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Measurement of electron–atom collision frequency in an arc plasma by a radiofrequency coil probe combined with a transverse magnetic field

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Abstract

The tensorial behaviour of electrical conductivity of an arc placed in a transverse magnetic field (≤ 360 G) has been explored to measure the electron–atom collision frequency (ν_{ce}). The measurements have been carried out in the range of currents 3.0–5.0 A, at a pressure 0.0625 Torr. © 2000 Elsevier Science B.V. All rights reserved.

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Measurement of azimuthal electrical conductivity in a plasma with the help of an inductor having the discharge as a core material has been proposed by several authors [1–3] and measured in an arc plasma by Ghosal et al. [4,5]. From the measurement of electrical conductivity electron–atom collision frequency (ν_{ce}) has been measured by Sen et al. [6] in an arc plasma by the radiofrequency coil probe in conjunction with a longitudinal magnetic field, taking the effect of radial distribution function of azimuthal conductivity as proposed by Ghosal et al. [5]. In fact, ν_{ce} has been measured as an average over the plasma cross section. More precisely, the tensorial behaviour of plasma conductivity was explored to determine ν_{ce} after plasma was subjected to a small steady longitudinal magnetic field. The object of the present work, in principle, is to establish that the radiofrequency coil probe jointly with a weak transverse magnetic field may also be used to measure ν_{ce} and verify whether the method as applied by Sen et al. [6] is valid in transverse magnetic field.

The generalised Ohm's law for a stationary plasma in the steady state may be written as

$$\boldsymbol{J} = \sigma_0 \boldsymbol{E} + \mu(\boldsymbol{J} \times \boldsymbol{B}), \tag{1}$$

where $\sigma_0 = ne^2/m\nu_{ce}$, $\mu = -e/m\nu_{ce}c$.

Here $\boldsymbol{J}$ is the current density, $\boldsymbol{E}$ the electric field, $\boldsymbol{B}$ the magnetic field, σ_0 the electrical conductivity in the zero magnetic field and ν_{ce} is the electron–

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atom collision frequency. If B is applied along the z-axis and ion contribution to the conductivity is ignored, J and E will be expressed by the tensor, which follows from Eq. (1), as

$$\begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \begin{bmatrix} \sigma_{\parallel} & -\sigma_{\perp} & 0 \\ \sigma_{\perp} & \sigma_{\parallel} & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \tag{2}$$

where

$$\sigma_{\parallel} = \sigma_0/(1+\mu^2B^2) = \sigma_0\nu_{\mathrm{ce}}^2/(\nu_{\mathrm{ce}}^2+\omega_{\mathrm{eB}}^2),$$

$$\sigma_{\perp} = -\sigma_0\,\mu\mathrm{B}/(1+\mu^2B^2) = \sigma_0\,\omega_{\mathrm{eB}}\nu_{\mathrm{ce}}/(\nu_{\mathrm{ce}}^2+\omega_{\mathrm{eB}}^2), \tag{3}$$

and ω_{eB} is the electron cyclotron frequency.

Thus, $\sigma_{xx} = \sigma_{yy}$ $(=\sigma_{\parallel})$, which is known as magnetoconductivity, becomes different from σ_{zz} $(=\sigma_0)$ when the plasma is subjected to a magnetic field, which may be noted as

$$\sigma_{\parallel} = \sigma_0/(1+\omega_{\mathrm{eB}}^2/\nu_{\mathrm{ce}}^2). \tag{4}$$

It may be stated that the frequency of the applied field is $\ll \nu_{\mathrm{ce}}$ and that $\omega_{\mathrm{eB}} = 0$ in the absence of transverse magnetic field.

We may introduce the constriction parameter a [5,6] as

$$\int_0^R r^3\sigma(r)\,\mathrm{d}r \Big/ \int_0^R r\sigma(r)\,\mathrm{d}r = a = (E/I)\left[(\alpha-1)R_0/f^2k^2l\right] = a'R_0/f^2k^2l, \tag{5}$$

with

$$a' = (E/I)(\alpha-1), \tag{6}$$

where $\sigma(r)$ is the radial variation of electrical conductivity, E the axial electric field strength per unit length, I the discharge current, α the ratio of the radiofrequency current without and with the plasma of interest, R_0 the radiofrequency resistance, f the frequency of the radiofrequency coil probe, k a constant depending upon the number of turns of the primary coil and l is the length of the coil.

In the presence of magnetic field we may write, in the light of Eq. (5), the constriction parameter a_{B} [6] as

$$\int_0^R r^3\sigma_{\parallel}(r)\,\mathrm{d}r \Big/ \int_0^R r\sigma_0(r)\,\mathrm{d}r = (\sigma_{\parallel}/\sigma_0)a_{\mathrm{B}} = (E_{\mathrm{B}}/I_{\mathrm{B}})\left[(\alpha_{\mathrm{B}}-1)R_0/f^2k^2l\right] = a'_{\mathrm{B}}R_0/f^2k^2l, \tag{7}$$

with

$$a'_{\mathrm{B}} = (E_{\mathrm{B}}/I_{\mathrm{B}})(\alpha_{\mathrm{B}}-1). \tag{8}$$

It is now assumed that for weak magnetic field the confining effect is less significant. Thus, the

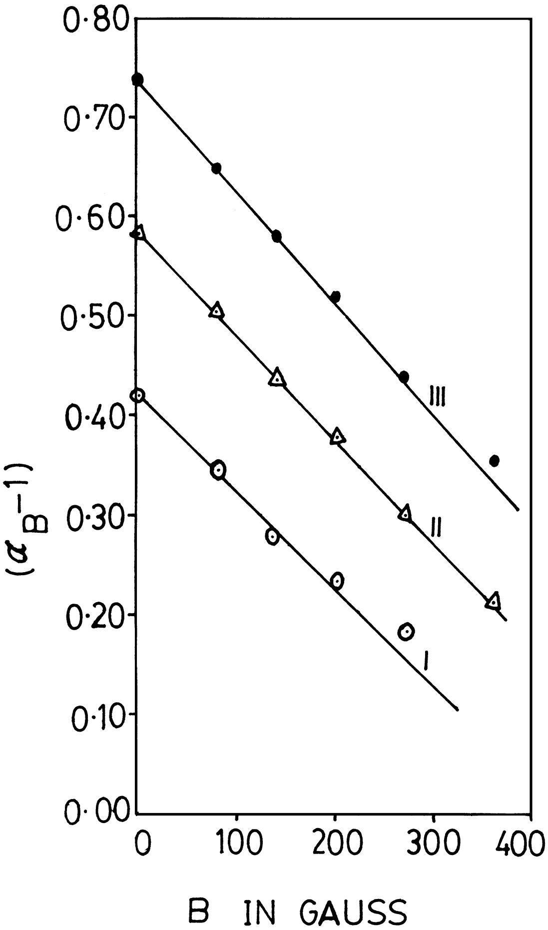

Fig. 1. Variation of $(\alpha_{\mathrm{B}}-1)$ with magnetic field at $P = 0.0625$ Torr; initial arc current: 3.0 A (I); 4.0 A (II); and 5.0 A (III).

distribution function may be considered to be the same in the presence and in the absence of magnetic field i.e. $a = a_B$.

Therefore, from Eqs. (5) and (7),

$$\sigma_{\parallel}/\sigma_0 = a'_B/a'. \tag{9}$$

The quantities a'_B and a' may be measured experimentally. From Eqs. (4) and (9), we may write

$$\begin{aligned}\nu_{ce} &= \omega_{eB}/\left[(a'/a'_B) - 1\right]^{1/2} \\ &= 1.76 \times 10^7 B/\left[(a'/a'_B) - 1\right]^{1/2}, \end{aligned} \tag{10}$$

where B is expressed in gauss.

Details of the experimental arrangement for this work has been reported by Sen et al. [6]. Measurements have been made for a mercury arc plasma formed within an arc tube of length 31.5 cm and internal diameter 1.75 cm in which anode-cathode spacing is around 24 cm and is energized by stabilised DC source. The main discharge current has been controlled by the high current capacity rheostat inserted in series with the DC supply. The mercury arc is cooled by the external circulation of air. The pressure inside the tube is maintained at 0.0625 Torr with the help of a variable microleak needle valve fitted to the pump line of the discharge tube. The two tungsten probes within glass capsules with a bare tip of 0.1 cm have been utilised to measure the axial electric field strength in the plasma column. The mercury arc is placed between the pole pieces of an electromagnet energized by a stabilised DC source. The magnetic lines of force are perpendicular to the direction of the flow of the discharge current.

The oscillator coil was placed close to the work-coil wound around the discharge tube and induced radiofrequency (3.69 MHz) voltage was tuned with a variable condenser which forms a secondary tank circuit with the work-coil. The tuned currents were measured by a radiofrequency milliammeter in the presence and in the absence of the magnetic field for three different arc currents, namely, 3.0, 4.0 and 5.0 A. The probe-to-probe voltage with or without magnetic field was measured simultaneously, by high impedance voltmeter.

Measurements of the tuned radiofrequency (coil probe) current without the arc being excited and the same when the arc is excited in the absence and in the presence of transverse magnetic field, were taken for three different initial arc currents (3.0, 4.0 and 5.0 A) at 0.0625 Torr pressure. The values of $(\alpha_B - 1)$, as determined experimentally, have been plotted against different magnetic fields ($B \leq 360$ gauss) for three initial arc currents in Fig. 1. It is observed that $(\alpha_B - 1)$ decreases linearly with the increase of

Table 1

Arc current A	B Gauss	$\alpha_B - 1$	I_B/E_B amp cm/volt	a'_B	$[(a'/a'_B) - 1]^{1/2}$	ν_{ce}
3.0	0	0.421	5.657	0.0744	0.0000	4.507×10^9
	80	0.345	5.200	0.0663	0.3867	
	140	0.285	4.917	0.0580	0.5334	
	200	0.232	4.550	0.0510	0.6777	
	270	0.185	4.238	0.0436	0.8396	
4.0	0	0.586	8.223	0.0713	0.0000	5.333×10^9
	80	0.518	7.750	0.0655	0.3391	
	140	0.440	7.524	0.0585	0.4675	
	200	0.380	7.200	0.0528	0.5919	
	270	0.315	6.750	0.0467	0.7262	
	360	0.223	6.250	0.0357	0.9217	
5.0	0	0.742	11.000	0.0674	0.0000	6.443×10^9
	80	0.658	10.425	0.0631	0.3067	
	140	0.581	10.170	0.0574	0.4295	
	200	0.523	9.780	0.0535	0.5395	
	270	0.438	9.295	0.0471	0.6566	
	360	0.353	8.748	0.0407	0.8190	

magnetic field but shows departure for higher magnetic field.

The probe-to-probe voltages for the above mentioned three different arc currents at pressure 0.0625 Torr have been measured, and the values of I/E and $a' = (E/I)(\alpha - 1)$ for zero applied magnetic field are shown in the Table 1. Similarly, corresponding quantities, namely, I_B/E_B and a'_B in the presence of different magnetic fields, 80, 140, 200 and 270 G in the case of arc current 3.0 A and 80, 140, 200, 270 and 360 G for arc currents 4.0 and 5.0 A, have been measured, and the details have been entered in Table 1. The values of I_B/E_B have been plotted against magnetic fields for three initial arc currents in Fig. 2 and the nature of the graph is fairly linear.

The values of $[(a'/a'_B) - 1]^{1/2}$ have been calculated and plotted against magnetic field in Fig. 3. The linear proportionality between $[(a'/a'_B) - 1]^{1/2}$ and B confirms the assumptions made in arriving at the formula (9). It is particularly worth mentioning that although the transverse magnetic field has been employed upto 270 G in the case of arc current 3.0 A and 360 G for 4.0 and 5.0 A arc currents, the linear proportionality remains effective upto 150 G (approx.) magnetic field, which may be construed as the limiting value of magnetic field, below which the measurements of the parameters are to be conducted. In other words, the assumptions that the distribution function remains unchanged and the confining effect is negligible are valid upto the magnetic field of 150 G or so for the present experiment. However, the said linear proportionality between $[(a'/a'_B) - 1]^{1/2}$ and B holds upto a much higher value of the magnetic field in the previous work by Sen et al. [6], indicating that the confining effect vis-a-vis the limiting value of magnetic field depends on the alignment of magnetic field with respect to the discharge axis. It is concluded by Sen and Gantait [7] that both orientations of the magnetic field have similar effect on the arc plasma though a transverse magnetic field has stronger effect than a longitudinal field on the

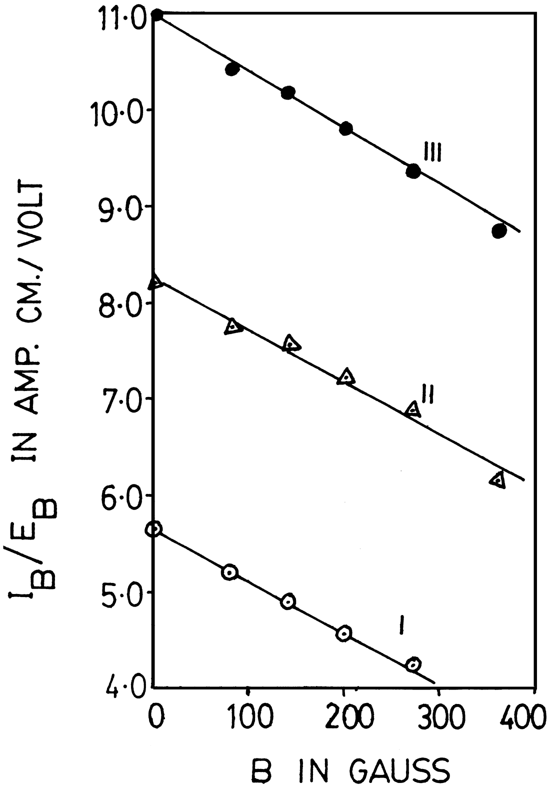

Fig. 2. Variation of I_B/E_B with magnetic field at P = 0.0625 Torr. Symbols as in Fig. 1.

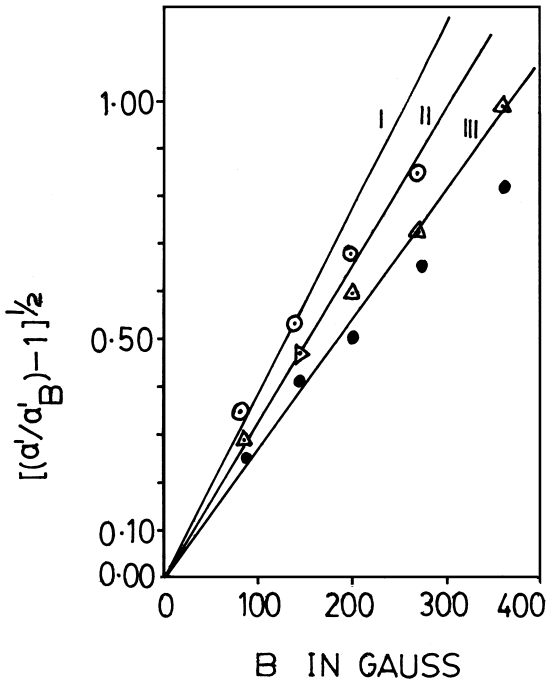

Fig. 3. Variation of $[(a'/a'_B)-1]^{1/2}$ with magnetic field at P = 0.0625 Torr. Symbols as in Fig. 1.

discharge. This may be attributed to the fact that though the arc of interest is of low temperature collisional plasma, it cannot be considered fully isotropic, probably due primarily to electron drift velocity. This causes more pronounced change in the electron density and temperature in the presence of transverse magnetic field, affecting electron distribution function. Thus, it explains as to why a relatively lower transverse magnetic field is the limiting value as compared with that of longitudinal magnetic field.

The value so obtained for ν_{ce} increases with the increase of arc current as it makes the mercury hotter. In a recent paper [8] the author has shown that the on-axis conductivity decreases exponentially with the tube radius and that the rate of dimunition of the radial conductivity is much less for tubes with larger radii. More precisely, it is observed therein that the plasma column contracts with the decrease of the tube radius, making the conductivity higher and hence ν_{ce} smaller for smaller tube radius for same value of I/E. Therefore, ν_{ce} depends not only on the discharge current, voltage drop across the arc and positive column, pressure and the ‘cooling’ used for the arc, as reported earlier [6], but also on the radius of the discharge tube and hence on the plasma profile.

It may be concluded by noting that this technique provides an alternative arrangement which is somewhat straightforward to determine the electron–atom collision frequency (ν_{ce}) for momentum transfer with some accuracy at various currents, in fact, at various I/E values. Further, the same may be extended to find ν_{ce} at various mercury vapour pressures and tube radii too. Finally, it is concluded that the values of ν_{ce} obtained are consistent with standard literature values and the method can be considered as an alternative one for measuring ν_{ce}.

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