

CONFERENCE PRE-PRINT**THEORY OF FAST ION POPULATION EFFECT ON TURBULENCE SELF-REGULATION IN MAGNETIZED FUSION PLASMAS**

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Abstract

This paper presents an analytic theory of fast ion population effect, namely thermal ion dilution effect by significant portion of the fast ions, to the drift wave turbulence-zonal flow system in magnetized plasmas, which results in probably the simplest self-consistent dynamical model that captures the favourable roles of the fast ions to the enhancement of tokamak confinement. A simple 0D predator-prey model shows that the fast ion population can lead to a drastic nonlinear suppression of turbulent transport in tokamak core, due to its strong dependence on the dilution factors originating from the fast ion population. Further analytic work on the longer-term evolution of the saturated turbulence-zonal flow system in the context of the $E \times B$ staircase reveals that the initial saturated $E \times B$ flow shear level should be strong enough to maintain its saturated structure, without being destroyed with the emission of a bursty bump-hole pair. Again, the fast ion population gives a beneficial effect to maintain the $E \times B$ staircase, lowering the required minimal flow shear strength. The theoretical predictions are consistent with experimental observations from KSTAR FIRE mode.

1. INTRODUCTION

Experimental findings of new kinds of enhanced confinement modes from various tokamaks around the world in 2020s [1-8] with significant neutral beam injection (NBI) and/or ion cyclotron resonance heating (ICRH) have aroused interests in favourable roles of fast ions on fusion plasma confinement. The findings have therefore largely changed fusion researchers' perception on fast ions from a passive element providing heat and particle sources to thermal plasma to an active participant significantly affecting transport and confinement levels.

Since the first experimental finding of the H-mode [9], the most widely accepted universal mechanism of the transition to an enhanced confinement regime in fusion plasmas has been suppression of drift wave turbulence by $E \times B$ flow shear [10-14]. In particular, extensive theoretical, simulation, and experimental studies [15-20] have revealed that self-generation of the $E \times B$ shear flow, namely zonal flow, from drift wave turbulence triggers the transition to an enhanced confinement regime. In the presence of fast ions in tokamaks, the fast ion-driven Alfvén eigenmodes and fishbone can also generate zonal flows by self-beating [21-25], which could nonlinearly interplay with microturbulence [26-32] resulting in the confinement enhancement.

At the meantime, there have been studies of direct fast ion effects on turbulent transport and plasma confinement which does not rely on the energetic fast ion-driven Alfvénic modes. Primarily, theories and simulations have shown that as fast ions significantly raise total plasma beta, they enhance the finite-beta, or in other words the electromagnetic stabilization of the drift wave turbulence [33-36]. More recently, the effects of the wave-particle interactions between drift wave modes and fast ions have been addressed, showing strong dependence on the fast ion profile condition and the turbulence mode [1,26,37]. But the simplest effect of the fast ions on the drift wave turbulence as a distinctive ion species would be the thermal ion dilution by fast ion population, which has been found to linearly stabilize ITG modes and temperature-gradient-driven CTEM [38-43]. Still, there has been lack of a universal theory of direct fast ion effect on the turbulence-zonal flow system, which is the minimal set to

understand experimentally observed transition to an enhanced confinement regime with fast ions. Motivated by this, we have developed a simple analytic theory of coupled drift wave turbulence-turbulence system in the presence of fast ion population effect [44,45], which could be a backbone to the fast ion-induced transition to an enhanced confinement mode.

2. MODIFIED HASEGAWA-MIMA EQUATION WITH FAST ION POPULATION EFFECT

The paradigm model of zonal flow-turbulence interaction in magnetized plasmas is the modified Hasegawa-Mima equation [46]. While it has been derived from the fluid equations conventionally [47], here we present a derivation using the modern gyrokinetic formalism [48-50], which enable us a conceptually clear extension to include the fast ion contributions. We start with the perturbed part of the quasi-neutrality condition

$$\delta n_e = \delta N_i + \delta n_{ipol}, \quad (1)$$

where the perturbation of the ion particle density δn_i , which balances with that of the electron density δn_e , has been decomposed to the ion gyrocenter density δN_i and the ion polarization density δn_{pol} . General definitions and explicit expressions of the gyrocenter and polarization densities can be found in Refs. [51,52]. Taking long-wavelength limit $k_\perp \rho_i \ll 1$, the expression of the ion polarization density can be simplified so that

$$\frac{\delta N_i}{n_{e0}} = \frac{e\tilde{\phi}}{T_e} - \rho_s^2 \nabla_\perp^2 \frac{e\phi}{T_e}, \quad (2)$$

Where we have used the adiabatic electron response $\delta n_e/n_0 = e\tilde{\phi}/T_e$ and the quasi-neutrality $n_{e0} = N_{i0}$. Here, the tilde denotes the component of a perturbation which varies along the magnetic field, i.e., the one having finite $k_\parallel$. That is, we have assumed the parallel force balance in electron response to a turbulent perturbation, and no electron response to the zonal flow which has $k_\parallel = 0$. Note that the expression of perturbed ion gyrocenter density shown in Eq. (2) is identical with that of the potential vorticity (PV) in magnetized plasmas, which is the essential quantity in the zonal flow dynamics [53-56]. $\rho_s = \sqrt{T_e/m_i}$ is the sound gyroradius. Substituting Eq. (2) into the ion gyrocenter continuity equation in the uniform magnetic field $\mathbf{B} = B\hat{z}$

$$\partial_t N_i + \nabla \cdot (\mathbf{u}_E N_i) = 0, \quad (3)$$

we readily obtain the modified Hasegawa-Mima equation

$$\partial_t (\tilde{\phi} - \rho_s^2 \nabla_\perp^2 \phi) + \rho_s c_s [\phi, \tilde{\phi} - \rho_s^2 \nabla_\perp^2 \phi] + \rho_s c_s \frac{1}{n_{e0}} \left(\frac{dn_{e0}}{dx} \right) \frac{\partial \tilde{\phi}}{\partial y} = 0, \quad (4)$$

where we have normalized the potential $\phi \rightarrow e\phi/T_e$. Here, x is the direction of transport (“radial” direction) and y is the binormal direction, and $[A, B] = (\partial_x A)(\partial_y B) - (\partial_y A)(\partial_x B)$ is the Poisson bracket. The first part of the Poisson bracket in Eq. (4) corresponds to the E×B nonlinearity, and the second part is called the Hasegawa-Mima nonlinearity. Linearizing Eq. (4) and Fourier-decomposing, one can readily obtain the electron drift wave $\omega = \omega_{*e}/(1 + k_\perp^2 \rho_s^2)$, the most fundamental drift wave, where $\omega_{*e} = \rho_s c_s k_y / L_{ne}$ and $1/L_n \equiv -dn/ndx$. Also, after some massage one can obtain the global energy conservation law from Eq. (4) as follows.

$$\frac{d}{dt} \int d^3 \mathbf{x} \frac{1}{2} [\tilde{\phi}^2 + |\nabla \tilde{\phi}|^2 + |\nabla \langle \phi \rangle|^2] = 0, \quad (5)$$

where $\langle \phi \rangle$ is the flux-surface-average part, i.e., the zonal part of the potential $\phi = \langle \phi \rangle + \tilde{\phi}$. Eq. (5) indicates the energy-conserving property of the drift wave-zonal flow interaction. This is an example showing that the modified Hasegawa-Mima equation is the paradigm equation for the drift wave-zonal flow system.

Now, we extend the modified Hasegawa-Mima equation by including fast ions. The quasi-neutrality condition

$$\delta n_e = \delta n_f + \delta N_i + \delta n_{ipol}, \quad (6)$$

which now includes the fast ion particle density δn_f . Taking appropriate sub-orderings to the linear gyrokinetic equation, we can arrive at the simplest fast ion density response $\delta n_f/n_{f0} = -e\tilde{\phi}/T_f$, the adiabatic response [44]. Here, T_f is the fast ion temperature and we have assumed a Maxwellian fast ions for simplicity. As $T_f \gg T_e$, we find that we can simply neglect the adiabatic response of fast ions to that of electrons. As a result, we obtain the following long-wavelength expression of the perturbed thermal ion gyrocenter density, i.e., the PV.

$$\frac{\delta N_i}{n_{e0}} = \frac{e\tilde{\phi}}{T_e} - (1-f)\rho_s^2 \nabla_\perp^2 \frac{e\tilde{\phi}}{T_e} - \rho_s^2 \nabla_\perp^2 \frac{e\langle\phi\rangle}{T_e}, \quad (7)$$

where $f = n_{f0}/n_{e0}$ is the density fraction of the fast ion population. Note that Eq. (7) shows that the drift wave vorticity is reduced by the fast ion-induced dilution by a factor of $(1-f)$, while the zonal flow vorticity is unchanged. Substituting Eq. (7) into Eq. (3), we obtain the modified Hasegawa-Mima equation with fast ions

$$\begin{aligned} \partial_t (\tilde{\phi} - (1-f)\rho_s^2 \nabla_\perp^2 \tilde{\phi} - \rho_s^2 \nabla_\perp^2 \langle\phi\rangle) + \rho_s c_s [\phi, \tilde{\phi} - (1-f)\rho_s^2 \nabla_\perp^2 \tilde{\phi} - \rho_s^2 \nabla_\perp^2 \langle\phi\rangle] \\ + \rho_s c_s \frac{1}{n_{e0}} \left(\frac{dn_{i0}}{dx} \right) \frac{\partial \tilde{\phi}}{\partial y} = 0, \end{aligned} \quad (8)$$

which yields, after linearization, the electron drift wave eigenfrequency

$$\omega = \frac{(1-f)\eta_n}{1 + (1-f)k_\perp^2 \rho_s^2} \omega_{*e}. \quad (9)$$

Note that the electron drift wave eigenfrequency is significantly downshifted by the thermal ion dilution, as both factors $(1-f)$ and $\eta_n \equiv L_{ne}/L_{ni}$ are smaller than unity. This will play an important role in the next section.

3. DILUTION EFFECT ZONAL FLOW GENERATION AND CONFINEMENT ENHANCEMENT

Using the extended Hasegawa-Mima equation with fast ions, we have analytically calculated the modulational growth rate of zonal flow from a pump drift wave. We have closely followed the previous works [17,18], and thus the calculation process is straightforward. Therefore, here we present schematics of the calculation of the zonal flow growth only, shown in Fig. 1. Details can be found in Ref. [44].

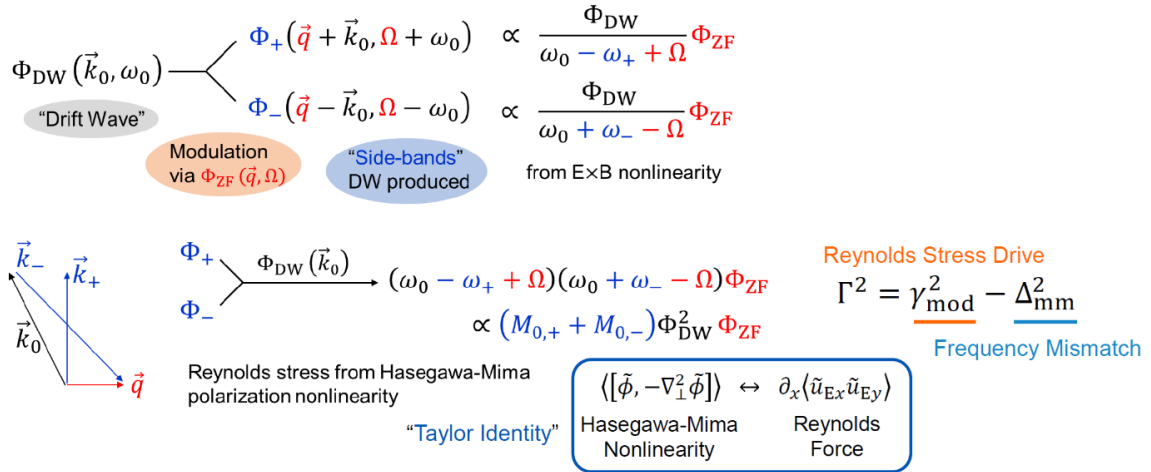


Fig. 1. Schematics of the modulational zonal flow generation from a pump drift wave [44].

As shown in Fig. 1, the drift wave sideband is produced by the nonlinear coupling of the pump and the seed zonal flow through the $E \times B$ nonlinearity. Then, the sideband and the pump drift waves are nonlinearly coupled through the Hasegawa-Mima nonlinearity, resulting in the amplification of the zonal flow, i.e., the modulational zonal flow growth. Since the Hasegawa-Mima nonlinearity can be converted to the Reynolds stress by Taylor's identity [57], this modulation process can also be interpreted as a mean flow generation by the Reynolds stress in the fluid momentum equation [15].

Consequently, we obtain the following long-wavelength expression of the modulational zonal flow growth rate Γ in the presence of fast ion population effect.

$$\Gamma^2 = \gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2, \quad (10)$$

where

$$\gamma_{\text{mod}}^2 = 2(1-f)k_y^2 q_x^2 |\tilde{\phi}_0|^2, \quad (11)$$

is the zonal flow drive from the Hasegawa-Mima nonlinearity, in other words the $\mathbf{E} \times \mathbf{B}$ advection of PV, and

$$\Delta_{\text{mm}}^2 = [((\omega_0 - \omega_+) + (\omega_0 + \omega_-))/2]^2 \cong (1-f)^4 \eta_n^2 k_y^2 q_x^2, \quad (12)$$

is the frequency mismatch between the pump drift wave ω_0 and the sidebands $\omega_{\pm}$. From Eqs. (11) and (12), we readily find that the frequency mismatch term Δ_{mm}^2 has much stronger reduction factor dependence than the Reynolds stress drive γ_{mod}^2 , so that we have easier zonal flow generation with fast ions.

Then, we have extended our theoretical work to the case of the broadband drift wave turbulence, which is more relevant to the usual case of magnetic fusion plasmas [45]. For this, we have closely followed previous works [18] using the wave-kinetic equation describing evolution of the wave packet population density $N(\mathbf{x}, \mathbf{k}) = \mathcal{E}_{\mathbf{k}}/\omega_{\mathbf{k}}$ in $(\mathbf{x}, \mathbf{k})$ phase space. After a standard procedure, we obtain the zonal flow dispersion relation as follows.

$$-i\Omega = -(1-f)^2 q_x^2 \eta_n \sum_{\mathbf{k}} \frac{k_y^2 \omega_*}{[1 + (1-f)k_{\perp}^2]^2} R_{q_x} k_x \frac{\partial \langle N \rangle}{\partial k_x}, \quad (13)$$

where q_x and Ω are the zonal flow radial wavenumber and frequency, and $R_q = 1/(-i\Omega + iq_x v_{gx} + 2\gamma)$ is the response function for the wave population density modulation by the zonal flow. Here, $v_{gx} = \partial \omega_{\mathbf{k}} / \partial k_x$ and γ are the radial group velocity and the linear growth rate of the drift wave turbulence.

Simplifying this response function by going to the weak turbulence, or non-resonant regime $2\gamma < |\Omega - q_x v_{gx}|$, we find that if we neglect the wavevector dependence of v_{gx} heuristically, we recover the form of the previously calculated zonal flow growth from a pump wave, where $q_x v_{gx}$ which is the continuum version of the frequency mismatch, plays the role of a threshold for the zonal flow generation. Note that the latter regime is more relevant to the core enhanced confinement mode. Again, although the Reynolds stress drive of zonal flow is reduced by a factor of $(1-f)$ (another $(1-f)$ cancels with the change of the definition of $\langle N \rangle$), as the reduction of the threshold $q_x v_{gx}$ is more drastic, we have a more favourable condition to the zonal flow generation with fast ions.

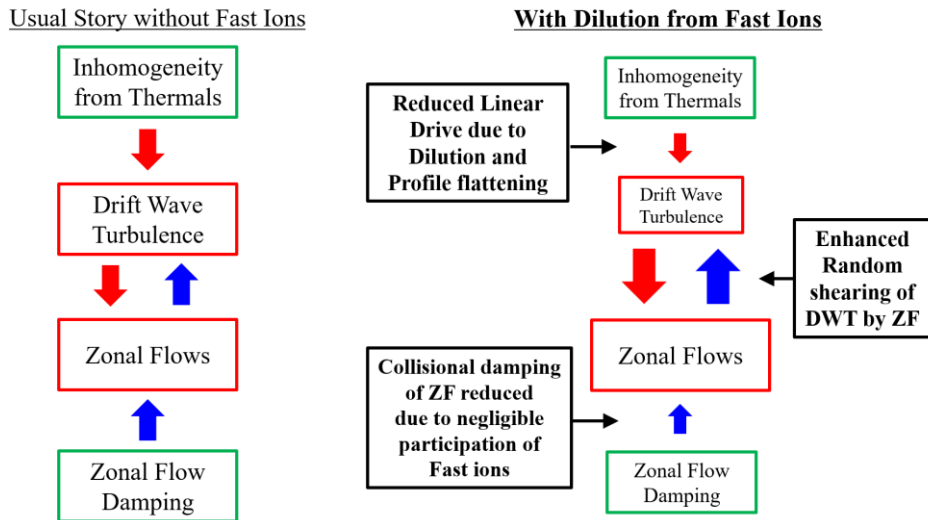


Fig. 2. A diagram summarizing effects of fast ion population on drift wave turbulence-zonal flow system [45].

So far, we have calculated the fast ion population effect on the rate of drift wave turbulence-zonal flow interaction, but in addition to this we have three more effect of fast ions. First, fast ion population can significantly reduce linear turbulence drive. Second, turbulence self-damping can also be reduced, depending on the type of dominant nonlinearity. Finally, collisional zonal flow damping is also reduced due to negligible participation of fast ions. All these fast ion effects are summarized in Fig. 2.

Combining all the pieces together, we constructed a 0D predator-prey model of turbulence-zonal flow system with fast ions, in weak turbulence regime relevant to tokamak core plasmas.

$$\partial_t u^2 = \sqrt{\gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2} H(\gamma_{\text{mod}} - \Delta_{\text{mm}}) u^2 - (1-f) \gamma_{d(0)} u^2, \quad (14a)$$

$$\partial_t \mathcal{E} = 2\gamma \mathcal{E} - \sqrt{\gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2} H(\gamma_{\text{mod}} - \Delta_{\text{mm}}) u^2 - (1-f) B \mathcal{E}^2. \quad (14b)$$

From the steady-state solution with zonal flows, we finally obtain the saturated turbulence level that is proportional to the turbulent transport. Its expression in the collisionless limit, relevant to core confinement enhancement, is

$$\mathcal{E} \approx (1-f)^3 (L_{ne}/L_{ni})^2 \mathcal{E}_{(0)}, \quad (15)$$

which has very strong reduction factor, indicating the significant impact of fast ion population on the suppression of turbulent transport and confinement enhancement.

The primary target of application of our analytic theory of fast ion population effects on the turbulence-zonal flow system is KSTAR FIRE mode having significant ion temperature internal transport barrier (ITB) that is strongly correlated with fast ions [3,58], but usually having no role of Alfvénic activities during the transition. Indeed, for a typical KSTAR FIRE mode with $f \sim 1/3$, from Eq. (15) we expect $\sim 1/3$ decrease of turbulent transport level solely from the factor $(1-f)^3$, already significant. Then, with the additional reduction factor $(L_{ne}/L_{ni})^2$ in Eq. (15) due to thermal ion density profile moderation, our theory predicts a much more drastic suppression of transport during transition to FIRE mode, which is consistent with experimental findings. Another good candidate to examine our theory would be recently found hot ion mode in ST40 with strong NBI [6].

4. FAVORABLE ROLE OF FAST ION POPULATION IN MAINTAINING E×B STAIRCASE

While we have observed significant ion thermal ITB in the KSTAR FIRE mode, the confinement enhancement in the electron thermal channel is not so drastic as shown in Ref. [3]. Interestingly, we have found electron temperature profile corrugation in the FIRE mode from recent analysis of ECEI data, which is a symptom of the E×B staircase [59,60], the quasi-periodic radial structure consisting of mini transport barriers with avalanching bump-hole pairs in between [61,62]. Furthermore, the blob propagation in between the staircase and dissipation at the staircase location have been observed by the ECEI system in the KSTAR FIRE mode as shown in Fig. 3.

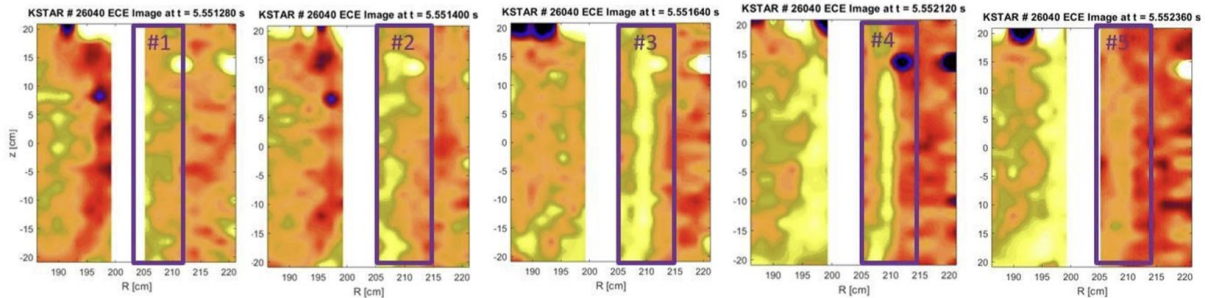


Fig. 3. Avalanching blob and its dissipation at the staircase location were observed in FIRE mode by KSTAR ECEI system.

Motivated by these observations, we extended our wave kinetic theory to study the fast effect on the E×B staircase. Specifically, we have combined a theory of energetic particle clump-hole pair formation with Alfvén eigenmode [63] and wave trapping theories of E×B staircase [64,65] to analytically calculate the condition for a dangerous bursty bump-hole pair formation which destroys the staircase [66,67].

We start with the general zonal flow dispersion relation without fast ions, keeping both resonant and non-resonant zonal flow drives and the mean radial group velocity of the drift wave packet V_{gx}

$$1 + \frac{\gamma_{\text{mod}}^2}{\Omega(\Omega + iv)} \left(1 - \frac{2q_x V_{gx}}{\Omega} - \frac{\Delta_{\text{mm}}^2 - q_x^2 V_{gx}^2}{\Omega^2} \right)^{-1} + \text{Res} \int d^2\mathbf{k} \frac{q_x k_y^2}{2} \frac{q_x v_{gx}}{\Omega - q_x v_{gx}} \frac{\partial N_0}{\partial k_x} = 0. \quad (16)$$

Then, we consider a nontrivial saturated state with $\Gamma_0^2 = \gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2 = 0$ and a locally flattened, shelflike mean wave population density N_0 in (x, k_x) phase space as the initial condition. This means that we focus on physics around a single step of the periodic $E \times B$ staircase. Note that the locally flattened profile can be regarded as an initial bump-hole pair by comparing it to the profile at the very beginning before the zonal flow growth. Assuming Gaussian shape of N_0 in k_y , we have calculated the stability of this initial bump-hole pair $\Omega \rightarrow \Omega + \delta\Omega$.

As a result, we found that while the $E \times B$ staircase is intrinsically stable against the dangerous bump-hole pair formation and propagation in significantly broadband turbulence $\Delta k_y > k_{y0}$, but with a narrower turbulence bandwidth $\Delta k_y < k_{y0}$ the $E \times B$ staircase has a certain threshold in its shearing rate $\omega_{E \times B}$ to be safe from the bursty transport. Finally, repeating the calculations including the fast ion population effect, we have obtained

$$\omega_{E \times B} > \omega_{E \times B}^{\text{crit}}, \quad (17)$$

where $\omega_{E \times B}^{\text{crit}} = (1 - f)^3 (L_{ne}/L_{ni})^2 \omega_{E \times B(0)}^{\text{crit}}$. Our results indicates that the presence of fast ions are favourable to sustain the initially formed $E \times B$ staircase. While our simple theory doesn't cover all the complicated properties and features of $E \times B$ staircases observed in fusion experiments, the tendency we found is consistent with recent ECEI data analysis of KSTAR ITB discharges, where we have found longer lifetime of the $E \times B$ staircase in FIRE mode compared to that in ITB L-mode. Details of the KSTAR experimental data analysis will be presented and published elsewhere.

ACKNOWLEDGEMENTS

Work supported by R&D Program of “High-performance reactor plasma research development (code No. EN2501-16)” through the Korea Institute of Fusion Energy(KFE) funded by the Government funds, Republic of Korea, National R&D Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (NRF-2021M1A7A4091135, 2021M3F7A1084418, 2023R1A2C100773511), Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2022R111A1A01072713), and U.S. Department of Energy under Award Number DE-FG02-04ER54738.

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