Observation of nonthermal electron tails in an rf excited argon magnetoplasma

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(Received 25 June 1990; accepted 13 December 1990)

Nonthermal beamlike electron tails have been observed in an argon magnetoplasma excited by rf without electron beam injecting. The plasma is highly ionized (~100%) with central density ~10^{14} \text{ cm}^{-3}, and is based on the excitation of helicon waves. Nonthermal electron tails are observed at the beginning of the plasma pulse and last for about 1 msec. There is a maximum in the electron energy distribution at 30-80 eV and a minimum at 20-30 eV. The mechanism responsible for driving this beamlike tail is not yet known.

I. INTRODUCTION

Plasma generation based on rf excitation of helicon waves has attracted attention recently because of its unusually high ionization efficiency.\textsuperscript{1-3} This type of plasma source has been used in plasma wave studies and has now found applications in plasma etching\textsuperscript{4} and in the laser field.\textsuperscript{5}

The helicon is essentially a Hall wave that propagates between the electron and ion gyrofrequencies. Its dispersion relation in cylindrical geometry has been investigated previously\textsuperscript{6,7} (and references therein) and, in the simple case of plane propagation parallel to the magnetic field, reduces to

\[ N^2 \sim \omega_p^2/\omega \omega_{ce}, \]

where \( N \) is the refractive index, \( \omega_p \) is the electron plasma frequency, \( \omega \) is the wave frequency, and \( \omega_{ce} \) is the electron gyrofrequency. For \( \omega/2\pi = 7 \text{ MHz} \), \( N \) is 1 and the free-space wavelength is about 40 m, whereas with this plasma, \( N \) is a few hundred and the wavelength is around 10 cm allowing a half-wavelength antenna to be constructed.

We report here the observation of nonthermal beamlike electron tails during the formation time of such a plasma under various experimental conditions. The observed nonthermal tail can last for ~1 msec. Although the beamlike electron tails have been experimentally studied since the 1970's,\textsuperscript{8-9} such a tail has been only observed in the plasmas with electron beam injecting and normally only for a very short time of the order of 10^{-11} sec. This is the first time, so far as we know, such a distribution is observed in a laboratory plasma without electron beam injecting and for a long time of 1 msec.

Figure 1 shows the plasma apparatus (BASIL) used in this study. A 1.6 m long glass plasma tube of 4.5 cm inner diameter is mounted coaxially to 14 magnetic field coils that can produce an axial magnetic field up to 1600 G. Up to 5 kW of rf power at 7 MHz can be coupled to an external double-loop antenna [Fig. 2(a)] that excites helicon waves in the plasma. The plasma has a nearly 100% ionization core of ~1 cm diameter with a central density ~10^{14} \text{ cm}^{-3}. More details of the plasma can be obtained in Ref. 10. The experiments were carried out under the following conditions: working gas, argon; filling pressure, 1 Pa; input rf power, 1.5-5 kW, 7 MHz, and axial magnetic field, 400-1400 G.

The electron energy distribution is derived from the characteristics of a single Langmuir probe. Under certain plasma operation conditions, there is clearly a bump and a minimum in the energy distribution, centered at 30-80 and 20-30 eV, respectively.

Section II of this paper discusses the probe characteristics measured in the plasma and Sec. III presents the experimental results. The last section is a summary of the results.

II. PROBE CHARACTERISTICS

The electron energy distribution was measured by a negatively biased single Langmuir probe. The 2 mm long probe, which is mounted 16 cm away from the antenna, is made of a tungsten wire of 0.3 mm diameter and can be moved radially from the plasma tube [Fig. 2(b)].

To correctly interpret the probe traces, the effect of the magnetic field and rf oscillating fields on the probe characteristic has to be considered. The rf field in the plasma will cause an oscillation in probe potential with respect to the plasma. This effect can be minimized by carefully choosing the diagnostic position near the helicon wave node, where the rf field has its minimum value. In a plasma with a mag-

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**FIG. 1.** Experimental apparatus.
Vacuum seal

FIG. 2. The construction of the (a) antenna and (b) Langmuir probe.

netic field, the probe characteristic would also be affected if the gyroradii of the charged particles \( (p_e) \) are much smaller than the radius of the probe \( (r_p) \). Table I gives \( p_e/r_p \) as a function of the energy of the charged particles for \( B_0 = 800 \) G, the typical magnetic field applied. From Table I, assuming \( p_e/r_p > 1 \) is required to neglect the effect of the magnetic field, we can find that the probe characteristic will not be strongly affected by the magnetic field if the probe potential is more negative than \( \sim -20 \) V. For less negative probe potentials, the effect of the magnetic field can cause serious distortions that would be difficult to interpret. Hence this simple probe is not appropriate for studying low-energy electrons but is suitable for studying high-energy electrons and hence is suitable for studying the electron tail.

A typical probe characteristic obtained from the BASIL plasma (Fig. 3) can be divided into four regions (Secs. II A–II D).

A. Positive ion collection region

In this region, the probe is so strongly negatively biased \( (V_{bias} < -70 \) V) that few electrons can penetrate the probe sheath. The characteristic is mainly determined by positive ion current and is nearly independent of the form of the electron distribution, provided the distribution is not too far from Maxwellian. Since the trajectory of the heavy ions is mainly determined by the applied potential for this small probe, the magnetic field has little effect on the characteristic. The ion current detected is proportional to the electron density for singly ionized ions, provided that the ion temperature is much less than the electron temperature, as follows:

\[
I_e = 0.5 n_e e (k T_e/m_e)^{1/2} A_1
\]

where \( A_1 \) is the area of the sheath surface, which does not differ very much from the area of the probe for the normal case, although there is some slow increase in \( A_1 \) as the probe is made more negative. This means \( I_e \) is only very weakly dependent on the probe potential so the effect of the rf field inside the plasma on the characteristic is negligible. The characteristic in this region can then be used to estimate the electron density:

\[
n_e = (2I_e/eA_1) (m_e/k T_e)^{1/2}
\]

B. Nonthermal fast electron collection region

In this region, the probe potential with respect to the plasma is still sufficiently negative \( (-70 \) V \( \leq V_{bias} \leq -15 \) V) such that only very fast electrons can reach the surface of the probe. It is this part that provides information on the nonthermal electron tail since the number of thermal electrons in this energy range is negligible. It has been found that a calculated characteristic for a plasma that includes an electron beam can fit the measured characteristic quite well. The probe electron current for an electron beam escaping the plasma can be written as

\[
I_e = e n_b \sqrt{k T_e/2 \pi m_e} \exp(-x_m^2)
+ (e n_b v_b/2)[1 + \text{erf}(x_m)],
\]

where

\[
\text{erf}(x_m) = \frac{2}{\sqrt{\pi}} \int_0^{x_m} \exp(-x^2) dx,
\]

and

\[
x_m = \sqrt{E_b/k T_e} - \frac{1}{\sqrt{e}} |V_{pp}|/k T_e,
\]

### TABLE I. \( p_e/r_p \) for \( B_0 = 800 \) G.

<table>
<thead>
<tr>
<th>Type of charged particles</th>
<th>Energy range (eV)</th>
<th>( p_e/r_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0–10</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.63–0.88</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>0.88–1.25</td>
</tr>
<tr>
<td></td>
<td>40–100</td>
<td>1.25–2</td>
</tr>
<tr>
<td>Ar⁺ ion</td>
<td>0.5–1</td>
<td>38–53.75</td>
</tr>
</tbody>
</table>

FIG. 3. The probe characteristics measured at the axis of the plasma at \( t = 0.5 \) msec, \( B_0 = 750 \) G, and input rf power of 3.5 kW.
where $E_b$ is the beam energy, $V_p$ is the probe potential with respect to the plasma, and $v_b$ is the beam velocity. Note that $T_b$, the beam temperature, is a measure of the beam thermal spread and can be written as:

$$T_b \approx \Delta E_b (\Delta E_b / 4E_b),$$

(6)

where $\Delta E_b$ is the spread in the beam energy that corresponds to the half-width of the beam distribution at the $e^{-1}$ point.

The effect of the magnetic field on this part of the probe characteristic is not strong since the gyroradius of these fast electrons is about twice the probe radius. The derivative of the probe current with respect to the probe potential, is relatively small, so rf fields do not play a major role since the uncertainty of the probe current due to the rf is proportional to the derivative of the current as follows:

$$\Delta I = \frac{dI}{dV} \Delta V,$$

where $\Delta V$ is the rf level. In this region, an uncertainty of only a few eV drift in the electron energy could be involved because of the effect of the rf field. The potential variation due to the rf field has been experimentally estimated as $\sim 3$ V.

### C. Thermal electron collection region

The probe is still negatively biased in this region ($-15 \leq V_b < -7$ V). Some thermal electrons with high energy ($\sim 20$ eV) can reach the surface of the probe. It is these thermal tail electrons that dominate the probe current in the characteristic. One can expect to get some information about the bulk electron temperature from this part.

However, there are several factors that may cause considerable errors in determining the bulk electron temperature. First, those thermal electrons that can be collected are only a small fraction of the bulk electrons, and the distribution function is very likely to be distorted in some way. Second, as the gyroradii of the electrons in this energy range are of the same order as the probe radius, the magnetic field will have some effect on the probe characteristic. The effect of the rf field is also larger than in regions A and B since the derivative of the current with respect to probe potential is no longer negligible. Hence only a rough estimate of the bulk electron temperature can be expected.

### D. The bulk electron region

When the probe potential with respect to the plasma is made less negative ($V_b > -7$ V), bulk electrons with low energy can be collected by the Langmuir probe. However, the probe characteristic is strongly affected by the magnetic field since the gyroradii of these slow electrons is much smaller than the probe radius. The characteristic can be used to determine the bulk electron temperature only in those cases where such a weak magnetic field is applied that their gyroradii is similar to the probe radius. In BASIL, this requires a magnetic field smaller than 500 G.

From the above discussion, it is clear that, although the theory of the probe characteristic for this plasma is quite complicated, the saturated ion current can still be easily identified. The extraction of the ion current from the characteristic is not difficult in practice, hence particular attention need only be paid to the electron current. In a magnetized plasma, since a Langmuir probe will collect all those electrons that are traveling along the magnetic field, one can consider a one-dimensional case for simplicity. Although Langmuir probe theory normally becomes very complicated when a non-Maxwellian electron distribution is concerned, the original equation for the current density to the probe is still valid:

$$I = eA_p \int_{-\infty}^{\infty} f(v) v \, dv,$$

(7)

where $A_p$ is the surface area of the probe, $v_{\text{min}} = \sqrt{2e/m_e |V_p|}$. Probe theory can yield a theoretical probe characteristic only when the form of the electron distribution in the plasma is known and, in most of the non-Maxwellian distribution cases, the characteristic can be obtained only through a process of numerical integration. Fortunately, from the measured probe characteristic, one can normally have quite a good estimate of the form of the distribution, which in turn can be put into Eq. (7) to derive a corresponding characteristic. By comparing the measured characteristic with the calculated one, another closer estimate can always be made. By iteration, the assumed distribution can be made so close to the real one that the calculated curve can reasonably fit the measured data. In practice, this method needs a knowledge of the plasma potential, which is not easy to measure experimentally in this case. Since $V_p \sim (kT_e/2e) \ln(m_e/m_i) + V_o$, $T_e$ is estimated to be $\sim 5$ eV, and the measured floating potential $V_p$ is $7$ to $10$ V, an assumed figure within the range of $11$ to $14$ V for the plasma potential is used in the interpretation of the measured characteristic. The uncertainty of the plasma potential will only cause a few eV shift in the tail of the electron distribution but can cause significant error in determining the bulk electron temperature, which, as has been shown above, cannot in any case be measured accurately for a number of reasons.

### III. EXPERIMENTAL RESULTS

It is found that the measured probe characteristics for various experimental conditions can be reasonably fitted by the characteristics calculated from the distribution functions with the general form of

$$F = \sqrt{eV} \times (f_1 + f_2 + f_3),$$

(8)

where $f_1$ is the Maxwellian distribution:

$$f_1 = n_e \sqrt{m_e / \pi kT_e} \, e^{-eV/kT_e}.$$  

(9)

The tail “hole burning” function is $f_2$:

$$f_2 = S_1 \times f_1 \times e^{-S_2 \times V_p - \sigma V_p/kT_e}.$$  

(10)

Here, $0 > S_1 > -1$ and $S_2 > 20$ are parameters that characterize the “hole burning” depth and width, respectively, and $f_3$, the distribution of an electron beam, is

$$f_3 = n_b \sqrt{m_e / \pi kT_b} \, e^{-eV_p - V_p/kT_b}.$$  

(11)

with $T_b = \Delta E_b (\Delta E_b / 4eV_b)$, and $\Delta E_b$ is the beam $e^{-1}$ spread half-width in eV. The parameters that define the distribution function are determined using an iterative tracing method to fit the measured Langmuir probe data for various
The variation of the electron distribution tail as a function of experimental conditions can thus be interpreted from the probe data.

Figure 5 shows the nonthermal electron tails for various times after the initiation of the plasma. A Maxwellian distribution of 5 eV in $T_e$ is also plotted for comparison. The distribution was measured on the axis of the plasma for $B_0 = 750$ G, with input power of 3.5 kW. It can be seen that there is a hole in the tail, compared with the Maxwellian distribution, in the range of 22–32 eV, and a bump in the range of 30–80 eV. This energy range of 22–32 eV is important for the excitation of the upper levels of the $Ar^+$ visible transitions, since the excitation energy for those levels is in the range of 18–22 eV. The time evolution of the electron density and the 488 nm $Ar^+$ spontaneous emission (Fig. 6) is consistent with the results shown in Fig. 5. The emission intensity is very low and the electron density has a maximum in the first 1 msec of the plasma pulse. This can be explained as a result of a low excitation rate due to the lack of electrons in the 22–32 eV range and a relative higher ionization rate due to the bump in the energy range of 30–80 eV. The unusual sharp peak in the emission at $t \sim 0.2$ msec can be explained by the distribution at $t = 0.2$ msec, which has more electrons in the range of 22–32 eV. The integral of the electron energy distribution function over 22–32 eV as function of time is also included in Fig. 6. The last point ($t = 1.2$ msec) represents a Maxwellian of 5 eV.

In the following discussion, we will concentrate our attention on the high-energy electron beam term ($f_3$), which can be expressed by three parameters, the beam energy $E_b = eV_b$, the beam $e^{-1}$ spread $\Delta E_b$, and the normalized beam density $n_b/n_e$. Figure 7 shows these three parameters as the functions of time, and this is another representation of Fig. 5. From Fig. 7, we can see that, while the beam energy increases with time, the beam spreads and decays in density. However, the flux remains relatively constant. It is curious that the beam lasts for such a long time ($\sim 1$ msec), as contrasted with the knowledge of fast decay of a beamlike distribution due to beam plasma instability. This means that there must be some mechanism that keeps driving the beam. It has been reported that an electron beam will be absorbed by the plasma to form a flattened nonthermal electron tail within a time $t \sim 50$ nsec, and the equilibrium time for the thermalization of the electron tail is typically 3–5 electron–electron collision times. In this plasma, the electron–elec-
The electron collision time can be estimated as $t_{ee} = 1/\mu_{ee} = 2 \times 10^{-7}$ sec. This suggests the mechanism has to be strong enough to overcome not only the fast decay due to the beam-plasma instability but also the thermalization of the tail due to electron-electron collision.

The radial profiles of the parameters are shown in Fig. 8. The plasma operation condition for Figs. 7 and 8 is the same as that for Fig. 5. From Fig. 8, we can see the beam is restricted radially, is the most dense, and with the highest energy on axis. For $r > 10$ mm, there is no trace of the nonthermal tail and the distribution is Maxwellian with $T_e \sim 5$ eV.

As a function of input rf power (Fig. 9), all $E_b$, $\Delta E_b$, and $n_b$ increase after a threshold power of 2 kW. The electron distributions for powers lower than this threshold are close to Maxwellian with $T_e \sim 3-5$ eV.

The beam parameters also depend on the axial magnetic field (Fig. 10). There is no trace of the nonthermal tail until $B_0 = 600$ G, when the beam density jumps. This sudden jump could imply some resonant mechanism. There are peaks in both $E_b$ and $n_b$, but at a different field $B_0 = 900$ G [Fig. 10(a)] and $B_0 = 750$ G [Fig. 10(b)]. Note the peak in the beam density appears at a magnetic field (750 G) close to that (678 G) required for the lower-hybrid resonance condition

$$f_{rf} = f_l,$$

where $f_{rf} = 7$ MHz is the excitation radio frequency and $f_l = (1/2\pi)\sqrt{\omega_i/\omega_{ce}}$ is the lower-hybrid frequency.
We have observed nonthermal beamlike electron distribution tails near the axis of an argon plasma, which is excited by a helicon antenna at 7 MHz. The tail of the distribution has a maximum at 30–80 eV and a minimum at 20–30 eV, which is consistent with the time evolution of the electron density and the Ar⁺ emission. The nonthermal tail appears at the beginning of the plasma pulse with the input rf power exceeds 2 kW and the axial magnetic field \( B_0 > 600 \text{ G} \). It can last for a time of 1 msec. The energy of the electron beam is approximately proportional to time and input rf power, while the density of the beam decreases with time but increases with input power. There is a peak in the beam density at \( B_0 = 750 \text{ G} \), which is close to that required by the lower-hybrid resonance, and a peak in beam energy at \( B_0 = 900 \text{ G} \). The mechanism responsible for this nonthermal distribution tail is not yet known.

Experiments have also been carried out using an asymmetric Langmuir probe that suggest that the high-energy electrons do not have a preferred axial direction. Hence, on average, they do not represent a directed current.

The above results imply that there is a strong instability in this plasma that drives electron beamlike tails for about 1 msec, and this instability is restricted near the axis of the plasma and will be excited only if \( B_0 > 0.06 \text{ T} \) and the rf input power over 2 kW.

IV. SUMMARY

The energy and density of the electron beam are approximately proportional to time and input rf power, while the density of the beam decreases with time but increases with input power. There is a peak in the beam density at \( B_0 = 750 \text{ G} \), which is close to that required by the lower-hybrid resonance, and a peak in beam energy at \( B_0 = 900 \text{ G} \). The mechanism responsible for this nonthermal distribution tail is not yet known.

\[ \text{FIG. 10. } E_b, \Delta E_b, \text{ and } n_b/n_e \text{ as function of the magnetic field for rf power of 3.5 kW, measured on axis at } t = 0.5 \text{ msec.} \]

\[ n_b/n_e \times 10^4 \text{ as function of the magnetic field for rf power of 3.5 kW, measured on axis at } t = 0.5 \text{ msec.} \]