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

G. Vlad, S. Briguglio, G. Fogaccia, K. Shinohara[†], M. Ishikawa[†], M. Takechi[†], F. Zonca Associazione EURATOM-ENEA, CR ENEA-Frascati, Via E. Fermi 45, 00044 Frascati, (Rome) Italy

†Japan Atomic Energy Agency, Naka, Ibaraki 311-0193, Japan

e-mail contact of main author: vlad@frascati.enea.it

Abstract. The results of particle simulations of a typical NNB-heated JT-60U discharge (# E036378), performed by the HMGC particle-in-cell code, are presented. We observe that the linear-growth phase is dominated by a fast-growing mode, localized at half radius, near the maximum of the energetic-ion pressure gradient and with a significant coupling with the Alfvén continuum, showing the energetic-particle-driven nature of the mode. As the nonlinear effects become important, a macroscopic outward displacement of the energetic ions is observed, producing a significant reduction of their density in the central region. These results seem to match quite well the dynamics of the abrupt large-amplitude event (ALE) experimentally observed in the JT-60U discharge. The time scale and frequency spread of the ALE are well reproduced too. Then, the issue of the almost quiescent phase following the ALEs, characterized by weaker fast frequency sweeping (fast FS) modes, is investigated. We show that it is not possible to explain such a phase as the consequence of the mere relaxation of the energetic-ion density profile produced by the ALE. The decrease of the instability level of the system can however be fully accounted for by properly taking into account the nonlinear modification of the energetic-ion distribution function in the velocity space. An interpretation of the full JT-60U bursting-mode phenomenology is finally presented.

1. Introduction

In a burning plasma, alpha particles are expected to transfer their energy via Coulomb collisions to the thermal plasma, thus providing a nuclear self-heating mechanism and a route to ignition. The fusion reactions generate energetic particles characterized by velocities in the super-Alfvénic range, and it is well known that they can resonate with, and possibly destabilize, shear Alfvén modes. The mutual nonlinear interaction of shear Alfvén and energetic particles can, in turn, affect the energetic ions related with fluctuations in the Alfvén-mode frequency range have been observed in plasmas heated by different auxiliary power systems [1], as reported, e.g., in the JT-60U tokamak [2, 3, 4], in connection with the so called Abrupt Large amplitude Events (ALEs). A review of experimental observations of collective mode effects on fast ions is given in Ref. [1] and references therein. Meanwhile, evidence that energetic-ion redistribution can take place because of fast growing Alfvén modes (e.g., Energetic Particle driven Modes (EPMs) [5]) has been found in particle-simulation studies [6, 7, 8, 9, 10, 11, 12].

In this paper we test the particle simulation approach versus the experimental observations of the Alfvén mode dynamics in JT-60U discharges. We will show that simulations performed by the Hybrid MHD-Gyrokinetic Code HMGC [6, 13, 14] yield results in fair qualitative and quantitative agreement with those observations.

2. The Model

The plasma model adopted in the HMGC code consists of a thermal (core) plasma and an energetic-ion population. The former is described by reduced $O(\epsilon^3)$ MHD equations [15, 16] in the limit of zero pressure (ϵ being the inverse aspect ratio of the torus), including resistivity and viscosity terms. The reduced MHD equations expanded to $O(\epsilon^3)$ allow us to investigate equi-

libria with shifted circular magnetic surfaces. The energetic-ion population is described by the nonlinear gyrokinetic Vlasov equation [17, 18], expanded in the limit $k_{\perp}\rho_H \ll 1$ (with k_{\perp} being the perpendicular component of the wave vector to the magnetic field, and ρ_H the energetic-ion Larmor radius) but retaining full magnetic drift orbit widths, and solved by particle-in-cell (PIC) techniques. The coupling between energetic ions and thermal plasma is obtained through the divergence of the energetic-ion pressure tensor, which enters the vorticity equation [19]. Numerical simulations are performed retaining the relevant thermal-plasma quantities – the on-axis equilibrium magnetic field, major and minor radii (R_0 and a, respectively), the safety-factor q, the plasma density n_e , the electron temperature T_e –, the anisotropy of the energetic-ion distribution function and the ratio β_H between fast ion and magnetic pressures.

Energetic ions are loaded in the $(\mu, v_{||}, \psi)$ space, $(\mu \text{ and } v_{||} \text{ being the magnetic moment and the parallel velocity, and <math>\psi$ the magnetic flux function, respectively) according to a slowing-down (SD) distribution function. A strongly anisotropic SD distribution function is assumed, with an upper energy cut-off given by the injection energy of the (almost tangential) Negative Neutral Beam (NNB) ions and the critical energy E_c given by the Stix expression [20]. Experimental values are adopted for bulk ion (deuterium) and electron densities.

For simplicity we neglect the nonlinear mode-mode coupling among different toroidal mode numbers, then limiting the analysis to the evolution of a single toroidal mode n, while keeping fully nonlinear dynamics for energetic ions. Fluid nonlinearities are not expected indeed to considerably alter shear-Alfvén mode dynamics [6] for the cases under investigation [21].

3. Bursting modes in JT-60U

Two different types of bursting modes, both in the frequency range of Alfvén modes, have been observed by MHD spectroscopy in auxiliary heated (NNB) discharges in the JT-60U tokamak. The first one, the ALE [2], is characterized by a time scale of the order of hundred microseconds, a relatively large fluctuating magnetic field level $(\tilde{B}_{\theta}/B_{\theta} \sim 10^{-3} \text{ at the first wall})$ and large growth rates (corresponding to wide frequency spectra $\Delta \omega \sim \omega \sim 50 \text{ kHz}$). The ALEs are followed by a significant drop of the neutron emission rate in the central plasma region, which has been interpreted as a radial redistribution of the energetic ions, producing a marked reduction of their on-axis density. The repetition rate of ALEs appears to be related with the intensity of the event itself, as measured by the amount of such reduction. In the relatively quiescent phase between two ALEs, bursting modes of a second type, the fast frequency sweeping (fast FS) modes [2], are observed. Such modes are characterized by longer time scale (few milliseconds), lower growth rate and fluctuating field level, and much smaller redistribution of the energetic ions than ALEs. Most of them consist of bifurcating branches, chirping up and down in frequency.

In order to provide a possible explanation of this phenomenology in the framework of the nonlinear behavior of Alfvén modes, we perform particle simulations of a typical NNB-heated JT-60U discharge (# E036378) with the HMGC code [13]. In particular, we simulate the dynamics of energetic ion interactions with Alfvén modes, assuming the radial profiles experimentally observed immediately before an ALE, and postulating a strongly anisotropic SD distribution function in velocity space for the energetic deuterons injected at 0.397 MeV by the NNB auxiliary heating system, with on-axis density $n_H \approx 0.12 \times 10^{19} \text{ m}^{-3}$. Other relevant parameters are: $a = 0.95 \text{ m}, R_0 = 3.3 \text{ m}$, toroidal magnetic field $B_T = 1.2 \text{ T}$, on-axis $n_e = 2.5 \times 10^{19} \text{ m}^{-3}$,



FIG. 1.: Contour plots of the power spectrum of the fluctuating scalar potential in the $(r/a, \omega/\omega_{A0})$ plane, for a typical JT-60U discharge (# E036378), during the linear-growth phase (left) and the early (centre) and late (right) saturated phases. Modes with toroidal number n = 1 are considered. The Alfvén continuum spectrum is also plotted by the black (solid) line. Here, $\omega_{A0} \equiv v_{A0}/R_0$ is the on-axis Alfvén frequency and v_{A0} the on-axis Alfvén velocity.

on-axis ion density $n_i = 1.74 \times 10^{19} \text{ m}^{-3}$ (main ion species: deuterium), on-axis $T_e = 2.1 \text{ keV}$, on-axis safety factor $q \approx 1.3$. Modes with toroidal number n = 1 are considered, to compare simulation results with the experimental observations. The linearly unstable phase is dominated, in this "ALE" simulation, by a fast-growing mode ($\gamma/\omega \approx 0.5$), located around the maximum energetic-ion pressure gradient ($r/a \approx 0.5$) and characterized by a significant coupling with the Alfvén continuum, showing the energetic-particle-driven nature of the mode (see Fig. 1. left, where the contour plot of the power spectrum of the fluctuating scalar potential is shown in the (r, ω) plane). Once the mode saturates, a complex phenomenology appears. At an earlier stage, the configuration is dominated by a Toroidal Alfvén Eigenmode (TAE)-like mode, localized around $r/a \approx 0.8$, on the lower part of one throat of the Alfvén continuum. The original mode, localized at half radius, is replaced by a couple of nearly degenerate modes. A weak corelocalized mode also appears, with frequency well localized in the toroidal gap (Fig. 1. centre). At later times, the core-localized mode becomes the dominant one, while the external mode still persists at lower amplitudes (Fig. 1. right).

Figure 2. shows the contour plot in the energetic-ion (\hat{E}, α) plane of the wave-particle power transfer (averaged over the poloidal and toroidal angles) during the linear phase at $r/a \approx 0.5$, where the most unstable mode is peaked. Positive sign corresponds to ions pumping energy into the wave. Here, \hat{E} and α are defined by $\hat{E} \equiv \hat{\mu} + \hat{v}_{\parallel}^2/2$, $\alpha \equiv \arccos[\hat{v}_{\parallel}/(2\hat{\mu} + \hat{v}_{\parallel}^2)^{1/2}]$, with $\hat{\mu} \equiv \mu \Omega_{H0}/m_H v_H^2$ and $\hat{v}_{\parallel} \equiv v_{\parallel}/v_H$ being the normalized magnetic moment and parallel velocity, and m_H , v_H and Ω_{H0} the energetic-ion mass, injection velocity and on-axis Larmor frequency, respectively. The resonant drive is apparently given by circulating energetic ions, consistently with the nearly tangential beam injection; it appears to be quite broad in energy, in agreement with the estimates based on the experimental measurements [22].

As the nonlinear effects become important, a macroscopic outward displacement of the energetic ions is observed, producing a significant reduction of their density in the central region (Fig. 3. *left*), which matches fairly well the observed energetic-ion density profile after the ALE (black curve in Fig. 3. *left*). The fluctuating poloidal magnetic field \tilde{B}_{θ} vs. t (at a radial position close to plasma boundary) is plotted in Fig. 3. *centre*, while Fig. 3. *right* shows the power spectrum of the same quantity in the plane (t, ω) . The time scale Δt of the "burst" is $\Delta t \simeq 200 \omega_{A0}^{-1}$, which corresponds to $\Delta t \simeq 150 \,\mu$ s. The frequency spread is of order $\Delta \omega \simeq 40 \,\text{kHz}$. Both these

TH/P6-4



FIG. 2.: Contour plot in the energetic-ion (\hat{E}, α) plane of the wave-particle power transfer (averaged over the poloidal and toroidal angles) during the linear phase, at $r/a \approx 0.5$, where the most unstable mode is peaked. Positive sign corresponds to ions pumping energy into the wave. The solid lines contain the trapped particle region. $\hat{E} = 1$ corresponds to the injection energy of the NNB ions.

results are close to the experimental observations.

Given the fair qualitative and quantitative agreement between numerical results and experimental observations, we investigate whether the nonlinear dynamics described by our simulations can also explain the relatively quiescent phase (low amplitude fluctuating fields with negligible effects on the energetic-ion distribution) between two successive ALEs. A possible explanation of such a quiescent phase could be that the modification of the energetic-ion radial density gradient reduces the instability level of the system after an ALE. To check this hypothesis, we perform a simulation ("after ALE") initializing the energetic-ion density profile equal to that experimentally observed after the ALE, while postulating, as before, an anisotropic SD distribution function in the velocity space. The linear growth rate of the mode is lower ($\gamma/\omega \approx 0.28$) than that found in the "ALE" simulation but still very high (this could have been indeed ex-



FIG. 3.: "ALE" simulation. Left: nonlinear modifications of the energetic ion density profile (the blue curve refers to the initial profile and the red curve to the simulation relaxed profile; the black curve corresponds to the experimentally inferred profile just after the ALE and is plotted here for comparison). Centre: fluctuating poloidal magnetic field \tilde{B}_{θ} vs. t (at a radial position close to plasma boundary). Right: the power spectrum of the same quantity in the plane (t, ω) .

pected observing that, in the region where the linear mode is driven, magnitudes of the initial radial gradient of the energetic-ion pressure in the two simulations are not very different from each other: see Fig. 3. *left* and compare the blue and black curves). Correspondingly, in spite of fairly little nonlinear effects on the spatial energetic-ion distribution (Fig. 4. *left*), we get quite large fluctuating field levels (Fig. 4. *right*): approximately half of the values found in the "ALE" simulation, to be compared with the experimental observation of the *fast FS-to-ALE* amplitude ratio (~ 0.2). This seems to be inconsistent with the observed periodic character of the ALEs.



FIG. 4.: "After ALE" simulation. Left: nonlinear modifications of the energetic ion density profile (blue curve refers to the initial profile, red curve to the simulation relaxed profile). Right: fluctuating poloidal magnetic field \tilde{B}_{θ} vs. t (at a radial position close to plasma boundary).

Indeed, with such a level of instability, even a partial reconstruction of the spatial energetic-ion density profile would generate a fast instability, which would essentially clamp the energetic-ion density profile to the "after-ALE" shape. This is confirmed by a third simulation ("intermediate"), characterized by an intermediate initial energetic-ion density profile (namely, the average between the two initial profiles adopted in the "ALE" and "after-ALE" simulations): the final profile is substantially coincident with that found at the end of the two previous cases (Fig. 5.).



FIG. 5.: Nonlinear modifications of the energetic ion density profile obtained in the "intermediate" simulation. The blue curve refers to the initial profile (an average between the initial profiles adopted in the "ALE" and "after-ALE" simulations). The red curve represents the relaxed profile obtained after the mode saturation.

The reason for the detected disagreement could be traced back to the fact that, in assuming a SD for the initial distribution function in the "after-ALE" simulation, we have retained only part of the ALE nonlinear effects (the spatial redistribution), with no attention to the distortion produced in the velocity space. This assumption is very crude, as it can be observed in Fig. 6.,

TH/P6-4

where the plot in the (\hat{E}, α) plane of the SD distribution function (left) and that for the distribution function obtained, in the "ALE" simulation, after the nonlinear saturation of the most unstable mode (centre) are shown. Both functions refer to the radial position $r/a \approx 0.5$, where that mode is peaked, and are normalized to the energetic-ion density at that radius. We see that the nonlinear ALE dynamics causes both a spread of the distribution function in the low energy region and a depletion of its high-energy portion. The net effect is reported in Fig. 6. right, which shows the plot of the difference between the two normalized functions. Note that the modifications due to the ALE effects appear to be a redistribution in the velocity space. This is due to considering the normalized distribution functions (depurated from the density factor). Regions with negative (positive) difference have then to be considered, in an absolute sense, regions where the depletion of the distribution function is larger (smaller) than that in density.



FIG. 6.: Plot in the energetic-ion (\hat{E}, α) plane of the slowing-down distribution function (left) and that for the distribution function obtained, in the "ALE" simulation, after the nonlinear saturation of the most unstable mode (centre). Both functions refer to the radial position $r/a \approx 0.5$, where that mode is peaked, and are normalized to the local energetic ion density. Right: plot of the difference between the two normalized functions.

On the basis of this result, we have to seriously question the relevance of the "after-ALE" simulation: we can expect that the observed distortions of the distribution function significantly affect the mode-particle resonant interactions and, in turn, the stability of the system. In principle, the fact that the distribution function is distorted does not imply by itself that the energetic ions are less effective in driving the mode unstable. Indeed, the displacement of energetic ions in the velocity space could even allow them to resonate with the mode in a more efficient way. We can get a reasonable guess on the overall effect on the plasma stability by weighting the difference shown in Fig. 6. right by the power transfer plotted in Fig. 2.. The resulting contour plots are reported in Fig. 7., showing 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. Note however that both considering the (\hat{E}, α) structure of the resonance obtained in the linear phase of the "ALE" simulation (before the nonlinear displacement takes place) and looking only at the radial location of the most unstable mode of that simulation could be misleading. Indeed, we cannot rule out that both the radial displacement and the velocity-space redistribution modify mode frequency and structure in such a way to make the displaced ions more effective in driving the mode itself. In this sense, the previous argument is based only on a purely "local" picture of the nonlinear mode dynamics.

To get a conclusive response, we have to resort to a further self-consistent numerical experiment

TH/P6-4



FIG. 7.: Plot in the energetic-ion (\hat{E}, α) plane of the difference shown in Fig. 6. right weighted by the power transfer plotted in Fig. 2..

("after ALE modified"): we initialize the energetic-ion distribution function according to the distribution function obtained from the "ALE" simulation, after the rapid dynamics of the event has taken place ($t\omega_{A0} \approx 500$, see Fig. 3. *centre*); in such a way, we retain both the radial profile broadening and the distortions of the distribution function in the velocity space. Figure 8. *left* shows the normalized amplitude of the fluctuating poloidal magnetic field close to the plasma edge for the "after ALE modified" simulation. The fluctuation level is close to the experimental observations (~ 0.2 the level found in the "ALE" simulation). Moreover, the characteristic time scale of the mode becomes longer, as expected, with the power spectrum traces bifurcating in two branches, chirping up and down in frequency (Fig. 8. *right*): the frequency sweeping of the weaker fluctuation supports its identification with a fast FS mode.



FIG. 8.: "After ALE modified" simulation. Left: fluctuating poloidal magnetic field \hat{B}_{θ} vs. t (at a radial position close to plasma boundary). Right: the power spectrum of the same quantity in the plane (t, ω) . Note that the two quantities have been reported in the same scales adopted in Fig. 3. centre and right, respectively.

On the basis of these results, a possible interpretation of the experimental observations is the following: given the energetic-ion source provided by the beam injection, the free energy reconstruction rate is set by the need of rebuilding the velocity space distribution function. In this way, the intermediate configurations between two successive ALEs are characterized by a lower drive than that of a SD distribution with the same energetic-ion density radial profile. Low growth rates and amplitude modes, such as the fast FS modes, are then excited and have a weaker effect than that of ALEs in contrasting the density profile reconstruction. As soon as the combined restoration of the configuration and velocity space distribution provides enough drive for a fast growing Alfvén mode, a new ALE occurs.

References

- [1] HEIDBRINK, W.W., Phys. Plasmas 9 (2002) 2113–19
- [2] SHINOHARA, K., et al., *Nucl. Fusion* **41** (2001) 603–612
- [3] SHINOHARA, K., TAKECHI, M., ISHIKAWA, M., KUSAMA, Y., MORIOKA, A., OYAMA, N., TOBITA, K., OZEKI, T., THE JT-60 TEAM, GORELENKOV, N.N., CHENG, C.Z., KRAMER, G.J., and NAZIKIAN, R., *Nucl. Fusion* **42** (2002) 942–8
- [4] SHINOHARA, K., TAKECHI, M., ISHIKAWA, M., KUSAMA, Y., TSUZUKI, K., URATA, K., KAWASHIMA, H., TOBITA, K., FUKUYAMA, A., CHENG, C.Z., DAR-ROW, S., KRAMER, G.J., GORELENKOV, N.N., NAZIKIAN, R., TODO, Y., MIURA, Y., and OZEKI, T., *Plasma Phys. Contr. Fusion* 46 (2004) S31–45
- [5] CHEN, L., Phys. Plasmas 1 (1994) 1519–22
- [6] BRIGUGLIO, S., ZONCA, F., and VLAD. G., *Phys. Plasmas* **5** (1998) 3287–301
- [7] BRIGUGLIO, S., VLAD, G., ZONCA, F., and FOGACCIA, G., Physics Letters A 302 (2002) 308–12
- [8] VLAD, G., BRIGUGLIO, S., FOGACCIA, G., and ZONCA, F., Proc. 29th EPS Conf. (Montreux, 2002) vol 26B(ECA), (2002) P-4.088
- [9] ZONCA, F., BRIGUGLIO, S., CHEN, L., DETTRICK, S., FOGACCIA, G., TESTA, D., and VLAD, G., *Phys. Plasmas* **9** (2002) 4939–56
- [10] TODO, Y., NAKAJIMA, N., SHINOHARA, K., TAKECHI, M., ISHIKAWA, M., and YAMAMOTO, S., "Nonperturbative effects of energetic ions on Alfvén eigenmodes", Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004), CD-ROM file TH/3-1Ra and http://wwwnaweb.iaea.org/napc/physics/fec/fec2004/datasets/index.html
- [11] TODO , Y., WATANABE, T.H., PARK, H.B., and SATO, T., *Nucl. Fusion* **41** (2001) 1153–9
- [12] TODO, Y., BERK, H.L., and BREIZMAN, B.N., Phys. Plasmas 10 (2003) 2888–902
- [13] BRIGUGLIO, S., VLAD, G., ZONCA, F., and KAR, C., Phys. Plasmas 2 (1995) 3711
- [14] VLAD, G., KAR, C., ZONCA, F., and ROMANELLI, F., Phys. Plasmas 2 (1995) 418-41
- [15] STRAUSS, H.R., Phys. Fluids 20 (1977) 1354-60
- [16] IZZO, R., MONTICELLO, D.A., PARK, W., MANICKAM, J., STRAUSS, H.R., GRIMM, R., and MCGUIRE, K., *Phys. Fluids* **26** (1983) 2240–6
- [17] FRIEMAN, E.A., and CHEN, L., Phys. Fluids 25 (1982) 502-8
- [18] LEE, W.W., J. Comp. Phys. 72 (1987) 243-69
- [19] PARK, W., PARKER, S., BIGLARI, H., CHANCE, M., CHEN, L., CHENG, C.Z., HAHM, T.H., LEE, W.W., KULSRUD, R., MONTICELLO, D., SUGIYAMA, L., and WHITE, R., *Phys. Fluids* B 4 (1992) 2033–7
- [20] STIX, T.H., Plasma Phys. 14 (1972) 367-84
- [21] CHEN, L., and ZONCA, F., "Theory of Alfvén waves and energetic particles physics in buring plasmas", this conference, CD-ROM file OV/5-3
- [22] ISHIKAWA, M., et al. 2005 Nucl. Fusion 45 1474–1480