Interaction of fast particles and Alfvén modes in burning plasmas

G. Vlad, S. Briguglio, G. Fogaccia, F. Zonca
Associazione Euratom-ENEA sulla Fusione
C.R. Frascati - C.P. 65 - I-00044 - Frascati, Rome, Italy

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Outline

• Introduction:
  – on the interaction of fast particles and Alfvén modes;
  – its importance in burning plasmas.
• Experimental observations on JT-60U:
  – Abrupt Large amplitude Events (ALEs) and fast Frequency sweeping (FS) modes;
  – propose an interpretation based on nonlinear particle simulations.
• Apply the same simulation approach to ITER scenarios:
  – addressing the problem of consistency of the proposed scenarios with nonlinear Alfvén dynamics.
Introduction - 1

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

Fusion $\alpha$-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 (TAEs, EPMs, …)

• Interaction of such modes with energetic-particle can induce outward $\alpha$-particle transport, degrading performance of burning plasmas and eventually damaging the first wall
Introduction - 2

- Experimental evidences of rapid transport of energetic ions related with fluctuations in the Alfvén-mode frequency range have been observed in strongly heated plasmas (e.g., in the JT-60U tokamak, in connection with the so called Abrupt Large amplitude Events (ALEs), TFTR, DIII-D, JET).

- Evidence that energetic-ion redistribution can take place because of fast growing Alfvén modes (e.g., Energetic Particle driven Modes (EPMs)) have been predicted theoretically and observed in particle-simulation studies.

- Operation scenarios for next-step proposed burning-plasma experiments (ITER) are obtained from equilibrium and transport codes which do not include the physics required to describe shear Alfvén modes: possible inconsistency!
In this talk we will:

1. present an interpretation of the experimental observations made on JT-60U based on the results of nonlinear particle simulations performed by the Hybrid MHD-Gyrokinetic Code (HMGC);
2. apply the same simulation approach to the nonlinear evolution of unstable modes in the proposed ITER scenarios: 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
• In the weak shear JT-60U tokamak experiments with negative-ion-based neutral beam (NNB) injection, variation in the radial profile of the neutron emission rate has been observed, indicating a change in the energetic ion density profile and a large enhanced transport.

• Use of neutron emission profile and charge exchange neutral particle measurements (Ishikawa et al., NF 45 (2005) 1474-1480)

$$n_b(r) \text{ from neutron emission rate: } S_n = n_{th} n_b \langle \sigma v \rangle_{bt}$$

• 20% particles are redistributed $r \leftrightarrow 0.6$

• others are lost (lost fraction ≈ 4%)
JT-60U: experimental evidences - 2

- Simultaneously, on the frequency spectrum and amplitude of magnetic fluctuations, bursting modes ($n=1$) (Abrupt Large amplitude Events, ALEs), are observed.
- Between two bursts, fast Frequency Sweeping (fast FS) modes are also observed.
• Period between two ALEs increases with drop ratio of neutron emission rate $\Delta S_n/S_n$

• **ALE**: large-amplitude event with timescale $\sim 200-400$ $\mu$s, amplitude $\delta B_\theta/B_\theta \sim 10^{-3}$ at the first wall; significant redistribution of energetic ions

• **Fast FS**: bifurcating branches with timescale $\sim 1-5$ ms, lower amplitude than that of ALEs and negligible redistribution of energetic ions
Simulation approach

• Aim: explanation of the experimental phenomenology in terms of nonlinear interaction of Alfvén modes and energetic ions

• Hybrid MHD-Gyrokinetic Code (HMGC):
  – thermal plasma described by zero pressure reduced $O(\epsilon^3)$ 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 loaded according to anisotropic slowing-down distribution function, with birth energy $E_{\text{beam}}$ and critical energy $E_{\text{crit}} \propto T_e(r)$ (Stix);
  – energetic particles coupled to the thermal plasma through their pressure tensor, which enters the MHD momentum equation;
  – self-consistent simulations (particles treated non perturbatively);
  – mode-mode coupling neglected in this paper (but particle nonlinearities fully retained).
JT-60U: “ALE” simulation - 1

• Initial energetic-ion configuration:
  – density profile from experiment (E036378), just before ALE
  – distribution function in velocity space: anisotropic slowing-down (nearly tangential beam injection)

• Power spectrum of the fluctuating electrostatic potential in the \((r, \omega)\) plane (n=1 Alfvén continuum spectrum in black):

  - Linear phase
  - Early saturation
  - Late saturation
JT-60U: “ALE” simulation - 2

- Wave-particle power transfer in the energetic-ion ($\mu, v_\parallel$) space, over the radial region $(0.36 \leq r/a \leq 0.67)$ where the most unstable mode is localized, in the linear phase
  $\Rightarrow$ circulating energetic ions give the resonant drive, consistently with nearly tangential beam injection

- Broad resonance region:

![Graph showing power distribution and resonance region](image)

\[ E = E_{\text{beam}} \]

trapped ions

expected resonance region (note: for E43014)
JT-60U: “ALE” simulation - 3

- Nonlinear redistribution of energetic ions: very good agreement on central drop

- $\delta B_\theta(t)$ and power spectrum of $\delta B_\theta(t,\omega)$ close to the plasma boundary.
  Frequency and time scale of the “burst”:
  $\Delta\omega \approx 40$ kHz
  $\Delta t \approx 150$ $\mu$s

⇒ identify the strongly unstable Alfvén mode with ALE
JT-60U: “After ALE” simulation - 1

• Could the nonlinear dynamics described by our simulation also explain the quiescent phase between two ALEs (low amplitude fields and negligible effects on the energetic-ion distribution)?

• “After ALE” simulation:
  – density profile equal to the experimental one, after ALE
  – same distribution function in the velocity space (slowing-down) as the “ALE” simulation

• Negligible nonlinear redistribution of energetic ions (simulation compare well with exps. but ...)

![Graph showing density profile comparison]
JT-60U: “After ALE” simulation - 2

- $\delta B_\theta(t)$ close to plasma edge: too large!
  - $\delta B_\theta^{\text{After ALE}} / \delta B_\theta^{\text{ALE}} \approx 0.5 \iff \delta B_\theta^{\text{Fast FS}} / \delta B_\theta^{\text{ALE}} < 0.2$

Too strong instability (this could be expected observing that, in the region where the linear mode is driven, the absolute value of the radial gradient of the energetic particle pressure is very close to the “ALE” value)
We expect that even a partial reconstruction of the spatial energetic-ion density profile by the NNB injection would yield a fast instability:
⇒ the reconstruction process would be prevented;
⇒ profile clamped to the “after ALE” shape
(as observed by simulations with intermediate density profiles);
⇒ no chances of obtaining ALE repetition.
JT-60U: “After ALE-mod” simulation - 1

- More realistic “After ALE Modified” simulation:
  use radial profile and velocity space \((\mu, v_{||})\) distribution as obtained from the “ALE” simulation (different from slowing-down!) as new initial conditions

- Reduced \(\delta B_\theta(t)\) close to the plasma edge:
  \(\delta B_\theta^{\text{After ALE Modified}} / \delta B_\theta^{\text{ALE}} \approx 0.2\)

- Note: our simulation does not include neither energetic-ion source nor realistic damping mechanisms
JT-60U: “After ALE-mod” simulation - 2

- Negligible further redistribution of energetic ions due to the weaker mode

- Power spectrum of $\delta B_\theta$ close to the wall in the $(t, \omega)$ plane: frequency sweeping of the weaker fluctuation $\Rightarrow$ possible identification with a Fast FS mode
JT-60U: Conclusions

- Particle simulations (HMGC) show that:
  - ALE reproduced by assuming, for the energetic ions, an initial density profile equal to the experimentally observed one and a slowing-down velocity-space distribution function
  - Quiescent phase between two successive ALEs (FS modes) could be reproduced by assuming spatial redistribution of the energetic ions and the ALE-induced nonlinear modifications of their velocity-space distribution function

- Possible interpretation of the experimental observations:
  - After ALE, low growth rates and amplitude modes (fast FS modes) are possible, because of the modified distribution function
  - Repetition rate between two successive ALEs is given by the time needed to reconstruct the original slowing-down distribution function
ITER scenarios - 1

- **SC2**: monotonic $q(r)$, inductive, $I_p = 15$ MA, $P_\alpha = 400$ MW, $Q \approx 10$

- **SC4**: steady state, $I_p = 9$ MA, $q_{\text{min}} \approx 2.4$ ($r/a \approx 0.68$), weak-neg. shear, $P_\alpha = 300$ MW, $Q \approx 5$

- **SCH**: steady state, $I_p = 11.3$ MA, weak-pos. shear, $P_\alpha = 400$ MW, $Q \approx 5$
ITER scenarios - 2

• Linear stability analysis (toroidal modes n≤8)

• Nonlinear dynamics

• Sensitivity analysis to energetic particles drive intensity:
  – extend investigation to values of the on-axis beta $\beta_{H0}$ larger than the reference value $\beta_{H0, \text{scenario}}$, while keeping the normalized profile, $\beta_H(r)/\beta_{H0}$ unchanged;
  – the strong dependence of the $\alpha$-particle density on the electron and bulk-plasma ion temperatures $n_H \sim T_i^2 T_e^{3/2}$ could give to these investigations more than only an academic importance: an uncertainty of few tens percent in these quantities, which is plausible in consideration of the approximation of transport models, can easily yield a corresponding quite large uncertainty in $\beta_{H0, \text{scenario}}$. 
ITER: linear dynamics
ITER: nonlinear dynamics - 1

- ITER reversed shear scenario (SC4), $n=2$:
ITER: nonlinear dynamics - 2

\[ n = 2 \]

\[ \beta_{H0,SC2} \]

\[ 2 \times \beta_{H0,SC2} \]

\[ \beta_{H0,SC4} \]

\[ 2 \times \beta_{H0,SC4} \]

\[ 3.3 \times \beta_{H0,SCH} \]
ITER: nonlinear dynamics - 3

- ITER reversed shear scenario (SC4), \( n=2 \): single particle orbits, born parameters:

\[
\begin{align*}
\text{r/a} &= 0.1, \\
\mu &= 0.8 \frac{E_{\text{fus}}}{\omega_{\text{cH}}}, \\
v_{||} &= 0;
\end{align*}
\]

\[
\begin{align*}
\text{r/a} &= 0.05, \\
\mu &= 0.4 \frac{E_{\text{fus}}}{\omega_{\text{cH}}}, \\
v_{||} &= 0;
\end{align*}
\]

\[
\begin{align*}
\text{r/a} &= 0.05, \\
\mu &= 0.2 \frac{E_{\text{fus}}}{\omega_{\text{cH}}}, \\
v_{||} &= 0.3 (E_{\text{fus}}/m_H)^{1/2}.
\end{align*}
\]
ITER reversed shear scenario (SC4), $n=2$: contour plot of the wave-particle power transfer, i.e. the resonance region in the alpha-particle ($\mu, v_\parallel$) space:

Gap mode centered at $r/a \approx 0.4$ =>

<= Cascade mode centered at $r/a \approx 0.6$

($q_{\min}$ radius)
ITER: Conclusions

- SC2 and SCH scenarios are consistent with the presence of nonlinear dynamics of shear-Alfvén modes.
- SC4 scenario, instead, shows some broadening of the alpha-particle pressure profile, indicating a certain level of inconsistency of the scenario itself.
- Over-driven simulations:
  - SC2: strong flattening of the $\alpha$-particle pressure profile in the inner plasma region, global confinement not significantly affected.
  - SC4: more pronounced effects in the outer portion of the discharge, (mode is localized outward), less impact for on-axis pressure value.
  - SCH: no effects below the EPM threshold. Above threshold effects similar to SC4, but more limited for given growth rate.
End of presentation
Numerical methods of HMGC

MHD module:
- finite difference in the radial direction, Fourier expansion in the poloidal and toroidal directions
- the system of coupled equations for the Fourier components of the magnetic and velocity streamfunctions $\psi$ and $\varphi$ is advanced in time using a semi-implicit algorithm:
  - all the linear terms that couple with cylindrical part ($O(\varepsilon^2)$) of the equilibrium ($m,n = (0,0)$) Fourier components are treated implicitly
  - nonlinear terms and terms which couple to the toroidal corrections ($O(\varepsilon^3)$) of the equilibrium ($m,n = (1,0)$) are treated explicitly

Kinetic module:
- solved by particle-in-cell (PIC) techniques. At each time step:
  - the electromagnetic fields are computed at the points of a discrete spatial grid (transform from Fourier space to real space) (field solver phase)
  - they are interpolated at the (continuous) particle positions in order to evolve particle phase-space coordinates according to the eqs. of motion (particle pushing phase)
  - particle contribution to the required moment of the distribution function (pressure) is collected at the grid points (and Fourier transformed) to close the field equations (pressure computation phase)
Numerical verifications of HMGC


- **linear:**
  - Alfvén continuum structure, continuum mode asymptotic decay in time $\propto 1/t$
  - toroidal gap
  - GAE, TAE, Resistive Periodic Shear Alfvén modes (resistive counterpart of KTAE)
  - continuum damping

- **nonlinear:**
  - fluid saturation (MHD nonlinearities) of TAE and RPSAE

Comparison with analytic theory for kinetic module and kinetic + MHD (Briguglio et al., Phys. Plasmas, 2, 3711 (1995)):

- **linear:**
  - single particle orbit,
  - growth rate $\gamma/\omega_A$ vs. $v_H/v_A$ for a KTAE mode ($\beta_{H0}=4\%$):
    - **squares:** numerical simulations
    - **dashed line:** analytical with only local contribution to the drive from the gap region retained
    - **solid line:** analytical with full eigenfunction profile retained