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Investigation of ICRF heating scenarios in ASDEX-Upgrade with the full-wave TORIC package

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Introduction

Radio frequency (rf) heating with waves in the Ion Cyclotron (ICRF) range of frequencies plays an important role in the operation of the present fusion devices, and will be one of the most relevant heating systems for ITER. The capability to simulate propagation and absorption of ICRF waves is central for the analysis of experiments, and in designing scenarios with optimal ICRF performances. Here some possible ICRF scenarios in ASDEX-Upgrade (AUG) are analyzed with the full-wave TORIC code [1], whose capability to simulate large devices and challenging scenarios (such as mode conversion) has recently been greatly improved by the parallelization of the solver [2]. TORIC solves the wave equation in general toroidal axisymmetric configurations and describes the propagation and absorption of the externally excited fast wave (FW). It models ion absorption at the fundamental $\omega = \Omega_{\rm ci}$ and first harmonics $\omega = 2\Omega_{\rm ci}$ cyclotron resonances, and electron absorption via Landau and transit time damping. In addition, TORIC can simulate the excitation of ion Bernstein waves (IBW) and ion cyclotron waves (ICW) at the ion-ion resonance layer (IIRL). TORIC has been recently provided [3] with new modules, and in particular with a Fokker-Planck code for ions (SSFPQL) [4], which solves the steady state surface-averaged quasilinear Fokker-Planck (FP) equation for ions heated at $\omega = \Omega_{\rm ci}$ and at $\omega = 2\Omega_{\rm ci}$. SSFPQL gives an approximate 2–dimensional distribution function and the collisional redistribution of the heating power absorbed by the ions at the fundamental cyclotron resonance. The implemented algorithm is very fast, but the suprathermal tails can be described only up to moderate energies $v/v_{\rm thi} \lesssim 7$, and some toroidal effects important at large energies are omitted. The consistency loop between the two codes can be closed, since, in calculating the wave-equation coefficients, TORIC can use the distribution function of the minority ions evaluated by SSFPQL [3].

The richness of ICRF physics is mainly due to the strong dependence of the wave propagation and absorption on the plasma composition, i.e. the presence of more ion species with different charge to mass ratios. Limiting our analysis to the main plasma compositions used in AUG, we study the transition from the minority (MH) to mode-conversion (MC) heating regimes as function of the minority concentration. To guarantee numerical convergence in the MC regime these simulations are performed with up 500 radial elements and 255–511 poloidal modes.

Hydrogen in Deuterium

The AUG ICRF system works mainly at 30 MHz of frequency, and the most common ICRF scenario in AUG is minority heating in D(H) plasmas. The ICRF antennas consist of two straps such that the mean peak of the excited spectrum is centered around $n_\phi = 6$ and $n_\phi = 12$, respectively for $\pi/2$ and π phasings ($k_\parallel \approx 3.5\,\mathrm{m}^{-1}$ and $k_\parallel \approx 7.\,\mathrm{m}^{-1}$). In this scenario the waves launched from the low field side (LFS) encounter first the H cyclotron resonance $\Omega_{\mathrm{cH}} = 2\Omega_{\mathrm{cD}}$ and then the ion-ion evanescence layer (IIEL), bounded by ion-ion $S = n_\parallel^2$ resonance towards the high field side (HFS) and by the $L = n_\parallel^2$ cutoff towards the LFS. The rf power not absorbed neither by ions at $\omega = \Omega_{\mathrm{cH}}$ nor by the electrons is partially reflected and transmitted at the IIEL, and mode-converted to IBWs. As an example, we have considered the discharge #17297 at $t = 5.1$ sec, characterized by central confining magnetic field $B_0 = 2$ T, density $n_e(0) \approx 6.8 \times 10^{19}\,\mathrm{m}^{-3}$, electron temperature $T_e(0) \approx 4.6\,\mathrm{keV}$, and ion temperature $T_i(0) \approx 4.9\,\mathrm{keV}$. As function of the H concentration $\nu_H \equiv n_H/n_e$, Fig. (1) shows (solid lines) how the rf coupled power is distributed among the two ion species and the electrons. The values reported for electrons are comprehensive of the contributions due to damping of FWs and IBWs. The transition to mode-conversion regime starts when the $S = n_\parallel^2$ resonance emerges from the Doppler-broadened cyclotron resonance layer, which happens when ν_H is larger than a critical value [5]:

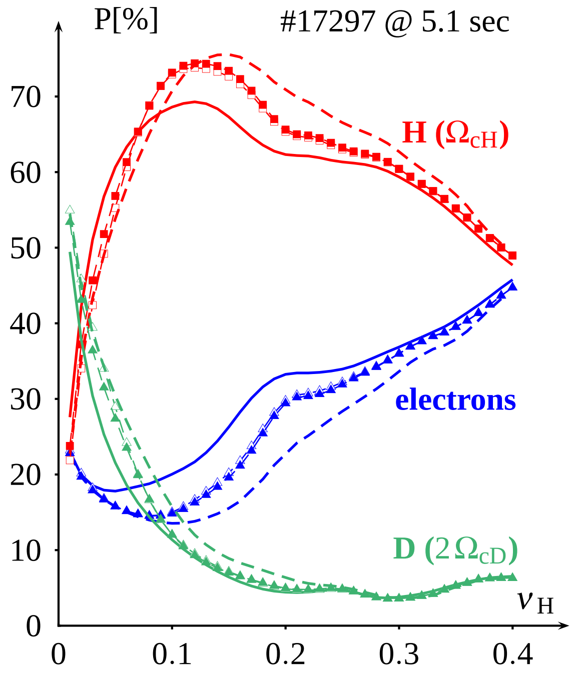

Figure 1: *rf power distribution in a D(H) plasma as function of the H concentration for $n_\varphi = 12$: solid lines with Maxwellian distribution functions (df) for the minority, open symbols with df calculated by SSF-PQL with 4 MW of coupled power, and full symbols are the second iteration of TORIC-SSFPQL. The dashed lines are the first iter. with 10 MW of rf power.*

$$\nu_c = \frac{2}{\alpha} n_\parallel \frac{\mathrm{v_{thm}}}{c} \left\{ \frac{\alpha^2}{1-\alpha^2} + (n_\parallel^2 - 1)\, \frac{\mathrm{v_{AM}^2}}{c^2} \right\} \tag{1}$$

with $\alpha = \Omega_{\mathrm{cM}}/\Omega_{\mathrm{cm}}$, and $\mathrm{v_{AM}}$ the Alfvén speed of the majority ion species. According to Eq. (1), MC starts to play a role for $\nu_H \gtrsim \nu_c \approx 18\%$, in agreement with TORIC results. In

Fig. (1), around $\nu_H \approx 20\%$ the decrease of the power absorbed by H with ν_H is due to the increase of the IIEL optical thickness with ν_H in combination with the fact that the reflected FWs crosses again the $\omega = \Omega_{\mathrm{cH}}$ resonance, with further absorption by the minority. When ν_H is further augmented, the increase of screening of the wave field component E_+ by H is such that the ion absorption at $\omega = \Omega_{\mathrm{cH}}$ is overwhelmed by electron Landau damping. The open symbols of Fig. (1) refer to TORIC results after an iteration with SSFPQL, with a realistic value of coupled rf power of 4 MW. At low concentrations ($\nu_H \lesssim 7\%$) the finite Larmor radius effects of the fast minority-ion tail reduces the power absorbed by the minority. However, as soon the ν_H increases, the effective perpendicular temperature of the tail decreases, and a slight increase of the parallel effective temperature causes an increase of the power absorbed and a shift of the MC transition to a slightly larger concentration. In the case of 10 MW of coupled power, reported in dashed lines in Fig. (1), there is a further shift of the MC to higher concentrations and an increase of the minority heating for medium values of ν_H.
The results of the 2^{nd} iteration TORIC-SSFPQL for 4 MW are reported in full symbols in Fig. (1). At moderate values of coupled rf power one iteration is enough to reach convergence.

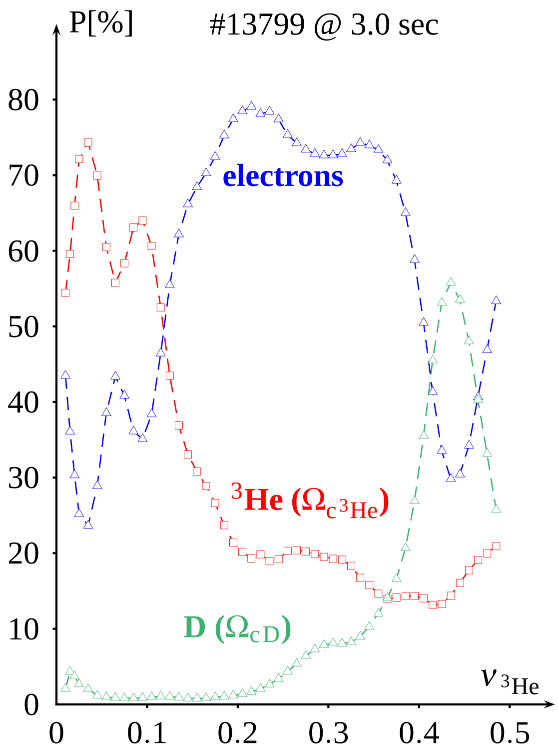

Figure 2: *rf power distribution in a D(^{3}He) plasma as function of ^{3}He concentration.*

Helium 3 in Deuterium and in Hydrogen

The main difference of D(^{3}He) respect to D(H) is that the cyclotron resonance of the minority does not correspond to the first harmonics resonance of the majority. This implies that the thermal correction σ of the S element of the dielectric tensor is not resonant, and the IBWs have much shorter perpendicular wavelengths ($n^2_{\perp\,\mathrm{IBW}} \approx -S/\sigma$) [6]. In addition, part of the reflected FWs are converted to ICWs, which are efficiently damped via electron Landau damping. Using the same temperature and density profiles of #17297, Fig. (2) shows the power distribution for the equilibrium of #13799 at 3 sec ($B_0 = 3.15$ T). In D(^{3}He) scenario there is a clear transition to MC dominant regimes around the concentration $\nu_c \approx 9\%$, as predicted by Eq. (1). When $\nu_{^3\mathrm{He}} \gtrsim 20\%$, E_+–screening by D ions around $\omega = \Omega_{\mathrm{cD}}$ decreases, and they start to play the role of the minority. Consequently, to an increase of the fraction of power absorbed by D it corresponds a decrease of the power converted in IBWs and ICWs, absorbed by the electrons. The modulation of the peak absorption around $\nu_{^3\mathrm{He}} \approx 9\%$ is due to radially standing waves between the plasma boundary and the $L = n_\parallel^2$ cut-off [7]. The "virtual cavity" length, dependent on $\nu_{^3\mathrm{He}}$, determines the magnitude of $|E_+|^2$ at the $L = n_\parallel^2$ cutoff, and thus influences the amount of rf power transmitted to IBWs, which are mainly absorbed by electrons.

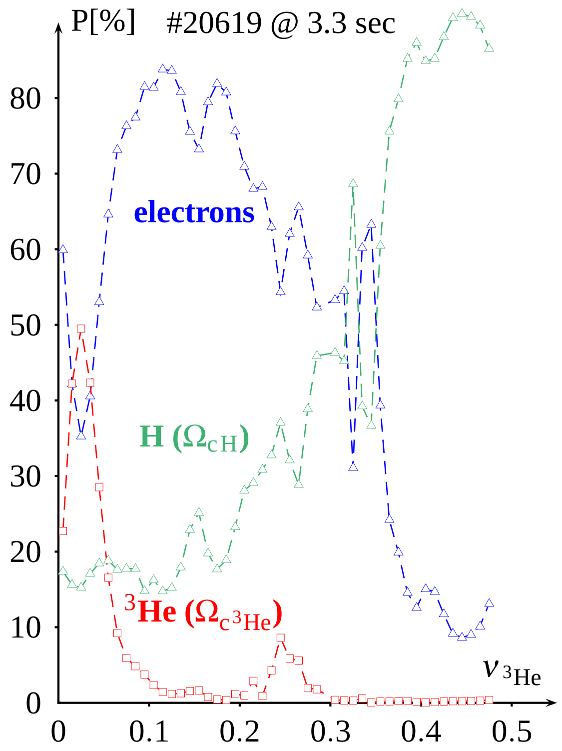

Figure 3: *rf power distribution in a H(^{3}He) plasma as function of ^{3}He concentration.*

Finally, in H(^{3}He) mixture the transition to MC regime is at lower concentrations ($\approx 3.80\%$, value predicted by Eq. (1)) and much sharper, as shown in Fig. (3) for $B_0 = 2.29$ T. In this scenario, the waves have to tunnel across IIEL to reach the minority cyclotron layer. Thus, as $\nu_{^3\mathrm{He}}$ increases, the fraction of rf power which can reach $\omega = \Omega_{c^3\mathrm{He}}$ decreases rapidly. This scenario is similar to ^{3}He(D) represented in Fig. (1) at high $\nu_{^3\mathrm{He}}$. However, the transition to MC in H(^{3}He) is sharper and at lower values of the concentration than in ^{3}He(D) , since at the same ion temperature the Doppler broadening is less for ^{3}He than for D ion species.

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