*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-2.107 (2007)*

Correlation Between Accretion Theory and Toroidal Rotation Experiments*

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The experimental observations that are consistent with the main point of the accretion theory [1,2,3] of the spontaneous rotation phenomenon include the following: i) the reversal of rotation of the plasma column in the transition from the L-regime to the H-regime that is attributed, by the theory, to the inversion of the phase velocity direction of the modes excited at the edge of the plasma column. ii) the strong effects of the magnetic field topology of the outermost magnetic surfaces and of the edge plasma regimes on the magnitude and direction of the spontaneous rotation. iii) the penetration of the angular momentum from the outer edge toward the center of the plasma column during the transition from the L-regime to the H-regime. iv) the influence of the neutral population on the rotation velocity and on the L-H transition.

In particular, experiments have shown, in agreement with the detailed theory of the collisional ballooning modes excited at the edge of the plasma column that are proposed as responsible for the ejection of angular momentum, that neutrals have a damping effect on the spontaneous rotation present in the H-regime. The transition from a phase velocity of these modes in the ion diamagnetic velocity in the H-regime is of the same type that was found [4] for the "mode switching" in order to arrive at the first experimental identification of drift modes. For this a linear Q-machine was used and the transition marked the switch-off and on of modes with different mode numbers.

According to the accretion theory, plasma angular moment is ejected through a collisional ballooning mode excited in the edge of the plasma column. The (cubic) dispersion relation for the collisional ballooning mode is analyzed in the companion paper [5] at this conference. This dispersion relation leads us to identify two dimensionless parameters that correspond to a change of regime and a change of the mode phase velocity:

$$\mathcal{L}_c = \frac{\nu_m}{\left|\omega_{*e}^T\right|} \qquad \text{and} \qquad \mathcal{H}_c = \frac{k_\parallel^2 \, \mathrm{v}_A^2}{k^2 \, D_m \, \nu_\mu} \left|\frac{\omega_{*e}^T}{\omega_{di}}\right|$$

where $\nu_m = D_m \, k^2 = \nu_{ei}^{\parallel} \, k^2 \, c^2 / \omega_{pe}^2$, D_m is the magnetic diffusion coefficient due solely to collisional effects, $\nu_\mu \approx D_\mu^{\perp\perp} \, k^2 + \nu_{in}$, $D_\mu^{\perp\perp}$ is the effective "viscous" diffusion coefficient relevant to poloidal flows, ν_{in} is the ion-neutral collision frequency, v_A is the Alfven velocity, $\omega_{di} = k_y\, c\left(dp_i/dx\right)/\left(enB\right)$, $\omega_{*e}^T = -k_y\, c\left(dp_e/dx\right)/\left(enB\right) - \alpha_T\, k_y\, c\left(dT_e/dr\right)/eB$, and $\alpha_T \simeq 0.7$.

We note that, numerically,

$$\mathcal{L}_c \approx 0.3\left| r_{pe}\, \frac{k^2}{k_y} \right| \left(\frac{B}{3\ \mathrm{T}}\right) \left(\frac{50\ \mathrm{eV}}{T_e}\right)^{5/2}$$

where $r_{pe} = \left| d \ln p_e / dr \right|^{-1}$ is the scale length for the electron pressure, and we have taken $Z_{eff} \approx 2$ in evaluating D_m. Typical values for the Alcator C-Mod machine are $B \sim 4\ \mathrm{T}$, $r_{pe} \sim 0.2\ \mathrm{cm}$, and $T_e \sim 50\ \mathrm{eV}$ for the H-regime. Then $\mathcal{L}_c \sim \left(0.15\ \mathrm{cm}\right) k^2/k_y$. Conversely, for the L-regime $T_e \sim 20\ \mathrm{eV}$ and $r_{pe} \sim 0.5\ \mathrm{cm}$ may be more appropriate values, yielding the estimate $\mathcal{L}_c \sim \left(4\ \mathrm{cm}\right) k^2/k_y$.

In order to assess the value of ν_m we have to take into account that k^2 should include an important contribution from the radial localization of the mode. To simulate this we may take $k^2 \approx k_y^2 + k_x^2$ and $k_x^2 \approx k_y^2$. Referring to repeated experiments carried out on the Alcator C-Mod machine [6] we may take $k_y \approx 1.5\ \mathrm{cm}^{-1}$, corresponding to $m^0/r_0 \approx 1.5\ \mathrm{cm}^{-1}$, $m^0 \approx 30$, and $r_0 \approx a \approx 20\ \mathrm{cm}$, where m^0 is the poloidal mode number and a is the plasma minor radius. This value for m^0 was chosen as it corresponds to the prevalent ballooning mode observed in the EDA (enhanced D-alpha) regime, a special type of H-regime produced only with the high densities that can be produced by the Alcator C-Mod machine. Therefore we may normalize k^2 to about 5 cm^{-2} for our estimates. This value, together with the plasma parameters specified in the previous paragraph, leads to the estimate $\mathcal{L}_c \approx 0.9$ for the H-regime. For the L-regime the corresponding estimate is $\mathcal{L}_c \approx 12$, although there is no evidence of a prevalent mode emerging from the fluctuation spectrum with a clearly identified mode number. Therefore the choice of k^2/k_y may not be appropriate to this regime.

In the limit $\left| D_m\, k^2 / \left(\omega - \omega_{*e}^T\right) \right| \gg 1$ it can be shown [5] that the unstable solution of the collisional ballooning mode dispersion relation gives

$$\gamma \approx \frac{\gamma_I^2 + \omega_R(\omega_R - \omega_{di})}{\frac{\omega_A^2}{\nu_m} + \nu_\mu + \gamma}$$

where $\gamma = \mathrm{Im}(\omega)$, $\omega_R = \mathrm{Re}(\omega)$, $\gamma_I^2 = -2(dp/dr)/(n\, m_i\, R_c)$, and R_c is the magnetic radius of curvature. This equation applies for the Q-machine experiments except that $\gamma_I = 0$. Thus, $(\omega_R = 0) \Rightarrow (\gamma = 0)$. The switching on and off of the modes found theoretically in Ref. [4] and used to identify collisional drift modes therefore involved the vanishing of both γ and ω_R.

The L-regime in toroidal experiments corresponds to the $\mathcal{L}_c \gg 1$ limit, and to $\mathcal{H}_c < 1$ in order that the phase velocity of the mode is in the electron diamagnetic velocity direction. Using the estimates given above, we find that $D_m \approx 2\times10^5$ cm^2 s^{-1} and $D_m\ (k^2/5\ \mathrm{cm}^{-2}) \approx 10^6\ \mathrm{s}^{-1}$. In fact, in this case the spectrum of modes which are excited may peak at larger values of k. If we consider modes whose poloidal profile is relatively flat, we may take $k_\parallel \approx 10^{-4}$ cm^{-1} and thus have $\omega_A \approx 2.5\times10^5$ s^{-1}. Since $\nu_m \approx 10^6$ s^{-1} we may argue that values of $\nu_\mu \geq 6\times10^4$ s^{-1} are sufficient to make $\mathcal{H}_c < 1$. For $n_e \approx 10^{13}$ cm^{-3}, $Z_{eff} \approx 2$, and $\langle \sigma_{in} \mathrm{v} \rangle \approx 2\times10^{-8}$ cm^3 s^{-1} (reasonable for T=20-50 eV) we find $\nu_{in} \approx (1\times10^5\ \mathrm{s}^{-1})\varepsilon_n$ where $\varepsilon_n = n_n/n_i$. Therefore, ion-neutral collisions can make an important contribution to ν_μ for reasonable values of the neutral fraction ε_n. The assessment of $D_\mu^{\perp\perp}$ is more difficult to make in that it is likely to be anomalous. Thus if we take $D_\mu^{\perp\perp} \approx D_B$, the Bohm diffusion coefficient, we have $D_\mu^{\perp\perp}\ (k^2/5\ \mathrm{cm}^{-2}) \approx 2.5\times10^5\ \mathrm{s}^{-1}$.

For the Q-machine experiments, the plasma consisted of singly ionized cesium (mass number $A \approx 133$). Other plasma parameters were $B \approx 0.5$ T, $n_e \approx 5\times10^{11}$ cm^{-3}, and $T_e \approx 0.2$ eV. The classical $D_\mu^{\perp\perp}$ for these values is 1.5×10^3 cm^2 s^{-1}. If we take $\nu_\mu \approx D_\mu^{\perp\perp} k^2$ where $k \approx m^0/r_0 \approx 4-8$ cm^{-1} then it is easy to verify that this is sufficient.

An important point for comparison between accretion theory and experiments is the source of the plasma angular momentum. According to the accretion theory, the source should be preferably at the plasma edge, near the region where modes capable of ejecting angular momentum in the opposite direction should be localized. Time-resolved experimental measurements of the velocity profile during a L-H transition [7] when the toroidal velocity vanishes indeed suggest that the dominant momentum source is at the edge, showing the velocity increases from a zero value first at the larger values of r. The change then propagates towards the magnetic axis.

Since edge-localized ballooning modes play a key role in determining the plasma spontaneous rotation in the context of the accretion theory, we expect this rotation should be sensitive to conditions in the scrape-off layer. Indeed, it is found on most experiments that material wall conditioning (e.g. boronization) has a strong effect on whether the plasma can reach H-mode, and therefore, on the direction and magnitude of spontaneous rotation. Even within the L-regime, it is found that spontaneous rotation is different for upper-single-null and lower-single-null plasmas [8]. We argue that these topological differences in the equilibrium field affect the magnitude of the collisional ballooning mode, thereby affecting the plasma rotation.

Finally, we observe that traveling collisional modes that can have varying phase velocities can be excited at the edge of the plasma column as shown in Ref. [5], and that the role of these modes deserves further analysis.

*Sponsored in part by the U.S. Department of Energy, and, in the case of M.L., by the National Science Foundation.

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