Minority Ions Acceleration by ICRH: a tool for investigating Burning Plasma Physics

A. Cardinali, S. Briguglio, G. Calabrò, F. Crisanti, C. Di Troia, G. Fogaccia,
M. Marinucci, G. Vlad and F. Zonca

Associazione Euratom-ENEA sulla Fusione, C.P. 65 - I-00044 - Frascati, Rome, Italy

e-mail contact of main author: cardinali@frascati.enea.it

Abstract. A thorough numerical analysis of the quasi-linear plasma-ICRH wave interaction has been made and will be presented in order to determine the characteristic fast-ion parameters that are necessary for addressing some of the main ITER burning plasma physics issues, e.g. fast ion transport due to collective mode excitations, cross-scale couplings of micro-turbulence with meso-scale fluctuations due to energetic particles, etc. These investigations refer to the Fusion Advanced Studies Torus (FAST), a conceptual tokamak design 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. The destabilization and saturation of fast ion driven Alfvénic modes below and above the EPM (Energetic Particle Modes) stability threshold are investigated by numerical simulations with the HMGC code, which assumes the anisotropic energetic particle distribution function accelerated by ICRH as input. The results of this study, obtained by integration of many numerical tools, are presented and discussed.

1. Introduction

The main difference between present experiments and ITER will be the presence of alpha particles produced in DT reactions as the main heating source. Fusion alpha's, with small characteristic orbit size (compared with the machine size), will mainly heat electrons and excite meso-scale fluctuations, contrary to present day experiments where, in general, relatively low energy fast ions, such as those generated by neutral beam injection, are characterized by medium or large orbit size and transfer their energy to thermal plasma ions while exciting macro-scale collective modes. On the contrary, minority ions, accelerated by radiofrequency waves in the range of MeV energies, predominantly transfer their energy to plasma electrons via collisional slowing down. The use of ICRH in the minority scheme (H or ^{3}He) in D plasmas 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 ρ_H^* and β_H characterizing the alpha particles in ITER and preferentially heat thermal plasma electrons, provided that plasma current is sufficiently high [1,2,3,4]. Here, ρ_H^* is the fast particle Larmor radius normalized to the torus minor radius and β_H the fast particle beta. Meanwhile, characteristic thermal plasma dimensionless parameters as well as plasma-wall interaction conditions can be "simultaneously" chosen to be close to ITER relevant values [4]. 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 address a number of important burning plasma physics issues, e.g. fast ion transport due to collective mode excitations and cross-scale couplings of micro-turbulence with meso-scale fluctuations due to energetic particles themselves [3,5,6]. Precious information about the fundamental dynamic behavior of fast ions in burning plasmas can be obtained by experimental studies of the *fast ion tail* produced by Ion Cyclotron Resonant Heating (ICRH) despite their different distribution function with respect to that of fusion generated alpha particles [1]. In fact, more than the details of the velocity space distribution function, it is the mode number and frequency spectrum (normalized to the Alfvén frequency) that determines fast ion transport and cross-scale couplings between meso-scale phenomena and micro-turbulence. In this respect, radial envelopes of the spectra play a crucial role and increased flexibility could be achieved using Negative Neutral Beam Injection (NNBI) sources in the MeV energy range. The aim of the present paper is to determine the characteristic fast-ion parameters that are necessary for addressing the mentioned above burning plasma physics issues and to present a stability analysis of collective modes excited by the ICRH induced energetic ion tail. As already mentioned, the criteria are: (i) appropriate choice of the supra-thermal tail temperature in order to ensure dominant electron heating (fixed the electron temperature and as discussed in [4]); (ii) choose plasma current and density so that mode number and frequency spectra are close to those of ITER; (iii) determine ICRH power input necessary for obtaining the desired β_H and the minority density needed for a supra-thermal tail temperature consistent with (i). Here, we solve the coupled problems of ICRH propagation and quasi-linear absorption. The 2D full-wave code "TORIC" [7] is used in connection with the "SSQLFP" code, which solves the quasi-linear Fokker-Planck equation in 2D velocity space [8]. Using FAST H-mode reference equilibria considered in Ref. [9], power deposition profiles on the ion minority, majority and electrons are determined first; then, the effective temperature of the minority ion tail and the fraction of fast ions are evaluated consistently. Moreover, quasi-linear analyses determine how the power absorbed by the minority tail will be redistributed by collisions among the main thermal plasma particles: electrons and majority ions. A bi-Maxwellian distribution for energetic particles, which takes into account the anisotropy in the velocity space $\left(T_\perp > T_\parallel\right)$ due to ICRH, has been used as initial velocity space distribution function for a parametric study, based on density and temperatures profiles given by the TORIC code, investigating the destabilization and saturation of fast ion driven Alfvénic modes below and above the Energetic Particle Modes (EPM) [10] stability threshold. In particular, the resonance structure in the velocity space has been detected by means of synthetic diagnostics [10]. Numerical simulation results, based on the HMGC hybrid code [11], will be presented and discussed.

The paper is organized as follows: In Section II, the theory of quasi-linear absorption is outlined and the relevant 1-dimensional analytic limit of the Fokker-Planck equation is recovered together with the Stix analytic formulae [12]. In Sec. III, numerical results for the plasma reference scenario referring to the FAST H-mode are presented and discussed in detail. The relevant quantities characterizing burning plasma dynamics are determined and will be used for future studies of fast ion nonlinear behaviors by means of the HMGC hybrid code [11]. Finally, discussions of the results and conclusions are given in Sec. IV.

2. Theory of linear and quasi-linear absorption

The plasma-ICRH wave interaction is modeled by the Maxwell-Vlasov integro-differential wave equations, whose numerical solution is given in Ref. [7]. The ICRH process is essentially based on the excitation, by means of strap antenna placed in front of the plasma, of a fast magneto-sonic 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 that 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 mode can convert to the Ion Bernstein Wave (IBW). The wave is partially damped on the ion-cyclotron harmonic layer, where the power deposition is sufficiently tight, while electrons absorption profile is broad and extends from the antenna to the cut-off. Bulk electrons efficiently absorb the power fraction converted into IBWs 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 the power absorbed on the minority ions by choice of plasma and/or antenna parameters, such as minority concentration, density and electron temperature, antenna spectrum, frequency. To do this, the solution of the wave equation is obtained numerically in flux coordinates, taking into account the wave spectrum radiated by the antenna and exploring the solution in various ranges of the parameter space. Following Ref. [8], in the high velocity limit, an analytical solution of the Fokker-Planck equation can be obtained [12]. The solution is a Maxwellian distribution function characterized by a temperature of the supra-thermal tail for the minority species:

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

It is also possible to calculate the minority concentration in the supra-thermal tail, which is given by

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

where $\Gamma(a,x)$ is the incomplete gamma function and $y_{critical}$ is an a-dimensional quantity which depends on 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 minority ions. In next section, we present and discuss 2D numerical calculations of the above quantities, which are crucial to determine the parameters characterizing the burning plasma dynamics we are interested in.

3. Numerical Results and Discussion

FAST is a versatile tokamak device [4], which can operate in H-mode (HM) as well as in Steady State Operation (SSO) [9]. The H-mode scenario is reached by dominant ICRH additional heating, which provides the condition for the plasma to make a transition to the H-mode and, at the same time, can bring a large fraction of the minority species to very high energy by adding a small fraction of ^{3}He, making possible to investigate energetic particle physics in conditions similar to those of burning plasmas. To simulate the interaction of the ICRH wave with the plasma and, at the same time, to follow the simultaneous evolution of the profiles (density, temperature and current), we have used the JETTO code [13] coupled with the full wave electromagnetic codes TORIC and SSQLFP. The SSQLFP code, as mentioned before, solves the bi-dimensional Fokker-Planck equation and enables us to calculate the effective temperature of the energetic tail as well as the space density profile of the energetic ion minority fraction. With this information, we can self-consistently reconstruct the profiles of the quantities characterizing burning plasma dynamics, namely β_H, ρ_H^* and so on.

The antenna parameters we have considered for this study are the following: 1) coupled ICRH power between $20-30MW$ by essentially using two reference frequencies $f_1 = 67MHz$ and $f_2 = 84MHz$, such that the absorption layer can be moved from the off-axis low-field side radius $r/a = 0.3$ to the off-axis high-field side radius $r/a = -0.3$; 2) power spectrum centered at parallel wave-number $n_\parallel = 5$ and sufficiently broad $\Delta n_\parallel = 5$. The power level and the power spectrum are deduced from TOPICA calculations [14] and are consistent with antenna design and location. Moreover, we have considered operations at toroidal magnetic field $B_T = 7.5T$ with plasma current $I_p = 6.5MA$. Concerning density and temperature profiles, we have assumed those obtained by JETTO at the time of ICRH power injection, $t = 7\sec$ [9]. In particular, we have a central density of $n_{e0} = 2.4\times10^{20}m^{-3}$, and electron and ion temperatures $T_{e0} = 2.6KeV$ and $T_{i0} = 2.4KeV$. We consider a generalized parabolic profile for density $\left(1-(r/a)^{\gamma}\right)^{\alpha}$ and linear profiles for temperatures. When applying ICRH power with a 1% fraction of ^{3}He minority (minority heating), the power deposition profiles are sketched in Fig.1, where the power density in W/cm^3 is given vs. the normalized radius: “empty circles” indicate the power which is going to ^{3}He and “empty square” the power to electrons via Landau damping. The power deposited on minority ions is redistributed to the bulk deuterium ions and bulk electrons on the collisional time-scale. The quasi-linear code SSQLFP enables us to calculate the fraction as well the spatial profiles of the final power deposition on the majority deuterium ions and electrons, as reported in Fig. 2. The power deposition in W/cm^3 is shown vs x for the majority ions (empty circles), electrons (collisional plus direct RF heating, empty square) and minority ions (empty triangles). These power deposition profiles are used in the JETTO code for a successive iteration. The large amount of injected power triggers a H-mode transition, which is accounted for by JETTO; as a consequence, ion and electron temperatures increase up to 6 KeV, with a quasi-parabolic profile, and the density flattens remarkably, reaching the value $1.3\times10^{20}m^{-3}$ at the separatrix. In Fig. 3, the power deposition profiles (calculated at the end of the collisional process) is shown when using the density and temperature as given above for the time $t = 8\sec$. As it is possible to remark the electron species begins to absorb energy from the energetic ion minority tail in a consistent way.

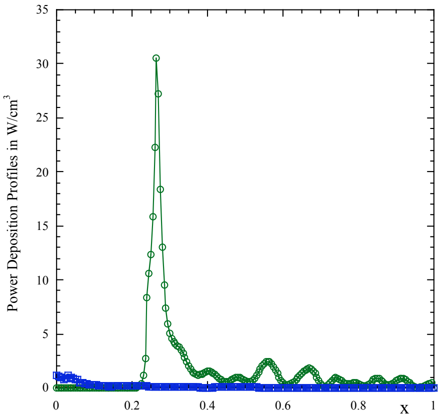


FIG.1- Power Deposition Profiles in W/cm^3 vs. the normalized radius (“empty circles” indicate the power on ^{3}He and “empty square” the power to electrons via Landau damping).

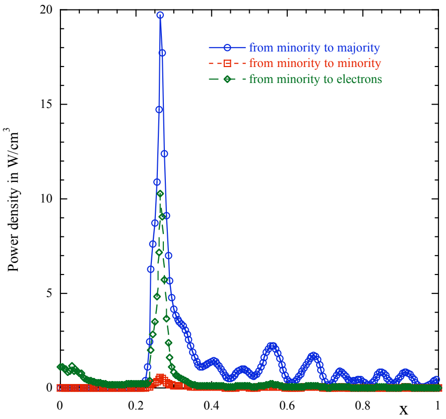


FIG.2- PDP in W/cm^3 vs x for the majority ions (empty circles), electrons (collisional plus direct RF heating, empty square) and minority ions (empty triangles) after the collisional redistribution of power among species.

Also the direct RF electron heating is consistent because of the high electron temperature. In Fig. 4, the effective parallel (empty square) and perpendicular (empty circles) temperatures of the supra-thermal minority tail are shown vs. the normalized radius. The perpendicular temperature reaches the value of $750KeV$, well above the critical energy value.

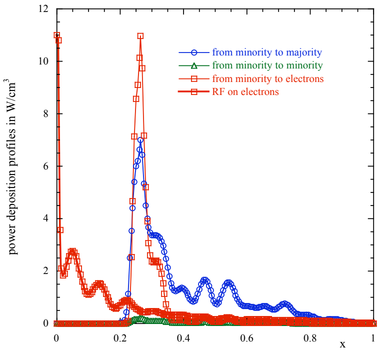


FIG.3-PDP as used in the JETTO code to have a further plasma evolution, at t=8s.

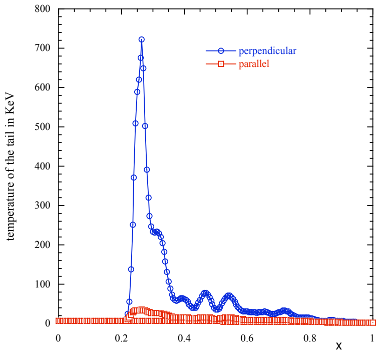


FIG.4-Parallel (empty square) and perpendicular (empty circles) temperatures vs. x .

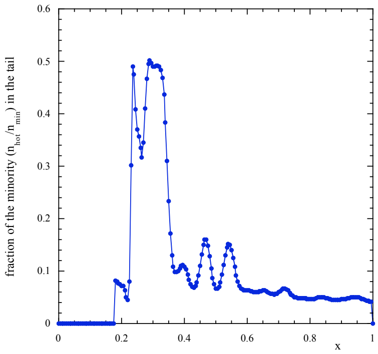


FIG.5-Minority fraction profile accelerated into the energetic tail by the RF action vs x .

The profile of the minority fraction, which is effectively accelerated into the energetic tail by the RF action, is plotted in Fig. 5: in the resonant layer region, the hot minority fraction reaches up to 50% of the total minority. The power deposition profiles shown in Fig. 3 are used once more in the JETTO code to have a further plasma evolution. As a result, ion and electron temperatures further increase and reach the value of 13 KeV with a broad quasi-parabolic profile and a pedestal temperature of about 2 KeV at the separatrix. We have run the "TORIC-SSQLFP" code on this new plasma target, obtaining the power deposition profiles (on the collisional time scale) shown in Fig. 6. It is interesting to note that the effect of this new target on plasma heating is essentially to broaden the deposition profiles for both deuterium ions and electrons. The parallel and perpendicular tail temperatures in this third iteration are shown vs. x in Fig. 7, indicating the broadening of the effective temperature profile and leaving the peak around $800\,KeV$. The fraction of "tail" minority vs. x is shown in Fig. 8. Summary plots are finally presented in Figs. 9a), b) and c), which show the evolution of the parallel (Fig. 9a) and perpendicular (Fig. 9b) effective temperatures, and of the "tail" minority fraction (Fig. 9c) for all the three iterations, corresponding to three different time of the discharge ($t = 7\sec$, $t = 8\sec$, $t = 9\sec$). A last iteration made by JETTO, using the power deposition parameters of Fig. 6 as input, shows that a steady state situation is reached, without further appreciable changes of temperatures values and profiles. Thus, ICRH is consistently forming the supra-thermal minority ion tail. A parametric study of ICRH absorption has been performed varying the resonant layer (changing the applied frequency from 67 to 84 MHz), the coupled wave spectrum, and the minority concentration, aimed at understanding the effects of these quantities on the power coupled to the minority ions, on the effective tail temperature and on the tail minority fraction. In particular the effect of increasing the minority fraction from 1% to 3% on the absorption of the power by the minority species, is pointed out. The power going to the minority ions reduces by increasing the minority concentration, the consequence is that the effective temperaure reduces too, consistently with the formula of Eq.3. From these results, 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 , and the ballooning factor $\alpha_H = -Rq^2 \left(d\beta_H / d\rho \right)$. They can be directly evaluated from the effective temperature profile, $T_{eff}(\rho)$, and from the minority tail density profile $n_{\mathrm{H}}(\rho)$, as given in Figs. (9b)-(9c). Using the standard definition of β_H , we have $\beta_{hot}(\rho) = \left(8\pi / B_0^2\right) n_{\mathrm{H}}(\rho) T_{eff}(\rho)$ and its profile is reported in Fig. 10 for the three JETTO iterations we have done. For the last iteration, the value of β_{0hot} at the point of maximum effective temperature is around 0.7%.

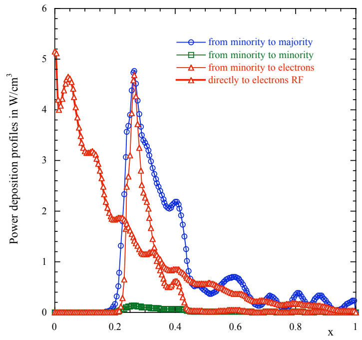


FIG.6-PDP vs the normalized radius for the JETTO second iteration plasma target.

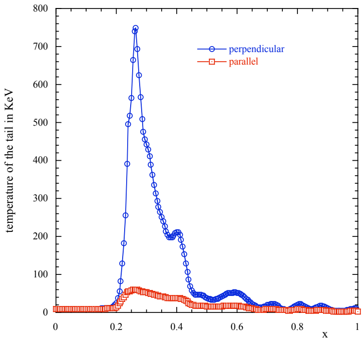


FIG.7-Effective temperature profile vs x.

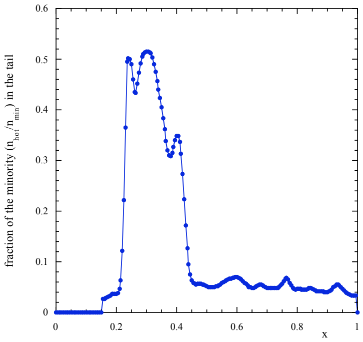
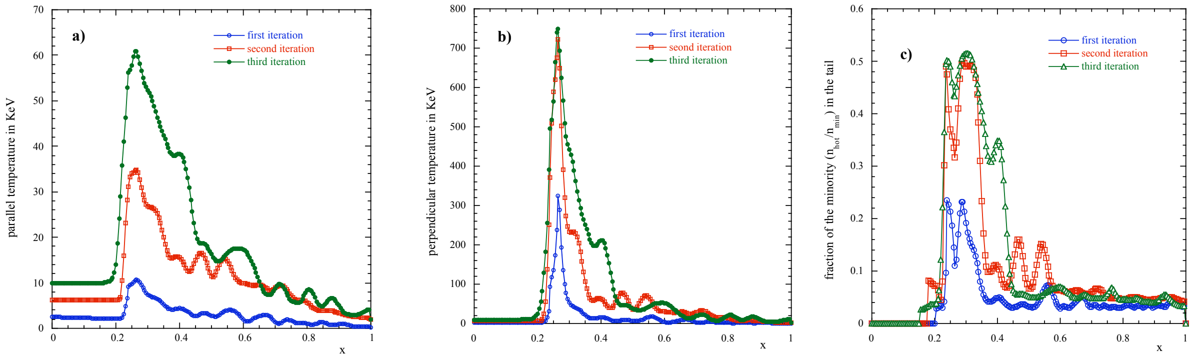


FIG.8-Fraction of “tail” minority vs. x *for the second JETTO iteration.*



FIGS.9a,b,c)-Evolution of the parallel (a) and perpendicular (b) effective temperatures, and of the “tail” minority fraction (c) for all the three iterations, corresponding to three different time of the discharge (t=7sec, t=8sec, t=9sec).

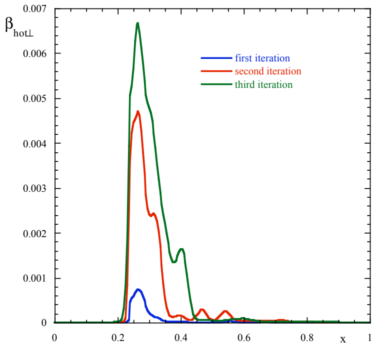


FIG.10-The fast ion beta, β_H *vs.* x, *for the three JETTO iterations.*

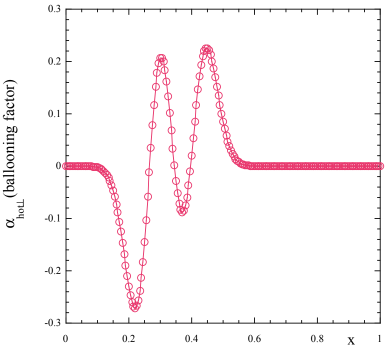


FIG.11-Ballooning factor α_H *plotted vs.* x *just for the third iteration (green line)* $t = 9\,\text{sec}$.

Note that this value is not optimized, since it refers to a case with low-field side off-axis deposition; yet β_H values obtained are consistent with those of ITER H-mode [15]. In Fig. 11, the value of the ballooning factor α_H is plotted vs. x just for the third iteration. Also in this case, at the point of maximum temperature $\alpha_H \sim O\left(10^{-1}\right)$ and these values are consistent with those in the ITER reference scenario SC2 [15]. Analogously, we can prove the similarity of the mode number and normalized frequency spectra for Alfvénic fluctuations (see section 1). The analysis so far and the information we have extracted by the combined use of JETTO and

TORIC-SSQLFP codes are used in the following for studying collective mode excitations by the supra-thermal ICRH tail and the corresponding fast ion transport with the HMGC hybrid code [11]. HMGC is a 3-D hybrid MHD-particle simulation code that properly takes into account kinetic effects and nonlinear dynamics with a Particle In Cell (PIC) approach. In our analyses, HMGC is the code adopted to simulate the interaction between energetic ions and Alfvén modes. This code has been recently extended to handle the case of anisotropic Maxwellian velocity space fast ion equilibrium distribution function, such as that expected for ICRH. Crucial physics issues in burning plasma, including energetic particle excitations of collective meso-scale fluctuations belonging to the Alfvén spectrum and their cross-scale couplings with micro-scale turbulence, can be addressed in FAST. In this conceptual device, the Alfvén fluctuation spectrum is expected to be dominated by the same toroidal mode numbers $(15 \le n \le 25)$, that will be relevant in ITER, and to have the same frequencies expressed in units of the Alfvén frequency. Investigating linear and nonlinear dynamics of $(15 \le n \le 25)$ Alfvénic oscillations is extremely demanding in terms of High Performance Computing (HPC) availability: these analyses will represent a significant part of FAST theory and modeling activities. For this reason, we have so far limited our investigations of high-n modes to few paradigmatic cases, and concentrated our analyses to moderate mode numbers. Since we are considering trapped particle excitations, dominated by precession and precession-bounce resonance interactions, the long wavelength limit (moderate-n) is expected to favor low frequency fishbone-like modes [3,6,15]. Numerical simulations have been performed for different toroidal mode numbers n, exploring the dependence of simulation results on the strength of the energetic particle drive by artificially increasing the on-axis value of the minority tail density n_H with respect to its nominal value in the reference scenario n_{H0}, while maintaining other parameters and radial profiles fixed. We observe that the instability of the system slightly increases with n. In Fig. 12a,b), the contour plot $(\omega - r)$ for two different times of the simulation is shown. The shear Alfvén continuous spectrum (black curves) and the precession and precession-bounce resonance (respectively $\omega_{dH}, \omega_{dH} \pm \omega_{BH}$) is also plotted. We can recognize the dominance of a TAE for the first and of an EPM for the second frame at $\omega = \omega_{dH} - \omega_{BH}$.

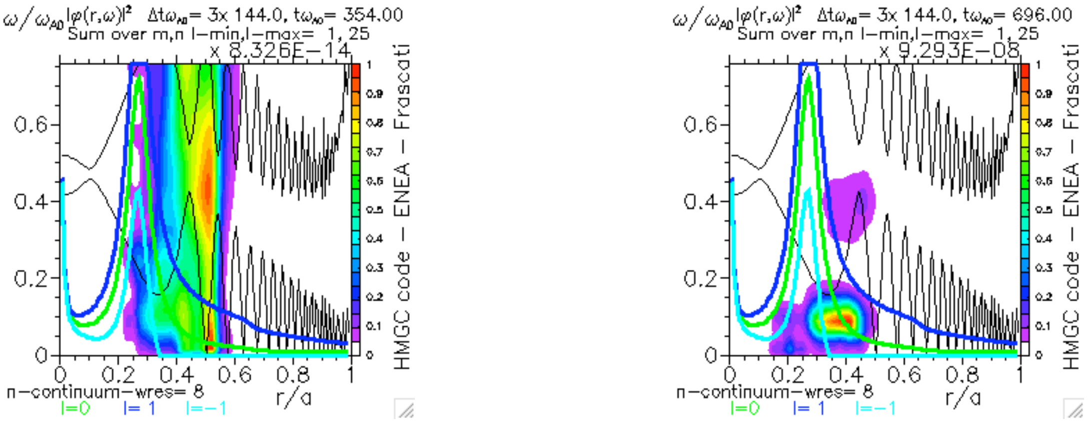


FIG.12a,b)-Contour plot $(\omega - r)$ *for two different times of the simulation for n = 8, with the Alfvén continuum and the precession and precession-bounce resonance plotted.*

4. Conclusions.

Linear and quasi-linear calculations of ICRH wave absorption have been extensively carried out for the FAST conceptual tokamak device, using a time dependent plasma target modeled by the JETTO transport code. This study is mainly devoted to the analysis of energetic particle physics in burning plasma experiments. A parametric study of the FAST H-mode plasma reference scenario has been performed, varying the minority concentration, the parallel wave-number of the radiated spectrum and the location of the resonant layer in order to maximize the perpendicular temperature. The obtained results have shown that the fast ion parameters relevant for collective mode excitations are consistent with those expected in corresponding ITER scenarios, e.g. the ITER reference scenario SC2. In particular, it has been shown that the H-mode scenario is very well indicated to study the effects of alpha particle dynamics in driving meso-scale instabilities. The minority tail density has also been varied to explore, in hybrid simulations with the HMGC code, the sensitivity of collective mode excitations and fast ion transport on the strength of the energetic particle free energy source. The HMGC code simulation results confirmed that, in reactor relevant plasmas, the Alfvén fluctuation spectrum will be dominated by a dense spectrum of modes with characteristic frequencies and radial locations, which cause rich nonlinear dynamics with impact on fast particle transport.

5. References

[1] ROMANELLI, F., et al., “FT3 - An Experiment to Study Burning Plasma Physics Issues in Deuterium Plasmas”, Fus. Sc. Technol. **45** (2004) 483.

[2] CARDINALI, A., ROMANELLI, F., “Simulation of burning plasma dynamics by ICRH accelerated minority ions”, Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), C&S Papers Series No. 1/C, IAEA, Vienna (2007), TH/P6-9.

[3] ZONCA, F., “The Physics of Burning Plasmas In Toroidal Magnetic Field Devices”. Int. J. Mod. Phys. **A 23** (2008) 1165.

[4] PIZZUTO, A., et al., “The Fusion Advanced Studies Torus (FAST): a proposal for an ITER satellite facility in support of the development of fusion energy”, presented at the 22nd IAEA FEC, 13-18 October 2008, Geneva, Switzerland, paper FT/1-5.

[5] ZONCA, F., et al., “Physics of burning plasmas in toroidal magnetic confinement devices”, Plasma Phys. Control. Fusion **48** (2006) B15-B28.

[6] CHEN, L., ZONCA F., “Theory of Alfvén waves and energetic particle physics in burning plasmas”, Nucl. Fusion 47 (2007) S727-S734.

[7] BRAMBILLA, M., “Numerical simulation of ion cyclotron waves in tokamak plasmas”, Plasma Phys. Control. Fusion 41 (1999) 1.

[8] BRAMBILLA, M., “Quasi-linear Ion Distribution Function During Ion Cyclotron Heating in Tokamaks”, Nucl. Fusion **34** (1994)1121.

[9] CALABRO’, G., et al., “FAST Plasma Scenarios and Equilibrium Configurations”, presented at the 22nd IAEA FEC, 13-18 October 2008, Geneva, Switzerland, paper FT/P3-11.

[10] CHEN, L., “Theory of magnetohydrodynamic instabilities excited by energetic particles in tokamaks “, Phys. Plasmas **1** (1994) 1519.

[11] BRIGUGLIO, S., et al., “Hybrid magnetohydrodynamic-gyrokinetic simulation of toroidal Alfvén modes”, Phys. Plasmas **2** (1995) 3711.

[12] STIX, T.H., “Fast-wave heating of a two-component plasma”, Nucl. Fusion **15** (1975) 737.

[13] CENACCHI G., TARONI A., “JETTO: a free boundary plasma transport code”, ENEA Report, RT/TIB/88/5 (1988).

[14] MIRIZZI F., et al., “The three RF additional heating systems for FAST“, Symposium on Fusion Technology, (Proc. Symp., Rostok, 2008), Paper P1.16.

[15] VLAD, G., et al., “Alfvénic instabilities driven by fusion generated alpha particles in ITER scenarios”, Nucl. Fusion **46** (2006) 1.