Electron-cyclotron heating and associated parallel cooling

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We have observed experimentally that during electron-cyclotron heating the electron longitudinal temperature drops as the perpendicular temperature increases. The experiment was carried out in a linear mirror machine with a low-density (10^{10} cm^{-3}) weakly ionized ($\leq 1.0\%$) plasma.

It has been shown numerically by Busnardo-Neto, Dawson, Kamimura, and Lin[1] and later analytically using quasilinear theory by Arunasalam[2] that during ion-cyclotron heating the increase in the perpendicular ion temperature is associated with a decrease in the parallel ion temperature. Since there is no reason to believe that this does not also work for electrons, we may think that the same effect would occur during electron-cyclotron heating and, indeed, there are recent reports in the literature to this effect.[3,4] It should also be mentioned that if in fact this effect occurs, then the electron-cyclotron current drive picture[5] in tokamaks should be changed, since the cooling would change both the collision frequency and the density of the trapped particles in the banana orbits of tokamak. To the best of our knowledge these effects have not been investigated yet and this is the subject of future work.

The main purpose of this article is to show that parallel cooling occurs for electrons during electron-cyclotron heating with the anisotropy in the temperature reaching a maximum of $T_{e_\perp}/T_{e_\parallel}=1.55$. The experiment was carried out on LISA, a linear mirror machine now operating at Universidade Federal Fluminense (UFF) (Table I and Fig. 1). This machine is 2.55 m long with an internal diameter of 0.17 m and it has a 1-m-long central section where the magnetic field is uniform (within 2%). More details on the machine can be found elsewhere.[6] For the experiments described here the dc current in the field coils was finely controlled so that the magnetic field varied from 150 to 1150 G in steps of 10 G, except for two points where a change of range in the control switch occurred. The diamagnetic effects are not very important because they are only of the order of 1.5 G. A Hall probe was used for careful measurements of the field which were later confirmed by means of a small magnetic probe used with a small ac current superimposed on the main dc current of the field coils. The helium plasma was produced by a microwave generator, which produces a power of 800 W at a frequency of 2.45 GHz, at 10^{-4} torr filling pressure with a background pressure of 10^{-6} torr, and the wave is injected through a rectangular waveguide at the side where there is a dip in the dc magnetic field (Fig. 1). The electron density n_e and the parallel temperature $T_{e_\parallel}$ were measured with a small planar Langmuir probe. The average electron temperature $\langle T_e \rangle$ was measured spectroscopically and the perpendicular electron temperature was then obtained from $\langle T_e \rangle=(T_{e_\parallel}+2T_{e_\perp})/3$. These values for $T_{e_\perp}$ were confirmed with a series of measurements of the electron density and the mirror ratio as a function of the axial position, which allows us to obtain the temperature ratio $T_{e_\perp}/T_{e_\parallel}$ via a classical relationship for the magnetic mirror.[7,8]

The waves were excited with an 800-W, 2.45-GHz magnetron (the corresponding field for electron resonance is 875 G) and a microwave horn was used as the antenna; more details about the antenna and wave fields can be found in Ref. 6. We observe that the Langmuir probe then detected the saturated parallel electron temperature in the sense that many rf and cyclotron periods occur during the magnetron pulses, which were 10 ms long. Also the temperature detected is an average between the times with the rf on and the times with the rf off and it could well be that $T_{e_\parallel}$ during the rf-on cycle is lower than the average. This same averaging effect is present in the spectroscopically measured $\langle T_{e_\perp} \rangle$, which in turn could be higher than the average during the rf-on cycle. The measurement has been made using a uv, Q24 spectrograph (Jenoptik Jena, G.m.b.h.) using the corona method,[9] which is based essentially on the ratio between the intensity of the light (He I 4771 Å) emitted from the helium plasma (singlet, $\lambda=4713$ Å; and triplet $\lambda=4921$

TABLE I. Summary of the basic LISA and target plasma parameters.

Parameter	Value
Total length L	255 cm
Inner radius a	8.5 cm
Uniform magnetic field B	10.5 kG
Mirror region B	13.0 kG
Extension of the uniform magnetic field	100 cm
Electron density n_e	10^{10} cm^{-3}
Electron temperature T_e	80 eV
Ion temperature T_i	10 eV

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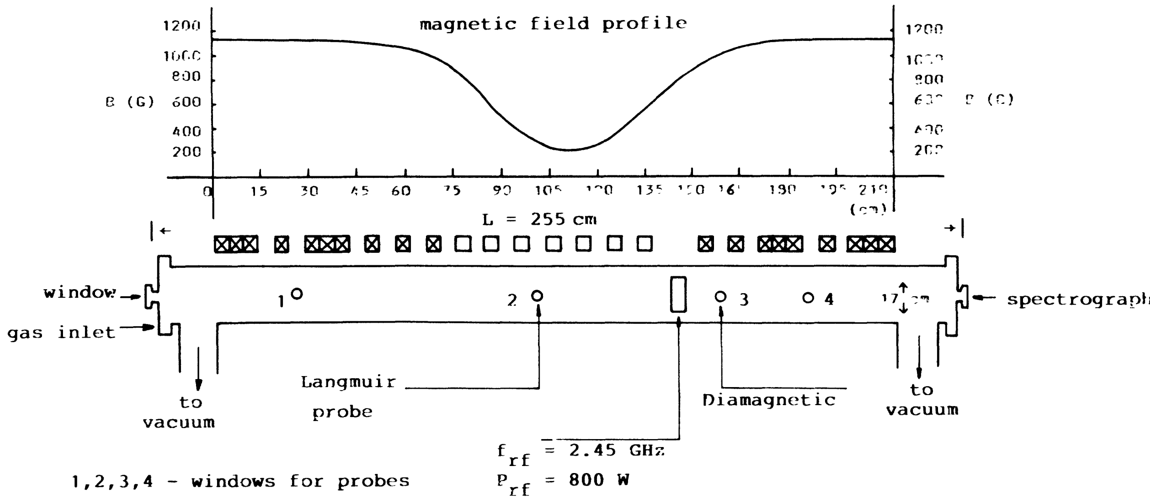

FIG. 1. LISA machine.

Å; with this method we can relate the ratio between the intensity of the light (λ4713 Å/λ4921 Å) versus the total electron temperature T_e. Therefore the ratios $T_{e_\perp}/T_{e_\parallel}$ reported here probably are underestimated due to the averaging process inherent in the diagnostics used.

Our results are presented in Table II and Fig. 2, which show the perpendicular and the parallel temperatures versus the magnetic field. It is seen that the parallel temperature drops and the perpendicular temperature increases as the resonance is approached from the high-field side ω/ω_c with ω being the microwave frequency and ω_c the electron-cyclotron frequency. The initially isotropic plasma becomes then anisotropic with the temperature ratio starting at unity and reaching 1.55 at the

TABLE II. The experimental values of the temperature $T_{e_\parallel}$ and $\langle T_e \rangle$, the magnetic fields B, and the calculated values of $T_{e_\perp}$, $\omega_c/(\omega_c-\omega)$, and the anisotropy $T_{e_\perp}/T_{e_\parallel}$. All temperatures in electron volts. $T_{e_\parallel}$ is obtained with the Langmuir probe, $\langle T_e \rangle$ obtained through the ratio of the He lines at 4713 Å and 4921 Å. The field is measured with a Hall probe and also with a magnetic probe with a small ac ripple.

B (G)	$T_{e_\parallel}$ (eV)	$\langle T_e \rangle$	$T_{e_\perp}$ (eV)	$T_{e_\perp}/T_{e_\parallel}$	$\omega_c/(\omega_c-\omega)$
1150	35.5	34.7	34.4	0.99	4.18
1100	35.0	35.0	35.0	1.00	4.89
1050	32.0	34.3	35.5	1.11	6.00
1040	31.0	34.0	35.6	1.16	6.30
1030	30.5	34.0	35.7	1.16	6.65
1020	30.0	34.7	37.0	1.23	7.03
1010	29.5	36.0	39.5	1.34	7.48
1000	29.0	37.7	42.0	1.45	8.00
990	29.0	37.7	42.0	1.45	8.61
980	29.0	37.7	42.0	1.45	9.33
970	28.5	38.5	43.5	1.52	10.2
960	28.5	38.5	43.5	1.54	11.3
950	28.2	38.6	43.8	1.55	12.7
940	28.7	39.0	44.4	1.55	14.5
930	29.0	38.7	43.5	1.50	16.9
920	28.5	38.8	44.0	1.54	20.4
910	28.8	40.2	46.0	1.60	26.0
900	29.0	39.0	44.0	1.52	36.0
890	28.9	39.1	44.2	1.53	60.0
880	29.0	38.8	43.8	1.51	193.5
875	35.0	45.0	50.0	1.42	∞

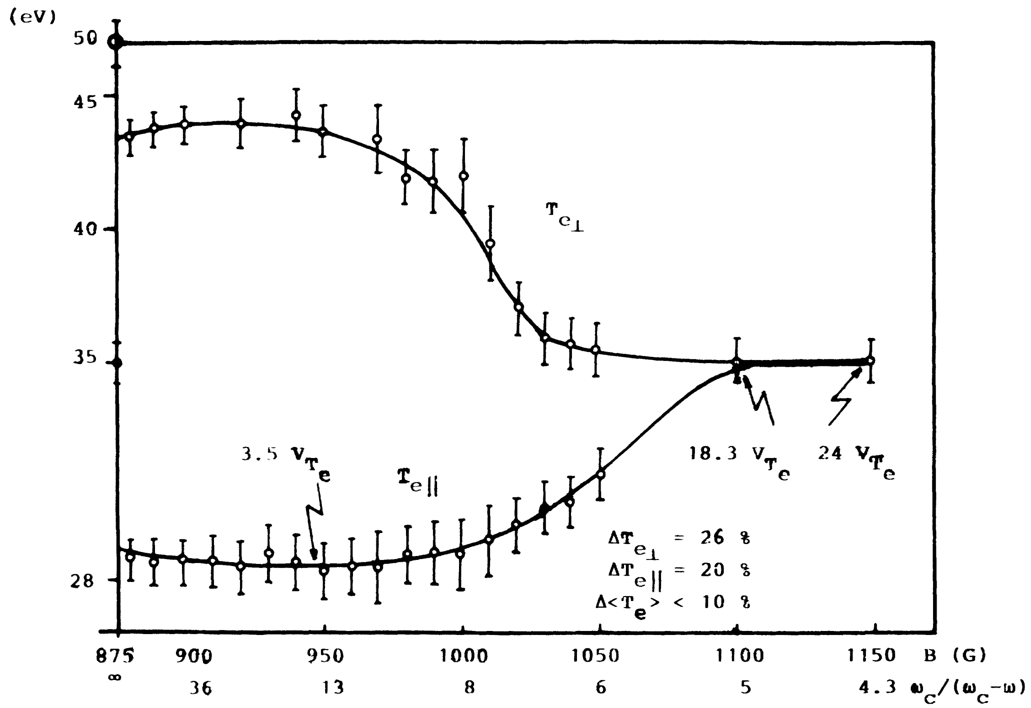

FIG. 2. The perpendicular $T_{e_\perp}$ and parallel $T_{e_\parallel}$ electron temperature plotted as a function of the dc magnetic field. Away from the resonance the electron temperature is isotropic and becomes anisotropic as the resonance is approached from the high-field side with a saturation in the anisotropy appearing around 950 G.

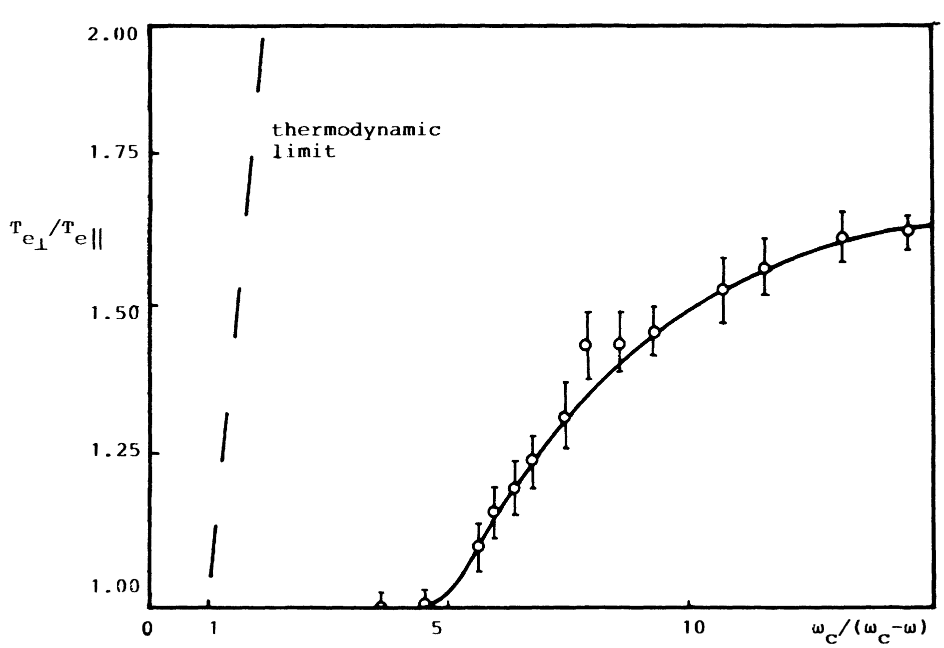

FIG. 3. The anisotropy in the electron temperature vs the parameter $\omega_c/(\omega_c-\omega)$, the theoretical upper limit to $T_{e_\perp}/T_{e_\parallel}$.

saturation point. For these values of the magnetic field the average temperature of the electrons remains fairly constant (within ±5% of 10%). At the very resonance (875 G for the field) all three temperatures rise abruptly with $\langle T_e \rangle = 45$ eV, $T_{e_\parallel} = 35$ eV, and $T_{e_\perp} = 50$ eV. In Fig. 3 we show the variation in the anisotropy versus the parameter $\omega_c/(\omega_c - \omega)$ which is the thermodynamic limit for the anisotropy; or, conversely, the threshold for the onset of instabilities in an anisotropic magnetized plasma. It is clear that the anisotropy obtained is smaller than the theoretical limit (the dashed line) and this can be seen clearly as a saturation of the electron-cyclotron damping mechanism, possibly due to the very anisotropy in the temperature. Or else this low value of the anisotropy is due to the averaging effect of the temperature measurements.

These electron-cyclotron waves resonate with particles that travel in the opposite direction of the wave and have a velocity $V_R = (\omega - \omega_c)/k$. For the waves and magnetic fields used in the experiments reported here these resonant velocities are very high, in the range $V_{T_e} \langle V_R \langle 26 V_{T_e}$. The thermal velocity V_{T_e} is calculated for the parallel direction only and the wave number K is obtained from the warm plasma dispersion relation for electron-cyclotron waves which is given by[10]

$$\det \begin{vmatrix} s - n^2 & -iD & n_\perp n_\parallel + T \\ iD & s - n^2 & -iV \\ n_\perp n_\parallel + T & iV & P - n_\perp^2 \end{vmatrix} = 0 .$$

For typical parameters of the LISA we have $0.8 \le \omega_{\rm rf}/\omega_{ce} < 1.0$, 20 eV $< T_e <$ 50 eV and $\omega_{Pe}/\omega_{ce} \ge 1.0$ where $n_\parallel = K_\parallel c/\omega_{\rm rf}$, $n_\perp = K_\perp c/\omega_{\rm rf}$ and $K_\perp v_{T_e}/\omega_{ce} = 0.2$. For more details see Refs. 10 and 11.

It is seen then that very few particles are present in this resonant region and therefore little wave absorption can occur. On close examination we see from Fig. 2 that the anisotropy appears around 1100 G for the magnetic field and saturates around 950 G for the field. The resonant velocities for these values of the field are $V_R = 4v_{T_e}$ at the point $B = 950$ G and $V_R = 26 v_{T_e}$ for the point $B = 1100$ G. This is surprising for it indicates that the wave-particle interaction is occurring in a region where very few particles are present. We may conclude that the mechanism that transfers energy from the waves to the particles, with perpendicular heating and parallel cooling, is a very strong one, since the effects are observable at such high resonant velocities. This same unexpected result—a strong wave-particle interaction in a region of the distribution function where few particles exist—is recurrent in the literature on current drive with lower-hybrid waves, and is frequently referred to as the spectral gap problem. On the other hand, for the experiments with $910 < B < 950$ G the resonant velocities for the waves lie in the interval between V_{T_e} and $4v_{T_e}$, that is, fairly close to the main body of the distribution function and here the waves have a large number of particles to interact with. It is surprising then that a saturation of the anisotropy obtained would occur with values that are still away from the theoretical limit. It could be that the parallel temperature is maintained because of the fast particles which do not interact with the wave or else there is a very efficient mechanism that destroys the anisotropy very rapidly. We have not identified this mechanism yet and observe that the plasma is still linearly stable to electron-cyclotron instabilities of the Weibel-Dreicer-type. As a matter of fact, the very limit to the anisotropy constitutes the threshold for the instability.

The original thermodynamic versus quantum argument led to the relationship $T_{e_\perp}/T_{e_\parallel} \le \omega_c/(\omega - \omega_c)$ as a limit to the anisotropy in the temperature that could be obtained through cyclotron heating. This limit is optimistic since the computer experiments were performed under idealized conditions not likely to be satisfied in a real experiment. In our case the anisotropy in the electron temperature was generated through electron-cyclotron wave pumping and this anisotropy depends on the magnetic field with the limit $\omega_c/(\omega_c - \omega)$ being observed.

It would be very interesting to be able to increase the ratio $T_{e_\perp}/T_{e_\parallel}$ to values closer to the theoretical limit. That could be achieved through stronger pumping (more magnetrons or more powerful magnetrons) or else through a modification in the conditions of the experiment to allow the launching of waves with a larger value of K, so that the resonant velocity $(\omega - \omega_c)/K$ will be closer to the main body of the distribution function and at the same time far enough from the cyclotron resonance so that the limit $\omega_c/(\omega_c - \omega)$ has a low value, around 3–5, say. The possibility of a turbulent spectrum with several waves (not electron-cyclotron waves) driven unstable even at low values of the ratio $T_{e_\perp}/T_{e_\parallel}$ should also be studied.

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