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A STUDY OF A WEAKLY IONIZED, ROTATING PLASMA

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Rotating plasmas are often studied for separation of species of different mass [1,2]. If in a cylindrical system with an axial magnetic field a current is drawn between a point-like cathode (on axis) and a ring-shaped anode, the radial component of the electrical current together with the magnetic field causes a Lorentz force which drives the ionized particles in azimuthal direction. Neutrals, present in the system will be driven in the same direction due to collisions with the ions. This azimuthal velocities of ions and neutrals lead to centrifugal forces which can be used for separation of species of different mass.

In this paper measurements are given on a stationary rotating plasma with a low degree of ionization (~ 2%). The values of the rotational velocity of the neutrals are compared with values calculated from a single fluid M.H.D. theory used by Klüber [3] and Wilhelm and Hong [4], which is adapted to our experimental arrangement. Ion conduction is also included in our theoretical calculations [5]. The measurements were done in argon or xenon at filling pressures of 1 to 10 torr.

Apparatus

The main difference between the present experiment (diameter 2R=12 cm, length L about 50 cm) and other rotating plasma experiments is that two cathode-anode configurations which face each other are used (fig.1). Calculations show that in this case the axial derivatives of the rotational velocity and the plasma potential are small in the volume between the two anodes [6]. The cylinder wall contains 24 electrically insulated stainless steel rings (2 cm thick). Two of these rings serve as anodes. Between the two anodes diagnostic ports are installed which allow optical and probe measurements in the symmetry plane of the experiment.

The rotational velocity and heavy particle temperature are determined from the Doppler shift and width of plasma spectral lines. The plasma density is determined by adding a small amount of hydrogen to the discharge and measuring the H β Stark broadening. The pressure distribution and the separation of species of different mass are measured by means of calibrated pressure probes which are designed such that only static pressures are measured.

Theory

In the magneto-gasdynamic approximation the equation of conservation of electric charge density ($\nabla \cdot J=0$) and the Navier-Stokes equation, both combined with the generalized Ohm's law give rise to the following set of equations:

$$\frac{1}{r} \frac{\partial}{\partial r} (r \frac{\partial \phi}{\partial r}) + \frac{\sigma}{\sigma_{\perp}} \frac{\partial^2 \phi}{\partial z^2} - B \frac{1}{r} \frac{\partial}{\partial r} (r v_{\theta}) = 0$$

$$\mu \left[\frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial}{\partial r} (r v_{\theta}) \right) + \frac{\partial^2 v_{\theta}}{\partial z^2} \right] - \sigma_{\perp} B \left(- \frac{\partial \phi}{\partial r} + v_{\theta} B \right) = 0$$

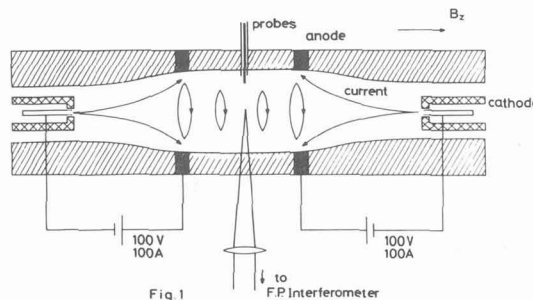


Fig 1

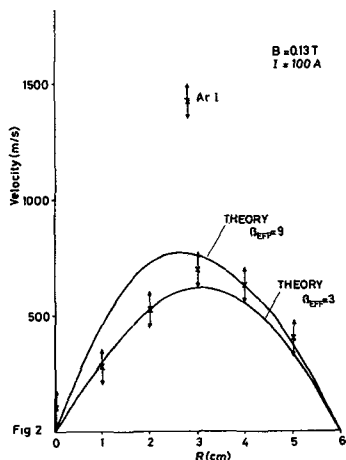
in which ϕ and v_{θ} are the potential and the azimuthal velocity, B_{θ} the magnetic field, μ the coefficient of viscosity and σ and σ_{\perp} the electrical conductivities parallel and perpendicular to B , respectively. The plasma is assumed to be homogeneous with respect to σ, σ_{\perp} and μ . These two relations fully determine the rotational velocity v_{θ} and the potential ϕ as a function of r and z . Secondary flows are neglected and v_{θ} is assumed to be zero on the walls. Wilhelm and Hong [4] showed that the solutions for v_{θ} and ϕ can be expressed in terms of the Hartmann number $H_{\perp} = (\sigma_{\perp} / \mu)^{1/2} BR$ and the Hall parameter β . In that case only electron conductivity was taken into account and consequently the Hall parameter was the electron Hall parameter β_e . In our experimental situation, however it is shown that the ion-Hall parameter β_i is of the order unity which means that the ion conduction has to be included. For that case Mitchner and Kruger [5] give the following expression for σ_{\perp} :

$$\sigma_{\perp} = \frac{(1+s)\sigma}{(1+s)^2 + \beta_e^2} = \frac{\sigma}{1 + \beta_{eff}^2}$$

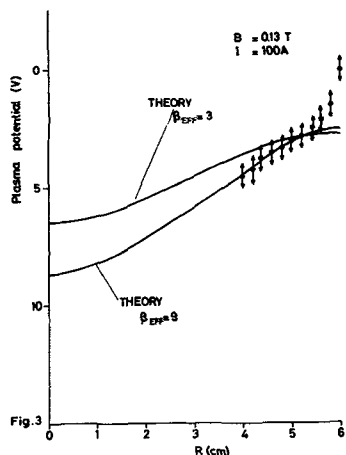
in which $s = \beta_e \beta_i$ is the so-called ion slip factor. An accurate theoretical prediction of the rotational velocity and plasma potential can be made provided $\mu, B, \sigma, \beta_{eff}$ and the electrical current I are known. It can be shown [6] that in the symmetry plane the quantity $v_{\theta} \mu / IB$ is only very weakly dependent on σ and β_{eff} and therefore these latter two quantities do not have to be known accurately.

Results

In fig. 2 the measured values for the rotational velocity of argon neutral particles are given at different radial positions at a filling pressure of 1 torr, magnetic field strength of 0.13 T and an electrical current of 100 A. The maximum value is about 700 m/sec; it lies about 3.5 cm outside the centre of the column. The theoretical curves are obtained as follows: For the coefficient of viscosity μ , the value $1.14 \cdot 10^{-4} \text{ kg m}^{-1} \text{ sec}^{-1}$ given by Dymond [7] for neutrals at an average temperature of 2900 K is used. In our situation for the parallel conductivity σ the Spitzer conductivity (which only depends on the electron temperature) can be taken. The electron temperature is measured in two ways:



It is determined from the line intensity ratios of neutral spectral lines (Boltzmann plot). This gives a value of 0.7 ± 0.2 eV, nearly constant with radius. This value is probably too low [8]. Besides that, two cm from the wall the electron temperature is also determined by means of a double probe. This yields a temperature of 1.0 ± 0.2 eV. Once the quantities μ, I, B, σ and β_{eff} are known one of the outputs of the calculations is the anode cathode voltage. Feeding in the experimental anode-cathode voltage ($\approx 18 \pm 2$ V, corrected for the cathode and anode falls), together with μ, I, B and σ gives a value for β_{eff} . For $T_e = 1.0$ eV this yields $\beta_{eff} = 3$. Because we do not know to what extent this T_e is characteristic for the whole vessel, and because usually the electron temperature of such discharges is higher [8] we also applied a value $T_e = 2.5$ eV, yielding $\beta_{eff} = 9$. Note that the differences in fig. 2 for these two cases ($T_e = 1$ eV; $\beta_{eff} = 3$ and $T_e = 2.5$ eV; $\beta_{eff} = 9$) are small. In fig. 3 the measured plasma potentials are given together with the calculated

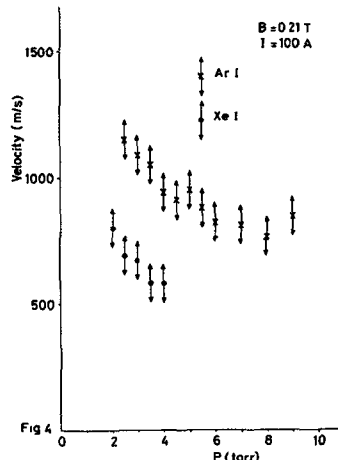


curves for the same two cases. There is a reasonable agreement between theory and experiment for the velocity as well as the potential. The pressure enhancement from the centre of the column to the wall for the conditions mentioned in fig. 2 is approximately a factor 2.5. This rather low value is probably caused by the high heavy particle temperatures. In the centre a temperature of 5900 ± 1300 K is measured. This temperature increases with the magnetic field strength; the ratio $\frac{1}{2}mv_0^2/kT$ remains approximately constant. This latter ratio is an important quantity for the radial pressure dis-

tribution and hence for the mass separation. In a discharge in which equal amounts of Ar and Xe are present a maximum relative separation factor of 2.2 is found [6].

The velocity of the neutral particles increases linearly with the electrical current and the magnetic field strength. The neutral Xe atoms in a pure Xe discharge have about a factor 1.5-1.8 lower velocity than the neutral Ar atoms in an Ar discharge. This means that $\frac{1}{2}mv_0^2$ is approximately constant in these cases.

In a forthcoming paper we will treat this more thoroughly [9]. At higher filling pressures the velocity of neutrals decreases (fig. 4). At pressures of 10 torr for Ar and 4 torr for Xe the originally rather



uniform discharge abruptly changes character. The rotational velocities drop to values below 200 m/sec. In this situation practically no radial pressure enhancement is found. We have no quantitative explanation for this phenomenon as yet.

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