observed by neutron scattering and predicted on the basis of roton-roton interactions.[9] Rough estimates of the reaction distance at which metastable destruction occurs are in order-of-magnitude agreement with a "bubble" model for the metastables.

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Measurement of the dc Plasma Electric Resistivity Perpendicular to the Magnetic Surface*

M. Okabayashi and S. Yoshikawa
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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The measurement of the dc electric plasma resistivity perpendicular to the magnetic surface in a toroidal device was carried out using the FM-1 spherator. It was found that the perpendicular resistivity is inversely proportional to the neutral gas density and is independent of plasma density for a He^+ plasma at $T_e = 1$ eV. These parametric dependences are consistent with the resistivity expected from classical collisional processes.

Plasma resistivity parallel to a magnetic field line has been measured in many plasma confinement devices to investigate plasma characteristics in a magnetic trap.[1] A recent theoretical interest concerning electric field generation due to the injection of neutral beams[2] for plasma heating raises a question as to whether an anomalous process similar to the anomalous particle loss could conveniently produce a short-circuit effect for the charge separation. The present investigation was started in order to understand the mechanisms which cause electric conductivity across the magnetic surfaces of an FM-1 spherator, in which the confinement time is close to the classical collisional time constant.[3]

In the following, we first present the basic physical picture of the perpendicular resistivity and then compare the experimental results compared with the theory.

When the plasma decay time is sufficiently slower than the electron-neutral collision time $1/\nu_{en}$ and the ion-neutral collision time $1/\nu_{in}$, the basic physical picture of the perpendicular resistivity can be described by fluid equations for ions and electrons:

$$0 = -e\nabla\varphi + e(\vec{v}_i\times\vec{B}) - m_i\nu_{ie}(\vec{v}_i - \vec{v}_e) - m_i\nu_{in}\vec{v}_i, \quad 0 = e\nabla\varphi - e(\vec{v}_e\times\vec{B}) - m_e\nu_{ei}(\vec{v}_e - \vec{v}_i) - m_e\nu_{en}\vec{v}_e, \tag{1}$$

where φ is the electric potential, $\vec{B}$ is the magnetic field, $\vec{v}_i$ and $\vec{v}_e$ are the ion and electron velocities, ν_{ie} is the ion-electron momentum collision frequency, and ν_{ei} is the electron-ion momentum collision frequency. As is known,[4] in the classical process, there exists no perpendicular current without neutral collisions. By solving Eqs. (1) for the case $\omega_{ce}, \omega_{ci}, > \nu_{en}, \nu_{in}$, the current density perpendicular to the magnetic surface, $j_\perp$, is found to be related to the electric field perpendicular to the magnetic surface by

$$\nabla\varphi = -(\omega_{ci}{}^2 m_i/e^2 n_e \nu_{in}) j_\perp. \tag{2}$$

Here, it is assumed that $m_e\nu_{en} < m_i\nu_{in}$. In this assumption the current is mainly carried by ion mobility. The electric field caused by the current across the magnetic field should produce the $\vec{E}\times\vec{B}$ flow on magnetic surfaces.

The FM-1 spherator plasma confinement device consists of the levitated superconducting ring, a set of external vertical field coils, and a toroidal field conductor. The average magnetic field strength is about 2.0 kG. As reported previously,[3] in the FM-1 spherator, plasma is confined with a time constant of 0.6–1.2 sec at a plasma density $n_e = (0.5-1)10^{11}$ cm^{-3}, with electron temperature $T_e \sim 1$ eV, and a neutral-gas density $n_n \sim 10^{11}$ cm^{-3}. The confinement time reaches about $\frac{1}{4}$ of the classical confinement time.

For the present experiment a helium-afterglow plasma is used. The electron temperature is kept about 1 eV by applying nonresonant microwave heating.[3] To produce the electric field perpendicular to the magnetic surface, a small electrode is inserted into the plasma volume at the outside horizontal plane and biased at a positive voltage with respect to the divertor conducting limiter plate, which is located just inside the most outside magnetic surface. The produced potential is measured by inserting a single Langmuir probe, which can travel the whole plasma column within 50 msec, driven by a pneumatic mechanism. This fast-moving probe is inserted at different times into the afterglow plasma, providing experimental results at different plasma density without changing the plasma production conditions. The typical parameters, size of the electrode, and notation are shown in Table I.

The relation between current to the electrode, I, and the observed potential is obtained by integrating Eq. (2) over the magnetic surface:

$$E_\perp \equiv -\frac{\partial\varphi}{\partial\psi} = \frac{\int j_\perp\, dS}{4\pi^2 n_e \nu_{in} m_i \int (R^2/B^2)\, d\chi}, \qquad \int j_\perp dS \equiv I, \tag{3}$$

where the toroidal coordinates (ψ, χ, θ) are used. The current to the electrode, I, is the same as that across the magnetic surface by continuity.

TABLE I. Typical experimental parameters.

n_e	(plasma electron density)	1.0×10^{11} cm^{-3}
n_n	(neutral gas density)	1.2×10^{11} cm^{-3}
T_e	(electron temperature)	1 eV
T_i	(estimated ion temperature)	0.5 eV
B	(average magnetic field)	2.0 kG
ω_{ce}	(electron cyclotron angular frequency)	3.5×10^9 sec^{-1}
ω_{ci}	(ion cyclotron angular frequency)	9.0×10^5 sec^{-1}
ν_{in}	(ion-neutral collision frequency)	0.4×10^2 sec^{-1}
ν_{en}	(electron-ceutral collision frequency)	2.4×10^3 sec^{-1}
ν_{ii}	(ion-ion collision frequency	4.0×10^3 sec^{-1}
$1/\tau_{conf}$	(inverse of the confinement time)	$1 \sim 0.6$ sec^{-1}
S_{MAG}	(area of magnetic surface)	6.3×10^3 cm^2
$S_{electrode}$	(area of electrode surface)	1.3×10^{-2} cm^2
S_{shaft}	(area of shaft of the electrode)	3.0×10^{-1} cm^2
V_{plasma}	(volume of plasma)	7.0×10^5 cm^2
a	(plasma column length at the outside forizontal plane)	10 cm
$\oint R^2/B^2\, d\chi$		2.6 m^3/weber
$E_{\perp observed}$	(observed perpendicular electric field)	40 V/weber
$E_{\perp cal}$	(calculated perpendicular electric field)	60 V/weber
I	(measured across current to the electrode)	0.8 mA

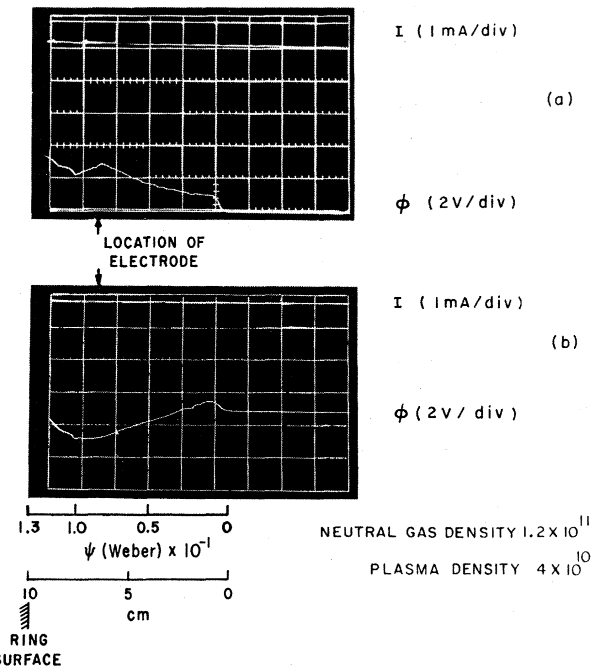

FIG. 1. (a) Cross current I to the biased electrode inserted in the plasma (the top line shows zero level), and potential φ versus distance from the surface of the ring, measured by a fast inserting probe. The electrode is applied at +120 V. (b) Potential φ versus distance without bias.

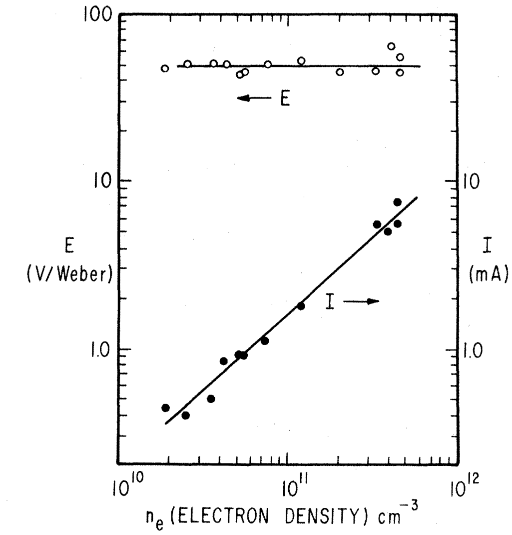

FIG. 2. $E_\perp$ and I versus neutral gas density at a neutral gas density of 1.2×10^{11} cm^{-3}.

Since the current I to the electrode biased with high positive potential is determined by the electron saturation current, I is proportional to the plasma density. Thus, it is expected that the perpendicular electric $E_\perp$ is insensitive to the change in plasma density and only inversely proportional to the neutral density due to ion neutral collisions.

In order to make a comparison of the experimental results with the simplified theory mentioned in the above, the electrode is inserted into the plasma to the region of peak density where the plasma density profile is relatively flat (the density-gradient effect is presumably small). Also, the positive bias voltage to the electrode is set up at 120 V to avoid the correction due to the temperature gradient. Figure 1 shows the observed potentials versus position measured by the pneumatic driven probe. It is noticed that the potential reaches a maximum at the biased electrode position. The electric field is obtained from the gradient of the electric potential at the electrode position. Figure 2 shows that measured electric field versus plasma density at the neutral gas density of 1.2×10^{11} cm^{-3}. The total current I changes linearly against the plasma density as expected from Eqs. (2) and (3). The electric field stays approximately constant with the range of $n_e = 1\times10^{10}$ cm^{-3} to 4×10^{11} cm^{-3}. In Fig. 3 we present the dependence of $E_\perp$ on the neutral density. For the measurement the plasma density is kept at 4×10^{10} cm^{-3}. The observed electric field $E_\perp$ is inversely proportional to the neutral pressure, while the current I is constant. These dependences are also consistent with the simplified theoretical argument. The numerical values shown in Table I yield the electric field

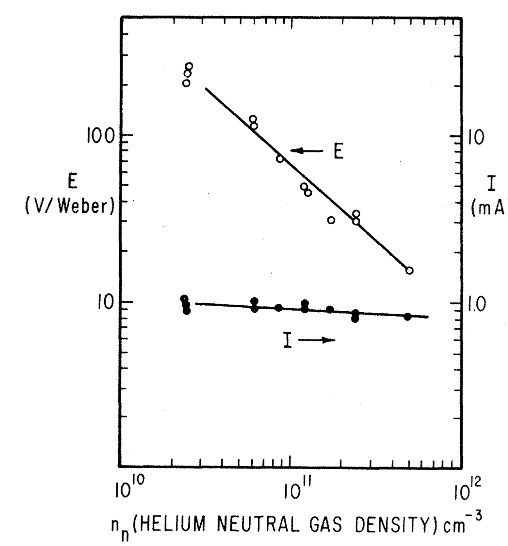

FIG. 3. $E_\perp$ and I versus neutral gas density at a plasma density of 4.0×10^{10} cm^{-3}.

$E_\perp = 60$ V/Wb at $n_e = 10^{11}$ cm^{-3}, which is in good agreement with the observed value of 40 V/Wb.

As described above, the observed electric field perpendicular to the magnetic field, $E_\perp$, is determined by the ion-neutral collisions, which is consistent with the simplified classical collisional theory. However, there are some questions concerning the present measurement: the ion-ion collision effect and the insertion of the electrode. For the ion-ion collision effect, the viscosity term[5] $\eta_0 \nabla^2 v$ has to be added to Eq. (1). It is expected that the viscosity effect tends to drag the $\vec{E} \times \vec{B}$ flow on the magnetic surface, which should balance the current across the magnetic surface. The potential decay length Λ, due to the viscosity effect obtained from Eq. (1) including the term $\eta_0 \nabla^2 v$, is

$$\Lambda = \frac{v_{\text{ith}}}{2\sqrt{2}} \frac{1}{\omega_{ci}} \left(\frac{\nu_{ii}}{\nu_{in}} \right)^{1/2}, \tag{4}$$

where v_{ith} is the ion thermal velocity. For numerical values given in Table I, Λ is 2.0 cm (which is less than the plasma radius), so that the effect of viscosity on the perpendicular field is not so important for the experiment.

In the present experiment, the electrode is inserted into the plasma volume. Since the existence of the electrode (including the shaft) acts as an obstacle, it is possible that (1) ions collide with the electrode as well as with the neutral gas, and (2) the particle flow resulting from $\vec{E} \times \vec{B}$ motion is absorbed by the obstacle. For the values given in Table I, these two time constants for cases 1 and 2 are much slower than the ion-neutral collisional time. Experimentally, the additional insertion of a similar probe produces no significant change on the electric field. Although the small electrode is located at a certain azimuthal position, the possibility of a nonaxisymmetric potential distribution is ruled out by measuring the electric field $E_\perp$ at different azimuthal directions. It might be possible to excite instabilities by a current across the magnetic surface, which has been observed in a straight tube discharge. In the present experiment, the confinement time is monitored by changing the bias voltage. No reduction of the confinement time is observed as the cross current I is increased, which indicates that no strong turbulence is produced.

In conclusion, the measurement of the electric field perpendicular to the magnetic surface was carried out in the FM-1 spherator by inserting an electrode into the plasma volume. The observed perpendicular electric field is inversely proportional to the neutral gas density, which is consistent with the classical collisional theory. The estimated numerical values are also in good agreement with the observed value. We note that the ratio of this observed perpendicular resistivity to the parallel resistivity[6] (which has been shown to agree with the theoretical value in various experiments carried in other devices[1]) is of the order of 10^8 to 10^9. To that extent we conclude that there exists no anomalous resistivity perpendicular to the magnetic surface in the FM-1 spherator for the afterglow plasma of $n_e \sim 10^{11}$ cm^{-3} and $T_e \sim 1$ eV, where the confinement time follows close to the classical collisional process. However, in this experiment, ions are forced to flow perpendicular to the magnetic surface. On the other hand, when electrons are forced to flow across the magnetic surface, there is an indication of anomalous conductivity as observed previously.[7] Thus, we cannot rule out the possibility that there exists an anomalous conductivity if the plasma is charged negative.

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