Nonlinear Simulation of Energetic Particle Modes in JT-60U

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Abstract:

Energetic particle mode (EPM) dynamics are simulated using a global nonlinear hybrid code (MEGA). The scenario considered is based on JT-60U shot E039672, just before the onset of a so-called Abrupt Large Event (ALE). The simulation model is gradually extended towards a more realistic representation of the JT-60U plasma, including realistic geometry, realistic pressure, and realistic fast ion distributions. It is found that the mode structure and frequency of the EPM is very robust and can be reproduced by simple models. In contrast, accurate prediction of the growth rate, fluctuation amplitude and fast ion transport may require realistic models. The progress made — in particular, the use of realistic geometry and a realistic fast ion distribution computed by an orbit-following Monte-Carlo code — constitutes an important step forward towards predictive simulations and integrated modeling of energetic particle dynamics in burning plasmas, such as in ITER and DEMO.

1 Introduction

Energetic particle modes (EPM) occur in magnetically confined plasmas that are driven by a source of fast ions with characteristic velocities comparable to that of shear Alfvén waves [1]. There is strong evidence that it is this kind of mode that causes abrupt (few 10μs) relaxations of the fast ion population in tokamak experiments driven by strong neutral beams. In JT-60U, these phenomena were called Abrupt Large Events (ALE) [2] and were shown to cause density variations of the order 10% for fast ions [3]. It is important to understand these phenomena and predict their effects as accurately as possible, since they are relevant to several critical issues of burning plasma research, such as current drive, external heating and self-heating.

In the present paper, we report recent progress made with respect to increasingly realistic modeling of bulk plasma and fast ion components in JT-60U shot E039672 before the onset of an ALE. The improvements include the use of realistic plasma geometry,

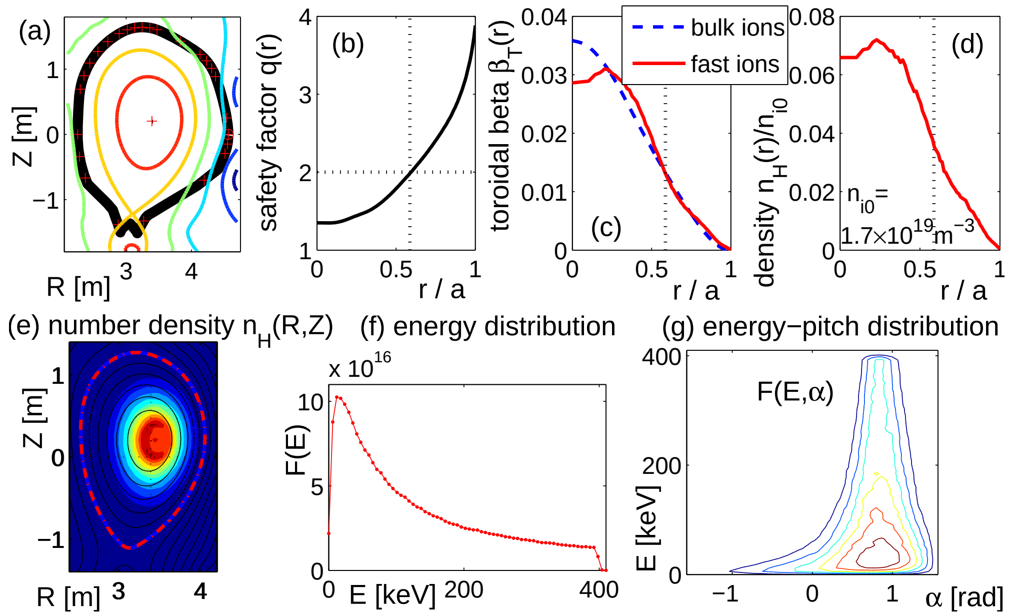

FIG. 1: JT-60U plasma in shot E039672 before the onset of an ALE. Panel (a) shows shape of magnetic surfaces and the wall, (b-d) the profiles of safety factor, bulk ions and fast ions, and (e-g) the phase-space distribution of fast ions computed by F3D-OFMC.

realistic plasma pressure, and realistic fast ion distribution functions. The relevance of these extensions is examined quantitatively with global nonlinear simulations using the hybrid code MEGA [7], which solves full MHD equations for the bulk plasma and drift-kinetic equations for the energetic particles (E.P.). The plasma profiles were chosen such that the continuous shear Alfvén wave spectrum and the fast ion distribution are similar to those before the onset of an ALE in JT-60U shot E039672 at about 4s. Figure 1 shows the plasma shape and profiles in this scenario. Although the trigger mechanism for ALE is not yet known, the experimental observations allow us to assume that an "excessive" amount of fast ions has been accumulated and an unstable EPM is (somehow) released.

Consistently with earlier simulations carried out by Briguglio *et al.* [5], we observe an unstable EPM with a mode structure and frequency that agree with experimental results. We find that the mode structure and frequency are very robust and insensitive to geometry and bulk pressure effects. This EPM remains dominant even when an isotropic fast ion distribution is used instead of a beam-like distribution. On the other hand, the growth rates and mode amplitude vary significantly when the model is altered. The mode amplitude plays an important role in the redistribution of fast ions. The results obtained so far show that the relation between amplitude and transport is not straightforward [6]. This is a problem of practical relevance and a subject of ongoing research.

In addition, we present first results of MEGA simulations initialized with a distribution function computed by an orbit-following Monte-Carlo code, F3D-OFMC [8], for JT-60U. This new capability constitutes a major step forward towards predictive simulation and integrated multi-time-scale modeling of energetic ion dynamics.

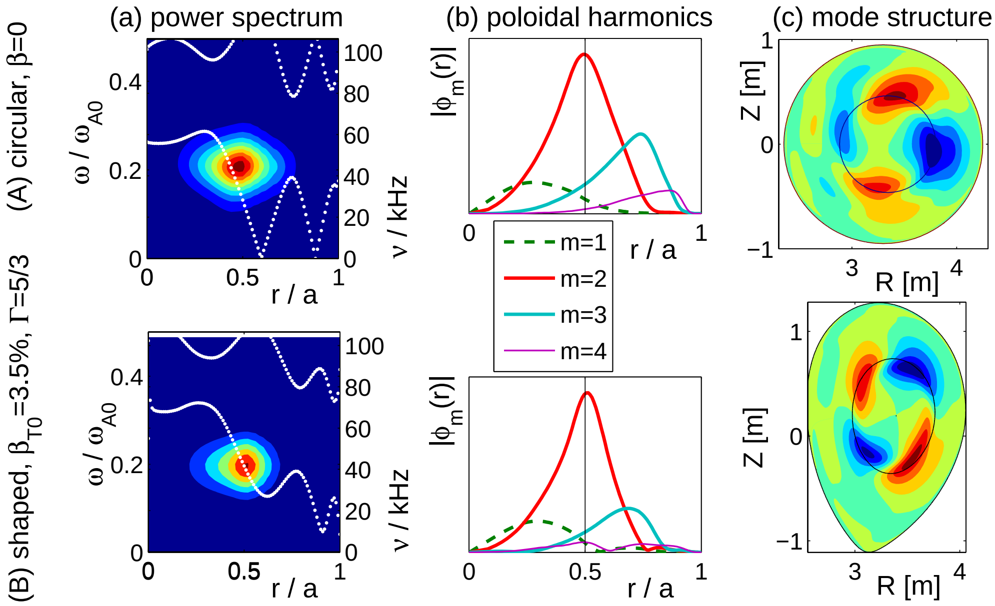

FIG. 2: Frequency ω (a) and mode structure ϕ (b,c) of EPM in the ALE scenario. Results are shown for two representations of the MHD equilibrium and bulk plasma response: (A) shifted-circle equilibrium with zero beta; (B) realistically shaped equilibrium with realistic pressure ($\beta_{\mathrm{T0}} = 3.5\%$ on-axis) and compressibility parameter $\Gamma = 5/3$ (adiabatic constant). The white dotted lines in column (a) are continuous shear Alfvén spectra $\omega_{\mathrm{A}}(r)$.

2 Simulation with realistic plasma shape & pressure

In Ref. [6], we have compared results obtained with circular and realistically shaped plasma, with and without bulk pressure, and for different values of the adiabatic constant Γ, which controls how compressibility affects the stability and dynamics of MHD modes.

The linear mode structure and frequency were found to be rather robust and varied little between the different cases inspected. Results for two cases are summarized in Fig. 2. The normalized frequency is $\omega/\omega_{\mathrm{A0}} \approx 0.2$, which corresponds to about 40 kHz and matches the local continuum frequency (a). The fluctuations with toroidal mode number $n = 1$ have a dominant poloidal harmonic $m = 2$ and peak in a region with steep fast ion density gradient (b,c). This is in agreement with experimental observations [3].

The growth rates, nonlinear mode amplitudes and the evolution of the fast ion distribution are found to vary significantly, depending on the magnetic geometry and bulk plasma response. This is shown in Fig. 3 for the same two cases as in Fig. 2. The growth rate in the shaped case with $\beta_{\mathrm{T0}} = 3.5\%$ is $\gamma/\omega_{\mathrm{A0}} = 0.041$, and thus more than a factor 2 lower than in the circular case with zero beta, where $\gamma/\omega_{\mathrm{A0}} = 0.083$. The peak amplitude of the $n = 1$ fluctuations is also reduced by a factor 2.5 (a). The same counts for the loss of energetic ions from the central region of the plasma during the first peak of mode activity (until $t\omega_{\mathrm{A0}} = 50$): the central fast ion density drops by about 10% in the circular case, but only 5% in the shaped case (c). However, 200 Alfvén times later ($t\omega_{\mathrm{A0}} = 250$),

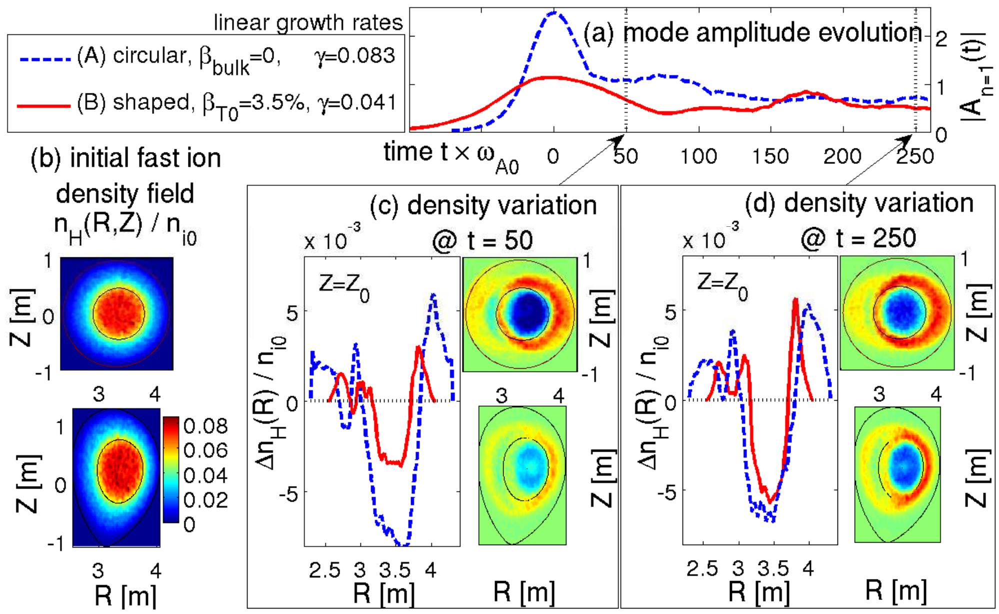

FIG. 3: Temporal evolution of $n = 1$ mode amplitude A (a) and fast ion density $n_{\rm H}$ (c,d) in the two cases (A) and (B) from Fig. 2. Growth rates $\gamma/\omega_{\rm A0}$ are given in the legend. The initial density fields are plotted in column (b). Columns (c) and (d) show snapshots of the density variation $\Delta n_{\rm H}(t) = n_{\rm H}(t) - n_{\rm H}({\rm initial})$ after the first peak of mode activity ($t\omega_{\rm A0} = 50$) and in the relaxed state ($t\omega_{\rm A0} = 250$).

the reduction of the central fast ion density compared to its initial value (b) settles around 7% in both cases (d). Thus, as far as the density profile of fast ions is concerned, the two cases predict a similar amount of transport despite significantly different mode stability properties and amplitudes. It will be interesting to analyze the fast ion dynamics in more detail by looking at the evolution of the distribution function at different energies.

3 Modeling of the E.P. distribution function

In the local limit, the fast ion slowing-down distribution is modeled semi-analytically [5]:

$$F_{\rm loc}(r, E, \alpha) = n_{\rm H}(r) \frac{\exp[-(\sin\alpha - \sin\alpha_0)^2/2\sigma_\alpha^2]}{[E^{3/2} + E_{\rm c}(r)^{3/2}] \ln|1 + E_0/E_{\rm c}(r)]^{3/2}|}; \qquad (1)$$

where $E = mv^2/2$ is the kinetic energy, $\alpha = \sin^{-1}(v_\parallel/v)$ the pitch angle, and E_0 the birth energy. The density profile $n_{\rm H}(r)$ [cf. Fig. 1(d)] and critical energy profile $E_{\rm c}(r)$ are given in numerical form as functions of volume-averaged minor radius $r(\Psi)$, with Ψ being the magnetic flux. Both radial profiles are based on experimental measurements. For simplicity, the results in Section 2 were obtained with an isotropic distribution ($1/\sigma_\alpha = 0$).

The distribution function in JT-60U is predicted by to be strongly anisotropic as shown in Fig. 1(g). The pitch-angle-dependence of the high-energy tail is approximated by the central pitch angle and half-width $\alpha_0 \pm \sigma_\alpha \approx 0.9 \pm 0.1$. Furthermore, we replace $\sin\alpha = v_\parallel/v$ by the variable $\sin\alpha_{\rm c} = u_{\rm c}/v \equiv \mathrm{sign}(v_\parallel) \times \sqrt{1 - \mu B_{\rm min}/E}$, which is a constant of unperturbed motion for passing particles. Similarly, we replace Ψ in the spatial profiles by the variable $\Psi_{\rm c} = P_\varphi/e - mR_0 u_{\rm c}/e$. This turns the function in Eq. (1) into a (approximate) equilibrium distribution, $F_{\rm loc}(\Psi, E, \alpha) \rightarrow F_{\rm model}(\Psi_{\rm c}, E, \alpha_{\rm c}, \mathrm{sign}(v_\parallel))$.

Figure 4 shows that the dominant instability is the same in the isotropic and anisotropic case: as can be inferred from the power spectra (A-c) and (B-c), the mode frequency is $\omega/\omega_{\rm A0} \sim 0.2$ and the mode peaks around $r/a \approx 0.45$ in both cases. The growth rates in the isotropic and anisotropic case are $\gamma/\omega_{\rm A0} = 0.044$ and $\gamma/\omega_{\rm A0} = 0.096$, respectively. The difference can be attributed to the difference in the pressure of resonant particles, since the total fast ion pressure is fixed (here $\beta_{\rm H0} = 3\%$ on axis). The finding that strong anisotropy is not essential for the excitation of EPM in an ALE scenario implies that ALE may also be driven by isotropically distributed alpha particles. Therefore, these relaxation events may play an important role for in the dynamics of the alpha particles in burning plasmas, such as ITER and DEMO.

Previous theoretical and numerical studies have shown that EPM are sensitive to the spatial distribution of fast ions; for instance, see Ref. [9]. For this reason, the density profile $n_{\rm H}(r)$ in Eq. (1) is given in numerical form in order to obtain a distribution function with a density moment that matches experimental data as closely as possible. However, this carefully set-up fast ion density field is modified in a complicated (velocity-dependent) way during the initial phase of a simulation, because in MEGA particles that cross the last closed flux surface are currently being discarded (prompt losses). In reality many of these particles will return to the plasma after traveling through the vacuum region [the space between orange and black curves in Fig. 1(a)]. In the present ALE scenario for JT-60U shot E039672, about 5–10% of the particles originating from the two tangential neutral beams fall in this category.

We have analyzed the role of these particles on EPM stability by running MEGA with the full-f scheme and using the shifted-circle model equilibrium, where all escaping simulation particles can simply be reinjected by reversing the sign of the vertical coordinate Z. Column (C) in Fig. 4 shows the results obtained with the anisotropic model distribution function when escaping particles are reinjected. It can be seen that reinjection reduces the growth rate by 20%, whereas the mode's frequency and radial location are not altered significantly. We assert that this difference in the growth rates is due to the steepening of the spatial gradients caused by discarding particles that traverse the vacuum region. Therefore, predictive simulations for plasmas with dimensions as in present-day tokamaks should consider the vacuum region even for core-localized modes as the EPM studied here. In larger devices, such as ITER, the effect may be weaker.

4 Generalized distribution function by OFMC code

Analytical and semi-analytical models as in Eq. (1) can capture key features of the real fast ion distribution function, but the detailed structure may be difficult to reproduce. In particular, the spatial gradients may be difficult to model when they depend on the

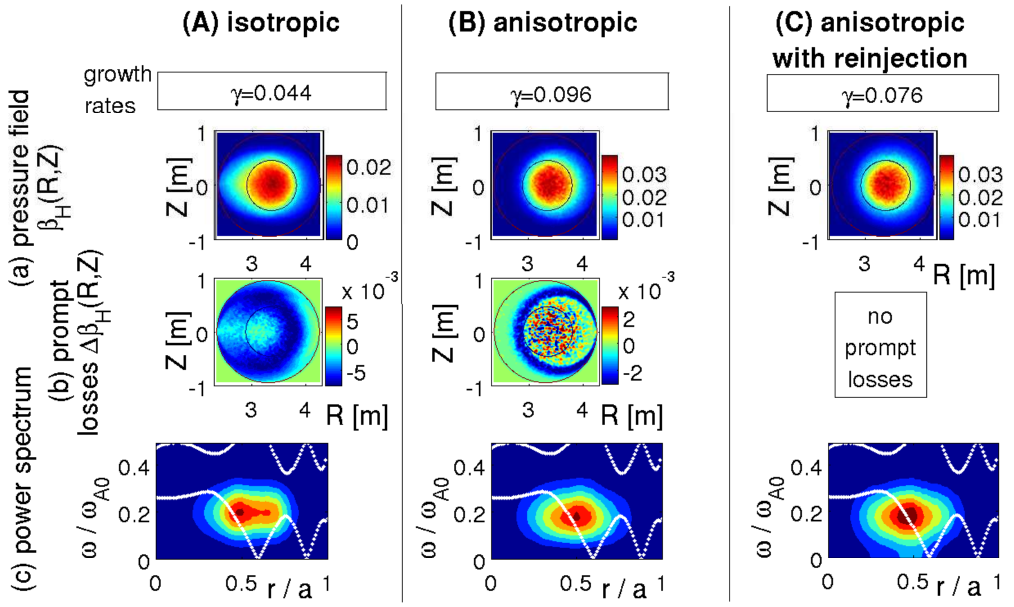

FIG. 4: EPM stability with (A) isotropic and (B) anisotropic fast ion distribution. Column (C) shows results for the anisotropic case with reinjection of escaping particles. The fast ion beta fields $\beta_{\rm H0}$ are plotted in row (a). Row (b) shows the prompt losses $\Delta\beta_{\rm H0}$ in the cases where escaping particles are discarded (A,B). The linear mode structures and frequencies can be inferred from the power spectra in row (c).

particle energy and pitch angle — not only via the toroidal canonical momentum P_φ, but also due to spatially varying collisionality and due to boundary effects (cf. Section 3). Modeling the anisotropy of the distribution is also challenging without using $\text{sign}(v_\parallel)$, which is not a constant of motion of trapped particles. Given these difficulties, and motivated by the goal to carry our predictive simulations, we have developed an interface that allows to initialize MEGA with distributions computed by the orbit-following Monte-Carlo code F3D-OFMC [8]. F3D-OFMC computes a steady-state distribution function taking into account realistic particle source geometry, collisional slowing-down processes, and the presence of a vacuum region between plasma and wall.

First results obtained with the novel method are presented in Fig. 5. In (a) it can be seen that the early evolution ($t\omega_{\rm A0} \lesssim -50$) is dominated by noise, in particular, near the magnetic axis. Once the signal-to-noise ratio is large enough, the linear eigenmode appears ($-50 \lesssim t\omega_{\rm A0} < 0$). Panels (b) and (c) show that this EPM has a mode structure and frequency similar to those obtained using analytical models for the initial distribution (cf. Sections 2 and 3). The results are still preliminary, but it seems that $F_{\rm ofmc}$ yields a higher growth rate and saturation amplitude than $F_{\rm model}$. In fact, $F_{\rm model}$ was designed to match the flux-surface-averaged fast ion density profile in Fig. 1(d), but the density field is not a function of flux as can be seen in Fig. 1(e). Such problems are avoided by using $F_{\rm ofmc}$, which may make this new method preferable for quantitative studies.

Based on our prior experience with full-f simulations, we consider the noise level in

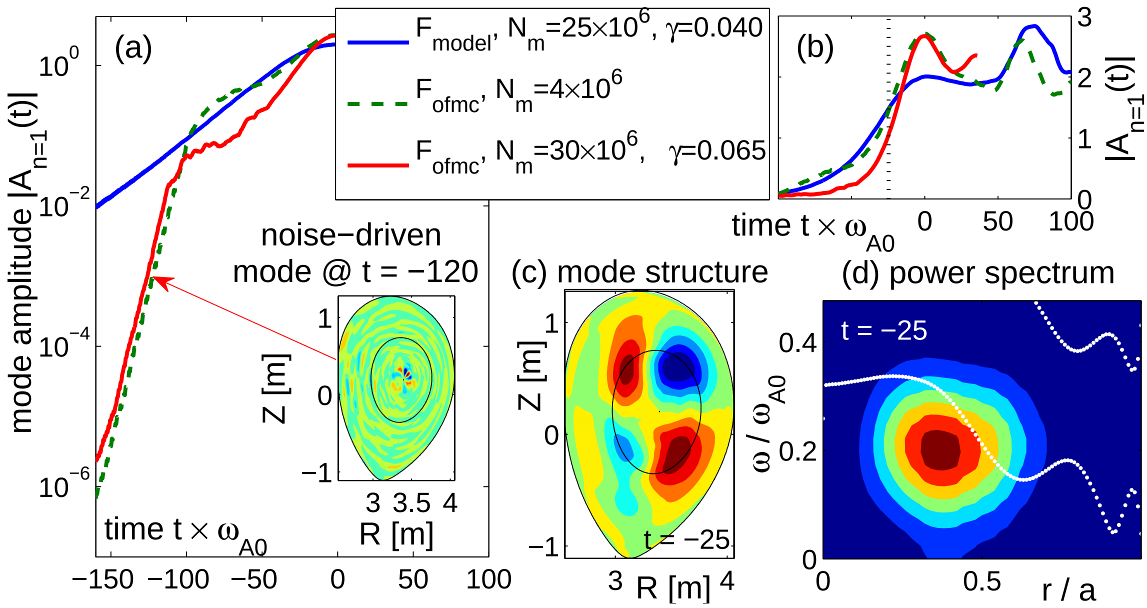

FIG. 5: First results obtained by initializing MEGA with a fast ion distribution computed by F3D-OFMC for the ALE scenario in JT-60U shot E039672. Panels (a,b) show the evolution of mode amplitude on logarithmic and linear scales. Results obtained with $F_{\rm ofmc}$ represented by $N_{\rm m} = 4 \times 10^6$ and 30×10^6 particles are plotted together with the result for an analytical model distribution $F_{\rm model}$ represented by 25×10^6 particles. Panels (c) and (d) show the linear mode structure and power spectrum of the physical mode. The mode structure during the noise-driven phase ($t\omega_{\rm A0} \lesssim -50$) is shown as an inset in panel (a).

these preliminary simulations to be unusually high for the large number of particles (up to $N_{\rm m} = 30 \times 10^6$) used to represent $F_{\rm ofmc}$. In particular, this is surprising since we have employed an orbit-based particle loading scheme [10], which was found to reduce noise effects when $F_{\rm model}$ is used. As the snapshot of the mode structure taken during the noise-driven phase in indicates [inset in (a)], there may be a problem near the magnetic axis. The radial structure of the power spectrum in Fig. 5(d) may still be affected by this, since it is obtained by Fourier transforming a time window of size $\Delta t\omega_{\rm A0} = 50$. We are now in the process of tackling these remaining numerical problems.

5 Conclusion

This paper summarizes recent progress made with the implementation of increasingly realistic models of a tokamak plasma for the numerical study and predictive simulation of interactions between energetic ions and shear Alfvén waves. Considering the particular case of Abrupt Large Events (ALE) in JT-60U shot E039672, we have simulated the dynamics of energetic particle modes (EPM) and analyzed their linear stability, nonlinear fluctuation level, and the resulting fast ion transport. The following points were addressed:

1. realistic plasma shape vs. shifted-circle model equilibrium,
2. realistic plasma beta vs. zero beta,
3. isotropic vs. anisotropic slowing-down distribution function,
4. role of particles with orbits passing through the vacuum region,
5. model distribution function vs. generalized distribution by an OFMC code.

The comparisons made show how the results are affected by the various improvements made with respect to realistic modeling of the JT-60U plasma. The relevance of the extensions was discussed. Here, we may add that the new interface between the codes F3D-OFMC and MEGA allows us to commence with the integrated modeling of energetic particle dynamics on multiple time scales, ranging from wave-particle interactions (μs $\sim$ ms) to collisional slowing-down (ms $\sim$ s). Once the methods and tools have been verified against experiments such as JT-60U, they may be used to make predictions for future machines, such as JT-60SA, ITER and DEMO.

Open issues with regard to modeling and physics that are directly related to the present work, but were not addressed or resolved yet, include (i) the self-consistent computation of an MHD equilibrium including the fast ion contribution, (ii) the physical trigger mechanism causing the onset of ALE, and (iii) the effect of ALE on the bulk plasma.

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