Flow braking due to non-resonant external perturbations in EXTRAP T2R and comparison with neoclassical toroidal viscosity torque

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External magnetic perturbations can be used in tokamaks to mitigate edge localized modes [1] and/or to influence the neoclassical tearing mode island dynamics in order to optimize ECCD stabilization [2]. On the other hand, the perturbation can produce flow braking with negative effects on plasma confinement. It has therefore high relevance for the tokamak community to understand the underlying physics related to the plasma flow braking by an external magnetic perturbation. The braking can be due to the interaction of the static perturbation resonant harmonic with the rotating plasma mode [3] and/or to the neo-classical toroidal viscosity (NTV) torque due to the non-resonant harmonics generated as side-band effects related to the small number of active coils [4].

This work will aim to quantify the effect of non-resonant magnetic perturbations (non-RMPs) on the plasma velocity. The first part describes the experimental study on EXTRAP T2R reversed-field pinch of the plasma flow braking due to non-RMP. The second part of the work compares the braking torque calculated from experimental data with the torque expected by the neo-classical toroidal viscosity (NTV) theory [4,5].

A clear study of the plasma braking effect is relatively complicated in tokamaks because of the limited number of active coils that inevitably produces a broad spectrum of side-band harmonics. On the contrary, the feedback systems installed in EXTRAP T2R has the capability of suppressing the entire RWM and error-field spectrum and simultaneously producing a clean external perturbation [6,7]. An example is shown in figure 1(a), where the

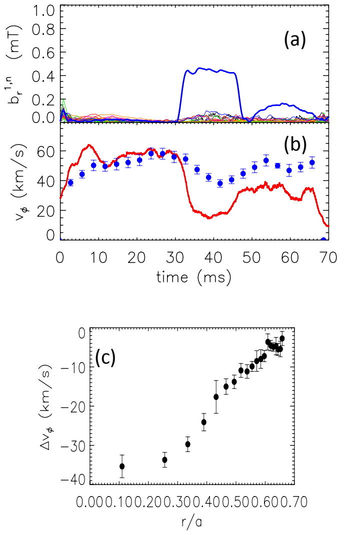

Figure 1. Frame (a): radial magnetic field at the plasma edge. The blue line corresponds to the non-RMP harmonic (1,-11). Frame (b): time evolution of the TM velocity (red) for the innermost resonant harmonic and of the line integrated OV velocity (blue). Frame (c): Profile of the TM velocity shift during the non-RMP.

time evolution of the radial magnetic field at the plasma edge is shown. An external perturbation with amplitude b_r=0.4mT and harmonic (m,n)=(1,-11) is applied between 30ms and 45ms.

In this work the plasma velocity is estimated from the tearing modes (TMs) dynamics, assuming that plasma and TMs co-rotate (assumption that in EXTRAP T2R has been studied in reference [8]). The TM helical angular phase velocity $\omega^{1,n}$ for each harmonic is obtained from the time derivative of the phase and then the toroidal TM velocity v_ϕ is obtained by correcting for the poloidal velocity v_θ measured with a spectrometer [8]: $\omega^{1,n}=v_\theta(r_s)/r+n\, v_\phi(r_s)/R$. The flow is estimated from the line integrated velocity of the OV impurity. In EXTRAP T2R, OV is mainly concentarted in the core and its velocity is therefore representative of the core flow. However, being a line integrated measurement and hence representative of the whole velocity profile, the OV velocity is used only for qualitative comparison with the TM velocity.

In figure 1(b), the toroidal velocity time evolution for the innermost resonant TM (m=1, n=-12) for the OV are shown. The TM with harmonic (1,-12) is resonant at r/a~0.1 and its velocity is therefore representative for the plasma core. During the application of the external perturbation the TM velocity clearly decelerates, with a reduction up to ≈35km/s.

The velocity profile is obtained by plotting the velocity of each TM at its corresponding resonant radius. In figure 1(c) the profile of the velocity shift during the non-RMP is shown. The non-RMP produces a larger reduction in the core, but its effect is global, affecting the plasma velocity up to r/a≈0.6. This behavior is significantly different from that of a resonant magnetic perturbation (RMP) for which an effect on the TM velocity localized at the RMP resonance is observed, as described in reference [9].

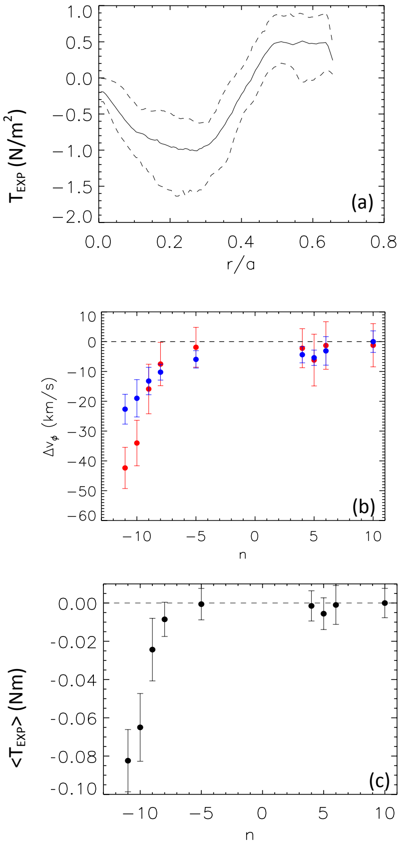

Figure 2. Frame (a): experimental braking torque density necessary to produce the velocity reduction of figure 1. Frame (b) and (c): dependence of the maximum velocity braking and of the corresponding volume integrated torque versus the non-RMP harmonic. Each data corresponds to a shot with a 0.4mT non-RMP.

The braking torque produced by the non-RMP in figure 1 can be determined using the steady-state torque balance equation:

$$T_{EXP} = \frac{R^2}{r}\frac{\partial}{\partial r}\left(r v_{kin} \frac{\partial \rho \Delta \omega}{\partial r} \right)$$

where ν_{kin} is the kinematic viscosity profile estimated in reference [9] and whose value is in the range 4-30m^2/s. The torque density consistent with the braking in figure 1(c) is shown in figure 2(a). Even if the maximum is reached in the region r/a≈0.25, the torque is global and not localized at any specific position.

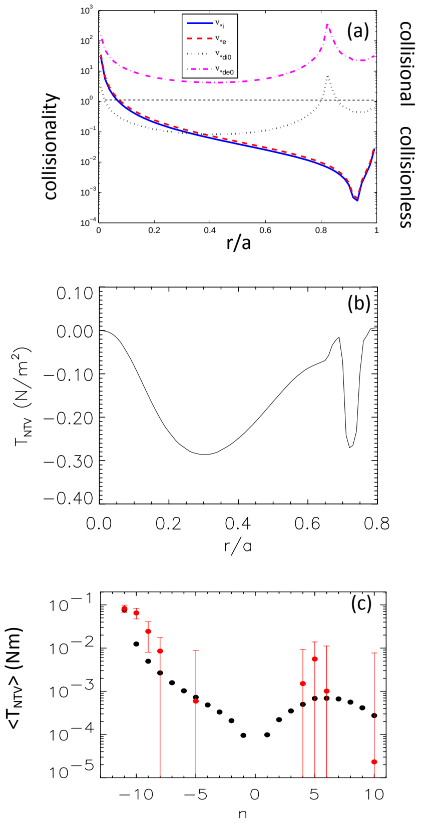

Figure 3. Frame (a): normalized ions and electrons collisionality in EXTRAP T2R. Frame (b): radial profile of the torque density produced by NTV effects. Frame (c): dependence of the NTV torque (black dots) on the harmonic of a non-RMP with amplitude 0.4mT and comparison with the corresponding experimental torque (red dots).

An important effect that needs to be studied in order to have a wide characterization of the non-RMP braking is the role of the perturbation harmonic. This is done by analysing several similar shots in which a non-RMP with amplitude 0.4mT is applied. Each shot is characterized by a different external perturbation harmonic, from n=-11 to n=+10. The results are summarized in figure 2(b), where the maximum velocity shift in each shot is plotted versus the corresponding perturbation harmonic. The red dots correspond to the TM velocity, while the blue dots to the line integrated OV velocity. The maximum braking occurs when a non-RMP with harmonic (m,n)=(1,-11) is applied. Lower n harmonics produce a significantly smaller braking. For n>-5 the braking is almost negligible. In figure 2(c) the corresponding volume integrated braking torque is shown. The trend versus the non-RMP harmonic is similar to that of the velocity shift.

The most accredited mechanisms for the explanation of the non-RMP braking is velocity deceleration induced by the torque produced by neo-classical viscosity effects (NTV torque). According to the NTV theory [5], the displacement produced by the non-RMP enhances the plasma viscosity and consequently produces a reduction of the flow. To compare the present experimental results with the NTV torque, the numerical code developed for JET [5] has been adapted to EXTRAP T2R.

For the NTV calculation, it is necessary to identify the plasma experimental regime of EXTRAP T2R. This is shown in figure 3(a). Both electron and ions are in the collisionless regime as shown in figure 3(a), where the collisionality is plotted (red and blue lines for electrons and ions respectively). Since the normalized collisionality for ions is $\nu_{*di0}<1$, ions are mainly in the $\nu-\sqrt{\nu}$ regime, while electrons are mainly in the $1/\nu$ regime since $\nu_{*de0}>1$, see reference [10] for details.

The NTV torque density expected from an external perturbation with amplitude 0.4mT and harmonic (1,-11) is shown in figure 3(b). The NTV torque is maximum at $r/a\approx0.3$ and in the core is not strongly localized at any specific radial position. From a qualitative point of view, the radial shape of the NTV torque is in good agreement with the experimental torque shown in figure 2(a). From a quantitative point of view, the NTV torque underestimates the experimental torque by a factor 3, since at $r/a\approx0.3$, $T_{NTV}\approx0.3\mathrm{N/m^2}$ while $T_{EXP}\approx(0.9\pm0.6)\mathrm{N/m^2}$.

To study the role of the non-RMP harmonic on the braking torque, the NTV torque expected by an external perturbation with amplitude 0.4mT but with different n harmonic has been calculated. Results are shown in figure 3(c). The NTV torque is significantly smaller at higher n, even if a maximum is obtained at $n\approx5$. In any case, the NTV torque corresponding to n=5 perturbation is two order of magnitude smaller than the torque corresponding to n=-11 perturbation. For comparison between experimental and theoretical results, the braking torque calculated from the experimental velocity shift is shown in figure 3(c) with red dots. Despite the large uncertainties, a qualitative agreement on the n dependence is present.

In conclusion, this work has experimentally quantified the torque produced by a non-resonant perturbation. The results show that the non-RMP torque is not localized in any specific position but affects the entire core and that the torque decreases as the perturbation harmonic is more far from the resonance. Theoretical results show a qualitative good agreement between the experimental torque and NTV torque, both concerning the radial shape of the torque density and the effect of the non-RMP harmonic. Possible reasons for the quantitative disagreement might be related to a non-precise estimation of the viscosity profile that would affect the value of the experimental torque and/or to the uncertainty in the experimental velocity profile.

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