

reflex tetrode. With this device, it might be possible to exceed significantly the 200-kA usable proton current produced with a coaxial reflex triode on the Gamble II generator.¹

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Anomalous Electron-Ion Energy Transfer in a Relativistic-Electron-Beam-Heated Plasma

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Studies at Cornell University show experimental evidence for an anomalous electron-ion energy transfer in a relativistic-electron-beam-heated plasma that is 10^3 times faster than can be predicted by classical processes. Electron cooling, ion heating, and a constant total plasma perpendicular energy on a time scale of $\sim 1 \mu\text{sec}$ after electron-beam injection are consistent with an empirically derived electron-ion energy equipartition time in the presence of current-driven instabilities.

In recent years, several experimental programs have been implemented to study the potential application of intense relativistic-electron beams to controlled thermonuclear fusion research.¹ With the capability of delivering several megajoules of energy in times of the order of $1 \mu\text{sec}$ or less, one of the more promising applications of a relativistic-electron beam is the rapid heating of a magnetically confined linear plasma.² Experimental results to date indicate the beam-to-plasma energy transfer is far faster than can be explained by classical processes. While several theoretical mechanisms have been suggested,³ that which is believed to be responsible for the beam-plasma coupling in most experiments is the electron-electron two-stream instability.^{3,4} Unfortunately, this mechanism has the undesirable

characteristic for application to controlled fusion that it heats primarily plasma electrons instead of ions. Ion heating is possible via other mechanisms, such as excitation of the ion-acoustic instability^{3,5} or generation of large-amplitude magnetosonic waves.^{6,7} However, it is probable that these mechanisms alone cannot provide the ion heating required by a high-density linear reactor system.² In this Letter, experimental evidence is presented for an observed anomalous electron-ion energy transfer in a magnetized beam-heated plasma that is approximately 10^3 times faster than classical ($1\text{--}2 \mu\text{sec}$ at an initial electron temperature and density of $T_{e\perp} = 300 \text{ eV}$ and $n_p = 4.5 \times 10^{13} \text{ cm}^{-3}$, respectively).

The Cornell University experimental facility used in the present study is shown in Fig. 1, and

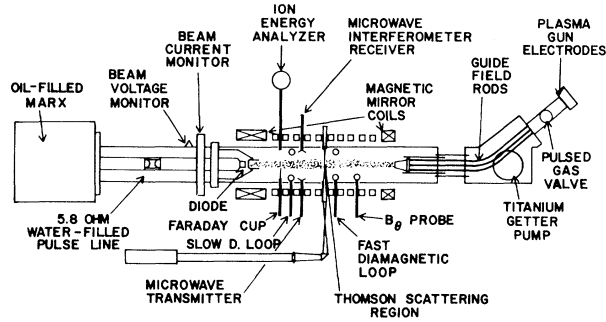


FIG. 1. The Cornell University relativistic-electron-beam-plasma experimental facility.

described in detail elsewhere.^{7,8} The work reported here extends the previous work by Ekdahl *et al.*⁷ to include Thomson-scattering measurements of n_p and $f_e(v_\perp)$, results in a density regime where the magnetosonic oscillations are no longer observed, and a study of the plasma energy partitioning as a function of time. The fully ionized cylindrical target plasma (150 cm long $\times$ 7 cm in diam), of initial peak electron density of $n_p = 4.5 \times 10^{13} \text{ cm}^{-3}$, and temperature $T_{e\perp} = 25 \text{ eV}$, is produced by a modified conical gun and injected through a curved hexapole guide field into a solenoidal 2:1 magnetic mirror trap (B_0 at the midplane = 2.6 kG). The resulting plasma column is 100% ionized, free of impurities, and confined by hard vacuum ($P \leq 2 \times 10^{-6} \text{ Torr}$) from the 40-cm-diam stainless-steel vacuum-chamber wall. The relativistic-electron beam is produced by an oil-insulated Marx generator driving a 5.9- Ω water-field-emission diode. The latter is composed of a 2.5-cm-radius carbon cathode and a 50- μm -thick Ti anode foil. The electron beam is injected into the peak of the upstream (opposite to plasma injection) mirror, which results in a beam diameter of $\sim 7 \text{ cm}$ at the midplane. Throughout these experiments, typical beam parameters were $V = 350 \text{ kV}$, $I = 22 \text{ kA}$, $t = 60 \text{ nsec}$ FWHM (full width at half-maximum). Plasma diagnostics include a ruby-laser-light Thomson scattering system,⁸ several diamagnetic loops, a 4-mm microwave interferometer, a charge-exchange neutral-particle energy analyzer,⁹ and hard-x-ray studies.¹⁰ The Thomson-scattering system, ion-energy analyzer, and one diamagnetic loop probed the plasma within 20 cm of the mirror midplane.

The partitioning of the plasma perpendicular energy is plotted as a function of time after electron-beam injection in Fig. 2. The upper curve

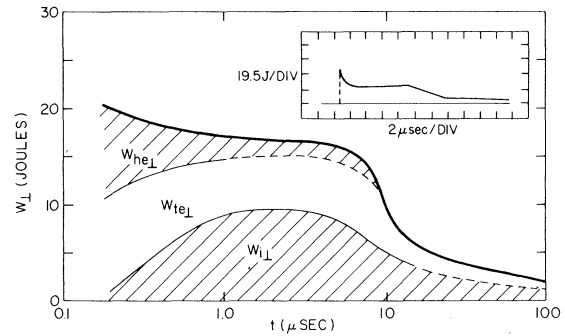


FIG. 2. Summary of the plasma perpendicular energy as a function of time after electron-beam injection. $W_\perp$ is the total plasma perpendicular energy, and the components $W_{he\perp}$, $W_{te\perp}$ and $W_{i\perp}$ are representative of the nonthermal plasma electron, thermal plasma electron, and plasma-ion perpendicular energies, respectively. A typical diamagnetic-loop trace is shown in the inset.

represents $W_\perp$, the total plasma perpendicular energy. The curve was compiled from sixteen diamagnetic-loop traces after compensating each for the contribution from trapped beam electrons, as determined by hard-x-ray studies. Each trace was normalized to give $W_\perp = 17.8 \text{ J}$ (the mean) at $t = 600 \text{ nsec}$. Comparison with a typical diamagnetic-loop trace shown in the upper right-hand corner of Fig. 2 shows the trapped-beam-electron contribution accounted for less than 10% of the observed diamagnetic signal and was significant only at times $t < 1 \mu\text{sec}$. The region indicated as $W_{te\perp}$ was obtained by multiplying the thermal electron energy density, $n_p k T_{e\perp}$ (from Thomson scattering), by the volume of the plasma column, $\pi r_p^2 l$, where r_p and l are the column radius and length, respectively. The use of the entire column length was justified as diamagnetic loops placed at different axial positions showed no variations in the plasma heating or risetime. At $t = 200 \text{ nsec}$, typical values were $T_{e\perp} = 300 \text{ eV}$, $n_p = 4.5 \times 10^{13} \text{ cm}^{-3}$, and $W_{te\perp} = 9.4 \text{ J} = 0.55 W_\perp$. The region in Fig. 2 labeled $W_{he\perp}$ is the contribution to $W_\perp$ from a nonthermal (high-energy) plasma electron component, as observed by Thomson scattering.⁸ Approximately 30% of the indicated $W_{he\perp}$ was estimated, since such a high-energy "tail," while constituting an appreciable fraction of the total plasma perpendicular energy, contains an insufficient number of electrons per unit energy interval to enable full analysis by Thomson scattering. For this reason, scattering signals were obtained only from those electrons with energies $E \lesssim 670 \text{ eV}$; a detector centered at $E = 811$

eV yielded an ambiguous signal. $W_{he\perp}$ was estimated by constructing a high-energy Maxwellian tail, such that scattering from electrons in this distribution would be consistent with the observed data at $E \lesssim 670$ eV and below the plasma background light level at $E = 811$ eV. The resulting high-energy component is found to have a characteristic temperature of 900 eV and contain approximately 20% of the plasma electrons at $t = 200$ nsec, decreasing to 350 eV and 15% at $t = 600$ nsec. Plasma background light prevented Thomson-scattering measurements at times $t < 200$ nsec, whereas the decreasing plasma density after beam injection precluded analysis of the high-energy tail at $t > 600$ nsec and the Maxwellian component at $t > 12$ μ sec. The estimated contributions of $W_{te\perp}$ and $W_{he\perp}$ in these regions are indicated by the dotted lines. The observed rapid decrease in $W_{\perp}$ at $t \sim 8$ μ sec is believed to be due to the sudden loss of these nonthermal electrons, whereas the late time decay of $W_{\perp}$ is thought to be due to either charge-exchange losses or scattering into the mirror loss cone. These results are discussed in detail elsewhere.⁷

From Fig. 2, it can be seen that at times close to electron-beam injection ($t < 200$ nsec), the plasma electrons contain almost all the plasma perpendicular energy, i.e.,

$$W_{e\perp} \equiv W_{he\perp} + W_{te\perp} \cong W_{\perp},$$

an observation consistent with those theories that predict the relativistic-beam energy is coupled primarily to the plasma electrons.^{3,4} However, at $t = 600$ nsec after beam injection, the electrons contain only 48% of the plasma perpendicular energy. This result suggests a transfer of energy between electrons and ions. The region indicated as $W_{i\perp}$ in Fig. 2 is representative of the plasma-ion perpendicular energy, obtained from the difference $W_{\perp} - W_{e\perp}$. Measurements with a charge-exchange neutral-particle energy analyzer yield ion temperatures of $T_{i\perp} \sim 350$ eV, in support of this claim.⁹ Whether this temperature corresponded to a Maxwellian distribution or a component of a high-energy tail could not be ascertained due to experimental limitations. However, assuming this measurement to be representative of an average ion temperature, it is sufficient to account for the remainder of the plasma perpendicular energy. Since primarily plasma electrons were heated during the beam pulse, these measurements indicated a significant electron-ion energy transfer had taken place.

Three possible mechanisms have been suggested as being responsible for this observed anomalous electron-ion energy transfer in a time of ~ 1 μ sec; (1) the excitation and dissipation of large-amplitude magnetosonic waves,⁶ (2) plasma turbulence induced by a lower-hybrid drift instability (excited by a cross-field plasma-electron drift,¹¹) or (3) plasma turbulence induced by an ion-acoustic instability (excited by a drift parallel to the magnetic field).

Ion heating via large-amplitude magnetosonic waves is not a viable mechanism in this regime. Calculations show $\beta \equiv n_p k T_{e\perp} / B_0^2 / 2\mu_0 \leq 0.05 \ll 1$, indicating the plasma pressure was not sufficient to result in significant radial expansion against the magnetic field lines. Moreover the fast rise, continuous decay, and lack of any oscillatory behavior in the diamagnetic-loop signals (see inset in Fig. 2) which were observed at lower plasma densities⁷ precludes the importance of this mechanism.

The plasma was expected to be unstable to the lower-hybrid drift mode, as the diamagnetic (cross-field) drift velocity exceeded the thermal velocity of the unheated ions immediately after beam injection. However, the amount of energy contained in the cross-field currents was sufficient to account for only 5% of the observed increase in $W_{i\perp}$.

The transfer mechanism was probably facilitated by turbulence induced in the plasma. B_0 probe measurements indicated the net current, I_{net} , was approximately 300 A at the termination of beam pulse. Assuming this current is carried by a fraction of the plasma electrons, this value is sufficient for $v_d \approx c_s$ during this phase, where v_d is the electron-drift velocity and c_s is the plasma sound speed. Moreover, since primarily plasma electrons were heated by the electron beam, T_e would exceed T_i , and the plasma would be unstable to the growth of ion-acoustic waves. The presence of plasma turbulence was manifested by the observed rapid radial expansion of the plasma column, as depicted in Fig. 3, which shows the rapid decrease in plasma density on axis (determined by Thomson scattering) during the first 2 μ sec after beam injection. Assuming the total number of plasma particles remained constant over this period (which is short compared to the 90° scattering time for a 300-eV electron) this decay corresponds to a radial expansion from $r_p = 3.5$ cm to $r_p = 7$ cm in $\tau = 2$ μ sec. Calculations of the anomalous resistivity, η^* , using this data and the expression for the cross-

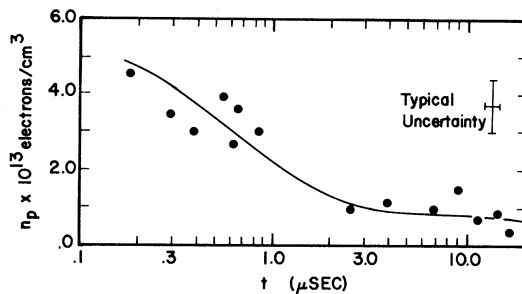


FIG. 3. Electron density n_p vs time after electron-beam injection.

field magnetic diffusion time yield

$$\eta^* = \frac{4\pi(\Delta_r)^2}{\tau c^2} = 1.2 \times 10^{-13} \text{ sec} \sim 10^3 \eta_s,$$

where η_s is the classical cross-field Spitzer resistivity at $T_e = 300$ eV.

The classical electron-ion energy relaxation time (in hydrogen) is approximately 1836 times the classical momentum relaxation time. If it is assumed, without particular justification, that this relationship is valid for the anomalous relaxation times in a turbulent plasma, then expressing the anomalous momentum-transfer collision frequency in terms of the anomalous resistivity, $\nu^* = \eta^* \omega_{pe}^2 / 4\pi$, where $\eta^* = 1.2 \times 10^{-13}$ sec, gives an energy relaxation time τ_E of

$$\tau_E = 1836 / \nu^* = 1.7 \times 10^{-6} \text{ sec}.$$

This value is comparable to the decay time of $W_{e\perp}$ represented in Fig. 2 (approximately 1 μsec), suggesting that some anomalous electron-ion energy transfer, scaling as the anomalous turbulent collision frequency, is taking place.

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