Particle Simulation Analysis of Energetic-Particle and Alfvén-Mode Dynamics in JT-60U Discharges

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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.

• We propose an interpretation of the observed phenomenology based on nonlinear particle simulations.
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.

• We 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).
JT-60U: NNB-heated discharge

- Weak negative magnetic shear, $q_0 \approx 1.3$, $q_{\text{edge}} \approx 4 \div 5$.

- Negative Neutral Beam (D): 0.397 MeV, $n_{H0} \approx 0.12 \times 10^{19} \text{ m}^{-3}$.

- Other relevant plasma parameters are:
  - $a = 0.95 \text{ m}$, $R_0 = 3.3 \text{ m}$;
  - $B_T = 1.2 \text{ T}$;
  - $n_{e0} = 2.5 \times 10^{19} \text{ m}^{-3}$;
  - $n_{i0} = 1.74 \times 10^{19} \text{ m}^{-3}$ (main ion species: D);
  - $T_{e0} = 2.1 \text{ keV}$.
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 flux measurements (Ishikawa et al., NF 45 (2005) 1474-1480).

Abel inverted

\[ n_H(r) \] from neutron emission rate:
\[ S_n = n_{th} n_H \langle \sigma v \rangle_{\text{beam-target}} \]

- 20% particles are redistributed \( r \leftrightarrow 0.6 \)
- others are lost (lost fraction \( \approx 4\% \))
JT-60U: experimental evidences - 2

- Simultaneously, on the frequency spectrum and amplitude of magnetic fluctuations, bursting modes (Abrupt Large amplitude Events, ALEs) are observed, with toroidal mode number $n=1$.
- 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 $\sim 200-400$ µs, 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 $O(\varepsilon^3)$ MHD equations (circular shifted magnetic flux surfaces);
  - energetic particles described by nonlinear guiding-center Vlasov equation ($k_\perp \rho_H \ll 1$) 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 $P$ in the energetic-ion ($\hat{E}$, $\alpha$) space, over the radial region ($r/a \approx 0.5$) 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:

  $\alpha \equiv \arccos \left( \frac{\hat{v}_\parallel}{(2\hat{\mu} + \hat{v}_\parallel^2)^{1/2}} \right)$

  $\hat{E} \equiv \frac{E}{E_{NNB}} \equiv \hat{\mu} + \hat{v}_\parallel^2/2$

  $\hat{\mu} \equiv \frac{\mu \Omega_{H0}}{m_H v_H^2}$

  $\hat{v}_\parallel \equiv v_\parallel/v_H$

- Broad resonance region:

  ![Graphical representation of the expected resonance region](image)

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

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

- \( \delta B_\theta(t) \) and power spectrum of \( \delta B_\theta(t, \omega) \) close to the plasma boundary.

Frequency and time scale of the “burst”:
\[ \Delta \omega \approx 40 \text{ kHz} \]
\[ \Delta t \approx 150 \mu \text{s} \]

⇒ 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 compares well with experiments but ...

![Graph showing density profile](image)

- initial profile (= after ALE exp.)
- relaxed profile (simulation)
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**

\[ r/a \approx 0.5 \]

- \( F_{SD} \): Slowing-Down distribution function (initialization)
- \( F \): distribution function after nonlinear saturation \((t \approx 500 \tau_{A0} \text{ of “ALE” simulation})\)
- Difference \(F - F_{SD}\)

**“After ALE-mod”**: initial distribution function from “ALE” simulation, after the nonlinear saturation has occurred \((t \approx 500 \tau_{A0})\), thus different from Slowing-Down.

G. Vlad et al. 21st IAEA Fusion Energy Conference, 16 - 21 October 2006 - Chengdu, China - paper TH/P6-4
• We can get a reasonable guess on the overall effect on the plasma stability by weighting the difference $F - F_{SD}$ by the power transfer $P$ (during linear phase).

• The resulting plot shows that the net effect is largely negative.

• According to this result, the velocity-space redistribution of energetic ions corresponds to scattering of resonant ions out of the resonant region yielding weaker instability.
JT-60U: “After ALE-mod” simulation - 3

• Comparison between the “ALE” simulation and the “After ALE-mod” one.

• Reduced $\delta B_\theta(t)$ close to the plasma edge:
  \[ \frac{\delta B_\theta \text{ After ALE-mod}}{\delta B_\theta \text{ ALE}} \approx 0.2. \]

• Note: our simulation does not include neither energetic-ion source nor realistic damping mechanisms.
JT-60U: “After ALE-mod” simulation - 4

- 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: “ALE” simulation - $\delta f - 1$

Wave-particle power exchange in $(\hat{E}, \alpha)$ plane, linear phase

$0. \leq r/a \leq 0.34$

$0.35 \leq r/a \leq 0.67$

$0.68 \leq r/a \leq 1.$

$\delta f$ in $(\hat{E}, \alpha)$ plane, at saturation
(blue $< 0$, red $> 0$)
JT-60U: “ALE” simulation - δf - 2

Wave-particle power exchange in $(\tilde{E}, \alpha)$ plane, at saturation

δf in $(\tilde{E}, \alpha)$ plane, at saturation

(blue $<0$, red $>0$)

0.0 ≤ r/a ≤ 0.34

0.35 ≤ r/a ≤ 0.67

0.68 ≤ r/a ≤ 1.

G. Vlad et al. 21st IAEA Fusion Energy Conference, 16 - 21 October 2006 - Chengdu, China - paper TH/P6-4
JT-60U: “ALE” simulation - $\delta f - 3$

Define resident particles as those who have not moved considerably from linear orbits.

$\delta f$ (resident particles) at saturation
(blue<0, red>0)

$0.0 \leq r/a \leq 0.34$

$0.35 \leq r/a \leq 0.67$

$0.68 \leq r/a \leq 1.$
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 and density profile of the energetic ions.