NORMAL AND ANOMALOUS CONDUCTIVITY IN A TOROIDAL DISCHARGE FROM THOMSON SCATTERING MEASUREMENTS*

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For many years now the electrical conductivity of plasmas has been used as a routine diagnostic tool for determining electron temperatures. This is particularly attractive for toroidal plasmas, since no electrodes need be introduced into the plasma.

With the advent of Thomson-scattered laser light as a diagnostic tool, it has become possible to measure the electron distribution function as a function of position in the discharge, and from these data derive an accurate comparison with conductivity data.

The necessary Thomson-scattering measurements have now been carried out on the Model C Stellarator.[1] This is a toroidal discharge of 12 m length which was operated with a 35-kG axial confining field, plasma diameters of 7.5 to 12.5 cm, and an $l=3$ rotational transform. The current in the plasma was 1.5 to 4 kA and the total rotational transform at the surface of the plasma was 0.6 to 1.2 rad. In this work the plasma used was an Ohmically heated discharge in hydrogen. The resulting plasmas had densities in the range 10^{12}-10^{13} cm^{-3} and temperatures of 20-100 eV. In this regime the Debye length is much greater than the wavelength of the ruby-laser light, and therefore we expect to see no scattering from collective modes of the plasma at our 90° scattering angle.

At these low densities it is necessary to use as much energy as possible and the largest feasible collecting optics, to get signals which are not seriously limited by photon shot noise. For this reason an approximately 1-msec pulse containing 50-100 J in 5 mrad was used, along with *f*:3 collecting optics. In addition, multiple total internal reflections in the photomultiplier face plates were used to enhance the sensitivity.[2]

The ruby laser and seven-channel monochromator were arranged to permit spatial scanning along a diameter of the discharge. The spatial resolution was 1 cm along the diameter, and 1 mm perpendicular to it.

This apparatus was completely calibrated before each run. The silicon diode monitor was checked against a calorimeter, and the monochromator against a tungsten ribbon lamp.

For each spatial point six sets of oscilloscope traces were taken. These consist of laser alone, plasma alone, and laser plus plasma, first with the center monochromator channel at 6942 Å and then with it displaced by 25 Å. This yields 14 wavelength points, of which several have to be discarded due to background or stray scattered laser radiation.

In all cases, to within the experimental errors, the wavelength distribution of intensity approximates well to a Maxwell-Boltzmann distribution, and therefore the data are interpreted in terms of an electron temperature perpendicular to the magnetic field. These temperatures were obtained by least-squares fitting of the data by a Maxwell-Boltzmann distribution.

By integrating the data for each spatial point over wavelength, one can obtain an electron density. When this, in turn, is integrated over the diameter of the discharge the integrated density can be compared with 4-mm microwave phase-shift measurements. This was done for each case and agreement was always to within 15%.

To compare the Thomson-scattering temperatures with conductivity temperatures we compute an equivalent conductivity temperature $T_\perp = [\int_0^{r_0} T^{\frac{3}{2}} r dr / \int_0^{r_0} r dr]^{\frac{2}{3}}$. This is the temperature to be expected from the conductivity, assuming that the conductivity formula of Spitzer and Härm[3] is valid.

In Fig. 1(a) the ratio of $T_\perp$ to the measured conductivity temperature T_C is plotted against Γ, the ratio of the applied electric field to the electric field which will double the speed of an average electron in the mean free time between electron-ion collisions. This is Dreicer's[4] runaway parameter, and, were the conductivity temperatures correct, it would be proportional to the ratio of electron drift velocity, v_d, to the thermal velocity of the electrons, $v_{\rm th} = (3kT/m_e)^{1/2}$. As long as $T_\perp/T_C$ is a function of Γ there remains a functional relationship between these two quantities. In Fig. 1(b) the temperature ratio is plotted against the ratio of electron drift to thermal velocity.

It is clear that for $\Gamma \leq 0.01$ we have confirmed

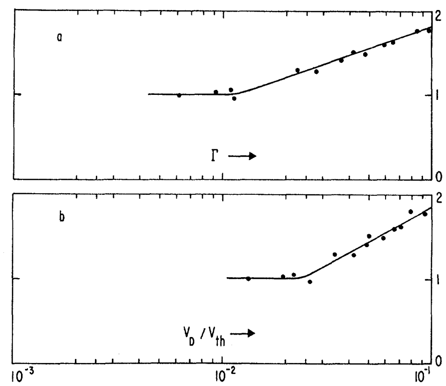

FIG. 1. The ratio of Thomson-scattering temperature to conductivity temperature plotted against (a) the runaway parameter Γ, and (b) the ratio of electron drift to thermal velocity.

the Spitzer and Härm conductivity to an accuracy of better than 5%. For $\Gamma > 0.01$ the plasma shows an anomalous resistivity which is an extraordinarily clean function of Γ or $v_d/v_{\rm th}$. These data include points for which a number of different plasma parameters have been varied. These include rotational transform, plasma diameter, current density, and time dependence of current density. None of these appears to result in any appreciable variation of the anomalous resistivity.

Previous measurements in the C Stellarator, including spectroscopic T_e,[5] microwave absorption,[6] Langmuir probes,[7] Doppler T_i,[8] and diamagnetic loops,[9] have all yielded approximate agreement with the conductivity formula. The precision of the present work is, however, unique, as is its clear indication of an anomalous resistivity in the C Stellarator.

That this anomalous resistivity does not arise from an influx of impurities is clear from the impurity measurements of Hinnov et al.[10] and, more recently, of Mickey,[11] showing impurity concentrations of less than 1%. For the low value of Γ at which the anomalous resistivity first appears, one can calculate from the theory of Dreicer[4] that only a negligible fraction of the electrons can have runaway. Thus it does not seem likely that the anomalous resistivity is related to the runaway phenomenon or to any significant difference between $T_\perp$ and $T_\parallel$. Looking at Fig. 1(b) one may note that the anomalous resistivity first appears when the drift velocity equals $(m_e/m_i)^{1/2}v_{\rm th}$.

Most previous work in which an anomalous resistivity has been observed involves high electric fields and a runaway discharge. An exception is the "Tokamak" work[12] in which a discrepancy exists, the conductivity temperatures being appreciably lower than those obtained with diamagnetic loops. From data given in Ref. 12 we attempted to estimate $v_d/v_{\rm th}$ versus the anomalous resistivity, and find that their temperature anomaly is similar in magnitude and occurs in the same range of $v_d/v_{\rm th}$ as ours. This suggests that the diamagnetic loop data may be the more reliable for the Tokamak device.

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