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Physics of burning plasmas in toroidal magnetic confinement devices

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Abstract

Some of the crucial physics aspects of burning plasmas magnetically confined in toroidal systems are presented from the viewpoint of nonlinear dynamics. Most of the discussions specifically refer to tokamaks, but they can be readily extended to other toroidal confinement devices. Particular emphasis is devoted to fluctuation induced transport processes of mega electron volts energetic ions and charged fusion products as well as to energy and particle transports of the thermal plasma. Long time scale behaviours due to the interplay of fast ion induced collective effects and plasma turbulence are addressed in the framework of burning plasmas as complex self-organized systems. The crucial roles of mutual positive feedbacks between theory, numerical simulation and experiment are shown to be the necessary premise for reliable extrapolations from present day laboratory to burning plasmas. Examples of the broader applications of fundamental problems to other fields of plasma physics and beyond are also given.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Two aspects, that are peculiar to burning plasmas and require a conceptual step in the analysis of magnetically confined plasmas, are investigated in this work. The first one is related to the fact that, in order to achieve reactor relevant conditions, it is necessary that fast ions (mega electron volts energies) and charged fusion products (hereafter generically referred to as energetic ions) are sufficiently well confined so that they transfer their energy and/or momentum to the thermal plasma without appreciable degradation due to collective modes. The identification of burning plasma stability boundaries with respect to energetic ion collective mode excitations and their nonlinear dynamic behaviours above the stability thresholds obviously impact the operation-space boundaries, since energy and momentum fluxes due to collective losses may lead to significant wall loading and damaging of plasma facing materials. Such analyses can be performed, at least in part, in present day experiments and provide nice examples of mutual positive feedbacks between theory, simulation and experiment. In a burning plasma, however, energetic ion power density profiles and characteristic wavelengths of the collective modes will be unique and not reproducible in existing experiments: the important implications of the predictive capabilities based on numerical simulations and modelling will be emphasized here along with the necessity of using existing and future experimental evidences for modelling verification and validation.

The second aspect is related with plasma turbulence and turbulent transport in a burning plasma. The presence of mega electron volts ion energy tails does not only introduce a dominant electron heating contribution on the local power balance and a different weighting of the electron driven micro-turbulence with respect to present experiments. It also generates long time scale nonlinear behaviours typical of self-organized complex systems, which are due to mutual interactions between collective modes and energetic ion dynamics on the one side and drift-wave (DW) turbulence and turbulent transport on the other side. It is important that these interactions do not deteriorate the thermonuclear efficiency of the considered system on long time scales. These issues will be analysed starting from their first principle theoretical grounds and introducing the possibility of investigating them via low-dimensional nonlinear dynamic models that can be formulated via formal theoretical–analytical approaches.

2. Energetic particle physics

The possible detrimental effects of collective shear Alfvén (s.A.) fluctuations [1, 2] as well as of lower frequency MHD modes [3–5] on energetic (fast) ion confinement properties were recognized in the early years of fusion research and ever since the stability properties of Alfvénic and MHD fluctuations have been an important subject of the field. The nonlinear behaviours of these modes were also investigated [6] at the time of the first systematic experimental studies of collective s.A. oscillations [7, 8] and together with the first numerical simulations of fast ion transports in the presence of these modes [9].

The various s.A. modes that can be excited in the presence of the energetic ion free energy source are strongly influenced by the presence of the s.A. continuous spectrum, which is characterized by gaps. The frequency gap at $v_A/(2qR_0)$ (v_A being the Alfvén speed, q the safety factor and R_0 the plasma major radius) is due to the finite toroidicity of the system [10], but other gaps generally exist at $\omega = \ell v_A/(2qR_0)$, due to either noncircularity of the magnetic flux surfaces ($\ell = 2, 3, \ldots$) [11], anisotropic trapped energetic ion population ($\ell = 1, 2, 3, \ldots$) [12] or finite-β ($\beta = 8\pi P/B^2$, mainly $\ell = 2$) [13]. A low-frequency gap also exists because of finite plasma compressibility [14] and is located at $\omega \lesssim \beta_i^{1/2}(7/4 + T_e/T_i)^{1/2} v_A/R_0$ [15]. Discrete s.A. modes or Alfvén eigenmodes (AEs) exist in all these frequency gaps and have been given different names accordingly, e.g. beta induced AE (BAE) [14, 16] for $\omega \simeq \beta_i^{1/2}(7/4 + T_e/T_i)^{1/2} v_A/R_0$, toroidal AE (TAE) [17] for $\omega \simeq v_A/(2qR_0)$, ellipticity induced AE (EAE) [11] for $\omega \simeq v_A/(qR_0)$, etc. Global AEs (GAE) [18] may also exist in a nonuniform cylindrical plasma equilibrium and are localized in both frequency and radial position near an extremum of the s.A. continuous spectrum. This is the case, e.g. of hollow-q plasma equilibria, where an AE can be excited in the local s.A. frequency gap which is spontaneously formed at the minimum-q surface [19], yielding the so-called Alfvén cascade

(AC) [20]. The regular patterns of ACs and their dependence on the minimum-q value [20] have facilitated the development and control of operation scenarios with internal transport barriers (ITB) on JET [21,22]. In addition, a variety of kinetic counterparts of the corresponding ideal AE also exists when, e.g. finite resistivity [17] or finite Larmor radius (FLR) are accounted for, as in [23] for the kinetic TAE (KTAE). A unified picture of all these modes was recently proposed in [24], where it was demonstrated that all AE from the BAE to the TAE frequency can be consistently described by one single dispersion relation which generally predicts the existence of two types of modes; i.e. a discrete AE and an energetic particle continuum mode (EPM) [25]. For AE, the weak interaction with the s.A. continuum makes the mode weakly damped [17], while the resonant wave–particle interaction with fast ions gives the mode drive. In the case of EPM, ω is set by the relevant energetic ion characteristic frequency and mode excitation requires the drive exceeding a threshold due to continuum damping [26–29]. The most recent systematic stability analyses of proposed burning plasma experiments are summarized in [30].

The fundamental problem to be addressed in studies of collective mode excitation by energetic ions in burning plasmas is to assess whether or not significant degradation in the plasma performance can be expected in the presence of Alfvénic fluctuations and, if yes, what level of wall loading and damaging of plasma facing materials can be caused by energy and momentum fluxes due to collective fast ion losses. Energetic particle losses up to 70% of the entire fast particle population have both been predicted theoretically and found experimentally. The particle loss mechanism is essentially of two types [9,31]: (1) transient losses, which scale linearly ($\approx \delta B_r/B$) with the mode amplitude, due to resonant drift motion across the orbit-loss boundaries in the particle phase space of energetic particles which are born near those boundaries; (2) diffusive losses above a stochastic threshold, which scale as $\approx (\delta B_r/B)^2$, due to energetic particle stochastic diffusion in phase space and eventually across the orbit-loss boundaries. Due to the large system size, mainly stochastic losses are expected to play a significant role in ITER. The stochastic threshold for a single mode is $(\delta B_r/B) \approx 10^{-3}$, although that may be greatly reduced ($(\delta B_r/B) \lesssim 10^{-4}$) in the multiple mode case [9,31].

For weakly unstable AEs, a possible nonlinear saturation mechanism is via phase-space nonlinearities (wave–particle trapping) [6,32]. This fact has been confirmed by many numerical simulations [33–36]. Another possible saturation scenario is by ion Compton scattering off the thermal ions [37], which locally enhances the mode damping via nonlinear wave–particle resonances or by mode–mode couplings which may cause poloidal flows [38] (see also section 3) or generate a nonlinear frequency shift and locally enhance the interaction with the s.A. continuum [39, 40]. Recently, numerical simulations confirmed that mode–mode couplings give an estimate for AE saturation amplitudes on TFTR that are closer to experimentally measured levels than if they were not included in the simulation model [41]. While the role of nonlinear wave–particle and wave–wave interactions is generally important in determining the AE saturation level [37–40], nonlinear evolutions of the energetic ion distribution function are affected by formation of phase-space structures. Noticeable examples of such structures are the pitchfork splitting of TAE spectral lines observed on JET [42] and explained in terms of hole–clump pair formations in phase space, near marginal stability [43]. Still, the nonlinear dynamics of AEs, discussed so far, refer to single wave–particle resonances or to local saturation mechanisms. It is then not surprising that AEs yield negligible energetic particle losses, unless phase-space stochasticity is reached, possibly via phase-space explosion (‘domino effect’ [44]). This fact has been confirmed also by numerical simulations of alpha particle driven Alfvén gap modes in ITER [36]. For this reason, the dominant loss mechanism below stochastic threshold is expected to be that of scattering of barely counter-passing particles into unconfined ‘fat’ banana orbits [9, 31].

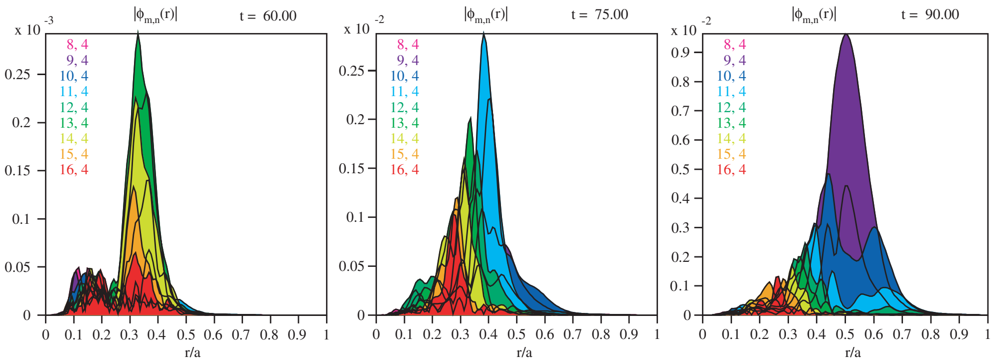

Figure 1. Radial structure of a typical EPM scalar potential fluctuation, with $n = 4$ and decomposed in (toroidally coupled) poloidal Fourier harmonics $m = 8 \div 16$. The radial envelope of the EPM wavepacket propagates radially as time progresses from left to right. Here, time is in units of $\tau_{A0} = R_0/v_{A0}$, with v_{A0} the on axis Alfvén speed.

Numerical simulations of collective excitations of MHD and Alfvén modes by energetic ions and of fast ion transports in burning plasmas mostly rely on global hybrid MHD-gyrokinetic codes, such as M3D [45], HMGC [46] and MEGA [47], which solve the hybrid MHD-gyrokinetic model equations [45], where the thermal (core) component of the plasma is described by nonlinear MHD and the energetic ion dynamics enter only via the divergence of the fast ion pressure tensor, $\nabla \cdot \boldsymbol{P}_E$, in the momentum balance equation. The nonlinear gyrokinetic equation [48] is solved, generally via particle in cell (PIC) techniques, for the direct computation of $\nabla \cdot \boldsymbol{P}_E$ in the self-consistent wave fields. Generally, the hybrid MHD-gyrokinetic model [45] is sufficiently accurate for the adequate description of those modes that are most relevant for both stability and fast ion transports [24], although more accurate kinetic models based on the Vlasov–Maxwell system are required for analysing energetic ion redistributions at shorter wavelengths [49, 50], typical of Alfvénic turbulence. For weakly unstable AEs, the use of global hybrid MHD-gyrokinetic codes provides the most promising route to exploring the issue of fast ion transport in burning plasmas. Along this path, two issues remain to be solved: (1) the multi-mode simulation in realistic equilibria, for adequate treatment of possible phase-space stochasticity effects; (2) the coupling of global wave-field solvers to evolution (transport) codes for the energetic particle equilibrium distribution function on long time scales.

The picture of nonlinear fast ion dynamics is further complicated if the plasma is significantly above marginal stability. Simulation results indicate that, above threshold for the onset of resonant EPM [25], strong fast ion transport occurs in 'avalanches' [51]. Such strong transport events occur on time scales of a few inverse linear growth rates (generally, $100 \div 200$ Alfvén times) and have a ballistic character [52] that basically differentiates them from the diffusive and local nature of weak transport. Experimental observations on the JT-60U tokamak have also confirmed macroscopic and rapid energetic particle radial redistributions in connection with the so-called abrupt large amplitude events (ALE) [53]. Numerical simulations of an $n = 1$ EPM burst [54] show that radial profiles of energetic ions, computed before and after the EPM induced particle redistributions, agree qualitatively and quantitatively with experimentally measured fast ion radial profiles before and after ALE, obtained by spatial inversion of neutron profile emissions [55]. Good agreement is obtained also on the burst duration [54]. Therefore, it is crucial to theoretically assess the potential impact of fusion product avalanches due to the hard limit that these may pose on burning plasma operations.

Recent numerical simulations of burning plasma operations proposed for ITER indicate that significant fusion-α losses ($\approx$5%) may occur due to a rapid broadening of α-particle profiles in the hollow-q 'advanced'-tokamak scenario [56]. Meanwhile, only moderate internal energetic ion relaxation are expected for 'conventional' q-profiles, whereas strong EPM excitation and significant convective fusion-α losses are predicted in the 'hybrid' centrally flat-q-profile case only if the volume averaged fast ion density is increased by a factor $\simeq$1.6 [56]. These results are obtained assuming an initial given fusion-α profile. In the EPM case, the coupling of global field solvers to evolution codes for the energetic particle reference distribution function on long time scales is even more demanding than for weakly unstable AEs, due to the bigger separation of time scales and the self-consistent evolution of the wave-field with the fast ion free energy source profiles. Similar considerations can be made for the nonlinear energetic ion dynamics in the presence of low-frequency MHD modes. Convective losses with ballistic character [52], similar to those of EPM avalanches, were originally proposed for explaining experimental observations of the fishbone mode [3]. Recent numerical simulations of both kink and fishbone instability confirm the fact that rapid fast ion transport is expected when the system is significantly above marginal stability [57]. Simulation results also elucidate the complex interplay between mode structure and fast ion source, showing that saturation is reached because of the rapid broadening of the energetic ion radial profile, even if fluid nonlinearities are important as well [57].

These results suggest that energetic ion transport in burning plasmas has two components: one identified by slow diffusive processes due to weakly unstable AEs and a residual component possibly due to plasma turbulence [49, 50]; another one characterized by rapid transport processes with ballistic or secular nature due to coherent nonlinear interactions with EPM and/or low-frequency long-wavelength MHD modes. In order to improve confidence on predictive capabilities of burning plasma operations it is necessary to rely on mutual positive feedbacks between experiment, theory and numerical simulations: on the one hand more fundamental studies provide the conceptual framework and the necessary insights for understanding results from numerical studies; on the other hand numerical simulations of increasingly realistic plasma conditions and verification of model predictions versus experimental data are crucial for validating theories and numerical codes. Examples of this were given above. It is also important to emphasize that progress in fundamental theories has often broader implications that are not restricted to fusion plasmas. This is the case, for example, of the theory of hole–clump pair formation in phase space [43], proposed for explaining the pitchfork splitting of TAE spectral lines observed on JET [42] and used for interpreting high resolution MHD spectrometry [22], and now being taken forward with studies of strongly nonlinear regimes via numerical simulations [58]. Another example is the theory of Alfvén wave bursts, avalanches and convective fast ion losses [51], recently observed on JT-60U [53, 55], which has been developed in the context of consistency studies of proposed burning plasma experiments [59, 60]. The avalanches, observed in energetic ion transports for strongly unstable conditions, qualitatively resemble those characterizing the bursty behaviour of thermal ion transport in nonlinear gyrokinetic simulations of ion temperature gradient (ITG) driven turbulence [61, 62] (see also section 3). These processes are intimately connected with turbulence spreading (see section 3), since avalanches involve turbulence spreading mediated by local gradient steepening and relaxation, as noted in [63]. The radial envelope of coupled poloidal Fourier harmonics composing the EPM wavepacket propagate radially (see figure 1) in phase with an unstable moving front [51] because of the finite radial group velocity and the nonlinear distortion of the energetic ion pressure profile. Toroidal geometry (via linear dispersiveness of the EPM wavepacket) and nonlinear dynamics are, thus, equally important to capture the avalanche physics. Under quite general assumptions, the time evolution equation for the radial envelope $A_n(r,t)$ in toroidal geometry can be formally written as

$$[\partial_t - \gamma_L + v_{gr}\partial_r + iD(V - \partial_r^2)]_n A_n(r,t)$$
$$= (C_{0,n} + C_{n,0}) \circ A_0(r,t)A_n(r,t) + \sum_{n'+n''=n}^{n',n''\neq n} C_{n',n''} \circ A_{n'}(r,t)A_{n''}(r,t), \quad (1)$$

after removing fast space and time scales. The left-hand side (lhs) is in the form of a Schrödinger wave operator and describes the linear excitation and propagation of the wave. The linear growth rate, $\gamma_L(r,t)$, the radial group velocity $v_{gr}(r,t)$, the dispersiveness $D(r,t)$ and $V(r,t)$, which plays the role of a potential well, are all functions of space and time. The time dependence tracks the slow time variation of the fast space and time scales that have been averaged out from equation (1). For example, this dependence could account for a frequency chirping of the wavepacket, that does not need to be a linear eigenmode: the eigenmode formation would require many bounces of the wavepacket in the radial cavity and this could never happen if the nonlinear interactions (on the right-hand side, rhs) regulate the dynamics on shorter time scales. The $C_{n',n''}$ operators on the rhs are generally integro-differential operators, which imply non-local interactions in k-space (here, the n-space). The formal separation of terms $\propto (C_{0,n}+C_{n,0})$ from those $\propto C_{n',n''}$ $(n', n'' \neq n)$ corresponds to isolating the effects of zonal flows (ZF) and zonal fields [64,65] (see also section 3) as well as those of radial modulations in the energetic particle profiles, which are dominant for EPM nonlinear dynamics [66]. The problem of three wave coupling and nonlinear turbulent behaviour of AE and EPM in the presence of multiple ns has received limited attention so far, although this is an important aspect to be addressed in the perspective of burning plasmas, as noted above. More attention has been devoted to the coherent nonlinear behaviour of single-n EPM and the associated fast ion avalanches [51]: it has been shown that equation (1) can be reduced to the form of the complex Ginzburg–Landau equation

$$\partial_\xi^2 A_n = i\frac{\gamma_L}{D}\left(\frac{\Delta\gamma_L}{\gamma_L} + \frac{L_{NL}^2}{\gamma_L}\partial_\xi^2\left(\gamma_L|A_n|^2\right)\right)A_n + \frac{\Delta\omega}{D}A_n, \quad (2)$$

where $\xi = r - v_{gr}t$, $\Delta\omega + i\Delta\gamma_L$ is the complex frequency shift due to plasma non-uniformities, L_{NL} is a nonlinear characteristic scale length and $\gamma_L \propto \alpha_H = -R_0q^2(\mathrm{d}\beta_H/\mathrm{d}r)$, with α_H the energetic particle free energy source profile. In case of a Gaussian source function $\alpha_H = \alpha_{H0}\exp[-(\xi - \xi_0)^2]$, the Ginzburg–Landau equation (2) reduces to its canonical form [67], which finds many applications other than fusion plasma physics [68]. A generalization of this can be proposed for a family of models when the profile function is given by a stretched Gaussian distribution, i.e. $\alpha_H = \alpha_{H0}\exp[-|\xi - \xi_0|^\mu]$ with some fractional μ between 1 and 2. In those cases, equation (2) can be rewritten in terms of fractional derivative operators, thus reminding about the issue of a fractional Ginzburg–Landau equation addressed in [69]. The fractional derivative Ginzburg–Landau equation incorporates the key features of non-Gaussianity and long-range dependence in thresholded nonlinear dynamical systems such as burning plasmas. Equation (2) is consistent with the convective amplification of the unstable EPM moving front, demonstrated via numerical simulations and analytical estimates based on equation (1) in the local limit [51]. On longer time scales, the nonlinear EPM dynamics causes radial modulations in the fast ion pressure profile [66], which may be relevant in the light of interaction with plasma turbulence and turbulent transport, as discussed in section 3.

3. Turbulent transport

For the writing of part of this section, the authors benefited from access to some unpublished material by Diamond [70]. Understanding the fundamental processes that are responsible for thermal ion turbulent transport is a good example of the capability of plasma theory and numerical simulations to capture the essence of accumulating experimental evidences on the existence of regions of reduced transport, or transport barriers, in magnetically confined toroidal plasmas [71,72]. The role of toroidally and poloidally symmetric $\boldsymbol{E}\times\boldsymbol{B}$ flows and their nonlinear decorrelation effect on plasma turbulence were investigated theoretically [73,74] and numerically via gyrofluid simulation approach [75], resulting in a rough criterion for turbulence suppression when the $\boldsymbol{E}\times\boldsymbol{B}$ shearing rate [74] exceeds the maximum linear growth rate [75]. The role of mean $\boldsymbol{E}\times\boldsymbol{B}$ flows and their effect on plasma turbulence are essentially well understood [76]. However, turbulence itself can generate toroidally and poloidally symmetric $\boldsymbol{E}\times\boldsymbol{B}$ flows [77], dubbed ZF, which are crucial in regulating the nonlinear dynamics of DW turbulence, e.g. ITG fluctuations, as shown in 3D gyrofluid [78] and gyrokinetic [79, 80] simulations. For symmetry reasons, ZFs do not cause any transport and can be excited only nonlinearly. Meanwhile, they are undamped [81] unless finite collisional dissipation is considered [82]. For this reason, ZF spontaneous excitation by ITG turbulence, demonstrated in gyrokinetic simulations [83], provided a key element for formulating a predator–prey model for the nonlinear self-regulation of DW turbulence by ZFs [84]. Spontaneous excitation of ZFs by DW turbulence is explained by either modulational instability of DW turbulence plasmons [84] or by modulational instability of the DW radial envelope in toroidal geometry [85] (see [64] for a recent review of the subject). ZFs are widely recognized to be responsible for the up-shift (with respect to the linear stability threshold) of the critical ion temperature gradient above which ITG turbulent transport is observed in numerical simulations [86]. Thus, the detailed understanding of the fundamental processes underlying ZF generation by DW turbulence has not only provided further insights into the nature of turbulent transport but it will be crucial for predicting confinement properties in plasmas of fusion interest. Another important aspect for quantitatively predicting turbulent transport in burning plasmas is turbulence spreading [87–89], which has been proposed as explanation for the dependence of turbulent transport coefficients on the device size [90–92]. Both three wave couplings [63, 93, 94] and nonlinear DW–ZF interactions in toroidal geometry [95] have been proposed as underlying dynamics of turbulence spreading. Recent analyses have shown that ballistic spreading of DW turbulence is possible for both weak and strong turbulence regimes in slab geometry [63]; however, in the realistic conditions of burning plasmas magnetically confined in toroidal systems, toroidal geometry is expected to play a crucial role in the spreading process [95]. In fact, the complex nature of turbulence spreading dynamics [63] depends on the competition of the different nonlinear [63, 64] as well linear time scales [96] of DW wavepacket propagation, which are significantly affected by equilibrium (toroidal) geometry [87]. As discussed in section 2 for energetic particle dynamics in burning plasmas, the fundamental physics of ZFs have much broader applications than fusion plasmas. A noticeable example is the nonlinear dynamics of the planetary magnetospheres [64]. Similar considerations apply for turbulence spreading: as an example, it is worthwhile mentioning that, starting with envelope equations in the form of equation (1) and taking appropriate closures for the three wave couplings [63, 93, 94], it is possible to derive turbulence intensity evolution equations in the form [94]

$$\frac{\partial}{\partial t} I = \Gamma I + \frac{\partial}{\partial r}\left(D\frac{\partial}{\partial r} I\right), \tag{3}$$

where $I \propto |A_n|^2$ and $\Gamma(I)$ and $D(I)$ are functions of the turbulence intensity, I. Equation (3) is a variant of the Fisher equation and recent numerical simulations [97] have shown that the propagation speed of the spreading turbulence front scales as $(\Gamma D)^{1/2}$, as theoretically expected.

In addition to the low frequency ZFs, DW turbulence can nonlinearly excite the geodesic acoustic mode (GAM) [98], which consists of higher intrinsic frequencies that are excited due to the toroidally and poloidally symmetric electric field fluctuation coupling to poloidal sidebands of parallel electric field and pressure perturbations via geodesic curvature. Due to the higher intrinsic frequency, GAMs are expected to have weaker decorrelation effect on DW turbulence [99]. The role of geodesics curvature in inhibiting turbulence suppression by ZFs has been pointed out for edge turbulence [100] and, similarly, the role of q in setting the oscillatory characteristics of ZFs [101] has been emphasized as well. These evidences have been recently shown to be due to the relative importance of ZFs and GAMs in the nonlinear DW dynamics, resulting in a linear scaling of the ITG turbulent diffusivity with the inverse plasma current [102]. These significant advances of plasma theory and numerical simulations have largely influenced the experimental studies of turbulent transport [64]. Still, more definite experimental proofs are needed on the role of ZFs and GAMs in reducing plasma turbulence and of their effectiveness in improving plasma transport [65]. In reference to experimental observations of modes at the GAM frequency, it is worthwhile emphasizing that the kinetic expression of the GAM dispersion relation [103] is degenerate with that of the low frequency s.A. accumulation point [15] in the long wavelength limit. This degeneracy is not accidental and is due to the identical dynamics of GAM ($n = m = 0$) and s.A. wave near the mode rational surface ($nq \simeq m$) under the action of geodesic curvature, the difference between the two branches standing in the mode polarization. Thus, besides measuring the mode frequency, it is necessary to measure polarization and toroidal mode number to clearly identify the mode.

Recent progress in understanding electron turbulent transport was obtained via successful modelling of experimental results from ASDEX Upgrade [104, 105], based on quasi-linear analyses of ITG and trapped electron mode (TEM) fluctuations in both fluid and gyrokinetic descriptions [106, 107]. The reduced density peaking with increasing collisionality is interpreted as a reduction of the ITG-induced (turbulent) particle inward pinch, which is gradually replaced by the much weaker Ware pinch [104]. The same model also explains the experimentally observed T_e profile, as well as the effect of increased electron heating at low collisionality, where the increased TEM drive causes an outward (turbulent) particle flux and, hence, density profile flattening. Density profile peaking is a crucial issue for burning plasma operations and for fusion performance. The competition between ITG-induced inward and TEM-induced outward particle pinch suggests that ITER-like plasmas at typically low collisionality and dominant electron heating should be characterized by a density profile scale length of the order of the plasma minor radius [106, 107], i.e. more peaked than originally assumed. Similar conclusions on the collisionality dependence of the turbulent particle pinch has been confirmed by nonlinear gyrokinetic simulations [108], although quantitative extrapolations to ITER-like plasmas still require further investigations in the light of recent quasi-linear gyrokinetic analyses [109]. There are experimental evidences that thermal electron turbulent transport remains well above the neoclassical theory prediction even when ITG/TEM (long) wavelength fluctuations are sufficiently reduced to a level to allow formation of transport barriers for ion heat and particle transport [110]. The clear indication that elongated radial structures dominate the nonlinear dynamics of electron temperature gradient (ETG) turbulence [111, 112] and the relatively weaker role played by ZFs with respect to the ITG case [113] have suggested that the radially extended ETG eddies, dubbed streamers, are a possible explanation of electron turbulent diffusivities at levels of experimental interest found in numerical simulations [111, 112]. However, there is still no clear indication of the actual level of ETG induced electron turbulent transport [114–116] and of the scaling of electron turbulent transport with the radial size of streamers [116, 117]. What emerges from both theoretical analyses [118] and numerical simulations [116, 117] is the role of low toroidal

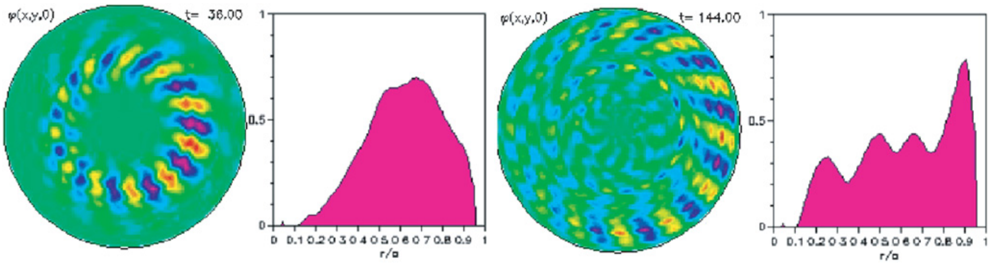

Figure 2. Evolution of the EPM radial structure. The two left-most frames refer to the scalar potential fluctuation contour plot and the energetic particle $\alpha_{\rm H} = -R_0 q^2 (d\beta_{\rm H}/{\rm d}r)$ in the linearly unstable phase at $t = 36$ in units of $\tau_{A0} = R_0/v_{A0}$. The two right-most frames are taken at $t = 144$ and show the radial modulation of the fast ion pressure profile. Here $n = 4$ and simulation parameters are those of [66].

(poloidal) mode numbers, which mediate the ETG nonlinear saturation by inverse cascade via nonlocal interactions in k-space [118], whose strength depends on the toroidal geometry of the system.

Plasma rotation is not only beneficial for turbulence suppression [73, 74] but for its stabilization effect on macroscopic MHD modes, like resistive wall modes (RWM), which would otherwise limit plasma performance. It is still debated whether ITER will have sufficient neutral beam injection (NBI) power for controlling the plasma rotation profile. However, the experimental evidence of spontaneous plasma rotation without net momentum input [119–121] demonstrates the existence of regimes which may be extremely relevant for burning plasma operations. Transport and spontaneous plasma rotation are intrinsically connected: radial transport of toroidal angular momentum into regions where it can be efficiently absorbed, e.g. at the plasma edge, can spin up the plasma. The flux of toroidal angular momentum, Γ_ϕ, has the general form of a diffusive plus a pinch term [122–124], which vanishes for symmetric fluctuation spectra in $k_\parallel$ space [124–126]. This symmetry argument has been shown to be a consequence of the more general symmetry properties [127] of the gyrokinetic equations for up–down symmetric equilibria [128]. For typical plasma equilibrium parameters, nonlinear fluid [129] as well as quasi-linear gyrokinetic theories [127] show that Γ_ϕ and heat transport coefficients by ITG turbulence are comparable. Recently, a quasi-linear theory based on modes rotating in the electron diamagnetic direction and driven by both ion temperature gradient and parallel velocity shear (velocity and temperature gradient (VTG) driven modes [130]) has been proposed to explain the toroidal rotation profiles in H-mode plasmas. This theory predicts a link between parallel viscosity, responsible for the $k_\parallel$-symmetry breaking, and the heat transport diffusivity, which are of comparable strength [130]. Spontaneous generation of toroidal rotation via the parallel Reynolds stress component [124–126] has been demonstrated by nonlinear fluid simulations [131]. Besides having great relevance to burning plasmas, the theory of toroidal angular momentum transport also plays a crucial role in other fields like space plasma physics and astrophysics, e.g. in the theory of accretion discs [132, 133].

A fundamental aspect, which still remains essentially unexplored is the issue of whether mutual interactions between collective modes and energetic ion dynamics on the one side and drift wave turbulence and turbulent transport on the other side, may decrease, on long time scales, the thermonuclear efficiency. Usual electrostatic DW turbulence will be weakly affected by the presence of energetic ions, due to their small density. Still, fast ion transports via slow diffusive processes due to plasma turbulence [49, 50] will be present, although subdominant (see section 2). Meanwhile, theory predicts that Alfvénic fluctuations near the low-frequency s.A. accumulation point can be excited for a wide range of mode numbers by fast ions (for long wavelengths) as well as by thermal ion temperature gradients (for short wavelengths). The fast ion driven modes were originally observed in DIII-D as BAE modes [16], while the Alfvénic ITG (AITG) [15, 134] remained a theoretical prediction till recent experimental measurements on DIII-D [135], confirming the broad wave-number spectrum of Alfvén fluctuations excited by both energetic and thermal ions. Alfvénic turbulence, meanwhile, may affect transport processes not only via $\boldsymbol{E} \times \boldsymbol{B}$ nonlinearity but also via magnetic flutter [136]. This example of positive feedbacks between theory and experiment shows the profound relationship between Alfvénic turbulence and AEs. Nonlinear interactions of Alfvénic fluctuations near the low-frequency s.A. accumulation point with long wavelength MHD modes are also possible, as shown by the experimental evidence of BAE modes nonlinearly excited by a large tearing mode island on FTU [137].

On the long time scale, AE and EPM nonlinear evolutions, as well as those of AITG or strongly driven MHD modes, can be predominantly affected by either spontaneous generation of zonal flows and fields [138, 139] or by radial modulations in the fast ion profiles [51, 57], depending on the proximity to marginal stability. For strongly unstable conditions, like those typical of EPM excitations, the latter ones dominate the nonlinear dynamics with respect to the $\boldsymbol{E} \times \boldsymbol{B}$ shearing, which becomes increasingly important as marginal stability is approached. The radial modulation in the fast ion profiles in burning plasmas (see figure 2) will reflect on the dominant electron heating source and, thus, on thermal plasma turbulent transport. ZFs generated by MHD and/or AE/EPM and AITG, meanwhile, may have higher intrinsic frequency with respect to similar flows generated by electrostatic drift turbulence: thus the possible nonlinear interplay between zonal structures, drift wave turbulence and collective modes excited by energetic ions remains to be assessed [99]. However, given the very disparate space–time scales of AE/EPM, MHD modes and plasma turbulence, their nonlinear finterplay via zonal flows and fields is expected to be one of the dominant mechanisms in the complex self-organized behaviours of burning plasmas. Realistic toroidal geometry for Alfvénic fluctuation studies will be even more crucial than for electrostatic DW turbulence, due to the fundamental importance of magnetic curvature couplings in both linear and nonlinear dynamics [140, 141].

The long time scale behaviours of zonal structures, i.e. ZFs and zonal fields as well as radial profile modulations, are important for the overall burning plasma performance. In fact, they can be viewed as generators of nonlinear equilibria [142]. The corresponding stability, meanwhile, determines the dynamics underlying the dissipation of zonal structures in collisionless plasmas and the nonlinear up-shift of thresholds for turbulent transport. An example is the nonlinear up-shift of the critical ion temperature gradient in ITG turbulence [86], which has been associated with a Kelvin Helmholtz like instability due to ZFs in fluid analyses [143–145] or, in kinetic studies [146], with a trapped ion instability driven by zonal structures in the ion temperature gradient. More generally, long time scale simulations will be crucial to understand how zonal flows and structures saturate in collisionless burning plasmas and their relevance for future devices such as ITER. However, theoretical approaches based on nonlinear evolution equations for the zonal response will be important as well for gaining the necessary insights into the corresponding complex behaviours.

4. Conclusions

Burning plasmas are complex self-organized systems, whose investigation requires a conceptual step in the analysis of magnetically confined plasmas. Integrated numerical simulations are crucial to investigate these new physics; however, fundamental theories also play a fundamental role of providing the conceptual framework and the insights that are needed to extrapolate with confidence numerical modelling to burning plasma operations in future experimental devices. Verification against experimental observations in present day machines, meanwhile, is a necessary step for the validation of physical models and numerical codes. The lack of understanding of some complex burning plasma behaviours, such as those discussed in the present work and typical of collective plasma behaviours and energetic particle losses as well as turbulent transport, can be likely filled in by increasingly complicated and more realistic modelling of plasma conditions as computing performances improve. However, some other unexplained behaviours may be just indications of fundamental conceptual problems: thus, mutual positive feedbacks between theory, simulation and experiment will be necessary.

The general problems posed by investigations of burning plasma physics often have broader applications than just fusion science. Here, we have given examples of how fusion plasmas can be considered as generators of a wide class of nonlinear dynamics problems, which may be readily extended to neighbouring fields, e.g. accelerator physics and plasma astrophysics.

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