Indian J. Phys. **49**, 434–439 (1975)

Determination of $\omega\tau$ and effective collision frequency in a weakly ionized magneto plasma

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(*Received* 14 *October* 1974, *revised* 28 *February* 1975)

The parameter $\omega\tau$ for electrons in a PIG type magneto plasma has been determined experimentally. From the measured values of $\omega\tau$, the effective collision frequency ν_e for electrons has been evaluated for two pressures (1.1×10^{-2} and 2.8×10^{-2} Torr) in argon gas. The values of $\omega\tau$ and ν_e found by us, although agree in order of magnitude with the values calculated for electron-neutral collisions, show an unusual dependence on the applied magnetic field. It is probable that the observed depedence arises due to the restriction of electron motion perpendicular to the magnetic field.

1. Introdction

The product of gyrofrequency and collision mean free time, $\omega\tau$, for charged particles in a plasma in presence of magnetic field is an important parameter. The transport properties of such a magneto plasma depend largely on the values of $\omega\tau$. For $\omega\tau < 1$ the plasma is collision dominated and in the reverse case, $\omega\tau > 1$, the effect of gyroradius predominates. Usually this parameter $\omega\tau$ is determined from the known values of ω and τ. In one case, Urazakov & Granoviski (1962) have made a direct determination of the values of $\omega\tau$ for electrons and ions in a positive column plasma in a longitudinal magnetic field. From the measured values of $\omega\tau$ these authors have also estimated the electron-neutral and ion-neutral collision frequencies (ν_{en}, ν_{in}) which agree satisfactorily with those calculated from the collision cross-section data.

In the present experiment we have extended these measurements to the case of plasma in crossed electric and magnetic fields as obtained in a PIG discharge. Since in the usual operating range the PIG contains large fractions of noise and instabilities, we have used the discharge in such regions of pressure and magnetic field where the discharge is known to be fairly stable and the contribution due to the instabilities is negligible. In the following sections we describe briefly our experimental study of $\omega\tau$.

2. Method

When a cylindrical plasma column is subjected to a uniform axial magnetic field, in addition to the radial diffusion the charged particles in the column experience a transverse diffusion in the azimuthal direction. The velocities v_r and v_θ

of the radial and azimuthal diffusion of electrons or ions in the plasma column are given, respectively, by the following expressions derived by Chapman & Cowling (1953)

$$v_r = \tau \frac{e}{m}\left(E_r - \frac{kT}{e}\frac{1}{n}\frac{dn}{dr}\right)\frac{1}{1+\omega^2\tau^2}, \tag{1}$$

and

$$v_\theta = \omega\tau^2 \frac{e}{m}\left(E_r - \frac{kT}{e}\frac{1}{n}\frac{dn}{dr}\right)\frac{1}{1+\omega^2\tau^2}, \tag{2}$$

where E_r is the radial electric field, $1/n.dn/dr$ the relative radial density gradient, k the Boltzmann constant, e the electronic charge and m, T, ω and τ are, respectively, the mass, temperature, gyrofrequency and collision free time of the charged species.

It can be seen in eqs. (1) and (2) that v_r and v_θ are related to each other by

$$v_\theta = \omega\tau v_r. \quad \ldots \tag{3}$$

Now since the radial and azimuthal current densities are given by $J_r = nev_r$ and $J_\theta = nev_\theta = \omega\tau nev_r$, we have

$$J_\theta/J_r = \omega\tau. \tag{4}$$

Thus the quantity $\omega\tau$ can be directly determined, if we can measure the radial and azimuthal diffusion currents in the plasma column by means of suitable electrical probes. Measuring $\omega\tau$ in this manner and knowing ω we can then find the effective collision mean free time τ or the mean frequency $\nu = \tau^{-1}$ for electrons and ions. For weakly ionised plasma, the electron-electron and electron-ion collisions are infrequent and, therefore, the value of τ or ν obtained in this case will represent those for the electron-neutral and ion-neutral collisions.

3. Experiment

The experiment was carried out in a cold cathode PIG (Philips Ionization Gauge) discharge using a number of directed electrical probes. Figure 1 gives a schematic representation of the experimental set up. The discharge tube consists of a 5 cm. dia. and 50 cm long pyrex glass tube fitted with two pairs of water cooled cathodes and anodes (K, A) at its two ends and having six side tubes for probes, vacuum connections, gas inflow and pressure gauges. The discharge tube was operated in presence of the longitudinal magnetic field provided by the solenoid magnet (M). The PIG system was constructed by us for studying problems related to the magnetic confinement of plasma. This type of discharge is usually operated in the low pressure region ($\leqslant 1\times10^{-2}$ Torr) for plasma studies. In order to avoid the inclusion of non collisional effects in the $\omega\tau$ measurements, the present experiment was carried out at pressures above

1×10^{-2} Torr, where the critical magnetic field for the onset of instabilities is fairly high, about 1 K.Gauss.

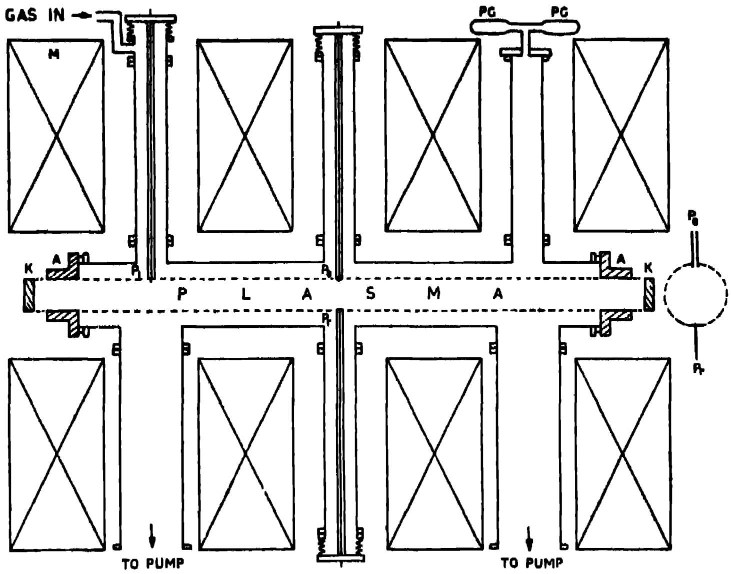

Fig. 1. Experimental arrangement.

The azimuthal and radial diffusion currents were measured, respectively, by the two directed probes P_θ and P_r placed at the same radial distance from the axis of the discharge. The azimuthal probe P_θ is a twin plane probe with its collecting faces oppositely directed and the near faces separated by a thin insulating layer. The two collecting faces of P_θ were operated at the common bias voltages and the value of azimuthal current density was found from the difference in the currents registered on the two faces, $J_\theta = J(0) - J(\pi)$. The radial probe P_r is a small area plane probe 1 mm. dia.) with its collecting face perpendicular to the radial direction. At its wall or floating potential this probe collects equal amounts of ion and electron currents as radial ambipolar diffusion current, $J_{r+} = J_{r-}$ (Loeb 1955). For the value of J_r (+ or —) the value of the ion saturation current of P_r was taken because P_r will collect this amount of ion and an equal amount of electron current when biased for the floating potential.

Measuring J_θ and J_r by the above procedure the corresponding values of $\omega\tau$ and ν were then estimated for different values of gas pressure and magnetic field. Table 1 gives several examples of our measurements for the electron component of the PIG plasma in weakly ionized condition. The gas used was argon. In table 2 are shown the values of the collision frequency ν_e estimated from the data in table 1 and also the calculated frequency ν_c from collision cross-section data (Brown 1955) for comparison. The value of electron velocity v

necessary for the calculation of ν_c was estimated from the measurement of electron temperature T_e in the discharge using the Langmuir probe P_1 in figure 1.

Table 1. Measured and calculated values of $\omega\tau$

P (Torr)	B (Gauss)	J_0 (mA. cm^{-2})	J_r (mA. cm^{-2})	$\omega\tau$ (Measured)	$\omega\tau$ (Cal)
2.8×10^{-2}	370	120.40	7.22	16.67	8.75
	510	104.70	6.70	15.63	12.06
	600	94.22	6.02	15.65	14.19
	850	89.00	5.86	15.19	20.10
	1040	57.58	4.97	11.58	24.58
1.1×10^{-2}	370	125.63	4.20	29.91	17.81
	510	120.40	3.30	36.48	24.55
	600	120.40	3.04	39.60	28.88
	850	115.16	2.77	41.57	40.92
	1040	94.22	2.62	35.96	49.91

Table 2. Effective collision frequency ν_e from $\omega\tau$ measurements and calculated electron-neutral frequency ν_c.

P (Torr)	B (Gauss)	ω ($\times10^9$c/s.)	ν_e ($\times10^8$c/s.)	ν_c ($\times10^8$c/s.)
2.8×10^{-2}	370	1.04	0.62	
	510	1.43	0.91	
	600	1.68	1.07	1.18
	850	2.38	1.57	
	1040	2.90	2.50	
1.1×10^{-2}	370	1.04	0.35	
	510	1.43	0.39	
	600	1.68	0.42	0.58
	850	2.38	0.57	
	1040	2.90	0.81	

4. Discussion and Conclusions

In the previous sections (2 & 3) we have described a procedure for determining experimentally the values of $\omega\tau$ and ν, and presented some of our results obtained with its help in the case of a weakly ionized PIG discharge. By using the same method Urazakov & Granoviski (1962) had found the values of electron-neutral and ion-neutral collision frequencies which agree satisfactorily with those calculated from the collision cross-section data. Our measurements shown in tables 1 and 2, although generally agree with the collision data, reveal one interesting feature of the electron component of the plasma. The measured value of $\omega\tau$ for electrons at a given pressure, intead of increasing with the increase of the magnetic field, remains almost constant up to about 1 K.Gauss and then shows a tendency of decrease (table 1). Our finding suggests that the effective collision mean free time for electrons τ_e is decreasing and the frequency ν_c is increasing with the increase of the magnetic field.

As to the reason for the above behaviour of the electron component of the plasma, two possibilities, may be considered. The first one is the influence of the plasma instabilities and the second possibility is the restriction of the electron motion perpendicular to the magnetic field. The PIG discharge in which we have carried out the present study is known to behave differently in different pressure region. The discharge operates in a stable manner in the low pressure region below about 10^{-4} Torr where it is used as a gauge for measuring low pressures. In the region between 10^{-2} and 10^{-4} Torr, the discharge is mostly dominated by noise and instabiliities which start appearing at almost the smallest value of the magnetic field (100 G or so) at which the discharge could be maintained. At pressures above 10^{-2} Torr the PIG operation is again stable, noise and instabilities contributing only at high values of the magnetic field ($\sim$ 1 KG and more). Since we have operated the discharge at its stable mode at pressures above 10^{-2} Torr and magnetic field below the critical value for the onset of instabilities, we can ignore the possibility that the plasma instabilities are causing the effect found by us. Our measurements of *rf* signals in the same PIG plasma have shown that, for pressures above 1×10^{-2} Torr, appreciable noise emission takes place only at magnetic field above about 1 K.Gauss. In a similar set up Briffod *et al* (1964) had found values of the critical magnetic field for the onsent of instabilities which agree with our observations. Thus in our case, instabilities could influence only our measured $\omega\tau$ at 1040 G, and other values of $\omega\tau$ for lower magnetic fields are free from the effect of instabilities.

The hindrance of electron motion perpendicular to the magnetic field is the other possibility of the observed effect. In order to interpret the effect of a perpendicular magnetic field in electrical discharges an equivalent electric field (Allis 1956) or an equivalent pressure (Blevin & Haydon 1958) concept has been used. Following Allis (1956), Heylen & Bunting (1969) have shown that the previously assumed constant electron collision frequency changes not only with the electron energy but also with the applied magnetic field. In their paper, these authors have given the calculated values of the electron collision frequency according to the equivalent field approach for successive values of the magnetic field. These values show that the electron collision frequency increases appreciably with the increase of the magnetic field even when the average energy of the electrons remains unaltered. This theoretical finding of Heylen and Bunting, therefore, agrees with our measurements reported here.

We conclude from our present experiment that the measurement of the radial and azimuthal diffusion currents in a magneto plasma provides a suitable method for determining $\omega\tau$ and ν for charged particles, which yielded for our case of the electrons in a crossed field PIG discharge the values of these parameters agreeing in order of magnitude with the corresponding values computed from the collision theory. Further, our observation of a nearly constant $\omega\tau$ and hence an increasing value of the effective electron collision frequency ν for both the pressures (1.1×10^{-2} and 2.8×10^{-2} Torr) investigated arises possibly as an effect of the confining magnetic field which can be interpreted in terms of the equivalent field approach as extended by Heylen & Bunting (1969).

Acknowledgments

The authors wish to express their gratitudes to Prof. D. N. Kundu, Director, Saha Institute of Nuclear Physics and Prof. B. D. Nagchaudhuri, Vice Chancellor, Jawaharlal Nehru University, Delhi, for their keen interest in the present work.

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