COMPARATIVE SIMULATIONS OF THE PLASMA RESPONSE TO RMPS DURING ELM-CRASH MITIGATED AND SUPPRESSED PHASES IN KSTAR

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Abstract

Control of the edge localized modes (ELMs) is one of the most critical issues for a ITER and the future tokamak fusion reactors. In order to develop a predictive model of the access to ELM-crash suppressed states, it is essential to understand first the underlying physics mechanism of ELM-crash-suppression. The paper reports simulation results for particular KSTAR experimental shots, where ELM-crash mitigated and suppressed phases were observed sequentially and distinctly with low-n resonant magnetic perturbations (RMPs). It has been observed that toroidal rotation and ion temperature are rapidly increased and decreased, respectively, near the top of the pedestal across the transition from ELM-crash-mitigation to suppression. This results in a small outward shift in the rotation zero-crossing points and the perpendicular rotation becomes even smaller at the rational surface located near the pedestal top. Correspondingly, linear plasma response modeling with the resistive MHD code M3D-C1 indicates that resonant tearing response is increased significantly at that surface, which is well correlated to the observed onset of ELM-crash suppression. Nevertheless, it is not yet clear which of the perpendicular rotations, ExB or perpendicular electron rotation, is actually important for the ELM-crash suppression in KSTAR. In order to understand the rotation zero-crossing effects more fundamentally, kinetic plasma response model has been newly developed and its numerical scheme briefly explained in the paper. Preliminary kinetic simulation results reproduce the main plasma response characteristics predicted by two-fluid resistive MHD although kinetically modified rotation zero-crossing effect may be slightly different from that based on MHD model.

1. INTRODUCTION

Recently, 3D non-axisymmetric (NA) magnetic perturbations have been extensively used for suppressing edge-localized modes (ELMs) in tokamaks, such as DIII-D [1], ASDEX-Upgrade [2], KSTAR [3], etc. Although several devices have reported full ELM-crash suppression up to now, the underlying physics mechanism is still not clear and needs to be clarified. Recent DIII-D experiments have suggested that ELM-crash suppression is accompanied by an abrupt shift in the perpendicular electron flow (or ExB flow) and the associated zero-crossing point aligns with a rational surface at the top of the pedestal [4]. Correspondingly, linear, two-fluid M3D-C1 [5] modeling shows that resonant tearing response is increased significantly at that surface, resulting in the possible island formation at the pedestal top. Similar observation of the bifurcation of perpendicular flow near the pedestal top ($v_{\perp,\text{ped}}$) at the transition into and out of the ELM-crash suppression has also been made directly in KSTAR by using electron cyclotron emission imaging (ECEI) diagnostic [6]. Therefore, it can be concluded that plasma perpendicular flow dynamics should play an important role in the access to the ELM-crash suppressed states. However, there still remains an open question, i.e., whether the ExB flow ($\omega_{\text{ExB}}$) or the perpendicular electron flow ($\omega_{\perp e}$) is more important for ELM-crash suppression. In fact, resonant field penetration is predicted to be induced at $\omega_{\text{ExB}}$ by single-fluid MHD theory, while at $\omega_{\perp e}$ by two-fluid MHD theory. In the past, there were contradictory experimental results on the relative importance of $\omega_{\perp e}$ over $\omega_{\text{ExB}}$ at pedestal top as necessary condition for ELM-crash suppression: Some experimental analysis of DIII-D discharge suggested that $\omega_{\perp e}$ captures the ELM-crash suppression behavior better than $\omega_{\text{ExB}}$ [7], while other inspection showed that there is no region of $\omega_{\perp e}$ in the vicinity of rational surfaces in the edge pedestal region of the ASDEX-Upgrade tokamak [8], making it difficult to accept the explanation of ELM-crash
suppression based on $\omega_0 \sim 0$ paradigm. It is thus reasonable to consider more advanced model (such as a kinetic modelling pursued in the present work) to understand the rotation zero-crossing effects correctly.

In section 2, we present results from comparative analysis of the plasma response to RMPs during ELM-crash mitigated and suppressed phases in KSTAR. Both of the representative n=1 and n=2 RMP-driven ELM-crash suppressed shots are analysed to understand how the rotation profiles are changed through the transition process and M3D-C1 [5] is used to model the plasma response to RMPs in KSTAR. In order to account for the rotation-zero-crossing effects more accurately, kinetic plasma response model has been newly developed and its preliminary simulation results are presented in Section 3. Finally, in section 4, we give a conclusion and some discussion of the obtained results.

2. COMPARATIVE ANALYSIS OF PLASMA RESPONSE TO RMPS IN KSTAR

We analysed two representative KSTAR experimental shots where clear transition from ELM-crash-mitigation to suppression has been obtained with low-n RMPs. In subsection 2.1, we briefly discuss how the perpendicular rotation profiles (ExB and perpendicular electron rotation) are changed across the transition under the application of n=1 and 2 RMPs to a typical H-mode plasma in KSTAR. In subsection 2.2, we show results from applying M3D-C1 code to a KSTAR ELM-crash-suppression shot.

2.1. Comparison of rotation profiles between ELM-crash mitigated and suppressed phases in KSTAR

Robust ELM-crash suppression has been routinely obtained near $q_{95} \sim 5$ by applying n=1 RMPs to a typical H-mode plasmas in KSTAR. Shot 16661 is one of such shots and specifically optimized for good divertor heat flux measurements [9]. In this shot, as RMP coil current is turned at t=2 sec, ELM mitigated phase occurs initially and at t=3.13 sec, suppression of ELM-crash finally follows. Figure 1 shows how the toroidal rotation velocity ($V_t$) and ion temperature ($T_i$) obtained from the charge exchange spectroscopy (CES) diagnostic evolve in time since RMP is turned on at t=2 sec. Here, both of $T_i$ and $V_t$ are spatially averaged values using CES channels located near the pedestal top. It can be clearly seen that both of $T_i$ and $V_t$ are strongly reduced as soon as RMP is turned on. Across the transition to ELM-crash suppression, however, $V_t$ is rapidly increased, while ion temperature decreased additionally, such that toroidal rotation ($\omega_t$) and ion diamagnetic ($\omega_i$) frequencies get larger and smaller at the top of the pedestal, respectively, compared with those during the ELM-crash mitigated phase between t=2 and 3.13 sec. Similar behaviour of $T_i$ and $V_t$ has also been ascertained in other representative n=1 RMP ELM-crash suppression shots (i.e., 19347) in KSTAR.

![FIG. 1. Temporal evolution of toroidal rotation velocity($V_t$) and ion temperature($T_i$) near the pedestal top through the transition to ELM-crash suppression on 16661.](image)

Figures 2(a) and 2(b) show edge $T_i$ and $V_t$ profiles measured at t=2.92 sec (ELM-crash mitigated) and 3.46 sec (ELM-crash suppressed), respectively. As expected from Fig. 1, ion temperature and its gradient are decreased, while the toroidal rotation increased near the pedestal top after the transition. These changes are consistent with the previous DIII-D observations [4] and due to the (unknown) RMP-driven transport effects. In contrast, electron density $n_e$ measured by Thomson scattering (TS) system remains almost the same or slightly reduced through the transition, as can also be checked from the temporal evolution of line averaged density [9].
Diagnostic data points are fitted by a modified tangent hyperbolic (mtanh) function and used to compute $\omega_{\text{ExB}}$ and $\omega_{\perp e}$ profiles. In the case of mtanh fitting of Thomson $n_e$ data, its pedestal center position is slightly adjusted to match that of CES $T_i$ data to give better alignment of steep gradient regions of different profiles. In addition, Thomson $n_e$ data is slightly rescaled to match measured line averaged density. Regarding electron temperature ($T_e$) profile, we use the approximation $T_e = T_i$ because of a larger fluctuation of Thomson $T_e$ data, which makes it rather difficult to use the Thomson data in this case. Computed ExB and perpendicular electron rotation profiles are shown in Figs. 2(c) and 2(d), respectively, where two vertical black lines indicate the locations of the resonant surfaces closest to the rotation zero-crossing points. Here, ExB rotation frequency ($\omega_{\text{ExB}}$) is calculated from radial force balance equation for carbon impurity species and given by

$$\omega_{\text{ExB}} = \frac{V_t}{R} - \frac{B}{RB_\phi} V_\phi + \frac{1}{\rho \eta C} \frac{d \rho_C}{d \varphi} = \omega_\phi + \omega_\theta - \omega_{\text{dc}}$$

where $V_t$ and $V_\theta$ are the carbon toroidal and poloidal velocities, $B_t$ and $B_\theta$ are the toroidal and poloidal magnetic fields, $\rho_C$ and $n_C$ are the carbon pressure and density. It can be seen that $\omega_{\text{ExB}}$ is the sum of the toroidal ($\omega_\phi$), poloidal ($\omega_\theta$), and diamagnetic ($\omega_{\text{dc}}$) rotation frequencies of the carbon ions. $\omega_{\perp e}$ is then given by the sum of the ExB and electron diamagnetic rotation frequencies: $\omega_{\perp e} = \omega_{\text{ExB}} + \omega_{\text{dc}}$. Because no poloidal CES data is available on 16661, we use instead the standard neoclassical expression for poloidal rotation velocity of impurity species [10]. Fig. 2(c) shows that an increase of $\omega_\phi$ as well as a reduction of $\omega_{\text{dc}}$ and $|\omega_\theta|$ contributes to an outward shift of $\omega_{\text{ExB}}$ profile after the transition and its zero-crossing point becomes closer to the 5/1 rational surface near the pedestal top. In contrast to this, Fig. 2(d) indicates that $\omega_{\perp e} \sim 0$ is initially close to the 4/1 rational surface and shifted outwardly to midway point between the 4/1 and 5/1 surfaces after the transition. Because the tearing response, i.e., resonant field penetration, peaks in the vicinity of $\omega_{\text{ExB}} \sim 0$ (single-fluid MHD) and $\omega_{\perp e} \sim 0$ (two-fluid MHD) when the zero-crossing point aligns well with a rational surface, $\omega_{\text{ExB}} \sim 0$ dynamics in Fig. 2(c) seems to be more consistent with the observed transition to ELM-crash suppression, suggesting that $\omega_{\text{ExB}}$ is actually important for ELM-crash suppression. This conclusion is qualitatively in agreement with the recent direct ECEI observation of perpendicular flow ($v_\perp$) changes at the onset of ELM-crash suppression in KSTAR where the change of ExB flow appeared mainly responsible for the change of $v_\perp$ [6].

**FIG. 2.** (a) Ion temperature $T_i$, (b) ion rotation frequency $\omega_\phi$, (c) ExB rotation frequency $\omega_{\text{ExB}}$, (d) perpendicular electron rotation frequency $\omega_{\perp e}$ as a function of the normalized poloidal flux during the ELM-crash mitigated (blue) and suppressed (red) phases on 16661.
Similar analysis has also been done for n=2 RMP case (shot 18594) where as RMP coil current is gradually ramp-up in time starting at t~5 sec, ELM mitigated phases occur initially and at t>12 sec, suppression of ELM-crash finally follows. Unlike shot 16661, however, Thomsson T_e and poloidal CES data are also available in shot 18594 thus can be used to compute $\omega_{ExB}$ and $\omega_{\perp e}$ profiles. In order to reduce large fluctuations inherent in measured diagnostic data, time averaging is explicitly applied to the data obtained during 7-8 sec (ELM-crash mitigated phase) and 12.22-13.1 sec (ELM-crash suppressed phase). Modification of the pedestal profiles in this shot (Figs. 3(a) and (b)) are very similar to those in shot 16661 discussed above (Figs. 2(a) and (b)) during the transition from ELM-crash mitigation to suppression, such as a small drop in ion temperature and an acceleration of the toroidal rotation throughout the pedestal region. The measured changes to $\omega_{ExB}$ and $\omega_{\perp e}$ profiles are plotted in detail in Fig. 3(c) and Fig. 3(d). It appears that $\omega_{\perp e}$ change in Fig. 3(d) is quite consistent with the observed transition to ELM-crash suppression in that $\omega_{\perp e} \sim 0$ is shifted outwardly and becomes close to the 7/2 rational surface after the transition, resulting in the increased tearing response drive there according to two-fluid MHD plasma response theory. On the other hand, because zero-crossing of $\omega_{ExB}$ moves away from the 8/2 surface during the transition, it is rather difficult to consider $\omega_{ExB}$ change in Fig. 3(c) as meaningful one from the standpoint of resonant field penetration. Therefore, it can be concluded that $\omega_{\perp e} \sim 0$ is more relevant to the transition to ELM-crash suppression by n=2 RMP compared with $\omega_{ExB} \sim 0$. Notice that this interpretation is opposite to that reached in the case of n=1 ELM-crash suppression discussed above.

FIG. 3. (a) Ion temperature $T_i$, (b) ion rotation frequency $\omega_i$, (c) ExB rotation frequency $\omega_{ExB}$, (d) perpendicular electron rotation frequency $\omega_{\perp e}$ as a function of the normalized poloidal flux during the ELM-crash mitigated (blue) and suppressed (red) phases on 18594.

2.2. M3D-C1 simulation results

Results from linear plasma response modeling with the two-fluid MHD code M3D-C1 are shown in Fig. 4. The simulation has been completed for both of the suppressed and mitigated cases on discharge 18594 using the same rotation profiles as exhibited in Figs. 3(c) and (d). It can be seen that the resonant response increases significantly at the m/n=7/2 rational surface near the top of the pedestal where $\omega_{\perp e}$ becomes small ($\omega_{\perp e} \sim 0$) during the ELM-crash suppressed phase as shown in Fig. 3(d), suggesting that resonant field penetration based on two-fluid MHD model correctly captures the ELM-crash suppression behaviour in KSTAR. Similar
simulation results are also expected for shot 16661, except the role of \( \omega_{\perp,e} \sim 0 \) would be replaced by \( \omega_{\perp,n} \sim 0 \) based on single-fluid MHD model.

![Graph showing the relationship between magnetic perturbation and q](image)

**FIG. 4.** Plasma responded magnetic perturbation \( B_{\text{mn}} \) as a function of safety factor \( q \) at resonant surface produced from the M3D-C1 simulations for the ELM-crash mitigated (blue) and suppressed (red) phases on 18594.

### 3. KINETIC PLASMA RESPONSE SIMULATION IN DIVERTED TOKAMAK GEOMETRY

#### 3.1. Kinetic simulation model

In kinetic plasma response calculation, the following two coupled equations should be solved self-consistently

\[
\frac{\partial \bar{J}_I}{\partial \phi} = F[\delta \psi] \tag{1}
\]

\[
\Delta \delta \psi^{\text{ind}} = \frac{\mu_0 I}{B} \sum_m \left( \frac{\partial \bar{J}_I}{\partial \phi} \right)_m \psi^{(m\theta-m\phi)} \tag{2}
\]

where \( I=RB \) with \( R \) being the major radius and \( B \) the magnetic field strength, \( \delta \psi \) is the perturbed poloidal flux, and \( \Delta \) is the two-dimensional Laplacian operator (Grad-Shafranov operator) in a toroidal geometry. Equation (1) means that perturbed plasma current \( \delta J_I \) is evaluated kinetically, as denoted symbolically by the operator \( F \), in the presence of perturbed non-axisymmetric magnetic field \( \delta \psi \). In the present study, we use the full distribution function (full-f) guiding center code XGC0 [11], which includes kinetic electron, ion, and neutral particles motions with perturbed 3D magnetic perturbation in diverted tokamak geometry, to evaluate the perturbed plasma current \( \delta J_I \) kinetically. Actually, the code evaluates each \( (m,n) \) Fourier components of the perturbed plasma current, i.e., \( (\delta J_I/B)_{mn} \), and the total perturbed current is obtained by summing each Fourier components as can be seen on the right hand side of Eq. (2). The second field equation solves for the induced perturbed poloidal flux \( (\delta \psi^{\text{ind}}) \) driven by the perturbed plasma response current obtained from Eq. (1). Considering the presence of external vacuum perturbed poloidal flux \( (\delta \psi^{\text{vac}}) \), the total perturbed flux \( (\delta \psi) \) should be given by the sum of \( \delta \psi^{\text{ind}} \) and \( \delta \psi^{\text{vac}} \), and is imported back as an input to Eq. (1) to enforce consistency between the perturbed magnetic field solution in Eq. (2) and the perturbed plasma current in Eq. (1).

Self-consistent solution satisfying the coupled equations (1) and (2) can then be obtained iteratively in the form of

\[
\Delta \delta \psi^{\text{ind},(k+1)} = \mu_0 I \sum_m \left( \frac{\partial \bar{J}_I}{\partial \phi} \right)_m \left[ \delta \psi^{(k+1)} \right] e^{im\theta} = \mu_0 I \sum_m \left( \frac{\partial \bar{J}_I}{\partial \phi} \right)_m (\psi^{(k+1)}) e^{im\theta}, \tag{3}
\]

where \( \delta \psi^{\text{ind},(k+1)} \) denotes the induced perturbed poloidal flux after \( (k+1) \)-th iteration step. Because the right hand side of the equation contains unknown solution also, the solution can not be simply obtained by inverting the Grad-Shafranov operator \( \Delta \). The simplest method of solving the above equation is to use direct iteration scheme inserting the known solution at \( k \)-th iteration step \( (\delta \psi^{(k)}) \) into the right hand side, i.e.,

\[
\Delta \delta \psi^{\text{ind},(k+1)} = \mu_0 I \sum_m \left( \frac{\partial \bar{J}_I}{\partial \phi} \right)_m \left[ \delta \psi^{(k)} \right] e^{im\theta} = \mu_0 I \sum_m \left( \frac{\partial \bar{J}_I}{\partial \phi} \right)_m (\psi^{(k)}) e^{im\theta}, \tag{4}
\]
where the hat notation above $\delta \psi$ indicates that the solution after $(k+1)$-th iteration step in this case is obtained from the perturbed plasma current induced by the (known) solution $\delta \psi^{(k)}$ at previous iteration step. Unfortunately, it was found that this direct iteration scheme usually leads to an unstable solution after a few iterations. In addition, the iteration needs to converge before background profiles in the code have been changed significantly.

In order to produce a robust stable solution, we introduce the conductivity function $\alpha_{mn}(\psi)$ for poloidal (toroidal) mode number $m \in S$ (n) whose rational surface is located inside the plasma boundary as follows:

$$\left( \frac{\delta \psi}{B} \right)^{(k+1)}_{m' n} (\psi) = im' \alpha_{n' n}(\psi) \delta \psi^{(k+1)}_{n' n}(\psi), \quad m' \in S$$

where $S$ represents a set of poloidal mode numbers whose rational surfaces are within the plasma boundary. Physically, $\alpha_{mn}$ indicates a level of shielding current induced at the $m/n$ rational surface, thus larger (smaller) $\alpha_{mn}$ should lead to a weaker (stronger) solution of the total perturbed flux. In the past, many theoretical expressions for $\alpha_{mn}(\psi)$ have been proposed as, for example, shown in [12]. In the present work, we evaluate it by direct kinetic simulation based on the XGC0 code. By using the direct iteration for poloidal mode number $m \in S$ and neglecting the small change in $\alpha_{mn}(\psi)$ through the iterations, Eq. (3) can be rewritten as

$$\Delta \delta \psi^{ind,(k+1)}_{mn} = \mu_i l \sum_{m'} \left( \frac{\delta I}{B} \right)^{(k+1)}_{m' n} \left[ \delta \psi^{(k+1)}_{m' n} e^{im\theta} + i \mu_i \sum_{m''} \sum_{n''} P_{mn''} (\psi) \alpha_{mn''} (\psi) e^{im''\theta} \delta \psi^{(k+1)}_{mn''} - \delta \psi^{(k+1)}_{mn''} \right]$$

where the perturbed poloidal flux function is expanded into a linear combination of piecewise linear basis functions $P_{mn}(\psi)$ near the $m/n$ rational surface with linear coefficients $\delta \psi_{mn}$ such that

$$\delta \psi^{(k+1)}_{mn} (\psi) \equiv \delta \psi^{* (k+1)}_{mn} (\psi) = \sum_{j \neq k} \delta \psi^{(k+1)}_{mn} (\psi), \quad P_{mn} (\psi) = \delta_{mn}, \quad \delta \psi^{(k+1)}_{mn} (\psi) = \delta \psi^{(k+1)}_{mn},$$

where $\psi = \varphi_{mn}$ denotes nodal points (on which $P_{mn}(\psi)$ center) located around the $m/n$ rational surface. Number of required basis functions ($N$) in the above expansion needs not to be large because significant contribution only comes from the ones with appreciable radial overlap between $P_{mn}(\psi)$ and $\alpha_{mn}(\psi)$, and $\alpha_{mn}(\psi)$ is usually highly peaked around the corresponding rational surface as shown in subsection 3.2.

By using the susceptibility function $\chi^{m, j(k)}_{mn}$ defined as the solution of

$$\Delta \chi^{m, j(k)}_{mn} = - i \mu_i l m' \left( \frac{\delta I}{B} \right)^{(k+1)}_{m' n} \left[ \delta \psi^{(k+1)}_{m' n} e^{im\theta} + i \mu_i \sum_{m''} \sum_{n''} P_{mn''} (\psi) \alpha_{mn''} (\psi) e^{im''\theta} \delta \psi^{(k+1)}_{mn''} - \delta \psi^{(k+1)}_{mn''} \right]$$

the resultant plasma-induced solution after $(k+1)$-th iteration step in Eq. (5) is given by

$$\delta \psi^{ind,(k+1)}_{mn} \equiv \delta \psi^{ind,(k+1)}_{mn} - \sum_{j \neq k} \sum_{m''} \sum_{n''} \chi^{m, j(k)}_{mn} \left[ \delta \psi^{(k+1)}_{mn'} - \delta \psi^{(k)}_{mn'} \right]$$

Taking the Fourier-harmonic component with poloidal mode number $m$ and adding the external vacuum perturbation to both sides of the above equation, we have

$$\delta \psi^{(k+1)}_{mn}(\psi) \equiv \delta \psi^{(k+1)}_{mn}(\psi) + \delta \psi^{ind,(k+1)}_{mn}(\psi) - \sum_{m''} \sum_{n''} \sum_{j \neq k} \chi^{m, j(k)}_{mn} \left[ \delta \psi^{(k+1)}_{mn'} - \delta \psi^{(k)}_{mn'} \right]$$

which is nothing but an implicit equation for unknown solution $\delta \psi^{(k+1)}_{mn}$ given the known $\delta \psi^{(k)}_{mn}$. In order to solve for $\delta \psi^{(k+1)}_{mn}$, evaluate both sides of the above equation at $\psi = \psi_{mn}$ ($m \in S, j=1, \ldots, N$) and subtract $\delta \psi^{(k)}_{mn}$ from both sides of the equation as

$$\delta \psi^{(k+1)}_{mn} - \delta \psi^{(k)}_{mn} \equiv \delta \psi^{(k+1)}_{mn} - \delta \psi^{(k)}_{mn} - \sum_{j \neq k} \sum_{m''} \sum_{n''} \chi^{m, j(k)}_{mn} \left[ \delta \psi^{(k+1)}_{mn'} - \delta \psi^{(k)}_{mn'} \right]$$

In matrix-vector notation, the above equation can be represented in iterative form as

$$\delta \psi^{(k+1)}_{n} \equiv \delta \psi^{(k)}_{n} + (I + \chi^{k+1})^{-1} \left( \delta \psi^{ind,(k+1)}_{n} - \delta \psi^{ind,(k)}_{n} \right)$$

where $\delta \psi^{(k+1)}_{n}$ denotes perturbed poloidal flux “column vector” after $(k+1)$-th iteration step with the constituent elements $\delta \psi^{(k+1)}_{mnj}$ ($m \in S, j=1, \ldots, N$), while $I$ and $\chi$ represent the two dimensional identity and susceptibility matrix (with elements $\chi^{m, j(k)}_{mnj}$), respectively. In actual numerical implementation as shown in the next subsection, we used slightly different but equivalent iteration form as follows:

$$\delta \psi^{(k+1)}_{n} \equiv (I + \chi^{k+1})^{-1} \left( \delta \psi^{vac}_{n} + \delta \psi^{om, ind,(k+1)}_{n} \right), \quad \delta \psi^{om, ind,(k+1)}_{n} = \delta \psi^{ind,(k+1)}_{n} + \chi^{k}_{n} \delta \psi^{(k)}_{n}. \quad (6)$$
3.2. Kinetic simulation results

Based on the iteration scheme given by Eq. (6), preliminary kinetic simulation results have been obtained for the ELM-crash suppressed low collisionality DIII-D discharge 126006 [11] with n=3 RMPs. Our primary purpose here is to test whether the kinetic method explained in subsection 3.1 is capable of giving the expected plasma response characteristics, i.e., no or weak shielding of applied 3D perturbation near the rotation zero-crossing points as shown from the two-fluid M3D-C1 modeling in Fig. 4. Furthermore, in order to shed some light on the relative importance of $\omega_{\perp e}$~0 over $\omega_{\text{ExB}}$~0 near the pedestal top, experimental plasma profiles in the shot are slightly modified to separate zero-crossing of ExB flow (red dashed in Fig. 5(a)) from that of perpendicular electron flow (blue dashed in Fig. 5(a)) as much as possible. One thing to notice here is the fact that radial electric field profile plotted in Fig. 5(a) is not experimentally obtained but evaluated self-consistently within the code, thus may differ slightly from the actual experimental profile. In the simulation, twenty Fourier harmonics (m/n=1/3, ..., 20/3) of the induced current perturbation are considered and a set of resonant poloidal mode numbers (S) consists of m=6, ..., 15. Very weak vacuum magnetic perturbation is applied (about one tenth of the level used in the experiments) in the simulation, such that nearly linear plasma response regime is anticipated ($\alpha_{mn}$ is almost independent of iterations). Obtained results for $\alpha_{mn}$ and Chirikov parameter ($\sigma_{\text{Chirikov}}$) after the iterations nearly converged are displayed in Fig. 5. Fig. 5(a) clearly shows that the conductivity function $\alpha_{mn}$ is well localized around each (m,n) rational surface and its magnitude becomes smallest near the rotation zero-crossing points of $\omega_{\text{ExB}}$ and $\omega_{\perp e}$. However, exact location of the smallest $|\alpha_{mn}|$ is found at the 9/3 resonant surface (denoted by black vertical line), which are different from the ones closest to $\omega_{\text{ExB}}$~0 (red vertical line) or $\omega_{\perp e}$~0 (blue vertical line). Because the smallest $\alpha_{mn}$ should generate the weakest shielding current, m=9 magnetic perturbation becomes most enhanced as shown in Fig. 5(b). Thus, it follows that the rotation zero-crossing effect is working in kinetic plasma response model but slightly differently from the one as expected from MHD model in Section 2: Kinetically modified rotation zero-crossing may be located somewhere between $\omega_{\text{ExB}}$~0 (single-fluid MHD) and $\omega_{\perp e}$~0 (two-fluid MHD). More work is planned in near future to clarify this point.

FIG. 5. (a) ExB rotation frequency $\omega_{\text{ExB}}$ (red dashed), perpendicular electron rotation frequency $\omega_{\perp e}$ (blue dashed), and real part of the conductivity function $\alpha_{mn}$ (solid) profiles versus the normalized poloidal flux in DIII-D-like geometry. (b) Chirikov profiles calculated from vacuum (blue open circle) and kinetic plasma response (red filled circle) models. $\omega_{\text{ExB}}$ and $\omega_{\perp e}$ are expressed in unit of krad/sec, while $\alpha_{mn}$ in arbitrary unit in (a). The vertical bars in (a) indicate the locations of the resonant surfaces for the n=3 perturbation. Blue and red bars indicate the resonant surfaces closest to the zero-crossings of $\omega_{\perp e}$ and $\omega_{\text{ExB}}$, respectively.
4. CONCLUSION AND DISCUSSION

We have analyzed two RMP-driven ELM-crash suppressed shots in KSTAR, particularly focusing on the understanding of whether $\omega_{\text{ExB}} - \omega \approx 0$ captures the observed ELM-crash suppression behavior more correctly than $\omega_{\perp} \approx 0$, and vice versa. In both of the shots, zero-crossing points of the perpendicular rotation were observed to be shifted outwardly across the transition from ELM-crash-mitigation to suppression, such that they align well with a rational surface near the top of the pedestal. Linear plasma response modeling with the M3D-C1 code was then performed, which showed that strong resonant field penetration is expected near the pedestal top during the ELM-crash suppression period. The overall results are quite consistent with those observed in DIII-D tokamak [4], supporting the model for ELM-crash suppression based on resonant field penetration near the zero-crossing of perpendicular rotation in KSTAR. Nevertheless, it is not yet clear which of the perpendicular rotations, $\text{ExB}$ or perpendicular electron rotation, is actually important for the observed ELM-crash suppression in KSTAR: On one hand, our analysis suggests that $\omega_{\text{ExB}} - \omega \approx 0$ at the pedestal top is more consistent with the observed behavior of $n=1$ RMP ELM-crash suppression, but in the other hand, $\omega_{\perp} \approx 0$ appears to explain the $n=2$ RMP ELM-crash suppression better than $\omega_{\text{ExB}} - \omega \approx 0$. Besides, we need to reduce some diagnostic uncertainties of perpendicular rotation profiles plotted in Figs. 2 and 3, which could significantly affect the exact locations of the rotation zero-crossing points. In order to understand the rotation zero-crossing effects more correctly, kinetic plasma response model has been newly developed and its numerical scheme explained in the paper. Initial simulation results reproduced the main plasma response characteristics predicted by two-fluid resistive MHD, while kinetically modified rotation zero-crossing may be located between $\omega_{\text{ExB}} - \omega \approx 0$ (single-fluid MHD) and $\omega_{\perp} \approx 0$ (two-fluid MHD). More work will be pursued in near future to clarify this point.

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REFERENCES