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How fast ions mitigate turbulence and enhance confinement in tokamak fusion plasmas

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Abstract

Along with high temperature and density, magnetic fusion requires good confinement and a degree of transport control for thermal plasmas. Meanwhile, fast ions are generated by the external heating used to raise plasma temperature as well as by the fusion reactions. As a result, the fusion plasmas are effectively rendered into systems with two coexisting populations of main interest — namely the fast ions and the thermal plasma. Interestingly, several recent experiments indicate that the fast ion population can improve the confinement of the thermal plasmas by mitigating turbulence. In this Review, we describe the physical mechanisms which underpin the improved confinement, and discuss recent experimental results in terms of these mechanisms.

Table-of-contents summary

Recent experiments have shown that fast ions generated in fusion plasmas improve confinement by mitigating plasma turbulence. This Technical Review explores possible physical mechanisms to explain these experimental observations.

Key points

- Recent tokamak experiments have shown that fast ions, generated both by external heating used to raise plasma temperature and by fusion reactions, can enhance the confinement of thermal plasmas by mitigating turbulence.
- Fast ions can modify the magnetic field structure, thereby reducing turbulence by decreasing the drive for curvature-type microinstabilities and increasing the E×B flow shear. Confinement improvements observed in hybrid modes in JET and KSTAR are examples of this mechanism.
- Fast ions can lead to thermal ion dilution and changes in the thermal ion density gradient, which have a stabilizing effect on microinstabilities by changing the nonlinear saturation level of microinstabilities and by enhancing zonal flow generation. This mechanism could explain internal transport barrier experiments in KSTAR (FIRE mode), HL-2A, and ASDEX Upgrade with neutral beam injection.
- Fast ions can interact with microinstabilities through wave-particle resonant interactions, extracting energy from the instabilities and thereby weakening their linear drive. The internal transport barrier formation in ASDEX Upgrade (F-ATB) with ion cyclotron resonance heating can be understood through this mechanism.
- Furthermore, fast ions can generate fast-ion-driven instabilities that interact with microturbulence via zonal flows, phase-space coherent structures, and nonlinear mode coupling, leading to turbulence mitigation. This mechanism could explain internal transport barrier formation in DIII-D and EAST, where fast-ion-driven instabilities are present.

[H1] Introduction

A key metric for the fusion performance of tokamaks, in which the fusion plasma is confined by magnetic fields, is the fusion triple product, $nT\tau_E$. This quantity combines plasma density (n), temperature (T), which is a crucial factor in the fusion reaction cross-section, and energy confinement time (τ_E), where τ_E is defined as the ratio of the energy stored in the plasma to the external heating power, in stationary conditions.

One way to increase the fusion triple product is to increase T, which is achieved using external heating schemes such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). These schemes are applied to confined plasmas composed of thermal electrons and ions in local thermodynamic equilibrium with local Maxwellian distributions. They result in steep pressure gradients of plasma in space mainly due to increase of T, which can destabilize drift waves and drive microturbulence. However, this turbulence substantially impairs τ_E.

External heating also leads to the generation of high-energy ions, known as fast ions, which have a mean kinetic energy much greater (tens to hundreds of keV) than the main thermal ions

(~keV), thereby forming a tail of the Maxwellian distribution of thermal ions. Additionally, fusion experiments produce alpha particles with 3.5 MeV of energy, resulting from the deuterium–tritium reaction. In other words, fusion experiments encompass different types of fast ions, each type distinguished by unique energies, densities, and phase-space characteristics. This mixture of different fast ion species is confined in the magnetic fields and heats the plasma, usually via collisions.

Fast ions can also excite various plasma instabilities, such as Alfvénic modes and fishbones, which can detrimentally impact both T and τ_E, and potentially damage the reactor wall. Therefore, fast ions can pose challenges by directly and indirectly degrading τ_E through the excitation of plasma instabilities.

Conversely, work from the past decade indicates that sometimes fast ions can make a large contribution to confinement enhancement, as reviewed in Refs 1 – 2. Experimental observations from various tokamaks have demonstrated confinement enhancement, including the formation and sustainment of what are known as internal transport barriers (ITBs), owing to transport bifurcation under conditions with high populations of fast ions. A transport bifurcation is an abrupt change in the plasma transport when a critical value of a control parameter is exceeded. Typically, the control parameter is external heating power. As one of highlights, FIRE (Fast Ion Regulated Enhancement) mode, recently established in KSTAR[3,4,5], has been maintained for up to 50 s with ITB in the ion energy channel (ion-ITB); NBI in FIRE mode has resulted in ion temperature above 10 keV at the centre. Other experimental examples are: ITB in ASDEX Upgrade with NBI[6] and with ICRH[7]; DIII-D with Alfvénic modes with NBI[8,9]; ITB with fishbones in EAST with NBI[10]; ITB with instabilities in HL-2A with NBI[11]; JET experiments with NBI and ICRH including hybrid mode, a confinement enhanced mode with a flat current density profile at the centre[12, 13,14,15,16,17]; and hybrid mode at KSTAR[18,19,20].

Despite these findings, the underlying physical mechanisms by which fast ions enhance confinement remain an open question. By leveraging the beneficial effects of fast ions, there is potential to improve fusion plasma confinement. Therefore, understanding these mechanisms is important for enhancing fusion performance in future reactors.

In this Review, we discuss confinement improvement due to turbulence reduction by fast ions in tokamak fusion plasmas. This is an important and developing field, since any fusion-dominant plasma, so-called burning plasma, such as in ITER, necessarily contains a substantial population of alpha particles. The scope of this Review is limited, and focused primarily on ion thermal confinement, usually regulated by ion temperature gradient (ITG) turbulence. Rather little is said about electron thermal transport and collisionless trapped electron (CTEM) turbulence, of importance because alphas slow down by collisions with electrons. Other confinement channels are not discussed. We note also that we deal mainly with the range of fast ion energy of 50–150 keV, which is outside the range of fusion-born alpha particles at 3.5 MeV.

Confinement improvement due to fast ions can occur via:

- Improved stability, usually due to fast ion effects reducing or eliminating growth rates of microturbulence;
- Mitigation of turbulence, due to enhanced effectiveness and efficiency of saturation mechanisms induced by the presence of fast ions. Of particular note here is the effect of fast ions on the generation and regulation of sheared zonal flows (ZFs), which govern ITG saturation. ZFs are a natural conduit for the multiscale interaction which can occur in such plasmas;
- Enhanced, usually anomalous, thermal transfer or heating, including what is often referred to as ‘alpha channeling’, the collisionless energy transfer from alpha particles to thermal ions via waves, in a broad sense. This last route to enhanced thermal confinement has not yet been extensively explored.

We first describe possible physical mechanisms of confinement enhancement by fast ions. We then apply these considerations to the experimental observations outlined above, in order to categorize the observations by their dominant mechanisms of confinement enhancement. We also sketch out some near-term future directions of research.

[H1] Physical mechanisms

In this section, the possible physical mechanisms of confinement enhancement by fast ions are addressed in terms of four phenomena: Changes in magnetic field structure induced by fast ions; thermal ion dilution and the associated changes in thermal ion density gradients due to fast ions; resonant interactions between fast ions and microturbulence; and interactions between microturbulence and fast-ion-driven instabilities. Theoretical background and numerical simulation results are described for each physical mechanism.

[H2] Change of magnetic field structure by fast ions

If the population of fast ions is large, their contribution to total plasma pressure can be substantial. In addition to raising the total pressure, fast ions can dramatically modify the radial profile of the ratio of the plasma pressure to the magnetic pressure (β), because in general the fast ions are mostly produced in the deep core region of the plasma.

A direct consequence of this extra pressure source from fast ions is the modification of the magnetic field structure and hence the nested magnetic surfaces. In particular, the centre of flux surfaces is radially displaced outward, a phenomenon known as the Shafranov shift, which is proportional to poloidal beta (β_p), the ratio of the plasma pressure to the poloidal magnetic pressure. The displacement of the centre of flux surfaces increases the ratio of the plasma pressure gradient to the magnetic field pressure gradient, $\alpha = -q^2 R \mathrm{d}\beta/\mathrm{d}r \sim \mathrm{d}\beta_\mathrm{p}/\mathrm{d}r$, where q is the safety factor, number of toroidal transits per poloidal transit, and R the major radius of the tokamak. Increased alpha implies enhanced stability.

The importance of changes in the magnetic surfaces arises because magnetic curvature inherent in tokamaks induces magnetic drift motions of the guiding center of charged particles, called curvature and ∇B drift. High values of α have an important consequence in stabilizing turbulence by reducing these drift motions. It can reduce or even suppress the drive for curvature-type microinstabilities[21,22]. Importantly, it affects turbulence driven at different spatial scales — such as ITG mode, trapped electron mode (TEM) and electron temperature gradient (ETG) mode — which makes it an efficient mechanism to reduce particle and energy transport driven by turbulence.

The modification of the magnetic field structure can also have an impact on other physics mechanisms that reduce turbulence. This is the case of the mean $E\times B$ flow shear ($\omega_{\mathrm{E\times B}}$), which quenches turbulence, as well known from nonlinear theory[23] and numerous experiments[24]. For instance, the Shafranov shift can further increase $\omega_{\mathrm{E\times B}}$ at the low magnetic field side by squeezing the equilibrium magnetic flux surfaces[25]. Its effectiveness is quantified in a general toroidal geometry[26],

$$\omega_{\mathrm{E\times B}} = (RB_{\mathrm{p}})^2/B(\partial/\partial\psi(E_{\mathrm{r}}/RB_{\mathrm{p}})). \quad (1)$$

Here, B_{p} the poloidal magnetic field, B the total magnetic field, ψ is the poloidal flux function designating a minor radius coordinate, and E_{r} the radial electric field. The particular combination $\partial/\partial\psi(E_{\mathrm{r}}/RB_{\mathrm{p}})$ can be understood from the fact that the relevant flow shear expression involves a radial variation of Doppler-shift due to the $E\times B$ flow, $\partial/\partial\psi(\mathbf{k}\cdot\mathbf{u}_E)$, where $\mathbf{k}$ is the wave vector and $\mathbf{u}_E$ is the $E\times B$ velocity. The binormal component of $\mathbf{k}$ is $k_y = lB/RB_p$ with l the toroidal mode number[26]. Equation (1) shows that the magnetic field structure also plays a role in $\omega_{\mathrm{E\times B}}$-induced turbulence stabilization through its dependence on B_{p}. $\omega_{\mathrm{E\times B}}$ should be compared to the decorrelation rate of turbulent eddies[23,26], but is usually compared to the linear growth rate of the microinstability, because that quantity is easier to estimate.

The impact on turbulence by the modification of the magnetic field structure by fast ions has been explored using gyrokinetic simulations[27,28,29,30]. Results show that the impact is twofold. First, the growth rate of turbulence can be lower by a direct impact on the magnetic drifts. Second, the threshold to destabilize fast-ion-driven instabilities can be modified, hence influencing turbulent transport.

[H2] Thermal ion dilution and change in thermal ion density gradient

In conditions of high NBI or ICRH power in low density plasmas, there is a high fraction of fast ions that do not thermalize but rather remain at high energies due to low collisions. The distribution function of the ions is therefore far from Maxwellian, with a ratio of fast ion density to electron density that can reach ~50%. Such conditions are called thermal ion dilution or fast ion dilution.

Fast-ion-induced confinement enhancement has been attributed to thermal ion dilution in some computational studies[6,31]. Note that fusion plasmas should satisfy the quasi-neutrality condition, implying that the negatively charged electrons are almost completely neutralized by the positively charged ions, including thermal, fast and impurity ions.

The thermal ion dilution effects can be classified into at least two levels. First, because the charge density of fast ions contributes to the quasi-neutrality condition, its presence can make the thermal ion charge density profile differ substantially from that of electrons. For instance, the main ion density profile can become hollow at the centre owing to a centrally peaked high population of fast ions. It has been known that such a hollow density profile has stabilizing effects on ITG[32] and its nonlinear saturation level[33], even when the electron density and main ion density are identical. When those are different, the main ion density profile matters more for the ITG stability, and indeed the hollow main ion density profile has been identified as the dominant linear stabilizing effects on ITG from local gyrokinetic analyses[3,34,35].

Second, the dilution can affect the dispersion properties of drift waves, which influence the generation of zonal flows (ZFs), known to stabilize turbulence (Fig. 1). ZFs are generated by energy transfer from drift wave turbulence via the three-wave nonlinear interaction involving two drift waves and ZF, therefore generation of ZF naturally acts to reduce the intensity and level of transport caused by drift wave turbulence[36]. Charged particles can respond to drift waves in different ways depending on the relative magnitude of their speed ($v_{\parallel}$) with respect to the phase velocity of the drift wave ($\omega/k_{\parallel}$) along the magnetic field.

Thermal ions satisfy $v_{\parallel} \ll \omega/k_{\parallel}$, and all respond to waves in a similar fashion. Therefore, a fluid description of them is justified. Conversely, fast ions with $v_{\parallel} \gg \omega/k_{\parallel}$, can respond to a wave almost instantaneously to set up a Boltzmann distribution that corresponds to a quasi-equilibrium, including a slowly evolving wave. This behaviour is called the adiabatic response in plasma physics (although that term has a different meaning in thermodynamics). This condition on the ion speed is satisfied for fast ions in many cases[34,37,38]. However, fast ions can sometimes resonantly interact with drift waves and change stability properties of the drift waves, as discussed below.

Thus, for $T_{\mathrm{f}} \gg T_e$ (where T_{f} is the temperature of fast ions and T_{e} is the electron temperature), fast ions with nearly adiabatic response do not contribute to the dispersion relation of drift waves, whereas thermal ions with fluid-like response do. Consequently, the drift-wave dispersion is modified as[39],

$$\omega = [(1 - f_{\mathrm{h}})\,(L_{\mathrm{ne}}/L_{\mathrm{ni}})\omega_{*\mathrm{e}}]/[1 + (1 - f_{\mathrm{h}})k_{\perp}^{2}\rho_{\mathrm{s}}^{2}], \quad (2)$$

where $f_{\mathrm{h}} = Z_{\mathrm{f}} n_{\mathrm{f0}}/n_{\mathrm{e0}}$ indicates the fast ion fraction with Z_{f} the charge number of fast ions, n_{f0}, n_{e0} and n_{i0} density of fast ions, electrons, and main ions, respectively in the equilibrium state ($n_{\mathrm{e0}} = n_{\mathrm{i0}} + Z_{\mathrm{f}}\, n_{\mathrm{f0}}$; quasi-neutrality condition). L_{ne} and L_{ni} are density gradient lengths for electrons and main ions, respectively, $L_{\mathrm{n}} = -\frac{1}{n}\frac{dn}{dr}$, $\omega_{*\mathrm{e}}$ is the electron diamagnetic frequency, $k_{\perp}$ is the wavenumber of the drift wave in the perpendicular direction to magnetic field and ρ_{s} is the Larmor radius of main ion at electron temperature. We note that, owing to dilution, the drift wave becomes less dispersive (that is, the $k_{\perp}^{2}\rho_{\mathrm{s}}^{2}$ term is reduced by the dilution factor $1 - f_{\mathrm{h}}$) with lower frequency, even when there is no profile change. This dilution-induced dispersion change is not caused by the presence of impurities, because their response, like that of the thermal main ions, would be fluid-like.

The effects of fast ions on ZF generation in the context of a quasi-2D drift wave turbulence[40] have been characterized in a formula[39] derived from the standard modulational instability calculation[36,41,42,43] in the non-resonant regime ($|\Omega - qv_{gx}| \gg \gamma_k$). Here Ω is the frequency of a ZF, v_{gx} and γ_k are the radial group velocity and linear growth rate of a drift wave, respectively. Under the assumption that $k_\perp{}^2\rho_s{}^2 \ll k_\perp{}^2\rho_f{}^2 \ll 1$, where ρ_f is the Larmor radius of fast ions, the ZF growth rate normalized to c_s/L_{ne}, with $c_s = \sqrt{T_e/M_i}$, M_i the mass of ions, is

$$\Gamma^2 = 2(1 - f_h)k_y{}^2q_x{}^2|\phi_{DW0}|^2 - (1 - f_h)^4(L_{ne}/L_{ni})^2k_y{}^2q_x{}^4, \quad (3)$$

where q_x is the wavenumber of ZF, and ϕ_{DW0} is a perturbed electrostatic potential of a pump drift wave normalized to $(\rho_s/L_{ne})T_e/|e|$.

In equation (3), the first term on the right hand side, related to the Reynolds stress drive for ZF growth, is reduced by $(1 - f_h)$. The second term on the right hand side represents the threshold of drift wave amplitude for ZF growth, which comes from the frequency mismatch of the three waves. Importantly, this term gets reduced by $(1 - f_h)^4$ because both the dispersion and real frequency are reduced by the dilution, as indicated by equation (2). Consequently, ZF is generated more readily even at a low amplitude of drift wave turbulence in the presence of a high fraction of fast ions. For a fixed drift wave amplitude, the wave number range of ZF growth becomes wider, owing to the dilution. It is noteworthy that a similar trend has been predicted for the collisionless TEM-driven ZFs for the resonant frequency regime ($\gamma_k \gg |\Omega - qv_{gx}|$)[44].

Zonal flow generation from Reynolds stress and turbulence eddy shearing by ZF shear occur simultaneously, conserving energy between ZFs and drift waves[42]. A self-consistent model of the effect of fast ions on turbulence reduction addresses both change in ZF growth and turbulence regulation as well as collisional damping of ZFs[45]. By employing the wave-kinetic approach, the aforementioned three-mode system has been extended to an ensemble of drift waves. In the non-resonant regime, relevant for core turbulence, the nonlinear saturation level of drift wave turbulence is given by

$$\mathcal{E}_{DW} = [(1 - f_h)^3(L_{ne}/L_{ni})^2\Delta_{mm(0)}{}^2]/A', \quad (4)$$

where $\Delta_{mm(0)}{}^2$ is a frequency mismatch in absence of fast ions, A' a coefficient related to the Reynolds stress drive for ZF such that $\gamma_{mod}{}^2 = (1 - f_h)A'\mathcal{E}_{DW}$, where $\gamma_{mod}{}^2$ is the Reynolds stress drive term. This result shows a strong effect of dilution on drift wave intensity, $\sim(1-f_h)^3$, leading to greatly reduced turbulence saturation level which would result in a reduction of transport as well.

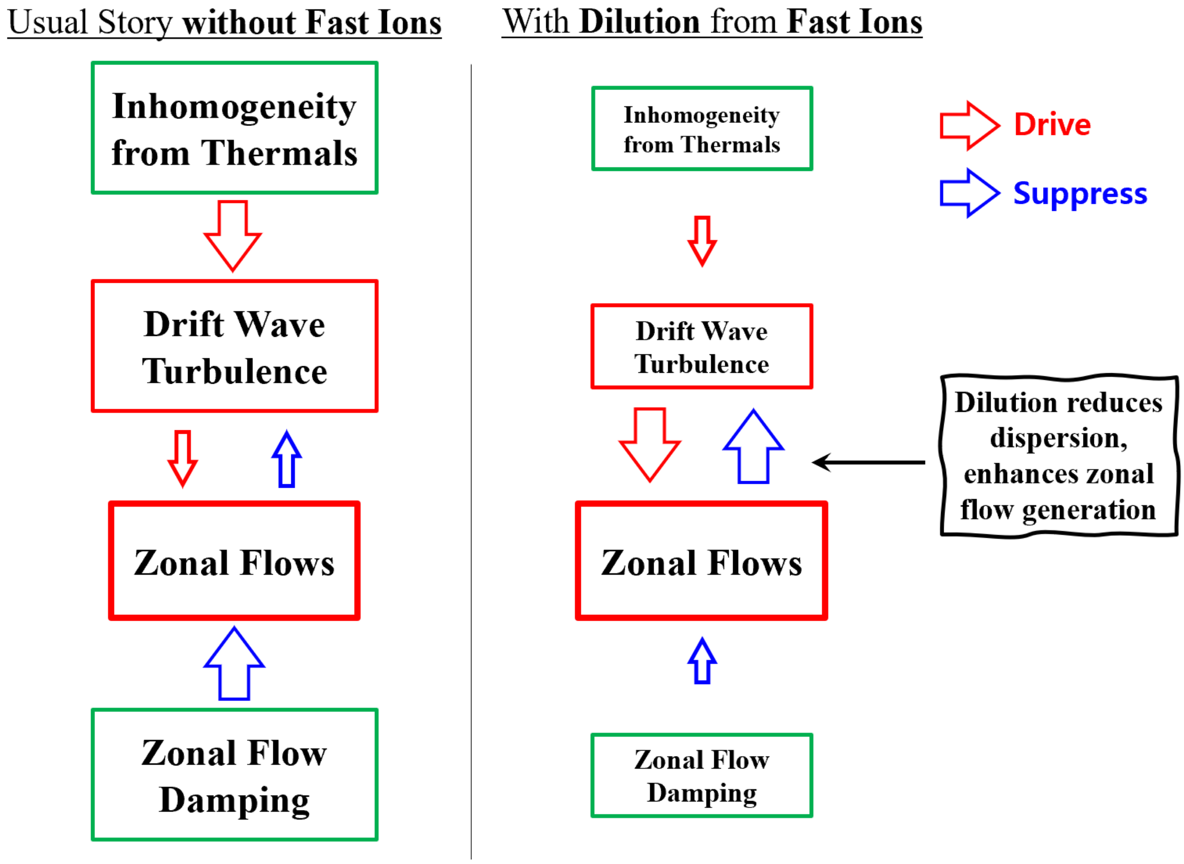


Fig. 1. The effect of dilution by fast ions on the drift wave turbulence–zonal flow (ZF) system. A typical case for core turbulence is illustrated. Magnitudes are indicated by box sizes and arrow thicknesses.

[H2] Resonant interaction between fast ions and microturbulence

Notably, fast ions can interact with the background ion-driven microinstabilities through a wave–particle resonant interaction[46]. The mechanism underlying this resonant interaction shares fundamental similarities to those explored in turbulent particle and impurity transport studies[47]. It can be elucidated through a simple kinetic picture (Fig. 2). Specifically, the curvature and ∇B drift motions of charged particles can synchronize with the instabilities, facilitating the exchange of energy between plasma instabilities and particles if specific conditions are satisfied.

This synchronization can be observed when examining the linear collisionless gyrokinetic equation for the perturbed distribution function of fast ions. Assuming the equilibrium distribution function F_0 to be Maxwellian and introducing a decomposition of all perturbed quantities into toroidal mode numbers, the non-adiabatic part of the perturbed distribution function $\hat{g}_{1,f}$ reads

$$\hat{g}_{1,\mathrm{f}} = \frac{(\omega_*^T - \omega) F_0 J_0(k_\perp \rho_\mathrm{f})\, \hat{\phi}_1}{\omega\ -\ \omega_\mathrm{df}}, (5)$$

where $\omega_*^T = \omega_{*\mathrm{f}} \left[\frac{R}{L_\mathrm{nf}} + \left(\frac{v_\parallel^2 + v_\perp^2}{v_{\mathrm{th,f}}^2} - \frac{3}{2} \right) \frac{R}{L_{Tf}} \right]$, where $\omega_{*\mathrm{f}} = \frac{k_y T_\mathrm{f}}{q_f B R}$ with q_f the fast ion charge, $\frac{R}{L_\mathrm{nf}}$ represents the logarithmic density gradient, L_nf is the gradient length of fast ion density and similarly for the temperature T_f, $3/2 {v_{th,f}}^2$ is the averaged kinetic energy of the fast ion with ${v_{th,f}}^2 = 2T_f/M_f$, M_f is the mass of fast ions. J_0 is the zero-order Bessel function and $\hat{\phi}_1$ the perturbed electrostatic potential. ω_df is the perpendicular drift frequency from the ∇B and curvature drifts, $\omega_\mathrm{df} = \mathbf{v}_\mathrm{df} \cdot \mathbf{k}$.

Equation (5) allows identification of a resonance that maximizes the fast ion distribution function and its contribution to the fields: The resonance between the ITG mode frequency and the magnetic drift frequency of the fast ions. By adopting the normalization used in the gyrokinetic code GENE[48,49], which facilitates comparison with equations discussed in the literature[50], the magnetic drift frequency of the fast ions reads $\omega_\mathrm{df} = \frac{T_\mathrm{f}(2v_\parallel^2 + \mu B)}{q_\mathrm{f} B} K_y$, where $K_y = -(\mathbf{B} \times \nabla B) \cdot \frac{\hat{\mathbf{y}}}{B^2}$ represents the binormal curvature term. For typical core plasma parameters, the wave–particle resonant condition can be satisfied only within phase space regions at the tails of the thermal ions distribution function, resulting in negligible effects, thus making this wave–particle resonant interaction highly ineffective for thermal ions.

Nonetheless, these magnetic drifts exhibit a temperature dependence. As a result of their elevated temperatures, the drifts of fast ions exceed those of thermal ions, allowing them to resonate with the linear frequencies of underlying modes at more favourable locations in phase space, thus leading to substantial energy redistribution. Not all fast ions can efficiently resonate with the background ion-scale instabilities. In particular, it is essential that the diagonal heat flux contribution of the fast ions overcomes the off-diagonal terms[50,51]. By simplifying the distribution function of these fast ions to an equivalent Maxwellian distribution for ease of analysis, this constraint dictates that fast ions must exhibit sharply peaked temperature profiles alongside relatively flat density profiles. When this criterion is fulfilled, a fraction of these fast ions (those with energies below $3/2 v_{\mathrm{th,f}}^2$) populate regions in phase space where they can extract energy from the underlying instabilities, thereby weakening the linear drive.

To enhance this stabilizing mechanism, it is essential to adjust the resonant layers by controlling the fast ion temperature to align with these regions in phase space, thereby amplifying this advantageous contribution. When this resonant interaction extends across a wide spectrum of wave numbers, it impacts the turbulent fluxes of each species as well. In a realistic scenario, this resonance effect can be optimized to create closely spaced layers where fast ions play a significant role in both stabilizing and destabilizing ion-scale microturbulence. This optimization generates highly localized, poloidally symmetric radial electric fields that effectively decorrelate turbulence eddies in close proximity, leading to the complete disruption of radially elongated turbulence eddies within the poloidal cross-section.

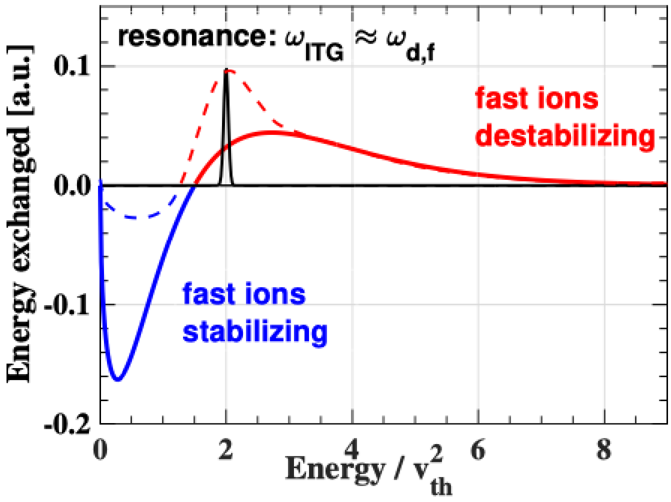


Fig. 2. Interplay between wave–particle resonant interactions and ion-scale plasma instabilities. The overall effect of this resonant interaction depends upon the phase-space characteristics of the fast ions and the localization of the resonance between the fast ion magnetic drift frequency (ω_{df}) and the linear ion-scale instabilities (ω_{ITG}). The dashed line highlights a scenario where this wave–particle interaction induces destabilization by matching the resonance condition within the destabilizing region of phase space at $E > 3/2 v_{th,f}^2$, where $v_{th,f}$ is the "thermal" velocity of fast ions, $v_{th,f} = \sqrt{2T_f/m_f}$.

[H2] Interaction between microturbulence and fast-ion-driven instabilities

Microturbulence and fast-ion-driven instability, the so-called energetic particle (EP) instability, often co-exist and interact nonlinearly in fusion plasmas. Whereas microturbulence develops from drift wave instabilities at the microscopic (thermal ion Larmor radius) scales, EP instabilities[52] such as fishbones and Alfvén eigenmodes (AEs) are magnetohydrodynamic (MHD) modes at the mesoscale (EP Larmor radius) or macroscale (device size). Linear excitation and nonlinear evolution of these MHD modes often depend on kinetic effects of thermal plasmas at microscopic scales[53]. They can generate and in return are regulated by nonlinear structures such as ZFs (due to wave–wave nonlinearity)[36,54] and phase space coherent structures (due to wave–particle nonlinearity)[55]. These nonlinear structures generated by one instability can sometimes serve as a nonlinear equilibrium for the other instability with faster time scale, and thus become the catalyst for cross-scale interactions between microturbulence and EP instability, which can induce effects of fast ions to reduce the turbulent transport of thermal plasmas. Furthermore, there can be direct nonlinear mode coupling between drift wave instability and EP instability.

In this section, we discuss the mechanisms of enhancing confinement caused by: Interaction between microturbulence and EP instability via ZFs, which could suppress turbulent transport;

interaction between microturbulence and EP instability via phase space coherent structures, which could enhance EP instability and associated ZFs that suppress turbulent transport; and nonlinear mode coupling between drift wave instabilities and EP instabilities that may lead to energy flow from microturbulence to EP modes.

[H3] Interaction between microturbulence and EP instability via zonal flows

Microturbulence is often regulated by micro-to-meso scale ZFs, which are $E\times B$ flows caused by flux-surface averaged electrostatic potentials generated by the nonlinear interaction of large amplitude drift waves. Effects of zonal current (flux-surface averaged current) are usually weaker than those of zonal flows due to the short electron collisionless skin depth[56]. Fast ions can reduce the amplitude threshold for the ZF modulational instability[57], which leads to reduced levels of turbulent transport[45]. Fast ions can affect the ZF residual level[57,58] and associated turbulent transport[58]. ZFs generated by microturbulence can also affect EP instabilities. For example, gyrokinetic flux-tube simulations with the GYRO code show that toroidal Alfvén eigenmodes (TAEs) can only be saturated by ZFs generated by microturbulence, when TAE growth rate is smaller than that of the drift wave instability[59].

The EP instability often saturates by self-generated ZFs at meso-to-macro scales. TAE saturation by self-generated ZFs has been observed in global simulations using gyrofluid code TAEFL/FAR3D[60] and kinetic-MHD hybrid code MEGA[61]. Analytic theory of nonlinear wave–wave interactions shows that ZFs can be generated by the modulational instability[62] or be forced-driven closer to the TAE marginality[63,64]. Away from marginality, the reversed-shear Alfvén eigenmode (RSAE) is saturated by self-generated ZFs, as seen in global gyrokinetic simulations using GEM[65] and GTC[8,66]. Beta-induced Alfvén eigenmodes (BAEs) can also generate ZFs, as seen in global gyrokinetic simulations using GTC[67] and ORB5[68]. Furthermore, ZFs dominate the saturation of the fishbone[9] in GTC simulations.

In return, microturbulence can damp ZFs generated by an EP instability[8]. Because ZFs often dominate the nonlinear saturation of the EP instability, microturbulence can thus indirectly regulate the EP instability. This ZF turbulent viscous damping comes from the diffusion of thermal ion guiding centers due to the random $E\times B$ drift by the microturbulence, which smooths out the radial profiles of the thermal ion zonal density associated with the ZF polarization density[69]. Note that this damping mechanism only involves thermal plasmas, so it does not decrease with the increase of the temperature ratio between fast ions and thermal ions, and thus could become the dominant effect in burning plasmas, where the fast ions are mostly 3.5 MeV alpha particles. Microturbulence damping of the ZFs is more important than collisional damping and leads to the oscillations in the RSAE amplitudes[8], reminiscent of the ITG amplitude oscillations due to the collisional damping of ITG-generated ZFs[70]. The intermittent RSAE amplitudes then, in turn, modulate the ITG transport[69]. Note that the three-body interactions between AEs, ZFs and microturbulence here are much more complicated than the interactions between microturbulence, ZFs and Coulomb collision. For example, AE-generated zonal flows can suppress microturbulence. At the same time, microturbulence can regulate AEs by damping AE-generated zonal flows and by destroying coherent structures in the fast ion phase space.

[H3] Interaction between microturbulence and energetic particle instability via phase space coherent structures

Both drift wave and EP instabilities are excited by wave–particle resonances. The linear instability drive diminishes when mode amplitude increases to a level at which the nonlinear wave–particle trapping frequency equals to the instability linear growth rate. In microturbulence, overlaps of phase space islands due to the dense linear resonances result in global stochasticity that drives the turbulent transport. Conversely, phase space coherent structures such as clumps and holes[55] can form nonlinearly in the EP instability due to the less dense linear resonances in the phase space. The dynamical evolution of these coherent phase space structures has been observed in GTC simulations to induce fast and repetitive frequency chirping and amplitude oscillations of the BAE in the non-adiabatic regime[71].

The EP phase space coherent structures can be destroyed due to the fast ion scattering by the random $E\times B$ drift of the ubiquitous microturbulence[72]. These coherent structures locally flatten the gradients of the fast ion distribution function across the linear resonance line and diminish the linear RSAE instability drive. However, in GTC cross-scale simulations that couple RSAE and ITG microturbulence, the fast ion scattering by microturbulence largely destroys these coherent structures. The destruction of the EP coherent structures by microturbulence restores the RSAE instability drive, and together with the microturbulence damping of the ZFs generated by the RSAE, results in a quasi-steady-state ITG–RSAE turbulence in the absence of artificial dissipation often used in MHD simulations. The resulting ZFs generated by RSAE affect the ITG transport. These simulations show that both EP and thermal plasma transport could be regulated by cross-scale interaction between microturbulence and EP instability via nonlinear structures such as ZFs and coherent phase space structures.

[H3] Nonlinear mode coupling between drift wave instability and EP instability

Analytic theory shows that scattering by electron drift waves can lead to TAE damping by reducing the wavelength of Alfvén waves subjected to electron Landau damping[73]. However, scatterings by TAEs have negligible net effects on the electron drift wave stability[74]. Nonetheless, global gyrokinetic GKNET simulations find that TAEs enhance the inverse cascade in the spectral space and turbulence spreading in the configuration space of the drift wave turbulence[75].

Two unstable TAEs can nonlinearly produce a beat wave which is a sound wave Landau-damped by thermal ions. This ion Compton scattering causes a downward energy transfer in frequency space[76]. An intriguing analytic prediction is that, when fast ions are involved, linearly stable long-wavelength high-frequency TAEs can be nonlinearly excited through Compton scattering of the short-wavelength low-frequency ITG modes[77]. This mechanism may provide an energy sink for turbulence to explain the reduction of the thermal plasma transport, and has been discussed in relation to flux-tube GENE simulation results which exhibit the enhanced ZF activity both in the JET hybrid mode with destabilized BAE[28] and L-mode with transfer of ITG energy to TAE[51]. However, the flux-tube simulations may fall short of correctly modelling the radially broad EP mode structure and the consequent global zonal patterns, so global turbulence simulations are likely required for the EP instability[78].

Finite β and the associated electromagnetic effects thereof can have a notable influence on the quality of confinement in fusion experiments[2]. In addition to observations from linear and nonlinear gyrokinetic simulations indicating reduction of linear growth rate and heat flux of ITG turbulence when increasing β[79], the increasing ZF activity with increasing β has been proposed as a physics mechanism for the important nonlinear electromagnetic reduction of ITG turbulence. In particular, the interplay between unstable and stable ITG modes and zonal modes has been highlighted to contribute to such an important effect[80]. The increasing intensity of high-frequency electromagnetic perturbations such as KBM or BAE, which can be eventually destabilized by the high-pressure thermal plasma in ITG regime, can also induce strong ZF activity[81] via the triplet interaction of ITG, KBM or BAE, and zonal modes. Fast ions can contribute to this mechanism by means of the destabilization of specific fast-ion-driven instabilities such as TAE or RSAE.

[H1] Experimental observations

In this section, the experimental observations addressed in the Introduction are examined and categorized according to the dominant mechanisms of fast ion stabilization discussed in the previous section.

[H2] Change of magnetic field structure by fast ions

Experiments carried out under strong plasma heating by means of fast ions can develop a high non-thermal plasma pressure, leading to change of the magnetic field structure. These changes in magnetic field structure can be found mainly in experiments with high NBI power. Such changes can result in confinement enhancement with a high core β and the enhancement of the edge region of H-mode plasmas, so-called pedestal. They can reach $\beta \approx 4\%$ with a substantial contribution from the fast ion pressure[28].

In hybrid mode, a type of H-mode but with higher confinement, at several tokamaks, such as JET[28], KSTAR[18,19,20], and ASDEX Upgrade[30], such high confinement has been observed accompanying the changes in magnetic field structure by fast ions. Dedicated gyrokinetic simulation analyses have shown that the impact of this mechanism on the energy transport reduction in the plasma core is low and it is not able to fully explain the reduction in core turbulence found in those experiments[18,27,28,29,30]. However, the change in magnetic field structure has a stronger global impact in the plasma edge by increasing the pedestal height. In the case of JET, the increase can reach 20%, leading to an overall improved confinement throughout the plasma radius thanks to the increased pressure, mainly temperature, of the edge plasma[28].

[H2] Thermal ion dilution

Plasmas with thermal ion dilution have been explored in several tokamaks, for example in ASDEX Upgrade, HL-2A, and KSTAR with NBI. ASDEX Upgrade showed fully suppressed turbulent transport in the plasma core, leading to formation of ion-ITB[6], where high temperatures of ~20 keV were obtained. Turbulent transport driven by ITG was suppressed in such conditions, but a minimum dilution level of ~30% is necessary to achieve complete stabilization. The thermal ion dilution by fast ions also triggered ion-ITB formation in HL-2A[11].

Further investigation occurred in KSTAR, where the FIRE mode was also obtained under conditions of high fast-ion dilution. An ion-ITB was obtained with >30% fast-ion dilution and suppressed ITG-driven energy transport. Unlike the results obtained in ASDEX Upgrade, FIRE mode could be sustained for a long duration, up to 50 s, and was achieved under $T_\mathrm{i} \approx T_\mathrm{e}$, with a high fraction of fast ions persisting[3,5], demonstrating that this plasma regime is suitable for sustained operation. In nonlinear gyrokinetic simulations, the reduced thermal ion density and density gradient due to dilution is the dominant cause of improvement in confinement[3,35]. In particular, the effect of the inverted thermal ion density gradient was outstanding. In addition, the high fraction of fast ions can lead to both ZF being generated much more readily, even at a low amplitude of drift wave turbulence[39], as well as to a greatly reduced turbulence saturation level, which could reduce transport[45]. Quasi-local nonlinear gyrokinetic simulations indicate the changes in ZF velocity and associated shearing rate due to the presence of fast ions (Fig. 3)[34]. Although this change is smaller than that seen in a case of dilution-induced ITG mode linear growth rate[34], a more thorough physical assessment should involve a self-consistent nonlinear analysis of the ZF–drift wave system, as discussed in the section on thermal ion dilution, rather than a rule of thumb based on linear growth rates and shearing rate.

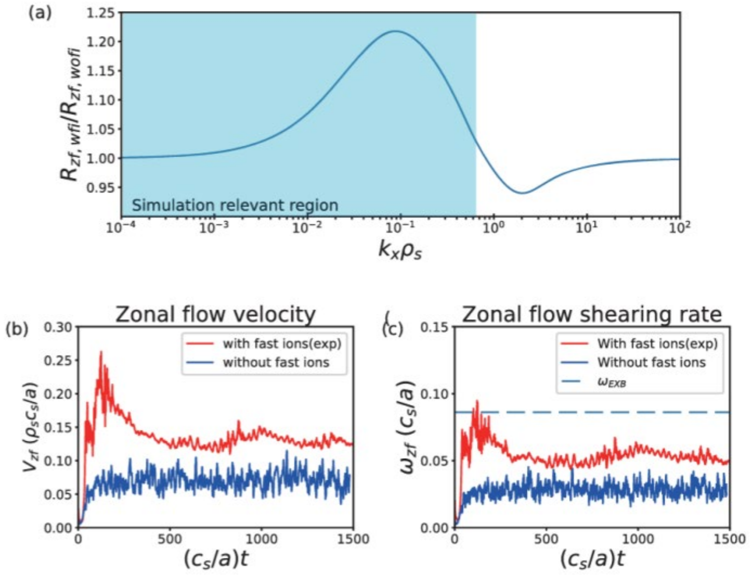


Fig. 3. Nonlinear simulation results on zonal flows (ZFs) for cases with and without fast

ions in FIRE mode on KSTAR. (a) Ratio of the residual ZF level with fast ions to that without fast ions calculated using equation (62) in Ref 57. Here, the blue shaded region indicates the wave number range covered by the simulations ($|k_x\rho_s| \leqslant 6.88$). At $k_x\rho_s \approx 0.2$, the residual zonal flow increases by 20% when fast ions are included. (b) ZF velocity (V_{zf}). (c) ZF shearing rate (ω_{zf})[34]. Here, "with fast ions(exp)" indicate that parameters for fast ions are taken from the KSTAR FIRE mode data for the simulation. The velocity and shearing rate are normalized to $\rho_s c_s/a$ and c_s/a, respectively.

[H2] Resonant interaction between fast ions and turbulence

Confinement enhancement has been observed in various experiments with ICRH. At JET, energy transport driven by turbulence is reduced in the presence of highly energetic ^{3}He in low rotating plasmas, mostly heated with ICRH. Among other physics mechanisms, the resonance between the ITG fluctuations and the fast ^{3}He reduces turbulent growth rates by 25%[82]. Experiments in ASDEX Upgrade were established to maximize ITG transport reduction by wave–particle resonant interaction using ICRH. In this case, full suppression of turbulent transport and ITB generation for the thermal ions, called F-ATB (Fast ion-induced Anomalous Transport Barrier), was obtained. Numerical simulations have demonstrated the effectiveness of this mechanism in inducing ITBs, resulting in broad regions with suppressed ion-scale turbulent transport (Fig. 4)[7]. Notably, this plasma exhibited minimal confinement degradation despite increased external power input, a departure from the expected behavior in conventional H-mode plasmas. Additionally, a pronounced peaking of the thermal ion profile was observed, which could not be solely attributed to external heating.

The resonant interaction between fast ions and turbulence turned out to play a minor role in KSTAR FIRE mode[5]. Fast ions, modelled with a Maxwellian distribution, can destabilize ITG turbulence due to a high fast-ion density gradient provided by NBI. Although a non-Maxwellian distribution usually has a minor effect on turbulence growth, especially for NBI-generated fast ions[83], it can be important in FIRE mode owing to the large quantity of fast ions. If the Maxwellian distribution is shifted instead to the numerical distribution calculated by NUBEAM[84], the ITG linear growth rate is reduced, but the reduction is relatively minor compared to the dilution effects.

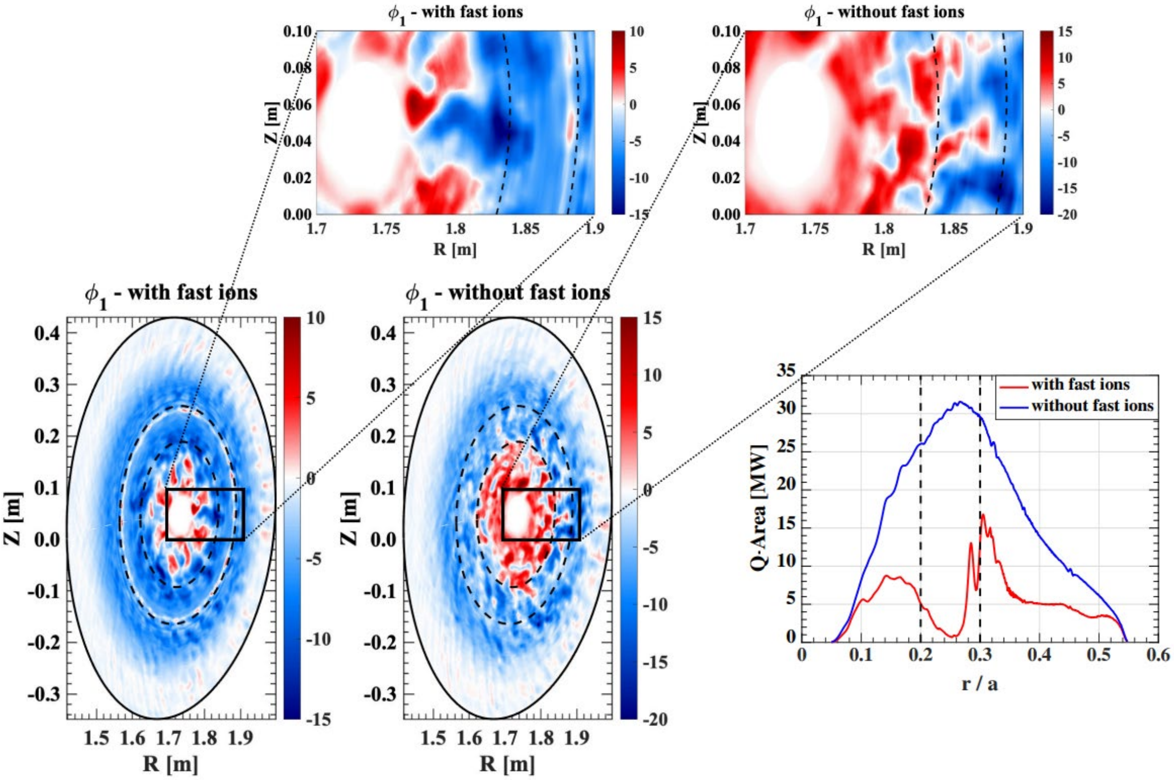


Fig. 4 Snapshots of simulations of the poloidal cross-section showing fluctuations in the electrostatic field ϕ_1 for the F-ATB (fast ion-induced anomalous transport barrier) discharge in ASDEX Upgrade[7], comparing cases with and without energetic particles. Simulations are obtained with the gyrokinetic code GENE[48,49] for the ASDEX Upgrade discharge #36637. Dotted black lines delineate the region where the wave–particle resonant interaction triggers an internal transport barrier (ITB), showcasing pronounced decorrelation of turbulent eddies solely in simulations, including energetic particles. Zoomed views of this region are provided in the top figures. The resulting total turbulent fluxes, demonstrating near-complete turbulence suppression within the ITB, are illustrated in the right figure. The vertical axis in the lower right figure represents the total turbulent flux, which is the sum of the contributions from all species as computed by GENE with (red line) and without (blue line) fast ions.

[H2] Interaction of drift waves and fast-ion-driven instabilities

Experiments have been performed in different tokamaks to characterize the impact of EP instabilities on thermal turbulent transport and thermal plasma confinement. In EAST, the presence of fishbones has been found to lead to turbulence-free plasmas in the region of fishbone activity and consequent ITB formation[10]. In this case, the fishbones were found to generate a perturbed localized E_r, which can produce a sheared $E\times B$ flow that triggers ITB formation[85,86]. In the HL-2A tokamak, other fast-ion-driven instabilities located at the $q = 1$ location, such as the long-lived mode, have been shown to play a role in sustaining ITBs, by increasing ZF activity and suppressing ITG turbulent transport, although the triggering of ITB was mainly obtained by thermal ion dilution[11]. At JET, the interplay between thermal turbulent transport and destabilized TAE has been identified in conditions of very low fast-ion dilution and the presence of MeV ions, which were accelerated with ICRH[1,16]. These plasmas show reduced core ion heat transport compared to equivalent plasmas heated with ~100 keV ions with NBI. Reflectometry measurements indicate that a lower density fluctuation intensity is observed in the typical ITG range of frequencies, when TAEs are destabilized. Similar findings were observed in ASDEX Upgrade H-mode plasmas and further confirmed through global gyrokinetic simulations. The simulations show that high-frequency electromagnetic modes, driven by fast ions, effectively suppress turbulence by enhancing ZF, thereby leading to improved plasma performance[87].

In DIII-D experiments, it was found that ZFs generated by the EP instability can suppress turbulent transport of the thermal plasmas. GTC simulations[9] show that ZFs generated by fishbone can be responsible for the ITB formation. Additionally, GTC simulations[8,66,69] show that the RSAE and ITG co-exist and nonlinearly interact in these plasmas. The electrostatic potentials are dominated by meso-scale RSAE and the electron density perturbations are dominated by microscopic ITG (Fig. 5). Cross-scale interactions are needed in the GTC gyrokinetic simulation to maintain a quasi-steady state RSAE with a mode structure and amplitude in agreement with DIII-D experimental measurements[8]. The thermal ion heat diffusivity in realistic simulations that couple RSAE and ITG is reduced by a factor of two compared to that in the control simulation, in which RSAE is artificially suppressed. This turbulence suppression has been identified to be caused by the larger ZFs generated by the RSAE[69].

In addition, there is an ongoing effort to characterize the trend of changes of transport due to the AE-drift wave nonlinear interaction, observed in various experiments, in terms of simple quantities which can be relatively easily estimated from global gyrokinetic simulations using the GKNET code[88].

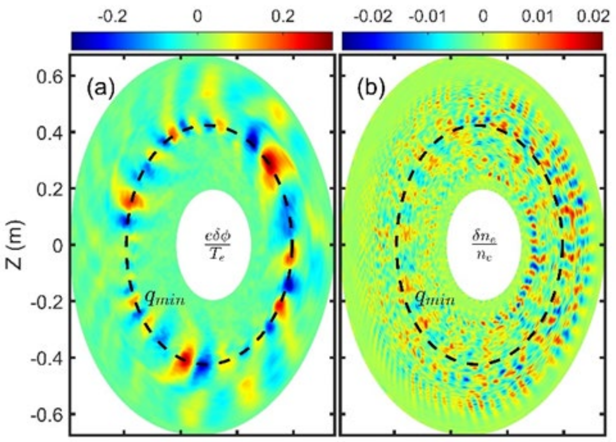


Fig. 5 Interacting RSAE and ITG turbulences. Poloidal contour plots of perturbed electrostatic potential $e\delta\phi/T_{\mathrm{e}}$ (panel a) and electron density perturbation $\delta n_{\mathrm{e}}/n_{\mathrm{e}}$ (panel b) from GTC simulation coupling ITG-RSAE turbulence in DIII-D shot #159243[8]. Here, e is the elementary charge, $\delta\phi$ is the perturbed potential, T_{e} is the electron temperature. n_{e} and δn_{e} are electron density and perturbed electron density, respectively. The location of q_{min}, the minimum safety factor value, is indicated by the black dashed curve.

[H1] Outlook

Fast ions can act either without or with the generation of Aes. The latter case introduces a new player in the game of thermal transport. Fast ions can drive Aes, which in turn can generate ZF shears. Sufficiently strong ZFs can then mitigate ambient drift–ITG turbulence, thus triggering thermal ITB formation. This scenario was suggested to explain recent favorable JET DT experimental results with a highly energetic fast ion population and further developed theoretically[89]. Simulations also suggest that AE-driven ZFs can grow strong enough to impact thermal confinement.

A critical question for this scenario is that of ZF regulation: Both damping and saturation. This is because — in the spirit of the predator–prey system — it is predator (that is, ZF) destruction which ultimately controls the prey (that is, drift–ITG turbulence) population. Simulations have indicated that various frictional damping mechanisms are at work. However, nonlinear mechanisms for AE-driven ZF saturation are likely also important, and should be explored. A recent study has presented a closed feedback loop analysis of the AE + drift ITG + ZF system incorporating nonlinear ZF damping[90]. This shows substantial collisionless thermal ion heating through the ZF. Thus, we see that the AE-driven ZF can become a conduit for 'alpha channeling[91]'. More generally, we also learn that feedback loop closure and energy conservation are crucial to a proper treatment of the structure of AE + drift ITG + ZF interactions.

Figure 6a summarizes the various effects in play in the fast ion + thermal ion system. In terms of physics content, a crucial milestone will be demonstration of the workings of the interconnected feedback loops shown in the figure. Even more substantive and interesting would be the revelation of transitions between different 'basins of attraction' where different feedback loops regulate the dynamics. More generically, a coordinated program of experiment, simulation, and theory is required. The experimental program should include studies of the multi-scale fluctuation dynamics (such as bicoherence studies). These are crucial to fundamental validation of the model.

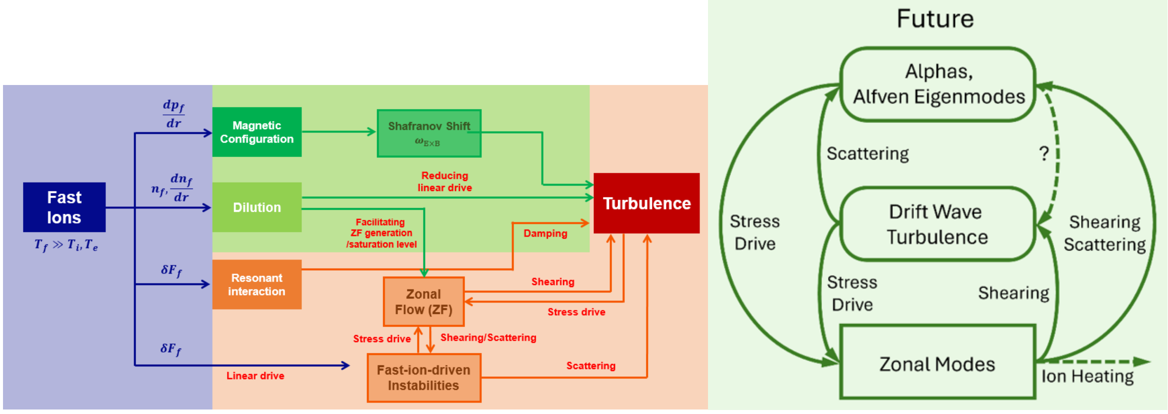
We sketch some other near-term future directions for research on fast ion-induced improvement in thermal confinement. First, we observe that, so far, nearly all the indicators of enhanced confinement have been macroscopic in character, and focused on profiles and global confinement. Associated fluctuation studies and measurements of ZFs and corrugations are essential for physics validation of the various models which have been proposed. BES (beam emission spectroscopy) velocimetry is promising as a means to study core ZFs. Coordinated fluctuation and confinement studies are a high priority for the future studies in this area.

A second direction that is currently emerging is to replace the traditional perspective of 'thermal ions plus fast ions population' with one of multiple components of particles and fluctuations, all of which interact on an equal footing. Confinement is then regulated by the interplay of Aes, drift-ITG turbulence, and zonal modes. The structure of the intersecting and overlapping feedback loops which can be expected for this system is suggested in Fig. 6b.

Several comments are in order here. First, zonal modes naturally couple both Aes and drift waves to the mean electric field[36,92,93], and thus can mediate the cross-scale interaction of fast ions and thermals. Second, the interaction of ZF drive, both with EP-driven Aes and by thermal-driven drift-ITGs, can have interesting consequences for the spatial structure of the shearing field. This question has not yet been addressed. In particular, the effect of fast ions on the $E\times B$ staircase, observed in KSTAR[94] and elsewhere is of great interest. Third, the multiple interacting feedback loops can enable systemic transport bifurcations, where transitions from dominance of one loop to another occur, thus changing the basic dynamics. Understanding such bifurcations remains an outstanding challenge. Fourth, we note that in this scenario, the physics of AE saturation likely controls (in part) the thermal plasma transport.

There is strong theoretical and experimental evidence that modification of the fast ion distribution in phase space plays an important role in the nonlinear evolution of Aes. These in turn drive ZFs which can trigger ITBs, in the thermal population. The fast ion population evolution is often associated with the formation and propagation of phase space structures, commonly referred to as 'clump' and 'hole'. However, recent simulations[69] suggest that thermal turbulence can, in some cases, destroy such phase space structures. Therefore, cross-scale interaction modifies this process, too. Most theoretical models address either the phase space dynamics or the ZF and turbulence dynamics, but not both. Yet understanding the branching ratio of the power dissipated by phase space redistribution to the power expended to drive ZFs is essential to quantitatively assess the possibility of AE-driven ITB formation. Thus, an outstanding challenge for theory is to treat both phase space relaxation of the fast ion distribution along with ZF generation and turbulence physics.

It is noteworthy that beyond conventional tokamak plasmas, fast ions have been found to substantially improve the confinement of thermal plasma in spherical tokamaks[95,96] and stellarators[97,98,99]. Direct heating of thermal ions by ion cyclotron waves excited by NBI has also been observed in the field-reversed configuration plasmas[100]. Clearly, the problem of fast ion + thermal ion interaction by Aes + Drift-ITG + ZFs is a rich but complex one, which requires a sustained, coordinated effort by theory, modelling and simulation, and experiment.



(a) (b)

Fig. 6. Core confinement feedback loops. (a) In the present, the feedback loops are simple and clear. Here, T_f, T_i, and T_e are temperature of fast ions, main ions, and electrons, respectively. P_f, n_f, and Δf_f are pressure, density, and perturbed distribution function of fast ions, respectively. $\Omega_{E\times B}$ is the mean $E\times B$ flow shear. (b) In the future, the situation is complex. Sources and slowing down effects are crucial.

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Author contributions

The authors contributed equally to the article as first authors. Y.-S.N. formulated the overall structure of the article, invited co-authors, and coordinated the entire writing activities. Y.-S.N. primarily contributed to Introduction, Outlook, and the section of ‘Experimental observations’. T.S.H. contributed to organizing the structure of the article and primarily focused on the sections titled ‘Thermal ion dilution and changes in the thermal ion density gradient’ and ‘Interaction between microturbulence and fast-ion-driven-instabilities’. P.H.D. mainly contributed to the Outlook and the Introduction section as well as a section titled ‘thermal ion dilution and changes in the thermal ion density gradient’. A.D.S. primarily contributed to the section titled ‘Resonant interaction between fast ions and microturbulence’ and the Introduction. J.G. mainly contributed to the sections ‘Change of magnetic field structure by fast ions’ and ‘Experimental observations’. Z.L. primarily contributed to the section ‘Interaction between microturbulence and fast-ion-driven instabilities’. All authors equally contributed to the compilation and review of the manuscript.

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Peer review information

Figure captions

Glossary

Tokamak

A magnetic confinement device in which magnetic fields are generated both by external coils and by currents flowing in the plasma to confine plasma in the shape of an axially-symmetrical torus. The magnetic field generated in the toroidal direction, following a large circular ring around the torus encircling the central void, by external coils wound along the torus is called as the toroidal field. The magnetic field generated in the poloidal direction, following a small circular ring around the surface, by currents flowing in the plasma is called as the poloidal field.

Neutral beam injection

A method to heat up a plasma confined in a fusion device with a beam of high-energy neutral particles injected into the plasma. These neutral particles are ionized by collision with the confined plasma particles and become fast ions. They transfer their energy to plasma particles by collisions.

Ion cyclotron resonance heating

A method to heat up a plasma confined in a magnetic fusion device using electromagnetic radio frequency waves with frequencies about 20-50 megahertz matching the frequency at which ions gyrate around the magnetic field lines, ion cyclotron frequency, is used. The ions in the plasma absorb the electromagnetic radiation and as a result, increase in kinetic energy.

Plasma turbulence

The complex and randomly fluctuating, as opposed to coherent, wave action in a plasma, characterized by a wide range of spatial and temporal scales resulting from multi-scale nonlinear interactions and from drift instabilities of large-scale fluid motions involving many degrees of freedom. In plasmas, turbulences can cause increased transport of energy and particles so to reduce the confinement in a fusion device.

Modulational instability

It refers to a process whereby a test large scale, slow perturbation on an ensemble of waves or modes grows by triggering a flow of energy which reinforces the original perturbation. Classic examples of modulational instability are self-focusing of a beam and amplification of test shears by drift wave turbulence. Modulational instability can be computed using either wave kinetics (i.e. quasi-particle method) or the envelope formalism.

Drift wave

A type of collective excitation that is universally occurring driven by a pressure gradient in magnetised plasmas, which can be destabilised by differences between ion and electron motion, known as drift wave instability.

Zonal flow

Azimuthally symmetric band-like shear flows, a ubiquitous phenomena in nature and the laboratory. In plasma physics, it is a plasma flow within a magnetic surface primarily in the poloidal direction arising via a self-organization phenomenon driven by low-frequency drift-type modes, in which energy is transferred to longer wavelengths by modulational instability or turbulent inverse cascade.

Plasma instability

The stability properties of a plasma in equilibrium under small perturbations. Instabilities occur if the perturbations grow in time.

Alfvénic instability

Magnetohydrodynamic oscillations of the nonuniform magnetically confined plasmas where eigenmodes of Alfvén waves destablised by fast ions with velocities comparable to the Alfvén velocity. Alfvén wave is a type of plasma wave in which ions oscillate in response to a restoring force provided by an effective tension on the magnetic field lines. There are several types of Alfvénic instabilities in a tokamak such as TAE (Toroidal Alfvén Eigenmode), appearing at the gaps of the Alfvén continuous spectra owing to toroidicity; BAE (Beta-induced Alfvén Eigenmode), appearing at the gaps of the Alfvén continuous spectra due to finite plasma pressure; RSAE (Reversed-Shear Alfvén Eigenmode), occurring in plasmas with a saddle-like current density profile (maximum in the off-axis region) where the wave is trapped in an effective potential well around the maximum current region.

Fishbone instability

A rapid burst of magnetohydrodynamic activity due to interaction between fast ions and internal kink instability with the shape of a fishbone when plotted as a function of time, sometimes observed when neutral beam heating is used in tokamaks.

Long-lived mode

A type of magnetohydrodynamic instability that persists for a significantly long duration within the plasma, often characterized by a steady-state oscillation with a helical structure, unlike other rapidly fluctuating instabilities. it is primarily driven by the interaction between fast ions and the plasma, occurring in conditions of low magnetic shear and substantial plasma rotation.

H-mode

A high confinement regime develops when a tokamak plasma is heated above a characteristic power threshold, which increases with density, magnetic field and machine size. It is characterised by a sharp pressure gradient near the plasma edge, so-called ‘edge transport barrier (ETB)’, resulting in an edge ‘pedestal’.

Internal transport barrier

A radially localized plasma region in which energy and particle transport is reduced and driven mainly by collisional transport due to suppression of turbulence.

Hybrid mode

A high performance, long duration plasma confinement mode that have favorable fusion and neutron fluence characteristics for ITER. It is characterized by low magnetic shear or flat q-profile in the central region of the plasma.

Gyrokinetics

A theoretical framework to study plasma nonlinear behavior on perpendicular spatial scales comparable to the Larmor radius and frequencies much lower than the particle cyclotron frequencies.

ASDEX Upgrade

“Axially Symmetric Divertor Experiment” a tokamak at the Max-Planck-Institut für Plasmaphysik, Garching, Germany that went into operation in 1991. Fast ions induced the internal transport barrier formation with neutral beam injection. Internal transport barrier was also formed with ion cyclotron resonance heating, so-called F-ATB (Fast ion-induced Anomalous Transport Barrier).

DIII-D

“Doublet III-D”, a tokamak at General Atomics in San Diego, California, USA that went into operation in 1986. Internal transport barrier was formed with Alfvénic modes with neutral beam injection.

EAST

“Experimental Advanced Superconducting Tokamak”, a superconducting tokamak at the Hefei Institutes of Physical Science, China that went into operation in 2006. Internal transport barrier was formed with fishbones with neutral beam injection.

HL-2A

“Huan Liuqi-2A”, a tokamak at Southwestern Institute of Physics/China National Nuclear Corporation in Chengdu, China that was constructed based on the former German ASDEX tokamak and went into operation in 2002. Internal transport barrier was formed with neutral beam injection and sustained with ling-lived mode.

JET

“Joint European Torus”, a tokamak at Culham Centre for Fusion Energy in Oxfordshire, UK that went into operation in 1983 and finished operations in December 2023. Confinement improvement was observed with fast ions in the experiments with neutral beam injection and ion cyclotron resonance heating including hybrid mode.

KSTAR

“Korea Superconducting Tokamak Advanced Research”, a superconducting tokamak at the Korea Institute of Fusion Energy, Daejeon, South Korea that went into operation in 2008. Fast ions induced internal transport barrier with the central ion temperature above 10 keV with neutral beam injection, which is called FIRE (Fast Ion Regulated Enhancement) mode. Fast ions also contributed to improved confinement in hybrid mode.