

## Impact of rotating magnetic islands on profile flattening and turbulence

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The presence of magnetic islands in nuclear fusion devices has strong consequences for the core confinement and can eventually lead to a disruption. It is therefore essential to analyse the stability of magnetic islands, which is mostly determined by the bootstrap current, in particular by the density gradient [1]. In the absence of turbulence, small magnetic islands rotating in the ion diamagnetic direction flatten the density due to the adiabatic response of trapped ions, reducing the stabilizing effect of the bootstrap current [2]. We elucidate in the present work whether the adiabatic response is still able to flatten the profile or not in the presence of turbulence. We analyse also the impact of rotating islands on turbulent transport and propose other mechanisms additional to the standard suppression of the linear drive. For this purpose we use the gyrokinetic code GWK [3], which solves the gyrokinetic equation for both ions and electrons in toroidal geometry, coupled to the quasi-neutrality condition.

The equations are solved in the flux-tube approximation with a linearized collision operator consisting only of the pitch-angle scattering part, essential for the trapping-detrapping physics. We do not solve Ampère's law, i.e. we impose the island width and rotation frequency. The parameters of the simulations are:  $R/L_n = 2.2$ ,  $R/L_{T,i} = R/L_{T,e} = 6.9$ ,  $T_e/T_i = 1$ ,  $\varepsilon = 0.19$ ,  $q = 1.5$  and  $\hat{s} = 0.16$ . We present results using sufficiently high numerical resolution to describe turbulent regimes as well as the physics around the separatrix of the magnetic island [4]. We perform a scan on the island width and the island rotation frequency. The island widths we consider are  $W = [2, 6, 9, 12, 18]$ , normalized to the ion Larmor radius. We perform also a simulation without island to have a turbulent reference case for comparison. This allows us to quantify the impact of the magnetic island on turbulence.

In figure 1 we give the relative modification of the turbulent intensity with respect to the ref-

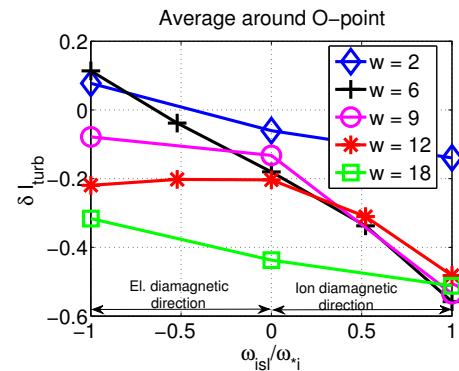


Figure 1: Turbulence modification with an magnetic island as a function of the island rotation frequency and width.

erence simulation as a function of the island width and rotation frequency,  $\delta I_{\text{turb}}$ , averaged in time over the saturated phase and in space around the O-point. The presence of an island tends to stabilize turbulence around the O-point. This general result is in agreement with previous gyrokinetic results [5], where the island was large enough to lead to a rather significant flattening of radial profiles and in addition it was a static island, i.e. there was no rotation frequency. The reduction of turbulence was due to the flattening of radial profiles leading to a reduction of the turbulence linear drive. However, in our case, we consider smaller islands and the flattening is not necessarily as significant as in the case of larger islands. We also observe that islands rotating in the ion diamagnetic direction are more efficient to reduce turbulence than islands rotating in the electron diamagnetic direction. Finally, very small islands ( $W \approx 2$ ) seem to impact turbulence in a less significant way than larger islands, characterized by  $W \geq 18$ . It is clear that the impact on turbulence due to intermediate islands ( $W \approx 6 - 9$ ) depends more strongly on the island rotation frequency than the impact of larger islands. In particular, the width  $W = 6 - 9$  seems to be the optimal range for the rotation dependence. Beyond those widths, the dependence on the island rotation frequency tends to disappear and the island reduces the turbulence independently of the direction of the rotation. To determine whether the reduction comes from the suppression of the linear drive, we analyse the impact of the island on the radial profiles.

On the left-hand side of figure 2 we plot the normalized density gradient averaged around the O-point. The island  $W = 6$  rotating in the ion diamagnetic direction is able to flatten the density profile and this flattening level is reduced when increasing the island width. This might be due to the adiabatic response of trapped ions [2], which is analysed later. On the right-hand side of figure 2 we plot the normalized ion temperature gradient as a function of the island rotation frequency and the island width. Also in this figure, for reference, we give the value of  $R/L_{T,i}$  for a static island  $W = 12$  when the turbulent modes are filtered out in the simulation. The suppression of the linear drive seems to be the dominating mechanism for turbulence reduction when the island is large enough. However, for intermediate magnetic islands, another mechanism should be considered, since the linear drive is increased.

This mechanism can be related to the increase of a radial electric shear around the separatrix when the island is rotating with respect to the plasma. The transfer of energy between modes is expected to be more efficient when island and turbulence structures are co-rotating because the time of interaction between large-scale (zonal flows and island) and small-scale (turbulence) structures is maximized. In addition to the time interaction, one must consider also the scale lengths. In particular when the shear of the radial electric field exhibits scale lengths close to the decorrelation length of turbulence, the transfer of energy can lead to a reduction of turbulence.

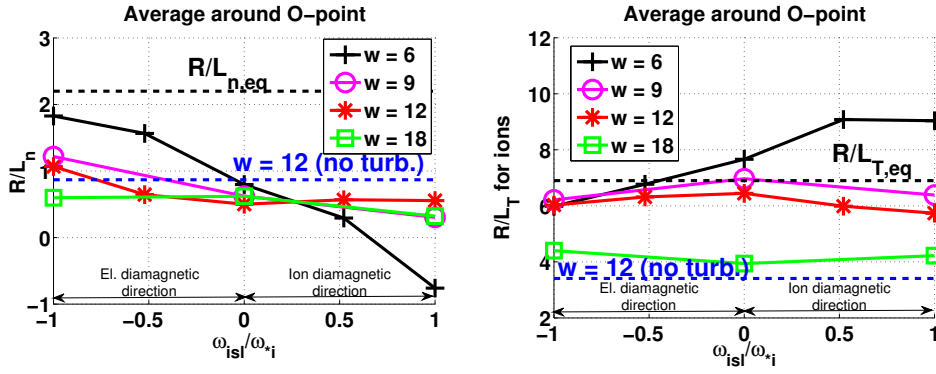


Figure 2: Normalized density (left) and ion temperature (right) gradients as a function of the island rotation frequency and width.

In figure 3 we plot for the island  $W = 6$  the radial profile of the radial electric shear through the O-point for two rotation frequencies: ion (solid line) and electron (dashed line) diamagnetic frequencies. The island separatrix is highlighted by two vertical lines. It can be observed that the shear is clearly increased when the island is rotating in the ion direction. To elucidate whether the flattening when the island rotates in the ion direction is due to trapped ions or not in the presence of turbulence, we analyse the perturbed ion density and compare it to that obtained in the absence of turbulence. In the top panel of figure 4 we give the perturbed ion density in velocity space on the separatrix of an island of width  $W = 6$  in the absence of turbulence.

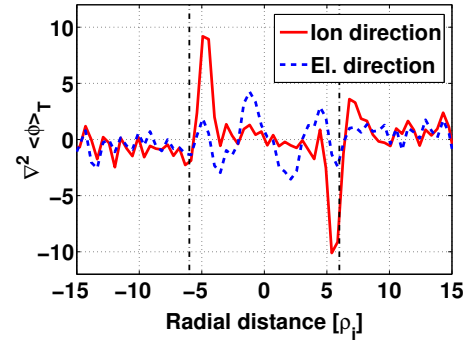


Figure 3: For  $W = 6$ , radial profile through the O-point of the shear of the radial electric field for two island rotation directions: electron (dashed line) and ion (solid line).

The left-hand side of the panel represents an island rotating in the ion diamagnetic direction and the right-hand side an island rotating in the electron diamagnetic direction. The solid black lines separate the population of trapped particles from that of passing particles. It can be observed that the resonant particles are mainly the trapped ones. The perturbed ion density is entirely positive (resp. negative), meaning that they contribute to the flattening (anti-flattening) of the profile when the island is rotating in the ion (resp. electron) diamagnetic direction. Since the response changes its sign when changing the sign of the rotation frequency, these results imply that trapped ions are responsible for the flattening and that their response exhibit an adiabatic behaviour.

We compare these results with the results obtained with an island of the same size in the presence of turbulence. This is illustrated in the bottom panel of figure 4, for an island rotating in the ion (left-hand side) and electron (right-hand side) directions. We observe that the perturbed density is also mainly localized in the trapped region. However, when the island rotates in the electron diamagnetic direction, the response of particles does not exhibit the opposite behaviour to the one observed when the island rotates in the ion diamagnetic direction. This clearly shows that, although the flattening is mainly due to trapped ions (the response is localized within the trapped region), their adiabatic response cannot be considered as the only reason for the flattening of density profile.

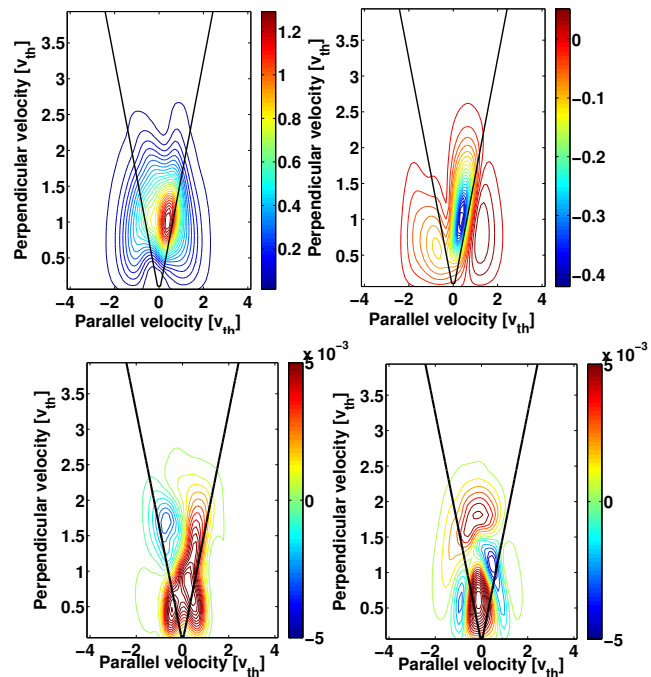


Figure 4: *Perturbed ion density on the separatrix as a function of the parallel and perpendicular velocities in the absence (top) and in the presence (bottom) of ITG turbulence. Left:  $\omega_{isl} = \omega_{*i}$ . Right:  $\omega_{isl} = \omega_{*e}$*

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