H-mode scenarios in FAST with combined NNBI and ICRH

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Introduction

1. In the Fusion Advanced Studies Torus (FAST) [1], the reference and extreme H-mode scenarios require 30-40 MW of external heating, mainly supplied by NNBI (10MW) and ICRH (30MW).

2. These H-mode scenarios, both reference and extreme, are characterized by high magnetic field $B=7.5-8.5\text{T}$ and high plasma current $I_p=6.5-8\text{MA}$ for a discharge time duration of about $13-20\text{sec}$, with peak density $2.4-5\times10^{20}\text{m}^{-3}$ and temperature of the order of $10\text{keV}$ at the plasma centre.

3. Strongly supra-thermal fast ions, such as those expected to be 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 [2].

4. The $\beta_{\text{hot}}$ (thermal/magnetic energy density ratio) of the supra-thermal population can reach values up to $3\%$, i.e. well in line with the needs for exciting meso-scale fluctuations with the same characteristics of those expected in various regimes of reactor relevant conditions.

5. Moreover, the combination of ICRH+NNBI adds great flexibility to the experimental study of these phenomena, owing to the generation of fast ion populations with different velocity space anisotropy and radial profiles, allowing to study the integrated transport processes of both thermal and supra-thermal plasma components.

6. Numerical simulations and modeling 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 NNBI-plasma Fokker-Planck equation.

7. In this work a parametric study of the beta of the supra-thermal population $\beta_{\text{hot}}$ is presented and discussed in terms of the prediction of different transport codes and of the RF+NBI power deposition profiles with various minority concentrations ($^3\text{He}$ 1-3%).

8. The value of $\beta_{\text{hot}}$ 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.
H-mode & Extreme H-Mode scenarii of FAST

1. The H-mode & EH-Mode scenario of FAST have been obtained from the equilibrium calculated by MAXFEA code, and using iteratively other two codes: the predictive 1.5-D transport code JETTO [3] and CRONOS [4].

ICRH minority heating and NBI heating of FAST

1. The FAST load assembling has been conceived to accommodate 30 MW of ICRH in $^3$He minority heating scheme and 10MW of NBI (NNBI - 0.7(H)+1(D) MeV). Simulation of heating is obtained by 2D full wave electromagnetic code TORIC [5] combined with SSQLFP, which solves the quasi-linear Fokker-Planck equation in 2-D velocity space) in presence of ICRH and NBI [6,7,8]. Note that the “heating code” is iteratively coupled to the transport code for four time step in the profiles evolution.

### Table 1: Operating scenarios

<table>
<thead>
<tr>
<th>FAST</th>
<th>H-mode referente HMR</th>
<th>H-mode extreme HME</th>
<th>AT</th>
<th>Full NICD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$ (MA)</td>
<td>6.5</td>
<td>8.0</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>3</td>
<td>2.6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$B_T$ (T)</td>
<td>7.5</td>
<td>8.5</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>$H_{95}$</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$&lt;n_{20}&gt;$ (m$^{-3}$)</td>
<td>2</td>
<td>5</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>1.3</td>
<td>1.7</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>$\tau_E$ (s)</td>
<td>0.4</td>
<td>0.65</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>$\tau_{Res}$ (s)</td>
<td>5.5</td>
<td>5</td>
<td>3</td>
<td>2 ÷ 5</td>
</tr>
<tr>
<td>$T_0$ (keV)</td>
<td>13.0</td>
<td>9.0</td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td>$Q$</td>
<td>0.65</td>
<td>1.5</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>$t_{discharge}$ (s)</td>
<td>20</td>
<td>13</td>
<td>55</td>
<td>170</td>
</tr>
<tr>
<td>$t_{flat-top}$ (s)</td>
<td>13</td>
<td>2</td>
<td>45</td>
<td>160</td>
</tr>
<tr>
<td>$I_{NI}/I_p$ (%)</td>
<td>15</td>
<td>15</td>
<td>60</td>
<td>&gt;100</td>
</tr>
<tr>
<td>$P_{ADD}$(MW)</td>
<td>30</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
Layout of the heating system: 1) ICRH antenna [9] & 2) NBI system [10]
1. **Summary of the evolution of the parallel, perpendicular temperatures and fraction of the energetic $^3$He minority ion tail for three different times (from 7 to 9 sec) of the discharge evolution.**

2. **At t=9sec the steady state is reached.**

3. **This simulation is referred to H-mode reference Scenario. The ICRH frequency is 68 MHz (off axis deposition $x\approx0.3$).**

**Figures a,b,c** - Evolution of the parallel (a) and perpendicular (b) effective temperatures, and of the density fraction of the minority on the energetic “tail” (c) for all the three iterations, corresponding to three different time of the plasma discharge (t=7s, t=8s, t=9s).
b-hot is the relevant parameter in establishing the relevance of the fast H-mode scenarii for the study of the energetic particles-induced Alfvenic instabilities.

Figures a,b,c) -

a) plot of b-hot vs the electron temperature for several values of the plasma density at fixed ICRH power density and toroidal magnetic field for H-mode Scenario 1\% of $^3$He.

b) as before but several values of power density and fixed density and magnetic field for the Extreme H-mode scenario 2\% of $^3$He;

c) b-hot (perpendicular and parallel) vs the radial coordinate for FAST Extreme H-mode f=82MHz.
b-hot as calculated by the ICRH code (TORIC-SSFPQL) and using the JETTO code (part of the JAMS JET suite of integrated codes). For ICRH heating profiles we have used the TORIC code which is run outside JETTO and requires a few iterations.

Theoretical arguments

1. The Alfvén fluctuation spectrum in FAST is expected to be dominated by the same toroidal mode numbers (15 < n < 25) that will be relevant in ITER and to have the same frequencies expressed in units of the Alfvén frequency.

2. More generally, Energetic Particle Modes (EPM) [1] can be excited by energetic particle characteristic motions in a broad range of mode numbers and frequencies [1,2].

3. Because of the relevance of the interactions between modes and trapped particles, dominated by precession and precession-bounce resonances at a localized radius (where $\frac{\nabla H}{H} = -Rq^2 \frac{\nabla H}{dr}$ is maximum), we expect that low frequency fishbone-like modes [3] are favored for low mode numbers.

4. Low frequency EPMs exhibit the same bursting nature of n = 1 fishbone, internal kink oscillations excited by a magnetically trapped population of fast particles [4,5] and are characterized by the same wave-particle resonance excitation mechanism: thus, they can be quoted as high (moderate)-n fishbone-like modes [6].
Results of the simulations [7,8]

- The hot particles density, perpendicular and parallel temperatures profiles obtained by TORIC-SSFPQL and fitted to be used as input for HMGC. The peak values are $n_H/n_{\text{min}} = 0.005$, $T_{\text{perp,hot}}=0.74$ MeV and $T_{\text{paral,hot}}=0.06$ MeV, all at $r \sim r_{\text{ICRH}}$. 
1. Spatial distribution of the energetic particles at the time $t=0$ (the toroidal angle is irrelevant due to axial symmetry) The loci where is located the maximum density of particles is the ICRH resonant layer.

Picture 1:

- Spatial distribution of the energetic particles at the saturation time ($t=276\, t_{Alfven}$).

Picture 2:
Picture 3: Energy as function of time for several m-poloidal at fixed toroidal n=4. The behavior is “clean” and shows the exponential growth followed by saturation.

- **Picture 4:** radial structure of the scalar potential $f$ corresponding to $n=4$ during the linear phase (exponential growth). The poloidal harmonics $m=3,4,5$ are dominating.
Picture 5:
Contour plot related to the power spectrum of the scalar potential $f$ in the space $(r,w)$ during the linear growth. The black curves represent the Alfven continuum for $n=4$.

![Contour plot](image)

Picture 6:
Radial profile of $b$-hot at $t=0$ $b$-hot perpendicular (red curve), $b$-hot parallel (blue points) and $b$-hot total (blue full).

![Radial profile](image)

Picture 7:
Same as Picture 6, but for the saturation time ($t=276$ $t$-Alfven).

![Saturation profile](image)
Conclusions

• Quasi-linear calculations of ICRH wave absorption and NBI injection have been extensively carried out for the FAST conceptual tokamak device, using a time dependent plasma target modeled by the JETTO and CRONOS transport code.
• This study is mainly devoted to the analysis of energetic particle physics in burning plasma experiments.
• The obtained results show 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.
• Collective mode excitations by supra-thermal tail minority ions and corresponding fast particle transport have been studied in hybrid simulations with the HMGC code for the FAST H-mode plasma reference scenario.
• These preliminary analyses confirm the theoretical prediction that the Alfvén fluctuation spectrum in FAST will be dominated, as in ITER, by a dense spectrum of modes with characteristic frequencies and radial locations.
References

Modeling Transport and ICRH.


Modeling instabilities.