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FAST ION TRANSPORT INDUCED BY EDGE LOCALIZED MODES

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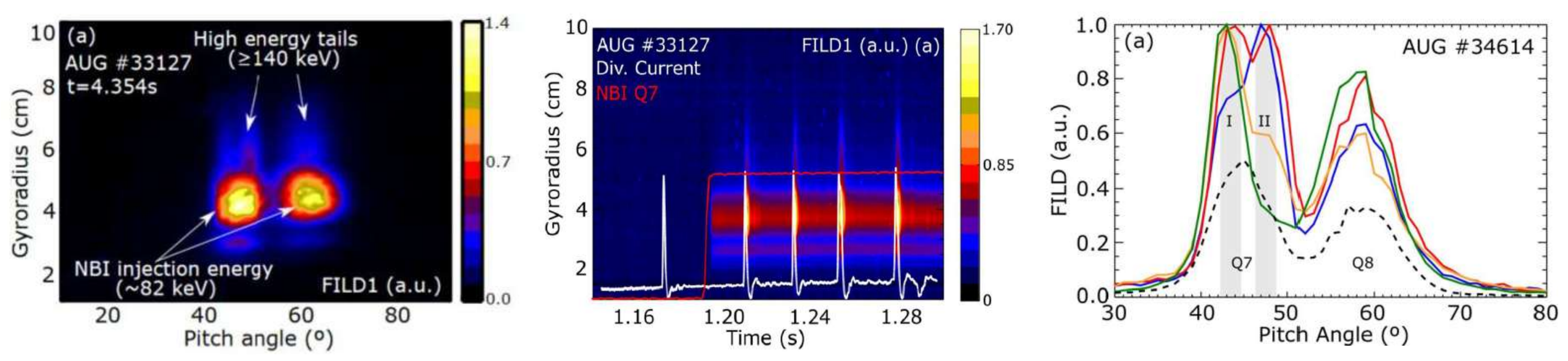
Abstract

- Fast ions exhibit a notable acceleration during edge localized modes (ELMs) in tokamak devices.
- This paper presents an analytical investigation into the phase-space transport of fast ions driven by ELMs.
- Contrary to previous simulation results, it is shown that ELMs with low-frequency characteristics are inefficient at accelerating fast ions.
- Instead, the transport of fast ions is dominated by radial particle transport, resulting from the exchange of canonical toroidal angular momentum.
- The associated diffusivity increases sharply for high-energy particles, making fast-ion loss measurements in velocity space appear as an acceleration process

Background

- Velocity space measurements of fast-ion losses reveal a population at energies well above the main NBI injection energy during ELMs [Galdon-Quiroga PRL, 2018;NF, 2019].
- Two populations can be observed at two main different pitch angles of π/4 (Q7,passing) and π/3 (Q8, trapped).
- NBI injects neutrals at three different energies E0 = 82keV , E0/2 and E0/3.
- The observation of high-energy tail is reproducible and well correlated with the NBI heating and the occurrence of ELMs.
- High-energy population exhibits a pitch angle structure ('spikes') that depends on the beam source and q.



Methods

Gyrokinetic Model

- The gyrocenter Hamiltonian in 5D phase space

$$H(\mathbf{X},\mu,w,t,\tau)=\mu B+\frac{w^2}{2}+\frac{e}{m}(\langle\delta\phi\rangle-\frac{w}{c}\langle\delta A_\parallel\rangle+\frac{v_\perp\rho}{c}\langle\delta B_\parallel\rangle_*).$$

Fluctuations

- During the ELM crash a broad spread in frequency is generally measured in AUG butlow frequencies ω ~ 10kHz are dominant, with n~5 and $\delta B_\perp/B \sim O(10^{-3})$.
- The inter-ELM modes in a high frequency range ω ~ 100kHz appears in the linear and early nonlinear phases, with n ~ 10 and $\delta B_\perp/B \sim O(10^{-5} - 10^{-4})$.
- Therefore, the perpendicular magnetic perturbation dominates the perturbed Hamiltonian of fast ions.

Fast Ion Acceleration

- An estimate for the time required for the particle acceleration

$$\Delta t\sim\frac{H_0}{\omega\delta H}\sim\frac{k_\perp\rho_0}{\omega}\frac{B_0}{\langle\delta B_\perp\rangle}$$

- Substituting into parameters of low-n modes and inter-ELM modes, respectively, one can estimate the required time as

$$\Delta t_{low}\sim\mathcal{O}(10^3)/\omega_{low}\sim 1s,\quad \Delta t_{int}\sim\mathcal{O}(10^4-10^5)/\omega_{int}\sim 1-10s.$$

- one concludes that both the inter-ELM modes and the dominant low-n modes cannot account for the observed fast ion 'acceleration' on ~ 100μs.
- Fast-ion is not accelerated by ELMs.

Lagrangian Perspective

Wave-Particle Resonance

- Near a single island, the maximum energy exchange is $\delta E=\frac{2\omega_n H_{m,l}}{\omega_B}$
- The maximum canonical momentum exchange, meanwhile, is $\delta P_\zeta=\frac{2nH_{m,l}}{\omega_B}$
- Qualitatively, for both the low-n modes and inter-ELM modes during ELM crash, the canonical momentum exchange dominates the transport.

Lagrangian Perspective

Fluctuations

An arbitrary perturbation, say δQ, can be decomposed into the Lagrangian description by introducing the fast (t_0) and slow (t_1) time scales

$$\begin{aligned}\delta Q_n &= e^{-in[\omega_\zeta t_0+\partial_{P_\zeta}\omega_\zeta\int_0^{t_1}\delta P_\zeta dt'+\partial_E\omega_\zeta\int_0^{t_1}\delta E dt']-in\int_0^{t_1}\delta\dot{\zeta}dt'}\\ &\sum_{m,l}e^{i(m\delta_c+l)[\omega_b t_0+\partial_{P_\zeta}\omega_b\int_0^{t_1}\delta P_\zeta dt'+\partial_E\omega_b\int_0^{t_1}\delta E dt']+im\int_0^{t_1}\delta\dot{\theta}dt'}c_{m,l},\end{aligned}$$

where

$$c_{m,l}(E,\mu B_0,P_\zeta,t_1)=\oint\frac{\omega_b dt_0}{2\pi}e^{-il\omega_b t_0-in\tilde{\zeta}+im\tilde{\theta}}A_n(\bar{r}+\underbrace{\tilde{r}+\int_0^{t_1}\delta\dot{r}dt'}_{\text{FDOW}}).$$

- Due to the finite drift orbit width (FDOW) effect, the orbit-averaged fields for trapped particles are typically smaller than those for circulating particles, leading to weaker cross-field transport.
- This is consistent with the experimental observation that trapped particles has a weaker FILD signal.

Eulerian Perspective

Quasilinear Theory

In the linear limit, the gyrokinetic equation can solved as

$$\delta G=i\delta\Phi L^{-1}[\omega\frac{\partial F_0}{\partial E}+n\frac{\partial F_0}{\partial P_\zeta}]$$

where the propagator L accounts for the wave-particle interaction.

- The effective potential

$$\delta\Phi=J_0(\delta\phi-\delta\psi)+J_0\frac{\omega_d\delta\psi}{\omega}+\frac{v_\perp J_1}{k_\perp c}\delta B_\parallel$$

is respectively due to three forces: the parallel electric field which vanishes in the ideal MHD limit; $v_d \times \delta B_\perp$; and the mirror force.

- The explicit quasilinear transport equation

$$\partial_t F_0=\frac{\partial}{\partial\boldsymbol{J}}\cdot[\boldsymbol{D}\cdot\frac{\partial F_0}{\partial\boldsymbol{J}}]$$

- The interaction of fast ions with turbulence is constrained to a two-dimensional J = (P_ζ,E) manifold embedded in the full 6D phase space.
- The associated transport coefficients are defined as

$$D_{P_\zeta P_\zeta}=-\mathrm{Im}[\frac{n^2|\delta\Phi|^2}{L}]\qquad D_{EE}=-\mathrm{Im}[\frac{\omega^2|\delta\Phi|^2}{L}]\qquad D_{P_\zeta E}=D_{EP_\zeta}=-\mathrm{Im}[\frac{n\omega|\delta\Phi|^2}{L}]$$

- In the low-frequency ELM scale, the diffusion will be constrained to a 1D manifold in P_ζ .

'Acceleration'

- For circulating particles, as an example, the radial diffusion coefficient $D_{rr} \propto v^3$ due to $\delta\Phi \propto \omega_d$ and the summation over p.
- In contrast to the microturbulence case [Zhang, PRL, 2009], high energy particles will be transported faster, leading to FILD signals seems like an acceleration process.
- For typical AUG parameters, the required time for cross-field diffusion at edge is on the order of Δt ~ 100μs, consistent with experimental observations.

'Spikes'

- The resonance condition for circulating and trapped particles are, respectively,

$$\begin{aligned}\omega+(m-n\bar{q}+l)\omega_b-n\omega_d &= 0,\\ \omega+l\omega_b-n\omega_d &= 0.\end{aligned}$$

- Note that the circulating particle resonance condition depends on poloidal mode number, spikes correspond to multiple phase space islands for circulating particles.

CONCLUSION

- The ELM crash cannot effectively accelerate fast ions, it induces an efficient radial transport of fast ions with Drr ∝ v3, yielding a strong FILD signal in high energy tail.
- Multiple spikes in pitch angle are due to multiple phase space islands for circulating particles.
- Theoretical predictions agree with the experimental observations:
  - Circulating particles are more easily transported, so the corresponding FILD signal is stronger.
  - The required time for cross-field diffusion process is estimated as t ~ 100μs, consistent with experimental observations.

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