Modelling the Fast-ion RF-Pinch Effect with a Toroidally Localised ICRF Antenna

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Introduction

The Finite Orbit Width (FOW) of a fast ion can greatly influence the interaction between the ion and Ion Cyclotron Range of Frequency (ICRF) waves, and what is not clear is what impact the toroidal localisation of the antenna might have on the behaviour of the ions at high energies, especially with it's anisotropy. The work carried out here studies the differences in the RF-Pinch effect when simulating toroidally localised ICRF waves.

The results presented in this paper were carried out using JET plasma profiles determined from shot number 89199 from the M15-27 'ICRH scenarios for DT' experiments. The data implemented in the simulations here was taken using EFIT data, which gave a q0 and q95 of 1.5 and 5.5 resp., Ti_0 and Te_0 of 4.4keV and 6.1keV resp. and ne_0 of 4.9e19m^{-2}. Within this shot 6.6MW of ICRF heating was applied using the minority heating scheme on the 3He ions which consisted of 3% of the plasma, of which the time average for EFIT was 51.25 ± 0.25s. Using this data, the SCENIC [1] package was used to study interactions of ICRF heating with fast 3He particles. Consisting of three main codes; ANIMEC, the anisotropic flavour of VMEC, to produce the 2D ideal-MHD equilibrium, LEMan, the wave-propagation code with warm plasma model and 0th order FLR effects, and finally VENUS-LEVIS, the guiding-centre particle following code. Within this work the phasing remains at +90, with 6.6MW of power applied to the minority 3He species of 3% and each simulation run for a total of 4.5 times the slowing down time on the electrons for convergence.

Antenna Model

In order to toroidally localise the wave in LEMan, the total electric field will be the summation of the different toroidal wave numbers, the contribution of each wave weighted according
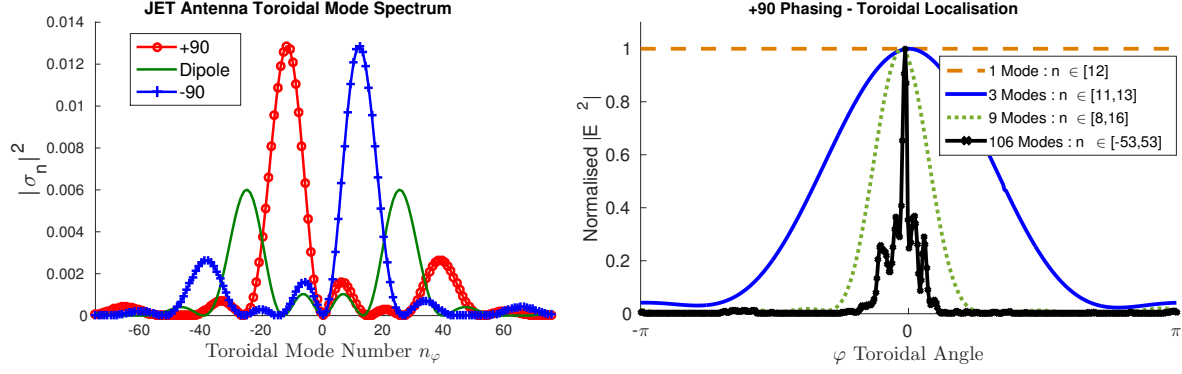
Figure 1: *The toroidal localisation of the JET antenna: a) the toroidal fourier spectrum coefficients of the $j_{antenna}$ decomposition, b) the influence of the number of toroidal modes used on the electric field produced by LEMan*

to the antenna current spectrum given by:

$$J_{n_\varphi} = \sum_k j_k^{(n_\varphi)} \frac{sin(\frac{n_\varphi}{R}W_k)}{\frac{n_\varphi}{R}W_k} exp\left(-\frac{n_\varphi d}{R} \right) \qquad \text{with} \qquad j_k^{n_\varphi} = j_{0k} exp\left(i\frac{n_\varphi}{R}z_k + i\varphi_k \right) \qquad (1)$$

Where W_k is the half width of the antenna strap, z_k is the strap location and φ_k is the phasing of the antenna. Note that the exponential term includes the effect of the plasma damping on the wave for the ROG distance d. The toroidal mode spectrum obtained from this equation is plotted on the left of figure 1. Therefore LEMan calculates the electric field for each toroidal mode number and the Monte-Carlo ICRF operator implemented in VENUS-LEVIS ensures a coherent reconstruction of the wave according to equation 1. Furthermore, the antenna that is implemented in LEMan is constructed independantly in s, θ and φ:

$$J_{ant} = \sigma_s(s)\sigma_\theta(\theta) \sum_n \sigma_n e^{in\varphi} \vec{e}_{ant} \qquad (2)$$

Where this box function representation is constructed in the same way for s and θ:

$$\sigma_\alpha(\alpha) = f_B\left(\frac{\alpha - \alpha_1}{\alpha_2 - \alpha_1} \right)(1 - \chi_\alpha^2)^2 \qquad (3)$$

For $\alpha = s, \theta$ and f_B the box function. In order to calculate the effects of the antenna localisation, +90 phasing was used to provide insight into the differences in the inward pinch of using multiple toroidal modes. Thus three different simulations were made: using one mode of $n_\varphi \in [12]$, 3 modes of $n_\varphi \in [11, 13]$ and 9 modes of $n_\varphi \in [8, 16]$, chosen according to the magnitude of the mode contribution. The results shown in figure 2 indicate that by localising the wave toroidally, the total fast ion pressure reduces. In this case the losses associated with toroidally localising the antenna increase, such that for 1, 3 and 9 modes the lost particles from the fast ion population are 43.3%, 54.7% and 58.1%. Additionally, the collisional power on the background electrons
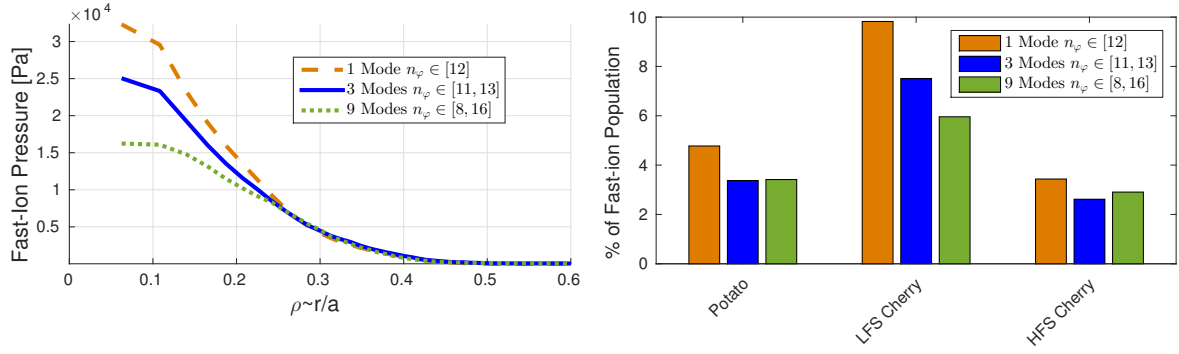
Figure 2: *Influence of toroidally localising the antenna on fast ion population: left) the fast ion pressure, right) percentage of exotic orbits*

and deutrium ions increases as 3.34MW, 3.54MW 3.62MW for 1, 3 and 9 modes respectively. Further evidence that using one toroidal mode induces a larger inward RF-pinch effect is to study the number of different types of exotic particle orbit behaviours in the plasma, as with a higher inward pinch the trapped resonant particles tend to be driven more towards the passing limit. Thus three different exotic particle orbit types are defined here: potato orbits are trapped particles that circle the magnetic axis, and Low Field Side (LFS) and High Field Side (HFS) cherry orbits, which are co and counter-current passing particles (resp.) which do not circle the magnetic axis. In order to classify the orbits, a simple consideration of the background magnetic equilibrium and the constants of motion of a particle suffices to allow a categorisation of the exotic orbits[2], noting that there has been more extensive research into more complicated orbits described by the work of L-G Eriksson and F. Porcelli, also based on the constants of motion [3]. A simple method to achieve this is to rearrange the equation for the toroidal momentum of the particle in terms of the dimensionless variable $H_p = B_0/B_{particle}$, the toroidal magnetic flux ψ and the constants of motion of the particle. This can provide insight into the drift a particle will undergo from it's average flux surface during it's motion around the tokamak, carried out extensively in [4]. With this information a simple categorisation of the particle orbits can be evaluated.

The bar graph shown on the right of figure 2 indicates that more exotic particles are found when the antenna is not toroidally localised, implying that when the wave is toroidally localised the inward pinch is not as effective on the particles. The reason for the larger inward pinch for using 1 mode only is most likely due to a broadening of the doppler shift of the wave, where resonance occurs at $\omega = \Omega + v_{||}k_{||}$, and as $k_{||} = n_{\varphi}/R$, by including a broader range of toroidal mode numbers the inward pinch of the particle might not be as peaked on the resonance layer. Despite the small percentage concentration of these types of orbits, they can have a large influence on
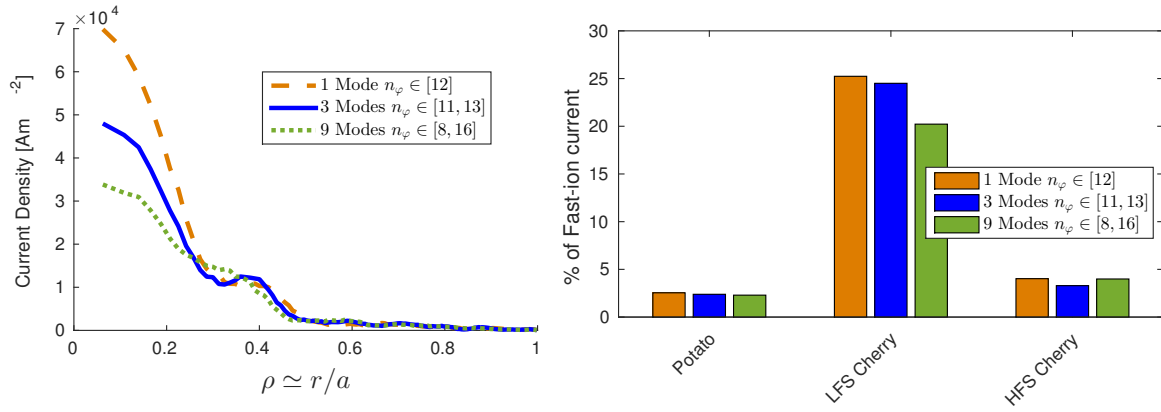
Figure 3: *Influence of changing B_{res} on the RF-Pinch: pressure of minority ion species*

the fast-ion current, which is shown in figure 3. The LFS cherry orbits provide a large current contribution as they are produce by trapped particles that have their bounce tips aligned with the resonance layer such that the bounce tips collapse to form a LFS cherry orbit; high energy passing particles still aligned with the resonance layer; thus almost continually accellerated. For the potato orbits, despite usually being exhibited by high energy particles, due to the fact that they are still nonetheless trapped, the potato orbits do not tend to induce large currents. Finally, the HFS cherry orbits also tend not to contribute as much of a current as those on the LFS because if their anisotropy further increases then there is a limit to which they will become re-trapped, and therefore there will be a net co-directional current from the LFS orbit ions.

Conclusion

The effects of toroidally localising the ICRF antenna on the RF-pinch effect in tokamak plasmas was investigated, to find that most likely due to the larger doppler-shifted broadening of the resonance layer, the results suggest that using multiple toroidal modes for a +90 phasing ICRF antenna has a reduced inward pinch, which reduces the number of exotic particle orbits observed after convergence of the mean energy of the fast ion distribution.

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