Energetic particle physics in FAST H-mode scenario with combined NNBI and ICRH

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Abstract. The combination of ICRH+NNBI in FAST allows the generation of fast ion populations with different velocity space anisotropy and radial profiles. These energetic ion populations can excite meso-scale fluctuations with the same characteristics of those expected in reactor relevant conditions and, for this reason, FAST can address a number of important burning plasma physics issues. Numerical simulation and modeling of energetic particle physics are based on the use of various transport codes that are iteratively coupled with a bi-dimensional full wave-quasi-linear solver for ICRH, which also includes the solution of the Fokker-Planck equation for NNBI-plasma interactions. Self-consistent profiles evolution is obtained by the suite of codes CRONOS, with combined ICRH/NNBI heating. The ICRH frequency is in the range 78-85 MHz and the NNBI from 0.7 to 1 MeV energy depending on species (hydrogen or deuterium). A parametric study of the normalized supra-thermal population pressure $ß_{hot}$ is presented and discussed in terms of the ICRH+NNBI power deposition profiles with various minority concentrations (^{3}He 1-3%). The value of $ß_{hot}$ as well the energetic particle distribution functions can be used as initial condition for numerical simulation studies, investigating the destabilization and saturation of fast ion driven Alfvénic modes by means of a recently extended version of the HMGC code.

1. Introduction

In the Fusion Advanced Studies Torus (FAST), the extreme H-mode scenario requires 40 MW of external heating, mainly supplied by negative neutral beam injection (NNBI) (10MW) and ion cyclotron resonance heating (ICRH) (30MW). The extreme H-mode is characterized by high magnetic field B=8.5T and high plasma current I_p=8MA for a discharge time duration of about 12s, with peak density $\approx 5\times 10^{20} m^{-3}$ and temperature ≈9 keV at the plasma centre [1]. Strongly supra-thermal fast ions in burning plasmas, such as those generated in FAST by NNBI and minority ICRH in the MeV range of energy, are characterized by small orbit to machine size ratios and predominantly transfer their energy to plasma electrons via collisional slowing down. This energetic ion population can excite meso-scale fluctuations with the same characteristics of those expected in reactor relevant conditions and, for this reason, FAST can address a number of important burning plasma physics issues, such as radial transport of energetic ions due to collective mode excitations, coupling of meso-scale fluctuations with micro-turbulence, etc.

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Moreover, the combination of ICRH+NNBI in FAST adds great flexibility in the experimental study of these phenomena, for it allows the generation of fast ion populations with different velocity space anisotropy and radial profile; especially power density radial profiles regulate fluctuation intensity profiles and, ultimately, transport processes of both thermal and supra-thermal plasma components [2,3]. It has been shown [1,3] that ICRH in the minority scheme (H or ^{3}He) in FAST D plasmas produces fast particles that, with an appropriate choice of minority concentration, RF frequency and power, are characterized by ITER-relevant radial profiles of crucial dimensionless parameters such as the fast particle normalized radius $\rho^*_{hot}(\rho)$ and perpendicular pressure $\beta_{\perp hot}(\rho)$. The aim of this work is to study the dynamic scenario formation in the FAST extreme H-mode plasma with combined NNBI and ICRH. Thus, extensive numerical simulations have been carried out, based on the solution of the governing transport equations as well as of the Vlasov-Maxwell system for the ICRH, iteratively coupled to a Fokker-Planck solver accounting for both ICRH and NNBI. Modeling is based on the JETTO transport code [4] and the suite of codes CRONOS [5], which are iteratively interfaced with the NNBI deposition code NEMO [6,7] as well as with a bi-dimensional full wave-quasi-linear solver (TORIC/SSFPQL) [8,9,10,11] for ICRH, also including the Fokker-Planck equation solver for NNBI-plasma interactions. Given the self-consistent evolution of plasma profiles, our integrated simulations allow computing β_{hot} profiles (ratio of kinetic to magnetic pressures) of the supra-thermal population as function of the plasma, ICRH antenna and NNBI system parameters. At fixed plasma current profile, β_{hot} determines the strength of resonant wave-particle interaction drive of energetic particles-induced Alfvénic instabilities; in FAST, ITER-relevant experimental conditions are obtained for β_{hot} of the order of 1%. The corresponding energetic particle distribution functions in the “flat-top” phase can be used as initial condition for numerical investigations of destabilization and saturation of fast ion driven Alfvénic modes below and above the Energetic Particle Modes (EPM) stability threshold by means of a recently extended version of the HMGC [12] code, which is able to simultaneously handle two generic initial particle distribution functions in the space of particle constants of motion: XHMGC [13,14].

2. Computation of ICRH+NBI supra-thermal tails in the ion distribution function

The plasma-Ion Cyclotron (IC) wave interaction is modelled by the Vlasov-Maxwell integro-differential wave equations, whose numerical solution is given in Ref. [8], iteratively coupled to a 2D Fokker-Planck solver [9], which takes into account both ICRH and NNBI sources [15]. The ICRH absorption scenario is the ^{3}He minority heating in deuterium plasma, while the NNBI source is either hydrogen (0.7MeV) or deuterium (1MeV). Our aim, here, is to maximize the power absorbed by minority ions with a suitable choice of plasma and/or antenna parameters, such as minority concentration, density, electron temperature, and frequency in order to obtain the target a-dimensional energetic ion quantities (like β_{hot}) to investigate high energy particle physics. To achieve and control the desired ICRH power deposition profiles, 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. [16], the Fokker-Planck equation, which governs the evolution of the ion distribution function (minority and majority) under the action of ICRH and NNBI, is solved numerically and returned to the transport solver until convergence is reached and the next time step in the plasma profiles evolution can be computed.

The SSFPQL routine gives a very accurate evaluation of the steady state distribution function, $f_\alpha(\nu,\mu)$, for the minority and beam ions in terms of the velocity ν and pitch angle $\mu=\nu_{||}/\nu$. The steady state distribution function is then directly used to calculate the β_{hot} profiles (parallel and perpendicular):

$$\beta_{\parallel hot} = \frac{2\mu_0 p_\parallel}{B^2} = \frac{4\pi\mu_0 m_\alpha}{B^2}\int_{-1}^{1} d\mu \int_0^{\infty} dv v^4 \mu^2 f_\alpha\left(v,\mu\right) dv d\mu$$

$$\beta_{\perp hot} = \frac{2\mu_0 p_\perp}{B^2} = \frac{2\pi\mu_0 m_\alpha}{B^2}\int_{-1}^{1} d\mu \int_0^{\infty} dv v^4 \left(1-\mu^2\right) f_\alpha\left(v,\mu\right) dv d\mu$$

3. Heating systems

The heating systems in FAST are, as said before, ICRH and Negative NBI. The FAST ICRH and NNBI system are described in [1]. The main physics requirements for the NNBI on FAST are that the beam generated fast particles should be super-Alfvénic, in order to be relevant to burning plasma physics issues, and their pressure of the order of 10^{-2} times the magnetic pressure. In addition, the injection energy must be high enough to ensure deep beam penetration into the dense FAST plasma core and also to preferentially heat electrons. Momentum input and current drive capabilities are important ingredients as well, useful for micro-turbulence and MHD stability as well as advanced scenarios studies. Such type of NNBI system must be interfaced with a relatively compact high magnetic field device, taking into account the narrow space available between toroidal field coils [17]. A preliminary configuration for this injector has been designed with the criterion of closely reproducing the actual ITER design. The considered beam energy ranges between 700keV to 1MeV, with two different injected species (H and D) and a total input power of 10MW. With these requirements, the source area can be small enough to produce a narrower beam, which can fit into the FAST portholes. The injection is tangential, as required by the compact machine dimensions and by the high beam energy, with a tangency radius of 1.283m, the largest permitted by port geometry. The NNBI system integrated within the FAST facility can be seen in Fig.1a.

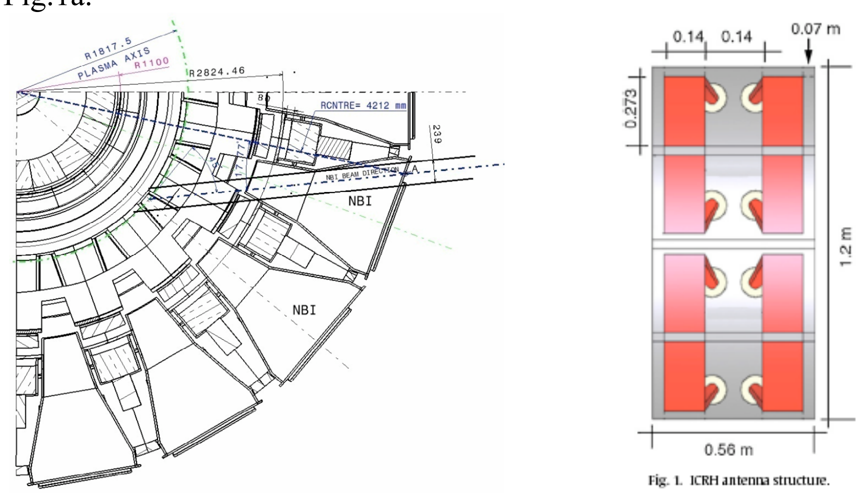

FIG.1 - a) Layout of the NNBI injector as allocated in FAST; b) Design of the 8 straps ICRH antenna, which fits one port of FAST.

Concerning the ICRH heating system, the antenna structure (Fig. 1b) consists of a single cavity containing eight straps, two toroidal by four poloidal, protected by a Faraday Shield (FS) made of 30 conducting bars with squared cross-section. The analysis of the structure has been made with TOPICA (a computer code developed by the Plasma Facing Antenna Group of Politecnico di Torino) [18]. The optimization process has been carried out for the FAST parameters of the reference H-mode scenario considering a 5cm thick scrape off layer (SOL). A 2% average value of ^{3}He minority ions, a magnetic field (central value) of 7.5 T and a plasma current of 6.5MA have been adopted in that analysis. The optimized analysis for the extreme H mode scenario is underway. The operational frequency has been set to 80MHz for slightly high field side deposition. The main parameter considered for the optimization is the coupled power, computed by means of the impedance matrix by imposing a maximum voltage of 48 kV along the coaxial lines. The best performance of the launcher (P_{max}≈4MW) has been obtained for the geometrical dimensions shown in Fig. 1b. Typical power spectra generated by the optimized antenna geometry and for both considered plasma profiles, with a fixed SOL thickness of 3 cm, are obtained by the TOPICA code and used as input data for the ICRH propagation and absorption analysis. In both cases, the maximum power is delivered at parallel wave-number $n_{||}$ =±5 [19].

4. Fokker-Planck Calculations and Modeling

Numerical simulation and modeling are based on the use of various transport codes that are iteratively coupled with the NNBI deposition code NEMO as well as with a bi-dimensional full wave-quasi-linear solver for ICRH (TORIC/SSFPQL) [8-11], which also includes the solution of the NNBI-plasma Fokker-Planck equation. Synergy between ICRH and NNBI is also accounted for in our numerical simulations. Here, we report self-consistent numerical simulation results obtained with the JETTO transport code with combined ICRH/NNBI heating in the extreme H-mode FAST plasma conditions [1], using 30MW of ICRH on 1-3% ^{3}He minority concentration in D plasma and 10MW of NNBI delivered by 1 MeV D beam [17]. In these simulations, we have considered the ICRH frequency range $78MHz \le f_{ICRH} \le 82MHz$ to deal with an off-axis power deposition profile (normalized poloidal flux function ρ_{pol}=0.1-0.3), while the 1-3% ^{3}He dilution is chosen to optimize the minority-heating scheme efficiency. In Fig. 2, the effective temperature of the high-energy minority ion population is shown at the end of the iteration process with JETTO t=9sec, versus the normalized radial position ρ_{pol} and for two selected operational frequencies f=78MHz and f=82MHz. Due to limitations of available computing resources, the full self-consistent simulation of dynamic scenario formation, by the iterative approach described above, has been carried out for the nearly on-axis deposition at f=82MHz only. For the parametric study of ICRH supra-thermal ion minority tail dependences on RF frequency, we have assumed thermal plasma profiles to be the same as those obtained self-consistently with f=82MHZ (see [20] for details) and then varied the resonance frequency. Self-consistent simulations of dynamic scenario formation at different RF frequencies are underway. As it is possible to see in Fig. 2, the nearly on-axis localization (ρ_{pol}=0.1) of the ICRH resonance produces higher perpendicular temperature of the energetic tail (1MeV) with respect to the more external deposition (ρ_{pol}=0.3 at f=78MHz).

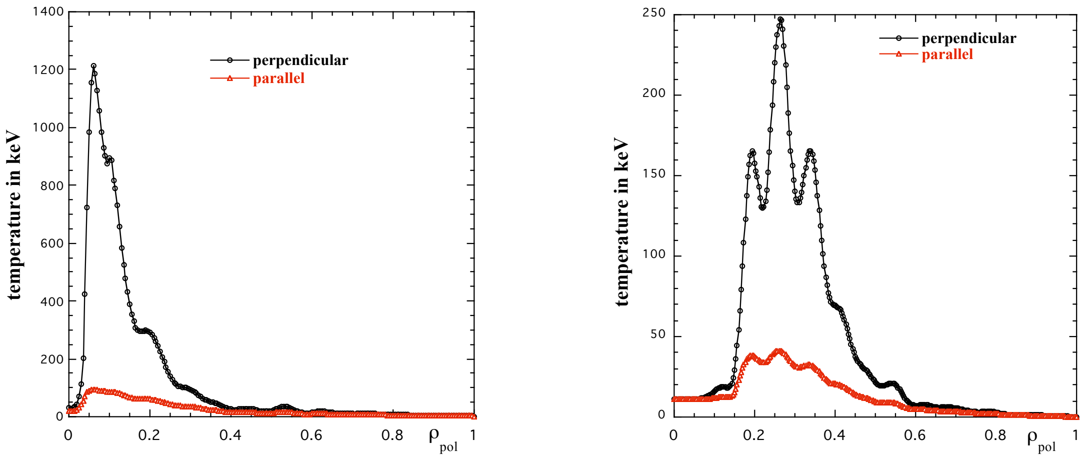

FIG. 2 - Effective perpendicular (black) and parallel (red) temperatures vs ρ_{pol} for FAST extreme H mode for a) f=82MHz and b) f=78MHz.

The corresponding β_{hot} profiles are reported in Fig. 3, calculated as shown in section 2 by means of the anisotropic distribution function obtained by TORIC+SSFPQL as a tabulated 2D function.

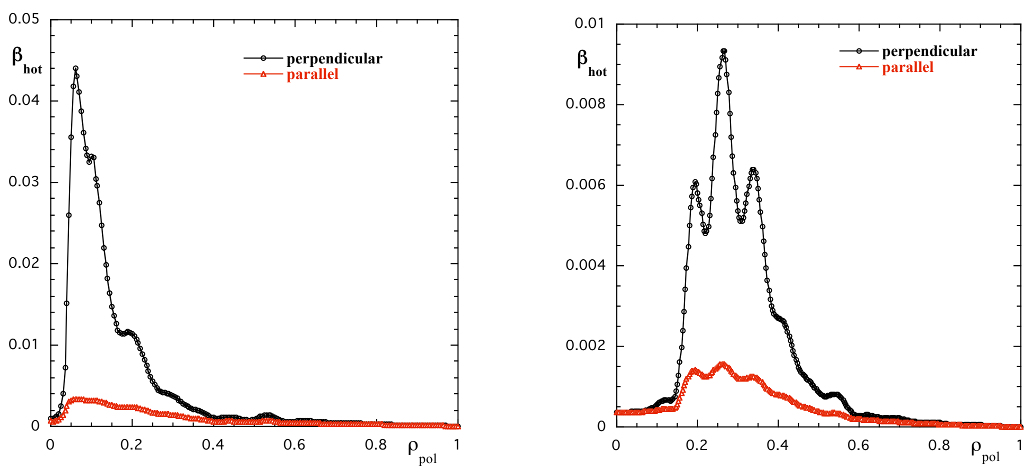

FIG. 3 - β_{hot} perpendicular (black) and parallel (red) vs ρ_{pol} for FAST extreme H mode for a) f=82MHz and b) f=78MHz.

The $\beta_{\perp hot}$ profile reaches a peak of about 4% in the 82MHz case, where the deposition is very close to the tokamak axis, while at 78MHz peak values are very close to 1%. These values are consistent with the request of accessing ITER-relevant conditions [1,3], whose flexibility is crucial for energetic particle physics studies. The effect of minority concentration on β_{hot} profiles is shown in Fig. 4, where $\beta_{\perp hot}$ and $\beta_{||hot}$ are plotted vs. ρ_{pol} for three different concentrations of ^3He in the case of FAST H-mode reference scenario: it is shown that β_{hot} increases by increasing the minority concentration. In Fig. 5, meanwhile, $\beta_{\perp hot}$ peak values are plotted vs. electron temperature for several values of the plasma density at fixed absorbed power ($10MW/m^3$) and minority concentration (1% ^{3}He) for the FAST H mode reference scenario (B=7.5T). This last plot may be

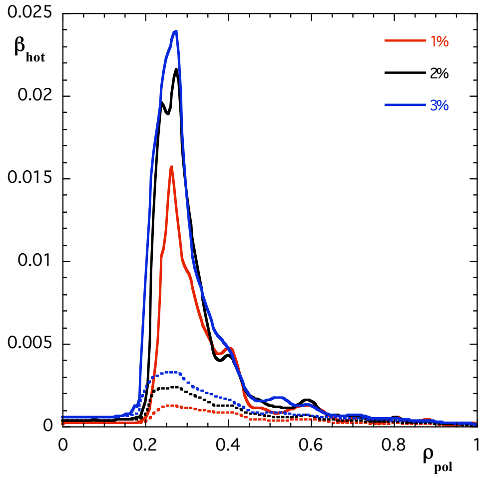

FIG. 4 - β_{hot} perpendicular (full line) and parallel (dashed line) vs. ρ_{pol} for FAST H mode reference scenario for three minority concentration of ^{3}He.

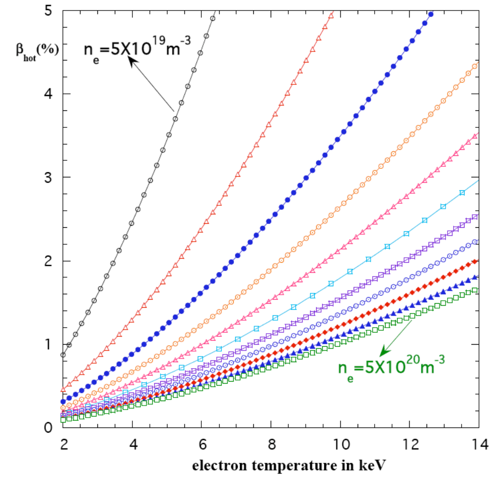

FIG. 5 - Parametric curves of β_{hot} vs. the plasma temperature for several values of the plasma density and fixed absorbed power density (10MW/m^3) and minority fraction (1% ^{3}He).

useful in choosing plasma parameters and the corresponding experimental scenario achieving the expected values of β_{hot}.

The extreme H-mode scenario with combined NNBI and ICRH has also been studied by means of the integrated suite of codes CRONOS [5], which includes NEMO and SPOT [6,7] as subroutines for computing NNBI deposition profiles. The 2D fast ion birth rate (m^{-3}s^{-1}) for a standard case with on-axis injection of 1MeV deuterons is plotted in Fig. 6. The ion birth profile is then used in SPOT [6], a Monte Carlo code that generates test particles according to the birth distribution given by NEMO, and follows their path along magnetic field lines until they thermalize by collisions with bulk plasma. The simulation takes into account the evolution of NNBI fast ion population at each time step and stops when the fast ion population reaches the equilibrium state. Finally, fast ion kinetic quantities are computed, such as the equilibrium fast ions distribution in energy space, pitch angle and real space. Other important NNBI related quantities are also calculated, as the driven current, deposited power and injected torque. The output power densities deposited on electron and ions are plotted in Fig. 7.

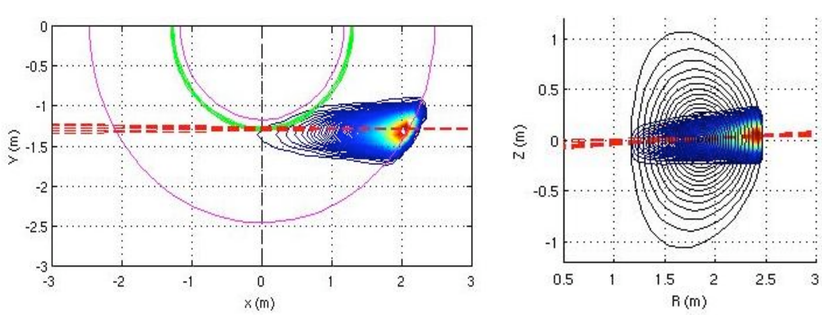

FIG. 6 - 2D NB deposition for on axis injection, top view (left) and poloidal view (right). Hyperbeamlets axes are over-plotted as dashed red lines.

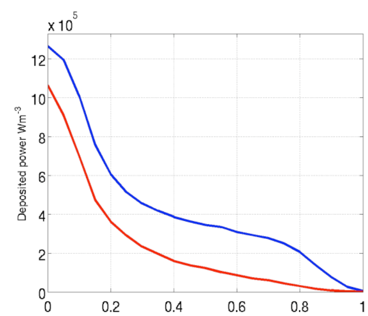

FIG. 7 - Deposited power on electrons (blue) and ions (red) as a function of normalized radius

Once the FAST extreme H-mode scenario profiles are determined self-consistently with the iterative procedure described above, these are used as initial condition for numerical studies of resonant excitations of energetic particle driven Alfvénic fluctuations and related transports [21]. The FAST extreme H-mode scenario is characterized by a dense spectrum of Alfvénic fluctuations with the same wavelength and frequency spectra that are expected in ITER (peaked at $15 < n < 25$) [21-25]. This can be seen in Figs. 8a and 8b, investigating the 78MHz case of Fig 3b, where the intensity contour plots of toroidal mode number n=8 and n=16 fluctuations in the nonlinear saturated phase, respectively, are shown in the space of normalized frequency (ω normalized to the on-axis Alfvén frequency $\omega_{A0}=v_A/R_0$, with v_A the Alfvén speed and R_0/a the tokamak major/minor radii) and radial position ρ_{pol}. Simulation results are obtained with the hybrid MHD gyrokinetic code HMGC [12] and its recently extended version XHMGC [13,14], which is able to simultaneously handle two generic initial particle distribution functions in the space of particle constants of motion. For simplicity, we assume that only ICRH accelerated energetic ions are present. More detailed simulations, investigating separate and combined effects of energetic particle populations due to ICRH and NNBI, will be reported elsewhere. Both figures demonstrate the destabilization of EPM fluctuation branches [26], which track the toroidal precession resonance with the ICRH induced supra-thermal ion tail, as expected in this case and as predicted by theory [21,27]. The crucial role played by radial non-uniformities and by the shear Alfvén continuous spectrum, shown as solid lines in Figs. 8a and 8b, is also evident and is consistent with the theoretical framework discussed in [21,27]. The effect of n=8 and n=16 saturated EPM on the $\beta_{\perp hot}$ radial profile, shown in Fig. 8c, suggests that significant radial redistributions of energetic particle are expected with limited global losses.

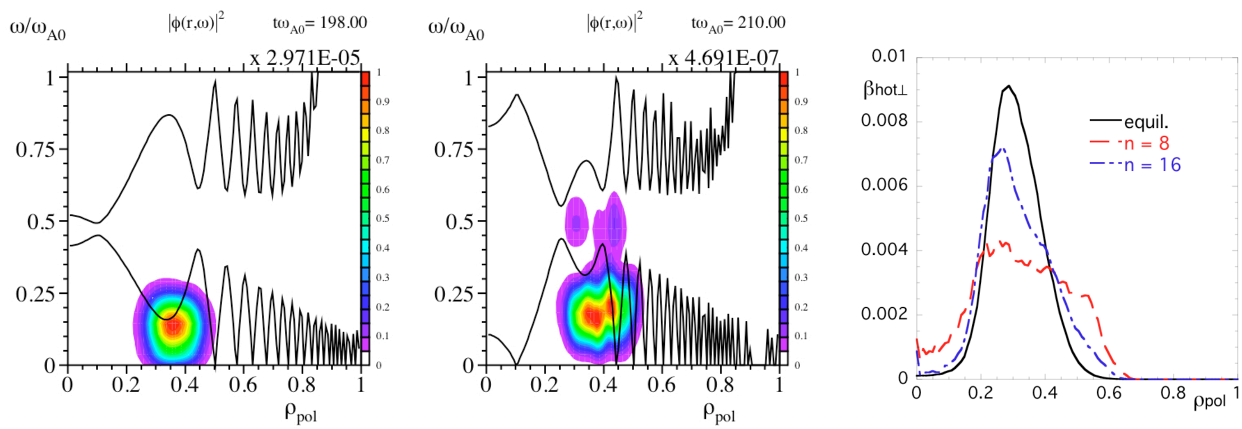

FIG. 8 - a) Intensity contour plot of the n=8 Alfvénic mode in the space of normalized frequency and radial position. The shear Alfvén continuous spectrum for n=8 is indicated by the black solid line; b) Intensity contour plot of the n=16 Alfvénic mode in the space of normalized frequency and radial position. The shear Alfvén continuous spectrum for n=16 is indicated by the black solid line; c) Effect of n=8 and n=16 saturated EPM on the $\beta_{\perp hot}$ radial profile.

5. Conclusions

In this work, we have studied the self-consistent dynamic formation of the FAST extreme H-mode scenario, iteratively interfacing several numerical tools: transport codes (JETTO and the CRONOS suite of codes, including NEMO and SPOT) and the ICRH full wave code TORIC, coupled with the quasi-linear solver SSFPQL, which accounts for both ICRH and NNBI. Using the FAST extreme H-mode scenario profiles as initial condition, we also investigated energetic particle physics issues, including Alfvénic mode excitation and supra-thermal particle transports, using the hybrid MHD gyrokinetic code HMGC and its recently extended version XHMGC, capable of handling two different kinetic particle species, including the thermal plasma ions. The results of our analysis show that, as for the FAST H-mode reference scenario, the envisaged extreme H-mode scenario not only maximizes the machine performance and neutron yield, but is as well capable of addressing integrated experiments that are relevant in the view of ITER (e.g. preparation of ITER operations), where core and edge plasma parameters are simultaneously in reactor-relevant regimes and dimensionless quantities related with supra-thermal particle populations are well in the range required by ITER.

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