Effect of Ion-Neutral Collisions on Plasma Rotation

H. W. Drawin, M. Fumelli, and D. Voslamber

Groupe de Recherches sur la Fusion, Association EURATOM-CEA, Fontenay-au-Roses (Seine) France

(Z. Naturforsch. 20 a, 859—860 [1965]; received 26 April 1965)

By calculating the Boltzmann collision integral for collisions between ions and neutral particles, two different formulae for the rotation velocity \( v_R \) of a cylindrical plasma column driven by \( I \), \( B_z \) forces have been derived. For \( v_R < v_{th} \), the rotation velocity is proportional to \( I \), \( B_z \), whereas for \( v_R > v_{th} \), one gets a dependency \( v_R \sim (I, B_z)^{1/2} \). \( v_{th} \) denotes the mean thermal velocity of the ions.

In experiments with a rotating plasma driven through a neutral gas by the \( I \), \( B_z \) force, different variations of the rotation velocity \( v_R \) with the magnetic field strength \( B_z \) have been observed. Probe measurements made in a Penning discharge \(^1\) at Fontenay-au-Roses for a limited range of magnetic fields (1000—3000 gauss) indicated the rotation frequency to be roughly proportional to the square root of the magnetic field strength. In a similar device \(^2\) the plasma rotation velocity was measured spectroscopically from the Doppler shift of spectral lines. The rotation velocity was found to be proportional to \( (B_z/100)^{1/3} \), \( r \) denoting the radial distance of the observed plasma shell.

A larger range of magnetic fields including field strengths down to 50 gauss was investigated by Cukrs \(^3\) with probe diagnostics in the “Short PIG” helium discharge. For weak fields the rotation frequency observed in this experiment was directly proportional to the field strength \( B_z \), while for strong fields the observed frequency was similar to that reported in ref. \(^1\).

In two probe experiments (ref. \(^1\) and \(^3\)) the signal is supposed to be caused by an azimuthal “flute like” anisotropy \(^4\) of the plasma column rotating roughly with its macroscopic velocity.

We propose an explanation of both the \( B_z^{1/2} \) and the \( B_z \) dependency of the rotation velocity by simply calculating the collision integral in the stationary momentum equation, assuming that the dominant cross sections are those of charge exchange and elastic collisions between ions and neutrals. We further assume \(^5\) that the mean free path of the neutral particles is large compared with the diameter of the plasma column. Thus, there is a strong coupling between the neutral particles and the walls, keeping the neutral gas at rest and approximately at the wall temperature. The wall temperature is negligibly small compared with the temperature of the charged particles. A charge exchange collision is then equivalent to a complete loss of momentum of the ion. Since the fast neutral particles escape rapidly from the plasma region after a collision, no inverse encounters (between fast neutrals and slow ions) need to be taken into account.

The collision integral is now calculated assuming that the charge exchange cross section is a constant in the velocity range of interest and that the elastic collisions can be treated in the rigid sphere approximation.

A rigorous calculation of the collision integral would require the knowledge of the distribution functions which should be determined as stationary solutions of kinetic equations of the Boltzmann type. However, it is sufficient for our purposes to postulate the ionic distribution to be locally Maxwellian around the rotation velocity \( v_R \) and the neutral particles to be completely at rest.

The azimuthal component of the momentum equation is in our case

\[
\dot{v}_r B_z = \int \left( m_i \dot{v} \right) \cdot \mathbf{a} \, d\mathbf{v} \tag{1}
\]

where \( \dot{v} \) denotes the radial current density, \( B_z \) the azimuthal component of the momentum variable and longitudinal magnetic field, \( m_i \) the ion mass, \( (m_i \dot{v}) \cdot \mathbf{a} \) the ion distribution function.

Momentum transfer by collisions between electrons and neutral atoms is neglected in this equation. This approximation is valid if the electron temperature does not greatly exceed the ion temperature, so that the contribution of the electrons to the mean momentum is then small compared with that of the ions.

The Boltzmann collision integral yields for charge exchange and elastic collisions respectively

\[
\frac{3f_i}{2\pi} - f_0 \int \left( v \cdot \mathbf{a} \right) \, d\mathbf{v} \tag{2}
\]

\[
\frac{3f_i}{2\pi} = \frac{\alpha_{\text{elast}}}{2\pi} \int \left( v \cdot \mathbf{a} \right) \, d\mathbf{v} \tag{3}
\]

(\( \alpha \) denoting a unit vector, the integration with respect to \( \mathbf{a} \) is carried out over a sphere).

In these expressions the distribution functions \( f_i \) and \( f_0 \) of the ions and the neutral particles have to be expressed as follows

\[
f_i(v) = \frac{n_i}{2(kT_i)^{1/2}} \exp \left( -\beta (v-v_0)^2 \right) \tag{4a}
\]

\[
f_0(v) = n_0 \delta(v) \tag{4b}
\]

with \( \beta = m_i/(2kT_i) \), and \( n_i, n_0 \) are the number den-

---


\(^2\) A. Schon, Phys. Fluids 6, 382 [1963].

\(^3\) F. F. Cukrs, private communication. The result was obtained in the experiment of ref. \(^4\) and will be published.

---

Dieses Werk wurde im Jahr 2013 vom Verlag Zeitschrift für Naturforschung in Zusammenarbeit mit der Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. digitalisiert und unter folgender Lizenz veröffentlicht: Creative Commons Namensnennung-Keine Bearbeitung 3.0 Deutschland Lizenz.

On 01.01.2015 it is planned to change the License Conditions (the removal of the Creative Commons License condition "no derivative works"). This is to allow reuse in the area of future scientific usage.
Fig. 1. The function $F^{-1}(x)$. Here $I_r = 2\pi r L i_r(r)$ denotes the total radial current which traverses the shell of length $L$ at radial distance $r$. The function $F^{-1}(x)$ is plotted in Fig. 1, showing the $B_z$- and the $\mu / \ell$-dependency of $\nu_0$ for very small and very strong field strengths respectively, and a mean behaviour between these two ranges.

Note that no $z$-dependence of $\nu_0$ has been observed in spite of the particular geometry of the electrodes. This may be explained by the large mobility of the charged particles along the magnetic field lines which tends to establish a uniform radial current density along the whole line. Further, there is some evidence for "magnetic rigidity" due to magnetic flux conservation, as has been pointed out in ref. 1. Following these arguments one would find a rotation of the plasma column with the same frequency for all $z$ even in those cases where the main part of the radial current flows only in the regions near the electrodes.

It should be emphasized that a highly accurate comparison of our formulae with the experimental results 1-3 cannot be carried out since several of the physical quantities in equs. (5), (8), (9) and (10) are not very well known for these experiments. Taking this into consideration the results of this paper are consistent with the experiments.

Acknowledgments

The authors are indebted to Dr. F. F. Chen for the communication of his experimental results and for his permission to quote them in this article. They thank also Dr. B. Bonnevier for his comments on the rotation frequencies of plasma columns.