Consistency of proposed burning plasma scenarios with alpha particle transport induced by Alfvénic instabilities

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Introduction-1

- Next generation Tokamaks (ITER-FEAT, IGNITOR, FIRE), should approach the so called ignition condition: heating due to fusion α-particles (hot particles) is able to sustain the burning plasma
- Good confinement of the α-particles is crucial in getting such condition
- Fusion α-particles are generated with \( v_{th,H} \approx v_A = B/(4\pi n_i m_i)^{1/2} \) and peaked density profile ⇒ free-energy source for the resonant destabilization of shear Alfvén modes (TAE, EPM, …)
- Interaction of such modes with energetic-particle dynamics can induce outward α-particle transport
Introduction-2

- Normally, transport codes aimed to define burning-plasma scenarios do not include the possibility of Alfvén mode - $\alpha$ particle interaction
- Are the proposed scenarios consistent with the $\alpha$-particle dynamics?
- Which are the effects on $\alpha$-particle profiles and confinement?
- Aim of our investigation: check the consistency of several burning-plasma scenarios, by means of particle simulation techniques
The numerical model-1

- Hybrid MHD-Gyrokinetic Code (HMGC):
  - thermal plasma described by Magnetohydrodynamic (MHD) equations
  - energetic particles described by gyrokinetic equations
- Energetic particles and thermal plasma are coupled through the $\alpha$-particle pressure tensor, $\Pi_H$, which enters in the MHD momentum equation
The numerical model-2

1. Electromagnetic fields computed at the points of a discrete 3-D spatial grid: reduced MHD equations \(O(\varepsilon^3)\), with \(\varepsilon = a/R_0\), \(a\) and \(R_0\) the minor radius and the major radius of the torus)

2. Interpolation of the e.m. fields at the (continuous) particle positions to compute the forces and perform \(\alpha\)-particle pushing

3. \(\Pi_H\) computed at the grid points to close the MHD equations
Burning-plasma devices/scenarios

ITER-FEAT

IGNITOR

FIRE

\[ q(r) = rB_\phi / RB_\theta \]
\[ \beta_H = 8\pi n_H T_H / B^2 \]
\[ \alpha_H = R_0 q^2 \beta'_H \]
Results: linear stability-1

- Consider $\beta_{H0}$ (central $\alpha$-particle pressure) a free parameter
- **Growth rate** of shear Alfvén modes vs $\beta_{H0}/\beta_{H0,nom}$
- $\beta_{H0,Th}$: threshold for destabilization
- All the considered scenarios are stable w.r.t. shear Alfvén modes ($\beta_{H0,Th} >> \beta_{H0,nom}$) with the exception of the Reversed-Shear ITER-FEAT scenario
Results: linear stability-2

- **FIRE** and **IGNITOR** are high magnetic field devices $\Rightarrow$ low $\beta_{H0,nom} \Rightarrow$ low drive $\alpha_H = R_0 q^2 \beta'_H$

- **Reversed-Shear** and **monotonic-q** **ITER-FEAT** have similar $\beta_{H0,nom}$ values, but the **RS** **ITER-FEAT drive** is much larger because of larger $q$ and steeper $\beta_H$ gradient
Results: linear stability-3

Monotonic-q ITER-FEAT

- Transit frequency
- Precession frequency
- Maximum-drive radial position $r = r$
- Resonance with the $\alpha$-particle precession frequency
- For each scenario, the most unstable $n$ is that corresponding to precession frequency inside the gap, at $r = r$
- At $r = r$, the gap frequency for Reversed-Shear scenario is lower than monotonic-q one (larger $q$ value at $r = r$) $\Rightarrow$ precession frequency lower ($\propto n$) $\Rightarrow$ most unstable $n$ lower ($n = 2$)

Reversed-Shear ITER-FEAT

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Results: nonlinear effects on $\alpha$ confinement-1

- **ITER-FEAT RS** scenario ($\beta_{H0} = \beta_{H0, nom}$)
- Power spectra in the $(r, \omega)$ plane and $\beta_H$ profiles

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Results: nonlinear effects on $\alpha$ confinement-2

- **Convective phase** *(avalanche)*: maximum gradient of $r\beta_H$ shifts outward, first steepening and then relaxing
Results: nonlinear effects on $\alpha$ confinement-3

- Saturation of EPMs takes place via an avalanche mechanism, which produces a macroscopic convective redistribution of the energetic-particle source.
- After the convective displacement has completed, a significant diffusion of energetic particles survives because of the continuous scattering of the energetic particles in the saturated electromagnetic fields.
- Define $(r/a)_y$: the radial position of the surface containing a fraction $y$ of the $\alpha$-particle energy:

$$y = \frac{\int_0^{(r/a)_y} x \beta_H (x; t) \, dx}{\int_0^1 x \beta_H (x; t_{relax}) \, dx}$$
Results: nonlinear effects on $\alpha$ confinement-4

- Both convection and diffusion are more pronounced for larger $\beta_{H0}$ (larger saturated field levels)
- Characterize the convection with $(r/a)_{85\%}$ at the end of the convection phase
- Characterize diffusion by $\tau_{\text{diff,}85\%} \equiv (r/a)_{85\%} \left[ \frac{\partial (r/a)_{85\%}}{\partial t} \right]^{-1}$, $\left( \tau_{\text{diff,}85\%}^{-1} \propto D \right)$
Conclusions

- Shear Alfvén dynamics and interactions with $\alpha$ particles must be retained in order to determine self-consistent fusion-product profiles for the reference scenario.
- The Reversed Shear ITER-FEAT proposed scenario, in particular, appears to be unstable w.r.t. Shear Alfvén Modes.
- These modes are able to broaden $\alpha$-particle profiles both via convective (avalanche) and diffusive mechanisms.
- Small increase of the $\alpha$-particle energy content (w.r.t. the reference scenario) could produce large thermal loads on the first wall.
- Future work: general equilibrium code (in progress).