Experimental Observation of Asymptotic State of Turbulently Heated Electrons*

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The acceleration and heating rates of plasma electrons observed in a toroidal device have demonstrated the existence of an asymptotic state in which the electrons are isotropically heated with a thermal velocity approximately equal to the drift velocity.

The asymptotic behavior of a collisionless plasma in a dc electric field has been theoretically studied by several authors.[1] It is predicted that after being freely accelerated by the electric field, the electrons assume an asymptotic state in which they are continuously accelerated with a smaller rate than free acceleration, and consequently they are turbulently heated. The electron drift and thermal velocities both increase, remaining closely equal in order to maintain conditions beyond threshold for ion wave instability.

This is in contrast to previous predictions[2] that ion-wave instability would stop electrons from being accelerated indefinitely and sustain the electron drift velocity close to the ion acoustic velocity. A detailed experiment has been reported by MacKenzie and co-workers[3] in which they observed initial free acceleration of electrons followed by sudden reduction in the electron drift velocity, in apparent agreement with the theory. Unfortunately, however, the temporal evolution of the electron temperature, the most important plasma parameter to account for the energy balance, was not measured in the experiment, and thus it is not clear if the plasma was in lossless and collisionless conditions. Actually, a similar drift-velocity turnover has been observed in other toroidal experiments,[4] in which the turnover was attributed to rapid electron energy loss.

In this Letter, we report experimental observations of the asymptotic stage for plasma electrons in an electric field ($E \lesssim 10$ V/cm). The experiment is performed in a toroidal device previously described.[4] The main modification in the system is that the vertical magnetic field acting on the plasma ring is now controlable in order to improve the energy containment time of the electrons. An argon plasma is prepared by an rf discharge in a toroidal magnetic field ($\lesssim 2$ kG), before inductively applying an electric field. The quarter period of the electric field has been lengthened (to ~ 5 μsec) by adding an extra inductance so that the dc condition is well satisfied for the present experiment. The plasma density is typically 2×10^{11} cm^{-3}, and the neutral-gas pressure is less than 0.1 mTorr, assuring collisionless conditions in the plasma for at least several microseconds.

Diagnostics employed in the experiment include a Rogowsky coil (plasma current), a 2-cm microwave interferometer (plasma density), an electron energy analyzer[5] (electron temperature perpendicular to the magnetic field), and electrostatic probes (fluctuations).

In Fig. 1 the applied electric field, measured plasma current, and electron temperature perpendicular to the toroidal magnetic field are shown. The average electron drift velocity can be calculated from $u = I/\pi r_p^2 \bar{n} e$, where I is the measured current, r_p is the plasma radius determined by the size of a limiter ($\simeq 2.5$ cm), and $\bar{n}$ is the average plasma density. Figure 2 shows the electron drift velocity expected from free ac-

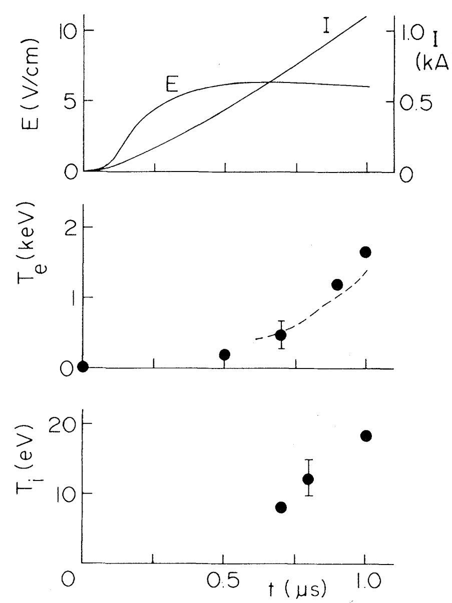

FIG. 1. Applied electric field (E), observed plasma current (I), perpendicular electron temperature (T_e), and ion temperature (T_i) as functions of time up to 1 μsec.

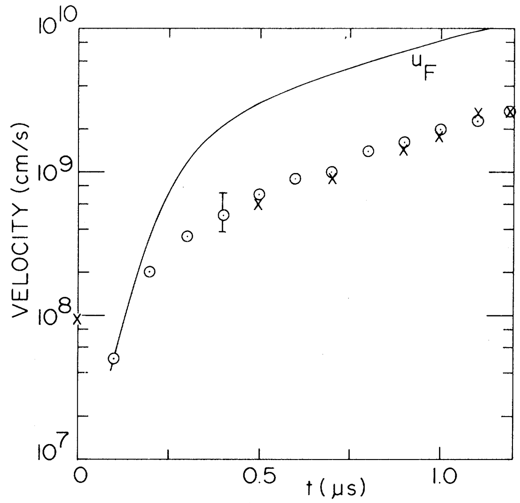

FIG. 2. Expected free-acceleration velocity (U_F), observed drift velocity, (circles), and thermal velocity (crosses) of electrons.

celeration (u_F), the measured actual drift velocity, and the electron thermal velocity $[v_{\rm therm} = (T_e/m)^{1/2}]$ expected from the energy balance condition

$$\frac{d(\frac{1}{2}mu^2+\frac{3}{2}T_e)}{dt}=eEu.$$

It can be seen that the electrons are first accelerated freely for approximately 0.5 μsec. When the drift velocity exceeds the initial thermal velocity by a factor of about 2, the departure from free acceleration occurs, and consequently electron heating takes place. The electron drift velocity continues to increase although it is closely followed by the thermal velocity. The acceleration rate (du/dt) asymptotically approaches one-quarter of the free acceleration rate, and the thermal velocity $v_{\rm therm}$ also follows the same law.

The maximum effective collision frequency accounting for the observed acceleration rate is $\nu_{\rm eff} \sim 2\times10^7$/sec, which is higher than the ordinary electron-ion or electron-neutral collision frequency by a factor of 10. However, $\nu_{\rm eff}$ decreases with time, and in the asymptotic regime $\nu_{\rm eff} \propto t^{-1}$. Since the electron-neutral collision frequency is rather insensitive to the electron energy above 15 eV, the turbulence-induced collision frequency is finally exceeded by the binary collision frequency, and the electron drift velocity saturates.

Figure 3 shows the observed acceleration rates (du/dt) normalized by the rate corresponding to

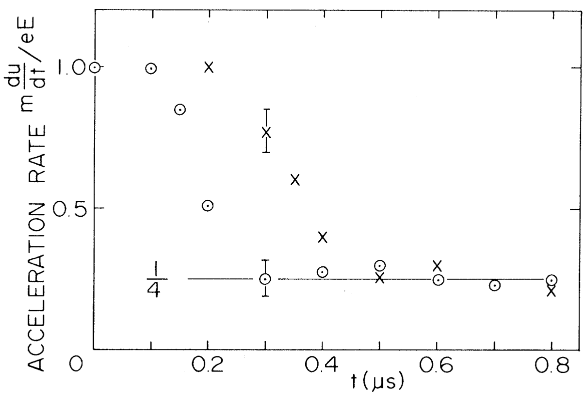

FIG. 3. Observed acceleration rate normalized by the free-acceleration rate for two different electric fields: × for 3 V/cm and ⊙ for 6-V/cm peak electric fields.

the free acceleration (eE/m) for various electric fields. The departure from free acceleration occurs earlier as the electric field is increased. This is expected since the time at which the drift velocity overtakes the initial thermal velocity becomes shorter at higher electric fields, and, as will be shown later, turbulence develops only after this crossover. Although the time of departure from free acceleration depends on the electric field, the acceleration rates asymptotically approach approximately one-quarter of the free acceleration rates for the electric fields (0.5 to 5 V/cm) applied in the experiment. The observed general behavior is quite insensitive to the toroidal magnetic field which was varied from 0.5 to 2.5 kG.

Figure 4 shows an example of the instability observed on electrostatic probes. It is evident that the instability starts to grow after the electron drift velocity well exceeds the initial thermal velocity. The amplitude saturates after only a few oscillation periods and subsequently a stochastic behavior rapidly develops. The frequency spectrum of the instability is dominated by components around ω_{pi}, the ion plasma frequency. Since the electron drift velocity never exceeds the thermal velocity by more than a factor of 2, it is expected that the frequency having the maximum growth rate is always close to ω_{pi}.[6]

Cross-correlation measurements carried out by using two asymmetric probes indicate that no preferential angle in space exists for the instability, i.e., the spectrum is quite isotropic in the hemispherical region whose axis is in the direction of the electron drift velocity. This is under-

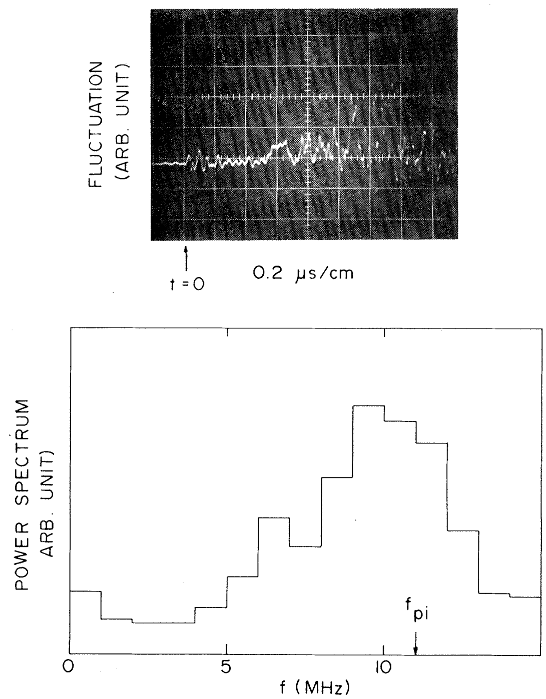

FIG. 4. Fluctuations observed by an electric probe (top) and calculated power spectrum (bottom). Average of eight oscillograms was taken for calculation of the spectrum.

standable if we notice that the unstable Cherenkov angle is close to $\pi/2$, and the growth rate is not too sensitive to the propagation angle. That the ion waves with frequency higher than the ion cyclotron frequency can propagate at almost arbitrary angles to the magnetic field has been experimentally verified[7] previously.

In the present experiment, the electron distribution function parallel to the magnetic field has not been measured. However, since the measured perpendicular electron thermal velocity satisfies the energy balance equation assuming equipartition of energy among the three degrees of freedom, it is concluded that the electron thermal velocity parallel to the magnetic field cannot differ appreciably from the perpendicular ones.

The fact that energy balance is observed for relatively long periods of time also indicates that the energy density of the fluctuations is almost negligible compared with the kinetic energies of the electrons. This is especially true at later times when the electron temperature keeps on increasing while the observed fluctuation level stays more or less constant. In the asymptotic regime the effective collision frequency is actually decreasing with time.

The Ar^+ ion temperature was measured by a spectrometer with an instrumental resolution of 0.15 Å. The Ar II 4806-Å line was used. The ion heating rate dT_i/dt is approximately 3.6×10^7 eV/sec (Fig. 1). This is to be compared with the electron heating rate ($\sim4\times10^9$ eV/sec). The ratio between the heating rates is approximately 10^2, which is of the same order as $(M/m)^{1/2}$. Some theoretical studies have predicted a heating ratio of $(M/m)^{1/2}$ for the current-driven ion-wave instability.[8]

In conclusion, we have observed an asymptotic state of a turbulently heated plasma. The electrons are isotropically heated even in a strong magnetic field. In the asymptotic regime, the electrons are accelerated with one-quarter of the free acceleration rate.

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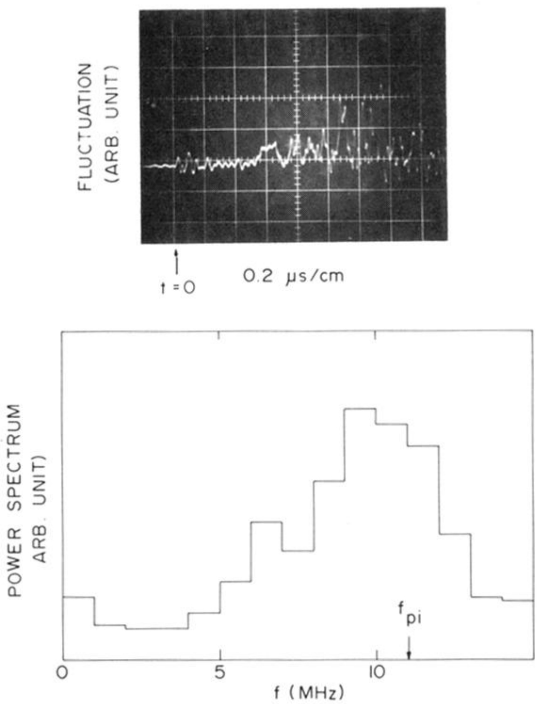

FIG. 4. Fluctuations observed by an electric probe (top) and calculated power spectrum (bottom). Average of eight oscillograms was taken for calculation of the spectrum.