FAST ION TRANSPORT INDUCED BY EDGE LOCALIZED MODES

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The high confinement mode (H-mode) [1] is the preferred operational scenario for next-generation tokamak fusion devices, such as ITER [2]. This mode is characterized by the formation of a narrow transport barrier at the plasma edge, creating a pressure pedestal. Due to the steep pressure gradient at this pedestal, H-mode is typically associated with burst-like edge perturbations known as edge localized modes (ELMs) [1, 3, 4]. These recurring bursts can lead to a rapid expulsion of stored plasma energy towards plasma-facing components, resulting in unwanted material erosion and surface melting [5]. Therefore, understanding the interactions between ELMs and charged particles, along with the related transport processes, is essential for optimizing fusion performance. Meanwhile, confining fast ions presents a significant challenge for self-sustaining tokamak reactors, as successful ignition depends on the self-heating effect from fusion-generated alpha particles. While previous studies have extensively investigated the role of Alfvénic fluctuations in fast ion transport [6], the influence of ELM fluctuations on this transport mechanism is also critical. However, the key characteristics and underlying physical mechanisms of ELM-induced fast ion transport remain to be elucidated.

Recent experiments at the ASDEX-Upgrade (AUG) tokamak have reported an unusual acceleration phenomenon of fast ions during type-I edge localized modes (ELMs) [7, 8]. Direct velocity-space measurements from the fast-ion loss detector (FILD) have detected a population of fast ions with energies around 160 keV, significantly exceeding the typical energy of neutral beam-injected (NBI) deuterium ions, which is 82 keV. This phenomenon is reproducible and shows a strong correlation with NBI heating and the occurrence of ELMs. The acceleration occurs on a timescale of approximately 10 to 100 μs during an ELM crash and disappears in the ELM-suppressed phase. The high-energy tail is observed for both circulating and trapped fast ions; however, the FILD signal for trapped particles is noticeably weaker than that for circulating particles. Additionally, the high-energy signature of circulating fast ions displays distinct pitch angle structures, characterized by multiple 'spikes' in the FILD signal that vary with the safety factor q_{95}. In contrast, the high-energy component of trapped particles only shows a single spike in the FILD signal, which remains constant regardless of q_{95}. Here, q_{95} refers to the safety factor at 95% of the plasma minor radius.

Simulation results suggest that the parallel electric field may account for the observed energy gain in fast ions, assuming magnetic reconnection occurs during ELMs [7, 8]. However, this hypothesis presents several challenges: (i) it relies on a significant parallel electric field amplitude, which is contingent on previous simulations that link its strength to the magnitude of artificial hyper-resistivity [9]; (ii) it accelerates charged particles solely in the parallel direction, while experimental observations indicate minimal changes in fast ion pitch angle; and (iii) if present, the parallel electric field would be highly localized around a thin current sheet, whose width is considerably smaller than the fast ion gyroradius [10]. Consequently, such fine-scale fluctuations experienced by a fast ion would be effectively averaged out due to the finite Larmor radius (FLR) effect.

In this study, we present a gyrokinetic analysis of the phase space transport of fast ions influenced by ELM fluctuations. Unlike previous simulations [7, 8], our results indicate that the high-energy fast ion population, as observed through intra-ELM velocity space measurements of fast-ion losses in the AUG tokamak, cannot be accelerated by low-frequency ELM fluctuations. From a Hamiltonian perspective, effective acceleration of fast ions necessitates mechanisms involving high-frequency and/or high-amplitude fluctuations, which require comprehensive 6D orbit modelling—beyond the intended scope of this gyrokinetic analysis. Instead, low-frequency ELM fluctuations primarily facilitate the radial transport of fast ions through magnetic perturbations.

In contrast to fast ion transport driven by microturbulence, our findings show that fast ion diffusivity scales with the cube and square of the energies of circulating and trapped particles, respectively. As a result, higher-energy fast ions are expelled outward more rapidly by ELMs, producing a distinct FILD signal in the high-energy tail. The theoretical estimates for cross-field diffusion time align reasonably well with experimental data. Furthermore, the fine pitch angle structures observed in the FILD signals—specifically, the spikes—are linked to the presence of multiple phase space islands for circulating particles and can be adjusted by the safety factor through resonance conditions. Additionally, due to the effects of finite drift orbit width and precessional resonance, the diffusivity of trapped particles is generally lower than that of circulating particles, leading to a less pronounced FILD signal. These observations are consistent with prior experimental findings [7, 8].

Finally, we note that these results have significant implications for the performance of future tokamak fusion reactors. While the high confinement mode is the designated operational scenario for ITER [2], our analysis highlights potential concerns regarding the adverse effects of ELMs on the self-sustainment of fusion reactions, particularly due to their preferential transport of high-energy alpha particles. The resultant heat loads may also impose stringent material constraints on plasma-facing components.

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