COMPREHENSIVE SIMULATIONS OF BURSTING AND NON-BURSTING ALFVÉN WAVES IN ICRF HEATED TOKAMAK PLASMAS

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Recurrent bursting Alfvénic instabilities can drastically degrade plasma confinement. Unlike beam-driven shear Alfvén waves (SAWs), which often exhibit bursting behavior [1], SAWs during ion cyclotron resonance frequency heating (ICRH) typically maintain steady amplitudes [2,3], despite theoretical predictions suggesting the possibility of a bursting state [4]. This work reports the first comprehensive simulations of ICRH-driven tokamak plasmas on the slowing-down time scale, where SAW-induced fast-ion transport is self-consistently included during the high-energy tail formation. Bursting toroidal Alfvén eigenmodes (TAEs) are observed in both multi-n and single-n simulations of plasmas with a relatively low magnetic field (1.5T) and an ICRF resonance layer located at the magnetic axis or on the inboard side, while outboard heating always leads to non-bursting TAEs, where n is the toroidal mode number. The maximum fast ion beta in the non-bursting case reaches almost double that of the busting one. A stronger magnetic field can avoid the bursting of ICRF-induced TAEs regardless of the RF power. These results indicate that RF layer position and magnetic field strength play a decisive role in the occurrence of bursting TAEs, outweighing factors like multi-n interactions [5] and RF power. Moreover, the strong effect of ICRF-driven velocity space diffusion in preventing bursting TAEs identified in this work opens a new avenue for bursting-AE control in burning plasmas through fast-ion phase space engineering via RF wave.

An extended kinetic-MHD hybrid code MEGA with ICRH is used. Previously, the extended code has successfully predicted ICRF-induced SAWs in the LHD [6]. A so-called multi-phase simulation [7] is employed to save computational resources, where a classical simulation (MHD solver off) and a hybrid simulation (MHD solver on) are executed alternately until a steady state, followed by a continuous hybrid simulation till the end. A deuterium plasma with a minority hydrogen ratio 4% is adopted. The major and minor radii are 2.6m and 0.9m, respectively. The central electron density and temperature are $3.0 \times 10^{19}\mathrm{m}^{-3}$ and 8.0keV, respectively. The shape of the outermost magnetic surface is circular. The absorbed RF power is 6MW.

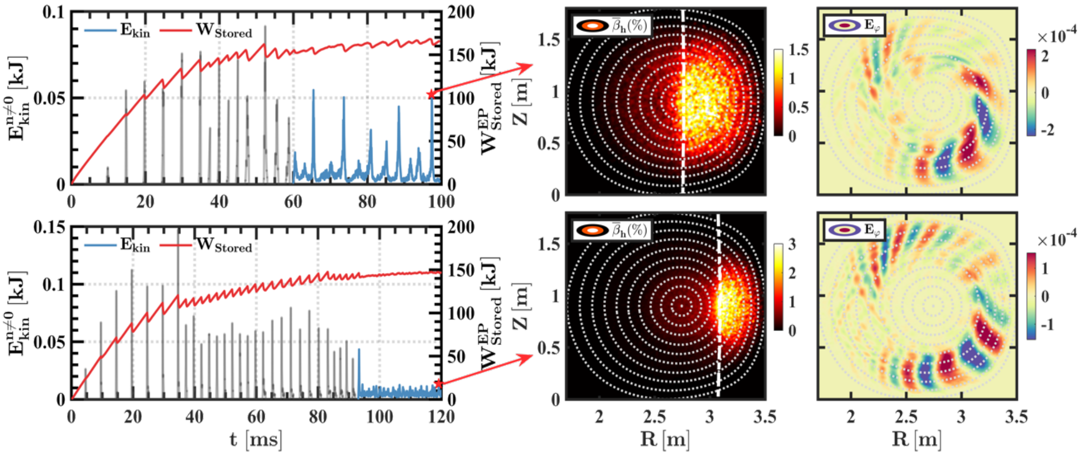

FIG. 1: Multi-phase simulations of ICRF-induced bursting (top) and non-bursting (bottom) events with a toroidal field of $B_0 = 1.5T$. (Top) ICRF Resonance layer is located at the magnetic axis. (Bottom) ICRF Resonance layer is located at $\rho/a = 0.4$ of the outer equatorial plane. The middle and right panels show the minority hydrogen beta and mode structure at the selected moment, respectively. Kinetic energy evolutions with grey curves represent the phase with alternate classical and hybrid simulations, while the curves in blue indicate continuous hybrid simulations.

Fig. 1 shows the bursting and non-bursting ICRF-induced TAEs in a plasma with $\mathrm{B}_0 = 1.5\mathrm{T}$. The bursting mode is observed during the continuous hybrid simulation phase when the ICRF resonance layer is moved from the outboard side to the magnetic axis or inboard side. In these simulations, dominant harmonics with $n \leq 8$

are retained. It should be noted that ICRF-induced bursting TAEs can even be reproduced by considering only a single toroidal harmonic, which is different from the beam-induced abrupt large bursting mode, where a synergy of multi-*n* modes is essential [5]. The significant redistribution of minority ions, deviating from the RF resonance layer, is noticed in both cases, indicating the necessity of including AE-induced transport in evaluating ICRH. A much higher minority ion beta peak value is achieved in the non-bursting case, but the total stored minority ion energy is comparable in these two cases. Both bursting and non-bursting modes show a similar mode structure in the poloidal plane. The spatial profiles and the frequency spectra for the decomposed toroidal harmonics help to clarify the triggering mechanism of the busting ICRF-induced TAEs, as shown in Fig. 2. During the interval of two burst events, a series of discrete TAEs for each toroidal harmonic is formed. Discrete TAEs in the outer region of each series are destabilized by a similar group of minority ions transported from the core region, forming a staircase-like structure in phase space. The free energy is accumulated in each discrete phase space region. The broadening and overlap of discrete structures trigger the avalanche. When it comes to the non-bursting case, a considerable amount of minority ions remains in the region with strong velocity diffusion by RF wave and destabilize a mode with a broad coherent structure. Such a long-lived low-amplitude mode helps to avoid the accumulation of free energy in discrete phase space and the subsequent overlap, but leads to a continuous minority ion redistribution. The averaged loss powers in busting and non-bursting cases are comparable.

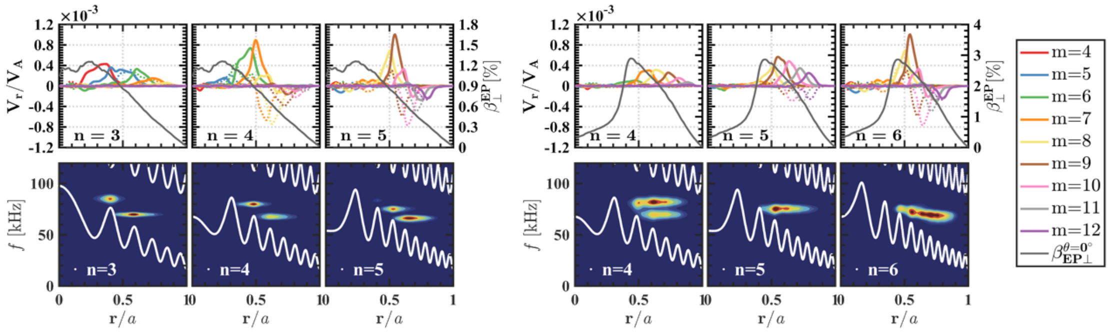

FIG. 2: Spatial profiles and frequency spectra for bursting (left) and non-bursting (right) events shown in Figure 1.

Fig. 3 shows multi-phase simulations of ICRH in a plasma with a higher field $B_0 = 3.0$T, where only non-bursting modes are observed. TAEs during on-axis heating remain non-bursting even at a high RF power of 18MW. The results are consistent with JET experiments from earlier years, where TAE remained non-bursting under a high ICRH power (>10MW) for a plasma with $B_0 = 3.45$T [8]. One of the reasons is that minority ion radial transport is significantly weakened. The transported minority ions are unable to stay sufficiently far away from the resonance layer to form a series of discrete structures and preserve the coherence against collisions over a wide spatial region. Most present-day tokamaks conducted minority ion heating in similar field strengths and only non-bursting modes were observed in experiments.

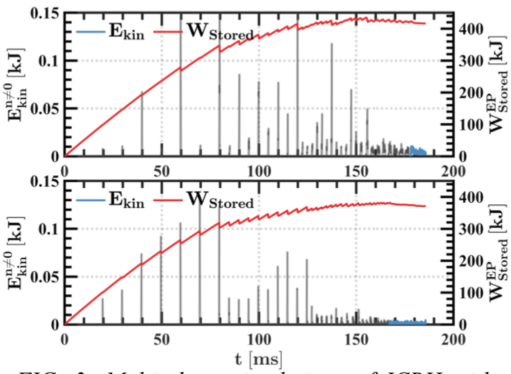

FIG. 3: Multi-phase simulations of ICRH with $B_0 = 3.0T$. ICRF Resonance layers are located at the magnetic axis (top) and at $\rho/a = 0.4$ of the outer equatorial plane (bottom), respectively.

To conclude, state-of-the-art hybrid particle-in-cell simulations of ICRF-induced TAEs in tokamak plasmas were conducted, showing under what conditions TAEs can be bursting or not. The formation of discrete but coherent structures in phase space plays a pivotal role in triggering the bursting TAE by ICRH. The strong effect of ICRF-driven velocity space diffusion in preventing bursting TAEs is identified.

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