Modelling of ICRF fast ion generation in 2D and 3D plasma configurations.

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Introduction

Fast ion populations can be produced in tokamaks by the absorption of Ion-Cyclotron Range of Frequency (ICRF) wave. As well known the absorption of ICRF wave by the majority ion species cannot occur at the fundamental resonance because the left-handed component of the electric field E^+ vanishes at that location. The Minority Heating (MH) scheme requires to introduce in the plasma a second ion species in small concentration and is successfully used in experiments in order to exploit fundamental ICRF wave absorption. A newly developped ICRF scenario [1] shows tremendous potential for fast ion generation. It is intended that the recently started stellarator Wendelstein 7-X (W7-X) will use ICRF waves for fast generation. In the present work, we use the SCENIC package [2] in order to initiate a comparison between these scenarios in typical axisymmetric JET-like and W7-X plasma configurations.

Two-Dimensional configuration

A typical JET-like equilibrium is established in order to demonstrate the capacity of the three-ion species scheme to generate a large population of fast ions in comparison to a classic Minority Heating scheme. The background electron density and temperature profiles are respectively given as functions of the normalised minor radius r by
$n_e(r) = \left((4.0 - 0.4)(1 - r^2) + 0.4\right) \times 10^{19}[\text{m}^{-3}]$
and $T_e = T_i = (4.0 - 1.0)(1 - r^2)^{1.5} + 1.0[\text{keV}]$.

Figure 1: Relative power absorbed by the plasma species.

For simplicity, an analytic estimate for the safety factor is used: $q(r) = q_0 + (q_1 - q_0)r^2$ where $q_0 = 1.1$ and $q_1 = 5.1$. The plasma major and minor radii are respectively $R_0 = 2.96\,\text{m}$ and $a = 0.9\,\text{m}$ and where the magnetic field amplitude is $B_0 = 3.2\,\text{T}$. The
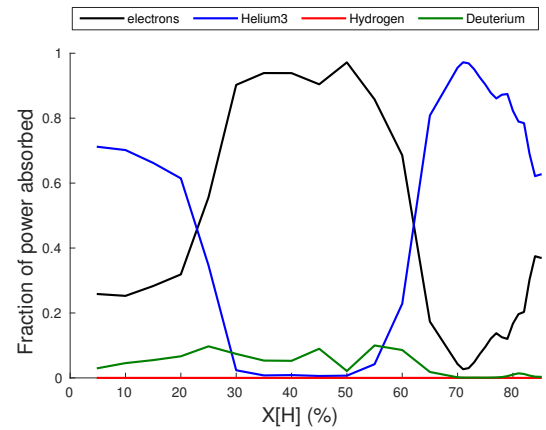
ICRF wave input power is $P_{RF} = 3\,\mathrm{MW}$ and the frequency is fixed at $f = 32.5\,\mathrm{MHz}$ which corresponds to on-axis fundamental resonance for ^{3}He ions. Following Ref. [1], the background ion species is a mixture of Deuterium, Hydrogen and 0.1% of ^{3}He. The full-wave code LEMan is used for the estimation of the mixture of Hydrogen and Deuterium which an optimal power absorption on ^{3}He ions. Fig. 1 shows the relative power absorbed by each plasma species as the Hydrogen concentration increases. The LEMan code estimates an optimal mix of H:D$\simeq 71\% : 29\%$ which is in good agreement with the estimation given in Ref. [1].

The SCENIC package is used on the basis of this plasma configuration in order to resolve the self-consistent ^{3}He ion distribution function. The ICRF wave toroidal mode number is varied in order to investigate typical antenna phasings: dipole ($n_\varphi = \pm 27$), $+90°$ (co-current travelling wave: $n_\varphi = -13$) and $-90°$ (counter-current travelling wave: $n_\varphi = 13$). Fig. 2 shows that for each wave configuration, around 7 iterations (i.e. the procedure of up-dating the equilibrium and the plasma dielectric tensor according to the fast ions contribution [2], marked as squares in Fig. 2) are required in order to reach good convergence. It is seen that the mean energy of the ^{3}He is in between $600 - 800\,\mathrm{keV}$ for all considered phasings indicating the presence of high energy particles. The saturated energy distribution functions are shown in Fig. 3. The tails of the distributions extend easily in the MeV range which is expected from this heating scheme. The same set of parameters (thermal profiles, ICRF wave frequency) is used to establish a Minority Heating scheme (Deuterium plasma with [^{3}He]=1%) for comparison. The energy distribution function for this scenario is plotted in Fig. 3 and shows clearly a much shorter fast ion tail than the one obtained for the three-ion species scenarios. Note that the number physical particles represented by the numerical markers is obviously not the same for the Minority Heating and three-
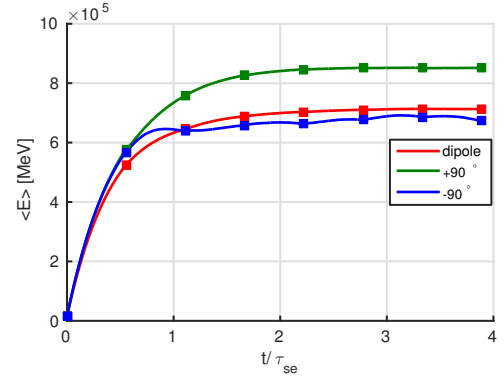

Figure 2: Mean energy per ^{3}He ions as a function of time normalised by the slowing down on electrons $\tau_{se} = 0.18\,\mathrm{s}$.
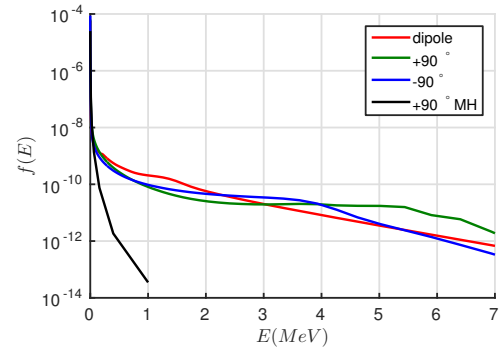

Figure 3: Saturated ^{3}He energy distribution functions obtained for each phasing and compared to a typical minority heating scheme.

ion species scheme. Therefore, the distribution functions have been normalised so that $\int_0^\infty \sqrt{E} f(E) \mathrm{d}E = 1$ for the sake of comparison. Figs. 2 and 3 show that the fast ion energy range is higher when +90° phasing is applied. This can be justified by the inward RF-pinch effect [3] resulting from the wave-particle interaction causing an increase in the resonant particles interaction time with wave compared to -90° and dipole phasings. The RF-pinch effect can clearly be seen by the peaking position in the fast ion pressure profile illustrated in Fig.4.
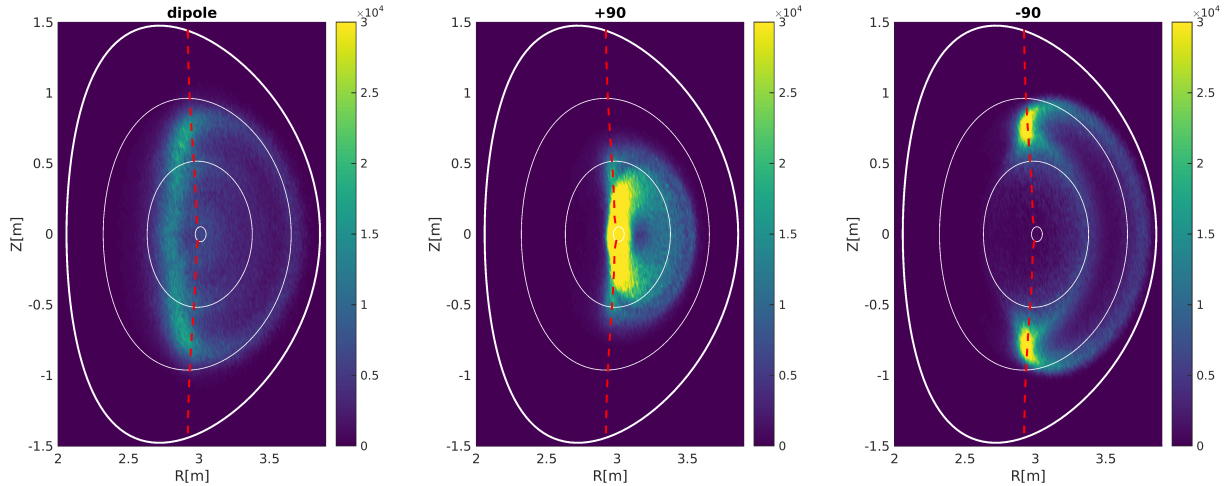

Figure 4: Fast ion pressure profiles for each investigated antenna phasing

Three-Dimensional configuration

The W7-X stellarator is the first optimised quasi-isodynamic stellarator and has recently started operation. One of the experimental goal of this machine is to demonstrate the capacity of the quasi-isodynamic configuration to magnetically confine α-like fast ions. ICRF is foreseen in W7-X as a potential source of fast ions within $50 - 100\,\mathrm{keV}$. It was shown in Ref. [4] that Minority Heating scheme will not be able to produce significant ion population in that range of energy, at least with the foreseen available power of 1.5 MW. This is mainly due to the high core density which prevents the fast ion tail formation. A typical high-mirror W7-X equilibrium is constructed with the following density and temperature profiles expressed in terms of normalised toroidal flux s: $n_e = 1.5 \times 10^{20} \left(0.9 \times (1 - s^{10})^2 + 0.1 \right) [\mathrm{m}^{-3}]$ and $T_e = 4 \times 10^3 (1 - s)[\mathrm{eV}]$. This equilibrium is used to resolve the ICRF distribution function for both Minority Heating and three-ion species schemes. The resonant layer was set in both cases on-axis in the bean-shaped cross section. The Minority Heating scenario uses a Deuterium plasma with 0.5% of Hydrogen minority. The three-ion species scenario features a H:D$\simeq 68\% : 32\%$

plasma with 0.1% of ^{3}He. The intrisic 3D dependency equilibrium imposes a strong coupling between the wave poloidal and toroidal modes. Therefore it is not possible identify a dominant mode spectrum as it was done for the 2D simulations. Instead, the antenna excitation modelled with `SCENIC` is fully spatially localised in ICRF simulations of W7-X.

It is seen from the resulting distribution functions shown in Fig. 5, that for the same input power $P_{RF} = 1.5\,\text{MW}$, the three-ion species scenario generates proportionnally a larger fast ion population than obtained when applying Minority Heating. The three-ion species distribution function obtained in the W7-X case still shows a relatively weak fraction of ions in the range of energy relevant for experiments. The concentration of ^{3}He can in principle be reduced, still making the scenario physically possible, in order to enhance the high energy disitribution. This case is still to be numerically investigated and compared to the present simulations.
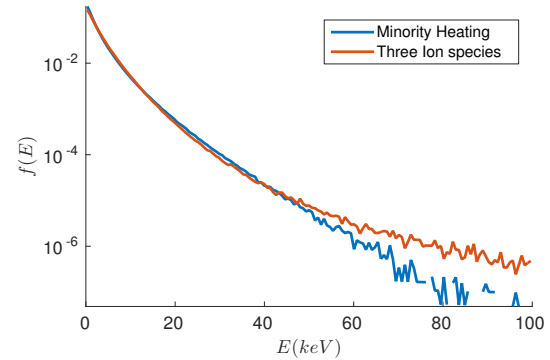

Figure 5: Fast ion distribution functions obtained for a Minority Heating and a three-ion heating scheme applied to W7-X.

Conclusion

The `SCENIC` package has been used in order to resolve and compare the ICRF distribution functions obtained when applying Minority Heating and three-ion species scheme in typical axisymmetric tokamak and stellarator configurations. Simulations confirm the higher potential of the three-ion species scenario to generate a larger fast ion population in both type of magnetic configuration.

References

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