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 waves in the range of Ion-Cyclotron Range of Frequency (ICRF). As is 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 the addition of a second ion species in low concentration, and has been successfully used in experiments in order to exploit fundamental ICRF wave absorption. This scheme generally allows for the generation of fast ions no less than a few hundreds keV. Generating fast ions in higher energy range can be addressed by a newly developped ICRF scenario [1] known as the "three-ion species" method which 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 capability 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: $n_e(r) = \left((4.0-0.4)(1-r^2)+0.4\right)\times 10^{19}[\mathrm{m}^{-3}]$ and $T_e(r) = T_i(r) = (4.0-1.0)(1-r^2)^{1.5} +$

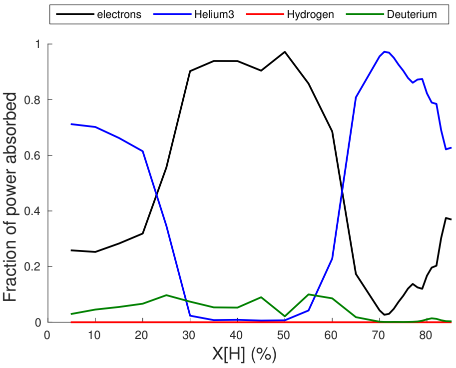

Figure 1: Relative power absorbed by the plasma species.

1.0[keV], where $r^2 \leq 1$ is the normalised toroidal flux. 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 $R_0 = 2.96\,\mathrm{m}$ and $a = 0.9\,\mathrm{m}$ and where the magnetic field amplitude is $B_0 = 3.2\,\mathrm{T}$. 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 at $B_0 = 3.2\,\mathrm{T}$. The full-wave code `LEMan` is used for the estimation of the optimal mixture of Hydrogen and Deuterium which maximises 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].

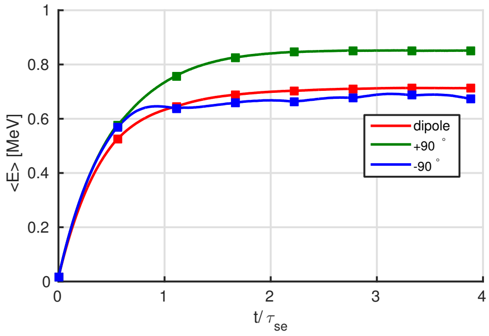

Figure 2: Mean energy per ^{3}He ions as a function of time normalised by the slowing down on electrons $\tau_{se} = 0.18\,\mathrm{s}$.

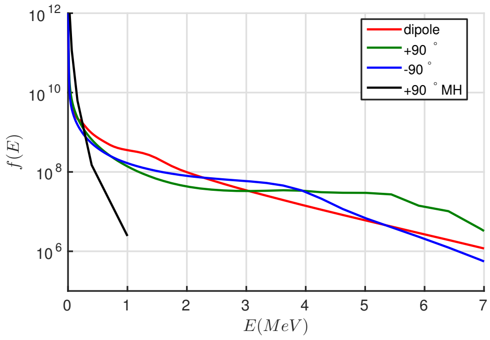

Figure 3: Saturated ^{3}He energy distribution functions obtained for each phasing and compared to a typical minority heating scheme.

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 updating the equilibrium and the plasma dielectric tensor according to the fast ion contribution [2], marked as squares in Fig. 2) are required in order to reach good convergence. It is found that the mean energy of the ^{3}He is around $600 - 800$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,as expected for 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. Fig. 3 clearly shows a much shorter fast ion tail for Minority Heating than for the three-ion species method. Figs. 2 and 3 show that the fast ion energy range is higher when +90° phasing is applied. This can be understood via the inward RF-pinch effect [3] which for +90° phasing causes the resonant particles interaction time with the wave to increase as compared with -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.

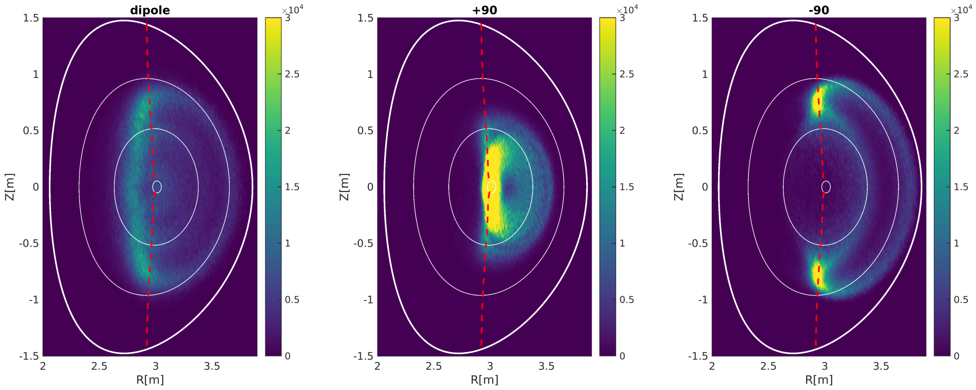

Figure 4: Fast ion pressure profiles for each investigated antenna phasing

Three-Dimensional configuration

The W7-X stellarator is the first optimised quasi-isodynamic stellarator and has recently started operation. One of the experimental goals 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 the 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 $1.5\,\mathrm{MW}$. This is mainly due to the high core density which prevents 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: $n_e = 1.5\times10^{20}\left(0.9\times(1-s^{10})^2+0.1\right)[\mathrm{m}^{-3}]$ and $T_e = 4\times10^3(1-s)[\mathrm{eV}]$. 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 to be on-axis in the region containing the antenna. 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 of the equilibrium imposes a strong coupling between the waves' poloidal and toroidal modes. Therefore it is not possible to identify a dominant mode number as generally done in 2D simulations. Instead, the antenna excitation modelled with `SCENIC` uses a range of coupled poloidal and toroidal modes and is therefore fully spatially localised in the ICRF simulations of W7-X.

It is seen from the resulting distribution functions shown in Fig. 5, that for the same input power $P_{RF} = 1.5\,\mathrm{MW}$, 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 above 100 keV. The concentration of ^{3}He can in principle be reduced, in order to enhance the high energy disitribution, but 0.1% of ^{3}He is already below the noise of experimental detection in the plasma. Lower concentrations are still to be numerically investigated and contrasted with the simulations presented here.

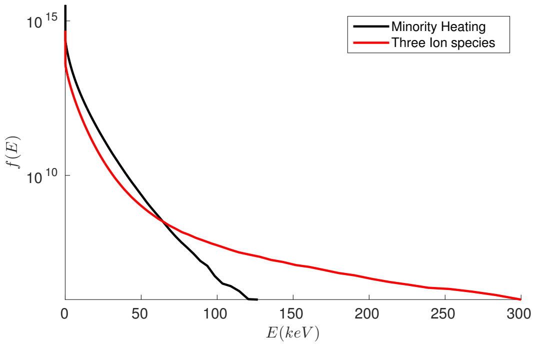

Figure 5: Fast ion distribution functions obtained for a Minority Heating and a three-ion heating scheme applied to W7-X.

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 schemes in typical axisymmetric tokamak and stellarator configurations. The new simulations confirm the higher potential of the three-ion species scenario to generate a larger fast ion population in both types of magnetic configuration.

Acknowledgement

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