MHD-particle simulations and collective alpha-particle transport: analysis of ITER scenarios and perspectives for integrated modelling

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Introduction

- Next generation Tokamaks (e.g., ITER), should approach the so called ignition condition: heating due to fusion α-particles (hot particles) able to sustain the burning plasma
- Good confinement of the α-particles is crucial in getting such condition

Fusion α-particles are generated with $v_H \approx v_A = B/(4\pi n_i m_i)^{1/2}$ and peaked density profile

free-energy source for the resonant destabilization of shear Alfvén modes (TAE, EPM, …)

- Interaction of such modes with energetic-particle can induce outward α-particle transport
Introduction-cont.

- Transport codes aimed to define burning-plasma scenarios do not include the possibility of Alfvén mode - \( \alpha \)-particle interactions
- Are the proposed scenarios consistent with the \( \alpha \)-particle collective dynamics? Which are the effects on \( \alpha \)-particle profiles and confinement?
- Aim of our investigation: to check the consistency of several ITER scenarios by means of particle simulation techniques
- If \( \alpha \)-particle pressure profile in presence of fully saturated modes is:

  - close to initial one \( \Rightarrow \) scenario is consistent
  - different from initial one \( \Rightarrow \) scenario could be inconsistent
The Model

- **Hybrid MHD-Gyrokinetic Code (HMGC):**
  - thermal plasma described by zero pressure reduced $O(\varepsilon^3)$ Magnetohydrodynamic (MHD) equations (circular shifted magnetic flux surfaces);
  - energetic particles described by nonlinear guiding-center Vlasov equation ($k_\perp \rho_H << 1$) solved by particle-in-cell (PIC) techniques;
  - energetic particles are loaded according to an isotropic slowing-down distribution function, with birth energy $E_{\text{fus}} = 3.52$ MeV and critical energy $E_{\text{crit}} \approx 33.0 T_e(r)$ (Stix);
  - assume $n_D = n_T = n_i/2$ and $n_i = n_e$.
  - energetic particles and thermal plasma are coupled through the $\alpha$–particle pressure tensor, which enters the MHD momentum equation;
  - mode-mode coupling neglected (only particle nonlinearities retained).
ITER scenarios

• Three different ITER scenarios have been considered:
  a) the reference monotonic-$q$ scenario (“scenario 2”, SC2, from ITER Joint Work Site): inductive, 15 MA scenario, with 400 MW fusion power and fusion yield $Q=10$;
  b) the reversed shear scenario (“scenario 4”, SC4, from ITER Joint Work Site): steady-state, 9 MA, weak-negative shear, with about 300 MW fusion power and $Q=5$; $q_{\text{min}} \approx 2.4$ and $r_{q_{\text{min}}}/a \approx 0.68$.
  c) a recently proposed “hybrid” scenario (“scenario H”, SCH, from CRONOS package simulations): 11.3 MA weak-positive shear, with about 400 MW fusion power and $Q \approx 5$.

• Simulations are performed retaining on-axis equilibrium magnetic field, major and minor radii, the safety-factor $q$, the plasma density $n_e$, the electron temperature $T_e$ and the $\alpha$-particle density $n_H$. 


Equilibrium profiles and parameters

<table>
<thead>
<tr>
<th></th>
<th>SC2</th>
<th>SC4</th>
<th>SCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a(m)$</td>
<td>2.005</td>
<td>1.859</td>
<td>1.8017</td>
</tr>
<tr>
<td>$R_0(m)$</td>
<td>6.195</td>
<td>6.34</td>
<td>6.3734</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>3.14</td>
<td>5.13</td>
<td>3.22</td>
</tr>
<tr>
<td>$B_T(T)$</td>
<td>5.3</td>
<td>5.183</td>
<td>5.3</td>
</tr>
<tr>
<td>$n_e(10^{20}m^{-3})$</td>
<td>1.02</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>$T_e(keV)$</td>
<td>24.8</td>
<td>23.9</td>
<td>30.0</td>
</tr>
<tr>
<td>$n_H_0(10^{18}m^{-3})$</td>
<td>0.78</td>
<td>0.62</td>
<td>0.88</td>
</tr>
<tr>
<td>$\beta_H_0$ (%)</td>
<td>1.10</td>
<td>0.92</td>
<td>1.37</td>
</tr>
<tr>
<td>$\alpha_{H,max}$</td>
<td>0.085</td>
<td>0.600</td>
<td>0.155</td>
</tr>
<tr>
<td>$\max(-R_0q^2\beta'_H)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{\alpha_{H,max}/a}$</td>
<td>0.25</td>
<td>0.50</td>
<td>0.60</td>
</tr>
</tbody>
</table>

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Linear dynamics: SC2

- Power spectra of scalar-potential fluctuations in the \([r, \omega]\) plane, during the linear phase (\(\beta_{H0}=\beta_{H0, SC2}\)). Upper and lower Alfvén continuous spectra are also plotted (black).

\[ n=2 \quad n=4 \quad n=6 \]
Linear dynamics: SC2-cont.

- Toroidal mode number $n=2$ is found to be the most unstable.
- The mode is located around $r_{\alpha-H,\text{max}}/a$ in radius, and below the Alfvén continuum in frequency.
- The mode belongs to a MHD branch (it exists also at zero $\beta_{H0}$).
Linear dynamics: SC4

- Power spectra of scalar-potential fluctuations in the \([r, \omega]\) plane, during the linear phase \((\beta_{H0} = \beta_{H0}, \text{SC}4)\).
Linear dynamics: SC4-cont.

- Toroidal mode number $n=2$ is found to be the most unstable.
- The mode is located close to $r_{q_{\text{min}}}/a$ radius, and close to the tip of the lower Alfvén continuum in frequency.
- A second weaker mode appear in the toroidal gap around $r/a \approx 0.4 \div 0.5$, for $n=2$.
- The mode belongs to a MHD branch (it exists also at zero $\beta_{H0}$).
Linear dynamics: SCH

- Power spectra of scalar-potential fluctuations in the \([r, \omega]\) plane, during the linear phase \((\beta_{H0} = \beta_{H0, SCH})\).

\[ n=2 \quad \quad n=4 \quad \quad n=8 \]
Linear dynamics: SCH-cont.

- This scenario is weakly unstable at nominal $\beta_{H0}=\beta_{H0,\text{SCH}}$ value:
  - the mode belongs to a \textbf{MHD branch} (a similar mode exists also at zero $\beta_{H0}$);
  - it is localized close to the magnetic axis.
- Above a certain threshold in $\beta_{H0}$ a stronger unstable mode appears:
  - it belongs to a \textbf{EPM branch};
  - it is localized at $r_{\alpha-H,\text{max}}/a$, where the local drive is maximum.
Linear Dynamics: EPMs localization

- **Radius**: the mode is localized where the local drive $\alpha_H$ has its maximum.
- **Frequency**: expected wave-particle resonances ($\varepsilon<<1$, small orbit width, well circulating/deeply trapped particles):
  
  $$\omega = \omega_t \approx \sqrt{\frac{E_{fus}}{2m_H}} \frac{1}{q(r)R_0}$$
  
  transit frequency:
  
  $$\omega = \overline{\omega}_d \approx \frac{E_{fus}}{m_H R_0 \omega_{ch}} \frac{nq(r)}{r}$$
  
  precession frequency:
  
  $$\omega = \overline{\omega}_d + l \omega_B, \ell = \pm 1$$
  
  precession-bounce frequency:

  - $\ell = -1$, precession-bounce and precession resonances seem to dominate.

  $$\omega_B \approx \frac{1}{R_0 q(r)} \left(\frac{E_{fus}}{m_H} \frac{r}{R_0}\right)^{1/2}$$

- $\beta_{H0}=3.3\times\beta_{H0,\text{SCH}}$. Mode disappears if **mirroring term** is switched off!

- **SCH, n=4**
- **SCH, n=6**
- **SCH, n=8**

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Nonlinear dynamics: phenomenology

- Maximum gradient of $r\beta_H$ shifts outward:
  - first steepening (convective phase, avalanche),
  - then relaxing (diffusive phase: saturated e.m. fields scatter $\alpha$-particles)

\[ r_{\max} \]

\[ 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad r/a \]

Linear phase

Convective phase

Diffusive phase

\[ \frac{d(r\beta_H)}{dr} \]
Nonlinear dynamics: cont.

**SC2** \((n=2):\) scarcely affected by nonlinear saturation (mode localization close to linear-phase one); continuum damping “barrier” prevents the mode to displace outwards.

**SCH:** similar to **SC2** at nominal \(\beta_{H0}\) value.

**SC4** \((n=2):\) the mode is located around \(q_{\text{min}};\) \(\alpha\) particles have larger orbit width (higher \(q\)): larger convection and diffusion.
Nonlinear dynamics: cont.-2

Define $r_y(t)$ as the radial position of the surface containing a fraction $y$ of the $\alpha$-particle energy:

$$y = \frac{\int_0^{r_y} r \beta_H(r,t) dr}{\int_0^1 r \beta_{H,\text{init}}(r) dr}$$

Time behavior of central $\alpha$-particle beta, $\beta_{H0}$:
Nonlinear dynamics: cont-3.

Increase artificially $\beta_{H0}$ to investigate the dependence of transport on the intensity of energetic particle drive. **Convection** phase:

SC2, $n=2$

SC4, $n=2$

SCH, $n=8$

Also diffusion, characterized by: $\tau_{\text{diff},95\%} \equiv r_{95\%} [\partial r_{95\%}/\partial t]^{-1}$, $\tau_{\text{diff},\beta H0} \equiv \beta_{H0} [\partial \beta_{H0}/\partial t]^{-1}$, increases with $\beta_{H0}$. 

No $\alpha$-particle dynamics, relaxed value!
Conclusions

- Standard ITER monotonic-\(q\) scenario (SC2):
  - unstable w.r.t. \(\alpha\)-particle driven Alfvén modes;
  - nonlinear saturation produces negligible modifications to the \(\alpha\)-particle radial profile: consistent scenario;
  - central \(\beta_{H0}\) very sensitive to increasing drive, \(r_{95\%}\) not sensitive.

- Reversed shear scenario (SC4):
  - unstable;
  - appreciable changes to the \(\alpha\)-particle radial profile (\(r_{95\%}\)): possibly inconsistent scenario;
  - both \(\beta_{H0}\) and \(r_{95\%}\) sensitive to increasing drive.

- Hybrid scenario (SCH):
  - Very weakly unstable (MHD branch mode);
  - Above \(\approx 1.6 \beta_{H0, SCH}\) EPM branch is driven strongly unstable.

- Caveat:
  - multiple toroidal-mode-number dynamics could enforce \(\alpha\) transport;
  - dynamic approach to the reference \(\alpha\)-particle pressure could regulate the stronger energetic particle mode dynamics via nonlinear effects of weaker modes.
Next…

- Multiple toroidal-mode-number simulations: mode-mode coupling could enforce $\alpha$ transport.
- Could the dynamic approach to the reference $\alpha$-particle pressure regulate the stronger energetic particle mode dynamics via nonlinear effects of weaker modes? (Counter example: ALE?).
- New (upgraded) code under development: full MHD, general curvilinear geometry (start with a linear module, MARS), energetic particles described by nonlinear gyro-kinetic Vlasov equation (finite $k_\perp \rho_H$) solved by particle-in-cell (PIC) techniques.
- Needs for detailed inputs ($\alpha_H$, $n_{\text{beam}}$, $n_{\text{ICRH}}$ detailed distribution functions, radial profiles, …).
- How to integrate the results of $\alpha$-particle collective dynamics with transport code?