Electron Acceleration Using Helicon Waves in the Linear Mirror Machine Lisa

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The production of an energetic electron beam during radio frequency (RF) plasma heating, using helicon waves, in the linear mirror machine LISA (Linear Spiegel Apparatus), has been observed. The mechanism responsible for driving the beam is still not completely clear to us; however we consider a good candidate the electron runaway created by a quasi-static wave electric field.

I. Introduction

It is well known that helicon waves (whistler waves) are very efficienty to produce plasmas with very high degree of ionization[1-3]. These modes have also been used for technological applications such as plasma etching[2]. However, the mechanism responsible for driving the beam like tail, observed during the excitation of an Argon magnetoplasma by RF (helicon) without an electron beam injection[2], is still not clear.

A helium plasma was produced by a microwave generator, built at the Universidade Federal Fluminense[4], which uses the oscillator 6F5ORA (Toshiba) that produces a RF power of 350 W at the frequency of 28 MHz. The antenna was built to excite this mode at the same frequency, and the array consists of a 22 cm long helicoidal structure with five loops. Close to the antenna, it was created a quasi-electrostatic electric field of 1.8 V/cm, which is larger than the Dreicer critical field for LISA parameters, $E_D = 1.26$ V/cm. The LISA machine consists of a 255 cm long and 8.5 cm inner radius stainless steel tube covered on the left hand side by a stainless steel tube and on right hand side by a glass tube. The antenna was placed closer to the glass cover and the beam propagated from the antenna center to that side. The cylindrical vacuum was replaced by a single ionized helium plasma with working pressure of 10^{-4} Torr. The beam density was around 5×10^9 cm^{-3}.

In this paper, we would like to report the excitation of a similar nonthermal beamlike structure during helicon wave plasma production in the machine LISA, and give some possible explanations on how this beam can be produced.

Fig. 1 shows the LISA machine and the experimental apparatus[5-8]. The helium plasma produced with the helical array is confined in a mirror magnetic field of maximum 1200 Gauss and minimum of 200 Gauss. The working pressure was 10^{-4} Torr. We remark that our experiment is different from tlie one presented in Ref. [2] since our tube is metallic, closed on the left hand side by a metallic cover and on the antenna side by a glass cover. The antenna is placed inside the tube and not outside as in Ref. [1]. In relation to Ref. [2] they also use, as in Ref. [1], a glass tube, stronger RF power and also a confining magnetic field. In Ref. [3], a pyrex vessel filled with Argon was used but the magnetic field configuration was not of a mirror type.

Therefore, we are confident that our experiment is

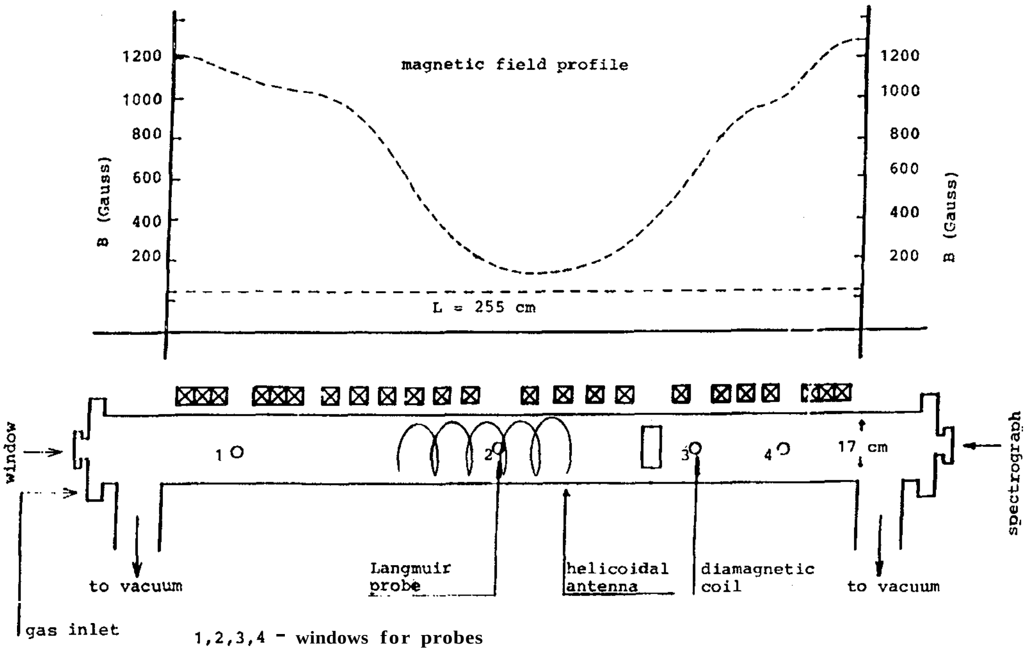

Figure 1: LISA machine.

not just a repetition of the previous ones, and that new interesting data is here reported.

II. Theoretical model for the helicon waves

The dispersion relation and eigenmode equation for helicon waves can be obtained considering a cylindrical plasma contained in a conducting cylinder. The mode equation is[1]

$$(1/r)(\partial/\partial r)[(r/(K^2-k^2))(\partial B_z/\partial_r)]+$$
$$+\{1-(m^2/r^2)[1/(K^2-k^2)]+$$
$$+(m/r)(\partial/\partial r)[(1/K^2)/(K^2-k^2)]\}B_z=0\ ,\quad (1)$$

where $K = en_e\omega(kB_0)$, m is the poloidal mode number, k is the axial wave number, and B_z is the wave field aligned magnetic field, respectively. The solutions of (2) have been already obtained in Ref. [1]. For an uniform plasma column of radius a, it is the mth order Bessel function of first kind $J_m(\rho)$, where $p = a^2(K^2 - k^2)$. Considering the boundary conditions we obtain the following dispersion relation

$$k/K = -mJ_m(\rho)/\rho J'_m(\rho)\ ,\quad (2)$$

where J'_m is the derivative of J_m with respect to its argument. Due to the antenna features and the working frequency, we expect to excite more easily lower poloidal m-modes. In this way, it is possible to use the approximated dispersion relation presented in Ref. [1], that is,

$$\omega/k = (A/ae\mu_0)(B_0/n_e)\ ,\quad (3)$$

which is valid for the m $= 0, 1$ modes[1]. The collisional and Landau damping rates are, respectively,

$$I_m(k)/k = (\nu_{\text{eff}}/\omega)(c^2/\omega_{\text{pe}}^2)(A^2/a^2)\ ,\quad (4)$$

and

$$I_m(k)/k = 2\pi^{1/2}(v_{\text{th}}/\omega_{\text{ce}})(\omega/kv_{\text{th}})(A/a)\exp(-\omega^2/k^2v_{\text{th}}^2)\ ,\quad (5)$$

where A, ω_{ce}, ω_{pe}, ν_{eff}, c and v_{th} are the argument which gives the first zero of $J_1(\rho)$, the electron cyclotron angular frequency, the electron plasma angular frequency, the effective collision frequency ($\nu_{\text{eff}} = \nu_{\text{ei}} + \nu_{\text{en}}$), the light speed, and the electron thermal velocity, respectively.

Note that in the low density regime that we operate our machine, $n_e < 10^{12}$ cm^{-3}, the collisional damping is not effective[1]; therefore we are left with only the possibility of Landau damping. However, for LISA parameters, the Landau damping of the helicon mode seems to be also ineffective, unless the spectral gap phenomenon, that occurs in lower hybrid current drive experiments[9], occurs also here, since $\omega/k_{\|})^{\text{LISA}}_{\text{helicon}} >> v_{\text{the}})^{\text{LISA}}$. Accordingly, we have to look for another possible mechanism that might be responsible for the creation of the electron bearn.

The second possibility that should be considered and that might be related to the beam formation is the runaway electron production by a DC electric field. It is well known that when an uniform DC electric field $\vec{E}$ is acting on an uniform plasma, a certain fraction of electrons will run away, that is, they will gain energy such that the electric force on thern exceeds the collisional drag force[9]. As a consequence, they will be accelerated indefinitely by the electric force. These are called runaway electrons and the critica1 velocity for occuring this effect is given by

$$v_c = (E_D/E_{DC})^{1/2} v_{\text{the}} , \tag{6}$$

where E_{DC} is the applied DC electric field,

$$v_{\text{the}} = (k_b T_e/m_e)^{1/2} \tag{7}$$

and

$$E_D = m_e \nu_{\text{eff}} v_{\text{the}}/2e . \tag{8}$$

Here E_D is the well known Dreicer field, with

$$\nu_{\text{eff}} = \nu_{ei} + \nu_{en} \cong \nu_{en} \cong 2.8 \times 10^3 s^{-1} , \tag{9}$$

where ν_{ei} and v,, are the electron-ion and electron-neutral collision frequencies, respectively. Using LISA data, the critical electric field is [10]

$$E_D \cong 1.0 V/cm , \tag{10}$$

that is smaller than the applied field $E_{DC} \simeq 1.8 V/cm$.

The runaway (beam) density can be estimated using the following expression[11]

$$n_r = n_e \exp(-E_D/2E_{DC}) \tag{11}$$

III. Experimental results

III.1 Power absorption and wave fields

Fig. 2 shows the radial profile of the measured perpendicular power. It is clear that an axisymmetric mode m = 0 was excited. This is consistent with the expectation that this mode is preferentially excited for our conditions. The power was measured using a linear wattmeter.

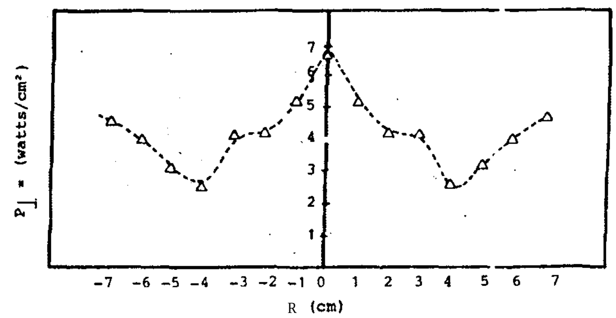

Figure 2: Power profile versus radius.

Fig. 3 shows the radial profiles of the wave field, measured by a double floating electrostatic probe. We see that the amplitudes of E, and E, peak at the center of the plasma whereas the one of E_θ has a minimum there. In our experiment $\omega_{RF} << \omega_{ce}$ and $|E_\theta|$ is small close to the plasma center; therefore cyclotron damping is not an effective mechanism of wave absorption close to the plasma center.

111.2 Density and temperature profiles

Fig. 4 shows the plasma density profile. It can be clearly seen that the maximum density is achieved at the center and that it starts to increase around r = ±4, in agreement with the power absorption profile shown in Fig. 2. Around the plasma center, where the beam is supposed to be generated, the density is around 5.0 x 10^9 cm^{-3}, as can be seen in Fig. 4. This number is very close to the obtained runaway density given by Eq. 10 using the LISA parameter n, $\cong 4.8 \times 10^{-9}$ cm^{-3}. This information by itself does not garantee that a runaway electron beam was created. However, corroborating this coincident density number we have verified that the energy analyser (Faraday cup) used to measure the parallel electron energy had its grid melted by the energetic electronic population, what we did not expect. Also, as a strong evidence for the energetic electron beam, the glass cover was burned just around the center where the beam was supposed to be as inferred from the energy analyser break down. In order to show that energetic ions did not melt the analyser, we have polarized the cup so that ions could not reach it. The density was measured using a movable plane Langmuir probe.

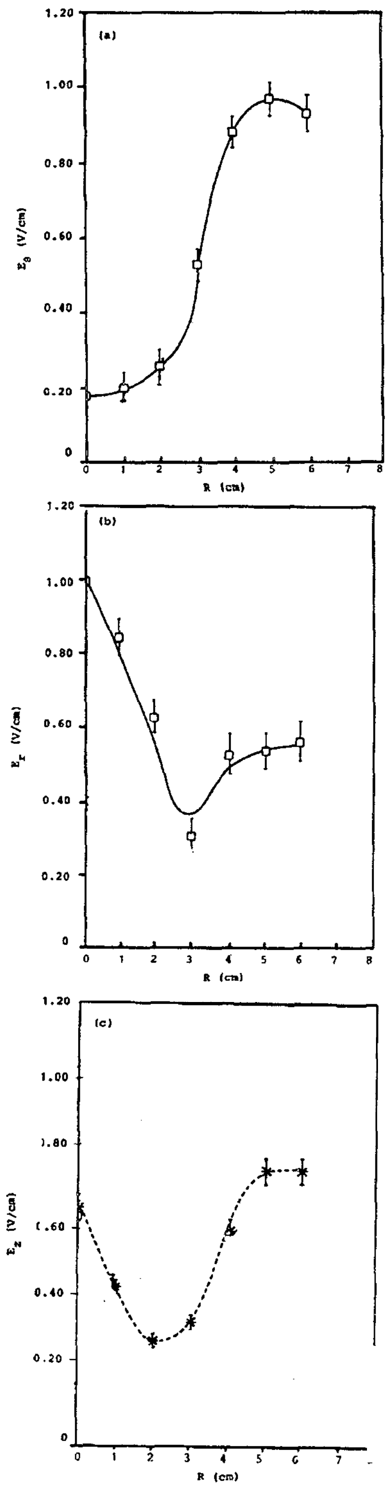

Figure 3: Electric field profiles versus radius.

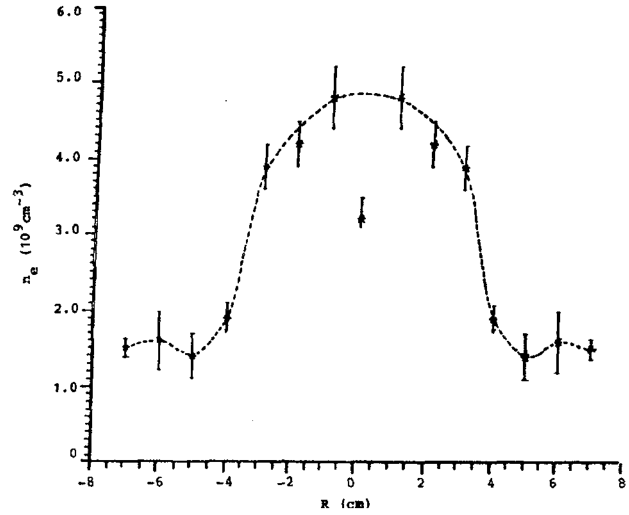

Figure 4: Electron density profile versus iadius.

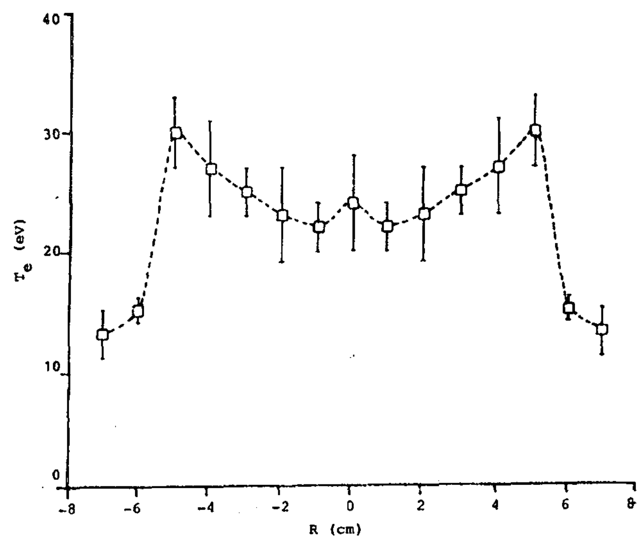

Figure 5: Electron temperature profile versus radius.

Fig. 5 shows the temperature profile measured using cylindrical and plane movable Langmuir probes in order to access both the parallel and perpendicular electron temperatures. The value of the parallel electron temperature was also measured using a movable energy analyser (Faraday cup) and agrees well width the results obtained using the Eangmuir probe.

The following important features can be seen in this profile:

At r = ±5.0 cm a temperature peak can be observed. Examining the wave electric field profiles, it is possible to see that E_θ has also a peak in amplitude around r = 5.0 cm which means that this field's component might increases the electron perpendicular energy, around this point. Subsequently, this energy might be thermalized via collisional effect. We have not observed strong visible energy emission from this region as the one that could be seen from the plasma center. Of course, this peak might also be associated with more plasma ionization rather than real electron heating. We have not tried to solve this possible ambiguity.

From $r = \pm 5.0$ cm toward to the plasma center, one can see that the temperature decreases and exactly at the plasma center it has a secondary peak. The plasma heating via the E, component can also put continuously electrons in the loss cone region and they can also be accelerated in the direction of the glass cover, but the high degree of colimation, that we have found, might be difficult to explain if this mechanism is to be used to explain the beam formation.

IV. Conclusion

In conclusion we can say the following:

a. A helicon $m = 0$ wave was excited in the LISA machine; a plasma of low degree of ionization for $|r| > 2.0$ cm and of high degree of ionization at $|r| < 2.0$ cm was created.

b. Apart from being created by the helicon wave the plasma was also heated at $r = \$5.0$ cm by the E_θ component, and at the center by the E, component.

c. An energetic electron beam seems to be present in this experiment as we could infer from the breakdown of our energy analyser and from the burning of the glass cover that was placed immediately after the helical antenna. We have not yet a clear explanation why the beam propagated to the glass cover side.

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