OVERVIEW OF ERROR FIELD SCALING STUDIES IN EAST AND IMPLICATIONS FOR ITER

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Abstract

Error field is a great concern for fusion reactors, such as tokamak devices. The estimated error field in future reactors, about $b_r/B_T \sim 10^{-5}$, however, may result in locked mode, degrading the plasma confinement and even leading to disruption. Therefore, disclosing the underlying law of error field locked mode on relevant plasma confinement parameters is one of the primary issues in error field. However, the empirical scalings from different devices can derive large difference when extrapolating to future reactors. By the same time, the proposed theories can seldom answer the difference among different devices. To clarify these doubts, a series of investigations in EAST have been carried out and some answers for the doubts between theory and experiment have been proposed. The implications for ITER have also been given.

1. INTRODUCTION

Non-axisymmetric magnetic perturbations have long been a concern in magnetic fusion research. The non-axisymmetric magnetic perturbations known as 'error fields' can penetrate the plasma, stimulating error field locked modes. The locked modes produce large magnetic islands, inducing plasma confinement degrading and even leading to deleterious disruption. On the other hand, the non-axisymmetric magnetic perturbations are also applied in controlling edge localized modes (ELMs) to mitigate the heat load of divertor targets. Both of these studies stimulate the investigation on error field relevant physics.

Series of experimental investigations on error field have been carried out. Resonant magnetic perturbation (RMP) coils used error field penetration is carried out in various tokamaks, such as JET, DIII-D, COMPASS, Alcator C-Mod, TEXTOR, MAST, NSTX, J-TEXT et al. One of the main purposes is to extrapolate error field tolerance region in ITER. After a series of experiments, the dependence of penetration threshold b_r on device and plasma parameters has been roughly derived, i.e. $b_r/B_T \propto n_e^{\alpha n} B_T^{\alpha B} q_{95}^{\alpha q} R^{\alpha R}$ (n_e is the density, q_{95} is safety factor at the 95% magnetic flux, R is the major radius), where $\alpha_n \sim 1$, $\alpha_B \sim -2.9$ to $\alpha_B \sim -1$, α_R satisfies $8\alpha_n + 5\alpha_B - 45\alpha_R = 0$. However, the scaling results still have differences in the above mentioned experiments. However, it should be noted that plasma beta and rotation are not included in the above empirical scalings.

Recently, it has been shown that the error-field tolerance for both ideal magnetohydrodynamic (MHD) and tearing-mode stability can be significantly reduced in high β_N neutral beam injection (NBI) heated plasmas, especially in low-input torque plasmas in DIII-D. Here, $\beta_N = \beta(\%)a(m)B_0(T)/Ip(MA)$, where β is the ratio of the plasma thermal pressure to the magnetic pressure, a is the minor radius of the plasma, B0 is the toroidal magnetic field and Ip is the plasma current. It is worth mentioning that the existing lockmode theory is established in cylindrical coordinates. In high-beta plasmas, toroidal effects become important. The coupling between different poloidal harmonics can generate an additional resonant component due to toroidicity. Another toroidal effect, i.e. neoclassical toroidal viscosity (NTV), induced by non-resonant magnetic field perturbations, can generate a global torque that damps plasma toroidal flow. The coupling between different toroidal harmonics has also been directly observed in EAST. The NTV effect on nonlinear field penetration may play an important role in this case. Nonlinear field penetration theory in toroidal geometry is still under investigation. The plasma-beta induced toroidal coupling may play a crucial role in the nonlinear process of field penetration.

Although many investigations can draw a rough conclusion on the effect of plasma rotation in error field penetration physics, a detailed comparison between theory and experiment is still essential to give a definite conclusion. The influence of variable multi-parameters on field penetration should be considered during experimental analysis. In addition, previous numerical modeling concerning error field penetration is established in cylindrical geometry, excluding the effect of toroidal coupling from numerical results. In recent years, it has been found that plasma toroidicity can significantly affect the penetration threshold. Moreover, the non-resonant components of the error field also affect the plasma rotation by giving rise to an NTV torque, which exerts a braking force. Hence, the extent to which toroidal geometry contributes to the penetration threshold cannot be evaluated in cylindrical modeling.

At the meantime, error field penetration theories have also been developed to make clear these diverse experimental results. The penetration theory under the frame of magnetohydrodynamics (MHD) has been established. However, it is mentioned that there is no density dependence in the MHD penetration theory. Furthermore, the two-fluid theories have been developed to try to reduce the gap between theories and experiments. However, it is not clear whether this key assumption is reasonable. Besides, some theoretical analyses also seem reasonable to clarify the experimental results in COMPASS-C, JET and J-TEXT. What factors these different results? A potential answer clarified in the following paper may help to resolve these issues.

The rest of this paper is organized as follows. Density scalings on error field penetration are given in section 2. Toroidal field and q_{95} scalings on error field penetration are given in section 3. Rotation scaling is presented in section 4. Plasma beta effect is presented in section 5. The implications for ITER are given in section 6. At last, a summary is given.

2. DENSITY SCALINGS

The most concerned scaling in error field penetration is the density scaling. To make clear why the classical error field penetration theory cannot explain the experimental results, two kinds of heating plasmas have been carried out, one is ohmically heated plasma, the other one is the lower hybrid wave dominating heated plasmas.

2.1. Density scaling in ohmically heated plasmas

Density scaling of error field penetration in EAST is investigated with different $n = 1$ magnetic perturbation coil configurations in ohmically heated discharges. The density scalings of error field penetration thresholds under two magnetic perturbation spectra are $b_r \propto n_e^{0.5}$ and $b_r \propto n_e^{0.6}$ (FIG.1), where b_r is the error field and n_e is the line averaged electron density. One difficulty in understanding the density scaling is that key parameters other than density in determining the field penetration process may also be changed when the plasma density changes. For example, the Waelbroeck regime scaling $[b_r/B_T]_{crit} \propto n_e^{7/16}\, \tau_V^{7/12}\, T_e^{7/12}\, f_0$, *where* τ_V *is the momentum* diffusion time (similar with energy confinement time), T_e *is the electron temperature and* f_0 *is the mode rotation* frequency. Therefore, they should be determined from experiments. The estimated theoretical analysis ($b_r \propto n_e^{0.54}$ in lower density region and $b_r \propto n_e^{0.4}$ in higher density region), using the density dependence of viscosity diffusion time, electron temperature and mode frequency measured from the experiments (FIG. 2-FIG. 4), is consistent with the observed scaling. One of the key points to reproduce the observed scaling in EAST is that the viscosity diffusion time estimated from energy confinement time is almost constant (FIG. 2). It means that the plasma confinement lies in saturation ohmic confinement regime rather than the linear Neo-Alcator regime causing weak density dependence in the previous theoretical studies.

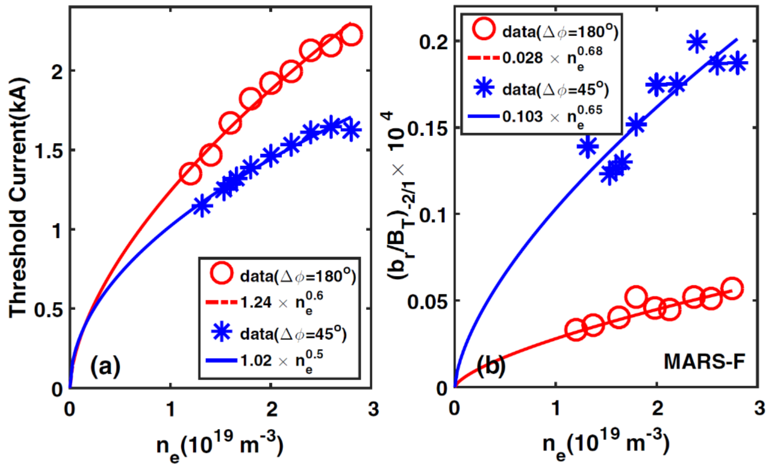

FIG. 1. Density scaling with penetration thresholds represented by (a) RMP current, (b) MARS-F calculated response field. The symbols are experiment measured penetration thresholds, and the lines are fitted curves.

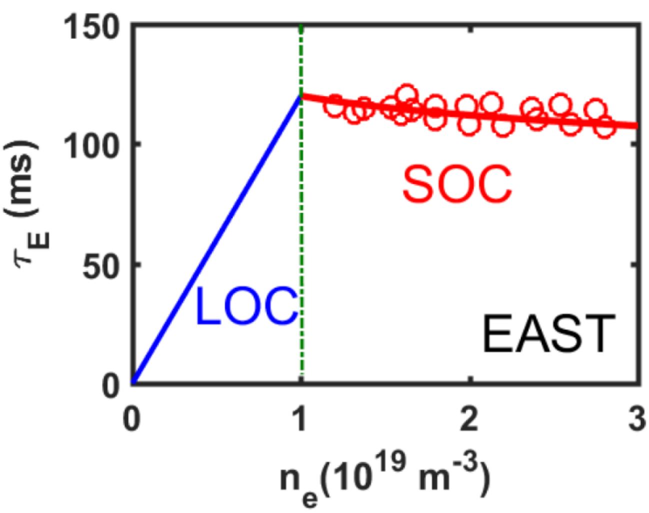

FIG. 2. Energy confinement time of error field penetration in ohmically heated plasmas in EAST.

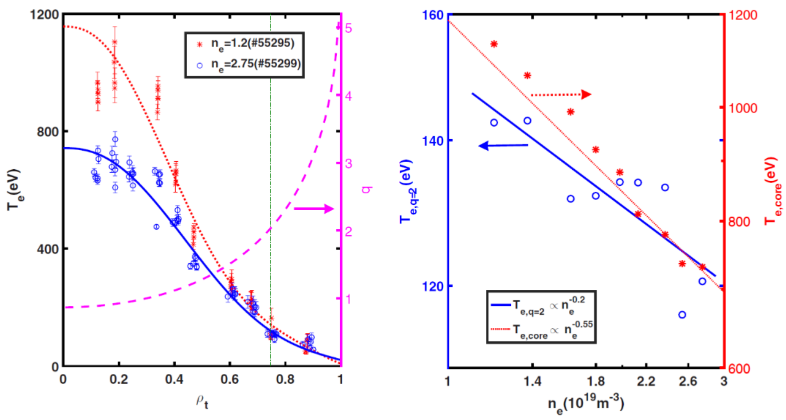

FIG. 3. Electron temperature comparison in two different density flattops. The symbols are the measured electron temperature from Thomson Scattering (TS) diagnostics. Left, the dotted and solid lines are the fitted profiles of electron temperature, whereas the dashed line is the q profile where cross point with the vertical line is q = 2 position. Right, the dotted and solid lines are the fitted curves of electron temperature in different densities at core and q = 2 surface, respectively.

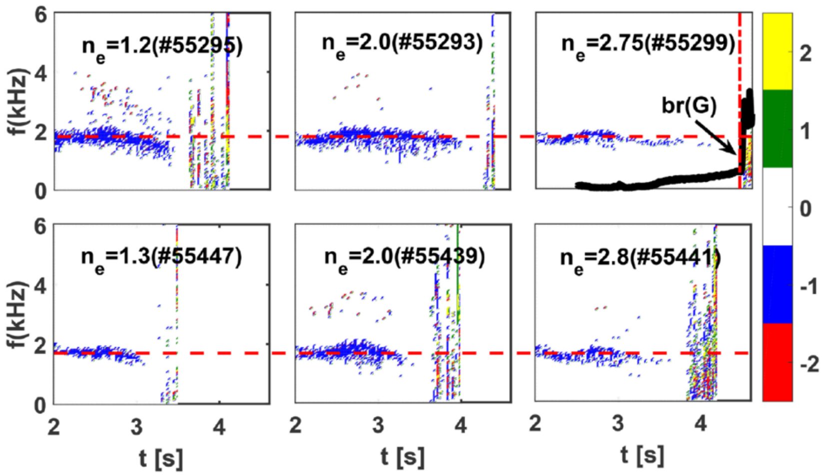

FIG. 4. Mode frequency comparison in different densities. The color bar represents the toroidal mode number. The black curve in upper right figure represents the radial magnetic perturbation of plasma response measured by saddle loops.

2.2. Density scaling in radio-frequency wave dominated heating plasmas

The density scaling of n = 1 error field penetration is investigated under radio-frequency (RF)-dominant heated L-mode discharges in the EAST tokamak. It is found that the density scaling of the threshold field strength for error field penetration in lower-hybrid current drive (LHCD) plasmas is about $b_r \propto n_e^{\,0.4}$ (FIG. 5), where br represents the error field amplitude. The results show a weaker density dependence compared to that observed in the previous ohmic heated discharges (Wang et al 2018 Nucl. Fusion 58 056024). For a better understanding of the density scaling, it is compared with field penetration theories, and it is found that it lies in the Waelbroeck regime. The observed scaling is consistent with that evaluated with the magnetohydrodynamic (MHD) theory on error field penetration, for which all the physical parameters are determined experimentally. Due to the density dependence of LHCD heating efficiency, the stronger negative correlation between density and temperature results in a weaker density scaling in these LHCD plasmas. Using realistic parameters under LHCD and ohmic heating as input, respectively, the numerical results based on a reduced MHD model reproduce well the scaling from the error field penetration theory and the observations. Besides, the density scaling in various tokamak operational regimes is also numerically investigated. This provides an excellent validation of MHD theory on error field penetration in the RF-dominant heated L-mode discharges.

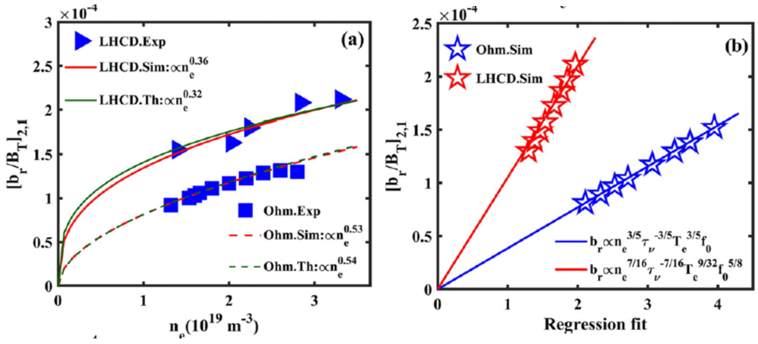

FIG. 5. (a) Comparison of the error field penetration scaling with density in experiment (blue scatter points), theory (green lines) and numerical modeling (red lines) in the ohmic (dashed lines) and LHCD (solid lines) plasmas. The variation of other parameters in the density scan used in theory and modeling are $T_e \propto n_e^{-0.2}$, $\tau_v \propto n_e^{-0.1}$, $f_0 \propto n_e^{0}$ for ohmic plasmas, and $T_e \propto n_e^{-0.65}$, $\tau_v \propto n_e^{-0.23}$, $f_0 \propto n_e^{-0.06}$ for LHCD plasmas, (b) the numerical critical penetration value $b_r/B_{T2,1}$ versus empirical scaling of the Rutherford (blue symbols) and Waelbroeck (red symbols) regimes, and the solid line represents the scaling expression of Rutherford (blue) and Waelbroeck (red).

3. TOROIDAL FIELD AND Q95 SCALINGS

Toroidal field and q_{95} scalings of error field penetration are investigated with n=1 resonant magnetic perturbation coil in EAST. The toroidal field scalings of error field penetration thresholds under fixed q_{95} are about $b_{r21}/B_T \propto B_T^{-1.0}$ in both ohmically and lower hybrid wave heated plasmas (FIG. 6), where b_{r21} is the vacuum error field at the q=2/1 rational surface and B_T is the toroidal field. These scalings indicate a favorable tolerance on error field in ITER. To make clear the underlying physics on toroidal field scaling, the theoretical analysis is given. By substituting penetration related scaling parameters into the theory (for example the Waelbroeck regime scaling $[b_r/B_T]_{crit} \propto [r_s^{11/8} s^{-7/8}] n_e^{7/16} \tau_V^{7/12} T_e^{7/12} f_0$, *where* r_s is rational surface radius and S is the magnetic shear*,* n_e *is the plasms density,* τ_V *is the momentum* diffusion time (similar with energy confinement time), T_e *is the electron temperature and* f_0 *is the mode rotation* frequency.), the obtained theoretical scalings are consistent with the experimental observations using the vacuum penetration thresholds (FIG. 7). To further investigate penetration threshold in larger operation region, the q_{95} scaling on penetration threshold with $b_{r21} \propto q_{95}^{1.66}$ has also been observed (FIG. 8). The rational surface radius r_s and magnetic shear s, which are crucial to q_{95} scaling, are included in the theoretical analysis. The theoretical analysis is also consistent with the experimental scalings using the vacuum penetration thresholds. Moreover, the obtained theoretical scalings are easy to compare with experimental scalings. These theoretical analyses will stimulate the extrapolation of error field tolerance towards future reactors.

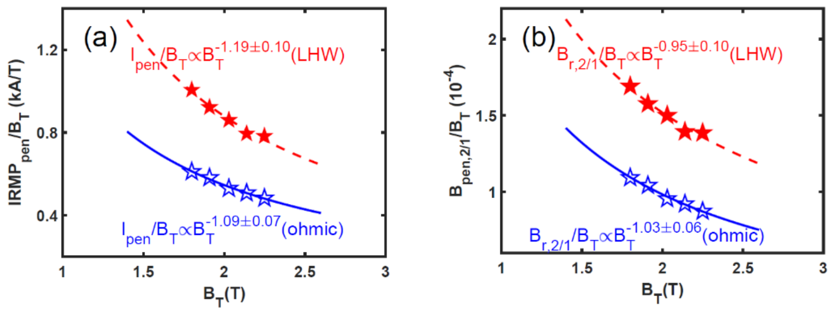

FIG. 6. Toroidal field scalings with (a) penetration threshold currents and (b) vacuum penetration thresholds at 2/1 resonant surface in ohmically heated (hollow blue symbols) and lower hybrid wave heated plasmas (solid red symbols).

4. ROTATION SCALING

An experiment was conducted to study the mode penetration of n = 1 resonant magnetic perturbation (RMP) in EAST under low neutral beam injection torque in the co-current direction (Co-NBI). The experimental results indicate that the threshold current $I_{RMP,th}$ for field penetration decreases with higher input torque T_{NBI}. Furthermore, it is observed that the plasma mode frequency $|f_{MHD}|$ at counter-current direction is greatly reduced when the plasma toroidal rotation frequency f_ϕ increases. The theoretical scaling of mode frequency ($I_{RMP,th} \propto |f_{MHD}|^{0.70}$) predicted by the field penetration theory is in good agreement with the experimental observation ($I_{RMP,th} \propto |f_{MHD}|^{0.53}$). The role of $|f_{MHD}|$ and f_ϕ on the mode onset threshold was separately investigated using the full toroidal

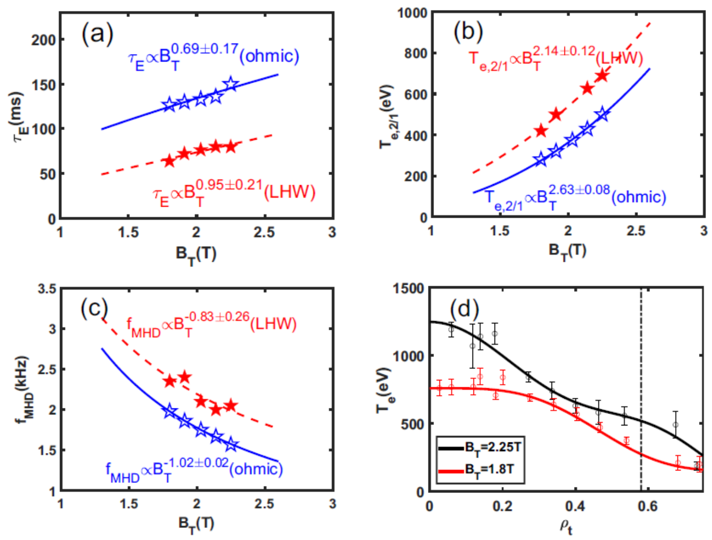

FIG. 7. Experimental scaling of (a) energy confinement time, (b) electron temperature at the 2/1 rational surface and (c) MHD mode frequency with toroidal field in ohmically heated (hollow blue symbols) and lower hybrid wave heated plasmas (solid red symbols) and (d) the sample profiles of electron temperature measured with Thomson scattering diagnostics. Note that the verticle line represents 2/1 rational surface.

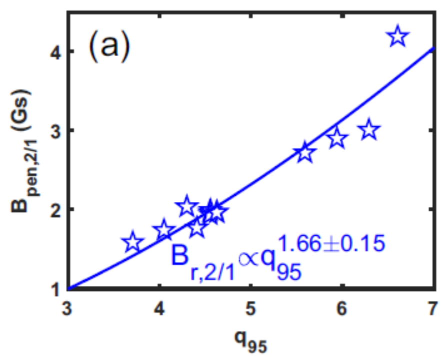

FIG. 8. Vacuum penetration threshold at the 2/1 rational surface scaling with q_{95} in ohmically heated plasmas.

geometry initial value code MARS-Q (Liu *et al* 2013 *Phys. Plasmas* **20** 042503). The numerical scaling based on the experimental mode frequency is consistent with the experimental and theoretical ones (FIG. 9). Numerical results suggest that evaluating the total mode frequency $|f_{MHD}|$ is crucial in field penetration analysis, in contrast to toroidal rotation frequency f_ϕ . With the increase of T_{NBI}, the decreasing $|f_{MHD}|$ leads to a reduction in the field penetration threshold. This suggests that more attention should be paid to error field tolerance in low Co-NBI torque scenarios, where the electron diamagnetic frequency may be canceled out by NBI-driven toroidal plasma rotation.

5. PLASMA BETA EFFECT

The plasma-beta effect on the n=1 resonant magnetic perturbation (RMP) field penetration in purely radio-frequency (RF) wave heated discharges has been investigated in EAST. The experimental results show that the dependence of the threshold RMP coil current for field penetration, $I_{RMP,th}$, on the total absorbed power P_{tot} scales as approximately $I_{RMP,th} \propto P_{tot}^{0.30}$ (FIG. 10), indicating that the error-field tolerance is improved with increasing RF power. This is benefited by the increased electron perpendicular flow dominated by a counter-current electron diamagnetic flow with increasing RF power. However, theoretical scaling in cylindrical geometry overestimates the power index. Assuming an additional term $\beta_N^{\alpha_{\beta N}}$ for the normalized beta in the scaling, it is shown that the fitted $\alpha_{\beta N}$ from the experimental observation is around −1, indicating a degradation effect of plasma beta. To clarify the underlying physics of the plasma-beta effect that was not included in the theoretical scaling in cylindrical geometry, the MARS-Q code with full toroidal geometry is employed for simulation of nonlinear field penetration (Liu *et al* 2013 *Phys. Plasmas* **20** 042503). The MARS-Q simulation results reproduce the β_N

dependence well, and hence the P_{tot} scaling of the threshold current in experimental observations (FIG. 11). The main reason for this is that the net total torque, which is mainly contributed by the neoclassical toroidal viscosity (NTV), increases with increasing plasma β_N (FIG. 11). The results demonstrate that the nonlinear toroidal coupling effect via NTV torque plays an important role in determining field penetration, even in cases with relatively low $\beta_N \in [0.3, 0.6]$, which is far less than the no-wall beta limit.

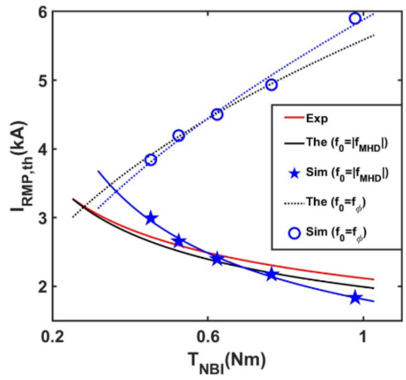

FIG. 9. Comparison of the scaling of penetration threshold with TNBI is shown for experimental results (red line), theory (black line) and simulation (blue line) at two distinct frequencies: $f_0 = |f_{MHD}|$ (solid line) and $f_0 = f_\phi$ (dashed line). Other plasma parameters, including n_e, T_e and τ_V, are varied using all experimental data. Numerical setup for $f_0 = |f_{MHD}|$ and $f_0 = f_\phi$ uses the experimental mode frequency f_{MHD} and toroidal rotation f_ϕ, respectively, to replace the plasma flow Ω in the MARS-Q model.

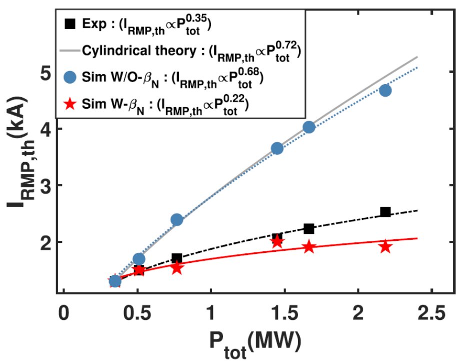

FIG. 10. Comparison of the n = 1 RMP penetration threshold current scaling on the heating power between experimental observation (black squares) and various theory and simulation results, including cylindrical theory (gray solid line), simulation without the β_N effect (cyan circles) and simulation with the β_N effect (red stars).

6. THE IMPLICATIONS FOR ITER

The classical error field penetration theory(Fitzpatrick98) is validated in a large range. This includes ohmically heated and lower auxiliary heated discharges. When β_N changes, the classical error field penetration theory is not suitable, and the non-resonant torque (NTV) should also be taken into consideration. And the physical process is also different from the classical EF penetration physics. It is confirmed that the mode frequency is the specific rotation scaling factor in EF penetration, not plasma rotation frequency. The significance in what ranges between the resonant amplification effect and non-resonant effect is still unclear.

7. SUMMARY

Parameter scalings on error field threshold for penetration physics have been carried out systematically. These include density scalings in ohmically and lower hybrid wave heated plasmas, toroidal field and q_{95} scalings in ohmically heated plasmas and toroidal field scaling in lower hybrid wave dominating heated plasmas. These experimental results have been analyzed with the classical theory in detail. These validated the application of classical error field penetration theory when considering the underlying assumptions, which give the resultant scaling results. When β_N changes, the classical error field penetration theory is not suitable, and the non-resonant torque (NTV) should also be taken into consideration. It is confirmed that the mode frequency is the specific rotation scaling factor in EF penetration, not plasma rotation frequency.

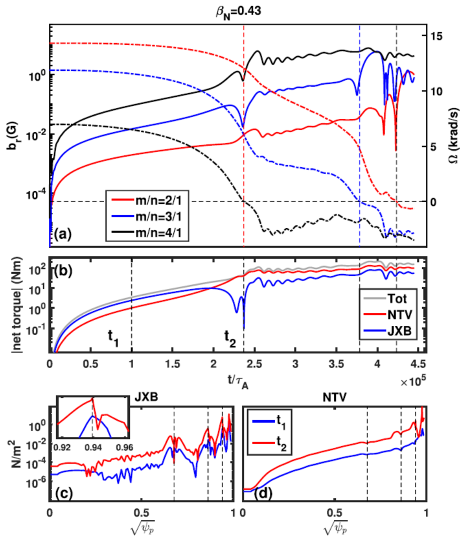

FIG. 11. (a) Simulated time traces of the perturbed radial magnetic field br (solid lines, left y-axis) and plasma rotation Ω at each rational surface (dash–dotted lines, right y-axis) for the m/n = 2/1 (red), m/n = 3/1 (blue) and m/n = 4/1 (black) resonant harmonics. The vertical dashed lines indicate the penetration moment. (b) Evolution of the net total torque, the electromagnetic torque and the NTV torque acting on the plasma with β_N = 0.43. Also shown are the simulated radial profiles of (c) the electromagnetic torque density and (d) the NTV torque density at two time slices, as marked in (b). The vertical dashed lines represent the position of rational surfaces.

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