systems. For very low Z ($Z\sim 2$), the 2s level of neon is deeper lying than is the 1s level of the projectile; hence the correlations will be changed, and a greater possibility of ionization of neon 2s and 2p electrons from two different channels must be expected.

The features of the singlet-to-triplet ratio shown in Fig. 1 can thus be explained qualitatively, and this is the first comprehensive experimental evidence for the new correlation rules suggested by Eichler *et al.*[6] In conclusion, the present experimental results can be understood when no dependence of the electron spin is assumed but rather a distinction between double ionization via *one channel* and via *two channels*. Further studies of the ratio of multiplet intensities may thus reveal the relative importance of different quasimolecular couplings, and they can be used as a detailed test of the MO model.

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Observations of Turbulent Resistivity at High Drift Velocities

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Resistivity and electron heating are measured for a hydrogen plasma in a toroidal magnetic field subjected to a parallel electric field at least 100 times the runaway value and lasting up to $400\omega_{pi}^{-1}$. Nearly constant in time, and scaling as $E^{1/2}$, the resistivity reaches values near $2(m/M)^{1/3}\omega_{pe}^{-1}$. Particle analyzer data reveal heating rates up to 100 keV/μs and indicate the presence of multiple electron beams at higher applied fields.

If a plasma is subjected to an electric field exceeding the Dreicer[1] runaway value, E_r, the electrons will accelerate until impeded by some instability, giving rise to a turbulent resistivity. In the absence of a magnetic field or in strong fields ($\Omega_{ce}\gg\omega_{pe}$), as considered here, the linear instabilities of significance are the ion-acoustic instability, which begins when the electron drift velocity v_d exceeds the sound speed and has growth rates well below ω_{pi}, and the Buneman instability,[2] which begins when v_d exceeds the electron thermal velocity v_e and has growth rates on the order of ω_{pi}. For applied electric fields moderately greater than E_r, the ion-acoustic instability provides sufficient resistivity to maintain $v_d < v_e$. Extensive experiments in this regime have been reviewed by Coppi and Mazzucato.[3] At higher applied fields, the electrons are accelerated to $v_d \geqslant v_e$ before the acoustic instability can develop, and stronger turbulence develops. Investigations of this regime began with Babykin *et al.*[4] in a linear device. More satisfactory experiments in toroidal devices, which are free of end and sheath effects, include those of Hamberger and Friedman[5] and Hamberger[6] which yielded values of resistivity $\eta\propto(m/M)^{1/3}\omega_{pe}^{-1}$, typical of the Buneman instability. Similar experiments by Hirose *et al.*[7] also found anomalous resistivity, but the mechanism appeared to be a beam-plasma instability. A more recent experiment by Hirose and Skarsgard[8] has dealt with a regime of slightly lower fields where $v_d\sim v_e$. Here, the results tend to differ qualitatively from previous work: The initial free acceleration quickly ends with the onset of turbulence, but the electrons continue to accelerate at one quarter of the free rate maintaining $v_e\sim v_d$, a result similar to that of the computer simulations.[9] The present experiments extend the observations of the high-applied-field regime by measuring the resistivity over two decades in field strength and by determining the resistivity as a function of time for the simplest case of constant applied field and for periods long compared with the characteristic times of the instability, thus giving evidence of a quasistationary turbulent resistive state.

The apparatus consists of a toroidal copper vacuum vessel of 6-cm minor radius, 68-cm major radius, and 3-mm wall thickness which is divided into quadrants by ceramic insulators. The toroidal magnetic field (< 1 kG) is provided by a set of 32 large-aperture coils; field ripple is held to 0.5% or less. A continuous electron-cyclotron-resonance discharge, which is energized by several hundred watts of microwave power at 2.5 GHz, produces the plasma. Hydrogen plasmas of densities $n \sim 2\times10^{10}$ cm^{-3} and generally flat profiles are obtained at filling pressures of 0.1 mTorr. The plasma radius of 4 cm is set by a limiter. The discharge temperature and density profiles are taken by a Langmuir probe[10] and electron line densities are monitored during the pulse by an X-band interferometer. The electric field is applied by switching a 2-μF or a 25-μF capacitor (termed the fast- and slow-pulse capacitors, respectively) across the torus quadrants in parallel. The torus then serves as the primary of an air-core transformer with the plasma as a secondary. Transmission lines to the gaps are designed so that the fringing magnetic field generated by the feed currents is quadrupole with a null on the toroidal axis. At the maximum fast- (slow-) pulse charging voltage of 40 kV (4 kV), an electric field of 100 V/cm (10 V/cm) is applied to the plasma, far greater than $E_r \sim 10^{-2}$ V/cm.

In contrast with most turbulent heating experiments, in which the density is sufficiently high that skin effects enter and inductive effects vary the field seen by the plasma, this experiment closely approximates the ideal case of a constant, uniform field applied to a plasma. The skin depth exceeds the plasma radius ($c/\omega_{pe} \sim 4$ cm), and the applied field remains nearly constant for times very long compared with the two-stream growth time of $\sim \omega_{pi}^{-1}$.

Typical wave forms for the applied field, plasma current, and inferred resistivity are shown in Fig. 1. The plasma current rises rapidly at a rate which corresponds closely to free-electron acceleration. This acceleration is soon ended, and the current thereafter remains nearly constant or increases slowly (at lower applied fields). After the acceleration ends, a resistivity may be calculated directly from $\eta = EA_p/I_p$, where A_p is the plasma area and I_p is the current. Periods of slow acceleration begin to develop as the electric field drops below 10 V/cm. The acceleration varies from 5% to 25% of the free rate, which is qualitatively similar to the results of Hirose and Skarsgard mentioned above. The average resistivity and the corresponding value of v_d, scaled to the initial thermal velocity, are plotted as a function of electric field strength in Fig. 2. The scaling appears to be $\eta \propto E^{1/2}$ over the entire range of E. The existence of such a simple power law is remarkable, especially over such a broad range of plasma parameters. No "plateau" regions in $\eta(E)$ resembling those reported by Demidov, Elagin, and Fanchenko[11] are observed in this experiment. Maximum values for η are near $2(m/M)^{1/3}\omega_{pe}^{-1} = 15\ \Omega$ cm at a density of 2

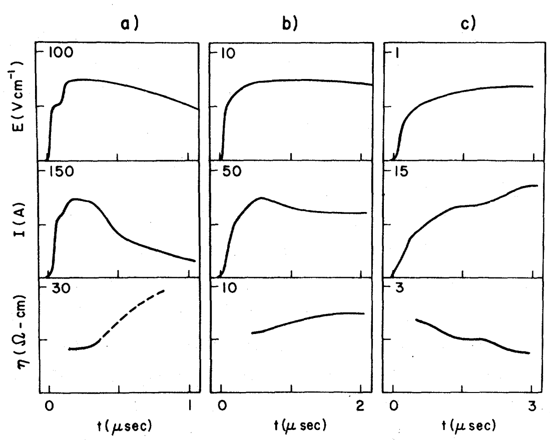

FIG. 1. Representative wave forms for the applied electric field $E(t)$, plasma current $I(t)$, and inferred resistivity $\eta(t)$. Different pulse lengths are obtained by a choice of discharge capacitor and series inductor. Dashed line in (a) indicates that the increasing resistivity is probably due to plasma loss.

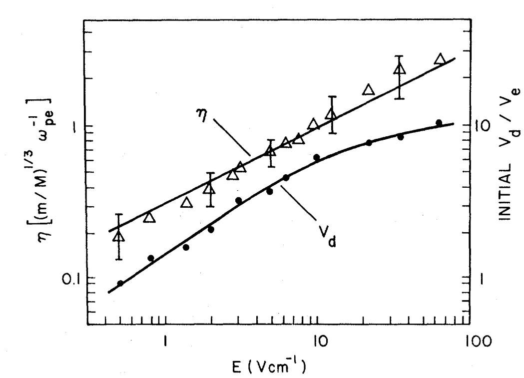

FIG. 2. Average resistivity η, plotted in units of $(m/M)^{1/3}\omega_{pe}^{-1}$, as a function of average applied electric field (runaway field $\sim10^{-2}$ V/cm). The solid line through the triangles shows a $\eta \propto E^{1/2}$ fit. Also plotted is the value of v_d just prior to breakover from free acceleration, normalized to the initial $v_e \sim 2\times10^8$ cm/s; $n_e \sim 2 \times 10^{10}$ cm^{-3}.

$\times 10^{10}$ cm^{-3}. For reference, the value of Spitzer[12] resistivity for our plasma is less than 10^{-2} Ω cm, while that due to electron-neutral collisions is about 5×10^{-2} Ω cm. Initial measurements of the fluctuations using probes reveal a much broader and more complex spectrum than can be attributed to the two-stream instability.

As can be seen from Fig. 1, the plasma response to the applied field can be reasonably characterized as resistive with a value which does not greatly change during the pulse duration of up to $100\omega_{pi}^{-1}$, a time interval sufficient to heat the plasma to temperatures orders of magnitude above its initial temperature. To ascertain that this apparent resistivity was a genuine characteristic of the plasma as its temperature increased and not an artifact caused by rapid losses in the apparatus, direct measurements of the plasma density and energy were made. As measured by the interferometer, the plasma density is generally constant during the pulse. Ionization processes are negligible in this experiment. Only at the higher applied fields, $E \gtrsim 20$ V/cm, is the density observed to fall, indicating loss of containment late in the pulse. As the field is raised, plasma loss begins earlier. At these times, as indicated by a dashed line in Fig. 1(a), the apparent resistivities cannot be taken as indicative of bulk plasma behavior. However, as noted below, loss of containment and cessation of useful results occur only after the plasma has already absorbed considerable energy, sufficient to destroy the equilibrium. Prior to loss, containment is good, and the observed resistivities represent the bulk plasma response.

Determination of energy containment included careful measurements with diamagnetic loops which revealed no signals clearly above noise levels, far below the values inferred for $T_{e\perp}$ if the energy dissipated were isotropized. Since $\Omega_{ce} > \omega_{pe}$ in this experiment, it is possible that little of the energy input would appear as $T_{e\perp}$.

To determine the parallel energy, an electron velocity analyzer of the $\vec{E}\times\vec{B}$ type was placed at the plasma edge to sample (and scrape off) the outer layer. It is similar to the one described by Barr and Perkins,[13] but it employs direct measurement of current as opposed to a scintillation technique. The analyzer has been calibrated with an electron beam and is capable of detecting particles with energies up to 40 keV at a resolution of 10% in velocity. By combining data from many shots, the analyzer yields the full, time-dependent electron velocity distribution with no *a priori* assumptions of general functional form.

By taking the moments of the velocity distribution, one obtains v_d, v_e, and T_e. The fact that the v_d thus determined is consistent with the total observed plasma current gives credence to the assumption that the distribution sampled by the analyzer is representative of the bulk plasma. Figure 3 shows plots of the energy density inferred from the distribution function and compares them with those calculated from the time integral of $\vec{j}\cdot\vec{E}$. Figure 3 also shows the evolution of the ratio $v_d(t)/v_e(t)$. Energy balance obtains and the plasma behaves as a contained, isolated system for times up to the onset of a significant depletion process, which can be either the gross loss of plasma at high fields because of loss of equilibrium at high energy densities or merely the depletion of the outer layer of plasma sampled by the analyzer. Both mechanisms are consistent with longer containment at lower fields. Heating rates approaching 100 keV/μs and $T_e \sim 10$ keV have been recorded. Measurements of the x-ray bremsstrahlung from a small carbon target lend support to the analyzer results. X-ray signals near the plasma boundary (analyzer location) do not differ significantly from those seen across the full plasma diameter. Heating rates

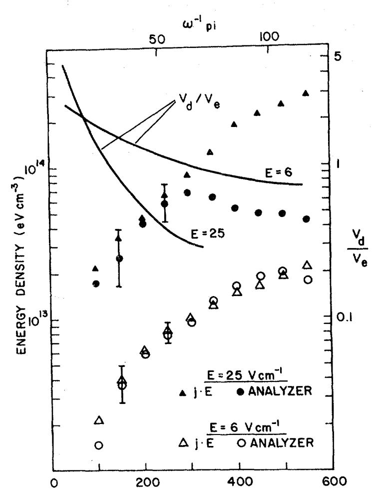

FIG. 3. Time dependence of the total energy density and the ratio $v_d(t)/v_e(t)$ for two values of average applied field. Triangles are the total plasma energy densities inferred from the time integral of $\vec{j}(t)\cdot\vec{E}(t)$. Circles are the total electron parallel energy densities ca calculated from the second moment of the time dependent velocity distributions obtained from an $\vec{E}\times\vec{B}$ particle analyzer. Turnover of the analyzer signal at 300 ns (solid circles) is due mainly to rapid scrape off of the outer plasma layer by the analyzer housing.

also appear to extend to the point that the density begins to decrease. From Fig. 3, it is clear that energy is contained for at least $50\omega_{pi}^{-1}$. The containment times are sufficient to demonstrate that a nearly constant turbulent resistivity is sustained in the plasma as it is heated to temperatures many times its initial temperature; the turbulent resistivity remains even when v_e rises above v_d.

The electron velocity distributions observed generally resemble Maxwellians on a coarse grain, but they exhibit regions of large positive slope (beams) on a fine scale as illustrated in Fig. 4. These beams persist throughout the pulse and occur at reproducible velocities for a given applied field. The stability of such a distribution is clearly not characterized by any parameter as simple as v_d/v_e. The mechanism governing beam formation has not yet been identified. However, at least one computer simulation by DeGroot *et al.*[14] predicts the existence of large potential jumps (double layers) which could generate such electron beams. Although observed in numerous linear devices,[15] the existence of double layers and beams has only been suggested[16] for toroidal geometry. A detailed treatment of the analyzer results will be given in a future publication.

In conclusion, we have found the dynamic response of a hydrogen plasma to electric fields $E \gg E_r$ to be generally a state of nearly constant turbulent resistivity with a value given by $\eta \sim 2(E/50)^{1/2}(m/M)^{1/3}\omega_{pe}^{-1}$(esu), where E is V/cm, and the scaling with E has been observed over two orders of magnitude. The resistivity thus increases with the initial value of v_d/v_e, but it

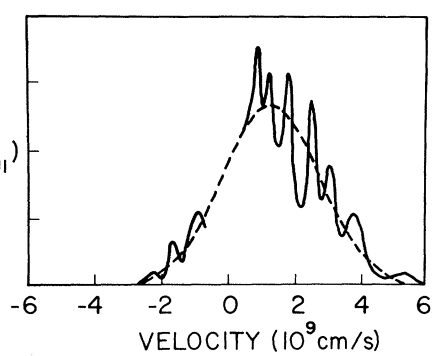

FIG. 4. Typical electron parallel velocity distribution obtained from the $\vec{E}\times\vec{B}$ particle analyzer. Time $t = 600\omega_{pe}^{-1} = 75$ ns from application of a step function electric field of 25 V/cm. Dashed line is a Maxwellian of the same T_e (1200 eV) and v_d.

shows no corresponding decrease during the pulse as v_d/v_e decreases because of rising v_e. The geometry and containment are such that this result should be representative of an infinite, uniform plasma subject to an electric field. A complex and broad fluctuation spectrum coupled with a multibeam velocity distribution, suggest that the nonlinear evolution of the two-stream instability is more complex than had been expected.

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