

INTEGRATED PHYSICS DESIGN OF CONVENTIONAL H-MODE SCENARIO FOR
CHINA FUSION ENGINEERING DEMO REACTOR

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Alpha particle confinement in CFEDR H-mode scenario

Zhiyong QIU (仇志勇)^{1,2,*}, Youjun HU (胡友俊)^{1,2}, Wei SHEN (申伟)^{1,2}, Jian BAO (包健)³, Zhenzhen REN (任珍珍)⁴, Yifeng ZHENG (郑艺峰)¹, Pengjuan SU (苏鹏娟)^{1,2}, Yingfeng XU (徐颖峰)⁵, Feng WANG (王丰)⁶, Jiale CHEN (陈佳乐)^{1,2} and Guoqiang LI (李国强)¹

¹ Institute of Plasma Physics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

² CAS Key Laboratory of Frontier Physics in Controlled Nuclear Fusion, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

³ Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

⁴ School of Physics and Optoelectronic Engineering, Anhui University, Hefei 230039, People's Republic of China

⁵ College of Physics, Donghua University, Shanghai 201620, People's Republic of China

⁶ Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People's Republic of China

*E-mail of corresponding author: zqiu@ipp.ac.cn

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Abstract

The alpha particle confinement in the CFEDR H-mode scenario is investigated. It is found that, within engineering limitations, 500 mm ferromagnetic insert can reduce the alpha particle and power loss caused by magnetic ripples to 1% and 0.65%, respectively, leading to an acceptable 0.1 MW/m² peak heat load on the outboard mid-plane of plasma facing components. Global gyrokinetic simulations show that multiple toroidal Alfvén eigenmodes (TAEs) with toroidal mode number $n \sim 20\text{--}40$ can be driven marginally unstable by alpha particles in the core region, with $\gamma/\omega_r \leq 2\%$. Here, γ is the linear growth rate, and ω_r is the mode frequency. Multiple- n nonlinear simulations show that TAEs saturate at a low saturation level, that lead to a negligible alpha particle diffusion rate $D_a \sim 0.06 \text{ m}^2/\text{s}$. Fishbone is shown to be unstable in the present scenario, which may lead to weak radial redistribution of alpha particles, with the dominant contribution from magnetically trapped particles.

Keywords: burning plasmas, alpha particle, shear Alfvén waves, fishbone instability, ripple loss

(Some figures may appear in colour only in the online journal)

1. Introduction

In fusion reactors like International Tokamak Experimental Reactor (ITER) or China Fusion Engineering Demo Reactor (CFEDR) [1], energetic particles (EPs) are expected to crucially determine the behaviour of burning plasmas [2, 3]; and is thus, a primary scientific challenge faced by fusion

research to understand the confinement of EPs and their impact on overall performance of the reactor burning plasmas. EPs, in particular alpha particles born from fusion reactions, with the energy significantly higher than bulk thermal plasmas, contribute significantly to the overall power density of the reactor, and play an important role as mediators of cross-scale couplings from micro-turbulence to global profiles. In particular, the fusion alpha particle birth rate, which is determined by the local plasma profiles, then self-

* Author to whom any correspondence should be addressed.

consistently affect the bulk plasma profile via heat deposition. Interactions with multiple-scale symmetry-breaking turbulence including shear Alfvén wave instabilities and drift-wave (DW) turbulence will lead to both thermal plasma and EP transport loss. In this paper, the effort in conceptual design of CFEDR conventional H-mode scenario is reported [1], with focus on the transport loss of alpha particles, due to, toroidal field (TF) ripples, interaction with Alfvén eigenmodes (AEs), as well as fishbone instabilities. Due to the significantly higher contribution from fusion alpha particles than those from auxiliary heatings like neutral beam injection, only the effects of fusion alpha particles will be assessed. For the detailed description of the CFEDR program and the baseline based on conventional H-mode scenario, interested readers may refer to references [1, 4] that appear in the same issue of present paper.

Due to the discrete nature of the toroidal field (TF) coils, the toroidal magnetic field generated by TF coil current has a harmonic $n = N$, in addition to the toroidally symmetric $n = 0$ harmonic. Here, n is the toroidal mode number, N is the number of TF coils. As a result, the originally confined EPs may become unconfined due to two dominant mechanisms, ripple trapping and stochastic banana diffusion [5]. The ripple trapping mechanism is related to EPs with vanishing $|v_{\parallel}|/v < \sqrt{\delta}$ being trapped in the secondary magnetic “well” between two neighbouring TF coils, and the resulting losses concentrated at either the top or bottom of the torus, depending on the direction of the magnetic drift. Here, $v_{\parallel}$ is the parallel component of the particle velocity, and δ is the ripple degree, with the explicit expression given in section 2. On the other hand, the stochastic ripple diffusion is related to the additional radial excursion induced by ripples, which may lead to rapid radial diffusion if the successive banana tips become decorrelated, with the threshold given by $\delta > (\epsilon/N\pi q)^{3/2}/(2\rho q')$. Here, $\epsilon \equiv r/R_0$ is the inverse aspect ratio, q is the safety factor, and $q' \equiv \partial_r q$. The stochastic ripple diffusion typically leads to loss particle concentration on the outboard major radius. The ripple loss occurs in very short time, i.e., of the order of ten transit periods. In addition to the two major mechanisms, collisions are also expected to contribute weakly to ripple loss [6]. In our investigation in section 2 with collisional effects properly included, the obtained “ripple” loss rate includes the contributions from prompt loss, ripple trapping, stochastic ripple diffusion, as well as collisional ripple losses.

The interaction with low frequency magnetohydrodynamic (MHD) activities, including the modes driven unstable by EPs, is another important channel for EP transport loss. EPs may be scattered by 3D fields induced by MHD activities such as neoclassical tearing modes; on the other hand, EPs may stabilize MHD modes such as sawteeth, and lead to, potentially, giant sawteeth [7]. In particular, MHD activities such as fishbone instabilities [8, 9] can be resonantly excited by EPs, and lead to significant redistribution and convective loss of EPs. SAW instabilities are another kind of low frequency activities [3, 10, 11], and have draw much research attention as they are shown to dominate EP transport in present day devices. In the conceptual design of

CFEDR, the fishbone and SAW instabilities induced by fusion alpha particles, and the consequences on alpha particle redistribution are assessed, and are reported in sections 3 and 4.

The rest of the paper is organized as follows. In section 2, the orbital loss of alpha particles related to ripple fields is investigated, and consequent heat load on the first wall is evaluated. In section 3, the AE instability in CFEDR is investigated using gyrokinetic simulation, the saturated magnetic perturbation is given, and the alpha particle diffusion rate is evaluated. In section 4, the fishbone instability in CFEDR is investigated. Finally, in section 5, a brief conclusion is given.

2. Ripple loss

In this section, we investigate alpha particle orbital loss to the first wall due to the effects of the ripple field in CFEDR conventional H-mode scenario, with the effects of collisions also accounted for, which may lead to a stationary alpha particle distribution function, as well as higher order “collisional ripple loss” that takes place on longer time scale [6]. Because of the discrete nature of the TF coils, the toroidal magnetic field generated by the TF coil currents has a harmonic of $n = N$, besides the dominant toroidally symmetric harmonic, where n is the toroidal mode number, N is the total number of TF coils and $N = 16$ for CFEDR. This high- n harmonic is usually called the ripple field, which can cause additional particle loss, with the loss rate dependent on the ripple rate, defined as $\delta \equiv (B_{\max} - B_{\min})/(B_{\max} + B_{\min})$, with $B_{\max}$ and $B_{\min}$ being the maximum and minimum magnetic fields experience in the toroidal direction. In the present design of CFEDR, the ripple rate can be up to 1.63% at the outer mid-plane, which causes quite significant particle loss as well as heat load on the plasma facing components. Therefore, there is urgent need to reduce the amplitude of the ripple rate. One strategy for reducing the ripple field is via adding ferromagnetic steel between the double walls of the vacuum vessel. Like ITER, this strategy is adopted on CFEDR. Due to the engineer limitations of the present design, up to 500 mm ferromagnetic insert (FI) is allowed, which reduces the maximum ripple rate at the outboard mid-plane to 1.07%, which yields a tolerable particle loss as will be reported later. In the rest of this section, we compared the ripple loss between the case that adopts this mitigation and that does not. In the evaluation, the guiding-centre code TGCO is the main working code [12], which contains various effects such as finite Larmor radius effect, full collisions including slowing-down and pitch-angle scattering, and continuous alpha particle generation from DT fusion. Up to 50000 Monte-Carlo markers are tracked up to 10^8 time steps, and particles with the distance of their guiding-centre to the wall smaller than their Larmor radii are considered lost. Independent check also performed using guiding-centre codes PTC [13] and GYCAVA [14], as well as a full orbit-code ISSDE [15].

Figure 1 compares the ripple degree δ within the last

closed flux surface (LCFS) for the case without FI and that with FI. The results shows that δ near the LCFS low-field side mid-plane is reduced from about 1.63% to about 1.07%.

Figure 2 plots the radial profile of DT fusion rate, and 2D distribution of alpha particle birth rate in the poloidal plane, reconstructed from Monte-Carlo sampling of the fusion rate. This is the starting point of the present study. Together with the collisional slowing-down and orbital-loss processes, it

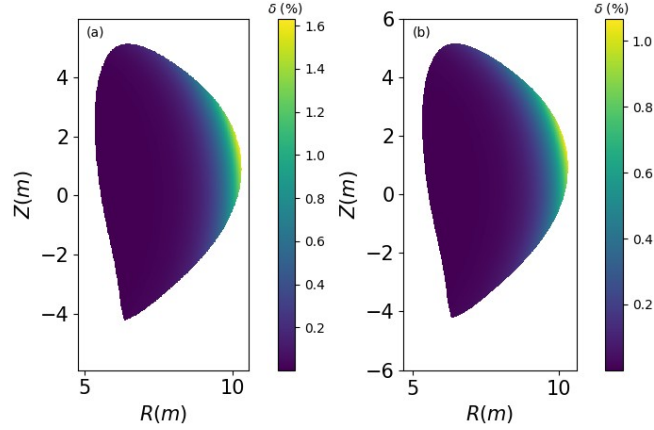


Figure 1. Ripple rates δ within the LCFS for the case (a) without FI and (b) with FI.

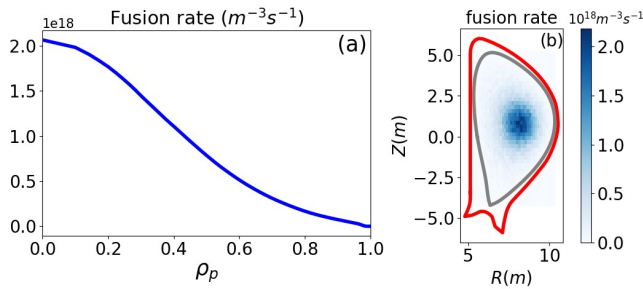


Figure 2. (a) Radial profile of fusion rate. (b) 2D distribution of alpha particle birth rate, reconstructed from Monte-Carlo sampling of the fusion rate.

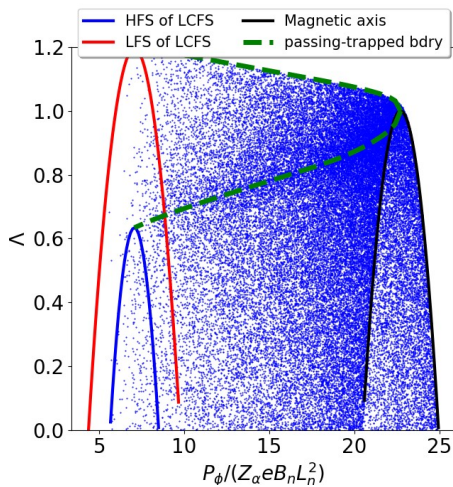


Figure 3. Distribution of the initially loaded 5×10^4 Monte-Carlo markers on (P_ϕ, Λ) plane, where $B_n = 1$ T and $L_n = 1$ m. Also shown are the magnetic axis, high-field-side, low-field side of LCFS for alpha particles of $E = 3.5$ MeV, and the passing trapped boundary (which is independent of the kinetic energy).

may give the steady state profile of alpha particles, consistent with that given by integrated modelling.

Figure 3 plots the initial positions of alpha particle markers in (P_ϕ, Λ) plane, where $P_\phi \equiv m_\alpha v_{\parallel} g / B + Z_\alpha e \Psi$ is the canonical toroidal angular momentum, m_α and $Z_\alpha e$ are the mass and charge of alpha particle, respectively, $\Lambda = \mu B_{\text{axis}} / E$ is the normalized magnetic moment, and μ is the magnetic moment defined by $\mu = m v_\perp^2 / (2B)$ with $v_\perp$ being the perpendicular speed. Using the passing-trapped boundary shown in the figure, we found that 29% of alpha particles are born in the trapped region. After sampling the positions and velocity vectors of alpha particles, the guiding-center position of each particle can be calculated. We then use guiding-center drift model to compute the particle trajectories in the phase space, taking into account of the ripple field and collisions.

The temporal evolutions of particle and power loss fraction are given in figure 4, while the corresponding slowed-down fraction of a pulse α source born at $t = 0$ is given in figure 5. It is shown that both the particle loss fraction and

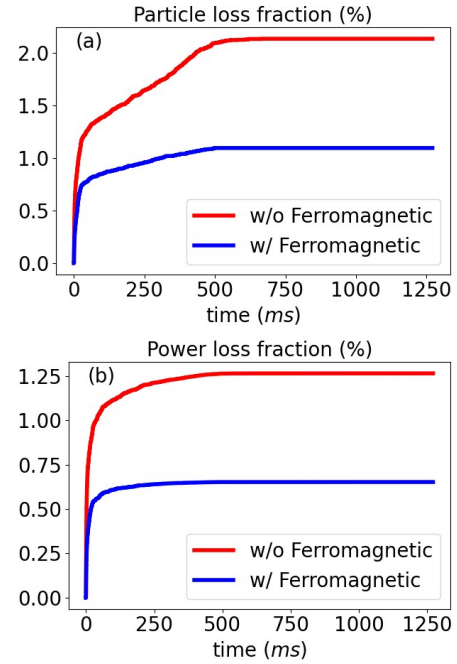


Figure 4. Comparison of ripple loss fraction between the cases with and without FI, with (a) being the particle loss fraction and (b) being the power loss fraction, respectively.

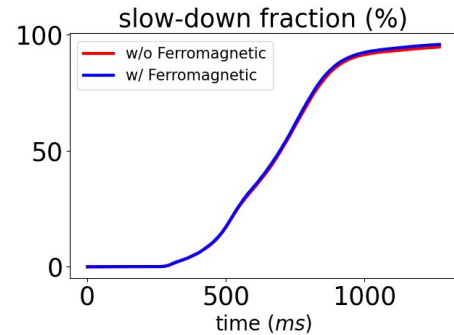


Figure 5. Comparison of slowed-down fraction between the cases with and without FI.

power loss fraction are reduced when FI is used. Specifically, the steady-state particle loss fraction is reduced from about 2% to about 1%, while the power loss fraction is reduced from about 1.25% to 0.65%. It is noteworthy that, those alpha particles born near the circulating/trapped boundary, or near the high field side last close flux surface, contribute most to prompt loss and ripple loss. Figure 5 shows that most alpha particles are slowed down (to the cutoff energy $2T_i(0)$) after 1000 ms, and the FI has negligible effect on the slowing-down process. It is noteworthy that, in figure 4, after the initial fast loss of alpha particles and power within several transit time, there is a slower continuous particle loss phase to 500 ms, with no significant power loss during this stage. This is also consistent with the observed increase of slowing-down fraction at ~ 500 ms, indicating the “secondary” particle loss could be the neoclassical transport of slowed-down alpha particles, which does not contribute much to alpha heating power. This is further confirmed in figure 6, where the energy spectrum of lost alpha particles in the cases with FI and that without are compared. It is shown that FI reduces the loss for all the energies, with the most important reduction lies in the range near the birth energy, showing the FI contributing to reducing the effects associated with the ripple loss, while their effect on collisional neoclassical transport is very weak.

The resulting wall loading due to the loss of energetic alpha particles is shown in figure 7, with (a) corresponding to the case without FI and (b) to the case with. As is expected, the wall loading is reduced by the FI, consistent with the reduced particle and power loss. Specifically, the peak wall loading is reduced from about 0.16 MW/m^2 to 0.10 MW/m^2 , well within the tolerable region of the plasma facing component.

The poloidal distribution of lost particles on the first wall is given in figure 8, which shows that the peak value appears near the low-field side mid-plane, consistent with that shown in figure 7. This suggests that stochastic ripple diffusion is the major mechanism for alpha particle loss.

Figure 9 plots the heat flux within a toroidal span of $2\pi/16$, which shows that the heat flux reaches its peak about half way between two TF coil central lines. This distribution has practical implication. Gaps between two TF coils are often used as access window to the plasma by various diagnostic sensors and heating actuators, which should avoid

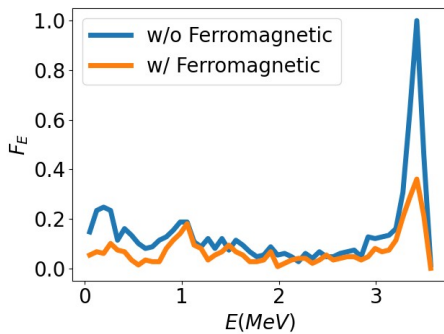


Figure 6. Energy spectrum of lost alpha particles (normalized by peak value for the case without FI).

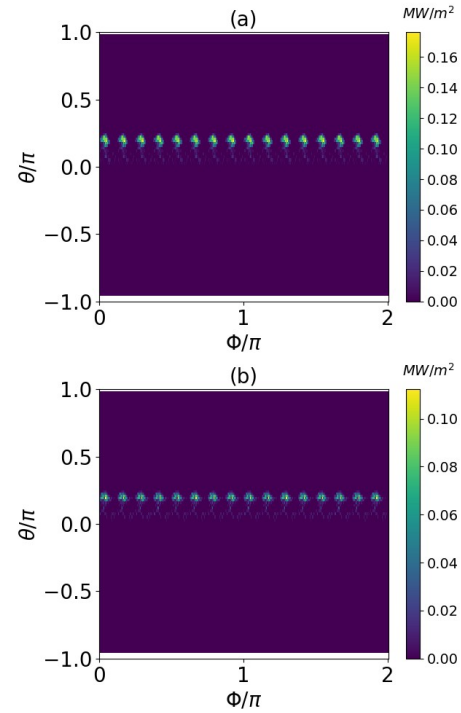


Figure 7. Wall load due to the loss of alpha particles, with (a) being the case without FI and (b) with FI, respectively. Here $\theta = \pm\pi$ correspond to the high-field-side midplane. Positive direction of θ is anticlockwise when viewed along $\nabla\phi$.

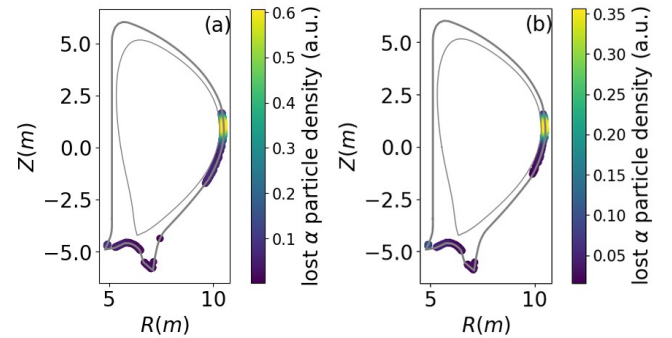


Figure 8. Poloidal distribution of lost alpha particles on the first wall, with (a) corresponding to the case without FI and (b) with FI, respectively.

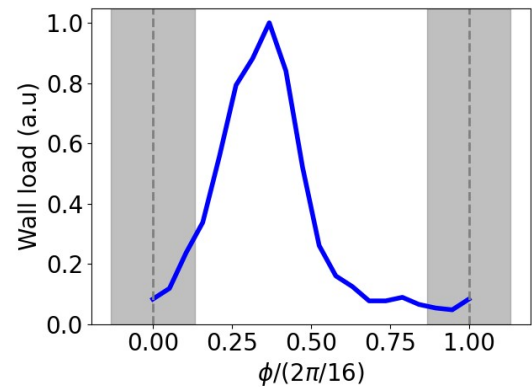


Figure 9. Wall load distribution along the toroidal direction. The dash lines indicate the central-lines of TF coils, and the shadow region indicates the coil span in ϕ near the the first wall midplane. Toroidal plasma current $I_\phi > 0$; toroidal magnetic field $B_\phi < 0$.

locations where the heat flux is large.

As a brief summary of this section on ripple field related loss, several orbital tracing codes are used to assess the ripple induced alpha particle loss in CFEDR. It is found that, with 500 mm FI allowed by the engineering limit, the ripple rate can be reduced from about 1.63% to 1.03%, and the resulting particle and power losses can be reduced to about 1% and 0.65%, respectively, that leads to a tolerable peak 0.1 MW/m^2 heat load on the outboard mid-plane. These results are also independently confirmed by several guiding-centre codes.

3. Alfvén eigenmode

Low frequency magnetohydrodynamic activities are also expected to interact with alpha particles, and lead to their anomalous transport loss. Among which, the shear Alfvén wave (SAW) instabilities including the celebrated toroidal Alfvén eigenmodes (TAEs) [10, 11, 16], are of particular concern as they are observed to dominate EP transport in present day machines. In this section, the SAW instability and their impacts on the alpha particle transport in CFEDR H-mode scenario are investigated, using flag-ship gyrokinetic code GTC [17] which has been applied in studying the SAW instability and alpha particle transport in ITER steady state scenarios, and independent check is also carried out using gyrokinetic code GEM [18].

In the GTC simulation, bulk plasmas consisting of deuterium (D) and tritium (T) are described by Maxwellian distribution, and alpha particles are described by isotropic slowing down distribution. The alpha particle dynamics are

evolved by gyrokinetic Vlasov equation with key physics effects being properly treated, such as all channels of wave-particle resonances, finite orbit width (FoW) and finite Larmor radius (FLR) and neoclassical polarization due to trapped ions to quantitatively accounting for the zonal flow (ZF) level [19]. Massless fluid model is used for describing electron dynamics with convective response of ballooning drive, while the higher order kinetic electron response that only induces slight damping on AE gap modes is omitted due to the huge computational cost. The present model may, thus, slightly overestimate the SAW instability, but the results are expected to be qualitatively correct. The CFEDR magnetic geometry and plasma profiles are shown in figure 10, and the simulation domain covers the region with primary alpha particle drive. To resolve the SAW instability in the simulation domain of $\rho_{\text{tor}} \sim 0.1 - 0.67$, we use 32 grid points in the parallel direction, 200 grid points in the radial direction, and 1000 grid points in the poloidal direction based on the convergence tests, and the number of particles per cell is 50 for alpha particle and thermal ion species. Since the number density and temperature are assumed equal between the dominant thermal ion species of deuterium and tritium, we treat thermal ion dynamics by one species with the isotope effects that modifies thermal ion mass at $m_i = 2.5m_p$. The CFEDR magnetic geometry and plasma profiles are shown in figure 10, and the simulation domain covers the region with primary alpha particle drive.

We first analyze the linear AE stability by scanning the toroidal mode number n . As shown in figure 11, there are two branches of TAEs in the core region of $\rho_{\text{tor}} \sim 0.2 - 0.5$ that can be destabilized by alpha particles: a “TAE1”-branch with $f \sim 60 \text{ kHz}$ and a “TAE2” branch with $f \sim 70 \text{ kHz}$, and

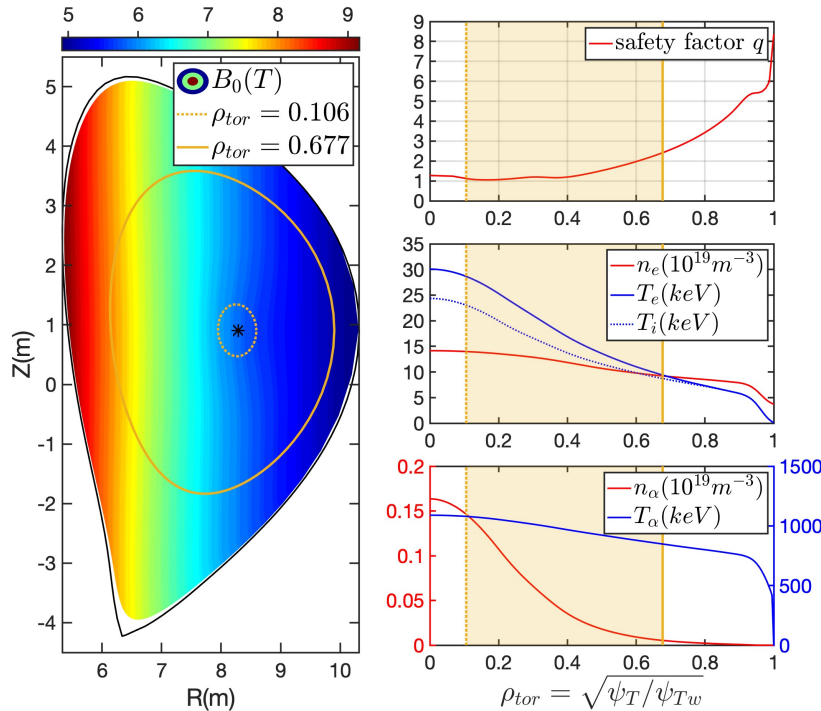


Figure 10. CFEDR magnetic field geometry and plasma profiles used in GTC simulation. The yellow dotted and solid lines represent the inner and outer simulation boundaries, which cover the region with main population of alpha particle.

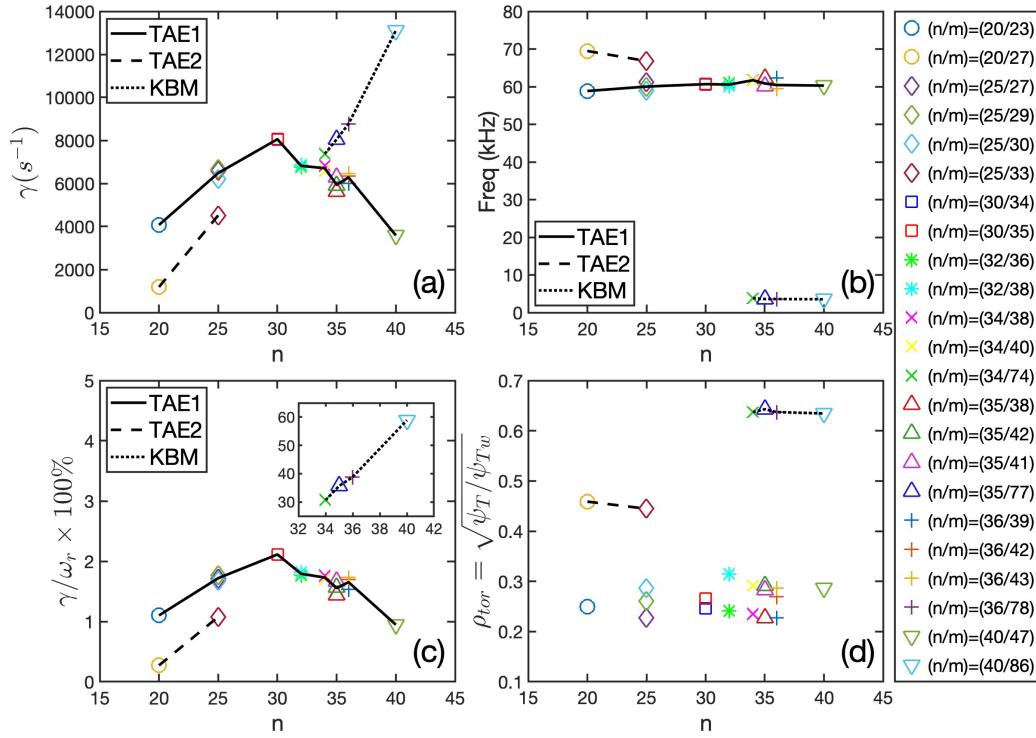


Figure 11. Linear spectra of unstable modes in GTC simulation. The dependences of (a) growth rate γ , (b) real frequency f in kHz, (c) γ/ω_r ratio and (d) radial location ρ_{tor} of peak amplitude on toroidal mode numbers n .

both are marginally unstable with $\gamma/\omega_r \leq 2\%$. The most unstable mode number is $n \sim 30$ for the dominant TAE1-branch, and $n \sim 25$ for sub-dominant TAE2-branch. It is worthwhile mentioning that the growth rates of TAE1 with different n number are close to and comparable with each other [2, 3, 18, 20], which is an important character of AE unstable spectra in fusion reactor with $\rho_h/a \ll 1$. Therefore, alpha particle anomalous transport process is determined by multiple- n TAEs and will be presented in later. As shown by the black dotted lines in figures 11(a) and (b), the growth rate of kinetic ballooning mode (KBM) in the outer region of $\rho_{\text{tor}} \sim 0.55 - 0.7$ exceeds those of TAEs when $n \geq 34$, which is characterized by much lower frequency, and are, thus, expected to contribute negligibly to alpha particle transport. We, however, note that, the emergence of KBM in the reactor parameter region with relatively high- β_e is expected, which may contribute significant to thermal ion transport, and is included in the transport model for scenario design [4]. The mode structures of TAEs and KBM of different toroidal mode numbers are shown in figure 12. It is seen that TAE1 and TAE2 co-exist in the $n = 25$ case, while only TAE1 with larger growth rate dominates in the core region for other toroidal mode numbers. The $n = 25$ Alfvén continuum structure and TAE locations are shown in figure 13. It is also noteworthy that, the choice of the simulation domain, will not introduce additional effects on the stability of the TAEs, as indicated by the SAW continuum structure shown in figure 13, where it is clearly shown that no global gap modes will extend to the boundary of the simulation box.

To estimate the alpha particle drive threshold for AE excitation, we focus on the more unstable TAE1-branch and

scan alpha particle density by multiplying factors of 1.3 and 1.5 in figure 14. For the simplicity of notation, from now on, we will omit the “1” for TAE1. It is found that TAE growth rate is almost proportional to alpha particle density, of which increment (i.e., the slope) differs between different toroidal branches. The original alpha particle density (i.e., $\beta_{a,\text{axis}} = 2\%$) slightly exceeds the excitation threshold of AEs. For comparison, TAE real frequencies of different alpha particle density cases are close to each other, which indicate that the effect of alpha particle with original density in CFEDR baseline scenario on AEs is mainly perturbative to provide instability drive. From figure 14(c), we note that the most unstable TAE mode number slowly shifts from $n \sim 30$ in the n_{a0} case to $n \sim 25$ in the $1.5 \times n_{a0}$ case, since alpha particle non-perturbative effect on AE frequency is enhanced by increasing its drive strength.

The TAE saturation amplitude and alpha particle transport in CFEDR are investigated by multiple- n nonlinear simulations, which cover the unstable $n = [20, 34]$ TAEs and $n = 0$ zonal modes. For each n number, the full spectra of poloidal m-harmonics are kept in the simulation. The nonlinear evolutions of some representative n and m components of marginal unstable TAE are shown in figure 15, which slowly increase in the linear stage and saturate around $t = 0.7$ ms. Note that the initial amplitude of each toroidal/poloidal harmonic is different due to the distinct linear eigenmode structure in figure 12, which might affect the nonlinear saturation level besides the growth rate and explain the large saturation amplitudes of $n/m = 28/33$, $22/26$, $34/40$. However, to verify this conjecture, a systematic analysis of spectral energy is needed, which is beyond the scope

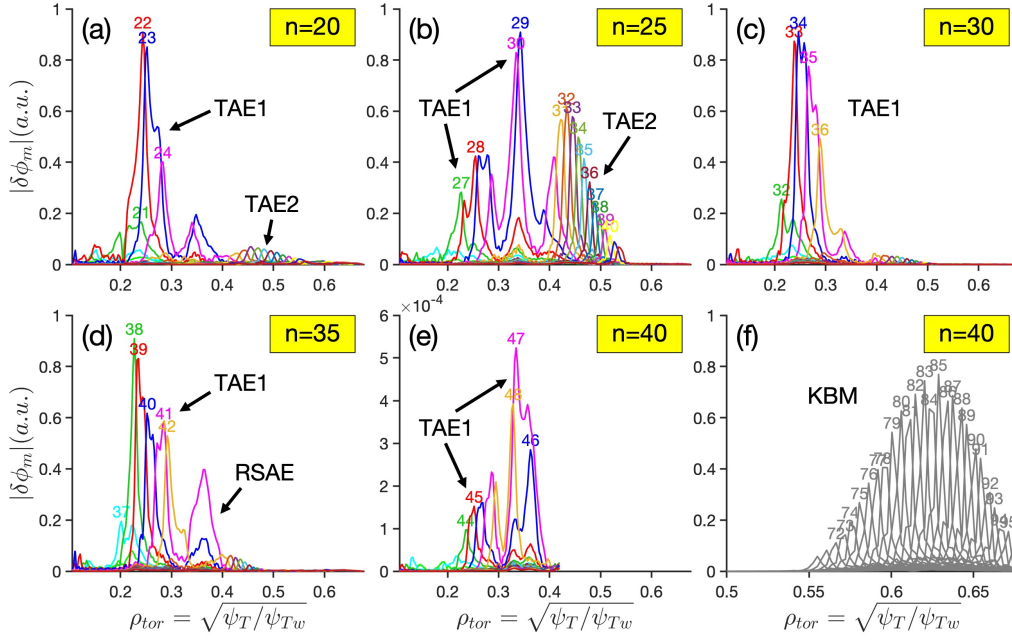


Figure 12. The radial profiles of electrostatic potential $\delta\phi$ for unstable AEs in the core with (a) $n = 20$, (b) $n = 25$, (c) $n = 30$, (d) $n = 35$ and (e) $n = 40$ respectively, and KBM in the outer region with (f) $n = 40$.

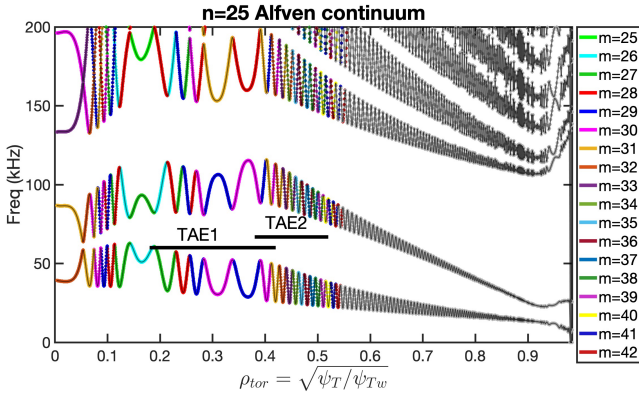


Figure 13. $n = 25$ Alfvén continuum and two TAEs driven by alpha particles in the core. The continuum is generated using MAS code [21], which solves ideal MHD equations based on slow sound wave approximation with gyrokinetic heat ratios of $\Gamma_i = 7/4$ and $\Gamma_e = 1$ for ion and electron species respectively, in consistency with GTC gyrokinetic simulation of AEs inside TAE gap in long wavelength limit. It should be noted that the Alfvén continuum is computed in the full region along radial coordinate that covers GTC simulation domain. The colors represent the poloidal harmonic m numbers of the continuous spectra.

of the present paper to evaluate the alpha particle confinement in CFEDR baseline. The time evolutions of flux surface-averaged $|\delta\phi|$ intensity, alpha particle diffusivity $D_\alpha = \Gamma_n / \nabla n_{\alpha 0}$ and heat conductivity $\chi_\alpha = \Gamma_T / \nabla T_{\alpha 0}$ are shown in figure 16, where Γ_n and Γ_T represent the alpha particle density and heat fluxes, respectively. From figures 16(a) and (d), it is seen that the maximal amplitude of TAE turbulence is about $|\delta\phi|/T_e \sim 3 \times 10^{-3}$, which are localized around $\rho_{tor} \sim 0.3 - 0.4$ that only induce negligible $D_\alpha \sim 0.06 \text{ m}^2/\text{s}$ in figure 16(e) by averaging D_α in figure 16(b) along time in the nonlinear stage between white dashed lines. The maximal amplitude of alpha particle heat conductivity is about $\chi_\alpha \sim 0.6 \text{ m}^2/\text{s}$ in figure 16(f) that is much larger than D_α , which is due to the smallness of alpha particle temperature gradient. Further considering the radial domains of TAE fluctuation and alpha particle transport coefficients in figures 16(a)–(c), we conclude that the TAE turbulence fluctuations mainly induce alpha particle local redistribution rather than global transport loss due to mode radial localization in CFEDR baseline scenario [22], although a much larger local redistribution rate is expected as we artificially increase the

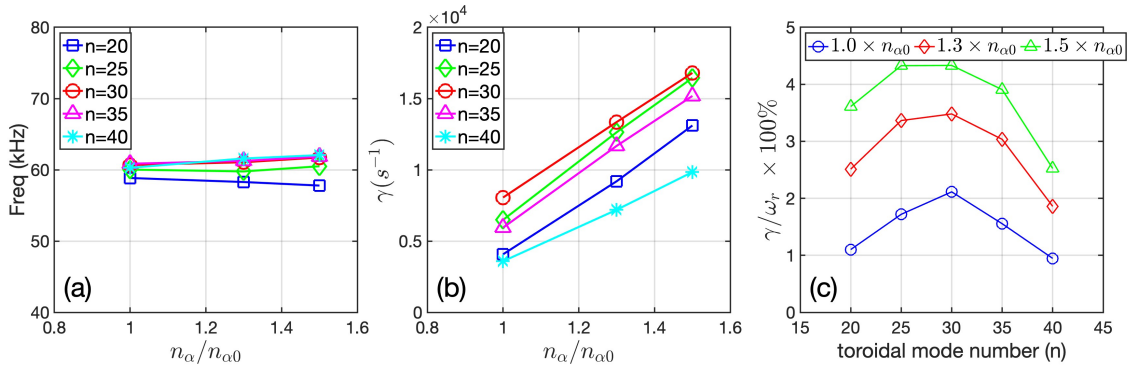


Figure 14. Dominant TAE1 real frequency and growth rate dependences on alpha particle density for different toroidal numbers.

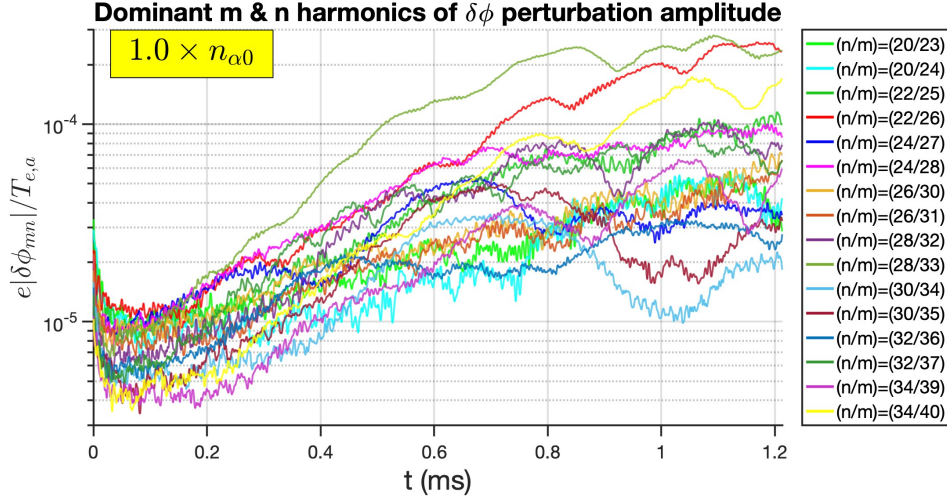


Figure 15. Time history of each $\delta\phi$ Fourier component amplitude with dominant TAE m and n numbers.

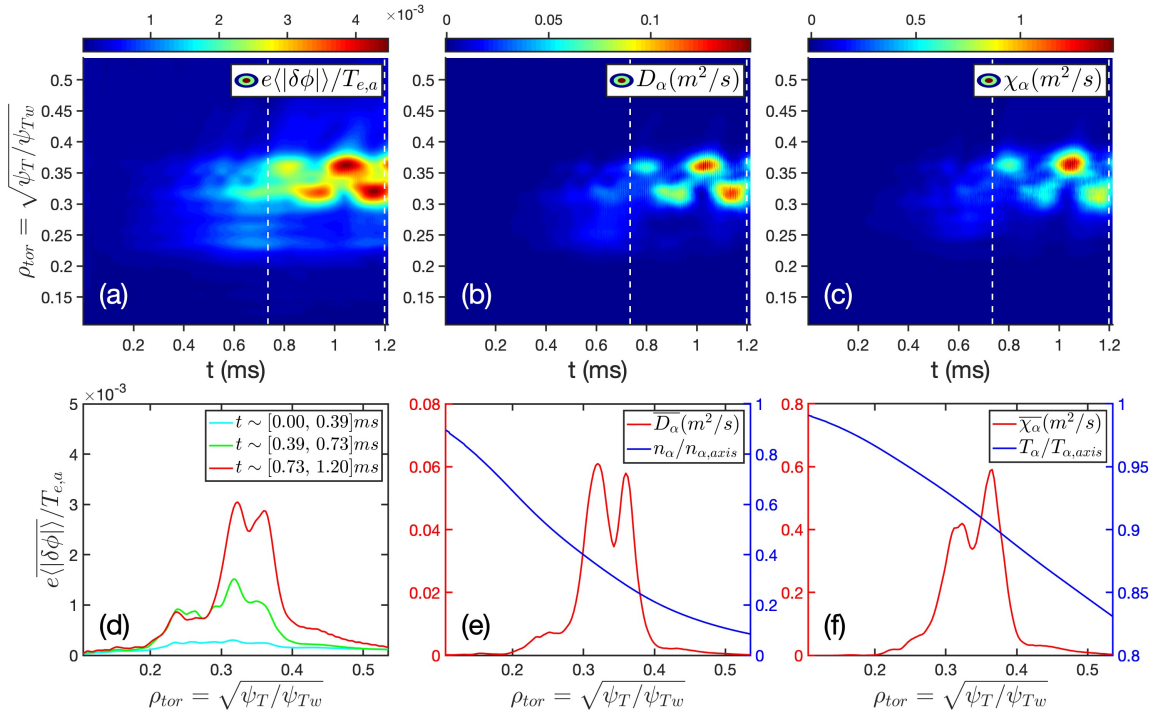


Figure 16. Radial-time profiles of (a) $\delta\phi$ intensity, (b) alpha particle radial diffusivity D_α and (c) heat conductivity χ_α from multiple- n TAE nonlinear simulations. (d), (e) and (f) are corresponding time-averaged radial profiles.

alpha particle drive to test the robustness of the results.

As shown by the red curves in figure 17, the whole volume-averaged alpha particle diffusivity induced by AEs is on the order of $D_\alpha \sim 0.01 \text{ m}^2/\text{s}$ for $1.0 \times n_{a0}$ case, and no obvious zonal flow is observed due to the smallness of linear growth and the consequent TAE amplitude [23, 24]. With artificially increased alpha particle drive by $1.3 \times n_{a0}$ and $1.5 \times n_{a0}$ indicated by the blue and green curves respectively, TAE turbulence amplitudes become much larger that can effectively drive zonal flow, which in turn regulates TAE turbulence, given the close TAE saturation amplitude and alpha particle transport level, and thus play a dominant role in the nonlinear saturation process.

As a brief conclusion of the present section on SAW

instabilities and related alpha particle redistribution in CFEDR conventional H-mode scenario, it is found that, multiple- n TAEs are marginally unstable, with $\gamma/\omega_r \leq 2\%$, and multiple modes can be simultaneously driven unstable, with the most unstable modes characterized by $n \sim 30$. Multiple- n simulation including dominant $n = [20, 34]$ and $n = 0$ components suggests that a negligible alpha particle diffusion rate $D_\alpha \sim 0.06 \text{ m}^2/\text{s}$ is induced by TAE turbulence. As one artificially increase the alpha particle density by 30 and 50 percents, the TAE linear growth rate, nonlinear saturation level and induced alpha particle diffusion rate can be significantly enhanced. However, even in these cases, no global loss is expected as the TAEs and the induced alpha particle redistribution are localized in the tokamak centre,

where alpha particle drive is localized.

4. Fishbone

In this section, hybrid simulations with the global kinetic-MHD code M3D-K [25, 26] have been carried out to investigate the linear stability and nonlinear dynamics of fishbones driven by alpha particles in CFEDR. In M3D-K code, thermal plasma is described by MHD model while the drift-kinetic equation is applied to treat energetic particles via particle-in-cell method, and is coupled to thermal plasma via pressure coupling.

Firstly, the linear simulations of the $n = 1$ mode are presented. Figure 18 shows the mode frequency and linear

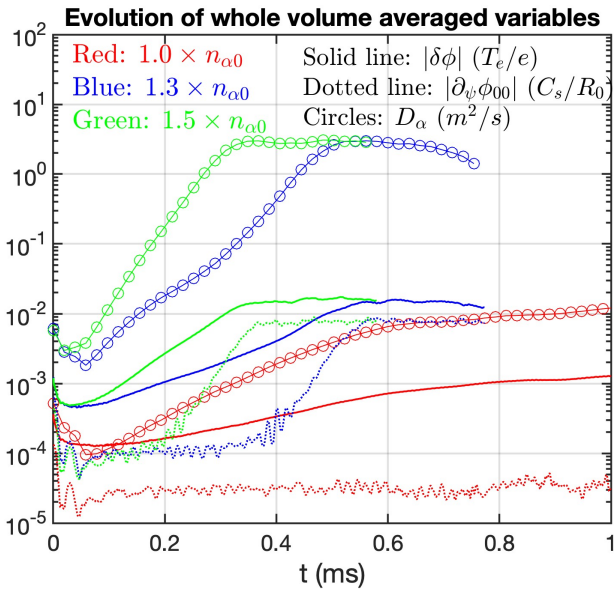


Figure 17. Time evolutions of whole volume-averaged $\delta\phi$ intensity normalized by T_e/e , radial derivative of zonal component intensity $|\partial_\psi \phi_{00}|$ normalized by C_s/R_0 , and alpha particle diffusivity D_α . Red, blue and green colors represent different alpha particle drive cases with $1 \times n_{\alpha 0}$, $1.3 \times n_{\alpha 0}$ and $1.5 \times n_{\alpha 0}$, respectively.

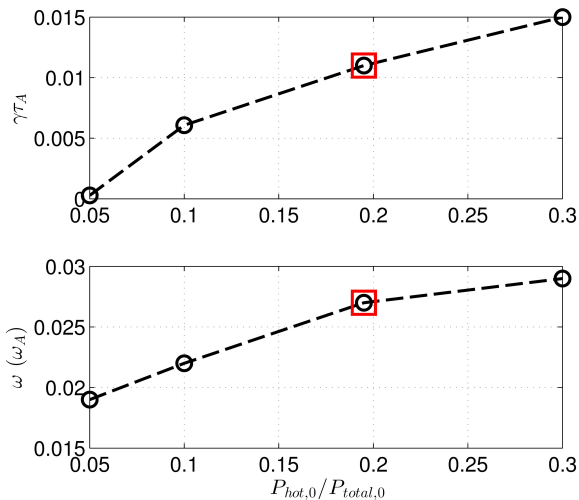


Figure 18. Mode frequency and linear growth rate as functions of P_{h0}/P_{tot0} . The red squares indicate the values corresponding to CFEDR design alpha particle pressure.

growth rate as functions of the alpha particle pressure fraction P_{h0}/P_{tot0} , where P_{h0} is the alpha particle pressure at the magnetic axis, and P_{tot0} is the total pressure at the magnetic axis. When $P_{h0}/P_{tot0} = 0$, the ideal kink mode is stable without alpha particle effect. As P_{h0}/P_{tot0} is larger than 0.05, the fishbone is driven unstable by alpha particles. When P_{h0}/P_{tot0} increases further, both the mode frequency and linear growth rate increase. At CFEDR alpha particle pressure fraction $P_{h0}/P_{tot0} = 0.195$, the fishbone frequency is around $0.027\omega_A$ which is comparable to 3.5 MeV alpha particle precession frequency $\omega_d \sim 0.5k_\theta \rho_h (v_h/v_A)\omega_A \sim 0.030\omega_A$. The corresponding mode structure with $P_{h0}/P_{tot0} = 0.195$ is shown in figure 19, which shows typical twisted feature of the fishbone. These results are consistent with the precession branch of fishbone proposed by Chen *et al* [9].

Secondly, nonlinear simulations of fishbone with CFEDR alpha particle pressure fraction $P_{h0}/P_{tot0} = 0.195$ are carried out by keeping toroidal mode numbers $n = 0$ and $n = 1$. Figure 20 shows time evolutions of the amplitude and frequency of the fishbone. It is observed that the fishbone amplitude firstly increases and then saturates. Correspondingly, the fishbone frequency firstly increases a little and then chirps down to around $0.01\omega_A$, which is, typically, related to the convective radial transport of resonant trapped EPs, as shown in figure 21(c). Interested readers may refer to references [27, 28] for the underlying physics mechanism.

As shown in figure 21, alpha particles are found to be weakly redistributed in the core region, and passing particles are redistributed smaller than trapped particles. The transports of alpha particle density, alpha particle pressure, and passing alpha particle pressure, are defined respectively as $\int |\delta n| dP_\phi / \int n_0 dP_\phi = 6.07\%$, $\int |\delta P_t| dP_\phi / \int P_{h0} dP_\phi = 6.95\%$, $\int |\delta P_{h||}| dP_\phi / \int P_{h||} dP_\phi = 3.22\%$. Alpha particle distribution change in phase space shows hole and clump structures, and the large δf structure becomes broader in the plasma central region, indicating the flattening region expands outward and inward in radial direction, as shown in figure 22. The potential consequences on alpha particle confinement, e.g., synergy with ripple losses, can be investigated in future work.

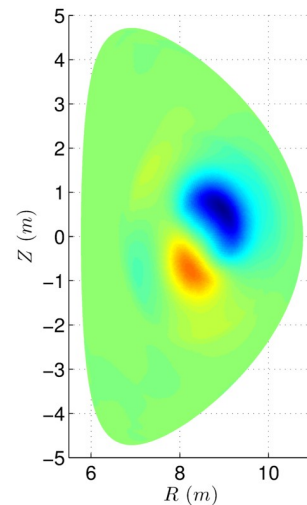


Figure 19. Fishbone mode structure in CFEDR.

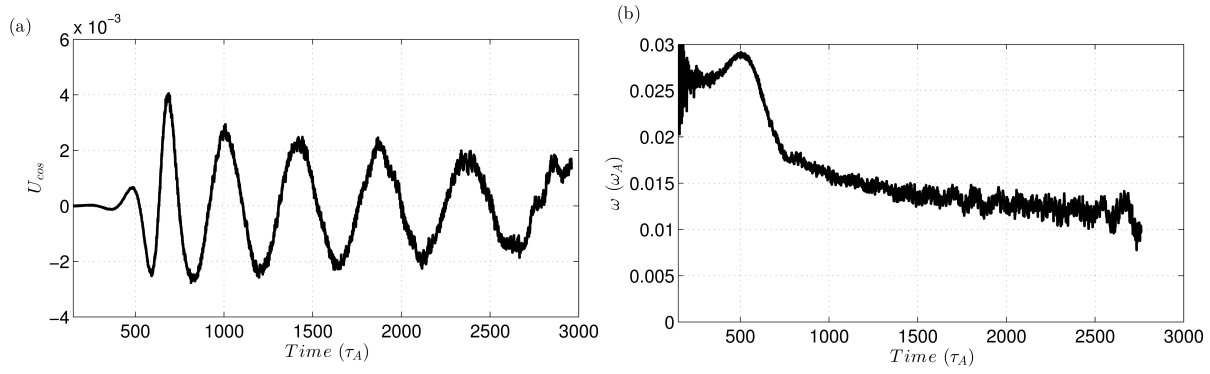


Figure 20. Time evolutions of fishbone mode structure, with (a) representing the mode amplitude, and (b) the mode frequency, respectively.

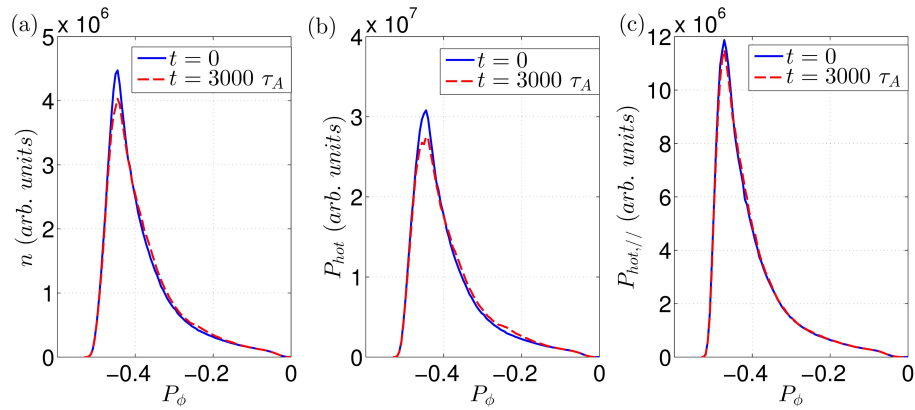


Figure 21. Redistributions of (a) density, (b) pressure, and (c) passing particle pressure of alpha particles, respectively.

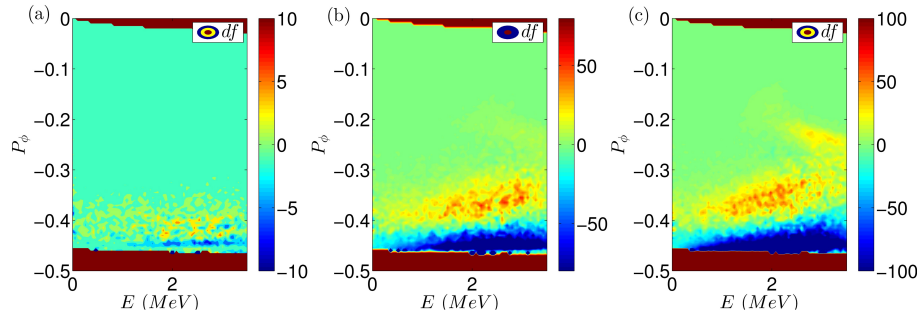


Figure 22. Alpha particle redistributions in phase space with $\Lambda \equiv \mu B_0/E = 1.0$ at (a) $t = 500\tau_A$, (b) $t = 1500\tau_A$, and (c) $t = 3000\tau_A$, respectively.

5. Discussion and conclusion

In conclusion, the assess of fusion alpha particle confinement in the conceptual design of CFEDR conventional H-mode scenario is reported, with particular emphasis on the alpha particle transport loss due to ripple fields, SAW instabilities, as well as fishbone activities.

It is found that, for the original design without ferromagnetic inserts, the ripple rate can be up to 1.63% at the outboard mid-plane, which may lead to up to 2% of alpha particle ripple loss. Within the engineer limit of 500 mm ferromagnetic inserts, the ripple rate can be reduced to 1.03%, and the alpha particle and power losses can be significantly reduced to about 1% and 0.65%, respectively. This will lead to a heat load of 0.1 MW/m² on the outboard mid-plane of the plasma facing component, well within the tolerable level

of the engineering design.

The SAW instabilities are marginally unstable for the present $Q = 15$ baseline scenario. Multiple- n TAEs can be driven unstable with $\gamma/\omega_i \leq 2\%$, and most unstable modes are characterized by $n \simeq O(10)$, consistent with the general understanding for reactors with EP orbit size being much smaller than the machine size. Multiple- n nonlinear simulations with effects of zonal flow accounted for, yields the saturated TAE spectrum and a negligible alpha particle diffusion rate $D_a \leq 0.06$ m²/s. By artificially increasing the alpha particle density by 30% and 50%, which is anticipated for CFEDR high gain scenarios, the local diffusion rate is significantly enhanced, which however, are only expected to cause local redistribution of alpha particles instead of global transport loss for the H-mode scenario, due to the radially localized TAEs. It is pointed out that by increasing the alpha

particle drive above a certain threshold, the large redistribution of alpha particle can occur due to the enhanced transport by multiple- n TAEs [29, 30], which might consequently excite TAEs that are linearly stable. However, further nonlinear excitation of these stable AEs through alpha particle redistribution by weak AE turbulence is difficult in CFEDR baseline scenario, attributing to the relatively weak alpha particle drive and dominant zonal flow regulation effect that lowers AE saturation level.

The fishbone is found to be unstable for the present alpha particle density. However, as $q_{\min}$ is larger than unity, fishbone instability is found to cause only tolerable radial redistribution of alpha particles, with dominant contribution from magnetically trapped particles.

While present work gives preliminary investigations of the major potential issues related to alpha particle transport loss in CFEDR baseline scenarios, and acceptable alpha particle loss rate is obtained, there are still open questions to be answered, e.g. the transport of alpha particles by neoclassical tearing modes (NTMs), the effect of alpha particles on NTM stability, and synergy of NTM/fishbone and ripples on alpha particle confinement. Another open question on EP physics is the effects of alpha particles on micro-scale drift wave stability and the consequences on thermal plasma confinement [31–34], that may self-consistently feedback to the fusion reaction and reactor performance. These open questions, together with alpha particle physics in advanced scenarios of CFEDR, will be the focus of future work.

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