode experiments and the observed heating was due to plasma currents driven by large axial electric fields within the plasma column.[8]

The experiments have been performed on the Cornell turbulent heating machine (THM) modified by the addition of a relativistic electron-beam accelerator.[6] A plasmoid is injected into a magnetic mirror trap where a plasma column is formed having a length of 1.8 m, a mean diameter of 6–10 cm, and a density that can be varied from 10^{12} to 6×10^{13} cm^{-3} on axis. It is confined by a 2.6-kG magnetic field in a cylindrical vacuum chamber of 40 cm. The device has the capability of heating the plasma column by the axial injection of a relativistic electron beam and by the application of a large axial electric field which produces current-driven turbulent heating.[9] The beam heating experiments are the subject of this paper.

The electron-beam accelerator consists of a Marx generator driving a 5.8-Ω, water-filled, coaxial pulse line which feeds a diode. It is capable of producing an 80-kA pulse of 500-keV elec-

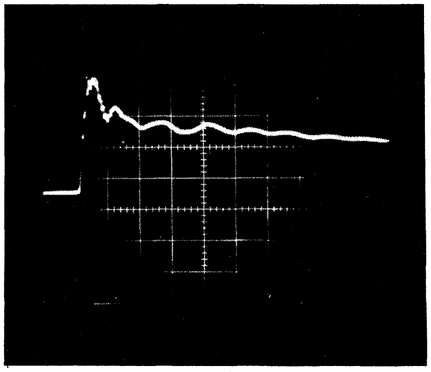

FIG. 1. Typical diamagnetic loop signal. Sweep speed is 200 nsec/(large) div.

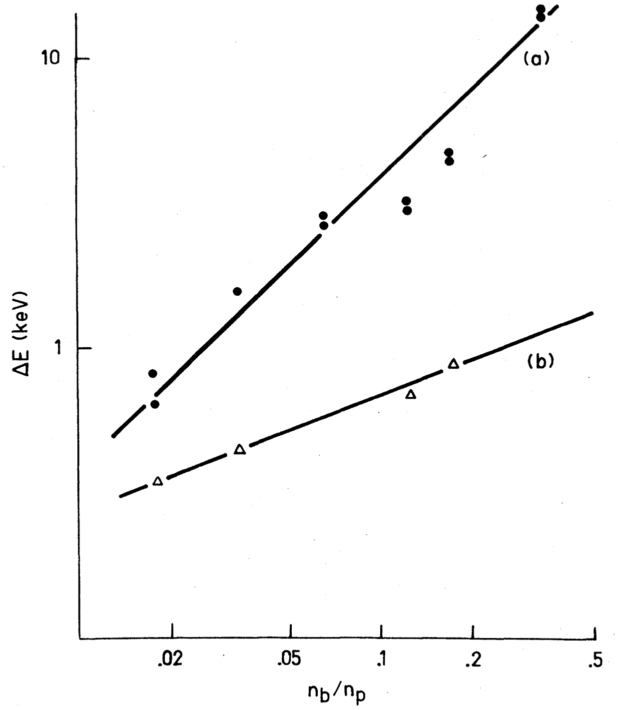

FIG. 2. The increase in net perpendicular energy per electron-ion pair (curve *a*) and perpendicular ion energy (curve *b*) versus the beam-to-plasma density ratio n_b/n_p. These data obtained by varying the plasma density with the beam parameters held fixed.

trons lasting 60 nsec; however, the beam currents in these experiments did not exceed 45 kA. The diode is located at the peak of the downstream magnetic mirror field and consists of a tungsten-coated aluminum cathode and a thin metal anode foil. Several foil thicknesses have been used, ranging from 12.5-μm aluminized Mylar to 50-μm titanium. In most of the experiments the initial beam diameter is 3 cm expanding to about 6 cm in the midplane of the trap. The plasma is monitored with 4- and 8-mm microwave interferometers, fast diamagnetic loops, capacitive wall probes, magnetic probes, charge-exchange neutral-energy analyzers, and x radiation from targets inserted into the plasma. The net plasma heating is determined from the diamagnetic loop output which measures the perpendicular energy transferred to the plasma. A typical oscilloscope trace of the diamagnetic loop output is shown in Fig. 1. The energy increase per electron-ion pair is shown in Fig. 2, curve *a*, as a function of the beam-to-plasma density ratio n_b/n_p. The dependence of the plasma heating on n_b/n_p is in agreement with observations in other heating experiments[4] and with the results of one-dimensional computer simulation of the relativistic electron-electron beam-plasma interaction.[10] In addition, the data in Fig. 3 show that there exists no threshold beam current for heating. Since magnetic probe observations show that the plasma column is at least 95% magnetically neutralized during the beam transit, these data also indicate that there is no threshold return current for heating in contrast to what has been observed in current-driven turbulent heating experiments. There currents in excess of 8 kA were required to produce significant heating.[11] Even when the plasma column was preheated by current-driven turbulent heating, no sharp threshold for beam heating was observed. Furthermore, the rate of plasma heating in the beam heating experiments is at least an order of magnitude greater than that observed in current-driven turbulent heating experiments on the same plasma column at comparable current levels. These observa-

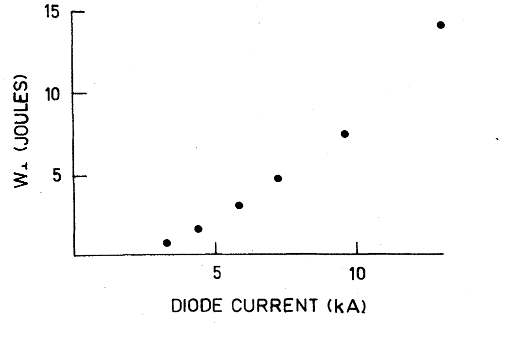

FIG. 3. The net perpendicular energy transferred to the plasma as a function of the diode current.

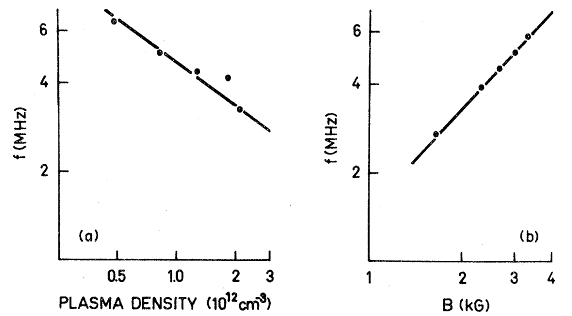

FIG. 4. Frequency of plasma column oscillations versus (a) plasma density and (b) magnetic field. The currents plotted in (a) and (b) are proportional to $n_p^{-1/2}$ and B, respectively.

tions indicate that the electron-electron two-stream interaction dominates the return-current interaction in these experiments. Under these circumstances most of the energy deposited in the plasma should show up in the electron distribution with little heating of ions. However, energy analyses of the charge-exchange neutrals escaping from the plasma column indicate that the ion energies, which are shown in Fig. 2, curve *b*, are comparable to the electron temperatures. It appears that ion heating occurs during a second stage after the electrons have been heated. The preferential electron heating results in the formation of positive plasma potentials of several kilovolts which have been observed with capacitive wall probes. The dominant radial electric field then accelerates the ions outward producing heating as the directed ion energies are randomized.[12]

The initial radial ion momentum leads to the excitation of $m = 0$ oscillations of the plasma column which are clearly evident on the signals from the diamagnetic loops (see Fig. 1). The frequencies observed are generally slightly greater than the ion-cyclotron frequency, i.e., $\Omega_i < \omega < 4\Omega_i$, where ω is the angular oscillation frequency and Ω_i is the ion-cyclotron frequency in the midplane. With the ordering of frequencies $(\Omega_i \ll \omega_{pi} \ll \Omega_e \ll \omega_{pe})$ which exists in the experiment, the angular frequency of radial oscillations for a magnetized plasma column is approximately[12,13] $\omega \propto V_A$, where the proportionality constant depends on the relative magnitudes of $k_\parallel$ and $k_\perp$. Here Ω_e is the electron-cyclotron frequency in the midplane, ω_{pi} and ω_{pe} are the ion and electron plasma frequencies, respectively, $k_\parallel$ and $k_\perp$ are the components of the wave vector parallel and perpendicular to the magnetic field, V_A is the Alfvén velocity $V_A = B/(4\pi n_p M_i)^{1/2}$, and n_p is the plasma density. The observed oscillation frequencies, plotted in Fig. 4, indeed show the expected dependences on both the magnetic field and the plasma density. The radial oscillations damp out in less than 2 μsec indicating that the radial ion motion is being randomized on that time scale. A time-dependent angular analysis of the charge-exchange neutral flux escaping from the plasma verifies this most clearly at low plasma densities, where energetic ions are observed in the radial direction, i.e., 90° to the magnetic field, immediately after beam heating. However there is a time lag of ~2 μsec before the maximum flux of energetic ions is observed at an angle of 110°. The mechanism responsible for the ion scattering has not been identified.

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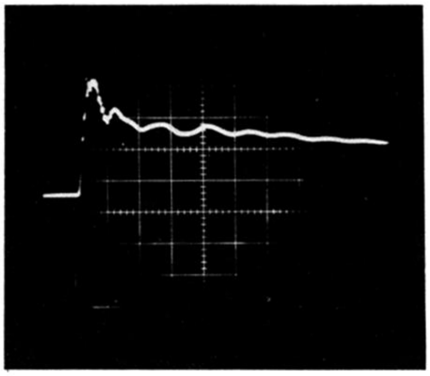

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