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Direct measurement of the radial electric field in a tokamak with magnetic field ripple

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Introduction

In the regions of the Tore Supra tokamak with a significant magnetic field ripple it is expected that a radial electric field (E_r) arises to ensure ambipolarity of the fluxes of thermal particles trapped in ripple wells. The neoclassical calculation in Ref. [1] shows that E_r is related to ion temperature (T_i) and density (n_i) gradients: $E_r \approx T_i\ (\nabla n_i/n_i + 3.37\ \nabla T_i/T_i)/Z_i e$. In this paper, the validity of this prediction is assessed in a series of Tore Supra L-mode discharges without external momentum input. Doppler reflectometry measurements of fluctuations perpendicular velocity, which is dominated by the $E_r \times B$ drift, are here used to determine E_r.

Neoclassical radial electric field

The principle of the physics of Ref. [1] can be summed up as follows: due to the ripple, which is characterized by $\delta = (B_{max} - B_{min})/(B_{max} + B_{min})$, a fraction of thermal particles of the order $\sqrt{\delta}$ is locally trapped in ripple wells. These particles experience uncompensated vertical drift due to gradients in the magnetic field and curvature. Owing to differences of collisional de-trapping time and vertical drifts between electrons and ions ($\Delta t_i \sim \delta/\nu_{ii}$ for ions, $\Delta t_e \sim \delta/\nu_{ei} \sim \Delta t_i/60$ for electrons) a radial electric field is induced to ensure that the fluxes are ambipolar. Its value is derived from the condition of equality between ions and electrons fluxes $\Gamma_i(E_r) = \Gamma_e(E_r)$, approximated as $\Gamma_i(E_r) \approx 0$ since $\Gamma_i >> \Gamma_e$. Ripple induced radial electric field is then found to be [1] $E_r = T_i\ (\nabla n_i/n_i + 3.37\ \nabla T_i/T_i)/Z_i e$ - note that this expression does not depend explicitly on δ. Moreover, the calculation did not include the effects of $V_{E\times B}$ on particle de-trapping.

A justification for the validity of these predictions on Tore Supra

The neoclassical predictions for the ion flux from [1] is:

$$\Gamma_i = -A\, n_i\, V_D^2\, \delta^{3/2}\, \nu_{ii,th}^{-1} (\nabla n_i/n_i + 3.37\, \nabla T_i/T_i\ - Z_i\, e\, E_r/T_i) \qquad (1)$$

where $A \sim 10$, $\nu_{ii,th}$ and V_D are respectively the thermal ion-ion collision frequency and the vertical drift velocity. A similar expression exists for the electron flux $\Gamma_e \sim \Gamma_i/60$. The expression of E_r mentioned above should be valid provided this ripple induced thermal flux is dominant over potentially non-ambipolar competing processes like turbulent particle fluxes and loss of fast non-thermal particles.

On Tore Supra, superconducting coils are limited to 18 in number, leading to a relatively large ripple: $\delta \approx 7\%$ at the plasma boundary in the outer midplane. In the absence of the regulating E_r, non-ambipolar thermal ion flux $\Gamma_i(E_r = 0)$ would be one or two orders of magnitude greater than typical flux of supra thermal ions (at mid-radius). The latter is estimated considering that losses of fast resonating ions can reach up to around 20 % of the ICRF power, and that the resonating ions energy is typically a few hundreds keV [2]. Thus, ICRF-heated discharges in Tore Supra should be suitable for testing the neoclassical predictions for E_r.

Plasma conditions

Measurements of E_r have been performed in a set of L-mode discharges with no external momentum input. In the resulting data base of these discharges, the ICRF power reaches up to 8MW and LH power up to 2 MW, the plasma current varies in the range $I_p = 0.6 - 1.2MA$, the magnetic field varies between $B_0 = 3.1 - 3.7T$ and the central electron density is in the range $n_e(0) = 3.5 - 6 \times 10^{19} m^{-3}$. Comparisons between predicted and measured E_r are done at r/a 0.6, where the ripple coefficient δ is of the order of 2-3%.

Measurement of E_r by Doppler Reflectometry

The radial electric field is measured from the plasma motion that it induces perpendicularly to the magnetic field lines and by which fluctuations, used as tracers of the plasma motion, are advected. The perpendicular fluctuation velocity $v_\perp = V_{E\times B} + v_{flu}$ is the sum of two contributions: the plasma $E \times B$ velocity $V_{E\times B} = E_r \times B/B^2$, and the turbulence phase velocity v_{flu} which is usually small compared to the $E \times B$ drift velocity [3]. Doppler reflectometry allows a local measurement of $v_\perp$ at a prescribed perpendicular wave-number $k_\perp$, through the backscattered signal Doppler shift $\Delta\omega = k_\perp\ v_\perp$ [4]. For the experiments discussed here, measurements have been obtained with the O- mode V-band channel (50-75 GHz), probing 0.6 < r/a < 0.9 with $k_\perp$ in the range 4< $k_\perp$ <10 cm-1.

Experimental evaluation of predicted neoclassical radial electric field

The predicted $E_r = T_i\ (\nabla n_i/n_i + 3.37\ \nabla T_i/T_i)/Z_i e$ is estimated from CXRS ion temperature and electron density measurements. Density radial profiles are obtained from the best fit which takes into account interferometry and reflectometry, assuming n_i homothetic to n_e. The E_r value is then computed based on local T_i and n_e measurements in the z=0 plane. The Doppler reflectometry measurements zone is also very close to the equatorial plane, with a poloidal extension typically from 0 to 15. Large error bars in the evaluation of E_r are due to the presence of gradients in the E_r expression, which make these predictions very sensitive in particular to CXRS ion temperature measurements.

Results

Figure 1 presents an example of comparison of predicted ripple-induced $V_{E\times B}$ and Doppler measured $v_\perp$ for a Tore Supra discharge (TS#36058, with $P_{ICRH} = 5MW$, $P_{LH} = 2MW$, $I_p = 0.6MA$, $n_e(0) = 4.5 \times 10^{19} m^{-3}$). As CXRS measurements typically extends between 0 < r/a < 0.65 whereas Doppler goes between 0.6 < r/a < 0.9, comparison is only meaningful in a narrow zone near r/a $\sim$ 0.6.

Figure 2 shows such comparisons for the set of L-mode discharges described in section 4. A good agreement is observed, with a tendency for the measured $v_\perp$ to be less negative than the predicted one. The typical difference between measured and predicted perpendicular velocities is of the order $\sim$ 1.5 km/s, which is greater than predictions for the turbulence phase velocity v_{flu}. Indeed, on figure 3 linear gyrokinetic analysis done with the code KINEZERO [5] for discharge TS#36058 shows a computed turbulence phase velocity v_{flu} of the order of 0.3km/s, in the ion diamagnetic direction (i.e $v_{flu} > 0$ with the conventions used here). A possible explanation for this difference might be the fact that E_r was calculated from a simplified neoclassical derivation which does not include the effects of ion de-trapping by $V_{E\times B}$ drift.

Conclusion

In Tore Supra, measurements of the radial electric field by Doppler reflectometry have been made at r/a $\sim$ 0.6 in a series of L-mode discharges with no external momentum input. Good agreement is found with neoclassical predictions of E_r, suggesting that fluxes of thermal ions trapped in ripple wells are in this case the dominating factor determining the radial electric field.

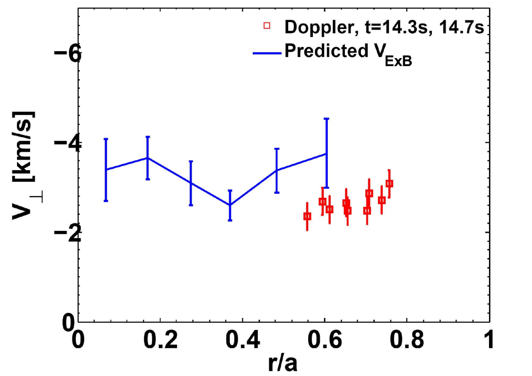

Figure 1. Example of a comparison of predicted $V_{E\times B}$ and Doppler measured $v_{\perp}$ in discharge TS#36058

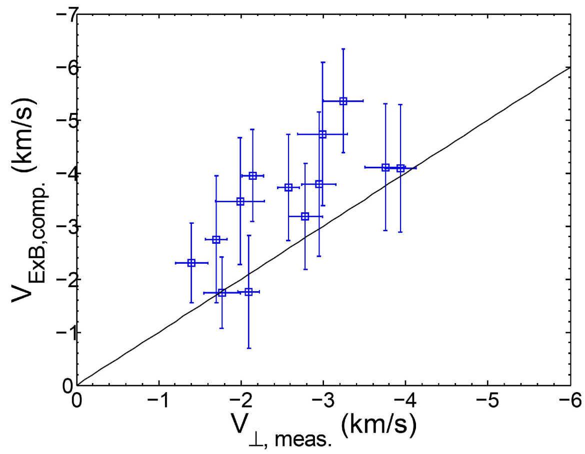

Figure 2. Predicted $V_{E\times B}$ (y-axis) versus Doppler measured $v_{\perp}$ (x-axis) for the set of L-mode discharges, at r/a=0.6.

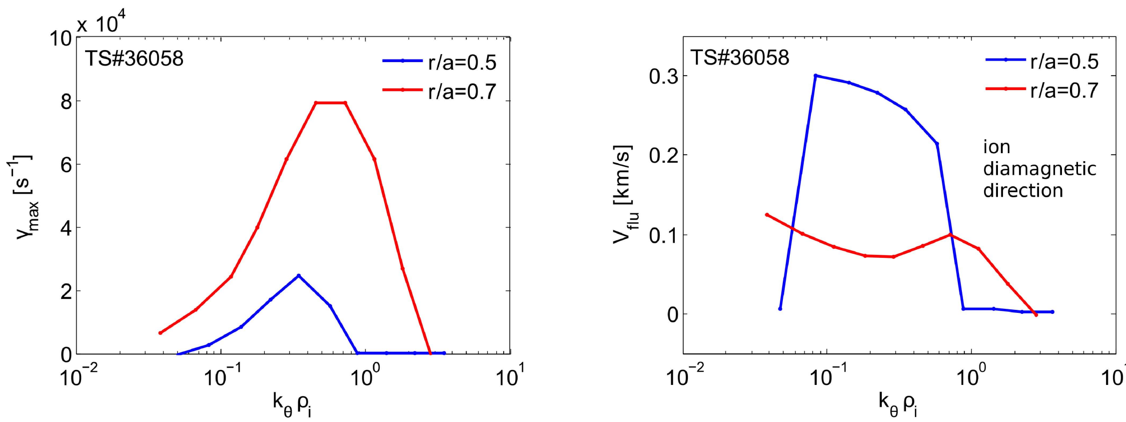

Figure 3. KINEZERO predictions of maximum growth rate γ_{max} and turbulence phase velocity v_{flu} for TS#36058, at r/a=0.5 and 0.7, as a function of poloidal wave number $k_\theta\ \rho_i$ (normalized to the ion thermal gyroradius).

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