Simulation of Burning Plasma Dynamics by ICRH Accelerated Minority Ions

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Abstract. A detailed analysis of the physics of interaction ICRH (Ion Cyclotron Resonant Heating) -plasma is presented by solving simultaneously the full wave and Fokker-Planck equations in the flux surfaces coordinates. The ICRH (Ion Cyclotron Resonant Heating) in the minority scheme (H or ^{3}He) can indeed produce fast particles that, with an appropriate choice of the minority concentration, of the RF power and of the plasma density and temperature, can reproduce the dimensionless parameters (fast particles radius and fast particle beta) characterizing the α-particles in ITER. Thus, a device operating with deuterium plasmas in a dimensionless parameter range as close as possible to that of ITER and equipped with ICRH as a main heating scheme would be able to reproduce the most important features of alpha-particles heated plasmas and therefore would be capable of assessing the relevant scenarios before their implementation on ITER itself.

1. Introduction

The main difference between present experiments and ITER will be the presence, as the main heating source, of the α-particles produced in DT reactions. Alpha particles will mainly heat electrons, contrary to the present experiments dominated by low energy neutral beam injection that mainly heats the ions. Moreover, α-particles can drive stronger collective modes than those observed in present experiments.
As proposed in Ref.[1], the α-particle dynamics can be simulated in pure deuterium plasmas by ions accelerated by radiofrequency waves. The use of ICRH in the minority scheme (H or ^{3}He) can indeed produce fast particles (although with a slightly different distribution function than that of fusion generated α-particles) that, with an appropriate choice of the minority concentration, of the RF power and of the plasma density and temperature, can reproduce the dimensionless parameters ρ_{*fast} and β_{fast} characterizing the α-particles in ITER. Here, ρ_{*fast} is the normalized fast particles radius and β_{fast} the fast particle beta. Thus, a device operating with deuterium plasmas in a dimensionless parameter range as close as possible to that of ITER and equipped with ICRH as a main heating scheme would be able to reproduce the most important features of α-particles heated plasmas and therefore would be capable of assessing the relevant scenarios before their implementation on ITER itself.
The aim of the present paper is to determine the characteristic fast-ion parameters, by solving the coupled problems of ICRH propagation and quasi-linear absorption. The 2D full-wave code TORIC [2] in the flux surface coordinate system is used coupled to the SSQLFP code, which solves the quasi-linear Fokker-Planck equation in 2D velocity space [3]. Using as reference parameters those considered in Ref.[1] for the FT3 conceptual study, the power deposition profiles on the ion minority, majority and electrons are first determined; then, the effective temperature of the minority ion tail and the fraction of fast ions is evaluated. Moreover, the quasi-linear analysis determines how much of the power absorbed by the minority will be redistributed by collisions on the main species of the plasma: electrons and majority ions. In particular, once established the “minority heating” scheme (H in D or ^{3}He in D), our study is devoted first to establish the fraction and the spatial distribution of the coupled ICRH power that is deposited on the minority when varying the concentration, including the effects of the wave spectrum, i.e. considering the effective field radiated by the antenna; second the quasi-linear evolution of ion minority distribution function in the parallel

and perpendicular velocity space, this enables to evaluate the effective temperature of the tail and the fraction of minority in the high energy tail.

1. The theory of linear and quasi-linear absorption

The interaction plasma-ICRH wave is modeled by the wave equation [2]

$$\nabla \wedge \nabla \wedge \vec{E}(\vec{r}) = \frac{\omega^2}{c^2}\left(\vec{E}(\vec{r}) + \frac{4\pi i}{\omega}\vec{J}^p(\vec{r})\right) \tag{1}$$

Where is the high frequency induced plasma current, evaluated by solving the linear Vlasov equation.
The ICRH is essentially based on the excitation, by means of strap antenna placed in front of the plasma, of a fast magnetosonic wave which propagates up to the ion resonant layer $\omega = n\Omega_{cM}$ of the majority ions or up to the minority ions resonant layer if the heating scheme has been chosen involves the presence of a minority species. Near the two-ion resonant layer there is the high-density cut-off on one side (where the wave is reflected back), whilst beyond the two-ion resonant layer, by tunneling, the wave can convert on the Ion Bernstein mode. The wave is partially damped on the ion-cyclotron harmonic layer where the power deposition is sufficiently tight while electrons absorb the wave in a broad profile between the antenna and the cut-off. The power fraction converting in the Ion Bernstein Mode will be absorbed efficiently by the bulk electrons just after the mode conversion layer. It is obvious that there is a competition between electrons, ion majority and ion minority in the absorption mechanism. Our aim is to maximize, by choosing some plasma and/or antenna parameters like minority concentration, density and electron temperature, antenna spectrum, frequency, the power absorbed on the minority ions. To do this, the solution of the wave equation is given numerically in the flux surface coordinate system by considering the wave spectrum radiated by the antenna and exploring the solution in various range of parameter space.
The Fokker-Planck equation that governs the evolution of the ions (minority and majority) distribution function can be written as [3]

$$\sum_{\beta=e,i} v^{i/\beta}\left\{\frac{1}{\hat{v}^2}\frac{\partial}{\partial \hat{v}}\hat{v}^2\left[\Psi(\gamma_{i\beta}\hat{v})\left(\frac{1}{2\hat{v}}\frac{\partial F_i}{\partial \hat{v}} + \frac{T_i}{T_\beta}F_i\right)\right] + \frac{\Theta(\gamma_{i\beta}\hat{v})}{2\hat{v}^3}\frac{\partial}{\partial \mu}\left((1-\mu^2)\frac{\partial F_i}{\partial \mu}\right)\right\} + \frac{1}{w_\perp}\frac{\partial}{\partial w_\perp}\left[w_\perp \frac{D_{ql}(w_\perp)}{v_{thi}^2}\frac{\partial F_i}{\partial w_\perp}\right] = 0 \tag{2}$$

Where

$$\Psi(u_\beta) = \frac{\Phi(u_\beta)}{u_\beta^2}$$

$$\Phi(u_\beta) = \frac{4}{\sqrt{\pi}}\int_0^{u_\beta} u^2 e^{-u^2} du = -\frac{2}{\sqrt{\pi}}u_\beta e^{-u_\beta^2} + erf(u_\beta) = -u_\beta erf'(u_\beta) + erf(u_\beta)$$

$$\Theta(u_\beta) = \frac{2}{\sqrt{\pi}}u_\beta e^{-u_\beta^2} + \left(u_\beta^2 - \frac{1}{2}\right)\frac{\Phi(u_\beta)}{u_\beta^2} = -\frac{1}{2}\left\{-2erf(u_\beta) + \left(\frac{erf(u_\beta) - u_i erf'(u_\beta)}{u_\beta^2}\right)\right\}$$

and $\hat{v} = (v/v_{thi})$, $\gamma_{i\beta} = (v_{thi}/v_{th\beta})$, $u_\beta = (v/v_{th\beta})$, v and m are respectively the velocity and the pitch angle. On the same equation $D_{ql}(w_\perp = (v_\perp/v_{thi}))$ is the quasi-linear diffusion coefficient due to the action of the wave field on the plasma ions, and

If we average Eq. (2) on the pitch angle μ we obtain an ordinary differential equation for the isotropic part $F_i(v)$ of the distribution function $F_i(v,\mu)$ at the steady state. The isotropic part of the distribution function is defined as:

$$F(\mu)=\frac{1}{2}\int_{-1}^{+1} d\mu F_i(v,\mu)$$

We consider, now, the limit of high velocity, we obtain the following solution

$$\ln F-\ln C=-\frac{v^2}{\frac{2kT_i}{m_i}\frac{(\varepsilon+D)}{\varepsilon}\left(\frac{T_e}{T_I}\right)}=-\frac{v^2}{\frac{2kT_{i,tail}}{m_i}}=-\frac{E}{kT_{i,tail}} \tag{3}$$

The solution eq. (3) is a Maxwellian that is characterized by a minority temperature of the tail:

$$T_{i,tail}=T_e\frac{(\varepsilon+D)}{\varepsilon}=T_e+T_e\frac{D}{\varepsilon}$$

Where for the minority heating

$$\frac{D}{\varepsilon}=\frac{1}{4}\frac{\sqrt{\pi}}{v^{i/e}v_{thi}^2}\frac{P_{abs}^{lin}}{m_i n_i}\left(\frac{m_i}{m_e}\right)^{1/2}$$

To start from eq. (3) is possible to calculate a minority concentration in the tail which is given by

$$n_{i,tail}=\frac{2n_i}{\sqrt{\pi}}\left(\frac{T_{i,tail}}{T_i}\right)^{3/2}\Gamma\left(\frac{3}{2},y_{critical}\right) \tag{4}$$

where $\Gamma(a,x)$ is the incomplete gamma function, $y_{critical}$ is the critical energy. In the above equations k is the Boltzmann constant, $T_{I,e}$ are the ion majority and electrons temperatures, $m_{i,e}$ the ion minority and electron mass, $v^{i/e}$ the ion/electron collision frequency, v_{thi} the ion thermal velocity and P_{abs}^{lin} the power density coupled to the minority ions.

2. Numerical Results and discussion

As an example, we have considered the following reference antenna and plasma parameters: 20-35MW of ICRH power coupled to the plasma, at a frequency f=68 MHz, the toroidal magnetic field is B_T=6.7T, the plasma current $I_p=5MA$, with $q_{95}=2.96$, the volume average density is $\langle n_e\rangle=3.67$ and a central value $n_0=4.1\times10^{20}m^{-3}$, with generalized parabolic profile $n_e=(n_0-n_S)f^{\alpha}(\bar{\psi})+n_S$, the central temperature is $T_0=9.22KeV$ with profile $T=(T_0-T_S)f^{1-\alpha}(\bar{\psi})+T_S$, where $f(\bar{\psi})=\sum_{k=1,N}\left(\frac{\alpha_k}{k}\right)(1-\psi^k)$ is a generalized function of the magnetic flux coordinate, n_0, n_S, T_0, T_S are, respectively, the central and separatrix densities and the central and separatrix temperatures, flat density profile $\alpha = 0.29$ has been chosen. A ^{3}He minority-heating scheme has been considered. This choice of parameters corresponds to a H-mode scenario, characterized by the enhancement factor $H = 1$, this corresponds to $\beta_N = 2.07\%$ while a $\langle\beta\rangle = 2.55\%$. A parametric study of the ICRH absorption has been performed when considering the realistic coupled wave spectrum (realistic antenna geometry), and when varying the minority concentration, aimed at increasing the power coupled to the minority ions and at obtaining the maximum effective temperature of the tail. As an example, we report here the results obtained by using the code TORIC for the "H-mode scenario". A scan in minority concentration of the power fraction coupled to the various species has been performed, as shown in Fig. 1. As it is possible to notice the fraction of power coupled to the minority is around 70% for a large part of the concentration range (2%-5%). For smaller or greater concentration (<2%, >5%) the electron heating becomes the dominant heating. In all cases the ion majority at the first harmonic absorb less than 5% of coupled power. In this calculation, the parallel wave-number has been chosen as the peak value of the power spectrum radiated by the antenna (n||=5.1). When considering the effect of the power spectrum on the power absorption the fraction of power on the various species vs the parallel wave-number is shown in Fig. 2, at fixed ^{3}He concentration (2%). The power fraction absorbed by the minority in the range 4<n||<6 (maximum of the radiated power) is included between 60-70% of the total power.

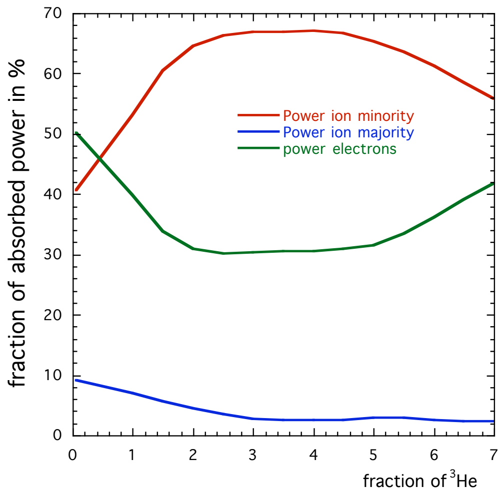

FIG.1. Fraction of absorbed power vs the minority concentration at fixed n||=5, for the plasma parameters of the H-mode scenario.

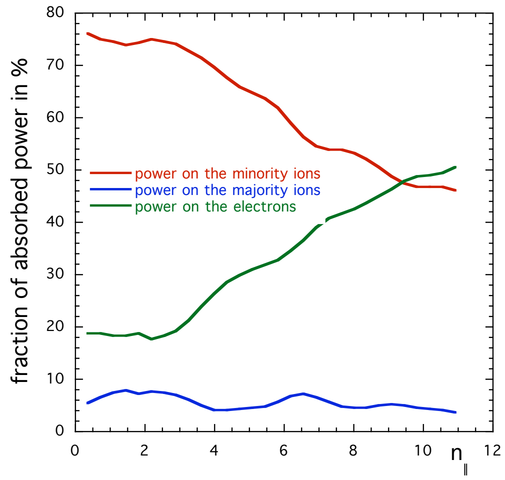

FIG.2. Fraction of absorbed power vs the parallel wave-number at fixed ^{3}He concentration 2%, for the plasma parameters of the H-mode scenario.

Using this result in the quasi-linear calculation (Fokker-Planck equation) we obtain the following relevant results. In Fig. 3, the power density coupled to the various species in (W/cm^3) is plotted vs. the plasma radius, when an optimum ^{3}He minority concentration of 2% (which maximizes the power absorbed by the minority) is considered. It is possible to deduce the localization of the deposition, $\rho \approx 0.35$ ($\sim 23cm$ from the plasma centre) the width of the deposition layer, $\Delta\rho \approx 0.1$ ($\sim 20cm$) for the minority and broader for the electrons, and the peak of the power density ($30\,W/cm^3$). This number is important in calculating the temperature of the tail. In Fig. 4 the distribution function for the minority, is plotted vs. the energy in logaritmic scale at several pitch angles values. As it is possible to see the tail extends up to energy value of the order of MeV.

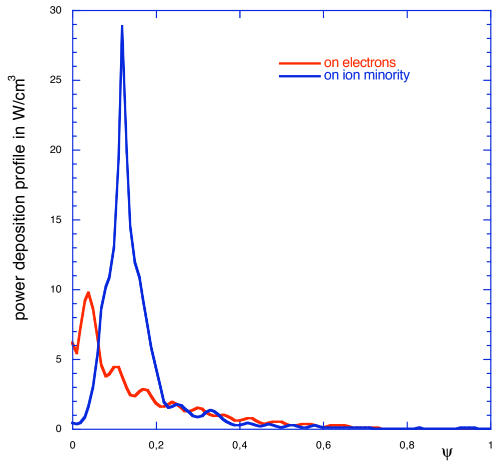

FIG.3. Power deposition profiles vs the plasma radius and for the various species.

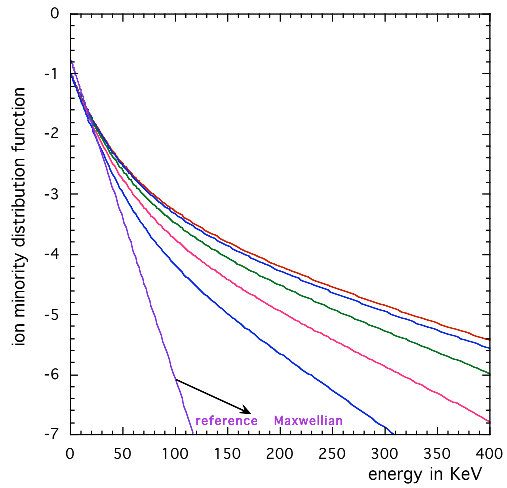

FIG.4. Ion minority distribution function vs the energy for several values of the pitch angle.

In Fig. 5, finally, the parallel and perpendicular temperature of the tail is plotted vs the plasma radius. While in Fig. 6 the fraction of minority ions is plotted vs the plasma radius. Both figures based on the quasi-linear analysis, allows the calculation of the effective temperature of the minority ions as well as the fraction of the minority at this energy in the layer of maximum deposition.

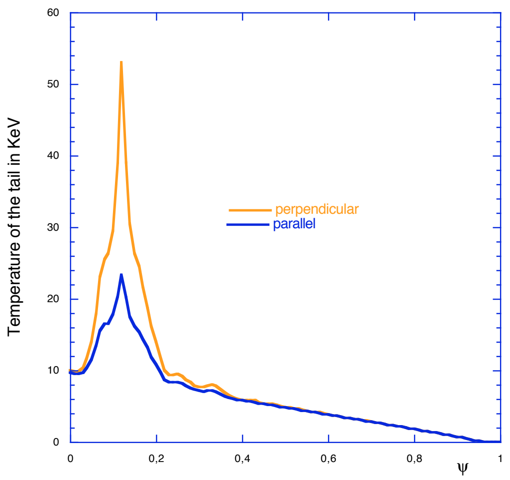

FIG.5. Parallel and perpendicular temperature of the tail vs the flux function variable.

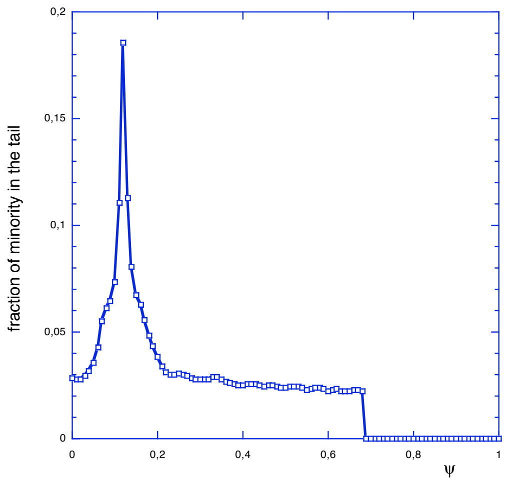

FIG.6. Profile of the ion minority fraction on the tail vs the flux function variable.

In Figs. (7) and (8) finally the peak values of the perpendicular tail temperature and tail minority are reported vs the minority concentration for several values of coupled ICRH power from 20 to 35 MW. As it is possible to see the optimum minority fraction which maximize the tail temperature and tail minority is included between 1.5-2%. For higher fraction the tail temperature, and minority drops to values too low for our goal.

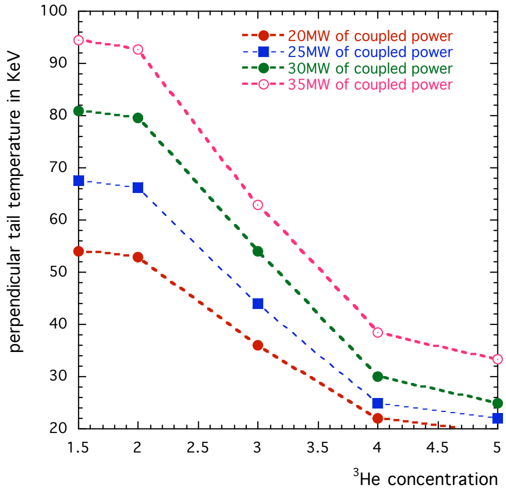

FIG.7. Perpendicular temperature of the tail at the peak vs the minority concentration.

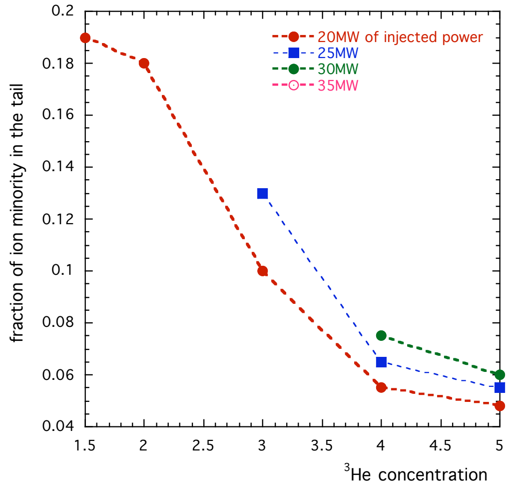

FIG.8. Minority fraction of the tail at the peak vs the minority concentration.

If we consider now a H-mode scenario characterized by a central density and temperature $n_0 = 1.93\times10^{20} m^{-3}$ and $T_0 = 14.5 KeV$ with a $\beta_N = 1.58\%$, the effective temperature increases up ≈220 keV (on the peak of the absorption layer, and for a coupled power of 20MW), up to 400 keV (for a coupled power of 40MW), with a fast ion fraction of about 50%, as it can be deduced by Figs. (9) and (10).

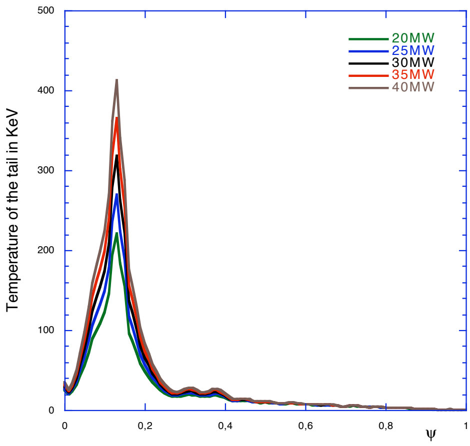

FIG.9. Perpendicular temperature of the tail vs the flux coordinate and for plasma parameters $n_0 = 1.93\times10^{20} m^{-3}$ *and* $T_0 = 14.5 KeV$.

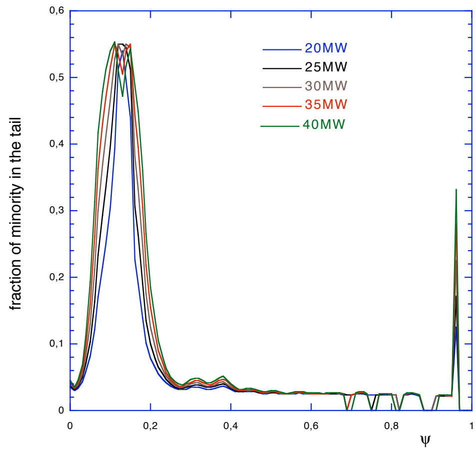

FIG.10. Minority fraction of the tail vs the flux coordinate and for plasma parameters $n_0 = 1.93\times10^{20} m^{-3}$ *and* $T_0 = 14.5 KeV$.

To start from this result, it is possible to calculate the characteristic fast ion parameters, which are relevant for collective mode excitations, i.e., the fast ion beta, β_H, the ballooning $\alpha_H = -R\, q^2 (d\beta_H / dr)$, and the characteristic fast ion speed normalized to the Alfvén speed, v_H / v_A. They can be directly evaluated from the effective temperature, T_{eff}, from the minority fraction in the tail, and from the profiles. The β_H, for example, for the plasma parameters of Figs. (9) and (10) and in the range of coupled power 20-40MW varies from 0.35% to 0.7%, the ballooning factor $\alpha_H \sim 10^{-1}$, these values are consistent with the ITER reference scenario SC2 [4].

3. Conclusions

Linear and quasi-linear calculation of ICRH wave absorption in the recently proposed tokamak FT3 are presented and mainly devoted to study the physics of high energetic particles in burning plasma experiments. A parametric study of a H-mode plasma scenario when varying the minority concentration, the parallel wave-number of the radiated spectrum, the input ICRH power, has been performed in order to maximize i) the fraction of power on the ^{3}He minority species, ii) the perpendicular temperature of the tail, iii) the fraction of minority particles on the tail. These quantities, indeed, are useful in calculating the fast ion parameters relevant for collective mode excitations. It has been shown that the H-mode scenario at 5MA characterized by a peak density $n_0 = 1.93\times10^{20} m^{-3}$, and temperature $T_0 = 14.5 KeV$ respectively, are very well indicated to study the effects of the α-particle dynamics in driving the instabilities. The fast ion parameters are consistent with that of ITER reference scenario SC2.

References

[1] ROMANELLI, F., et al., “FT3-An Experiment to Study Burning Plasma Physics Issues in Deuterium Plasmas”, Fusion Science and Technology, **45** 483 (2004).
[2] BRAMBILLA, M., “Numerical simulation of ion cyclotron waves in tokamak plasmas”, Plasma Physics and Controlled Nuclear Fusion **41** 1 (1999).
[3] BRAMBILLA, M., “Quasi-linear Ion Distribution Function During Ion Cyclotron Heating in Tokamaks”, Nucl. Fusion **34** 1121 (1994).
[4] VLAD, G., BRIGUGLIO, S., FOGACCIA, G., ZONCA, F., SCHNEIDER, M., Nucl. Fusion **46** 1 (2006).