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SPECIAL TOPICS

Fast Ion Interaction with Turbulence Mediated by Zonal Flows in Tokamak Plasmas: Overview of the Recent Insights

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Abstract

Recent findings on improved thermal plasma confinement in the presence of large-scale Alfvén Eigenmodes in tokamak plasmas have sparked a great interest in the complex physics at play, as it is relevant for next-generation fusion device optimization. These studies must be framed within the latest two decades of efforts in analyzing the various mechanisms through which the fast ions, i.e. ions with much larger energy than that of thermal ions, can interact with the background turbulence and, remarkably, reduce or even suppress the latter in magnetized plasmas. This contribution aims at reviewing the latest results about experimental and modeling observation of reduced outward ion heat flux triggered by the nonlinear and multi-scale interplay of fast-ion-driven modes and background turbulence, and framing it within the broad knowledge on the well-established fast-ion mechanisms reducing the tokamak plasma turbulence.

Keywords Fast Ions · Zonal Flows · Turbulence · Fast-Ion-driven Modes · Confinement

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1 Introduction

The fusion of deuterium (D) and tritium (T) nuclei in magnetically confined plasmas represents a promising route toward clean and virtually limitless energy. Among the various magnetic confinement concepts, the tokamak has emerged as one of the most advanced, exploiting a combination of toroidal and poloidal magnetic fields to confine high-temperature plasmas (Ongena et al. 2016).

To achieve the high energy gain expected from fusion reactions, the plasma in a fusion reactor must reach very high temperatures. This is made possible by external heating methods, among which Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) play a key role. A critical outcome of external heating and fusion reactions is the generation of fast ions—a distinct low-density population of highly energetic particles with a kinetic energy significantly exceeding those of thermal ions. These include NB-injected ions, ICRH-accelerated minorities, and fusion-born alpha particles with energies up to 3.5 MeV. Fast ions contribute to plasma heating through collisional energy transfer, and are essential in reactor scenarios where self-heating should dominate. However, they may also lead to relevant issues: because of their large energy, fast ions can excite a variety of macroscopic instabilities, such as Alfvén eigenmodes (AEs) and Energetic Particle Modes (EPMs), which may induce fast ion transport, damage plasma-facing components, and thereby adversely impact the overall plasma confinement and performance (Salewski 2025).

Another critical outcome of such heating schemes, however, is the steep spatial gradients in temperature and density of the various plasma species. The free energy contained in such large gradients can further enhance the destabilization of drift-wave type microinstabilities at the thermal ion Larmor radius scales in the plasma core (Horton 1999)— among which the ion temperature gradient (ITG) modes (Romanelli 1989) is the main cause of anomalous heat transport for the thermal ion species, even in future fusion reactors. The microinstabilities can nonlinearly interact among themselves, driving thus turbulence and causing anomalous transport. The turbulent transport is the primary limiting factor for the plasma confinement, as it significantly reduces the energy confinement time τ_E, and ultimately degrades the fusion performance.

Remarkably, recent experimental and numerical research has revealed that fast ions may also play a beneficial role on the confinement quality by reducing the turbulent transport. Evidence from various tokamak devices around the world has shown that plasmas with a significant presence of fast ions can develop enhanced energy confinement. These results have sparked interest in unveiling the underlying mechanisms by which fast ions interact with microturbulence and influence global confinement properties. Thus, they have led to renewed efforts to study, understand, predict and eventually control this crucial piece of physics.

Recent advances in high-performance computing (HPC) (Jenko 2025) have been instrumental in unraveling these mechanisms, as the multi-scale and complex physics at play is very difficultly appreciable through experimental measurements. Linear and nonlinear simulations using state-of-the-art gyrokinetic numerical codes have demonstrated that fast ions can suppress ion-scale turbulence via various different mechanisms. Beyond the linear stabilizing mechanisms, complex electromagnetic effects driven by fast-ion-triggered instabilities at the meso- or large scales have been observed to lead to enhanced zonal flow activity and reduced turbulence saturation levels, even reaching suppression of the outward turbulent fluxes in certain plasma regions. The degree of stabilization depends on many plasma parameters, such as the fast-ion pressure, distribution function anisotropy, and the inclusion of finite-β effects. These mechanisms highlight, once more, the nonlinear and multiscale nature of the turbulence regulation in fusion plasmas.

Fast ions may enhance this energy transfer complexity towards good plasma confinement properties, and influence thus the self-organization of the inherently out-of-equilibrium tokamak plasma system. While the direct impact of microturbulence on fast-ion confinement is typically subdominant compared to large-scale mode effects (see e.g. Angioni and Peeters 2008), the contrary, i.e. the impact of fast ions on turbulence, has emerged as a new exciting area of research (Na et al. 2025). Understanding this interaction is essential, especially in view of future burning plasma scenarios, where alpha particles will constitute a dominant fast-ion species.

This paper aims to review the current understanding of fast-ion-induced turbulence suppression and its implications for thermal energy confinement. This work falls within a recent series of review papers published on this very topic, such as Refs. (Garcia and Contributors 2022; Citrin and Mantica 2023; Na et al. 2025). Nonetheless, in this manuscript, a dedicated emphasis is put on the experimental observations and interpretation through advanced modelling of the interaction between the fast-ion-driven AEs and the microturbulence mediated by the zonal components of the electrostatic potential, the so called zonal flows (Diamond et al. 2005). Electromagnetic effects, fast-ion dynamics, and turbulence regulation are explored self-consistently to illuminate the improved confinement regimes achieved in the last decades. Through an overview of experimental data and theoretical insights, this work contributes to identifying viable directions for optimizing energy confinement in magnetically confined fusion plasmas.

The manuscript firstly reviews the main linear mechanisms triggered by the fast ions having a beneficial impact on the turbulent fluxes in Sect. 2. Then, in Sect. 3, some of the first experimental evidence of the stabilizing impact of the externally generated fast ions on the confinement properties are discussed. Section 4 is the core of this manuscript, highlighting the pathway from the first local (flux-tube) gyrokinetic modelling results up to the most recent global ones, with experimental validation and theoretical insights, of the complex interaction among fast ions, AEs, zonal flows and microturbulent transport. Additionally, Sect. 5 reports on some nonlinear mechanisms triggered by different fast-ion-driven large scale instabilities. Eventually, after highlighting some intriguing insights in Sect. 6, the relevance of these findings and the missing pieces of research towards their application in next-generation tokamaks conclude this review in Sect. 7.

2 Brief Overview of Fast-Ion-Triggered Linear Mechanisms of Turbulence Reduction

In the latest decades, diverse mechanisms triggered by the fast ions leading to turbulence reduction have been studied and demonstrated. In particular, linear mechanisms mainly impacting the ITG growth rate were demonstrated to be driven by the suprathermal ions. In this section a summary of these linear mechanisms triggered by the fast ions is given. It should be stressed that additional mechanisms leading to ITG stabilization are not triggered by the presence of the fast ions, but those are out of the context of this overview and thereby will not be discussed in detail.

2.1 Fast-Ion Enhancement of Shafranov Shift

In tokamaks, the equilibrium magnetic field is also composed of a vertical field generated through external coils, which pushes radially outward the plasma center (Zohm 2015), increasing the so-called Shafranov shift. This is strongly affected by the radial profile of β_p, the ratio of the plasma thermodynamic pressure to the poloidal component of the magnetic pressure, which in turn is determined by the plasma pressure profiles. A population of fast ions, having inherently a low density yet a pressure value comparable to that of the bulk plasma due to their high energy, therefore, can lead to large Shafranov shift, and to a major deformation of the magnetic-flux-surface geometry. Essentially, in the Low Field Side (LFS) of the tokamak plasmas with increased Shafranov shift, the particles experience smaller regions of 'bad curvature', with a decreased ∇B-drift-induced destabilizing mechanism (Bourdelle et al. 2005). This stabilization is mainly effective on the ballooned microinstabilities at low poloidal wavenumber, such as the ITG and TEM. Moreover, also the mean flow shear, well-known to reduce the turbulent transport by decorrelating the turbulent eddies (Diamond et al. 2005), is enhanced with an increased Shafranov shift (Hahm and Burrell 1995). In prior studies, it has also been proposed (Bourdelle et al. 2005) as a leading mechanism to the onset of internal transport barriers (ITBs), i.e. core plasma regions with a strong, local increase of the pressure gradient.

This purely geometrical effect is however limited to the plasma conditions with relatively low β. Indeed, there is a well-established critical β-limit (Pueschel et al. 2008) above which the Kinetic Ballooning Modes (KBMs) (Tang et al. 1980; Aleynikova et al. 2018) are destabilized and dominate over the ITG and Trapped Electron Mode (TEM) instabilities, leading to large turbulent fluxes. Sensitivity studies of KBM linear growth rate on the geometrical effects reported that the linear threshold may however be affected (Xie et al. 2016). Eventually, the Shafranov shift stabilization mechanism is strictly linked to the value of β_p, which should not overcome the critical threshold beyond which the ITG-TEM stabilization is overall beaten by the KBM-induced transport. This, hence, limits somehow the effective parameter space of the Shafranov shift stabilization, as in next-generation devices high-β plasmas will be targeted.

2.2 Fast-ion dilution of bulk ions

Being the fusion plasmas globally quasi-neutral, the injection or generation of fast ions in such plasmas leads to the dilution of the bulk ions, replacing part of this latter population with the fast ions. This, thereby, directly mitigate the linear growth rate of the ITG modes, which are driven by the *slow* thermal ion population. This effect is always present whenever fast ions are injected or generated, but its impact on the ITG stability strongly depends on the ratio of fast-ion to the total plasma density, and moreover on the fast-ion radial density and temperature gradients. Indeed, it is usually marginal in the case of ICRH minority heating, whereas more effective in the case of NBI, which produce a larger fast-ion density gradient (Iantchenko 2017). This is mainly due to the more efficient and broader generation of fast particles through NBI, rather than the more localized ICRH-generated fast population. Further, for the fusion-born alpha particles in ITER, this effect is expected to be very mild (Wilkie et al. 2018) due to the low alpha particle density (Garcia et al. 2018), but somehow present as observed in numerical analyses of selected pulses of JET DTE1 campaign (Testa and Albergante 2012a, b).

In numerical simulations, in which the quasi-neutrality is strictly imposed, this effect is retained, and it could be thus directly measured in the linear phase of the ITG instability. Indeed, linear gyrokinetic simulations have determined the crucial role of the fast-ion dilution in the formation of an ITB in NBI-heated ASDEX Upgrade plasmas (Tardini et al. 2007). As already pointed out in such a reference, the fast-ion dilution is more effective in low-density discharges, where the relative concentration of fast ions with respect to the bulk ion density is larger.

The same kind of mechanism is also responsible for the improved confinement obtained in the KSTAR Fast-Ion Regulated Enhancement (FIRE) regime (Han et al. 2022), in which a large concentration of NB-injected fast ions (up to 40%) in a low density plasma is confined in the core. In this regime, the fast-ion dilution is high enough to lead to an inversion of the thermal ion density gradient, further mitigating the ITG growth rate (Kim et al. 2023; Choi et al. 2023; Kim et al. 2024), as shown in Fig. 1(a). For the sake of clarity, other linear fast-ion-triggered mechanisms than the dilution are also involved in the FIRE mode sustainment, i.e. the Shafranov shift enhancement (see Sect. 2.1) and the increased linear electromagnetic stabilization due to the large fast-ion pressure (see Sect. 2.3). Furthermore, fast-ion dilution has also been observed recently to be the triggering cause of the ITB onset in NBI-heated HL-2A plasmas (Lin et al. 2023). Yet, the ITB self-sustainment is then guaranteed by a more complex nonlinear mechanism resembling the one thoroughly discussed in Sect. 4.

Therefore, the fast-ion dilution is an inherent mechanism of ion-scale ITG growth rate reduction in tokamak plasmas with fast ions, both externally generated or born from the nuclear fusion reactions. Nevertheless, although promising, for being effective such a mechanism requires to be applied to low-density plasma regimes, in which the ratio fast-ion to thermal ion density can rise up to relevant values ($\gtrsim 5\%$). Indeed, this is not the targeted regime for a fusion reactor device, in which the fusion gain must be maximized in the presence of 3.5 MeV alpha particles. It may still be an attractive triggering mechanism followed by a more complex dynamics of turbu-

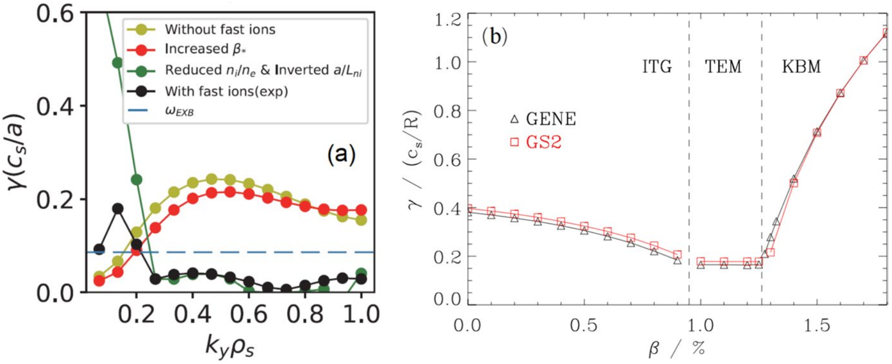


Fig. 1 (a) Growth rate spectra versus binormal wavenumber $k_y\rho_s$ for various KSTAR FIRE mode input configurations, showing the strong impact of the thermal ion density gradient inversion on ion-scale instabilities. Figure adapted from Kim et al. (2023). (b) Growth rate of the dominant mode at $k_y\rho_s = 0.2$ from GENE and GS2, identifying three instability regimes and illustrating ITG stabilization with increasing β. Figure from Pueschel et al. (2008) with permission

lence control (Lin et al. 2023), but additional experimental evidence is required to draw any definitive conclusion. In the same fashion, more reactor-relevant attempts on ITG-driven turbulence mitigation have been demonstrated through the seeding of low-Z impurities mainly through gas puffing, leading to a very similar kind of dilution mechanism (Garcia et al. 2022; de la Luna et al. 2024; Yang et al. 2020).

2.3 Electromagnetic stabilization of ITG enhanced by fast ions

It is quite well-established that the growth rate of the unstable ITG modes have a clear dependence on the β parameter, which as already said is representative of the electromagnetic character of the system. Indeed, the ITG growth rate decreases with increasing β (Hong et al. 1989) and such a dependence, due to the coupling between the shear Alfvén and the ion-scale ITG modes (Kim et al. 1993), has been clearly observed also in linear scan through gyrokinetic simulations, both global and local (Falchetto et al. 2003; Pueschel et al. 2008). An illustrative example of such a ITG growth rate stabilization obtained through gyrokinetic simulations is shown in Fig. 1(b). This is generally framed below the umbrella of the linear electromagnetic stabilizing mechanism on the ITG modes. On different core-microinstabilities occurring at thermal ion scales, such as the TEMs, this mechanism is not (or much less) effective (Pueschel et al. 2008).

The stabilization of ITG modes due to the linear electromagnetic effect enhanced by fast ions was proposed as an explanation for the improved confinement, and the ITB insurgence, in a specific low-density JET hybrid scenario (Romanelli et al. 2010). On top of the fast-ion dilution effect (see Sect. 2.2), local gyrokinetic simulations revealed a clear stabilization of the ITG growth rate when the ICRH-accelerated ions are retained in the simulations. The fast ions locally enhanced the β parameter, which decreased the ITG growth rate and the subsequent nonlinear transport. Such a mechanism is recalled also in other studies, in which the fast ions are not always considered (Citrin et al. 2014). Nonetheless, the inclusion of fast ions in the system leads to an enhanced coupling between the ITG and the shear Alfvén modes, and thereby to a stronger dependence on the β parameter which stabilizes more the ITG growth rate at lower β values (Citrin et al. 2014).

The complete suppression of any unstable mode is, however, prevented by the destabilization of high-frequency pressure-driven microinstabilities which sharply increases the growth rate of the dominant unstable mode at the critical β threshold. The transition to a KBM-dominated regime can indeed be observed in Fig. 1(a) for $\beta > 1.25\%$. This threshold mainly depends on the local pressure gradients, for both thermal and fast particles (Pueschel et al. 2008). Thus, beyond such a threshold the subdominant ITG modes are fully stabilized, but the overall transport is highly enhanced by these higher-frequency pressure-driven modes.

Therefore, the effectiveness of this mechanism is limited to the regime with β parameters lower than the critical threshold, similarly to what discussed for the Shafranov shift mechanism (see Sect. 2.1). The improvement of the global confinement and the subsequent increase of β for multiple reasons, among which the H-mode access is one of the most common, triggers a nonlinear feedback on the electromagnetic stabilization mechanism (Garcia et al. 2015). This may widen the operational space of effectiveness of such a mechanism to more reactor-relevant scenario, although its applicability remains to be confirmed for plasma scenarios envisaged for next-generation fusion devices.

The identification of these pressure-driven modes, which appear also in the absence of fast ions, is somehow subtle, but it is quite important for the remainder of this overview. They are spectrally located at low wavenumbers and their frequency is generally much larger than the one of the ion-scale unstable modes. For this reason, they can be easily noted in the linear spectrum. One of the first identification focuses on the kinetic thermal ion gap in the shear Alfvén continuum (Chen and Zonca 2007), which hosts differently termed instabilities depending on the diamagnetic and compressibility effects of the background plasma. Whereas the KBMs are generally destabilized by resonance with the thermal (or fast) particle diamagnetic frequency (Aleynikova et al. 2018; Mazzi et al. 2024), the Beta-induced Alfvén Eigenmodes (BAEs) are mainly found unstable when the thermal particle effects of compression are important (i.e. the ion transit frequency is much larger than the diamagnetic one) (Zonca et al. 1996; Heidbrink et al. 1993). Connecting these two branches within the same kinetic thermal ion gap, the ion temperature gradient driven Alfvén eigenmodes (AITG) were theorized to be strongly unstable in the presence of finite ion temperature gradient (and even without fast ions) close to marginal MHD stability (Zonca et al. 1998, 1999). The AITG has been later found unstable in gyrokinetic simulations and experimental tokamak plasmas, e.g. (Falchetto et al. 2003; Mazzi et al. 2020; Chen 2018).

2.4 Stabilizing linear fast-ion kinetic effect on ITG modes

An additional linear mechanism through which the fast ions can stabilize the background turbulence is via a direct fundamental interaction between the fast ion characteristic motion and the unstable mode frequency. In particular, it has been observed that the ITG modes can interact through the magnetic drift frequency of the fast ions, in a purely electrostatic mechanism (Di Siena et al. 2018). Depending on the fast-ion physical characteristics, mainly on the temperature ratio with the background plasma, such an interaction can reduce the ITG growth rate by more than 40% (Di Siena et al. 2019). This reflects into a reduced saturated level of the overall nonlinear fluxes. This stabilization is due to a negative contribution of the fast-ion-drive term to the ITG mode in the velocity space region where the interaction between the ITG modes and the fast particle occurs. Such a phase-space region is found to have a sweet spot for the fast-ion effective temperature around 10 times the bulk temperature, at which the turbulence is more stabilized (Di Siena et al. 2018). On the contrary, when the ratio T_f/T_e is low ($T_f/T_e < 5$) the mechanism is not beneficial, whereas its effect is almost negligible for large T_f/T_e. This can be understood through a more rigorous description of the interaction. Indeed, accounting for the variation of the magnetic drift frequency along the large fast-particle orbits (especially with respect to the typical ITG mode wavelength) shows that the larger the orbits of the considered fast particles, the more spatially localized and hence weaker the expected resonance. Therefore, this interaction through a broad range of transit/bounce resonant states, i.e. the orbit width effect (not retained in Ref. Di Siena et al. 2018), should be carefully considered (see, e.g., Zonca and Chen 2008; Qiu et al. 2008; Chen et al. 2018), particularly for fusion-born alpha particles in burning plasmas, for which, thereby, this interaction is expected to be weak.

The dependence of the ITG growth rate on the ratio T_f/T_e is displayed in Fig. 2(a), clearly showing a sweet spot at $T_f/T_e \approx 10$. Hence, for the 3.5 MeV fusion-born α particles the ITG stabilization due to this linear mechanism is not active due to the lack of possible resonance between the very fast α particles and the unstable ITG modes. Nonetheless, the fast-ion energy distribution could fulfill such a resonance in outer region of the plasma, in which the slowing-down of the very energetic ions leads to lower energy values, as observed in recent analyses at JET (Di Siena 2025).

Moreover, assuming a Maxwellian distribution for the fast-ion population, the fast-ion drive term in velocity space strongly depends on the local gradients of the

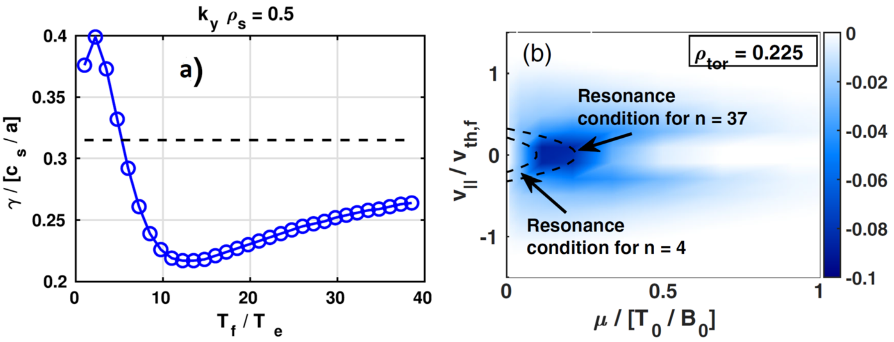


Fig. 2 (a) ITG growth rate vs. fast-ion to electron temperature ratio for a representative $k_y\rho_s$, with the horizontal dashed line indicating dilution-induced mitigation. A maximum stabilization is observed near $T_f/T_e = 12$, while for larger ratios the effect saturates near the dilution threshold. Figure from (Di Siena et al. 2019). (b) Resonant structure of the interaction between ITG and fast ion magnetic drift in the velocity space, highlighting the theoretical expected structures of different toroidal wavenumbers surrounding the ITG-dominated region of the spectrum. Figure adapted from Di Siena et al. (2021)

fast particle radial profile, i.e. R/L_{T_f} and R/L_{n_f}. It is shown that for an ICRH-generated fast-ion population, for which normally $R/L_{T_f} > R/L_{n_f}$, the stabilization is enhanced, whereas for NB-injected fast ions the resonant condition is almost prevented (Di Siena et al. 2018, 2019).

This mechanism was found to be beneficial in a low rotation JET scenario mainly heated by ICRH (Bonanomi et al. 2018). This scenario was developed to disentangle the impact of fast ions from the mean flow shear generated by the NB injection, in order to further corroborate the main role of the fast ions in the reduction of the ion heat flux stiffness observed previously in multiple JET scenarios, as thoroughly treated in Sect. 3. In the analyzed ICRH-heated plasmas, the linear electrostatic mechanism was responsible for a turbulence stabilization of 40%, plus an additional 20% was due to nonlinear electromagnetic effects. These latter electromagnetic effects can be framed within the nonlinear interaction between marginally stable high-frequency pressure-driven modes and the zonal flows, whose detailed explanation is given in Sect. 4.2. It should be noted, however, that in the high rotation NBI-heated JET scenarios with ion stiffness reduction (Mantica et al. 2009, 2011), the stabilization of the turbulence was mainly due to such a nonlinear electromagnetic mechanism (Citrin et al. 2013; Di Siena et al. 2019), differently to the one here discussed in which the main contribution was due to a pure linear electrostatic phenomenon.

A detailed analysis of this electrostatic mechanism triggered by only the presence of the ICRH fast ions revealed its dependence on the fast-ion characteristics and on the local magnetic equilibrium parameters, such as the magnetic shear $\hat{s}$. This opens up the possibility of an accurate tailoring of the local plasma parameters to trigger such a mechanism in a theory-driven experimental development. Thus, a so-called fast-ion-induced anomalous transport barrier (F-ATB) was formed and sustained by applying this linear resonant mechanism in a ICRH-heated ASDEX Upgrade scenario (Di Siena et al. 2021). Using a H-minority ICRH heating, a centrally peaked fast-ion population was generated with a steep temperature gradient meeting the first requirement of the linear resonant mechanism. To fulfill the second requirement, i.e. the right ratio T_f/T_e, the H minority concentration was adjusted to 11% to achieve around 100 keV of effective fast ion temperature at the plasma axis. Hence, the F-ATB was experimentally observed in the deep plasma core, and the main role of the linear electrostatic mechanism was validated through GENE global simulations (Di Siena et al. 2021). Figure 2(b) shows the contribution of the heat flux at the F-ATB radial position ($\rho_{tor} = 0.225$) in the velocity space, highlighting that the resonant condition for the ITG modes is fulfilled at such a position.

Applications of such an electrostatic linear mechanism of core-plasma turbulence stabilization have been studied also for next-generation tokamaks, such as ITER (Di Siena et al. 2018). Although appealing, these intuitions must be validated in other current tokamaks yet, and the complexity of fulfilling the requirements for its activation is still to be fully assessed.

3 First Experimental Evidence of Improved Plasma Confinement in the Presence of Fast Ions at JET

This section is dedicated to reviewing the early experimental observations that sparked strong interest in microturbulence stabilization in the presence of externally generated fast ions in tokamak plasmas. Indeed, based on striking observations of improved confinement properties in the presence of large NBI and ICRH input power a new line of research was opened, unveiling the complex dynamics between fast ions and the background turbulent transport.

The stiffness property of a temperature profile in tokamak plasmas is generally conceived to assess the dependence of the rate of change of the heat flux on the gradient of the temperature profile. In essence, it measures how much the gyroBohm normalized ion heat flux is increased with increased logarithmic ion temperature gradient, which is the fundamental energy reservoir driving the ITG turbulent transport (Romanelli 1989). The stiffness is usually an important parameter to qualify the confinement properties of tokamak plasmas, and it was extensively employed in specific JET experiments performed at the end of the 2000 decade to determine the plasma conditions in the improved confinement regimes. In Refs. (Mantica et al. 2009, 2011), dedicated efforts on understanding the observed improved thermal ion confinement in L-mode plasmas suggested that the combined effects of the low magnetic shear in the plasma core and the large NBI-induced rotational shear was the key mechanism in reducing the ion temperature stiffness. Figure 3 clearly shows this trend, with much larger stiffness in the low-rotation conditions in the plasma core (at $\rho_{tor} = 0.33$). Gyrofluid and gyrokinetic modelling studies confirmed the trend obtained in the experiments, corroborating the prior understanding that an improved confinement could be achieved by increasing the flow shearing through the plasma rotation (Biglari et al. 1990; Diamond et al. 2005) or tailoring the q-profile in the plasma core to widen the rational magnetic surfaces distance (Cardozo et al. 1997; Waltz et al. 2006). Nevertheless, the validation through such advanced simulations was not clearly achieved (Mantica et al. 2011), as a non-negligible discrepancy was still observed, suggesting that an additional ingredient was likely missing

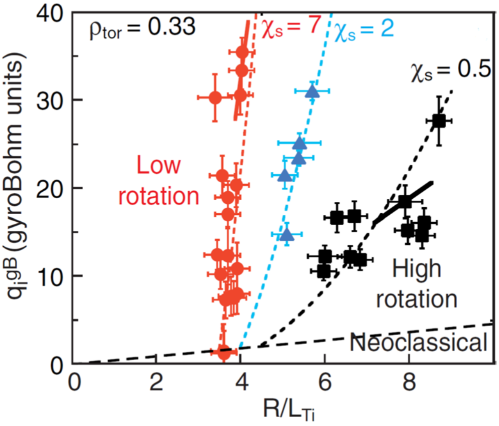


Fig. 3 Experimentally measured total ion heat flux q_i at $\rho_{tor} = 0.33$ against the local normalized logarithmic ion temperature gradient R/L_{T_i} for different plasma conditions. The black dashed line represent the theoretically computed neoclassical transport, whereas the other dotted curves represent the thermal diffusivity computed through the Critical Gradient Model (Mantica et al. 2009) at different values of the thermal ion diffusivity. This figure is adapted from (Mantica et al. 2011)

These experiments, hence, sparked more in-depth analyses in the following years, and further insights have since been gained. During those years, the relevance of optimizing the plasma current density profile, by inductive and non-inductive sources, was evaluated in conjunction of high-β plasma and ITB operations (Garcia and Giruzzi 2010, 2011). In this context, new ideas emerged about the impact of high-β_p conditions, drawing attention to the role of the heating system in providing the necessary ingredients for improved ion confinement. Indeed, it was observed that the shape of the radial profile of the poloidal current density j_p clearly discriminate the type of the enhanced plasma scenario obtained in JET (Garcia and Giruzzi 2010). The critical role of the current density pointed to the importance of the electromagnetic fluctuations, and in particular of the electromagnetically induced turbulence, contrarily to the previously established paradigm of the dominant electrostatic turbulence dynamics in tokamak plasmas.

As a figure of merit, the electromagnetic character of a tokamak plasma can be related to the β parameter, and in particular, as observed in Ref. (Garcia and Giruzzi 2010), to the poloidal beta parameter β_p. Interestingly, the observed enhanced confinement at JET in the presence of NB-injected power was not obtained in transient phases, but was rather sustained for the whole pulse duration. Therefore, assuming $j_p \sim 0$ in a stationary toroidal current and employing the pressure force balance $J \times B = \nabla P$, with J the plasma current density and ∇P the radial pressure gradient, it can be argued that the conditions required to obtain enhanced plasma confinement in the core are strictly linked to the pressure profile and its gradient.

This latter consideration clearly emphasized the crucial role of the fast ions, which, despite their limited concentration in the core, contribute significantly to the total pressure profile because of their large energy. In particular, the NBI heating system efficiently generates a large fraction of fast ions, whose beneficial effects on the turbulent transport properties were already suggested in prior studies (for more details see Sect. 2.2). Therefore, the enhanced plasma confinement, together with $j_p \sim 0$ and high-β_p conditions, was clearly associated with the suprathermal component of the ion distribution function, generated by external heating systems. Nonetheless, the underlying physical mechanism of the improved confinement observed at JET was still elusive. Dedicated analyses through advanced gyrokinetic modelling performed in the subsequent years shed light on the missing physics pieces that led to such improved confinement properties. This will be treated in the next Sect. 4.

4 Improved Plasma Confinement Triggered by Fast-Ion-Driven Alfvén Eigenmodes

In this section—the core of the overview—the impact of the complex multi-mode interaction between the fast-ion-driven AEs and the large/meso-scale zonal flows on the turbulence transport, and consequently on the plasma confinement in tokamak plasmas, is discussed in great detail. Theoretical analyses, motivated by striking observations from earlier modeling studies, explore the generation of zonal structure by large-scale MHD modes driven by fast ions. These analyses must be considered in the context of the recent outcomes stemming from an intense research activity carried out over the past few years, particularly about the unexpected improved thermal ion confinement observed in specific JET experiments. The various steps that have led to the current understanding of the complex influence of the fast-ion-driven modes on the background turbulence properties are then examined. First, the in-depth theoretical understanding of the interaction between fast-ion-driven AEs and zonal flows and fields—or more in general zonal structures (Falessi and Zonca 2019; Falessi et al. 2023)—is reviewed. This is an essential passage in order to contextualize the past and ongoing theoretical efforts aimed at comprehending the complex physics at play. This is crucial also in light of the most recent results from cutting-edge gyrokinetic simulations about the interplay among fast-ion-driven AEs, zonal fields and turbulence, which will be reviewed in detail in the following.

4.1 Early Analyses of Nonlinear Fast-Ion Effects on Turbulence Reduction

The experimental results presented in Sect. 3 sparked a great interest in uncovering the underlying physical mechanism responsible for the unexpected ion transport stiffness reduction. Gyrokinetic modeling, enabled by the increasing capability and availability of HPC systems, became a key tool to explore the fine details of such a novel piece of physics. Thus, pioneering numerical analyses with the gyrokinetic code GENE (Jenko et al. 2000; Görler et al. 2011) were performed in the local (or flux-tube) approach on selected pulses of JET, drawn from the database reported in the seminal Refs. (Mantica et al. 2009, 2011). Among these NB-heated pulses, JET pulses #66,404 and #73,224, both L-mode discharges with relatively low core β values, were chosen for detailed analysis.

Figure 4(b) perfectly summarizes the findings of this pioneering work: the heat fluxes of the thermal ions are strongly reduced when the fast ions are introduced in the nonlinear electromagnetic simulations (Citrin et al. 2013). In these simulations, the fast-ion distribution function was modelled using an equivalent Maxwellian peaked

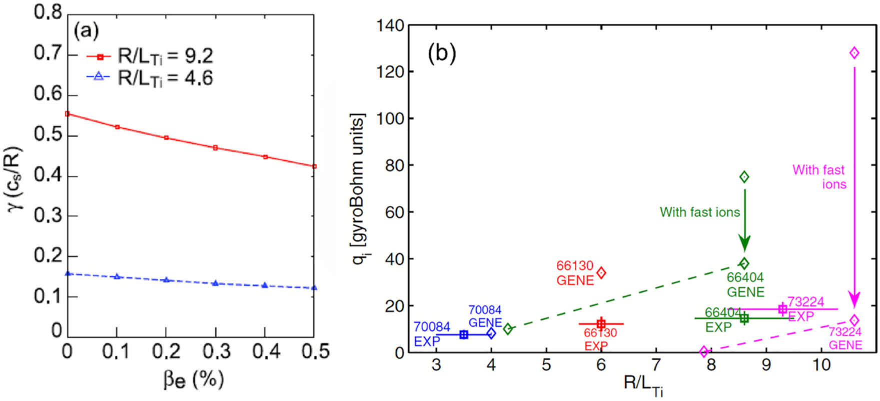


Fig. 4 (a) GENE-computed ITG linear growth rate against an electron β scan for the binormal wavenumber $k_y \rho_s = 0.4$ for two different ion temperature gradients. This scan is based on JET #66,404 pulse at $\rho_{tor} = 0.33$, but excluding the fast ions. (b) Nonlinear ion heat fluxes q_i at $\rho_{tor} = 0.33$ for different JET pulses are compared to the experimental measured ones. The introduction of the fast ions in the simulations is also highlighted. Both Figures are adapted from (Citrin et al. 2013)

at the average energy of the corresponding more realistic slowing-down distribution, as computed through dedicated NBI modeling codes. Notably, this transport reduction manifests predominantly in the nonlinear regime, whereas the linear spectra are less affected by the presence of the fast ions and the electromagnetic effects. This rules out, hence, the possibility that previously proposed linear mechanisms (briefly summarized in Sect. 2) are responsible for the observed reduction in ion stiffness. On the other hand, the nonlinearly triggered mechanism was observed to reduce largely the thermal ion heat flux driven by the ITG microinstability, finally validating the experimentally observed stiffness reduction in JET plasmas with large NBI power input.

It is thus also demonstrated that the previously hypothesized combined effect of low magnetic shear and strong toroidal flow shear (Mantica et al. 2011) alone cannot account for the improved confinement. Instead, the dominant parameter controlling the turbulence stabilization in the nonlinear dynamics was identified as the relative fast-ion pressure. Additionally, it was also observed that the fast-ion-induced stabilization is enhanced at low magnetic shear (Citrin et al. 2013), suggesting a path to be followed in the development of advanced scenarios with improved confinement triggered by the fast ions. Nonetheless, the local magnetic shear value is inversely proportional to the growth rate of some high-frequency pressure-driven instabilities (Kumar et al. 2021; Mazzi et al. 2024) that are generally destabilized at low binormal wavenumbers in these simulations (Citrin et al. 2014; Garcia et al. 2015; Doerk et al. 2016). This latter consideration is relevant for the remainder of this review, as even marginally stable high-frequency pressure-driven modes may trigger a complex mechanism that regulates the turbulence (see Sect. 4.2).

As previously mentioned, in the analyzed L-mode JET pulses #66,404 and #73,224, the critical electron β for the destabilization of KBMs lies well above the experimentally measured values, that is $< 0.5\%$. This is confirmed in Fig. 4(a), where no sharp increase in growth rate is observed as β_e increases, indicating that the KBM threshold is not reached, and no high-frequency instabilities emerge at low $k_y \rho_s$. This result is consistent with the absence of core-localized MHD activity in the experimental observations of this plasma scenario.

Although insightful, these early gyrokinetic simulations did not fully resolve the open questions of unveiling the underlying physical mechanism responsible for the observed ion transport stiffness reduction and improved thermal confinement. Some preliminary indications pointed to an enhancement of the zonal flow activity as a potential explanation for the increased stabilization in the nonlinear phase with respect to the linear one (Citrin et al. 2013). This interpretation is consistent with earlier studies that emphasized the crucial role of zonal flows in shifting nonlinear turbulence thresholds and regulating the turbulence saturation levels (Pueschel et al. 2008; Pueschel and Jenko 2010).

As from the first gyrokinetic analyses a clear indication of the predominant role of the fast-ion pressure over the electromagnetic effects to explain the reduction of the turbulent transport in the plasma core was given, subsequent analyses focused on H-mode plasmas with similar β in the plasma core but different fast-ion content. This comparative study was carried out on two JET discharges, #75,225 and #77,923 (Garcia et al. 2013; Hobirk 2012), which differed in plasma triangularity.

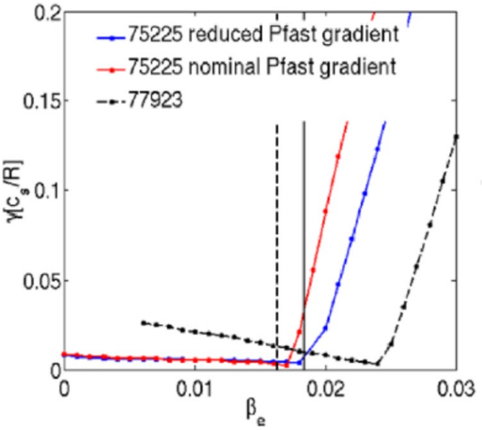


Fig. 5 GENE-computed linear growth rate against an electron β scan for the binormal wavenumber $k_y\rho_s = 0.3$ for JET pulses #75,225 and #77923. The vertical dashed and solid curves represent, respectively, the experimentally inferred β_e values for pulse #75,225 and #77923. Figure reprinted from Garcia et al. (2015)

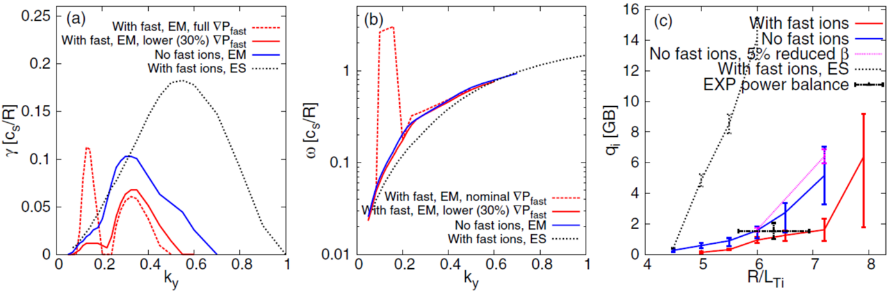


Fig. 6 Growth rate (a) and linear frequency (b) spectra, and the nonlinearly computed ion heat fluxes in an ion temperature gradient scan (c) for various configurations of the input parameters based on JET pulse #75,225 at $\rho_{tor} = 0.33$. Figure reprinted from Garcia et al. (2015)

Specifically, pulse #77,923 was performed at higher triangularity, resulting in a larger electron density and, therefore, a lower relative fast-ion density at the same input power.

Intriguing results from the gyrokinetic simulations with the GENE code unveiled a possible role of the critical β threshold of high-frequency pressure-driven modes such as KBMs, BAEs or AITGs, on the turbulence stabilization strength (as already discussed in Sect. 2.3). In fact, the plasma geometrical differences between these two pulses affect the critical value of β_e, as displayed in Fig. 5. The phase space region with the steep increase of the growth rate is reached at higher β_e for the pulse at higher triangularity. Moreover, whereas the low-triangularity case #75,225 is far from the destabilization of the pressure-driven modes, the high triangularity pulse #77,923 lies at the linear onset of these modes. By modifying the fast-ion pressure gradient, the critical β is slightly shifted, once more corroborating the subtle role of fast ions also on the electromagnetic stabilizing effects observed in these gyrokinetic simulations.

In Fig. 6(a) and (b), the linear binormal wavenumber spectra are shown of the analysis of JET pulse #75,225 at $\rho_{tor} = 0.33$, and the high-frequency modes destabilized at low-k_y indicate the crossing of the critical β_e threshold. In both pulses, nonetheless, the turbulence reduction observed in nonlinear simulations was primarily attributed to the electromagnetic effects rather than the fast-ion relative pressure impact (Citrin et al. 2014; Garcia et al. 2015). The introduction of the fast ions in the simulations leads to an additional, non-negligible turbulence stabilization, as it could be seen in Fig. 6(c). This effect became more pronounced at higher ion temperature gradients, where the system approached the threshold for pressure-driven mode destabilization. As a matter of fact, the high-frequency modes observed at low-k_y, generally identified in these simulations as KBMs, but also AITGs and BAEs, are driven by the total pressure gradient. Figure 6(c) further illustrates that a simulation without fast ions and with reduced β_e (magenta dashed line) yields significantly higher fluxes at the same R/L_{T_i}, highlighting the critical role of proximity to the instability threshold. Hence, even a slight modification of the pressure gradients can lead to substantial differences in the nonlinear phase and to have, thus, more important stabilizing effects.

In summary, the ion transport stiffness reduction was proven to arise from a synergy between the nonlinear electromagnetic and the fast-ion relative pressure effects on the background turbulence at the ion gyroradius scales. In both L- and H-mode plasmas at JET, the gyrokinetic simulations revealed that the inclusion of fast ions and the self-consistent evolution of the magnetic flutter are essential ingredient to match the experimental power balances. Nevertheless, whereas in low-β conditions the fast-ion relative effect is predominant, in the H-mode high-β plasmas the role of the nonlinear electromagnetic stabilization effects and the proximity to the onset of pressure-driven high-frequency modes (even when driven solely by thermal particle pressure gradient) are demonstrated to be essential. The critical β value remained, however, a hard limit that should have not been overcome. Indeed, a run-away behavior of the fluxes was observed beyond such critical β in the simulations, especially for the electron electromagnetic flux (Citrin et al. 2014). It should be noted that such pathological non-saturated states for fast-ion-driven fluxes in nonlinear simulations are generally ascribed to local flux-tube gyrokinetic codes (Bass and Waltz 2010), although theoretical and numerical assessment of saturation channels for fast-ion modes, both below and above threshold, are well established in the literature (Chen and Zonca 2016).

It became, thus, quite clear the necessity of simulating plasmas below the threshold limit for the onset of high-frequency pressure-gradient-driven modes, as no mode was observed in the corresponding experiments. In practice, this was often achieved by modifying the fast-ion input parameters, and in particular the temperature and/or the density gradients, which are subject to significant experimental uncertainties and offer flexibility for adjustment. This approach was also adopted in the analyses displayed in Fig. 6, where a reduction of the fast-ion pressure gradient by 30% (solid red curves in the three plots) was necessary to avoid the destabilization of the KBM/BAE instability at low-k_y, and a subsequent heat flux run-away in the nonlinear phase of the simulations.

4.1.1 Origin of the Nonlinear Electromagnetic Stabilization without Fast Ions

A parenthesis must now be opened on the underlying physical origin of the nonlinear electromagnetic effects discussed earlier. In the analysis of JET L-mode plasmas, a potential contribution from enhanced zonal flow shearing activity was identified (Citrin et al. 2013). Similar interpretations were proposed in the context of the electromagnetic stabilization mechanisms observed in H-mode pulses, as long as the high-frequency pressure-driven modes are stabilized (Citrin et al. 2014; Garcia et al. 2015).

Subsequent theoretical and numerical investigations have shed light on this issue, revealing that electromagnetic stabilization is generally associated with the linear stabilizing effect of field line bending (Kim et al. 1993), but more interestingly with increased zonal flow activity, amplified by more efficient nonlinear coupling with ion-scale unstable modes. In particular, ion-scale instabilities (especially ITG modes) can nonlinearly drive zonal flows via three-wave coupling, even in the electrostatic limit (Diamond et al. 2005). In this regime, energy is transferred from unstable modes to the zonal component of the electrostatic potential, regulating turbulent saturation and thus limiting transport. Nonetheless, it has been shown that this energy transfer becomes significantly more effective in finite-β ITG-driven turbulence, due to enhanced nonlinear coupling efficiency (Whelan et al. 2018, 2019) below the critical KBM threshold. As a result, the saturation level of turbulent fluctuations, and consequently the energy transport, is further reduced compared to the electrostatic limit. Notably, this nonlinear electromagnetic stabilization mechanism does not rely on the presence of fast ions or fast-ion-driven modes. Indeed, in high-β hybrid scenario plasmas at JET (Citrin et al. 2014; Garcia et al. 2015; Doerk et al. 2016), in strongly NB-heated plasmas at DIII-D (Holland et al. 2021) and in high-performance scenarios at ASDEX Upgrade (Doerk et al. 2015, 2017), the nonlinear electromagnetic effects from bulk pressure contributed the most to reduce the energy transport of the thermal ions. The presence of fast ions provides an additional stabilizing effect.

In these studies, beyond the electromagnetic reduction of the linear ITG drive (as described in section 2.3), a clear up-shift of the nonlinear ITG turbulence threshold was also observed, further confirming the strong role of electromagnetic effects in turbulence regulation.

4.2 The role of Near-Marginal Stability Alfvén Eigenmodes in the Electromagnetic Stabilizing Mechanism

Building upon these findings, both from theoretical insights and validated modelling results, subsequent analyses aimed to unveil the specific role of fast ions in the nonlinear stabilizing mechanism observed in JET scenarios. Importantly, the same gyrokinetic code, GENE, was used in its local (flux-tube) version. As a test-bed case, the JET L-mode pulse #73,224 was thoroughly analyzed, enabling a possible identification of the physical origin of the fast-ion-induced stabilization observed in the seminal work by (Citrin et al. 2013): the main beneficial role of the NB-generated fast ions is to directly transfer energy to high-frequency low-wavenumber modes, which were identified as TAEs (Di Siena et al. 2019). These TAEs were observed via the eigenvalue solver simulations, which allowed to identify them with negative linear growth rate. Such an identification was also made possible by the artificial increase of the local q-profile by approximately 20% in the modelled equilibrium. This adjustment effectively opened the TAE gap in the Alfvén continuum at the analyzed radial position $\rho_{tor} = 0.33$, a step justified by the significant uncertainties in equilibrium reconstruction in the plasma core of JET. Moreover, the simulation setup considered only the NB-generated ions, neglecting the ICRH ones, contrarily to what done in the earlier study of Citrin et al. (2013).

The observed stabilization mechanism is intrinsically nonlinear, involving complex mode-mode interactions and energy transfer across scales (Di Siena et al. 2019). This process unfolds in two main phases: in the first phase the low fast-ion drive is insufficient to linearly destabilize the TAEs, which remain subdominant and below their instability threshold; Meanwhile, the steep ion temperature gradient drives significant ITG-induced thermal transport. During this phase, the linearly stable TAEs receive energy from a multi-scale interaction through the coupling with ion-scale ITG modes, allowing a redistribution of the energy nonlinearly and driving, thereby, the TAEs unstable (Fig. 7) . Further theoretical interpretations of this mechanism proposed that the TAE stability is affected via the scattering of the TAEs by the background microinstabilities. In particular, this occurs through the interaction of the nonlinearly generated Kinetic Alfvén Waves (KAWs) by the original TAE with the microinstability through the electron Landau damping. For KAWs at frequencies lower than the original TAE, this interaction leads to the TAE damping, while for higher frequency KAW sidebands a stimulated absorption of the microinstability energy is observed (Chen et al. 2022, 2023). Another interpretation proposes that the TAE excitation could also occur via inverse Compton scattering of ITG turbulence by fast ions (Marchenko 2022). The precise identification of the theoretical explanation for the nonlinear TAE excitation could be however strongly related to the plasma regime, and in particular on the relative density of the fast ion component, and thereby to the proximity to burning plasma conditions.

Signatures of this energy transfer process are evident in the high-frequency oscillations observed in the time traces of the thermal ion heat flux consistent with earlier observations in similar analyses (Bass and Waltz 2010). Unfortunately, to save com-

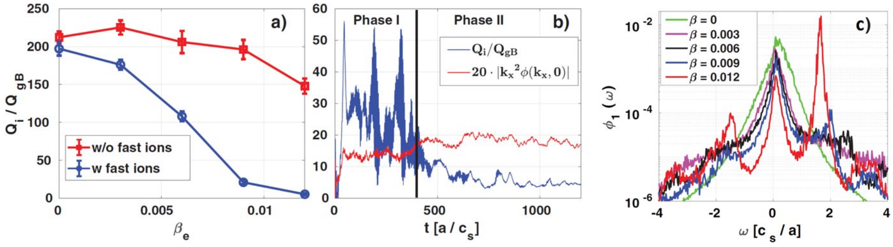


Fig. 7 (a) Dependence of the GENE-computed thermal ion heat fluxes on β_e for the cases without and with fast ions. Clearly, the simulations including fast ions achieved a larger turbulent transport reduction. (b) Time evolution of the thermal ion heat flux, displaying two different phases, correlating with the zonal flow shearing rate time traces, for the case with $\beta_e = 0.012$. (c) Time-averaged frequency spectra of the perturbed electrostatic potential ϕ_1 for various β_e values, displaying a growing peak at the TAE frequency range with increasing β_e. Figures adapted from Di Siena et al. (2019)

putational resources, the heat flux time traces saving process was purposely downsampled, eliminating thereby the high-frequency oscillations in Fig. 1 of Ref. (Di Siena et al. 2019).

Once the energy transferred to the fast-ion scales/modes becomes sufficient to nonlinearly destabilize them, a second characteristic phase begins. The energy redistributed to large-scale modes (i.e., TAEs) becomes further involved in a cross-scale interaction, in which part of this energy is subsequently transferred to the zonal components of the electrostatic potential. This complex mechanisms was elucidated through detailed analyses of the nonlinear coupling and energy transfer in the gyrokinetic local simulations. A dedicated diagnostic (Navarro et al. 2011), based on the free energy balance formalism (Maeyama et al. 2015, 2022), was employed to track energy exchanges at specific wavenumbers, in particular in the range involving the main cross-scale interactions, i.e. the zonal components, the TAE- and the ITG-scales.

As a result, the enhanced zonal flow activity driven by the AEs strongly stabilizes the ITG drive and reduce, thus, the overall thermal ion transport. Such a reduction, in turn, weakens the nonlinear drive for TAEs, which had been destabilized via energy redistribution from ITG turbulence. The system reaches a new quasi-steady state, characterized by complex spatio-temporal cross-scale interactions and an overall suppression of heat transport. This study thus demonstrated the central role of Alfvénic modes in nonlinear electromagnetic stabilization. Differently to what was reported in Sect. 4.1.1, in this case the fast-ion-triggered mechanism dominates over the pure β-driven electromagnetic stabilization in reducing ion-scale turbulent heat fluxes. However, it should be emphasized that this study was not validated against experimental results, and therefore the experimentally observed improved core confinement in JET pulse #73,224 could also be due to other beneficial mechanisms not considered here.

It is important to note that the most pronounced stabilization via such a mechanism occurs for the very marginal linear stability of the TAEs. This was demonstrated by modifying artificially the electron β parameter in the local simulations centered at $\rho_{tor} = 0.33$, scanning it from the experimentally-inferred value of $\beta_e = 0.33\%$ up to 1.2%. At the upper end of this range, the mechanism becomes so effective that the thermal ion heat flux is almost completely suppressed (Di Siena et al. 2019). The value of $\beta_e = 1.2\%$ is, nonetheless, typical of H-mode plasmas at JET for that specific radial location, and not of the L-mode plasma considered in the study. Indeed, at the nominal value of $\beta_e = 0.33\%$, the overall transport reduction was limited to $\sim$20% with respect to the simulation without including the fast ions. However, consistent with earlier studies (Bass and Waltz 2010; Citrin et al. 2014), it was also observed that once the TAE linear stability threshold is exceeded, i.e. at sufficiently large β conditions, the beneficial mechanism is not anymore valid. In that regime, linearly unstable TAEs generate strong (electro)magnetic flutter, which dramatically enhances electron transport to unphysical levels. As also discussed in the remainder of the review, the effectiveness of this mechanism appears to be highly sensitive to the β parameter, thereby defining a constrained operational parameter window in which fast-ion-induced Alfvénic activity can lead to turbulence suppression rather than degradation. Indeed, in other studies, treated in the following, this electron transport increase is not observed (Mazzi et al. 2022a),[87],(Garcia et al. 2024).

An additional point to be considered is that the concept of marginality is somehow subtle to achieve from an experimental point of view. This makes the validation of such a mechanism against actual experimental measurements particularly challenging. As a matter of fact, in the experimental pulses used as test cases in this study, no TAEs were observed nor measured by any diagnostic, limiting the possibility of confirming the presence of the cross-scale interactions predicted by the simulations. On the other hand, in future fusion reactors, where a substantial population of alpha particles is expected, strong Alfvénic activity is predicted (Pinches et al. 2015; Rodrigues et al. 2015; Scott et al. 2020).

This study revealed that fast-ion-driven AEs can enhance the zonal flow and current activity, as already previously reported (Chen and Zonca 2012; Qiu et al. 2016). This has clear implications for background turbulence, consistent with the pioneering work of Ref. (Zonca et al. 2014), which showed possible cross-scale interactions relating large- and/or meso-scale dynamics down to micro-scale turbulence evolution. Nevertheless, while the theoretical and computational insights are compelling, the mechanism still awaited experimental validation. Establishing its relevance in actual experimental conditions remained an essential step toward confirming the beneficial impact of fast-ion–Alfvén mode interactions on confinement.

4.3 Impact on Different Background Turbulence

The aforementioned results of Sects. 4.1 and 4.2 were all obtained in plasmas characterized by ITG-dominated ion-scale turbulence spectra. To assess the robustness of the fast-ion-triggered stabilization mechanism in different turbulence regimes, further studies were conducted focusing on plasmas dominated by trapped-electron modes (TEMs). In particular, a JT-60U plasma was analyzed using local GENE gyrokinetic simulations following a similar methodology (Mazzi et al. 2020). It was found that the impact of the fast ions, as well as the fast-ion induced nonlinear mechanisms, was almost negligible on the TEM linear stability and TEM-driven turbulent transport. In Fig. 8(a), the heat flux time traces for both thermal D and electron species show no impact from the introduction of the fast ions in the simulations, even at different fast-ion pressure gradient.

This lack of effect was primarily attributed to the weak role of zonal flows in regulating temperature-gradient-driven TEMs, as detailed in prior works (Merz and Jenko 2008; Ernst et al. 2009, 2016; Chen and Chen 2022). Although the zonal flow shearing rate was found to increase in the presence of fast ions, the corresponding influence on turbulence saturation and transport remained marginal. It should be, however, pointed out that such a result was again obtained in high-β_e plasma conditions ($\beta_e = 1.48\%$), at which high-frequency modes driven by the fast ions and identified as BAEs were found unstable (Mazzi et al. 2020). In such regimes, where large-amplitude magnetic flutter is present, the beneficial fast-ion-triggered mechanism may be strongly spoiled. This highlights the need for further dedicated studies to clarify the interplay between fast-ion-driven modes and turbulence in TEM-dominated regimes at lower β_e.

Panels (b) and (c) of Fig. 8 display the frequency spectra of the electrostatic potential of the simulations without and with fast ions, respectively. Even in the *modified*

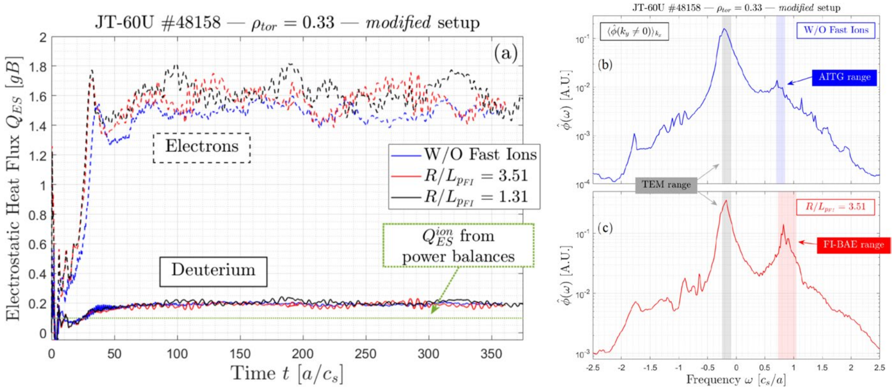


Fig. 8 Time traces of the electrostatic heat flux for both electrons and deuterium, computed by GENE, for cases without and with fast ions. The experimentally inferred deuterium heat flux level is indicated by the green dotted curve. Almost no effect of the fast ions is observed on the TEM-induced heat fluxes. (b) and (c) display the frequency spectra of the nonlinear electrostatic potential fluctuations for the cases without and with fast ions, respectively, showing the emergence of subdominant high-frequency instabilities in both configurations

setup, where the electron β_e was reduced by 20% and the fast-ion pressure gradient lowered by 80%, a clear signature of a subdominant high-frequency fast-ion-driven mode is still observed. The stabilization of these modes was found to be crucial for reproducing the experimentally inferred power balance, in line with earlier findings (Citrin et al. 2014; Garcia et al. 2015).

However, dedicated experimental studies in the TCV tokamak demonstrated that the fast-ion-driven TAEs have a mildly beneficial effects on the global confinement (Mazzi 2023), and in particular on the turbulence-induced density fluctuation amplitude measured by the reflectometer. Local gyrokinetic simulations revealed that in those conditions, TEMs are the dominant microturbulence at the mid-radius (Mazzi 2023), but those were not conclusive. Indeed, when including the fast-ion modes in the modelling frameworks, due to the appearance of streamer-like structures along the radial direction of the flux-tube domain, the local assumption was strongly impaired. Hence, global simulations are highly required for the TCV plasma with inherently large ρ^*.

In a different context, without involving directly AEs but more in particular the fast-ion-driven Fishbone instabilities, the effect of the Fishbone-induced zonal flow activity on the TEM background turbulence in a selected DIII-D pulse was also observed to be strongly beneficial (Brochard et al. 2024). Indeed, the ITB formation obtained in GTC simulation with unstable fishbones destabilized by NB-generated fast ions was validated against the experimental measurements, and it was attributed to the generation of a strong zonal flow activity by the fishbones and suppressing the TEM background turbulence in such plasma conditions. More details on this study are provided in Sect. 5.2.

4.4 Theoretical Understanding of the Interaction between Alfvén Eigenmodes and Zonal Structures

The first nonlinear investigations addressing the interaction between large-scale fast-ion-driven Alfvén Eigenmodes (AEs) and zonal perturbations of both electrostatic and electromagnetic fields were carried out with the gyrofluid TAEFL (now FAR3d) code (Spong et al. 1994). In parallel with this modeling effort, a theoretical framework describing the nonlinear saturation of TAEs, including the wave–wave coupling mechanism, was developed in Ref. (Zonca et al. 1995), which demonstrates that beyond a certain critical mode amplitude the nonlinear excitation of an additional electromagnetic field perturbation, dissipating the mode energy towards small-scale dynamics, is essential in particular TAE regimes (Vlad 1995). This illustrates that the pioneering efforts came simultaneously from both analytical and modelling fronts in the understanding of nonlinear wave–wave processes in the mode saturation of fast-ion-driven Alfvénic instabilities in tokamaks, thereby complementing the main focus of the community on wave-particle interactions (e.g. Berk and Breizman 1990; Berk et al. 1996). In this context, further studies deepened the wave-wave dynamics in the TAE nonlinear evolution. In particular, combining theoretical predictions and numerical investigations, it was shown that the mode-mode coupling cannot be neglected in the TAE evolution as the saturated mode amplitude is comparable in the two approaches (Chen et al. 1998).

Only more than a decade later, the modelling efforts on the TAE saturation mechanism through wave-wave coupling were revived by the findings of nonlinear global hybrid MHD-kinetic simulations (Todo et al. 2010). In these MEGA (Todo and Sato 1998) simulations, employing a simplified toroidal geometry with circular flux surfaces, only the $n = 4$ toroidal Alfvén Eigenmodes (TAEs) were destabilized, with the multiple-integer sideband harmonics also present in the nonlinear phase due to mode-mode couplings. The objective of this study was to detail the nonlinear evolution and the saturation mechanisms of the TAE instability. The fast-ion population was modeled with an initial slowing-down distribution, and the fast-ion pressure at the axis was scanned. Different fast-ion pressure profiles were used to determine a low- and a high-level of TAE saturation. Inspecting the radial structures of the principal modes, i.e. $n = 4$ TAEs and $n = 0$ zonal perturbations, during the linear growth of the modes in the simulation with high TAE saturation level, it was observed that their structures peak at very similar magnetic surfaces suggesting an interaction between the TAEs and the zonal flows. Furthermore, the TAE nonlinear amplitude was strongly reduced by half with respect to the first saturation level reached at the end of the linear phase. In this case, the zonal flow perturbations grows with a rate which is measured to be the double of the TAE growth rate. Interestingly, since the zonal flow radial structure was not varying during the linear growing phase, the study also unveiled that the zonal flows are directly generated by the TAE-induced perturbations. The implications of a large zonal activity on both the TAE saturation amplitude and the global plasma confinement were already preliminary discussed in this study. Thus, not only the effects of the zonal flows on the TAE saturation amplitude were analyzed, as already done in earlier studies (Spong et al. 1994), but also on the global properties of the plasma confinement and background turbulence were suggested to be relevant.

Such findings, therefore, inspired theoretical efforts that were carried out in subsequent years to unveil the physical mechanism causing the zonal flow growth (Chen and Zonca 2013, 2016). These confirmed that zonal structures can be generated by AEs through different mechanisms, depending on the nature and the phase of the modes themselves. The following two mechanisms takes the origin from a wave-wave interaction, rather than the wave-particle ones, which has previously set the reference for the linear growth, and nonlinear evolution/saturation of the AEs (Berk et al. 1996).

In Ref. (Chen and Zonca 2012), the mechanism of the modulational instability is described as a spontaneous generation of the zonal structures in the nonlinear phase when the AE amplitude exceed a specific threshold. Also, as it was observed for the drift-wave generation of the zonal flows (Chen et al. 2000), the growth rate of the zonal perturbations is comparable to the one of the free energy drive, i.e. the AEs. In this case, the zonal components of the vector potential, the so-called zonal currents, dominate over the zonal flows (Chen and Zonca 2012). The impact of the zonal currents on the microinstability saturation is still debated, but is generally assumed to be weaker(Chen et al. 2001). In this modulational instability process, the contribution of the fast-ion-driven AEs to the generation of zonal structures is larger than the one of the contribution coming from the bulk-plasma-driven turbulence, generally fed via the Reynolds and Maxwell stress tensors (Diamond et al. 2005).

One other possible mechanism describes that the zonal structures can be forced-driven by the finite-amplitude TAE perturbations, with these latter modes acting as a direct energy pump source (Qiu et al. 2016, 2017, 2023; Chen et al. 2024). This finds a confirmation in the generated zonal structure growth rate, which is the double of the TAE one, as measured in previous and later modeling analyses, e.g. (Todo et al. 2010; Zhang and Lin 2013; Biancalani et al. 2020; Sama et al. 2024). Additionally, EPMs such as fishbones have been observed to force-drive zonal structures in recent studies (Brochard et al. 2024; Brochard 2024). Interestingly, this mechanism is threshold-less, meaning that it could be active independently of the AE initial amplitude, but only with a finite and positive AE growth rate (Chen et al. 2018). This is crucial for the remainder of this review, as even marginally stable TAEs—driven unstable in the nonlinear phase through energy redistribution from the background turbulence—have been observed in gyrokinetic modelling to potentially generate a strong zonal flow activity (Di Siena et al. 2019). Up to date, most of the modeling results contemplate the forced-driven generation of the zonal flows as the principal mechanism for the nonlinear generation and growth of the zonal structures, although the modulational instability should not be discarded a-priori for specific cases.

Recent studies have yielded promising results in the development of reduced models that capture the essential dynamics of forced-driven zonal flows and their impact on the saturation and evolution of Alfvén Eigenmodes (AEs). In particular, Ref. (Barberis et al. 2025) presents a self-consistent description of the zonal flow evolution in the presence of an AE pump wave, without imposing any constraints on the initial saturation level of the mode. In parallel, another study (Yan and Diamond 2025) adopts a predator–prey-like framework to describe the interaction between AE-driven zonal flows and microturbulence, assuming a simplified evolution for the AE pump wave. Further, a very recent analytical study, performed in the radial local limit, pointed out that the interaction of AEs with microinstabilities mediated via zonal structures can also be weakly destabilizing (Qiu et al. 2025), but more detailed investigations must be carried out on this. Eventually, adopting a Kuramoto-type model (Acebrón et al. 2005), it has been recently shown that a phase synchronization between the microinstabilities and the fast-ion-driven modes can be induced by the dynamics of the fast ions, strongly affecting the zonal flow amplitude (Ghizzo and Del Sarto 2023) up to the generation of an internal transport barrier (Ghizzo et al. 2024). These complementary approaches contribute to a deeper theoretical understanding of AE–zonal flow dynamics and their role in turbulence regulation.

Furthermore, the zonal structures can also be generated, in a similar fashion, by other AEs, such as Reversed Shear Alfvén Eigenmodes (RSAEs) and β-induced Alfvén Eigenmodes (BAEs) (respectively Wei et al. 2021; Liu et al. 2022 and Qiu et al. 2016; Biancalani 2021), suggesting thereby that fast-ion-driven AEs and EPMs can generally be crucial in regulating the plasma turbulence and confinement properties through the forced-driven generation of zonal structures. Nevertheless, microturbulence can damp the zonal flows generated by large-scale fast-ion-driven modes through local profile relaxation caused by increased transport. This process affects the polarization of the zonal perturbations and, consequently, their amplitude (Liu et al. 2024). Such changes can also influence the origin of the zonal flows, namely the fast-ion-driven AEs, potentially leading to oscillatory dynamics (Liu et al. 2022), highlighting thus the complex interaction between all the actors described above.

4.5 Theory-driven Experiments with MeV-range Ions Destabilizing Alfvén Eigenmodes

Significant efforts were subsequently devoted to recovering this beneficial, complex, and multi-scale mechanism under more realistic plasma conditions. To this end, theory-driven experiments were pursued at JET, specifically designed to deliberately probe and observe the predicted dynamics. In parallel, attention was given to extending the investigation to more reactor-relevant regimes, characterized by MeV-range ions (mimicking the energy of fusion-born alpha particles), dominant electron heating, and low externally imposed plasma torque.

A novel ICRH scheme was, thus, applied to JET plasmas. Such a novel scheme, known as the three-ion heating scheme scenario (Kazakov et al. 2017), relies on the presence of three ion species whose charge-to-mass ratios (Z/A) satisfy the condition $(Z/A)_2 < (Z/A)_{abs} < (Z/A)_1$, where the indices 1 and 2 refer to the two main ion species, whereas *abs* stands for the absorber species present in traces. When such a mixture is well controlled, the radial profile of the dominant left-hand polarized component (rotating in the ion diamagnetic direction) of the ICRH wave electric field can be tailored to align with the ion-ion hybrid resonance layer. If the absorber species is present in small traces close to such a resonance layer, the ICRH power is efficiently absorbed (Ye et al. 2015; Kazakov et al. 2015). An additional smart expedient is to use the $\sim$100 keV NB-generated D as the absorber species, exploiting the Doppler-shifted wave resonance (Kazakov et al. 2020), further accelerating the already fast ions up to MeV-range energies (Ye et al. 2021).

Using this scheme, hence, a ^{3}He–D$_{\mathrm{NBI}}$–D L-mode plasma scenario was successfully developed at JET, mimicking reactor-relevant conditions. A significant population of co-passing MeV-range ions was generated, which excited a rich spectrum of Alfvénic activity (Nocente et al. 2020). Beyond TAEs, also Elliptic Alfvén Eigenmodes (EAEs) and Reversead Shear Alfvén Eigenmodes (RSAEs) were destabilized. Remarkably, despite the strong Alfvénic activity and high-energy ion content, plasma confinement remained robust. Compared to a reference pulse with identical engineering parameters but relying solely on NBI heating, this enhanced performance was clearly observed. This comparison is not reported here but is illustrated in Fig. 2 of Ref. (Mazzi et al. 2022b), in which the pulse #94,701, heated through the three-ion heating scheme (ICRH+NBI), is compared to pulse #94,704, heated with the same input power but only through NBI.

Under these improved-performance conditions, approximately 3% of concentration of MeV-range confined ions with respect to the total plasma density were generated at the analyzed radial location (Mazzi et al. 2022b), a value similar to the one expected for fusion-born alpha particles (Garcia et al. 2018). These ions also contributed to significant electron heating in the plasma core, as their energy exceeded the critical threshold for slowing down on electrons (Stix 1975). Additionally, due to the relatively low NBI power, the external torque was limited. Altogether, these features make this scenario a highly relevant test-bed for validating predictions for future fusion reactors such as ITER (Garcia et al. 2019).

Following these striking experimental outcomes, first principle gyrokinetic modeling efforts were undertaken to investigate the underlying physics. Flux-tube simulations with the GENE code were performed at the radial position at which TAEs were observed experimentally via reflectometer measurements, namely at $\rho_{tor} = 0.23$. The fast-ion distribution function is approximated with an equivalent Maxwellian function from the integrated modelling calculations, yielding a temperature ratio to the electron component of $T_{FI}/T_e = 33.8$. This value is significantly closer to the expected ratio for fusion-born alpha particles in ITER ($T_\alpha/T_e = 41.3$) (Garcia et al. 2018) than the previous numerical studies (see Sect. 4.2).

The linear simulations revealed that the very energetic ions destabilized high-frequency modes, clearly identified as TAEs, with a growth rate lower than the dominant ITG modes peaking at the thermal ion scales (Mazzi et al. 2022a). The linear spectra, compared to the case without including the suprathermal ions show only a negligible direct effect of the fast ions on the ITG linear stability, thereby excluding the possible channels of linear fast-ion/turbulence interaction mechanisms discussed in Sect. 2.

On the other hand, a clear influence of the fast ions emerged from the computationally demanding multi-scale nonlinear simulations, which captured both fast-ion and background ITG turbulence dynamics. Due to the large uncertainties in the fast-ion temperature and density profile reconstructions, a wide scan in the normalized fast-ion pressure gradient was performed, encompassing thus all the various stability conditions for the TAEs, from stable to unstable, passing through the marginality. The resulting thermal ion heat diffusivities for both majority species (D and ^{3}He) are shown in Fig. 9.

A marked reduction in transport was observed only beyond a certain threshold in $R/L_{p_{FI}}$, with values in good agreement with the experimental power balance as

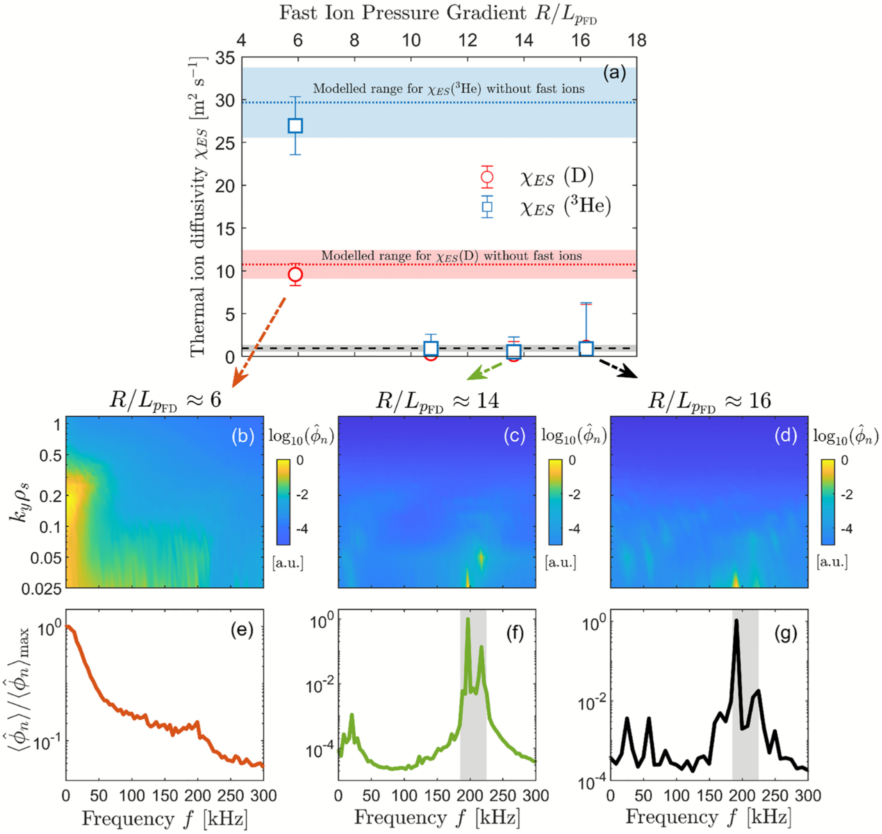


Fig. 9 (a) GENE-computed electrostatic heat diffusivities for both thermal ion species are shown as a function of the fast-ion pressure gradient $R/L_{p_{FD}}$. The experimentally inferred diffusivity level is indicated by the horizontal black dashed line and is matched only when $R/L_{p_{FD}}$ exceeds a threshold corresponding to the destabilization of fast-ion-driven TAEs in the simulations. This is confirmed by the peaking of the electrostatic potential fluctuation spectra within the gray shaded area (representing the experimentally measured TAE frequency range) shown in panels (c), (d), (f), and (g). Figure adapted from Mazzi et al. (2022b)

inferred from TRANSP simulations. Specifically, a strong suppression of turbulent transport appeared when the system approached the TAE marginal stability point ($R/L_{p_{FI}} = 10.7$), consistent with prior findings (Di Siena et al. 2019). This effect is primarily attributed to enhanced zonal flow activity. Importantly, the stabilizing trend persisted even in linearly unstable TAE cases, although some degradation of confinement was observed at higher $R/L_{p_{FI}}$ (see Fig. 10 of Ref. Garcia and Contributors 2022), mainly due to an increase in the electromagnetic component of the fluxes of both electrons and fast ions (as also observed experimentally Gorelenkov et al. 2010; Collins et al. 2016). This is consistent with earlier observations that strongly unstable AEs can induce substantial magnetic flutter, enhancing electron heat transport due to the lower electron mass and its stronger response to magnetic fluctuations.

However, it should be clarified that in the strongly unstable cases the local approximation employed in these gyrokinetic simulations may under-estimate the electron

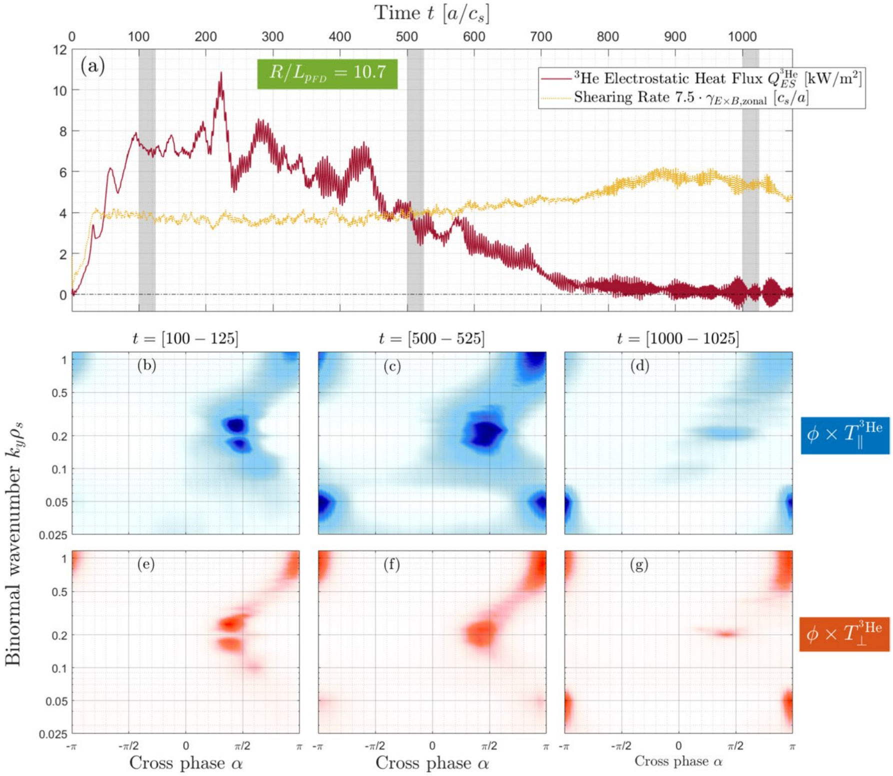


Fig. 10 (a) Time traces of the electrostatic heat flux of the thermal ^{3}He species and the zonal shearing rate for a marginal stability case. The vertical gray shaded areas indicate three different time windows corresponding to the three phases shown in panels (b)-(g). In the first row, panels (b)–(d) illustrate the histograms of the cross-phase $\phi - T_{3\mathrm{He},\|}$, whereas in the second row the cross-phase $\phi - T_{3\mathrm{He},\perp}$ is shown. A clear shift of the cross-phase towards large-scale in-phase structures is noted

and fast-ion fluxes, which need to be better assessed through radially global numerical analyses (Mazzi et al. 2022b).

Bispectral analyses of the wavelet-transformed (Meneveau 1991; Hudgins et al. 1993) electrostatic field components, were carried out to investigate the physical mechanism underlying the enhanced zonal flow activity. These analyses revealed a complex spatio-temporal mode-mode coupling between the TAE and the zonal flow scales (Mazzi et al. 2022b, a). The results suggest a net energy transfer from the dominant TAE wavenumbers to the zonal components of the electrostatic potential, with a consequential stabilizing impact on ITG-driven turbulence. Interestingly, this coupling mechanism remains active and well balanced even under conditions in which TAEs are linearly unstable. Moreover, analogous mode-mode coupling dynamics were observed in the magnetic vector potential, leading to increased zonal current activity (Mazzi et al. 2022b; Mazzi 2021). Nonetheless, the consequences of these magnetic zonal structures on turbulent transport, and on the overall turbulence dynamics, remain to be fully assessed under these plasma conditions. Possibly, the zonal current may locally modify the q-profile, impact on the Alfvén continuum, and thereby affect the mode damping (Spong et al. 1994).

More recent studies have demonstrated that this nonlinear coupling between TAEs and zero-frequency zonal flows can also be observed experimentally via density fluctuation measurements (Ruiz et al. 2025). This remarkable result was achieved by analyzing the Doppler Backscattering (DBS) reflectometry data from JET, obtained in a similar three-ion heating scheme scenario. A bicoherence analysis of the electron density fluctuations measured by the DBS at $\rho_{tor} \sim 0.3$, that is still within the TAE radial location, was performed. It is thus clearly shown that a triadic mode-mode coupling among counter-propagating TAEs and zero-frequency modes identified as zonal flows. Such a coupling extends to TAE harmonics higher than the fundamental, corroborating the coupling effectiveness.

Remarkably, similar correlation between AE and shear flow generation has also been observed recently in dedicated plasmas of the LHD stellarator (Varela et al. 2024).

An additional point of interest, analyzed in Ref.(Mazzi et al. 2022a), concerns the nonlinear modification of the cross-phase between temperature of the thermal ions and electrostatic potential fluctuations at large spatial scales, induced by the destabilization of TAEs. The transition to a TAE-dominated turbulence regime leads to a more in-phase interaction between these two quantities, which are the key contributors to the computation of turbulent heat flux. As a consequence, despite an increase in the amplitude of electromagnetic fluctuations, the net thermal ion heat flux is substantially reduced across the entire binormal wavenumber spectrum. This behavior is illustrated in Fig. 10, which shows the cross-phase between the electrostatic potential and both the parallel and perpendicular temperature fluctuations of the thermal ions. Depending on the phase of the simulation, the cross-phase structures are affected. At the beginning of the simulation, the cross-phase is predominantly out-of-phase and peaks around the ITG-dominated binormal wavenumber $k_y\rho_s \sim 0.25$, with no significant contribution from large-scale structures. As the TAEs begin to grow and zonal flow activity intensifies (highlighted by the yellow curve in the figure) the thermal ion heat flux starts to decrease, exhibiting clear modulations at the TAE frequency. During this intermediate phase, a new in-phase structure emerges at low-k_y scales, which, due to its phase alignment, does not contribute to radial transport. Finally, in the last phase of the simulation—when the beneficial mechanism is fully established—the dominant contribution in the cross-phase plot corresponds to this in-phase low-k_y structure, directly associated with the fast-ion-driven TAEs.

A similar nonlinear cross-phase modification effect had already been reported in earlier gyrokinetic simulations for another JET pulse (Doerk et al. 2016), and, as reported in Sect. 4.8, also in global GENE simulations of a JET DT pulse (Di Siena 2025), reinforcing the generality of this result.

4.6 Toward Robust Reproducibility of the Mechanism in DT Plasmas

With the striking observation of improved confinement in the presence of unstable Alfvénic activity driven by MeV-range ions, it was natural to investigate the application of this beneficial mechanism in a dedicated scenario designed for the DTE2 campaign at JET (Mailloux 2022; Maggi and Contributors 2024; Garcia and Contributors 2025), conducted in 2021. Thus, a plasma scenario was developed featuring dominant ICRH heating on the minority H ($\sim$1%) in a 50–50% D-T mixture (Garcia et al. 2024). This scenario aimed to reproduce the rich Alfvénic activity, dominant electron heating in the core, and low plasma torque observed in previous studies (Nocente et al. 2020; Ye et al. 2021), while simultaneously maximizing the fusion power output under these reactor-relevant conditions.

Unlike the previous scenario, the DT plasmas exhibited not only Alfvén Eigenmodes (AEs) in the high-frequency range but also core-localized Fishbone and Neoclassical Tearing Mode (NTM) instabilities. This makes the MHD dynamics even more complex, with clear nonlinear three-wave interactions between the TAEs and the NTM (Garcia et al. 2024), and the additional ingredient of the Fishbone activity to the meso-scale generation of zonal flows (more details will be given in Sect. 5.2).

Despite the typically detrimental impact of such MHD fluctuations, the global confinement of the reference pulse #99,896 was remarkable. Indeed, it even exceeded that of the equivalent pure-deuterium pulse #100,871, performed in the subsequent campaign under matched engineering conditions, with the additional observation of a temperature pedestal at the plasma edge, formed without the triggering of Edge Localized Modes (ELMs) (Garcia et al. 2024). Also the MHD activity was properly matched, thereby triggering all the nonlinear dynamics previously discussed. A clear isotope effect (Garcia et al. 2022), attributed to the presence of tritium, was also observed, manifesting as reduced thermal ion diffusivity in the deep core and an enhanced pedestal height at the edge.

In order to uncover the underlying physical mechanisms leading to such an optimum plasma state, extensive gyrokinetic analyses with CGYRO were carried out. Furthermore, to complement and extend the numerical modelling, global gyrofluid simulations with the FAR3d code (Spong et al. 2021; Varela et al. 2024). These analyses allowed to confirm the origin and evolution of the large-scale MHD activity observed in this reference pulse.

It was first established that the rich MHD activity, and especially the TAE activity, was not destabilized by the fusion-born alpha particles because of their low concentration, but rather by the ICRH ions generated in the plasma core (Varela 2025). Simulations with the FAR3d code confirmed that TAEs generate strong zonal flow activity through a cross-scale energy transfer to the zonal components of the electrostatic potential, consistent with previous findings. Fishbones were also found to generate zero-frequency axial-symmetric flows, albeit with lower amplitude compared to the TAE-induced zonal flows [154]. This enhanced zonal activity is, however, consistent with the optimum confinement achieved in this plasma scenario, supported by experimental power balance analyses showing very low thermal diffusivity in the plasma core, especially within the radial region where the TAE and Fishbone are measured.

To include a self-consistent evaluation of the complex interplay with also the background turbulence, first-principle gyrokinetic CGYRO simulations were performed, unveiling some interesting details on the underlying physical mechanism. These fluxtube simulations investigated both fast-ion and thermal-ion scales, thereby resolving transport contributions from TAE- and ITG-scale instabilities. Also in CGYRO, TAEs were indeed found unstable at low-wavenumber (see the linear spectra in Fig. 11(a) and (b)), and in such conditions the nonlinearly computed thermal flux of the thermal species remains close to the threshold and matches the TRANSP-calculated power balance. A recent benchmark study comparing GENE and CGYRO on the impact of fast ions on turbulent transport in L-mode KSTAR plasmas showed good qualitative agreement between the two codes in the absence of rotation effects (Kim et al. 2025).

A particularly interesting outcome from the CGYRO simulations was the sensitivity of turbulence stabilization to the characteristics of the fast-ion population and their role in TAE destabilization. When the fast-ion to electron temperature ratio was reduced by a factor of four (from $T_{FI}/T_e = 21$ to 5.25), the TAEs are not anymore linearly unstable, and the nonlinear suppression of turbulence was significantly diminished. A similar effect was observed when the fast-ion temperature gradient was set to zero (Garcia et al. 2024). These considerations are displayed in Fig. 11.

These findings highlight that the presence of linearly unstable TAEs in the simulation is a necessary condition to recover the experimentally inferred thermal transport levels. This aligns with previous JET studies (Mazzi et al. 2022b, a) but contrasts with earlier analyses assuming marginal stability to avoid heat-flux runaway (Di Siena et al. 2019). Although the former case is a validated study and the latter mainly a numerical study, the discrepancy between the two cases may arise from the different plasma conditions considered. A more detailed discussion is provided in Sect. 6.

Furthermore, the sensitivity of the turbulent heat flux to the fast-ion characteristics have already been discussed in prior isotope effect studies of JET L-mode plasmas, for which the fast-ion pressure in H plasma was half of the one in D plasma, leading thereby to a weaker turbulence reduction in H plasma (Bonanomi et al. 2019).

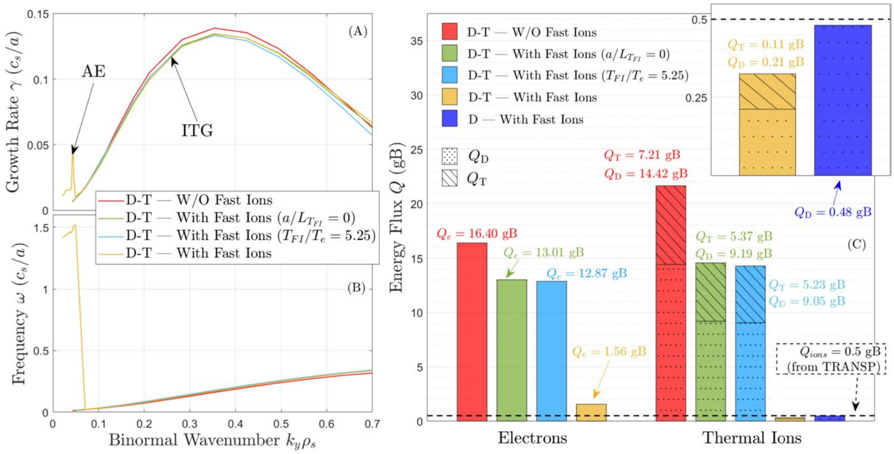


Fig. 11 (a) and (b) Linear growth rate and frequency spectra versus binormal wavenumber computed by GENE for different input configurations, showing almost no linear effects due to fast ions except for the destabilization of fast-ion-driven TAEs at small k_y. (c) Nonlinear electron and thermal ion heat fluxes for the same configurations as in panels (a) and (b). Agreement with the experimentally inferred heat flux level (horizontal black dashed line) is achieved only when TAEs are destabilized. Figure reprinted from Garcia et al. (2024)

Moreover, the good thermal confinement achieved for the bulk particles in the presence of large-scale MHD modes was further supported by the relatively weak fast-ion transport measured experimentally. While the Fishbone and NTM activity were found to cause alpha particle losses—despite not being driven by the alpha population—no signs of fast-ion depletion were observed for the higher-frequency modes such as TAEs (Garcia et al. 2024). This behavior was further verified through FAR3d simulations, which showed that the fusion-born alpha particles can indeed interact with the Fishbones and be expelled from the plasma core [154].

4.7 Comparison of Local and Global Approaches in Modeling the AE-Induced Transport Reduction

The simulations previously discussed, which explored the effect of fast ions on background microturbulence, were all performed using the local (flux-tube) gyrokinetic approximation. For the sake of clarity, the local approach assumes that turbulence occurs on spatial scales much smaller than the equilibrium gradients, so that the background plasma parameters (e.g. density, temperature, magnetic geometry parameters) can be treated as constant within a narrow, field-aligned simulation domain. Turbulence is then computed only along a thin flux tube around a chosen flux surface, capturing the localized unstable modes while neglecting global profile variations. While this approach can in practice also retain the large-scale and meso-scale activities, which are especially relevant for high-ρ^* fast ions (due to their large energy), it inevitably stretches the assumptions at the basis of the local approximation, raising questions about the robustness of the obtained results.

To address this, a series of extensive comparative analyses between local and radially global gyrokinetic simulations were carried out using the GENE code, applied to identical plasma conditions (Di Siena et al. 2023). The reference plasma conditions used for such a study were inspired by JET L-mode pulse #73,224, previously studied for its experimentally observed enhancement in thermal ion confinement in the presence of NB-generated fast ions (Citrin et al. 2013; Di Siena et al. 2019) (see Sect. 4.2 for more details). In contrast to earlier work, however, the safety factor profile was left unmodified in this study.

In line with the methodology of Ref. (Di Siena et al. 2019), a scan in the electron beta parameter β_e was performed to systematically investigate the role of electromagnetic AITG/KBAE activity. Four regimes were distinguished: the electrostatic limit, marginal stability, weak instability, and strong instability of fast-ion-driven modes. Linear simulations revealed a good agreement between the local and global approaches, particularly at low toroidal mode numbers, where high-frequency modes become unstable at sufficiently large β_e. These fast-ion-driven modes were identified as AITG/Kinetic-BAE (KBAE) rather than TAE-like modes, which had been observed in cases with modified q-profile. The identification of these instabilities was corroborated through detailed comparisons with LIGKA (Lauber et al. 2007) and ORB5 (Lanti et al. 2020) simulations, which also showed good quantitative agreement with the global GENE results.

The thermal ion heat flux computed through nonlinear flux-tube GENE simulations, performed at different radial locations, shows qualitative agreement with—or at least follows the trend of—the corresponding global simulations in the cases with marginally stable AITG/KBAE modes. As the fast-ion drive increases, leading to weakly and strongly unstable fast-ion mode conditions, discrepancies between the local and global simulations become more pronounced, particularly in the deep core and outer radial regions for the electron and fast-ion contributions. Interestingly, in the radial region where the AITG/KBAE modes are most strongly destabilized, the agreement in the thermal ion heat flux remains relatively good even under high fast-ion drive conditions (Di Siena et al. 2023). This is evidenced in Fig. 12.

However, it must be emphasized that the flux-tube simulations fail to reproduce the electron and fast-ion heat flux components (for both electromagnetic and electrostatic contribution) in the presence of unstable fast-ion modes, as compared to the radially global simulations. This discrepancy is mainly attributed to the significant differences in the amplitude of the zonal flow fluctuations between the two approaches, which in turn leads to a mismatch in the resulting fluxes (Di Siena et al. 2023).

These findings indicate that the electron and fast-ion transport results obtained from flux-tube simulations under conditions of high β_e and unstable fast-ion modes should be interpreted with caution. Hence, global simulations are required to reliably assess the electron and fast-ion transport in such harsh conditions for the gyrokinetic modelling. On the other hand, for the thermal ion counterpart of the heat fluxes, the local calculations are in a qualitative agreement with the global ones, retrieving the same radial trend and in specific region of the domain also a good quantitative agreement. This suggests that the underlying physics, that is the generation of strong zonal shearing flows by unstable AEs is qualitatively captured by local simulations,

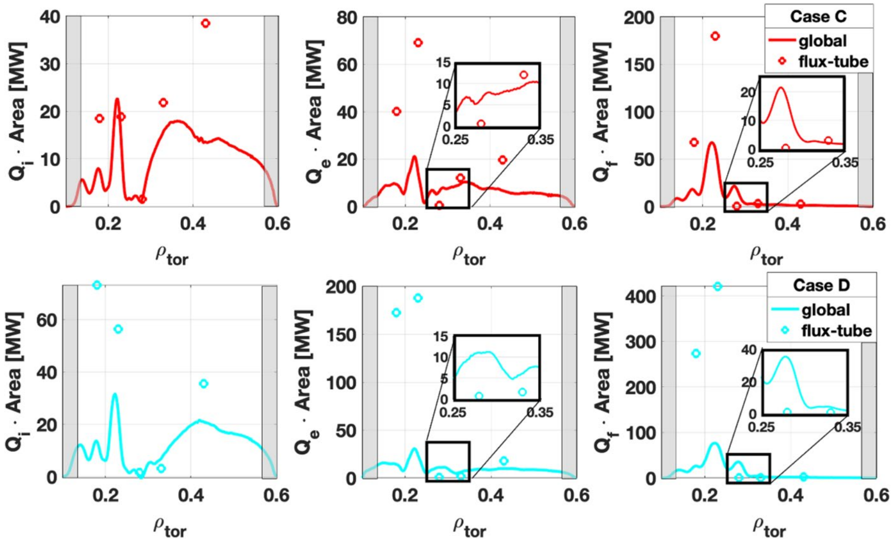


Fig. 12 Comparison of the thermal ion, electron, and fast ion heat fluxes from GENE global simulations (solid curves) and flux-tube simulations (points). The upper row shows the weakly AITG/KBAE unstable case, while the bottom row presents the strongly unstable case. Except for the inner radial region, the thermal ion heat fluxes agree relatively well even under high fast-ion drive conditions. Figures adapted from Di Siena et al. (2023)

even if the critical gradient threshold (including drive and damping contribution self-consistently) can be quantitatively different between local and global simulations. Hence, for a more complete and accurate characterization of total transport, including the spatial structure of the instabilities and associated fluxes and flows, global simulations provide a higher-fidelity framework and are highly required. As already highlighted above in this review, therefore, further efforts should be made in addressing the validity breaking of the local simulations in such harsh plasma conditions, with large β_e and (even weakly) unstable fast-ion or pressure-driven high-frequency modes. In particular, it would be extremely useful to determine the plasma parameter space (including thermal and fast-ion pressure) and the mode nature for which the local approximation fails.

Accordingly, recent numerical studies using global gyrokinetic simulations have been carried out to investigate specific plasma scenarios in ASDEX Upgrade and JET, in which Alfvén Eigenmodes may play a role in influencing confinement and turbulence characteristics. The results of these computationally demanding simulations are presented and discussed in the following section.

4.8 Gyrokinetic Global Analysis of Alfvén Eigenmode Impact on Turbulence Mediated by Zonal Perturbations

To overcome the possible limitations of the flux-tube approach in evaluating the impact of the AEs on the turbulent transport, global gyrokinetic GENE simulations have been performed for an ASDEX Upgrade case (Di Siena 2024a) and two JET cases (Di Siena 2024b, 2025). In addition, the GENE-TANGO framework (Di Siena 2022) was also employed for two of these cases, as highlighted below. This tool couples the first-principle gyrokinetic solver GENE with the transport code TANGO, enabling, in principle, the simulation of AE–turbulence interaction dynamics up to transport time scales. Moreover, also an overview of the flux-driven global electromagnetic ORB5 simulations performed over the last few years is provided. Eventually, a brief overview of results obtained with the recently developed ATEP code (Lauber et al. 2024; Meng et al. 2024) is provided. The code's approach, based on the concept of zonal state (Zonca et al. 2015; Falessi and Zonca 2018, 2019; Falessi et al. 2023), differs fundamentally from the traditional coupling strategy between gyrokinetic codes and 1D transport codes, by addressing the EP transport in the 3D constants of motion (CoM) space, where wave-particle resonances at the origin of EP transport are naturally defined.

4.8.1 H-Mode ASDEX Upgrade Case

The considered ASDEX Upgrade case (Di Siena 2024a) represents a promising candidate for the fast-ion-triggered beneficial mechanism discussed before, as it exhibits a clear peaking of the ion temperature in the deep plasma core during H-mode operations. It is observed that, in order to reproduce the experimental plasma profiles, the fast ions and the electromagnetic fluctuations of the fields must be included in the simulations. The deep analyses, performed on the underlying physical mechanism enhancing the ion temperature in the plasma core, revealed a crucial role of non-precisely identified KBM/AE instabilities, located near the q=1 rational surface. These low toroidal mode number instabilities were found to be weakly unstable in GENE stand-alone simulations, with a frequency falling within the TAE gap. However, they were also observed in sufficiently high-β_e simulations even in the absence of fast ions (Di Siena 2024a). Hence, in the study the modes were denoted as KBM/AEs.

Crucially, these weakly unstable high-frequency modes were shown to enhance the zonal flow shearing activity, leading to a reduction in turbulent transport, consistently with the findings from the previous flux-tube simulations discussed earlier in this review. The critical importance of weakly unstable high-frequency modes, in the presence of fast ions and fully electromagnetic fluctuations, in matching the experimentally inferred levels of transport is, thus, confirmed by such advanced and expensive global numerical analyses. These results are illustrated in Fig. 13.

It should also be emphasized that the dedicated local simulations performed for the ASDEX Upgrade case analyzed in Ref. (Di Siena 2024a) exhibit a significant mismatch with the global GENE-TANGO results, even at the level of linear stability. Indeed, the mismatch is appreciable also for the thermal ion heat flux, and in particular the largest deviation occurs at the outer edge of the analyzed radial domain ($\rho_{tor} = 0.6$), where the local simulations overestimate the ion heat flux by nearly a factor of four.

This discrepancy is likely augmented by the relatively high β_e value of 1.3% at mid-radius, which is considerably larger than the values in the previously analyzed JET cases (Citrin et al. 2013; Di Siena et al. 2019; Mazzi et al. 2022b; Garcia et al. 2024), and reflects the H-mode conditions of the ASDEX Upgrade plasma here analyzed. In high-β_e regimes, earlier flux-tube simulations were shown to produce unrealistically large fluxes (especially for the electron and fast-ion channels) when unstable low-n high-frequency modes were present (Citrin et al. 2014; Di Siena et al. 2019).

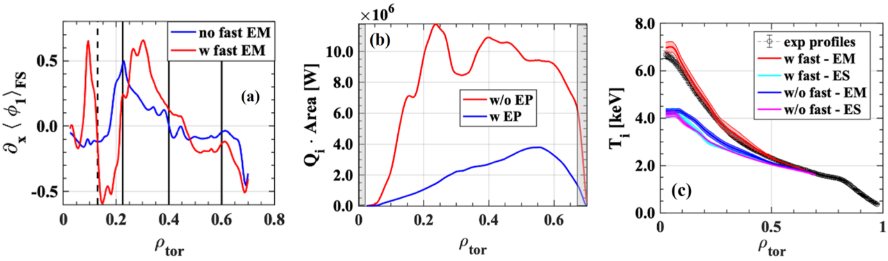


Fig. 13 (a) Radial profiles of the radial electric field with and without fast ions, showing a marked enhancement of the wells when fast ions are included in the region where KBM/AEs are destabilized. (b) Comparison of thermal ion heat fluxes without and with fast ions, highlighting a clear flux reduction when fast ions are retained. (c) Ion temperature profiles from various GENE-TANGO simulations compared to experimental measurements. Agreement is achieved only when both fast ions and electromagnetic effects, causing KBM/AEs destabilization, are included. Figures adapted from Di Siena (2024a)

4.8.2 JET Cases: Alpha Particle and ICRH-accelerated MeV-range Ions Impacts

The same modeling framework has also been applied to the reference JET pulse #99,912, which achieved the highest quasi-steady-state peak fusion power during the DTE2 campaign (Hobirk et al. 2023). This provided a unique opportunity to evaluate the impact of a substantial fusion-born alpha particle population on core confinement and overall performance using realistic plasma conditions. These simulations enabled the assessment of both the direct role of alpha particles in heating and plasma stability, and their potential contribution to triggering nonlinear interactions involving Alfvén Eigenmodes, microturbulence, and zonal flows. As a caveat, in those simulations, the NB- and ICRH-generated fast ions were not included, and the alpha particle distribution is approximated with an equivalent Maxwellian.

It is found that, beyond providing a clear source of core electron heating, the effect of alpha particles on the turbulent transport is minimal. This is demonstrated by comparing two GENE-TANGO simulations: one including the alpha particles only in the TANGO transport solver (red curves in Fig. 14(a) and (b)), and the other treating the alpha particles (as a kinetic species) in both transport and gyrokinetic blocks (blue curves in Fig. 14(a) and (b)). The resulting temperature and density profiles differ only marginally, indicating a negligible influence of alpha particles on turbulent transport within the studied conditions.

Such an absence of effect on the turbulent transport is attributed to the low concentration of the fusion-born alpha particles (Di Siena 2024b), that is $n_\alpha/n_e = 0.1\%$, even though the analyzed JET pulse achieved the highest fusion yield of the entire DTE2 campaign. Therefore, to assess the possible role of a higher alpha particle concentration, a parametric scan has been performed up to concentrations consistent with the ITER baseline scenario ($n_\alpha/n_e = 1.2\%$) (Garcia et al. 2018). However, this modification also corresponds to an increased β_α/β_e ratio nearly twice that expected in ITER, limiting the extrapolation of the results to reactor-relevant conditions. Nonetheless, at higher alpha particle concentrations, $n = 5$ TAEs are linearly destabilized, peaking around $\rho_{tor} \approx 0.4$. With unstable TAEs, both the electrostatic and electromagnetic components of the turbulent fluxes are abruptly increased for

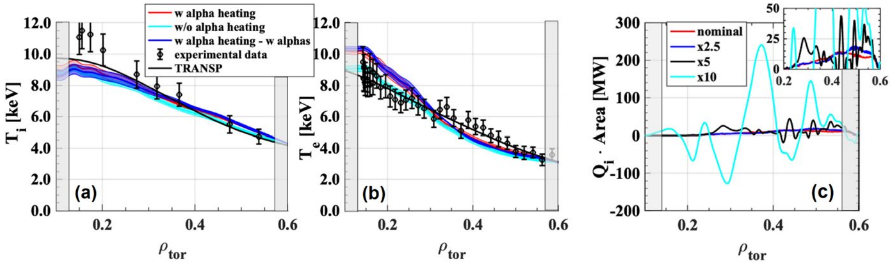


Fig. 14 GENE-TANGO-computed radial profiles with different input configurations are compared to experimentally measured and TRANSP-fitted profiles for thermal ions (a) and electrons (b). Only a mild effect is observed, indicating a weak influence of the alpha particle population on the confinement properties. (c) Effect of an alpha particle concentration scan on the thermal ion heat flux radial profiles is shown. The large alpha particle drive destabilizes TAEs, leading to heat fluxes with unrealistic radial shapes and markedly degraded confinement. Figures adapted from Di Siena (2024b)

all the species, by even orders of magnitude higher than the inferred ones from the experimental power balance. In Fig. 14(c), the ion heat flux levels for the parametric scan are displayed. These levels clearly lead to a marked degradation of the plasma thermal confinement. However, a strong correlation emerges between the flux-surface-averaged radial electric field and the radial structure of the thermal ion flux, reinforcing the critical mediating role of zonal flows in the nonlinear energy transfer from fast-ion-driven modes to turbulence.

Additional efforts (Di Siena 2025) have been made to analyze the JET D-T pulse #99,896 with the global version of GENE. Such a pulse was previously analyzed through local simulations with CGYRO (Garcia et al. 2024) (whose results are discussed in Sect. 4.6 of this review). These global simulations capture a complex interplay of mechanisms, primarily triggered by the MeV-range ICRH-generated fast ions, that collectively enhance thermal ion confinement in the plasma core. Firstly, electrostatic linear wave-particle resonance effects are non-negligible, but only in the outer core regions, in which the ICRH-generated fast-ion distribution presents lower-energy ions that better fulfill the resonance conditions (Di Siena et al. 2018) (see Sect. 2.4 for more details on such a linear fast-ion-triggered effect). This effect accounts for $\sim$10% reduction of the thermal ion turbulent flux in the plasma deep core, but up to $\sim$80% in the outer core regions. Additionally, a more moderate reduction (up to 40%) in the deep plasma core is attributed to a pure electromagnetic effect, unrelated to a direct fast-ion interaction (see Sects. 2.3 and 4.1.1 for more details on the linear and nonlinear electromagnetic effect). However, this effect reverses in the outer region, leading to a slight increase in transport.

Eventually, the dominant mechanism stabilizing turbulence in the plasma core is associated with the linear destabilization of TAEs near $\rho_{tor} \approx 0.25$ (as shown in Fig. 15(a) and (b)). This mechanism accounts for $\sim$80% of the total reduction in the thermal ion heat flux in the region $\rho_{tor} \lesssim 0.3$. These observations are summarized in Fig. 15(c). The turbulence stabilization correlates with the enhanced shearing effects of the zonal perturbations of the electrostatic field, which increase by a factor of 15 with respect to the case without unstable TAEs.

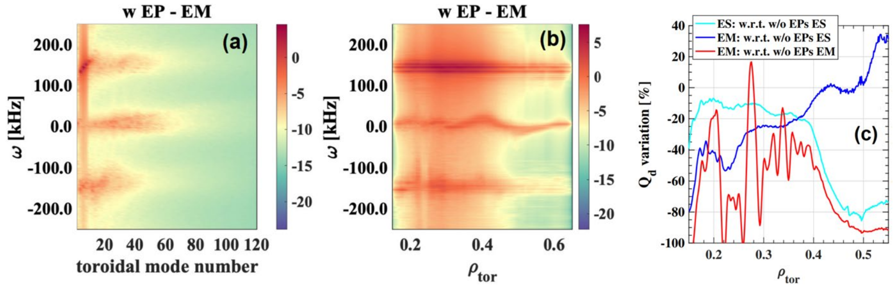


Fig. 15 The frequency spectra of the electrostatic potential as a function of the toroidal mode number and the radial coordinate ρ_{tor} are displayed, respectively in panels (a) and (b) for the GENE simulation including both the fast ions and the electromagnetic fluctuations. The TAE destabilization with a global structure is clearly observed. (c) Relative impact of the various fast-ion-triggered mechanisms on the thermal ion heat flux. It is clearly observed that the main reduction is achieved in the GENE simulation with fast ions and electromagnetic fluctuations (red curve), in which the TAEs are driven unstable. Figures are adapted from Di Siena (2025)

Interestingly, the zonal currents, i.e. the zonal fluctuations of the vector magnetic potential, have an impact on the fast-ion thermal flux but not on the thermal species ones. Similar observations pointing to the effect of zonal currents on the q-profile (and thereby on the Alfvén continuum) modification have been made in previous gyro-fluid analyses (Spong et al. 1994, 2021), but yet this is still a puzzling result. Moreover, the transition in the turbulence regime induced by TAE destabilization alters the cross-phase between temperature and potential fluctuations, yielding an in-phase interaction at the TAE scales. This cross-phase alignment significantly reduces heat flux despite an increase in fluctuation amplitude, consistent with earlier findings for JET plasmas (Mazzi et al. 2022a).

The presence of unstable TAEs in the gyrokinetic global simulations aligns with experimental observations, as already noted in Sect. 4.6, corroborating once more the results of these global numerical investigations. Remarkably, the reduction of the thermal ion turbulent transport occurs even in the presence of linearly (and then nonlinearly) unstable TAEs. This indirectly confirms also the trends described by the flux-tube gyrokinetic simulations reported in Refs. (Garcia et al. 2024; Mazzi et al. 2022b) for the thermal ion transport.

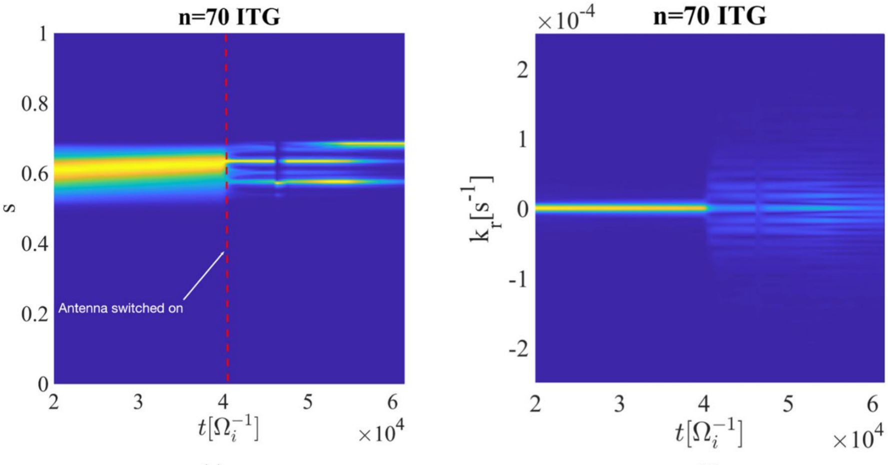
4.8.3 ORB5 Simulations of AE Interaction with Turbulence

Over the past few years, an extensive research effort has been undertaken using the global gyrokinetic code ORB5 (Lanti et al. 2020) to investigate the role of AEs in mitigating turbulence. Initial studies with the gradient-driven version of the code employed simplified magnetic equilibria, both to reduce computational costs and to allow for a more generalized analysis of the underlying physics. In these plasma conditions, the application of a fast-ion source leads to the destabilization of BAEs at amplitudes significantly higher than those of the background ITG-driven turbulence, resulting in large electron heat fluxes (Biancalani 2021). This enhanced thermal transport is consistent with other global gyrokinetic simulations with flux-driven GKNET, which shows an increased turbulence activity in the presence of TAEs (Ishizawa et al. 2021). Nevertheless, the forced-driven generation of the zonal perturbations in this regime is found to be an order of magnitude larger than that produced by ITG turbulence alone. Additionally, the simulations highlight the critical role of electron redistribution in the evolution of the zonal flow activity (Biancalani et al. 2020), corroborating the importance of kinetically treating all the species possibly involved in the dynamics.

The same modeling framework was subsequently applied to D-D JET pulse #92,416, part of the afterglow scenario (Dumont 2018), which was specifically developed to detect AEs driven by fusion-born alpha particles in DT plasmas. In this scenario, multiple TAEs were experimentally observed (Fitzgerald et al. 2022). In ORB5 simulations (Sama et al. 2024), the fast ion source excites a $n = 5$ TAE, which again generates strong zonal flow activity via a forced-driven mechanism. An antenna module, mimicking the zonal flow level previously obtained in the simulations retaining the fast ion source, was then applied to ORB5 simulations with a background turbulence dominated by the ITG only. This allows to disentangle thus the various possible effects from the zonal flow mitigation on ITG turbulence. These simulations clearly show that the induced zonal shearing scatters ITG turbulence into smaller-scale structures, as displayed in Fig. 16, thereby significantly reducing turbulent transport. This corroborates once more the essential role of AE-driven zonal flows in enhancing plasma confinement properties.

4.8.4 ATEP Model

The Advanced Transport of Energetic Particles (ATEP) model (Lauber et al. 2024; Meng et al. 2024) extends to the 3D CoM space the description of fast ions on confinement time scales. Such a development is particularly important to quantitatively evaluate the energetic ion transport in burning plasmas, for several reasons. First, resonant interactions between AEs/EPMs and fast ions through their orbit frequencies is at the origin of phase space fast-ion transport, as when exchanging energy with the modes, these particles are nonlinearly redistributed following $\Delta P_\varphi = (n/\omega)\Delta E$, where P_φ is the toroidal canonical momentum, E the fast-ion energy and n and ω the toroidal mode number and the mode frequency, respectively. Such a nonlinear transport occurs over 2D resonant plans in the 3D CoM space (P_φ, μ, E), as the fast-ion characteristic frequencies are purely functions of the constants of motion (Littlejohn 1982).Fast-ion transport on confinement time scales can therefore not a priori be restricted to a 1D diffusive process, as it is the case in traditional transport approaches. EP fluxes in 3D CoM space need to be retained for quantitative evaluation. Second, since fast ions are weakly collisional, their phase space distribution can differ vastly from local Maxwellians. Traditional 1D transport models however inherently assume that the fast ion distributions can be approximated to be a local Maxwellian, characterised by 1D density and temperature profiles. Such an approximation, therefore, needs to be relaxed to allow for realistic predictions. Lastly, the drive of AEs/EPMs



(a) (b)

Fig. 16 The time evolution of the radial profile (along the radial coordinate s) (a) and of the radial wavelength k_r (b) spectra of the electrostatic potential clearly show the scattering of the ITG structures in small-scale eddies when the antenna mimicking the zonal flow effect triggered by the TAE is switched on. Figure reprinted from Sama et al. (2024)

is directly connected to the EP distribution gradients in CoM space. The modelisation of the slowly evolving fast ion distribution in 3D CoM space over confinement time scales is therefore key in predicting realistically fast-ion-driven instabilities and their ensuing transport over burning plasma discharges.

The ATEP code is based on the concept of zonal state (Zonca et al. 2015; Falessi and Zonca 2018, 2019; Falessi et al. 2023), which describes the evolution of nonlinear plasma equilibria, containing on the one hand zonal electromagnetic potentials (zonal flows and currents), and on the other hand phase space zonal structures (PSZS). By analogy with the zonal potentials, PSZS are perturbations of the fast-ion distribution averaged over the angles of the angle-action formalism (or similarly over the fast-ion orbits), which can be described as long-lived 3D structures in CoM space. Based on this zonal state, a kinetic equation with sources, sinks and collisions can be derived for the zonal fast-ion distribution F_Z, taking into account phase space fast ion fluxes in the (P_φ, E) directions:

$$\frac{\partial \overline{F}_Z}{\partial t} + \frac{\partial}{\partial P_\varphi} \left\langle \delta \dot{P}_\varphi F \right\rangle_Z + \frac{\partial}{\partial E} \left\langle \delta \dot{E} F \right\rangle_Z = \left\langle \sum_s C_s[F, F_s] + S \right\rangle_Z$$

where $\langle \cdot \rangle_Z$ denotes orbit-averaging and s the different species.

The ATEP code was developed to solve this kinetic equation, taking into account fast-ion fluxes from a hierarchy of models. The implementation of sources and of a collisional operator in 3D CoM space was described in Meng et al. (2024). The HAGIS code (Pinches 1998) is used to compute the orbit-averaged collision coefficients in ATEP, in order to take into account the large finite-orbit width of fast ions. The slowing-down process of a NBI source in a ITER pre-fusion plasma using ATEP was successfully benchmarked against the Fokker-Planck code SPOT (Schneider et al. 2005), the beam distribution in ATEP converging smoothly towards the SPOT distribution projection in CoM space. The coupling between ATEP and phase space fluxes computed from the LIGKA-HAGIS set of codes is presented in Lauber et al. (2024). The code is applied to study the non-Maxwellian deviation of a NBI distribution in the same ITER discharge as in Ref. (Meng et al. 2024), due to the excitation of TAEs. LIGKA is used to model the TAE linear stability, and the HAGIS code to compute the TAE-driven CoM space fast ion fluxes, based on a quasi-linear approach. As expected from analytical theory, the fast ion distribution relaxes radially outwards and towards lower energies due to the drive imposed by the NBI distribution gradients ($\partial F_Z / \partial P_\varphi > 0$). These first ATEP results demonstrate that the code can be used as a reduced full-F fast ion transport model.

Beyond the current results, the ATEP model will be applied on existing plasma experiments, in order to provide an experimental validation for the code, which is crucial for the realistic prediction of fast ion transport in future burning plasmas such as ITER. In particular, ATEP simulations could be compared with fast ions phase space flow measured by an Imaging Neutral Particle Analyser diagnostic (see, e.g., Du 2023). The hierarchy of models used by ATEP to compute the CoM space fast ion fluxes will also be extended to nonlinear gyrokinetic codes, which should provide a more quantitative response compared to quasi-linear models. Connection between

ATEP and gyrokinetic codes is currently made possible, in particular with the ORB5 and GTC codes, through the implementation of PSZS diagnostics and numerical distribution functions for fast ions in CoM space (Bottino et al. 2022)[176].

5 Additional Fast-Ion-Triggered Nonlinear Mechanisms Impacting on Microturbulence

In this section, a brief overview of additional physical mechanisms, involving the fast ions and impacting on the confinement and turbulence properties, in tokamak plasmas is given. Although the main focus of the manuscript is dedicated to the role of the AEs as source of zonal flow activity shearing and reducing the microturbulent transport, it should be reminded that other mechanisms, triggered by other fast-ion-driven instabilities may have a significant impact on the small-scale fluxes and, thereby, on the confinement properties.

5.1 Fast-Ion-Driven GAM Impacting Background Turbulence

The complex interaction between fast ions and the background turbulence can also be mediated by the so-called Energetic Geodesic Acoustic Modes (EGAMs). Their theoretical interpretation was first presented in (Fu 2008), followed by several subsequent works (see, e.g., Refs. (Qiu et al. 2008; Zarzoso et al. 2012; Wang et al. 2013; Zarzoso et al. 2014; Biancalani et al. 2017; Chen et al. 2018), with a more comprehensive review in Ref. Qiu et al. 2018). EGAMs are excited by fast ions in the presence of the geodesic curvature of the magnetic field of tokamaks and, similarly to the standard Geodesic Acoustic Modes (GAMs) (Winsor et al. 1968), are finite-frequency perturbations of the zonal components of the electrostatic potential. Due to the finite frequency of the EGAM, its use as a knob to control turbulent transport by means of fast ions via shearing and decorrelation has been debated. However, it has been shown that EGAMs can interact (Qiu et al. 2014) with and significantly alter (Zarzoso et al. 2013; Dumont et al. 2013) the turbulence characteristics, as observed in global flux-driven simulations with the GYSELA code (Grandgirard 2016).

In those simulations, an ITB was triggered by the fast ion source, leading to a regime of reduced turbulent transport. The destabilization of the EGAMs by the fast ions led to oscillating radial electrostatic perturbations. The resulting oscillating sheared flows were not sufficient to stabilize the turbulent modes, which on the contrary increase their intensity. This can be observed in Fig. 17(a), where the heat flux is firstly suppressed due to the ITB onset, but increases rapidly again concurrently with the appearance of the EGAM as indicated by the dotted black curve in the figure. For comparison, the case without fast ions (therefore without any EGAM destabilization) but with the same amount of energy injected by the source is represented by the dashed blue curve. The detrimental dynamics induced by the EGAM has been identified in Zarzoso et al. (2013); Dumont et al. (2013) as a nonlocal coupling between the static EGAM oscillations (Dreval 2024) and the radially propagating turbulent eddies. Such scenario was theoretically analyzed in Sasaki et al. (2017), where it was demonstrated that EGAMs can indeed act as channel of turbulence clumps. Further

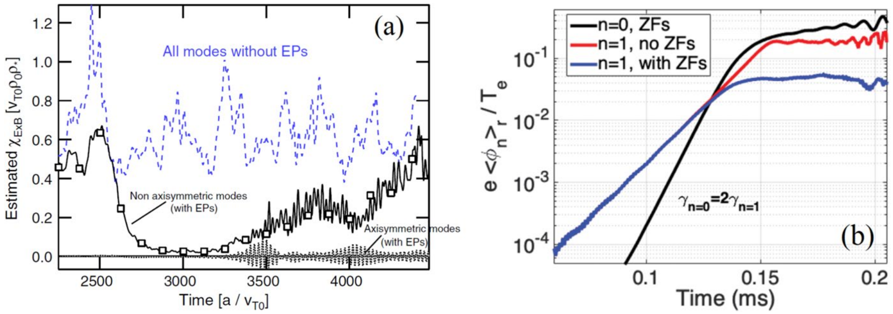


Fig. 17 (a) Time evolution of the $E \times B$-driven turbulent transport from GYSELA simulations without fast-ion source (blue dashed) and with fast-ion-induced EGAMs (black curves: solid for $n \neq 0$, dotted for $n = 0$). After an initial reduction, the onset of EGAMs, evident as regular $n = 0$ oscillations, leads to a transport increase, reaching levels comparable to the case without fast ions. Figure reprinted from Zarzoso et al. (2013). (b) Time evolution of the electrostatic potential of the $n = 1$ fishbone mode, with and without the $n = 0$ zonal component in the GTC simulation. The saturated amplitude is significantly reduced when the zonal mode is included, highlighting the role of forced-driven zonal flows in regulating the instability. Figures reprinted from Brochard et al. (2024)

investigations have also revealed a local interplay between EGAMs, zero-frequency zonal flows, and background microturbulence, involving a three-wave coupling mechanism (Zarzoso et al. 2017).

Regarding EGAM destabilization, the fast-ion distribution must exhibit a positive slope in specific radial regions. This implies that, for fusion-born alpha particles with slowed-down distributions in burning plasmas, triggering such a mechanism may be difficult. However, this remains somewhat speculative, and further experimental investigations are required.

5.2 Fishbone-triggered ITB through Zonal Flow Enhancement

The experimental observations of transport barriers in concomitance of unstable fast-ion-driven fishbone modes (McGuire et al. 1983; Chen et al. 1984) were reported since the beginning of this century in multiple tokamaks (see e.g. Günter et al. 2001; Gao 2018; Brochard et al. 2024). Nonetheless, the fine underlying physical mechanisms have been detailed only recently through advanced global gyrokinetic simulations with the GTC code (Lin et al. 1998) of a selected DIII-D pulse. Indeed, the numerical analysis reveals that the fishbone-generated zonal flows are crucial in saturating the growth of the instability itself (Brochard et al. 2024). In this case, the zonal flow growth rate is twice that of the unstable $n = 1$ fishbone mode, indicating a forced-driven process (Qiu et al. 2016) as discussed in depth in Sect. 4.4, and it clearly impacts on its saturation amplitude by a factor of $\sim$5 (see Fig. 17(b)). Beyond the forced-driven nature of this fishbone-induced zonal flow generation, the precise underlying mechanism for this generation was also identified (Brochard 2024). It is found that the EP transport induced by the fishbone (due to the fishbone self-interaction between its perturbed electrostatic potential and the perturbation it induces on the EP distribution) leads to a gyrocenter charge separation, giving rise to a zonal radial electric field and hence to the zonal flows. The zonal flows, then, impact the wave-particle drive of the mode, reducing it through preventing the nonlinear resonant interaction with certain region of the fast-ion distribution during the chirping-down of the mode (Brochard 2024). Importantly, the thus-obtained amplitude and the radial width of the fishbone instability have been validated against experimental measurements with the electron cyclotron emission diagnostic at DIII-D (Brochard et al. 2024). These results of the enhanced zonal flow activity in the presence of fishbone instabilities are also confirmed by gyrofluid simulations with FAR3d of a selected JET DT pulse (Garcia et al. 2024; Varela 2025[154]).

Remarkably, the fishbone-generated zonal activity may also explain the ITB formation in the presence of such an instability observed in the selected DIII-D pulse, as well as in other tokamaks. Additional electrostatic global simulations with the GTC code only focusing on the thermal ion scales revealed that TEM is the dominant microinstability in the core of the selected DIII-D pulse (Brochard et al. 2024). The TEM growth rate is then evaluated to be three times lower than the shearing rate determined by the fishbone-generated zonal flow activity, suggesting that the ITB formation could be ascribed to the fishbone dynamics. This result is also in line with previous MHD-kinetic numerical studies of fishbone-induced ITB in EAST (Ge et al. 2022). Although preliminary, such analyses should encourage further ambitious multi-scale studies including self-consistently the fishbone instabilities as well as the zonal perturbations and the microturbulence dynamics, which both an adequate self-consistent treatment of magnetic reconnection in gyrokinetic modelling.

Eventually, very recent experiments have been conducted in DIII-D to reproduce such a beneficial mechanism triggered by the fishbone instability. It is clearly highlighted that the plasma conditions, and in particular the presence of low/reversed shear q profiles, play a crucial role in determining the effectiveness of the mechanism on the plasma core confinement (Heidbrink et al. 2024).Consistently, nonlinear gyrokinetic simulations performed with the GTC code have verified that this NBI-ion-driven fishbone mechanism can also be active in ITER pre-fusion scenarios (Brochard et al. 2024; Brochard 2024). The resulting reduction of background turbulence suggests a promising pathway toward enhanced confinement, especially in view of the expected unstable alpha-driven fishbones in the ITER baseline scenario (Brochard et al. 2020).

6 Discussion on Possible Parameter Dependencies

Before wrapping up, an important point worth raising is the dependence of the AE-triggered beneficial mechanism on the fast-ion drive strength, as could be observed by investigating the wide range of simulations using different numerical codes and approximations reported in this review paper. A consistent trend emerges: the mechanism is most effective in plasma regimes at low and medium β, especially in L-mode or I-mode conditions. The clearest demonstrations come from studies of the JET three-ion scheme (Mazzi et al. 2022b; Ruiz et al. 2025) and the DT scenario (e.g., JET pulse #99,896) (Garcia et al. 2024; Di Siena 2025), both achieving I-mode-like regimes with $\beta_e < 0.75\%$ in the plasma core (at the radial position where the analyses are performed).

In contrast, in high-β_e regimes, the AE-triggered mechanism becomes detrimental, often resulting in a turbulent amplitude explosion and/or run away flux behavior. Examples include JET (Citrin et al. 2014; Garcia et al. 2015) and JT-60U (Mazzi et al. 2020) H-mode cases, which required artificial stabilization of the fast-ion-driven modes at large scales (generally achieved by reducing β_e or the fast-ion pressure gradients) to possibly match the experimentally inferred transport levels. A similar detrimental behavior was also reported in Di Siena et al. (2019, 2023), where increasing β_e triggered unstable fast-ion-driven modes that dominated over the beneficial zonal flow effect, leading to large turbulent fluxes through enhanced magnetic flutter.

A more relevant figure of merit to discriminate the efficiency of the AE beneficial mechanism, at least for the gradient-driven gyrokinetic simulations, could be the growth rate of the high-frequency fast-ion-driven modes, and more specifically its relative value compared to the dominant ion-scale instability. Early studies suggest that when the growth rate of fast-ion-driven instabilities approaches or exceeds that of the background ion-scale instability, the overall effect becomes detrimental (Bass and Waltz 2010; Citrin et al. 2014; Garcia et al. 2015; Doerk et al. 2016; Mazzi et al. 2022a). However, whether it is the growth rate ratio or the absolute value that matters remains unclear and further investigations are, thereby, required.

This hypothesis is supported by several representative examples, such as the growth rate spectra shown in Fig. 18 and Fig. 11, which illustrate cases where beneficial AE-induced turbulence reduction is observed. In these examples, as in other studies, the growth rate of the fast-ion-driven modes remains relatively low, and also below that of the dominant ion-scale instability (typically ITG). Under such conditions, the zonal flows excited by the AEs effectively control the microturbulence, resulting in an overall improvement of the confinement properties.

Remarkably, a β_e scan performed with the global version of GENE in Di Siena (2025) shows that when β_e is increased beyond a critical threshold (see Fig. 19), the high-frequency fast-ion-driven mode becomes dominant across the spectrum, giving rise to large overall transport that counteracts the beneficial mechanism. At the nominal β_e value (horizontal solid line in the Figure), the AE growth rate is lower than that of the ion-scale mode, and confinement improvement is recovered.

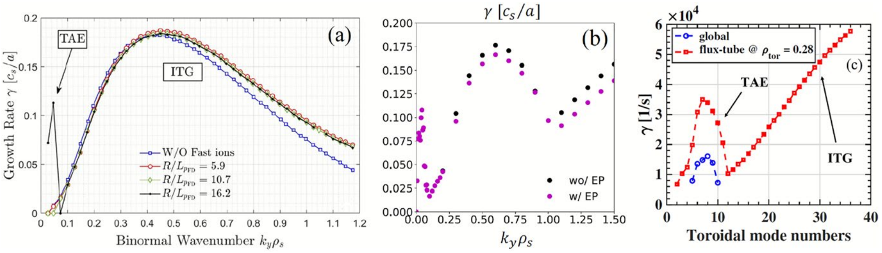


Fig. 18 (a) Linear growth rate spectra for various fast-ion pressure gradients for JET pulse #94701. Figure reprinted from Mazzi et al. (2022a). (b) Comparison of the linear growth rate without and with including fast ions in the simulations of JET pulse #97090. (c) Linear growth rate spectra for global and local simulations of JET pulse #99896. In all these cases, for which an enhanced confinement is observed, the TAE growth rate is lower than the ITG one. Figures (b) and (c) are reprinted from Refs. [87] and Di Siena (2025) respectively

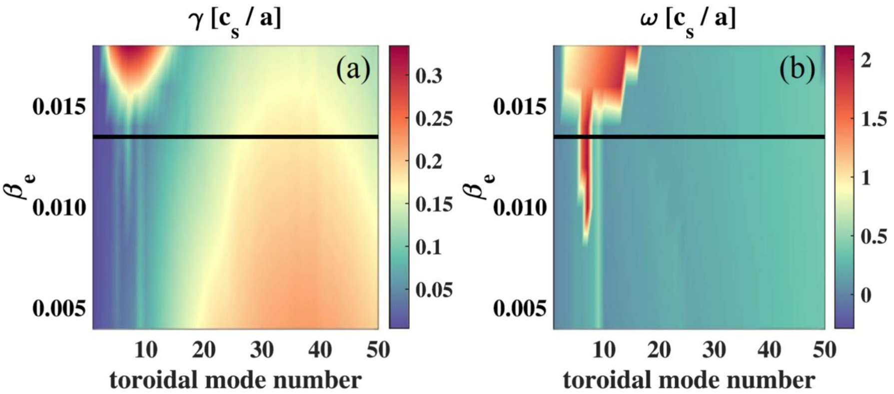


Fig. 19 Linear growth rate (a) and frequency (b) spectra for a scan over β_e for ASDEX Upgrade pulse #39,230 obtained through global GENE simulations. The KBM/AE instabilities become dominant beyond the horizontal black line, representing the experimental nominal value, and in these conditions the beneficial mechanism is not anymore effective. Figures reprinted from Di Siena (2024a)

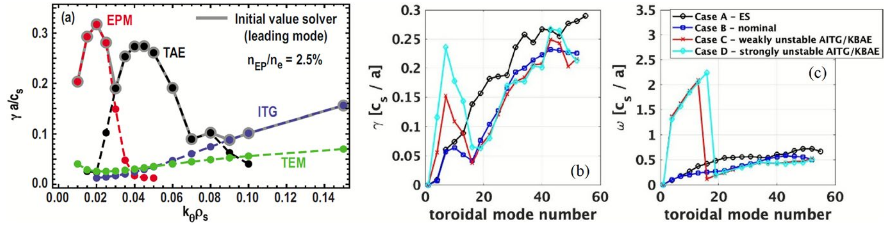


Fig. 20 (a) Linear growth rate spectra displaying the subdominant unstable modes for a numerical experiment with including fast ions. Clearly in this simulation, the TAE and EPM growth rates are much larger than the ITG one at the thermal ion scales (peaking $\gamma = 0.21, c_s/a$ for $k_\theta = 0.3$, not shown in the figure). Figure reprinted from Bass and Waltz (2010). (b) and (c) Growth rate and frequency spectra for the numerical analysis with different β_e and, thereby, at different levels of the AITG/KBAE instabilities amplitude. The configurations in panel (a) and for cases C and D of panels (b) and (c) displayed larger (or comparable) growth rates between the fast-ion-driven modes and the ITG modes, and indeed in these configurations the heat fluxes exhibit run-away behaviors. Figures reprinted from Di Siena et al. (2023)

In contrast, simulations where the fast-ion-driven instabilities dominate the spectrum and exceed the ion-scale growth rate tend to show degraded confinement. Thus, to match the experimental power balances, the artificial stabilization of these modes is necessary. This is illustrated in Fig. 5 and the additional Fig. 20. In panel (a) of Fig. 20, the ITG peak at $k_\theta = 0.3$ with $\gamma = 0.21, c_s/a$ (although not shown in the Figure) is smaller than the EPM and TAE growth rates. It is worth noting that high turbulent transport can still occur at low β_e, as in Bass and Waltz (2010) the $\beta_e = 0.2\%$, with the simulation resulting in unbounded flux growth for electrons and fast ions, highlighting the complexity of the problem.

In this regard, the impact of large β on the AE growth rate, and consequently on the effectiveness of the beneficial AE-triggered mechanism, may be inherently linked to operating conditions of specific devices. This is particularly relevant for large tokamaks operating at high plasma pressure and relatively low magnetic field, which naturally leads to high-β conditions. A prominent example is the JT-60SA tokamak, which operates with a toroidal magnetic field of only $B_t = 2.25$ T (Garcia et al. 2014; Yoshida 2022). This is not only a challenge in terms of fast-ion confinement in low-B_t conditions, but also a concern for the impact of the large NB-injected fast-ion pressure that could lead to destabilization of strong large-scale instabilities Indeed, recent predictive studies on JT-60SA (Iantchenko et al. 2023; Krutkin et al. 2025) have shown that such strongly unstable fast-ion-driven modes interact with the background turbulence in a highly detrimental fashion.

Some exceptions are, however, observed. In a gradient-driven global gyrokinetic simulation of DIII-D plasma conditions with the GTC code (Liu et al. 2024), RSAEs exhibit larger growth rates than ITG modes but still generate zonal flows that stabilize the turbulence. This suggests that the rule of thumb may not be universally applicable, and further systematic studies are needed to clarify its validity. Ultimately, a deeper understanding of these trends is essential for developing reduced models that accurately capture fast-ion and AE effects on global plasma confinement properties within integrated modeling frameworks for next-generation devices.

7 *Partial* Conclusions

This review has presented recent advances (framed within the broader context of the past few decades) on the understanding of fast-ion interactions with background microturbulence in tokamak plasmas. While a brief overview of the linear mechanisms (Sect. 2) and additional nonlinear effects involving fast ions and zonal perturbations (Sect. 5) has been provided, the main focus has been on the purely nonlinear electromagnetic mechanism triggered by the fast-ion-driven Alfvén Eigenmodes generating zonal flow activity (Sect. 4). This mechanism has been firstly detailed in gyrokinetic numerical analysis (Citrin et al. 2013; Di Siena et al. 2019), attracting significant attention due not only to its relevance in the saturation process of the fast-ion-driven AEs (Spong et al. 1994; Todo et al. 2010), but more remarkably also on reducing the microturbulence levels.

This gave rise to further investigations, including extensive analytical studies (Chen and Zonca 2012; Qiu et al. 2016; Barberis et al. 2025), on the implications of this AE-triggered mechanism enhancing the thermal plasma confinement in both present and future fusion devices. Notably, these studies have been revisited in light of earlier observations, such as the anomalous ion heating seen in the JET DTE1 campaign (Thomas et al. 1998), which remained unexplained for decades.

Flux-tube gradient-driven gyrokinetic simulations first highlighted the importance of fast ions and electromagnetic effects in mitigating the ITG-driven turbulence and reducing thermal ion transport stiffness (Citrin et al. 2013). Further numerical works revealed that AEs can mediate the nonlinear energy transfer from fast ions to thermal ion scales, mainly through enhancing the zonal flow activity (Di Siena et al. 2019). However, the mechanism appeared beneficial only in marginally unstable regimes (where the AE drive is not sufficient to excite the modes linearly) making experimental control potentially difficult.

In order to explore reactor-relevant plasma conditions and partly to address this specific phenomenon, dedicated experimental scenarios were developed at JET to test this multi-scale mechanism (Ye et al. 2021). Thus, these experiments were performed under reactor-relevant conditions, i.e. low plasma torque, dominant electron heating due to the large energy of the fast ions, and especially low fast-ion density. By combining external heating systems with advanced techniques (Kazakov et al. 2017), MeV-range ions were generated (Nocente et al. 2020), driving thus unstable the AEs. In this plasma conditions, a clear improved thermal ion confinement was experimentally achieved (Mazzi et al. 2022b). Flux-tube simulations again identified the AE-triggered zonal flows as the main driver of turbulence suppression, and experimental density fluctuation measurements supported these results (Ruiz et al. 2025[87]). Therefore, these findings extended the applicability of the mechanism to plasma parameter regions and operating conditions with unstable AEs.

Such results were further confirmed in dedicated experiments during the DTE2 experimental campaign at JET (Garcia and Contributors 2025), where the confinement was found to be even more enhanced with respect to the early studies in pure D or D-^{3}He plasmas (Garcia et al. 2024). While the enhanced thermal confinement of the ions in the presence of AEs driven unstable by MeV-range ions was initially demonstrated by flux-tube simulations, this has been confirmed and reinforced by recent global gradient-driven gyrokinetic simulations performed on the same JET pulses (Di Siena 2025). It is demonstrated that unstable AEs, as observed in the experiments, can indeed trigger the nonlinear energy transfer mechanism leading to enhanced zonal flow shearing and improved thermal confinement. This confirms thus that the beneficial AE-driven mechanism is a robust nonlinear process active under experimentally realistic conditions. And moreover it supports the idea that AE activity, if their amplitude is properly controlled, could enhance performance in future burning plasma scenarios, where fusion-born alpha particles are expected to drive these instabilities.

Despite these encouraging developments, many open questions remain. Recent global simulations (Sama et al. 2024) have revealed a more complex and parameter-sensitive picture, emphasizing the need for deeper exploration of the multi-scale interactions among fast-ion-driven modes, background turbulence, and meso-scale zonal structures with such models. These should also incorporate realistic external heating sources, with corresponding realistic fast-ion distributions, in a flux-driven framework and their validation against experimental measurements is crucial to grasp such multi-scale complex self-consistent dynamics. Some recent developments, supported by a robust theoretical framework, have opened a novel promising route towards this kind of approach (Lauber et al. 2024).

To extend the application of this beneficial mechanism to other devices, further experimental efforts, supported by advanced turbulence diagnosing, are essential. Investigating various turbulence regimes and machine configurations are a key point to be addressed in order to generalize the findings. Eventually, the interaction between fast ions and turbulence remains an inherently complex problem, involving a multitude of different mechanisms and non-trivial effects that often compete or act simultaneously in both experiments and numerical simulations. This complexity makes it important to break the problem into smaller components, for instance through the development of reduced models that can isolate specific fundamental dynamics. Such models can yield foundational understanding, guide interpretation, and allow reliable extrapolation and prediction for future fusion reactors. Of course, these efforts should complement global flux-driven fully electromagnetic simulations, including the evolution of fast ion phase space and its long-lived structures (Lauber et al. 2024), which provide the highest-fidelity descriptions of the issue at hand, and should be validated against advanced experimental measurements.

It should be emphasized, however, that the topic reviewed here is rapidly evolving, and the present understanding may be substantial revised as the access to experimentally available burning plasmas becomes reality. In such regimes, new mechanisms, either long theorized or yet to be identified, could emerge and even dominate over those discussed in this overview. This underlines the importance of developing a comprehensive theoretical framework capable of consistently describing the complex nonlinear interplay, including both wave–particle and wave–wave paradigms. Such a framework will be essential to interpret experimental results in forthcoming burning plasma device, such as SPARC, ITER, CFETR and STEP, and to verify, or falsify, the current theoretical interpretations. In conclusion, we hope that the insights outlined in this review may help producing new ideas and contribute to the broader effort towards optimized confinement in fusion plasmas.

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Data Availability The majority of the data, images, and concepts presented in this review are derived from previously published sources and are not original. The original data that support the findings introduced in this paper will be available from the author upon reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no Conflict of interest.

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