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Determination of the Electron Thermal Conductivity across Magnetic Surfaces in the FM-1 Spherator*

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A new approach was taken to measure the electron thermal conductivity across magnetic surfaces by utilizing localized upper hybrid resonance heating. The electron thermal conductivity coefficient measured in the FM-1 spherator was increased with an increase of electron temperature for $T_e > 1$ eV. The dependence is similar to that of the particle diffusion coefficient. The absolute value was 10–20 times smaller than the Bohm coefficient.

The thermal conductivity across magnetic surfaces in toroidal devices has been studied experimentally by many groups in an effort to understand the mechanisms responsible for the transport. In many cases the average thermal transport has been determined from the energy balance.[1,2] A new approach is reported in this paper to measure locally the electron thermal conductivity across the magnetic surfaces by utilizing localized upper hybrid resonance heating. The electron thermal conductivity measured in the FM-1 spherator with this new method was found to be anomalous. The electron thermal conductivity increases with an increase of electron temperature; this dependence is similar to that of the particle diffusion coefficient. The absolute value of the electron thermal conductivity was $10^{-1}-5\times10^{-2}$ of the one estimated from the Bohm coefficient. Within our best knowledge, the present report is the first direct observation of local electron thermal conductivity across the magnetic surfaces in toroidal devices.

As is well known,[3] microwave power with a frequency $\omega_0/2\pi$ close to the electron-cyclotron frequency $\omega_{ce}/2\pi$ is absorbed in a localized area which satisfies the upper hybrid resonance condition, $\omega_r^2(\psi,\chi)\equiv\omega_{pe}^2(\psi)+\omega_{ce}^2(\psi,\chi)$, where $\omega_{pe}/2\pi$ is the electron plasma frequency and (ψ,χ,θ) are the toroidal coordinates. At the resonance the energy is mainly deposited in the electrons with mild ion heating.[3] Although the localized resonance $\omega_r=\omega_0$ does not coincide with a magnetic surface, the strong energy absorption takes place on a magnetic surface which is tangential to the resonance surface. By reducing the pulse width of the resonant heating, it is possible to localize the heating around the maximum energy absorption surface. The pulse length should be long enough to allow the heat to spread uniformly on the magnetic surface. The observed spreading of the initially localized heat after the termination of the heat pulse provides a measurement of the electron thermal conductivity across magnetic surfaces. In the present paper we report experimental results in the FM-1 spherator on (1) the production of a localized heat source and the observation of heat spreading, (2) the determination of the local electron thermal conductivity coefficient $K_\perp$, and (3) the determination of the dependence of $K_\perp$ on the electron temperature. The identification of the heating mechanism is described elsewhere.[3]

The FM-1 spherator[4] is a toroidal plasma confinement device which has a magnetically levitated superconducting ring inside the plasma confinement volume. The superconducting ring was excited with a 250-kA ring current and the ratio of the ring current to the toroidal field current was about 1. The magnetic surfaces were shaped by varying an additional vertical magnetic field in order to maximize the local heating. (The resonance surface was adjusted to coincide with a magnetic surface as much as possible.) The variation of magnetic field strength was ~15–30% on a given magnetic surface. The properties of the present magnetic field configuration are (1) shear stabilizing configuration, (2) no average minimum B, and (3) no local good curvature. (Magnetic surfaces are similar to that in the case given by $B_E = 0.6-0.8$ in Okabayashi and Freeman.[5]) The average magnetic field strength was 3.5–4.5 kG. The plasma was produced by ionizing the helium gas with 10.5-GHz microwave power. The same microwave source was also used to provide the localized heating. The filling neutral gas density n_n was minimized to reduce the electron temperature decay due to ionization energy loss after the termination of the heating pulse ($n_n \lesssim 10^{11}$ cm^{-3}). The typical fraction of ionization was about 50%. Floating double probes were used to measure the ion saturation current. The electron temperature was obtained by swept Langmuir probes. The electron plasma density was measured by an 8-mm microwave interferometer. The ion saturation current profile was recorded by an on-line computer system with a time interval of 100 μsec and a 0.5-mm probe spacing.

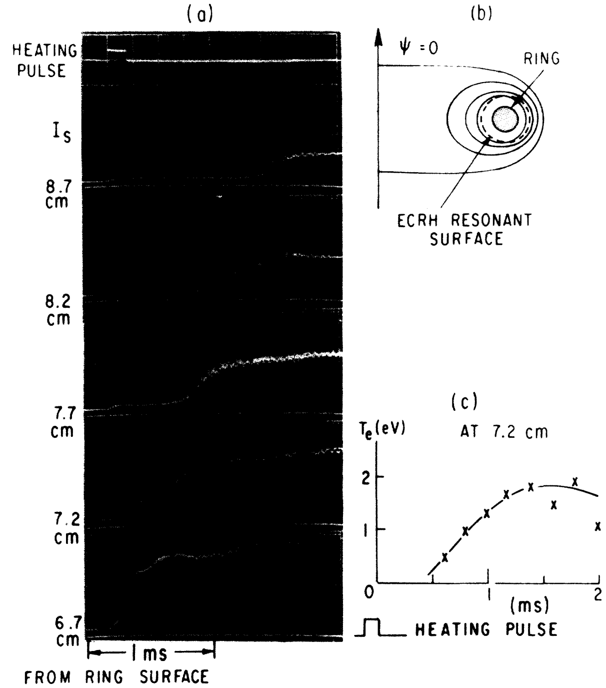

FIG. 1. (a) Heat spreading observed by ion saturation current. (b) Schematic of magnetic-field configuration used in the present experiment. (c) Time dependence of electron temperature measured by a swept Langmuir probe.

The initial localization and spreading of heat are shown in Fig. 1. In this case, the heating pulse of 150 μsec was applied to the preionized plasma of $n_e = 2\times10^{10}$ cm^{-3}. The electron temperature just before the heating pulse was about 0.1 eV all over the plasma volume. Figure 1(a) shows the heat spreading by ion saturation current I_s. The ion saturation current is proportional to $T_e^{1/2}$ and is, therefore, a good relative measure of the electron temperature. The ion saturation current measurement at the horizontal midplane shows an immediate increase at the location close to the resonance surface and the time of rapid increase is gradually delayed as the probe is pulled away from the resonance surface. (The small increase of the ion saturation current occurring simultaneously with the heating pulse is due to nonresonant heating on off-resonant surfaces.[6]) The delayed increase of I_s at the outside surfaces indicates that the initially localized heat spreads to the probe location with a certain time delay. This was confirmed by measuring the electron temperature as shown in Fig. 1(c). The gradual rise of electron temperature is similar to that of the ion saturation current at the same probe position. By rearranging the observed traces of I_s and T_e it is possible to obtain the spatial spreading of I_s and T_e as shown in Fig. 2. The ion saturation profile before heating indicates a flat density profile. (The density gradient length was about 10 cm at the horizontal midplane.) The time $t = 0$ msec corresponds to the termination of the heating pulse. In this case, the front velocity of the heat pulse is about 10^3 cm/sec. The measurements at different azimuthal locations show that the heat spreading takes place uniformly in the azimuthal direction. The dependence on plasma density was investigated by changing the heat pulse timing with respect to that of the breakdown pulse. It was noticed that decay of profile is relatively insensitive to the plasma density.

The determination of the electron thermal conductivity coefficient $K_\perp$ is as follows. To obtain $K_\perp$ from the observation of heat spreading as shown in Fig. 2, it is necessary to solve the heat

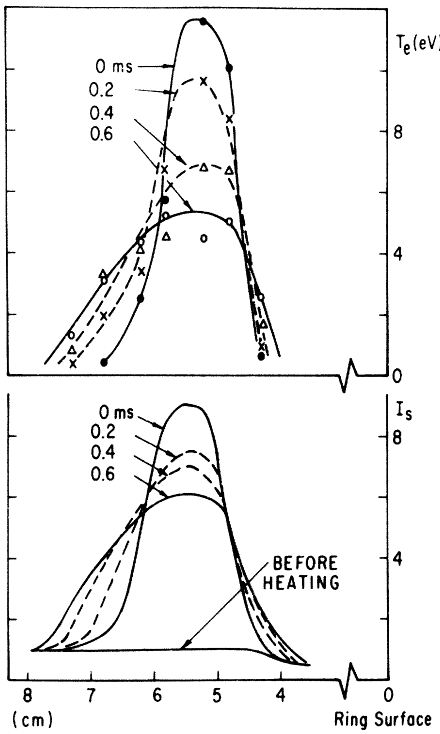

FIG. 2. Upper: electron temperature profiles at different times. Lower: ion saturation current profiles.

diffusion equation (here it is assumed that the density-gradient scale length is larger than the temperature-gradient scale length)

$$\frac{3}{2}\frac{dT_e}{dt}=\frac{d}{dx}\left[K_\perp\frac{dT}{dx}\right], \tag{1}$$

where x is the coordinate perpendicular to the magnetic surface. The calculated profile is then compared with those obtained experimentally. To solve Eq. (1) the relation between $K_\perp$ and T_e must be known. It is assumed that $K_\perp$ is independent of plasma density, on the basis of experimental results. In the present treatment $K_\perp$ is also assumed to be proportional to T_e. The validity of the assumption will be examined after the dependence of $K_\perp$ on T_e is obtained. A solution of Eq. (1) which satisfies $T_e(x=\pm x_0, t=t_0)=0$ and $T_e(x=0, t=t_0)=T_{e0}$ is

$$\frac{T_e(x,t)}{T_{e0}}=\frac{1}{4K_{\perp 0}}\frac{x_0^2}{t_0}\left(\frac{t_0}{t}\right)\left[\left(\frac{t}{t_0}\right)^{2/3}-\left(\frac{x}{x_0}\right)^2\right], \tag{2}$$

where $K_{\perp 0}$ is the electron thermal conductivity at $t=t_0$. $K_{\perp 0}$ can be determined from the condition $T_e(0,t_0)=T_{e0}$:

$$K_{\perp 0}=\tfrac{1}{4}x_0^2/t_0. \tag{3}$$

Equation (2) also provides another procedure to obtain the value of $K_{\perp 0}$ from the front velocity of the heat pulse determined by $T_e(x,t)=0$ and the definition of $K_{\perp 0}$ given in Eq. (3):

$$K_{\perp 0}=\tfrac{3}{4}x_0\,\Delta x/\Delta t, \tag{4}$$

where Δx is the spreading of the front edge of the T_e profile within the time interval Δt. The value of t_0 is determined by extrapolating the movement of the front edge to the resonance surface. Figure 3 shows the value of $K_\perp$ versus the peak electron temperature obtained by these two procedures—Eq. (3) with triangles and Eq. (4) with circles. The errors for Eq. (3) are due to the ambiguity in determining t_0, because Eq. (3) requires a point source at the original time. The errors in using Eq. (4) arise from the measurement of Δx. Data points in Fig. 3 also include the results obtained with different heating-power levels, consequently varying the initial electron temperature. These results indicate that the electron thermal conductivity $K_\perp$ increases with an increase in electron temperature, which is consistent with the *a priori* assumption. The observed dependence of $K_\perp$ on T_e can be approximated by $K_\perp \propto T_e^{\,a}$, where $a=\frac{1}{2}-\frac{3}{2}$. The value of $K_\perp$ at $T_e=10$ eV, $(1-2)\times 10^3$ cm^2/sec, is about

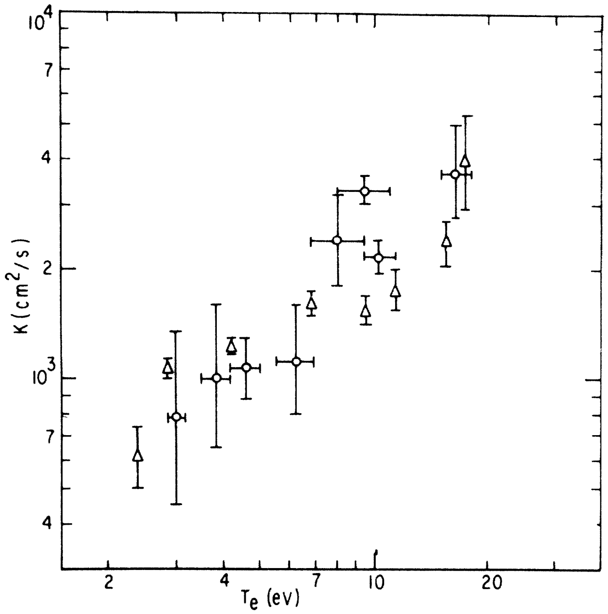

FIG. 3. Electron thermal conductivity K versus T_e.

$10^{-1}-5\times10^{-2}$ of the value estimated from the Bohm coefficient of $\frac{1}{16}kT/eB$ and is larger than the classical value by 3 orders of magnitude. The magnitude as well as the T_e dependence of the conductivity in the electron temperature range of $T_e > 1$ eV is similar to the particle diffusion coefficient as reported by Chen.[7] This indicates that the same mechanism may be responsible for the anomalous electron thermal diffusion and the particle diffusion.

In the determination of the value $K_\perp$, we simplified the equation as well as the geometrical factors. The electron energy loss due to ionizing neutral gas is neglected in Eq. (2). However, the change in electron temperature due to ionization is less than 30% during the time interval of 0.3 msec used to determine the electron thermal conductivity. The variation of plasma volume in the radial direction, $dV/d\psi$, should also be taken into account. The change of $dV/d\psi$ is less than 20% in the 2.0-cm radial extent over which the measurements were carried out, and was therefore assumed constant.

In conclusion, the electron thermal conductivity was measured by utilizing the localized upper hybrid resonance heating. The observed $K_\perp$ increases with an increase of T_e. This dependence is similar to that of the particle diffusion coefficient. The absolute value $K_\perp$ is $\frac{1}{10}-\frac{1}{20}$ of the Bohm coefficient. The success of the present approach suggests that other types of resonant heating, such as lower hybrid resonance and ion-cyclotron resonance, may be applicable to obtain electron and ion thermal conductivities in tokamak devices.

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NMR Studies of the *A* Phase of Liquid ^{3}He†

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We report measurements of the transverse and longitudinal NMR spectra of liquid ^{3}He in low magnetic fields which support the axial-state model for the liquid in the *A* phase. A quite unexpected additional result found in this work is that the width of the shifted transverse resonance line becomes extremely broad at temperatures well below *A*.

Direct evidence that the spins of the ^{3}He atoms in the *A* phase of the liquid are correlated in a most unusual way has been furnished through previous observations of a large shift in the position of the nuclear magnetic resonance line.[1] Leggett[2,3] has given a microscopic theory of the NMR behavior of the liquid in this phase in terms of a BCS-type[4] superfluid in which the atoms form Cooper pairs in a triplet spin state. He has considered several possible p-wave states of the liquid and suggests a number of phenomena that may be observed in NMR experiments under a variety of magnetic field configurations that will identify the particular state of the liquid. In this work we have performed the suggested experiments and find that *all* of Leggett's predictions are verified, in detail, for the state given by Anderson and Brinkman[5] as that which minimizes

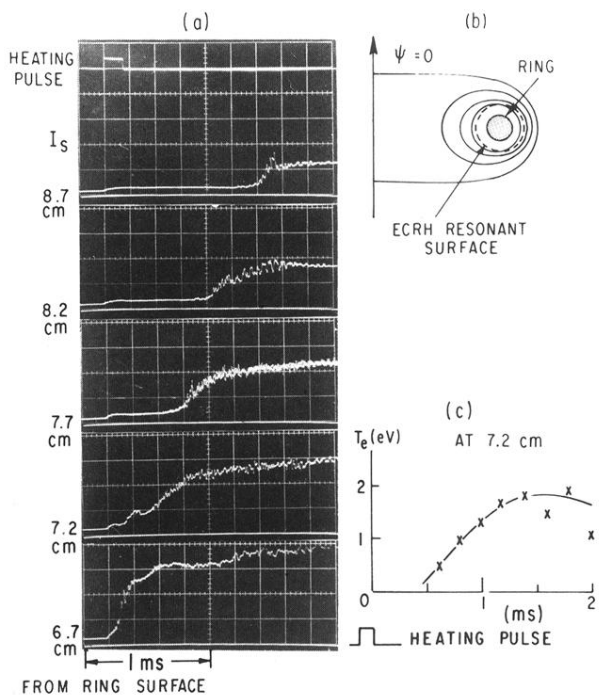

FIG. 1. (a) Heat spreading observed by ion saturation current. (b) Schematic of magnetic-field configuration used in the present experiment. (c) Time dependence of electron temperature measured by a swept Langmuir probe.