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Rotation of a magnetized plasma

B. M. Annaratone,^{a)} A. Escarguel,^{b)} T. Lefevre, C. Rebont, N. Claire, and F. Doveil
 PIIM, UMR6633 CNRS/Université de Provence, Campus St. Jérôme, Case 321, F-13397, Marseille, France

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The plasma rotation in the axial magnetic field of the linear machine Mistral [A. Escarguel, *Eur. Phys. J. D* **56**, 209 (2010)] is well described by the assumption that the electrons injected from the source exit radially from the central column and are subject to the Lorentz force. Electrons and ions rotate together by ambipolarity. The solution of the momentum equations foresees correctly the observed radial dependence of the ionic radial velocity measured by laser induced fluorescence. The resolution of these equations is also in good agreement with the measured dependence of the rotation frequency on the applied magnetic field and on the background pressure. © 2011 American Institute of Physics. [doi:10.1063/1.3566004]

Plasma transport in a magnetic field is “anomalous” in the sense that it is still not completely predictable in new configurations. From this derives the need of studying the physics of magnetized plasmas not only in fusion devices but also in laboratory machines where parameters can be better controlled.^{1–5} Mistral is a typical linear machine to study the plasma instabilities developing across the magnetic field lines. It addresses the low temperature plasma physics near the limiter and its shadow, in tokamaks, or other reactors aiming at controlled atomic fusion for energy purposes. Several papers have studied the plasma instabilities in Mistral; see for example, Refs. 6 and 7 and the references therein; other papers present the results of diagnostic investigation.^{8,9} A similar regime of magnetization and geometry have been dealt in Refs. 10 and 11 in a different context, i.e., Hall thrusters. No effort has been attempted, in the authors’ knowledge, to unravel the dependence on the frequency of the observed turbulences. With increasing magnetic field, the plasma, initially uniformly spread, concentrates in an internal plasma column from which one (mode $m=1$) secondary plasma, here also called ‘plasma arm’, uniform in the axial coordinate, attempts to reach the walls. In doing so, the ‘arm’ rotates around the internal plasma column. At higher magnetic fields more ‘arms’ appear, (higher m modes). In this paper, we disclose the theoretical analysis of the rotation frequency of the $m=1$ mode. The theory correctly predicts the experimental dependences on the magnetic field and on the background gas pressure; it provides also the radial velocity of ions, in good agreement with the laser induced fluorescence measurements.

I. THE EXPERIMENTAL CONFIGURATION

The experimental device has been described elsewhere,^{6–8} see also Fig. 1. It consists of a source chamber in which plasma is produced by the thermionic emission of electrons accelerated to a large anode. Energetic electrons can overcome a grid kept at -25 eV and enter in the magnetized plasma column. They are reflected by the floating

end plate and undergo several small angle elastic collisions before colliding in ionizing or exciting collisions. The electron energy distribution shows clearly, see Ref. 8, a directional part, “primary” electrons, and cold locally generated electrons. The primary electrons ensure the uniformity of plasma parameters all along the axial z direction. The space potential of the plasma column settles down to a negative voltage with respect to ground and this difference in potential forces electrons to travel perpendicular to the magnetic field lines, $B=B_z$, in order to close the path of the current to the grounded walls. A laser induced fluorescence (LIF) diagnostic is used to measure the velocity distribution function of argon ions in the ‘plasma arm’.^{12,13}

II. THE MODEL

Our model is based on two basic assumptions. The first is that the plasma arm rotating around the central column is quasineutral. It is much larger than several Debye lengths (typically 4×10^{-4} m) and fluctuations frequencies are lower than ω_{pi} (1 MHz). The second assumption is that ions lose momentum by collisions with the neutrals while the electrons collide rarely (the electron mean free path, λ_{fe} , is 2 m at $P=10^{-2}$ Pa, much larger than the device radius) and there is only a small loss of momentum per collision because of the small mass. Moreover, we neglect the ionization in the plasma arm in comparison with the fluxes of ion and electrons, i.e., $\partial(rnv_r)/\partial r \approx 0$ with n the plasma density and v the particles’ radial velocity. This is justified because the ionization rate, and the volume, of the central column are much higher than those of the ‘arm’. The electron cloud, traveling radially toward ground experiences an averaged density of Lorentz force, F_L , in the azimuthal direction, $\varphi: F_L = nev_{er}B$, with e the charge of the electron and v_{er} the electron drift velocity in the radial direction. The presence of an azimuthal electric field is probably the origin of the instability that controls the rotation of the plasma arm around the central column.¹⁴ The stationary momentum equations for the ions and the electrons in the azimuthal direction are, respectively,¹⁵

^{a)}deceased

^{b)}Electronic mail: alexandre.escarguel@univ-provence.fr.

FIG. 1. Schematics of the Mistral plasma device.

$$nM \left(v_{ir} \frac{\partial v_{i\varphi}}{\partial r} + v_{ir} \frac{v_{i\varphi}}{r} \right) + enBv_{ir} + enE_{\varphi} + MZnv_{i\varphi} + F_{i\varphi} = 0 \quad (1)$$

$$nm \left(v_{er} \frac{\partial v_{e\varphi}}{\partial r} + v_{er} \frac{v_{e\varphi}}{r} \right) - enBv_{er} - enE_{\varphi} + MZnv_{e\varphi} + F_{e\varphi} = 0 \quad (2)$$

with M the mass of the ions, Z the ionization rate of argon, v_{ir} and v_{er} (resp. $v_{i\varphi}$ and $v_{e\varphi}$) the ions and electrons radial (resp. azimuthal) velocity, and $F_{i\varphi}$ and $F_{e\varphi}$ the density of frictional forces in the azimuthal direction of the ions and the electrons, respectively. The addition of Eqs. (1) and (2) gives the azimuthal momentum equation for the plasma, for which several terms can be neglected: the much larger mass of ions compared to electrons allows to neglect the electronic convective term compared to the ionic one. This ionic term is also larger than the ionization forces. Indeed, we can express $\partial v_{i\varphi} / \partial r = \omega = 3.1 \times 10^4$ rad/s, and LIF results give the ratio $v_{i\varphi} / v_{ir}^{16}$. Then, for our experimental conditions, $MZnv_{i\varphi} / (Mn\omega v_{ir}) < 0.07$. Turning around the central column ions collide and loose momentum, Mv , in charge exchange collisions, and part of the momentum in elastic collisions with neutrals, the density of which is n_a . The drag force density is then given by: $F_{i\varphi} = nn_a M v_{\varphi} |v| \sigma_{i \text{ tot}}$, with $(\sigma_{i \text{ tot}} n_a)^{-1}$ also equal to the mean free path for ions λ_{fi} . The cross section $\sigma_{i \text{ tot}}$ represents the frictions processes for the ions. These are mainly Ar/Ar⁺ charge exchange collisions and Ar/Ar elastic collisions. For our conditions, $\sigma_{i \text{ tot}} \sim 8 \times 10^{-19}$ m².¹⁷ The similar expression for the electrons is: $F_{e\varphi} = nn_a m v_{e\varphi} |v_e| \sigma_{e \text{ tot}}$. The cross section $\sigma_{e \text{ tot}}$ corresponds to ionization of argon atoms and e /Ar elastic collisions: $\sigma_{e \text{ tot}} \sim 4 \times 10^{-20}$ m².¹⁸ The estimation of $|v_e|$ and $|v_i|$ can be done by considering the retarding field analyzer results⁸ and LIF results,^{13,16} respectively: $|v_i| / |v_e| > 0.1$. If we consider that the azimuthal velocities of ions and electrons are not too different, then $F_{i\varphi} \gg F_{e\varphi}$. The resulting momentum equation for the plasma is

$$nM \left(v_{ir} \frac{\partial v_{i\varphi}}{\partial r} + v_{ir} \frac{v_{i\varphi}}{r} \right) - enB(v_{er} - v_{ir})F_{i\varphi} = 0 \quad (3)$$

The difference $v_{er} - v_{ir}$ appearing in the Larmor force term of Eq. (3) can be derived considering the electron current density env_{er} inclusive of the electrons injected from the source, j_s , as well as the density of current of the electrons produced by the ionization in the central column. This latter density of

FIG. 2. Intensified video camera (ICCD) axial image of the ejected plasma with overimposed boundaries for uniform plasma density and v_{ir} proportional to r . The central column is covered by a black screen and the ejected plasma is rotating anticlockwise.

current equates the ion density of current: env_{ir} , so that we have $v_{er} - v_{ir} = j_s / en$, with $j_s = I_{\text{injected}} / S$, $S = lr \alpha$, l is the length of the plasma arm along z and $\alpha(r)$ is the angle that represents the shape of the plasma arm, see also Fig. 2. We can then write $v_{er} - v_{ir} = v_s$ at any radius. The hypothesis of uniform plasma density has been validated by Ref. 9. It could also be intuitively accepted because the arm is unbounded at his lateral sides and can then mold to avoid radial gradients of density. In steady state rotation, $v_{i\varphi} = \omega r$. Moreover, we suppose that the z component of ionic velocity is negligible in comparison to the radial and azimuthal ones. Eq. (3) becomes:

$$2v_{ir} - \frac{\omega_L}{\omega} v_s + \frac{r}{\lambda_{fi}} \sqrt{v_{ir}^2 + \omega^2 r^2} = 0 \quad (4)$$

with $\omega_L = eB/M$. Ions flow in the same direction as the electron produced by ionization, to recombine on the walls. The radial equilibrium equations for circulating electrons and ions, divided by the factor “ nM ,” here follow,

$$m' \left(v_{er} \frac{\partial v_{er}}{\partial r} - \frac{v_{e\varphi}^2}{r} \right) + \frac{eBv_{e\varphi}}{M} + \frac{eE_e}{M} + \frac{F_{er}}{nM} = 0 \quad (5)$$

$$v_{ir} \frac{\partial v_{er}}{\partial r} - \frac{v_{i\varphi}^2}{r} - \frac{eBv_{i\varphi}}{M} - \frac{eE_r}{M} + \frac{F_{ir}}{nM} = 0 \quad (6)$$

with $m' = m/M$. It is experimentally shown that the electron density n is approximately radially constant in the ejected plasma.⁹ Then, the pressure gradient term $\vec{\nabla} p$ has been neglected in the fluid Eqs. (5) and (6). The two first terms of Eq. (5) can be neglected because of the “mass” effect m' . Then, we can write

$$\frac{eE_r}{M} + \omega_L v_{e\varphi} + \frac{m' v_{er} |\vec{v}_e|}{\lambda_{fe}} = 0 \quad (7)$$

FIG. 3. Radial evolution of v_{ir} by LIF diagnostics (o) and calculated from Eq. (7) (—).

$$v_{ir} \frac{\partial v_{ir}}{\partial r} - \omega^2 r - \frac{eE_r}{M} - \omega_L v_{i\phi} + \frac{v_{ir} \sqrt{v_{ir}^2 + \omega^2 r^2}}{\lambda_{fi}} = 0 \quad (8)$$

where $\lambda_f = 1/n\sigma$ with σ the total momentum transfer cross section. Equations (7) and (8) can be combined to eliminate the electrical forces,

$$v_{ir} \frac{\partial v_{ir}}{\partial r} - \omega^2 r - \omega_L \Delta v_\phi + \frac{m' v_{er} |\vec{v}_e|}{\lambda_{fe}} + \frac{\sqrt{v_{ir}^2 + \omega^2 r^2}}{\lambda_{fi}} = 0 \quad (9)$$

with $\Delta v_\phi = v_{e\phi} - v_{i\phi}$. For typical experimental conditions, the third term “ $\omega_L \Delta v_\phi$ ” can be neglected compared to the second term “ $\omega^2 r$,” if we suppose that the ions and electrons velocities are different but have the same magnitude. In this equation, the fourth term in m' is much smaller than the others and therefore will be ignored in the following; physically this means that the electrical forces are negligible for the ion radial motion with respect to the convective acceleration (while they are the main driver for the electron radial motion). In the next paragraph, $v_{ir}(r)$ is calculated from the resolution of Eq. (9) and compared to experimental LIF results. Then, the couple of Eqs. (4) and (9) have been solved simultaneously to derive the dependence of ω on the magnetic field B and the gas pressure P .

III. RADIAL EVOLUTION OF v_{ir}

The radial evolution of v_{ir} has been measured with the LIF diagnostics.^{13,19} The experimental result shown on Fig. 3 indicates that v_{ir} increases linearly with r . Then, we have calculated the radial evolution of v_{ir} by replacing $\partial v_{ir}/\partial r$ by v_{ir}/r in Eq. (9). The result is also shown on Fig. 3, by considering the experimental conditions for the LIF measurements ($B=160$ G; $\omega=3.1 \times 10^4$ rad/s). The value of λ_{fi} is the one on the next paragraph. The agreement between experiment and theory is good.

FIG. 4. Experimental frequency (x) vs magnetic field and solution (o) of the system of Eqs. (4) and (7) at $r=6$ cm.

IV. DEPENDENCE ON B

The model has been validated recording the rotation frequency of the mode $m=1$ against increasing magnetic field in an argon pressure of 7×10^{-4} mbars, see Fig. 4. The dependence of the theoretical frequency of rotation against the magnetic field obtained from the solution of the system of Eqs. (4) and (9) is also shown. The azimuthal velocity of ions turning around the central column is comparable with their thermal speed, of the order of 10^2 – 10^3 m/s. In this case, the low energy cross section for ion neutral collision is 3×10^{-19} m² and $\lambda_{fi}=1.4 \times 10^{-1}$ m. This is comparable to the involved radii so that we are effectively in a regime of weak collisionality. For the primary electrons $\sigma_{E=20 \text{ eV}}=1.7 \times 10^{-19}$ m² with $\lambda_{ep}=1.2$ m and for the thermal (secondary) electrons $\sigma_{Te=3 \text{ eV}}=4.4 \times 10^{-20}$ m² with $\lambda_{es}=0.3$ m. Another unknown in Eqs. (4) and (9) are the electron velocities v_s and $v_{er}=v_{ir}+v_s$ associated to the density of current j_s and j_{er} . These are derived from the experimental measurement of two currents. I_p is the maximum current to a Langmuir probe biased at 16 V and placed in the arm swept volume. The probe voltage is well over the space potential that is slightly negative with respect to ground, so the probe is in the electron saturation regime and we assume the current to be roughly proportional to the plasma density. The other current is I_s , the current on the walls to the ground. This latter current is also representative of the electron current injected in the magnetized plasma column and of the excess of electron current, with respect to the ion current, in the ‘arm’. Then, $I_s=S \cdot e \cdot n \cdot v_s$ with $S(\alpha)=l \cdot r \cdot \alpha$, where $\alpha \sim \pi/2$ being the angle covered by the plasma arm at the radius corresponding to the exit of the central column. Eliminating n , v_s is then proportional to the ratio of the above mentioned input currents: $v_s=K(I_s/I_p)$. In practice, the theoretical curve in Fig. 4 has been obtained fitting the value of K for the point $B=160$ G and $f=5.9$ kHz ($K=21$); the points at other values of B have been obtained using the same fitting value to validate the theory comparing the slopes. The system of Eqs. (4) and (9) then provides the theoretical curve of Fig. 4.

V. DEPENDENCE ON PRESSURE

Figure 5 shows the matching of the theoretical prediction to the experimental rotation frequency when the argon gas pressure is varying, for two different magnetic field values.

FIG. 5. Experimental frequency vs argon pressure (+: $B=100$ G; $\times$: $B=180$ G) and solution of the system of Eqs. (4) and (7) (—: $B=100$ G; - - : $B=180$ G) at $r=6$ cm.

In our case, the limiting pressure is $P=2 \times 10^{-5}$ mbars below which instabilities and poor reproducibility has been observed. The low B case is in very good agreement with the experimental data, whereas the high B case can only reproduce the general trend.

VI. CONCLUSION

The $m=1$ instability of the Mistral magnetized plasma is interpreted by a global model, which is able to reproduce closely the experience in a large range of pressures and applied magnetic fields. In the light of the present model, we can explain the transition to higher m modes, which derive

from the limits set by ambipolarity and geometrical considerations. This will form the basis of a forthcoming paper. The model also provides prediction over the radial velocity of the ions that allows us to characterize the plasma in the rotating arm and to validate the theory of transport in magnetic field.

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