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Numerical study of helium ash and fast particle dynamics in a sawtoothing tokamak plasma

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We study the effect of a sawtooth crash on the dynamics of MeV-class fast deuterons, as produced by ion cyclotron heating, and alpha particles in the energy range 35-3500 keV, resembling helium ash and newly-born fusion alphas. The simulations are performed using the hybrid code MEGA [1], which solves visco-resistive MHD equations for the bulk plasma and drift-kinetic equations with gyroaveraging [2] for fast ions.

The internal disruption is simulated in a scenario resembling a tokamak plasma in the Joint European Torus (JET) with strong central heating as realized with 3-ion RF heating schemes [3]. The domain size and time scale of the crash match observations. Meanwhile, the profile of the safety factor q is chosen to be fairly flat as considered for ITER steady-state scenarios, with the on-axis q value lying only slightly below unity.

Both current and pressure gradients play a role, so that the phenomenology of the internal disruption is sensitive to simulation parameters. When pressure effects dominate (e.g., for lower resistivity or higher beta), the dominant toroidal mode number n can have values of 2 or greater. We focused primarily on cases where the n=1 component is dominant. Our two main results may be summarized as follows:

1. Although linear stabilization of the internal disruption could not be simulated with our model due to resistivity and pressure effects [4], we observe that reconnection of the plasma core saturates prematurely in the nonlinear regime when MeV-class deuterons are present and interact with the MHD modes. The island seen in magnetic Poincare plots is distorted into a tear-drop shape. This result suggests that nonlinear effects should be taken into account when interpreting delayed sawtooth crashes or monster sawteeth in experiments.
2. Mono-energetic, nearly isotropic alpha particles with energies 35 keV, 350 keV or 3.5 MeV are modeled as passive tracers and followed during an n=1 sawtooth crash lasting less than 0.5 ms. The initial peak of the alpha particle density profile is localized in the disrupting domain. While the 35 keV profile flattens, the 3.5 MeV profile undergoes relatively little change. Mass and velocity scans reveal that the better confinement of fast alphas can be explained as a synergy of four factors: (i) high transit frequency, (ii) field and orbit helicities close to unity, (iii) large magnetic drifts, and (iv) rapidity of the crash. While slow alphas are displaced by the electric drifts like an MHD fluid, the parallel speed and magnetic drifts of fast alphas are sufficiently large to compensate the displacement. This finding motivates the use of moderate sawtooth activity in a fusion reactor to remove helium ash without compromising fast alpha confinement [5].

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[4] Bondeson *et al.*, *Phys. Fluids B* **4** (1992) 1889.
[5] Bierwage *et al.*, *submitted to Phys. Rev. Lett.* (2021). Preprint: http://arxiv.org/abs/2109.03427.

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