Physics of Alfvén waves and energetic particles in burning plasmas

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Dynamics of shear Alfvén waves and energetic particles are crucial to the performance of burning fusion plasmas. This article reviews linear as well as nonlinear physics of shear Alfvén waves and their self-consistent interaction with energetic particles in tokamak fusion devices. More specifically, the review on the linear physics deals with wave spectral properties and collective excitations by energetic particles via wave-particle resonances. The nonlinear physics deals with nonlinear wave-wave interactions as well as nonlinear wave-energetic particle interactions. Both linear as well as nonlinear physics demonstrate the qualitatively important roles played by realistic equilibrium nonuniformities, magnetic field geometries, and the specific radial mode structures in determining the instability evolution, saturation, and, ultimately, energetic-particle transport. These topics are presented within a single unified theoretical framework, where experimental observations and numerical simulation results are referred to elucidate concepts and physics processes.

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I. INTRODUCTION

Since the mid 20th century, mankind has pursued magnetic fusion energy (MFE) research, which has reached a crucial stage with the construction of the International Thermonuclear Experimental Reactor (ITER) (Tamabechi *et al.*, 1991; Aymar *et al.*, 1997). The purpose of ITER is investigating the physics of burning plasmas, where deuterium-tritium (D-T) fusion reactions

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}(3.52\ \mathrm{MeV}) + n(14.06\ \mathrm{MeV})$$

produce α particles and neutrons. In ideal conditions for a fusion reactor, α particles thermalize (slow down) due to Coulomb collisions with the thermal plasma and sustain the fusion process by supplying the power input required to keep the plasma in "ignition" condition. Thus, α particles need to have sufficiently good confinement.

In toroidally symmetric magnetic fusion experimental devices (tokamaks), e.g., ITER, the geometry of the confining equilibrium magnetic field $\boldsymbol{B}_0$ is conceived to ensure properly confined charged-particle orbits, including fusion α particles. While transport due to classical collisional processes is sufficiently small, the concern is transport via collective fluctuations driven unstable by α particles via wave-particle resonances. Such collective instabilities may be toroidal symmetry breaking and, thus, lead to enhanced α-particle loss. Such "anomalous" enhanced loss is, of course, detrimental to the success of MFE research.

In order to achieve wave-particle resonances, the α-particle characteristic dynamical frequencies need to match the wave frequencies of collective instabilities. As typically α-particle velocity-space distribution function is isotropic and, after slowing down due to Coulomb collisions, decreases with energy; i.e., a velocity-space gradient is stabilizing, no collective fluctuations around the cyclotron frequency (or "gyrofrequency") will be excited. That is, the relevant instability drive is due to the finite real-space gradients. The dynamical frequencies are, thus, associated with the guiding-center motion, i.e., transit, bounce, and precessional frequencies in, e.g., a tokamak device. The corresponding wave frequencies then fall inside the magnetohydrodynamic (MHD) regime (Alfvén, 1942, 1950), which are $\mathcal{O}(10^{-2})$ smaller than the ion gyrofrequency Ω_i for typical tokamak parameters. As to the three finite-frequency MHD modes, the most relevant one is the nearly incompressible, anisotropic shear Alfvén wave (SAW) with dispersion relation $\omega = k_\parallel v_A$. Here $k_\parallel = \boldsymbol{k}\cdot\boldsymbol{B}_0/B_0$ is the parallel wave number and $v_A = B_0/\sqrt{4\pi\varrho_{m0}}$ is the Alfvén speed, with ϱ_{m0} the plasma mass density. The compressional, fast Alfvén wave with $\omega_f \simeq k v_A$ tends to have frequencies at least $\mathcal{O}(10)$ higher than those of SAW and generally is more difficult to excite. The slow sound wave with $\omega_s \simeq k_\parallel c_s$ (c_s is the ion sound speed) is also typically stable due to significant ion Landau damping with $T_e \sim T_i$, where T_e and T_i are, respectively, thermal electron and ion temperatures. This discussion is also applicable to energetic, fast (relative to the thermal background plasma) charged particles produced by auxiliary heating sources such as radio-frequency waves and/or neutral beam injection. Collective excitations of SAW instabilities by energetic, fast particles (EPs) and the ensuing nonlinear consequences on EP confinement as well as, on longer time scales, the confinement and stability of thermal background plasmas are, thus, crucial issues for both present-day MFE devices and future burning-plasma experiments.

A. Historical review

Energetic particles in burning plasmas consist of electrically charged fusion products as well as suprathermal ions and electrons, generated by external power sources that are used for heating and current drive or, more generally, for tailoring and controlling equilibrium plasma profiles. The possible detrimental roles of SAWs on EP confinement in burning plasmas was brought to researchers' attention since the pioneering works by Kolesnichenko and Oraevskij (1967), Belikov, Kolesnichenko, and Oraevskij (1968), Mikhailovskii (1975), and Rosenbluth and Rutherford (1975). In particular, Kolesnichenko and Oraevskij (1967) suggested that instabilities may be caused by fusion products, and Belikov, Kolesnichenko, and Oraevskij (1968) showed for the first time the existence of SAW instabilities with $\omega \simeq k_\parallel v_A$ driven by monoenergetic EPs. As the characteristic frequencies of EP motions in fusion devices are of the same order of those typical of SAWs, and the SAW group velocity is parallel to $\boldsymbol{B}_0$, resonant wave-particle interactions may directly excite a variety of SAWs as well as yield an efficient transport channel for EPs.

In the 1980s, increasing theoretical attention was devoted to the analysis of the effects of fusion α's in burning plasmas, e.g., in the works by Kolesnichenko (1980) and Tsang, Sigmar, and Whitson (1981). However, the problem of SAWs interactions with EPs and of related transport processes became an issue of immediate practical interest at the time of the first observation of the fishbone mode instability in the Poloidal Divertor eXperiment (PDX) tokamak (McGuire *et al.*, 1983), causing dramatic global losses of EPs due to a secular transport process (White *et al.*, 1983). This instability was explained as resonant excitation of an internal kink mode and its self-consistent nonlinear interplay with the EP nonuniform source (Chen, White, and Rosenbluth, 1984; Coppi and Porcelli, 1986). After fishbone observation and theoretical interpretation, MHD modes were considered on the

same footing as SAWs concerning their possible effect on EPs confinement. Essential physics ingredients in these analyses were nonuniform equilibrium profiles of EP sources, of SAW continuous spectrum (Chen, White, and Rosenbluth, 1984; Cheng, Chen, and Chance, 1985; Chen, 1988, 1994), the corresponding continuum damping by phase mixing (Grad, 1969), the specific equilibrium geometries of magnetized plasmas, and the resultant frequency gaps inside the SAW continuum (Pogutse and Yurchenko, 1978; D'Ippolito and Goedbloed, 1980; Kieras and Tataronis, 1982). In the same years, further demonstration of the articulated role played by EPs in tokamak plasmas came with the evidence of "sawtooth"[1] stabilization in plasma discharges with additional heating (Campbell *et al.*, 1988) observed in the Joint European Torus (JET) (Rebut, Bickerton, and Kenn, 1985). This was explained with the strong stabilizing effect of magnetically trapped EPs on the internal kink mode (Coppi *et al.*, 1988; White *et al.*, 1988) and is an important example of plasma operation control by external power input.

An important theoretical result was that discrete Alfvén eigenmodes (AEs), such as toroidal AEs (TAEs), can exist essentially free of continuum damping in the frequency gaps of the SAW continuous spectrum (Cheng, Chen, and Chance, 1985). Experimental observations of TAEs (Heidbrink *et al.*, 1991; Wong *et al.*, 1991) and of lower frequency AEs dubbed beta-induced AEs (BAEs) (Heidbrink, Strait *et al.*, 1993), and, most importantly, the evidence that these modes may have significant impact on EP transport were the findings that brought significant and continuing attention to the physics of SAWs and EPs in burning plasmas. In fact, only a small fraction of fusion α's or EP losses can be tolerated in ITER without significantly degrading the fusion yield or damaging the plasma facing components (ITER Physics Expert Group on Energetic Particles, Heating and Current Drive, 1999; Fasoli *et al.*, 2007; Pinches *et al.*, 2015).

Another important theoretical prediction was the existence of energetic-particle continuum modes (EPMs) (Chen, 1994), i.e., non-normal modes of the SAW continuous spectrum, which emerge as discrete fluctuations at the frequency that maximizes wave-EP power exchange above the threshold condition associated with continuum damping. In this respect, fishbones could be considered the first example of EPM. In the presence of EPM and/or fishbones, the low critical level of tolerable EP losses in a fusion device can become more severe. In fact, being non-normal modes, both fishbones and EPMs maintain maximum wave-EP power exchange and ensuing EP transport through their nonlinear evolution by phase locking with resonant particles via frequency sweeping (Briguglio, Zonca, and Vlad, 1998; Vlad *et al.*, 2004, 2013; Zonca *et al.*, 2005, 2015b; Briguglio *et al.*, 2007). In turn, phase locking is responsible for the secular transport process first introduced by White *et al.* (1983) to explain fishbone induced EP losses. Intuitively, secular losses of EPs are characterized by a different energy spectrum than EP diffusive losses and tend to be more critical, since resonant EPs are typically lost before significant thermalization (White *et al.*, 1983; Chen, 1988). The self-consistent nonlinear interplay of EP spatial distributions with the EPM radial mode structures plays a crucial role in all of these processes. Experimental observations of EPMs and corresponding EP transport came right after their theoretical prediction (Gorelenkov *et al.*, 2000; Gorelenkov and Heidbrink, 2002). Meanwhile, first spectacular observations of these phenomena, dubbed abrupt large amplitude events (ALEs) (Shinohara *et al.*, 2001), were reported in the JT-60U tokamak (Shinohara *et al.*, 2004) and are among the clearest experimental evidences of strong EP redistributions along with observations of EP losses and redistributions in the Doublet III-D (DIII-D) (Duong *et al.*, 1993; Strait *et al.*, 1993; Heidbrink and Sadler, 1994) and National Spherical Torus eXperiment (NSTX) tokamaks (Fredrickson *et al.*, 2009; Podestà *et al.*, 2009, 2011).

Since the early evidence of AEs and EPMs in tokamak plasmas, a whole "zoology" of modes have been observed (Heidbrink, 2002), with a classification following the qualitative features of experimental measurements. All these fluctuations can be actually understood and explained within the theoretical framework based on one single general fishbonelike dispersion relation (GFLDR) (Zonca and Chen, 2014b, 2014c), first introduced for the description of the fishbone mode (Chen, White, and Rosenbluth, 1984), and later on derived for different branches of SAW fluctuations, demonstrating its general validity (Zonca and Chen, 2006, 2007; Chen and Zonca, 2007a; Zonca *et al.*, 2007a; Chen, 2008). The usefulness of the GFLDR theoretical framework stands in its capability of providing a simple description of the underlying physics and extracting the distinctive features of the different AE and EPM branches that have been observed experimentally or in numerical simulations. Furthermore, the GFLDR also naturally introduces the spatiotemporal scales of the process involved, explaining thereby the connection between MHD fluctuations, SAWs, and drift wave turbulence (DWT). The historical review of various experimental observations of AE and EPM and their theoretical interpretations is further articulated in Secs. III and IV. Successful feedbacks between theory and experiment in this area were made possible by the development of impressive diagnostic techniques as well as numerical simulation capabilities, accompanied by detailed physics understanding. Meanwhile, one element of enrichment was brought by the fruitful exchanges between MFE tokamak and stellarator expert communities (Kolesnichenko *et al.*, 2011; Toi *et al.*, 2011).

Of the two "routes" to nonlinear dynamics of EP-driven SAW instabilities (Chen and Zonca, 2013), i.e., nonlinear wave-wave and wave-EP interactions (cf. Sec. IV), the former one was historically addressed first in the classic work by Hannes Alfvén, demonstrating the existence of the pure "Alfvénic state," where SAW can exist in uniform, incompressible MHD plasmas independently of their amplitude due to the cancellation of Reynolds and Maxwell stresses and the incompressible plasma motion produced by SAW (Alfvén, 1942, 1950; Walén, 1944). However, nonlinear SAW-EP interactions have attracted most of the interest until recently because of the important role of EP transport in burning plasmas.

Within the first route, it is illuminating to explore the various nonlinear wave-wave interactions that could lead to the breaking of the Alfvénic state (Chen and Zonca, 2013).

[1]This name refers to the "shape" of the time trace of plasma electron temperature on the magnetic axis.

The effect of plasma compressibility in the macroscopic MHD limit was investigated by Sagdeev and Galeev (1969), demonstrating the decay instability of a SAW into an ion sound wave (ISW) and a backscattered SAW. Later, plasma compressibility effects were explored by Hasegawa and Chen (1976) for microscale fluctuations with wavelengths of the order of the thermal ion Larmor radius. This analysis not only generalized the MHD results on the decay instability, but demonstrated important consequences on plasma transport due to the different features of scattered SAW fluctuation spectra. These processes are discussed in Sec. IV.B, while Sec. IV.C analyzes examples of processes that could break the Alfvénic state in toroidal geometry as well as lead to cross-scale couplings among MHD fluctuations, SAWs, and DWT.

Within the second route (cf. Sec. IV.D), the first nonlinear analysis of "thermonuclear Alfvén instability" was reported by Belikov, Kolesnichenko, and Oraevskij (1974), using the quasilinear description of a weakly turbulent plasma (Vedenov, Velikhov, and Sagdeev, 1961; Drummond and Pines, 1962). This case shows the important influence of original works on nonlinear wave-particle dynamics in one-dimensional (1D) systems, investigated by pioneers in the early 1960s (O'Neil and Malmberg, 1968), adopting the paradigmatic case of the interaction of a suprathermal electron beam with a plasma in a strong axial magnetic field. This system provides the framework in which various processes were investigated and understood, such as mode dispersion relations, Landau damping in a finite-amplitude wave (Mazitov, 1965; O'Neil, 1965), and nonlinear behavior due to wave-particle interactions (O'Neil, Winfrey, and Malmberg, 1971). The interest for the beam-plasma system was revived in the 1990s, when it was proposed as a paradigm for interpreting experimental observation of AEs excitation by EPs and related nonlinear dynamics processes near marginal stability (Berk, Breizman, and Ye, 1992a; Breizman, Berk, and Ye, 1993; Berk, Breizman, and Pekker, 1996; Berk, Breizman, and Petiashvili, 1997; Breizman *et al.*, 1997), based on their one-to-one correspondence with the evolution of the "bump-on-tail" instability (Langmuir wave) in a 1D uniform plasma (Berk and Breizman, 1990a, 1990b, 1990c). This bump-on-tail paradigm, recently reviewed by Breizman and Sharapov (2011), was extensively applied for comparisons of theoretical model predictions with experimental observations. There are, however, processes crucial to the dynamics of toroidal plasmas such as fishbone induced EP losses (White *et al.*, 1983) as well as nonlinear EPM dynamics and ensuing EP transport (Briguglio, Zonca, and Vlad, 1998; Zonca *et al.*, 2000, 2005; Vlad *et al.*, 2004), which would require theoretical analyses based on an alternative "fishbone" paradigm (Chen and Zonca, 2013; Zonca *et al.*, 2015b). Magnetic field geometry and plasma nonuniformities play major roles in this fishbone paradigm. In particular, nonlinear dynamics due to the self-consistent interplay of fluctuations evolution and EP transport leads typically to secular EP losses due to EPMs, fishbones, and phase locking of fluctuations with resonant particles via frequency sweeping. Ultimately, it is possible to demonstrate the unification of these two paradigms for nonlinear wave-EP interactions (cf. Sec. IV.D), based on the solution of the Dyson equation for the EP distribution function (Al'tshul' and Karpman, 1965).

Because of the intrinsic complexity involved in a self-consistent nonlinear description of SAW fluctuations with EPs, EP transport in burning plasmas has typically been addressed by test-particle methods (Hsu and Sigmar, 1992; Sigmar *et al.*, 1992), i.e., removing the possible feedback of EP redistributions on a given fluctuation spectrum (cf. Sec. V). As AE fluctuations are local in nature and have generally small intensity [see, e.g., Heidbrink (2008)], EP redistributions by AEs are expected to be typically small, unless stochastization threshold of EP motions in phase space is reached in the presence of many modes. Realistic predictions of test-particle transport in ITER are, however, still not available. In fact, not only is the threshold for stochastic EP transport sensitive to details of the underlying physics and adopted model (White *et al.*, 2010a, 2010b), but predicting EP redistributions and losses requires necessarily realistic sources, geometries, and boundary conditions. Such thorough and detailed calculation of AE spectra in ITER with comprehensive global gyrokinetic and/or extended hybrid MHD-gyrokinetic codes (cf. Sec. II) could be likely available in the near future due to the progress in both computational capabilities and understanding of essential physics ingredients.

B. Scope of the present review

The first and thorough experimental review of SAW and EP physics in burning plasmas was given by Heidbrink and Sadler (1994). This work was followed by that of Wong (1999), which was focused on experiments in the Tokamak Fusion Test Reactor (TFTR) (Grove and Meade, 1985) but provided a general overview in this area. A dedicated review of α-particle physics experiments in TFTR was given by Zweben *et al.* (2000), while high performance D-T experiments in JET (Gibson, 1998) were stable to SAW excited by fusion α's (Sharapov *et al.*, 1999). Meanwhile, the ITER Physics Expert Group on Energetic Particles, Heating and Current Drive (1999) gave the first review of the physics of SAW and EPs in ITER plasmas, which was updated later on (Fasoli *et al.*, 2007), while the most recent review of this topic can be found in Pinches *et al.* (2015).

Basic theoretical reviews can be found in Mahajan (1995), analyzing the general linear properties of the SAW fluctuation spectrum, and in Chen and Zonca (1995), with a discussion of the complications and twists of SAW physics in realistic toroidal geometries. A general overview of both linear and nonlinear SAW and EP physics was given by Vlad, Zonca, and Briguglio (1999), along with a discussion of numerical simulation results using the hybrid MHD-gyrokinetic model (Park *et al.*, 1992). The work by Pinches *et al.* (2004) mainly focused on the interplay between advancements in nonlinear theory, also reviewed by Breizman (2006), and comparisons with experimental data. Other brief overviews are available, with emphasis on the self-consistent interaction of nonlinear SAW dynamics with EP transport and complex behavior in burning plasmas (Zonca *et al.*, 2006; Chen and Zonca, 2007a).

Key issues for burning plasmas were summarized by Heidbrink (2002) and a general review of basic physics of SAWs and EPs in toroidal plasmas was given by Heidbrink (2008). An updated view of experimental results since Wong

(1999) and Heidbrink (2002) and of the further progress in nonlinear theory comparison with experimental data was presented by Breizman and Sharapov (2011). Recent overview works meanwhile focused on the progress made in developing innovative diagnostic techniques and on the modeling effort for the interpretation of the corresponding observations (Sharapov *et al.*, 2013; Gorelenkov, Pinches, and Toi, 2014) as well as on the kinetic models and numerical solution strategies adopted in comparisons of numerical simulation results to experiments (Lauber, 2013). For stellarators, a recent experimental review can be found in Toi *et al.* (2011), while theoretical aspects were reviewed by Kolesnichenko *et al.* (2011), with emphasis on both the "affinity and difference between energetic-ion-driven instabilities in 2D and 3D toroidal systems."

The scope of this review is to provide a comprehensive analysis of physics processes involved with SAW and EP behavior in burning plasmas within a unified and self-contained theoretical framework. As prevalent Alfvénic fluctuations are in the MHD frequency range ($|\omega| \ll \Omega_i$), basic equations are derived from the nonlinear gyrokinetic equation (Frieman and Chen, 1982); cf. Sec. II. Most detailed derivations, which interested readers can find in Zonca and Chen 2014b, 2014c), are omitted in Sec. II. The main scope of Sec. II is the discussion of fundamental physics processes described by basic equations, especially their characteristic spatial and temporal scales.

Experimental observations and numerical simulation results are important elements of existing literature in this area and are referred to in this work as a means for elucidating theoretical concepts. Thus, this review offers different levels of reading that are merged and integrated into the same narrative to address the different aspects that may be of interest to theoreticians, modelers, and/or experimentalists. The GFLDR (cf. Sec. III.C) provides the foundation for the unified theoretical framework used throughout this work and is derived and discussed in Zonca and Chen (2014b, 2014c). The present review shows the usefulness of the GFLDR theoretical framework in suggesting the interpretation of experimental observations and numerical simulation results on the basis of the underlying physics. In this respect, various models and computation techniques with different levels of approximation can also be employed to validate and verify theoretical predictions.

The application of the GFLDR theoretical framework to nonlinear SAW and EP dynamics (cf. Sec. IV) allows separating wave-wave and wave-EP nonlinear interactions based on the respective spatiotemporal scales and unifying the bump-on-tail and fishbone paradigms for nonlinear SAW-EP interactions (Zonca *et al.*, 2015b) based on the solution of the Dyson equation for the EP distribution function. It also naturally yields to the formulation of a general nonlinear Schrödinger equation (NLSE) with integrodifferential nonlinear terms (cf. Sec. IV.A), which can be used to draw analogies between this area of MFE and neighboring fields of physics research, such as fluid turbulence, condensed matter, nonlinear dynamics and complexity, fractional kinetics, and accelerator physics (cf. Secs. IV.D and IV.E). This unified approach also elucidates the role of EPs as mediators of cross-scale coupling and long time-scale behavior in burning plasmas (Zonca, 2008; Zonca and Chen, 2008; Zonca *et al.*, 2013), reviewed by Zonca *et al.* (2015a).

In spite of the broad range of topics discussed in this review, it is far from being complete. A summary of relevant issues left out of this work is given in Sec. VI, along with elements for reflections on some of the major research topics in the MFE field for the next decade or so, in the perspective of ITER operations.

II. BASIC EQUATIONS AND CONCEPTS

In this section, we consider a magnetized plasma in general geometry and briefly review equations for low-frequency electromagnetic fluctuations, produced by the self-consistent charged-particle motion. The low-frequency ordering in magnetized plasmas is referred as usual to oscillation frequencies that are much smaller than the ion cyclotron frequency Ω_i, where $\Omega = eB_0/mc$, with the subscript i denoting ions, B_0 denotes the strength of the local equilibrium magnetic field, e stands for the generic particle electric charge, and m for its mass. Similarly, the subscript e refers to electrons and the subscript E denotes EPs, which may be ions and/or electrons.

A self-consistent description of low-frequency fluctuations is based on the derivation of gyrokinetic Maxwell equations (Antonsen and Lane, 1980; Catto, Tang, and Baldwin, 1981; Frieman and Chen, 1982),[2] expressed in terms of moments of the gyrocenter Vlasov (Boltzmann) distribution. Within this approach, one can systematically decouple (Rutherford and Frieman, 1968; Taylor and Hastie, 1968) the nearly periodic particle gyromotion (Kruskal, 1962; Northrop, 1963) from the fluctuation dynamics. This is achieved in two steps (Dubin *et al.*, 1983; Hahm, 1988; Hahm, Lee, and Brizard, 1988; Brizard, 1989), based on asymptotic decoupling of the fast gyromotion time scale from a set of Hamilton equations by Lie-transform methods (Littlejohn, 1982; Brizard, 1990; Qin and Tang, 2004). First, the guiding-center Hamilton equations are derived eliminating the gyroangle dependence due to the gyromotion of charged particles about $\boldsymbol{B}_0$. Second, the new gyrocenter Hamilton equations are obtained eliminating the gyroangle dependence in the perturbed guiding-center equations due to the presence of electromagnetic fluctuations. In this way (Brizard and Hahm, 2007), it is possible to construct the gyrocenter magnetic moment as an adiabatic invariant corresponding to the fast and nearly periodic particle gyromotion in the gyrocenter gyroangle, while the guiding-center magnetic moment adiabatic invariance is modified by the introduction of low-frequency fluctuations (Taylor, 1967).

In the following, we discuss equations governing the low-frequency response of a quasineutral, finite-β, magnetized plasma, with $\beta = 8\pi P/B_0^2$ defined as the ratio between kinetic and magnetic energy densities. We describe the low-frequency plasma oscillations in terms of three fluctuating scalar fields, having chosen to work in the Coulomb gauge: the scalar potential perturbation $\delta\phi$, the parallel (to $\boldsymbol{b} = \boldsymbol{B}_0/B_0$) magnetic field perturbation $\delta B_\parallel$, and the parallel (to $\boldsymbol{b}$) vector potential fluctuation $\delta A_\parallel$. For simplicity and hence clarity, we,

[2]See Brizard and Hahm (2007) for a recent and comprehensive review.

exceeded,[33] EPMs, characterized by nonadiabatic frequency sweeping and rapid secular particle redistributions, as discussed in Sec. IV.D.5, may then be triggered. Further indications of interesting nonlinear interplay between mode structures and EP transport in the case of TAE avalanches (Fredrickson *et al.*, 2009) come from the experimental growth rates $\sim 10^{-1}(\omega_0/2\pi)$ (Podestà *et al.*, 2011) that are typically larger than those computed from linear stability analyses $\sim 10^{-2}(\omega_0/2\pi)$ and from the mode structures that are not always the same as those reconstructed from reflectometry measurements (Podestà *et al.*, 2009). More recent analyses of these phenomena are given by Fredrickson *et al.* (2013).

The synergy between AE and MHD activity, notably sawteeth, is also connected with nonperturbative redistributions of EPs. In the case of DIII-D, the use of high harmonic ICRH generates an EP population that transiently stabilizes the sawtooth instability but destabilizes TAEs (Heidbrink *et al.*, 1999). In the further evolution of the plasma discharge, saturation of the central heating correlates with the onset of the TAEs, while sawtooth crash is eventually caused by the continued expansion of the $q = 1$ surface radius. Similar observations are made in TFTR plasmas (Bernabei *et al.*, 2000, 2001), where the eventual crash of long-period sawteeth is explained in terms of the loss of the stabilizing effect of EPs that are transported outward by EPM from within the $q = 1$ surface. An effect similar to that of EPM on sawteeth can also be induced by TAEs when, with high values of the safety factor at the plasma boundary, their mode structures are shifted deeper into the plasma core, where they can cause sufficient EP redistributions to affect sawtooth stabilization. Meanwhile, in some TFTR discharges, it has been demonstrated that the loss of ICRH efficiency may be due to the combined effect of EPM and TAE, which eventually redistribute EPs in a broader region of the plasma volume and may even cause global particle losses (Bernabei *et al.*, 1999). More recent analyses of the impact of strongly driven fishbones and AEs on EP losses in JET are given by Nabais *et al.* (2010), while comparisons of numerical simulations and fast-ion loss detector measurements for fishbones are discussed by Perez von Thun *et al.* (2011, 2012).

C. Transport of energetic particles by microscopic turbulence

The problem of EP transport by microscopic turbulence was addressed in the early work by Belikov, Kolesnichenko, and Yavorskij (1976), discussing the energy spectrum of α particles escaping from a plasma as a result of turbulent diffusion. A later and more systematic theoretical description of the fusion α-particle confinement in tokamaks was provided by White and Mynick (1989), demonstrating that suprathermal particle confinement is much less deteriorated by microturbulence than that of thermal plasma, due to orbit averaging and wave-particle decorrelation effects. This picture was also confirmed by numerical simulations of test-particle transport in strong electrostatic drift wave turbulence (Manfredi and Dendy, 1996) and more recently by numerical simulation of turbulent transport of a slowing down distribution of suprathermal particles with high birth energy compared to the thermal plasma energy (Angioni and Peeters, 2008; Zhang, Lin, and Chen, 2008; Angioni *et al.*, 2009). Experimental observations confirmed these general expectations and quantitatively estimated the turbulent diffusivity of EPs to be 1 order of magnitude less than that of thermal ions for particle energies $E/T_c \gtrsim 10$ (Heidbrink and Sadler, 1994; Zweben *et al.*, 2000), with T_c standing for the core plasma thermal energy. Significant interest in this topic was revived more recently by experimental observations in plasmas with NBI, showing evidence of anomalies in EP transport in AUG (Günter *et al.*, 2007), JT-60U (Suzuki *et al.*, 2008), and DIII-D (Heidbrink, Murakami *et al.*, 2009; Heidbrink, Park *et al.*, 2009), which might have raised concerns about the negative NBI efficiency in ITER. These observations were connected with theoretical (Vlad and Spineanu, 2005) and numerical simulation analyses (Estrada-Mila, Candy, and Waltz, 2005, 2006; Albergante *et al.*, 2009; Angioni *et al.*, 2009), supporting the fact that a significant level of EP transport could be driven by microturbulence. This discrepancy between experimental measurements and neoclassical predictions of cross-field diffusion of EPs was clarified by Heidbrink, Murakami *et al.* (2009) and Heidbrink, Park *et al.* (2009) looking at DIII-D plasmas, where EP diffusivity was dominated by ion temperature gradient (ITG) driven turbulence, and showing that anomalies were more pronounced at low E/T_c, where the effect of microturbulence is strongest. Numerical simulation results (Zhang *et al.*, 2010) demonstrated that EP diffusivities are consistent with quasilinear predictions (Chen, 1999), confirming the conclusions of original theoretical and numerical works. Thus, EP transport by microturbulence in reactor relevant conditions and above the critical energy (at which plasma ions and electrons are heated at equal rates by EPs) is negligible and EP turbulent diffusivities have intrinsic interest mostly in present day experiments with low characteristic values of E/T_c. The potential problem of EP transport due to magnetic fluctuations in ITER (Hauff *et al.*, 2009), as also reported by Breizman and Sharapov (2011), is resolved by these findings (Heidbrink, Murakami *et al.*, 2009; Heidbrink, Park *et al.*, 2009; Zhang *et al.*, 2010), and is further confirmed in dedicated numerical simulations (Albergante *et al.*, 2010, 2011, 2012) as well as experimental studies in DIII-D, supported by numerical and analytic modeling (Pace *et al.*, 2013). The main possible concern remains as the increased suprathermal particle diffusivities that may be expected in DEMO, due to the significantly larger operation temperature and consequently lower value of E/T_c (Albergante *et al.*, 2012).

VI. CONCLUDING REMARKS AND OUTLOOKS

This work addressed a wide range of linear and nonlinear physics issues related to SAWs and EPs in burning plasmas without, however, the intention of being comprehensive.

[33] Note that for sufficiently strong mode drive, of the order of the real frequency shift from the continuous spectrum accumulation point, there is no clear distinction between AE and EPM, as discussed in Sec. III.C, and EPMs could easily exist inside the SAW frequency gap. In addition, in typical NSTX experimental conditions, equilibrium mean flow shear is strong enough to significantly alter the SAW continuous spectrum and generally cause strong coupling of TAEs with the SAW continuous spectrum and thereby with EPMs (Podestà, 2012).

Among the physics issues addressed in this work, the theoretical formulation of the GFLDR provides a unified framework for linear as well as nonlinear physics studies and may serve as a useful interpretative tool for numerical simulation results and experimental observations. Linear stability problems essentially require the use of already available comprehensive gyrokinetic (or equivalent) codes along with careful modeling of realistic plasma equilibria and physical boundary conditions. The many benchmarking activities in progress worldwide give confidence that such predictions on linear physics will be available in the near future. As to nonlinear physics, we have shown that the governing equation for the fluctuation radial envelope has the theoretical structure of a NLSE with integrodifferential nonlinear terms. In simplified examples, this equation is shown to yield convective amplification of radially outward-moving EPM wave packets, accompanied by secular displacement of resonant EPs, as well as a fishbone burst cycle. Comparisons among reduced nonlinear theoretical models, numerical simulations, and experimental observations in present toroidal devices have already started providing new insight into the fundamental issues underlying these processes. Current theoretical understanding of nonlinear physics have, in particular, indicated the crucial importance of equilibrium geometry, plasma nonuniformities, radial mode structures, and kinetic processes. Simplified descriptions based on the analogy of the resonant excitation of SAWs by EPs with the 1D bump-on-tail problem are capable of capturing some of the important nonlinear dynamics near marginal stability, but, however, do not address the important roles of radial mode structures and plasma nonuniformities. Nonlinear physics therefore require substantially more significant effort to reach the level of maturity for reliable predictions of Alfvénic fluctuation and related transport in reactor relevant conditions. The rapid development of impressive diagnostics systems and numerical simulation capabilities renders it feasible that one can expect rapid advance in this important area.

The intended scope of this review has left out several important topics. For example, high-frequency fluctuations ($|\omega| \gtrsim \Omega_i$) have been neglected, although there is evidence of fusion alpha-particle driven ion cyclotron emission [see, e.g., Cauffman *et al.* (1995)], interpreted as resonantly excited compressional Alfvén eigenmodes (CAEs) (Belikov, Kolesnichenko, and Silivra, 1995; Gorelenkov and Cheng, 1995a, 1995b; Fülöp *et al.*, 1997). The CAE phenomenology has been widely studied in NSTX (Fredrickson *et al.*, 2002; Fredrickson, Gorelenkov, and Menard, 2004). Another important aspect involving the interaction of EPs with waves in the high radio-frequency (rf) range is the so-called alpha channeling (Fisch and Rax, 1992; Fisch, 2006, 2010, 2012), i.e., "the diversion of energy from energetic alpha particles to waves" (Fisch, 2000), as an "attempt at detailed control over plasma behavior" to facilitate the development of an economical fusion reactor. The use of bucket transport in fusion plasmas for removing helium ash from the plasma core as well as burn control, profile control, and diagnostic tool was proposed by Mynick and Pomphrey (1994) (cf. Sec. IV.E). Kolesnichenko, Yakovenko, and Lutsenko (2010) and Kolesnichenko, Yakovenko, Lutsenko, White, and Weller (2010) pointed out that DAW may channel the energy and momentum of EPs to different spatial regions, where waves are absorbed. In this way, EP-driven instabilities may not affect only the EP radial profiles, but alter thermal plasma transport as well, notably, the electron heat transport across the equilibrium magnetic field and the plasma rotation profile, consistent with observations in NSTX (Stutman *et al.*, 2009) and W7-AS (Kolesnichenko *et al.*, 2005). Furthermore, it is worthwhile mentioning that Wong *et al.* (2005) showed the possibility of producing an internal transport barrier, induced by radial redistribution of EPs due to Alfvénic instabilities. Finally, this review has not addressed important issues related to the intrinsic 3D nature of all real systems, including "axisymmetric" toroidal devices. For issues such as toroidal field ripple induced transport (Goldston and Towner, 1981; Goldston, White, and Boozer, 1981), which arise from the breaking of axisymmetry in 2D toroidal system, see the comprehensive ITER summaries (ITER Physics Expert Group on Energetic Particles, Heating and Current Drive, 1999; Fasoli *et al.*, 2007) and recent reviews by Gorelenkov, Pinches, and Toi (2014) and Pinches *et al.* (2015). Here we emphasized that AEs may cause global EP losses through induced ripple trapping, as discussed by White *et al.* (1995). For the similarities and differences between tokamaks and stellarators, recent and comprehensive reviews are given by Kolesnichenko *et al.* (2011) and Toi *et al.* (2011).

Looking beyond, we note that there are two issues which have received increasing attention within the fusion community. One deals with EP transport in the presence of many modes as expected in ITER. The other deals with the investigation of burning fusion plasmas as complex systems, with many interacting degrees of freedom, where the long time-scale behavior will ultimately determine the reactor performance. These two interlinked issues are further articulated in Secs. VI.A and VI.B, which then conclude this review.

A. Energetic-particle transport in the presence of many modes

Collective oscillations excited by EPs in burning plasmas are characterized by a dense spectrum of modes with characteristic frequencies and spatial locations (Chen and Zonca, 2007a; Chen, 2008). One crucial issue, as noted at the beginning Sec. V, remains the realistic prediction of global transport of EPs and fusion products and their impact on the system material walls. While quasilinear theory is suited for explaining EP transport by plasma turbulence (cf. Sec. V), it was argued that the onset of phase-space stochasticity may be described by a "line-broadened" quasilinear model (Berk, Breizman, Fitzpatrick, and Wong, 1995), accounting for a discrete spectrum of overlapping modes in the case of multiple AEs (Berk *et al.*, 1996) and which was recently extended and applied to the analysis of beams interacting with AEs in DIII-D (Ghantous *et al.*, 2012). A detailed discussion of model assumptions and validity limits was given by Ghantous, Berk, and Gorelenkov (2014). The actual transition to stochastic behavior in realistic systems, however, depends on the details of plasma nonuniformities and equilibrium geometries via resonance conditions and finite mode structures (cf. Sec. V), as recently shown by White *et al.* (2010a, 2010b). For this reason, the only presently viable modeling of EP losses by multiple AEs is test-particle transport or more sophisticated

nonlinear simulations with gyrokinetic or equivalent codes (cf. Sec. II). Simulations along these lines, using linear fluctuation spectra and mode structures, were carried out for ASDEX Upgrade (Schneller *et al.*, 2013) and are being pursued for ITER (Lauber, 2015; Schneller, Lauber, and Briguglio, 2016) (cf. Sec. IV.D.4). Other reduced nonlinear dynamic descriptions are possible as discussed in Secs. IV.A and IV.D.5, which may offer a useful tool for gaining deeper insights into the underlying physics.

The DAW spectrum in present day experiments is, in general, significantly different from that expected of burning plasmas (much lower mode numbers, corresponding to much larger relative EP orbits compared with machine size). The same holds for the associated kinetic processes and cross-scale couplings yielding to complex behavior, which will be further discussed in Sec. VI.B. Nonetheless, some aspects of complex behavior may still be addressed in existing machines, providing precious feedbacks for theory and modeling. One example is the analysis of EP transport during TAE avalanches in NSTX, where multiple modes are excited and the resultant EP redistributions are so far not completely understood (cf. Sec. V). Nonlinear simulation tools may be needed to yield more reliable interpretations of these observations (Fredrickson *et al.*, 2009, 2013).

B. Complex behavior in burning plasmas

A burning plasma is a complex self-organized system, where among the crucial processes to understand there are (turbulent) transport and fast-ion–fusion product induced collective effects (Zonca *et al.*, 2006). Complexity and self-organization are intrinsic to the very nature of burning plasmas, where the self-sustainment of fusion reactions for efficient power production requires that stationary conditions are achieved when in D-T plasmas almost the whole power density balance to compensate losses is provided by heating from fusion alphas. Meanwhile, fast ions in the same MeV energy range, produced mainly by ICRH and negative NBI (NNBI), will be used to heat and fuel the thermal plasma, provide rotation, and drive current. Together with fusion produced alpha particles, these fast ions are a potential free-energy source for driving collective plasma oscillations, which may induce or enhance transport processes. Complexity and self-organization are consequences of the interaction of EPs with plasma instabilities and turbulence; of the strong nonlinear coupling mediated by the EP population that will take place between fusion reactivity profiles, pressure driven currents, MHD stability, transport, and plasma boundary interactions; and, finally, of the long time-scale nonlinear (complex) behavior that may affect the overall fusion performance and eventually pose issues for the stability and control of the fusion burn. The role of EPs is also unique as mediators of cross-scale couplings, for they can drive instabilities on the mesoscales, intermediate between the microscopic thermal ion Larmor radius and the macroscopic plasma equilibrium scale length. EP-driven Alfvénic instabilities could also provide a nonlinear feedback onto the macroscale system via the interplay of plasma equilibrium and fusion reactivity profiles, as well as excite microscopic radial mode structures at SAW continuum resonances, which by mode conversion yield fluctuations that may propagate and be absorbed elsewhere (Kolesnichenko, Yakovenko, and Lutsenko, 2010). Furthermore, noting that instabilities may also be excited from microscales to mesoscales to macroscales (cf. Sec. III) has made the theoretical approach based on an extended inertial range dubious for burning fusion plasmas.

These physics are unique to burning plasmas and require a conceptual shift with respect to the way phenomena are currently investigated in present day experiments. For example, EP power density profiles and characteristic wavelengths of the collective modes in reactor relevant plasmas will be different. MeV energy ion tails, meanwhile, will provide the dominant electron heating and, thereby, introduce different weighting of the electron driven microturbulence. Furthermore, plasma operation scenarios will reflect different plasma edge conditions and plasma wall interactions at high density and low collisionality. For these reasons, important roles will be played by predictive capabilities based on numerical simulations (Batchelor *et al.*, 2007; Lauber, 2013) as well as by fundamental theories for developing simplified yet relevant models, to provide the necessary insight into the basic physics processes. Experiments in this respect have a key role in providing experimental evidence for modeling verification and validation. In the perspective of ITER (Tamabechi *et al.*, 1991; Aymar *et al.*, 1997), it is crucial to investigate these physics issues, exploiting positive feedbacks between experiment, numerical simulation, and theory, and integrating the largest number of aspects that are important for complexity in reactor relevant plasmas.

In addition to spontaneous generation by DWT, zonal flows including the finite-frequency geodesic acoustic mode (GAM) (Winsor, Johnson, and Dawson, 1968) or more generally ZS can also be generated by nonlinear AE and EPM dynamics, depending on proximity to marginal stability (cf. Sec. IV.C). Meanwhile, strongly driven EPMs cause radial modulations in EP profiles, affecting thus the EP distribution function (cf. Secs. IV.D.5 and IV.D.6), which may produce similar structures in the electron temperature profile and eventually alter the free-energy source driving DW turbulence and transport. In general, the ZS evolution must be self-consistently determined with that of all other relevant nonlinearly coupled degrees of freedom and could determine the long time-scale nonlinear dynamics of burning plasmas and, thereby, the reactor fusion performance.

In this respect, one important issue is the determination of hierarchy of relevant nonlinear time scales for the various cross-scale couplings including realistic conditions, such as proper equilibrium geometry, spatial nonuniformity, and kinetic effects (Zonca, 2008; Zonca and Chen, 2008; Zonca *et al.*, 2013, 2015a). Numerical simulations as well as experimental studies are beginning to address these issues.

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