

New Tokamak Plasma Confinement Regime Realized by Utilizing Small Magnetic Perturbations in the EAST Tokamak

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Achieving sustained high plasma confinement both in the core and at the edge, without crashes due to edge instabilities, is highly desirable for efficient fusion energy production in a tokamak device. However, control of edge instabilities usually results in core plasma confinement degradation. Here we demonstrate a new improved core confinement plasma regime in EAST, characterized by a sustainable internal transport barrier (ITB) and effective control of edge instabilities, both achieved by applying small resonant magnetic field perturbations (RMPs) at just 0.1% of the equilibrium field amplitude. The key is to localize the perturbations at the edge, which can be effectively realized by use of RMPs with high toroidal mode numbers. Nonlinear interaction between the perturbed magnetic fields and plasma, especially tungsten impurities, on different scales plays a key role in lowering the threshold heating power by a factor of 2 for triggering the formation of an ITB to improve core confinement. More importantly, the improved core confinement can be actively controlled by tuning the perturbed field profile. This provides an attractive method and a physical basis for an integrated solution of keeping high core confinement during edge stability control for a future fusion reactor.

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I. INTRODUCTION

Magnetically confined nuclear fusion, a possible solution for providing clean and safe energy, requires the achievement of high plasma confinement while avoiding dangerous crash events due to plasma instabilities [1]. The tokamak, which confines plasmas in nested tori formed by an axisymmetric magnetic field, is one of the most promising approaches for building a fusion reactor [2].

The success of tokamak experiments in the 20th century led to the building of a reactor-scale tokamak, ITER, in France by a global collaboration [3]. A state of sustainable high energy confinement both in the core and at the edge, characterized by the presence of an internal transport barrier (ITB) facilitated by reversed or flat magnetic shear profiles and an edge transport barrier (ETB), is highly desirable for a tokamak fusion reactor achieving high fusion gain and steady-state operation [4–7]. Meanwhile, a quiescent edge without crashes known as edge-localized modes (ELMs) [8] caused by the steep pressure gradient near the plasma edge due to the ETB is critical for safe operation to avoid harmful large transient heat loads on the plasma-facing components of the machine [9,10]. However, these are often contradictory objectives, i.e., controlling ELMs often degrades plasma confinement performance [10–12].

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Although an ITB can significantly enhance core plasma performance [13–17], it is more challenging to generate and sustain than an ETB [6] because of plasma current relaxation [14], instabilities [18], and impurity accumulation [18,19], which will be severer in a future fusion reactor with metal-plasma-facing components [20]. The underlying physics involves complex nonlinear phase transitions [21–23]. Although the suppression or mitigation of ELMs by resonant magnetic field perturbations (RMPs) with a nonaxisymmetric field strength on the order of 10^{-3} relative to the equilibrium field has been demonstrated in many tokamaks [10,12,24–29], it often causes a significant degradation of core plasma confinement, making it difficult to achieve high fusion gain in a future fusion reactor. One has to carefully choose the RMP field spectrum to optimize the control effect on the basis of its interaction with plasmas [11,30–34]. Because of complex coupling between core and edge physics at different scales, it has been unclear how to simultaneously achieve the improved core confinement and ELM suppression required for fusion reactors, up to now.

In this paper, we report the finding of a new tokamak plasma regime that simultaneously achieves improvement of core confinement with a sustainable ITB and suppression of ELMs using optimized edge-localized RMPs. It involves complex nonlinear coupling between edge and core plasma dynamics. More importantly, it differs from the ITBs observed in other devices, which typically form under specific initial conditions involving rapid current ramp-up and preheating [14–16]. Reproducing these conditions in future superconducting devices, such as ITER, is particularly challenging. The formation of an ITB in this experiment is reliable and insensitive to the initial conditions, and the ITB can be well-controlled (triggered and sustained or suppressed) by tuning the RMP field profile during a discharge. The key to effective ITB formation lies in generating sufficiently strong edge RMP fields while avoiding strong core RMP fields, a condition that high- n RMPs can readily achieve. It provides an attractive integrated solution for keeping high core confinement during edge stability control using small magnetic perturbations for a future fusion reactor.

II. ACCESSING A NEW REGIME WITH ITB FORMATION AND ELMS SUPPRESSION REALIZED BY RMPs IN EAST

EAST is a medium-sized superconducting tokamak with major radius $R_0 \approx 1.85$ m that started operation in 2006. It is equipped with a tungsten divertor and a molybdenum wall [35,36]. The RMP system in EAST [12,37] (Fig. 1), comprising two arrays of coils, is capable of generating RMP fields with a toroidal mode number n up to 4 (four periods along the toroidal direction), a configuration being considered for ELM control in ITER [38]. The two arrays

of coils provide the possibility to compose different RMP field profiles by changing the toroidal phase of the coil currents in the different arrays.

Recent experimental results in EAST demonstrated the advantage of using $n = 4$ RMPs, or even improvements in some cases, for core energy confinement during ELM suppression in an ELMy H-mode [39,40]. In these experiments, the plasma q_{95} range, where q_{95} denotes the safety factor at 95% of the poloidal magnetic flux, the input torque, and the RMP configurations were all similar to those in the ITER high fusion gain $Q = 10$ scenario [39,40]. The high- n RMPs are more localized near the plasma edge compared with the low- n ones (e.g., $n = 1$ and $n = 2$), as shown in Fig. 1. This limits the interaction of the 3D fields with the plasma to the edge region and provides an effective way to increase W outward flux and decrease the likelihood of core W accumulation [41,42]. This motivates us to study the detailed influence of RMPs on core plasma confinement.

Significant efforts have been made to optimize RMPs in terms of RMP mode number, RMP spectrum, and q_{95} —all of which are critical to the plasma response—in order to achieve this new regime with good ELM suppression and improvement of core plasma confinement in EAST. Figure 2 illustrates an example in EAST discharge 91548, in which this new regime is achieved during the application of RMPs. In this discharge, the toroidal field strength $B_T \approx 1.65$ T, $q_{95} \approx 3.7$, the normalized plasma $\beta \beta_N \approx 1.2$ – 1.6 , and the additional heating power is 1.8 MW of neutral beam injection (NBI) and 1 MW of lower hybrid wave (LHW), both kept constant throughout the application of $n = 4$ RMPs with opposite phase of the coil currents in the upper and lower coil arrays.

The general phenomena of density reduction and ELM suppression induced by RMPs are observed in this discharge, as shown in Figs. 2(a) and 2(b). Contrary to previous observations [12], a significant increase in stored

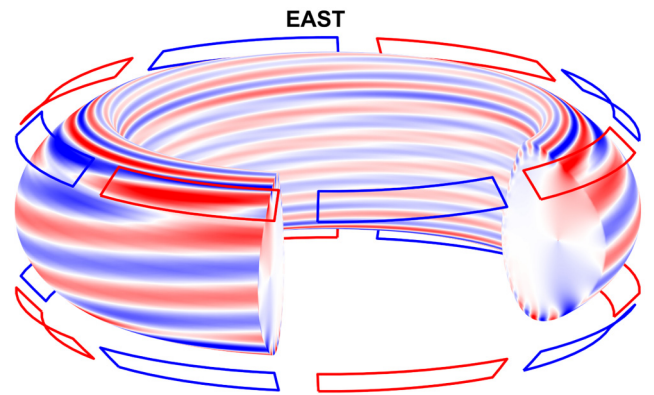


FIG. 1. EAST RMP coils and fields. Shown here is an $n = 4$ odd-parity (opposite current in upper and lower coils) RMP coil configuration to generate edge-localized magnetic perturbations.

energy is noted during the RMP ELM suppression phase, as illustrated in Fig. 2(b). The formation of an ion ITB (transport barrier in the ion thermal transport channel with a steep gradient in the ion temperature profile) at the normalized radius ρ of approximately 0.25 during the application of RMPs is crucial for the improvement in confinement, as shown by the red line of the ion temperature profile T_i in Figs. 2(b) and 2(f). The transition to the ion-ITB regime appears after the RMP application, as seen in the abrupt increases in the core T_i at $t \approx 4.8$ s in Fig. 2(d), while the edge T_i at $\rho \approx 0.75$ remains almost constant. As shown in Figs. 2(c) and 2(e), the core toroidal rotation increases simultaneously, and its profile exhibits a

similar ITB structure. This phenomenon is a common feature of ion-ITB formation in this regime and can be used to identify ITB formation. More importantly, the ITB can be sustained during the application of RMPs in the later phase, which is around 4 times the current diffusion time in EAST and is limited only by technical constraints. The plasma density is also increased during the ITB phase, as shown in Fig. 2(b). As soon as the RMPs are terminated, the ITB collapses and the stored energy decreases with a short time delay. The RMPs can effectively reduce the W impurity concentration, even in the presence of ELM suppression and ITB formation, as shown in Fig. 2(a). Here, the unresolved transition array (UTA) from the 45–65 Å

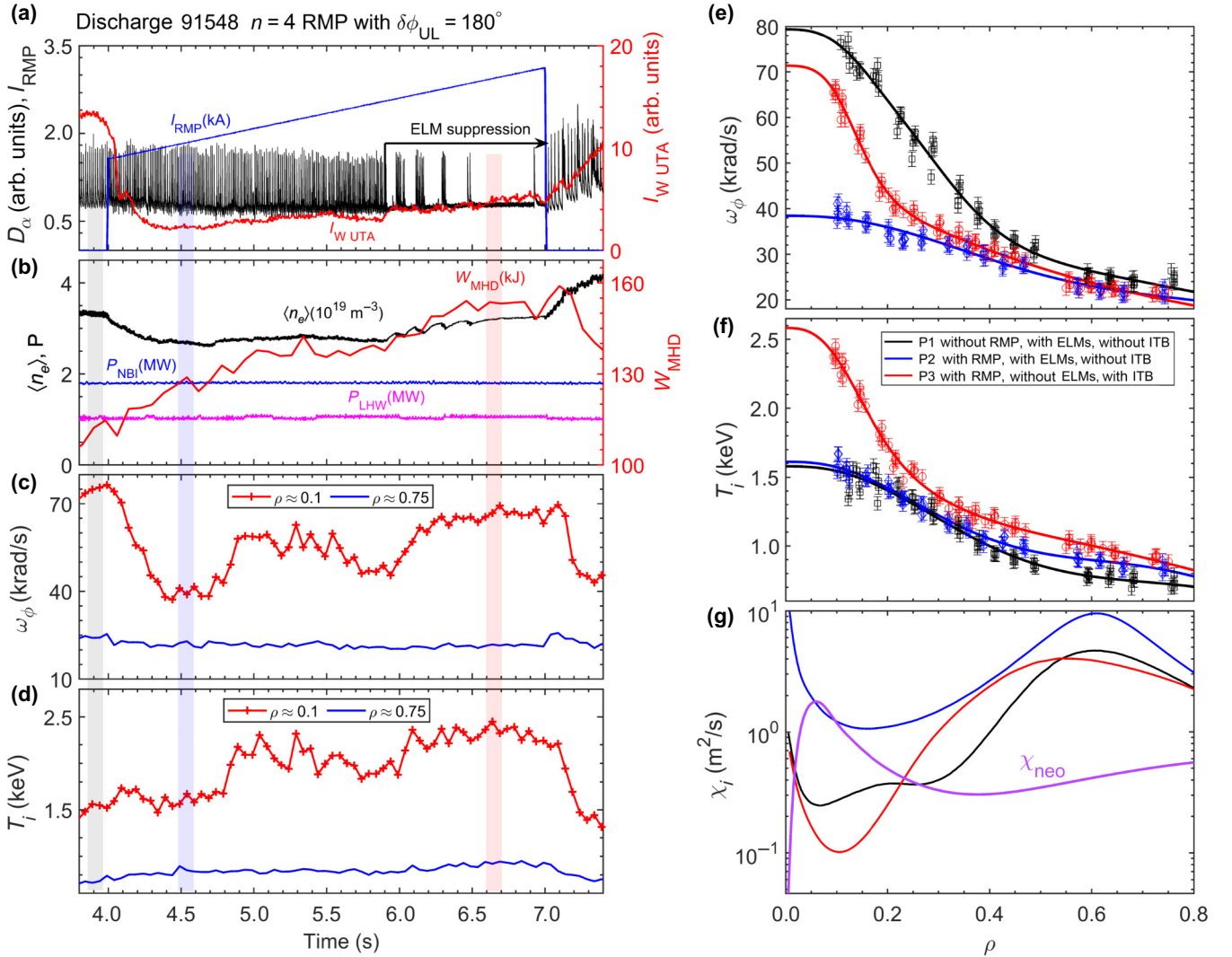


FIG. 2. (a) Temporal evolution of Balmer- α emission of deuterium D_α (black), intensity of the tungsten unresolved transition array in the 45–65 Å wavelength range $I_{W\text{UTA}}$ (red), and RMP coil current I_{RMP} (blue). (b) Line-averaged density $\langle n_e \rangle$ (black), stored energy W_{MHD} (red), NBI power (blue), and LHW power (magenta). (c) Toroidal rotation ω_ϕ at $\rho \approx 0.1$ (red) and $\rho \approx 0.75$ (blue). (d) Ion temperature T_i at $\rho \approx 0.1$ (red) and $\rho \approx 0.75$ (blue). Radial profiles of (e) the toroidal rotation ω_ϕ , (f) the ion temperature, and (g) the ion thermal diffusivity χ_i at three different phases indicated by shaded regions in the left subgraphs, i.e., before RMP application with W accumulation (phase 1, black), with RMP application before ITB formation (phase 2, blue), and with RMP application and the ion ITB (phase 3, red). The purple line represents the neoclassical level of the ion thermal transport.

wavelength range in EAST is composed primarily of W^{26+} to W^{45+} ions and is commonly used to characterize the behavior of the W impurity in the plasma core. These results prove that RMPs can induce and maintain the ITB in this regime compatible with ELM suppression and W impurity control.

To further demonstrate that the formation of the ion ITB with the use of RMPs is beneficial to the energy confinement, Fig. 3 compares the differences in density and stored energy with and without an ion ITB under RMP application. The databases are from H-mode plasmas with

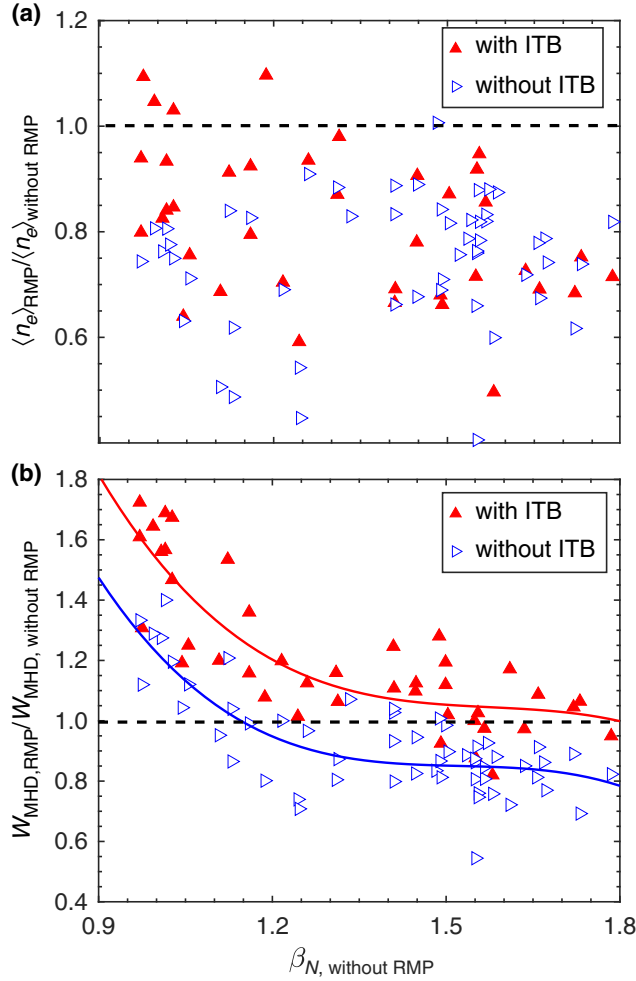


FIG. 3. Relative changes of (a) plasma density and (b) stored energy with the ion ITB (red) and without the ion ITB (blue) during the application of RMPs normalized to the values without RMPs vs β_N . Here $\beta_N = \beta a B_T / I_p$ is the normalized pressure, where β is the ratio of the plasma pressure to the magnetic field pressure, a is the plasma minor radius, B_T is the toroidal magnetic field, and I_p is the plasma current. The data are derived from 56 discharges, with no more than three time slices selected from each discharge. The parameters at the selected time need to remain constant for at least 0.1 s, which is twice the energy confinement time on EAST. The criteria for identifying the ion ITB are described in Appendix A 4.

application of $n = 1$ –4 RMPs and similar heating methods and power in experiments from 2016 to 2019. It is obvious that the stored energy in the ITB regime is about 20% higher than that in the absence of an ITB, as shown in Fig. 3(b). Moreover, the stored energy with RMP application can be higher than that without RMPs, despite the density pump-out caused by RMPs, as shown in Fig. 3(a). These statistics indicate that not only do the RMPs not cause a reduction in energy confinement, but that they are also beneficial to energy confinement due to ITB formation and impurity concentration reduction.

Another promising result in this regime is that the threshold heating power for ITB formation during the application of RMPs is significantly lower than that without RMP application. As shown in Fig. 4, the threshold for ITB formation in EAST without RMPs requires a power input of more than 3.5 MW and is consistent with the ITER Tokamak Physics Activities (ITPA) scaling law [5,43,44]. The ITPA scaling law for the ion-ITB power threshold is given by $P_{\text{thre}} = 3.14 n_{19}^{0.9} a^{2.13} k_{95}^{1.34} (0.2 + \delta_{95})^{-0.15} B_T^{0.23}$. The units of the line-averaged electron density n_e and toroidal field B_T are 10^{19} m^{-3} and teslas, respectively. In this expression, k_{95} and δ_{95} represent the elongation and triangularity of the plasma cross section at 95% of the poloidal magnetic flux surface, and a denotes the tokamak minor radius in meters. The power P_{loss} is calculated by the equation $P_{\text{loss}} = P_{\text{abs}} + P_{\text{OH}} - dW_{\text{MHD}}/dt$, where P_{abs} is the absorbed heating power, P_{OH} is the Ohmic heating power, and dW_{MHD}/dt is the change rate of stored energy. Because of the small differences in the injected power but the large range of densities among these discharges, the variation in P_{loss} is minimal, while the range of P_{thre} is wide.

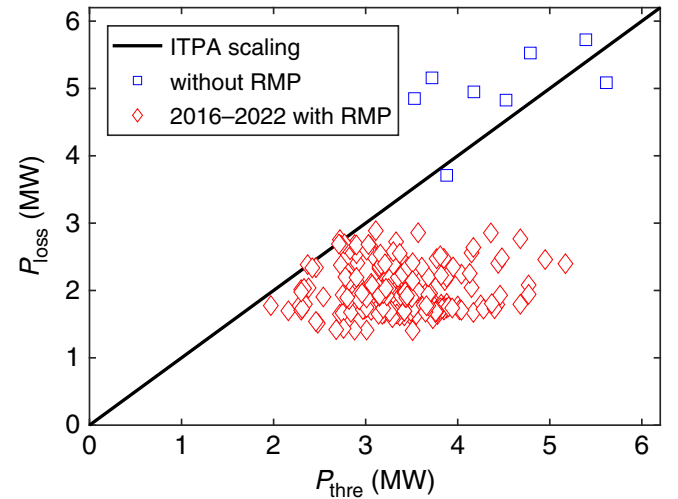


FIG. 4. Demonstration of beneficial effects from RMPs (red diamonds) on lowering the threshold heating power for accessing the ITB regime, compared with cases without RMPs (blue squares).

The encouraging results shown by the red diamonds indicate that the power threshold for ITB formation is significantly reduced with RMP application. The minimum power required for ITB formation with RMPs is approximately 1.4 MW, which is less than half of the threshold without RMP application or that from the ITPA prediction, as shown in Fig. 4. A plausible explanation for this beneficial effect is the significant reduction in core W impurity concentration induced by RMPs [42]. These findings illustrate the beneficial role of RMPs in facilitating ITB formation.

III. UNDERSTANDING OF THE ITB FORMATION TRIGGERED BY RMPs

The formation of the ion ITB induced by RMPs involves complex nonlinear coupling between edge and core plasma dynamics at different scales. A schematic overview of the dynamic loop for ITB formation induced by RMPs is illustrated in Fig. 5. Because of the poor quality of the q_0 signal from discharge 91548, discharges 91471 and 91466, which exhibit similar characteristics, are depicted in Fig. 5. To further enhance the credibility of this process, discharge 80640, from a different campaign, is also shown in Figs. 5(d) and 5(e). The plasma conditions in discharges

91466 and 91471 are similar to those in discharge 91548, except for the RMP configurations and the time of RMP application. The current of $n = 4$ RMPs is fixed at 3 kA with phase differences $\delta\phi_{UL} = 0^\circ$ for discharge 91466 and $\delta\phi_{UL} = 180^\circ$ for discharge 91471. The plasma density in discharge 80640 is lower than that in discharge 91548, and $n = 3$ RMPs with $\delta\phi_{UL} = 0^\circ$ are adopted. q_{95} and the heating power of discharge 80640 are similar to those of discharge 91548. There is a positive feedback loop, i.e., self-organization process, in the core plasma dynamics that finally triggers the formation of an ITB with enhanced core plasma confinement, as shown in Fig. 5(a). The change of core confinement links strongly to the reduction of core W concentration, which results mainly from the edge transport effects due to the application of RMPs, as shown in Fig. 5(b).

The ITB forms when the minimum safety factor approaches unity with a weak reversed magnetic shear, similar to previous observations in the other machines, in which ITB formation has been found to be associated with low-order rational surfaces [13, 17, 45–47]. After the application of RMPs, as illustrated in Figs. 5(c)–5(e), there is a significant reduction in W concentration in the plasma core, which results in an increase of the core electron temperature, and hence changes the current density profile

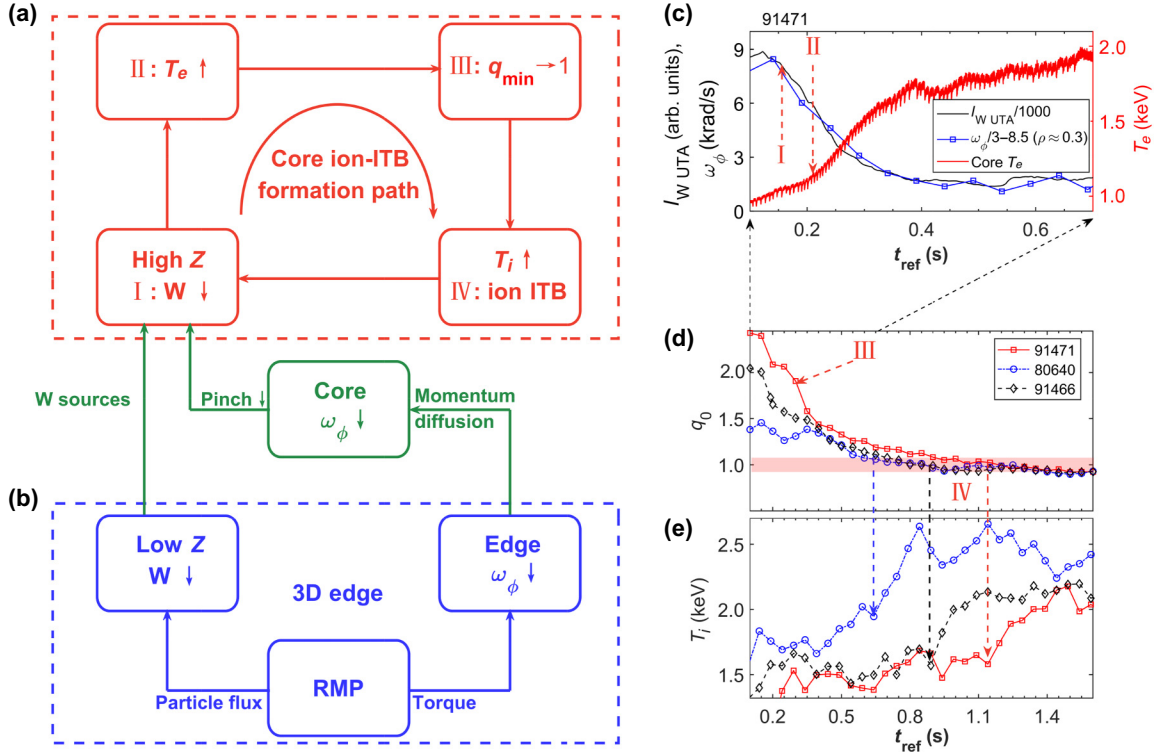


FIG. 5. Dynamic loop for (a) ITB formation in the plasma core and (b) transport effects induced by RMPs near the plasma edge. (c) Temporal evolution of the emission intensity of the tungsten unresolved transition array in the 45–65 Å wavelength range $I_{W\ UTA}$ (black line), ω_ϕ at $\rho \approx 0.3$ (blue square line), and core electron temperature T_e (red line) in EAST discharge 91471. Evolution of (d) the safety factor at the axis q_0 and (e) T_i near the plasma core in EAST discharges 91471 (red square line), 80640 (blue circle line), and 91466 (black diamond line) after the application of RMPs at $t_{ref} = 0$.

or equivalently safety factor profile as indicated in the evolution of the safety factor at the magnetic axis, q_0 . There is a time delay for the ITB formation after the application of RMPs, as shown in Figs. 5(e) and 2(d). The duration of the delay is determined by the relaxation of the plasma current until q_0 approaches 1, as shown in Figs. 5(d) and 5(e). Among the three discharges, the higher initial q_0 requires a longer time delay to access the ITB after the application of RMPs. After the formation of the ITB, the appearance of fishbones, which are not necessary for the ITB formation, also supports the view that the minimum safety factor is approaching unity. The plasma current relaxation and redistribution are caused by increasing electron temperatures, resulting in increases in Ohmic current, bootstrap current, and NBI-driven current in the core region. The weak reversed magnetic shear near the plasma core is mainly due to the bootstrap current and the NBI-driven current during the application of RMPs, while it is mainly due to the high core radiation associated with W impurity accumulation in the plasma core in the phase before the RMP application. The ITB foot in our cases is near the minimal q , i.e., $q = 1$ surface. After the enhancement of core confinement, the increased T_i gradient can further increase the shielding effects on the W impurity from the outside. This positive feedback loop triggers the formation of the ITB in the plasma core. The ion thermal diffusivity χ_i in the core drops dramatically with the ITB formation and is significantly lower than the neoclassical level [14] [Fig. 2(g)].

The reduction of the core W impurity concentration, which enables the plasma to enter the loop for ITB formation, is due to the enhanced edge transport induced by RMPs. Before the ITB formation, the plasma enters a phase characterized by reduced core toroidal rotation and low W impurity levels (phase 2 shown in Fig. 2). The core W impurity accumulation is strongly correlated with core plasma rotation, as shown in Fig. 5(c), because of neoclassical impurity pinch effects [42,48]. Because of the strong coupling between the W impurity and rotation in the core region, both the additional torque and the W particle flux induced by RMPs contribute to the reduction of the W impurity concentration [42]. As shown in Fig. 6(a), the edge rotation decreases almost immediately after application of the RMPs, whereas core rotation and W concentration decrease after a short delay of several hundred milliseconds. This observation is supported by the simulations with NTVOK [49], revealing that the neoclassical toroidal viscosity (NTV) exerts its peak torque and W flux predominantly in the edge region, as shown in Fig. 6(b). This is a consequence of the three-dimensional (3D) fields induced by the high- n RMPs being localized at the edge. Here, the W flux induced by RMPs is mainly on the low charge state one near the edge [41,42]. The effective particle diffusion coefficient D_{eff} is defined as $D_{\text{eff}} = a\Gamma_{\text{NTV}}^{\text{W}}/n_{\text{W}}$, where a is the minor radius, $\Gamma_{\text{NTV}}^{\text{W}}$ is

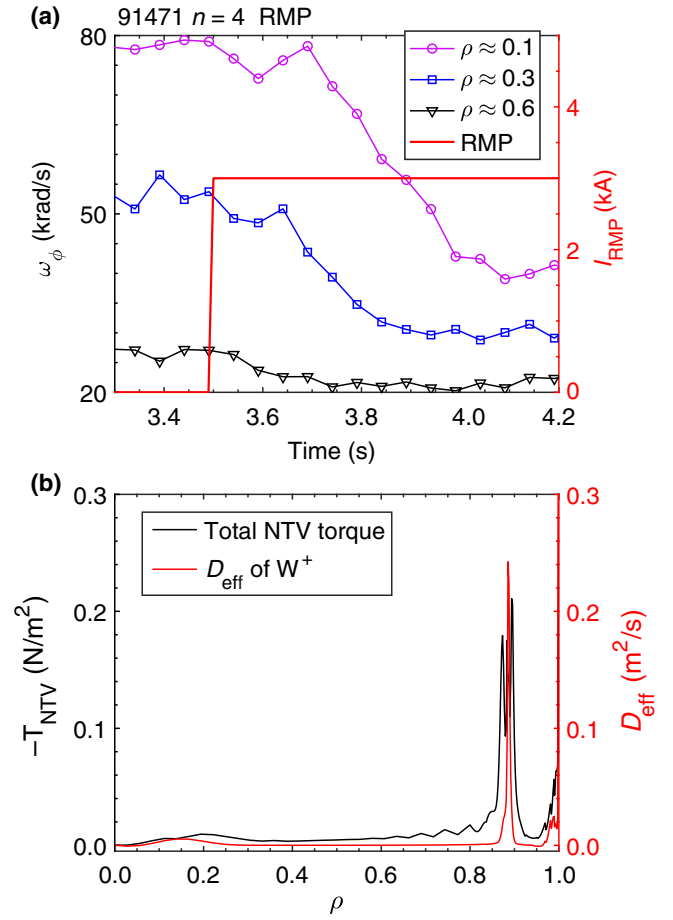


FIG. 6. (a) Evolution of the rotation at different radii after the application of RMPs. (b) Radial profile of the NTV torque and effective particle diffusion coefficient D_{eff} of W^+ induced by RMPs.

the NTV flux of W, and n_{W} is the density of W. The 3D transport effects induced by RMPs also provide a beneficial condition for sustaining a stable ITB during the application of RMPs. This result demonstrates a strong nonlinear coupling between the core and edge plasma dynamics, in which localized small perturbations at the edge can significantly modify the core confinement state via cross-scale processes.

IV. ACTIVE CONTROL OF THE ITB USING RMPs

The ITB can not only be induced and maintained by RMPs but can also be actively controlled by adjustment of the RMP profile. The response of the ITB to different RMP configurations is illustrated in Fig. 7. All of the $n = 1-4$ RMPs can be applied for triggering and sustaining ITBs. In Fig. 7, q_{95} in discharge 71217 is about 4, and other plasma parameters are similar to those for discharge 91548. q_{95} for discharges 79024 and 79029 is slightly lower than that for discharge 91548, and the NBI power for them is about 2.4

MW. The density and NBI power are slightly higher for discharge 102490 than for discharge 91548.

For the low- n (1, 2) RMPs, the ITB cannot form within the core resonant RMP spectrum due to strong 3D fields in the core region. Figure 7(a) illustrates the application of $n = 1$ RMPs with a two-period phasing $\delta\phi_{UL}$ scan ranging from 0 to 2π , showing a clear dependence of the ITBs on the RMP spectrum. The ITB is triggered at the core nonresonant phasing ($\delta\phi_{UL} \in [160^\circ, 310^\circ]$) and collapses at the core resonant phasing ($\delta\phi_{UL} \in [-50^\circ, 160^\circ]$), which has a strong core harmonic, based on the modeling results obtained with MARS-F [30]. Similar results are also observed in the case of $n = 2$ RMPs. As shown in Fig. 7(c), the ITB can be formed in discharge 79029 with the core nonresonant spectrum $\delta\phi_{UL} = 0^\circ$. In the core resonant spectrum case in discharge 79024 with $\delta\phi_{UL} = 180^\circ$, the ITB also forms at about 4.7 s, while it is terminated when the current of the $n = 2$ RMPs exceeds about 2 kA. This means that one has to choose carefully the spectrum and

amplitude of low- n RMPs for triggering and sustaining ITBs.

The 3D fields produced by high- n (3, 4) RMPs are generally localized in the edge region, which is beneficial for ITB formation [Fig. 8(a)]. This is why ITBs form more easily in experiments using high- n RMPs. As shown in Fig. 7(d), the ITB fails to form during the initial $n = 2$ RMP phase, but it forms and is sustained throughout the phase with $n = 4$ RMPs. In the final $n = 2$ phase, the ITB begins to form, but collapses when the RMP current exceeds a threshold for penetration of core resonant harmonic perturbations. Reproducible ITB formation and sustaining by use of $n = 3$ RMPs has also been achieved in EAST, as shown in Fig. 7(e).

To further demonstrate the impact of different RMPs on the ITB, the RMP profiles modeled by MARS-F are shown in Fig. 8. For the $n = 4$ RMP and nonresonant low- n RMP, the magnetic perturbations are localized in the edge region, which is beneficial for ITB formation. However, the ITB

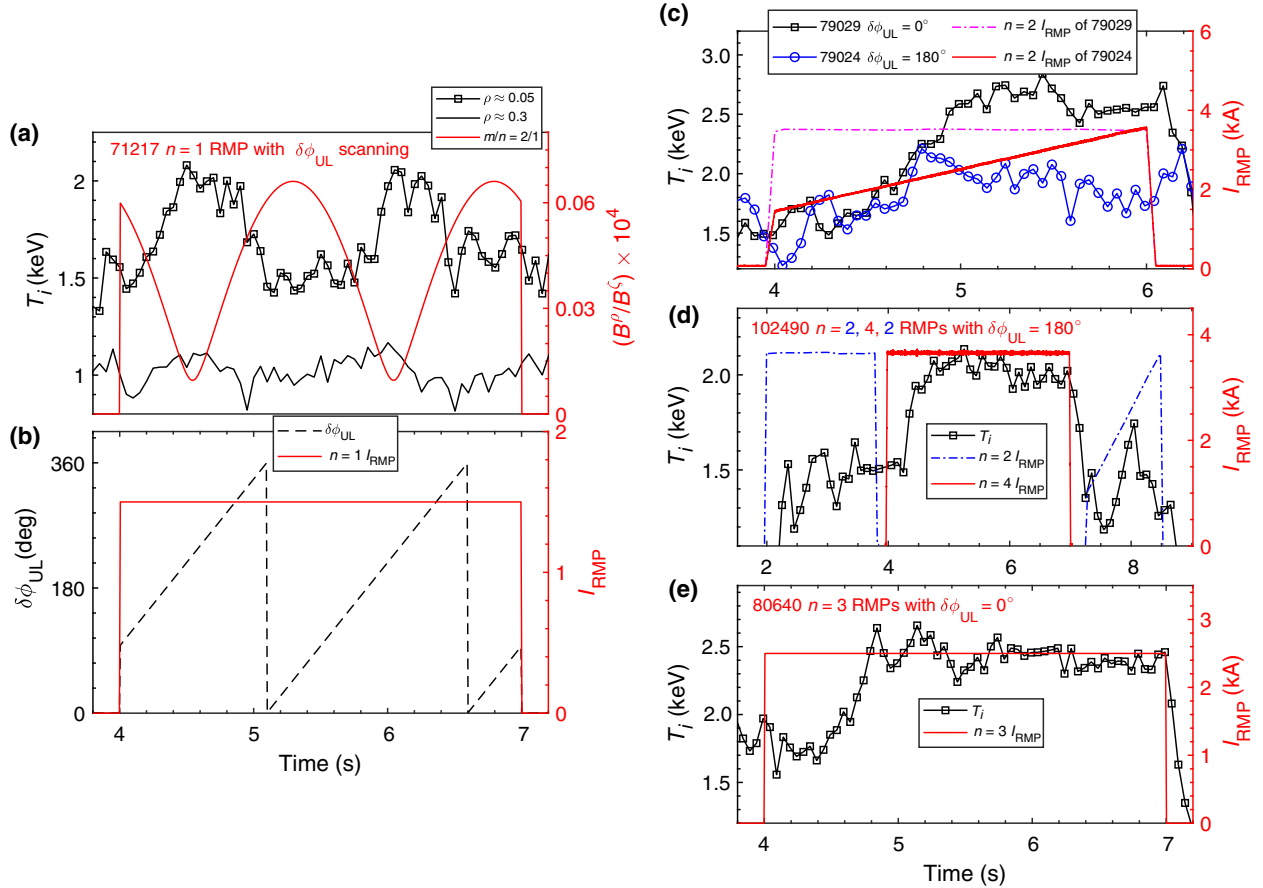


FIG. 7. (a) Temporal evolution of the core T_i (black squares), T_i outside the ITB (solid black line), and the $m/n = 2/1$ component of the RMPs modeled by MARS-F, as well as (b) the phasing (dashed black line) and amplitude (solid red line) of the $n = 1$ RMP coil current in EAST discharge 71217. (c) Temporal evolution of the core T_i in EAST discharges 79029 ($\delta\phi_{UL} = 0^\circ$, black square line) and 79024 ($\delta\phi_{UL} = 180^\circ$, blue circle line) with $n = 2$ RMP application. (d) Temporal evolution of the core T_i (black square line) in EAST discharge 102490 with $n = 2$ (dashed blue line) and $n = 4$ (solid red line) RMPs applied at different time windows. (e) ITB formation by application of $n = 3$ RMPs in EAST discharge 80640.

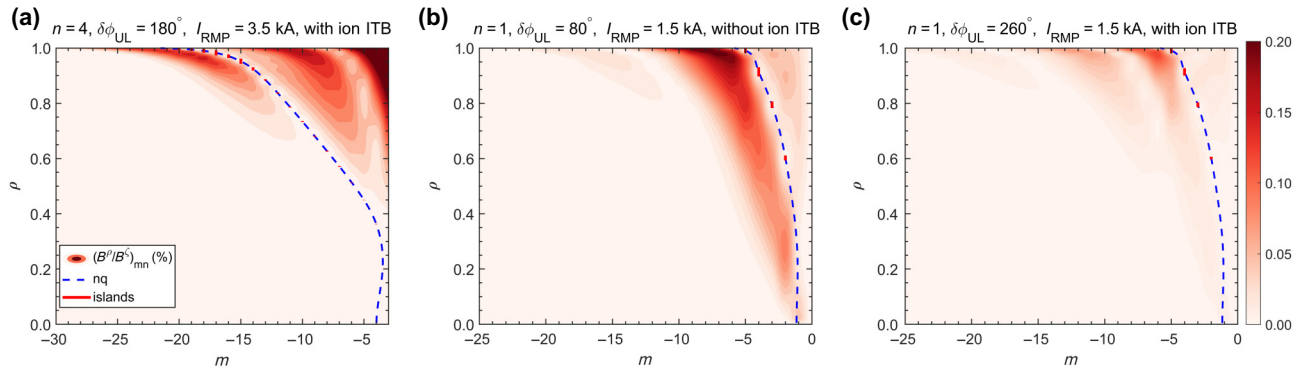


FIG. 8. Modeled (a) $n = 4$ magnetic perturbation spectrum obtained with MARS-F for EAST discharge 91548 with $\delta\phi_{UL} = 180^\circ$ and (b),(c) $n = 1$ magnetic perturbation spectra for discharge 71217 with (b) $\delta\phi_{UL} = 80^\circ$ and (c) $\delta\phi_{UL} = 260^\circ$. For the $n = 1$ RMPs, the ion ITB cannot form in the core resonant phasing $\delta\phi_{UL} = 80^\circ$.

cannot be formed in the presence of strong core magnetic perturbations from RMPs, as shown in Fig. 8(b). These results indicate that 3D fields in the core region are detrimental to the ITB, while the 3D fields localized in the edge region are necessary for the formation and sustaining of the ITB. Therefore, more edge-localized perturbations are better for triggering and sustaining a reliable ITB. This highlights the benefits of ELM control using high- n RMPs, which may contribute to achieving enhanced plasma performance by dealing with W accumulation in future fusion devices, e.g., ITER.

The above findings also demonstrate that ITB formation with the use of RMPs in this regime is insensitive to the initial state of the plasma. The spontaneous formation of an ITB induced by RMPs here differs from the conventional approach, which relies on substantial power injection at low density [13] or preheating during the plasma current ramp-up phase [14]. The periodic triggering and suppression of the ITB during the continuous RMP spectrum scan, as shown in Fig. 7(a), demonstrate that the formation of the ITB with the use of RMPs is highly robust and does not appear to require specialized techniques to control the initial profiles. The ITB can form repeatedly and reliably with the use of RMPs, even after periods of disappearance. This demonstrates another advantage of this method by using RMPs to improve the core confinement with W-plasma-facing components.

V. CONCLUSIONS

The new regime discussed in this paper may be applicable for ITER, where the high- n RMPs will be applied to control ELMs. Compared with previous results in other machines, where RMPs often cause deterioration in plasma confinement, the promising results in EAST indicate that high- n RMPs may reliably improve plasma confinement

by avoiding W accumulation and forming the ITB during RMP ELM suppression. More importantly, the ITB can be formed with this method without special techniques to control the initial profiles. This suggests that RMPs can be a useful and adaptable method for integrated control of both edge and core plasma performance in future tokamak fusion devices. The further optimization of this scenario at high β_N will be the focus of future studies for ITER applications.

This work opens a new area of research on complex nonlinear dynamics of plasmas in tokamaks with 3D fields and provides a new method for studying ITB physics.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: METHODS

1. EAST and RMP system

EAST is a medium-sized tokamak with a major radius of 1.85 m and a minor radius of 0.5 m. The W divertor has been installed, and the graphite guard limiters of the LHW antenna have been replaced by W. The RMP system in EAST has two arrays of coils with up and down symmetry located at the upper and lower parts of the last closed flux surface on the low-field side, as shown in Fig. 1. The RMP coils are made of conventional copper conductors. They can generate RMPs with toroidal mode numbers n up to 4, which will be used for ELM control in ITER. Full ELM suppression using $n = 4$ RMPs has been demonstrated in EAST [39].

2. Experimental conditions

The experimental conditions for ITB formation are much less strict with the specific RMPs. There is no requirement for preheating during the plasma current ramp-up phase, and the formation of the ion ITB in this regime is insensitive to the timing of the RMP application. Therefore, the formation of the ion ITB in this regime is highly reproducible and predictable with the use of RMPs. The plasma parameters of the discharges discussed in this paper are presented in Table I. The new plasma regime with the ion ITB has been realized across a wide range of plasma conditions, including both upper and lower single null configurations. The discharges discussed in this paper are heated by co-current NBI and LHW. The line-averaged density can currently reach up to $0.53n_G$ (Greenwald density limit). The ion ITB can be formed within the q_{95} window from 3 to 4.5, and no clear dependence of the ion ITB on q_{95} is observed within this window. Experiments have shown that the windows can be widened with higher injected power.

3. Description of experimental measurements

Throughout this work, the ion temperature and toroidal rotation are measured by charge exchange recombination spectroscopy (CXRS) measurements. The radial range of ion temperature and toroidal rotation measured by CXRS in these discharges is within $\rho = 0.8$. In these discharges,

the uncertainties associated with the measurements of rotation and ion temperature by CXRS are less than $\pm 5\%$. The evolution of the core electron temperature is determined through a combined analysis of electron cyclotron emission and Thomson scattering; the profile of the electron temperature is obtained from Thomson scattering. The density profiles are derived from a combined analysis of reflectometer and polarimeter-interferometer data. The density error of the reflectometer is $\pm 0.01 \times 10^{19} \text{ m}^{-3}$. The relative profiles of the W impurity are measured by extreme ultraviolet (EUV) spectrometers. The space-resolved EUV spectrometer covers a vertical range of $-8.5 \text{ cm} \leq Z \leq 40 \text{ cm}$ with a spatial resolution ΔZ of 2.5 cm and a temporal resolution of 20 ms per frame. The temporal resolution of the fast EUV spectrometer is 5 ms per frame. In the calculation of the ITPA threshold power of the ITB P_{thre} , the plasma parameters at the selected moment should remain stable for at least 0.1 s, which is approximately twice the energy confinement time. The plasma parameters are averaged over this 0.1-s interval. The error in calculation of P_{loss} is within 10%. It should be noted that the data selected are from discharges with an established ion ITB, rather than those near the formation of an ion ITB. Therefore, the required power for ion-ITB formation in this regime should be even lower than P_{loss} .

4. Determination of ITB formation

ITB formation in this regime is clear with many plasma parameters changing abruptly at the time of the ITB transition. The ion temperature and toroidal rotation inside the ITB increase abruptly, while they remain almost constant outside the ITB. The core soft x-ray and absolute extreme ultraviolet increase abruptly upon ITB formation. The scale length of the ion temperature decreases upon ITB formation, and the ion thermal diffusivity is reduced below the neoclassical level [14].

5. Power balance analysis and equilibrium reconstruction

The transport code ONETWO [50], incorporating NUBEAM [51] and CQL3D [52] plus GENRAY [53], is used for power

TABLE I. Discharge parameters for ITB discharges with the use of RMPs described in the main text.

Discharge number	Time (s)	RMP configuration	Heating power (MW)	B_T (T)	q_{95}	n_e (10^{19} m^{-3})
91548	6.6	$n = 4, \delta\phi_{UL} = 180^\circ$	$P_{\text{NBI}} \approx 1.8, P_{\text{LHW}} \approx 1$	1.65	3.71	3.18
91471	6.5	$n = 4, \delta\phi_{UL} = 180^\circ$	$P_{\text{NBI}} \approx 1.8, P_{\text{LHW}} \approx 1$	1.65	3.71	3.42
91466	6.5	$n = 4, \delta\phi_{UL} = 0^\circ$	$P_{\text{NBI}} \approx 1.8, P_{\text{LHW}} \approx 1$	1.65	3.73	3.65
102490	6.8	$n = 4, \delta\phi_{UL} = 180^\circ$	$P_{\text{NBI}} \approx 2, P_{\text{LHW}} \approx 1$	1.72	3.43	3.51
80640	6.4	$n = 3, \delta\phi_{UL} = 0^\circ$	$P_{\text{NBI}} \approx 2, P_{\text{LHW}} \approx 0.8$	1.65	3.73	2.4
79029	5.9	$n = 2, \delta\phi_{UL} = 0^\circ$	$P_{\text{NBI}} \approx 2.4, P_{\text{LHW}} \approx 1$	1.53	3.71	2.8
71217	4.65	$n = 1, \delta\phi_{UL} = 260^\circ$	$P_{\text{NBI}} \approx 1.75, P_{\text{LHW}} \approx 1.4$	1.65	3.95	3.35

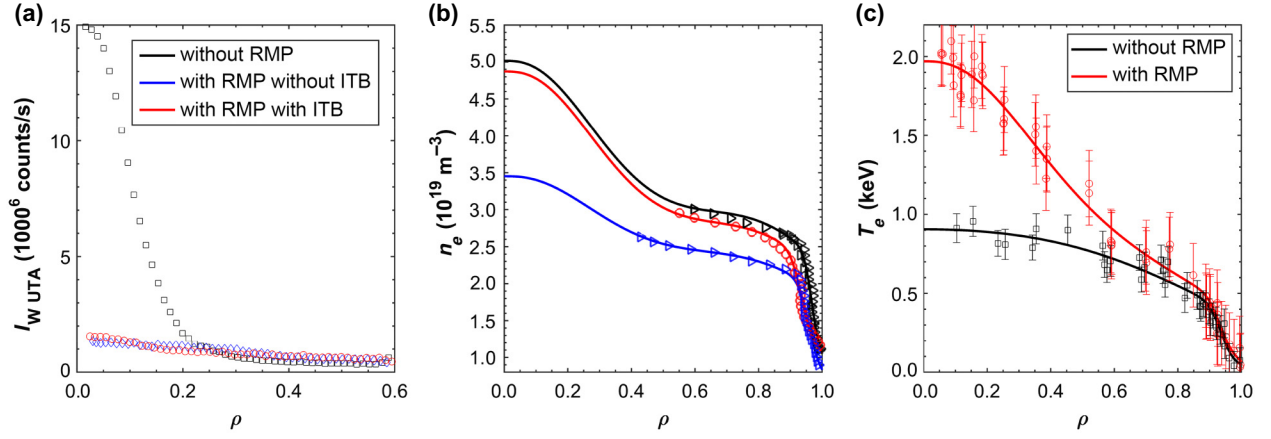


FIG. 9. Measured radial profiles of (a) $I_{W UTA}$, (b) electron density, and (c) electron temperature measured by Thomson scattering. The impurity density is from discharge 80640, and the electron density and temperature are from discharge 91548. The edge data for density are obtained from reflectometer measurements, and the core data are reconstructed with constraints from the polarimeter-interferometer. Because of limitations in diagnostic resolution and uncertainties, combined with the minimal change in electron temperature before and after ITB formation, the electron temperature profiles before and after ITB formation are not presented.

balance analysis. The current drive by NBI is calculated with NUBEAM [51], and the current drive by LHW is calculated with CQL3D [52] plus GENRAY [53]. The equilibrium is reconstructed by k-EFIT, constrained by polarimeter-interferometer data and magnetic and pressure profiles, and calibrated with sawtooth and fishbone observations.

6. Modeling of plasma response and NTV

The plasma response to the RMPs is modeled with the use of MARS-F, a linear single-fluid resistive magnetohydrodynamics (MHD) model [30]. The NTV torque and NTV flux of the W impurity are calculated by NTVTOK, which solves the drift-kinetic equation [49].

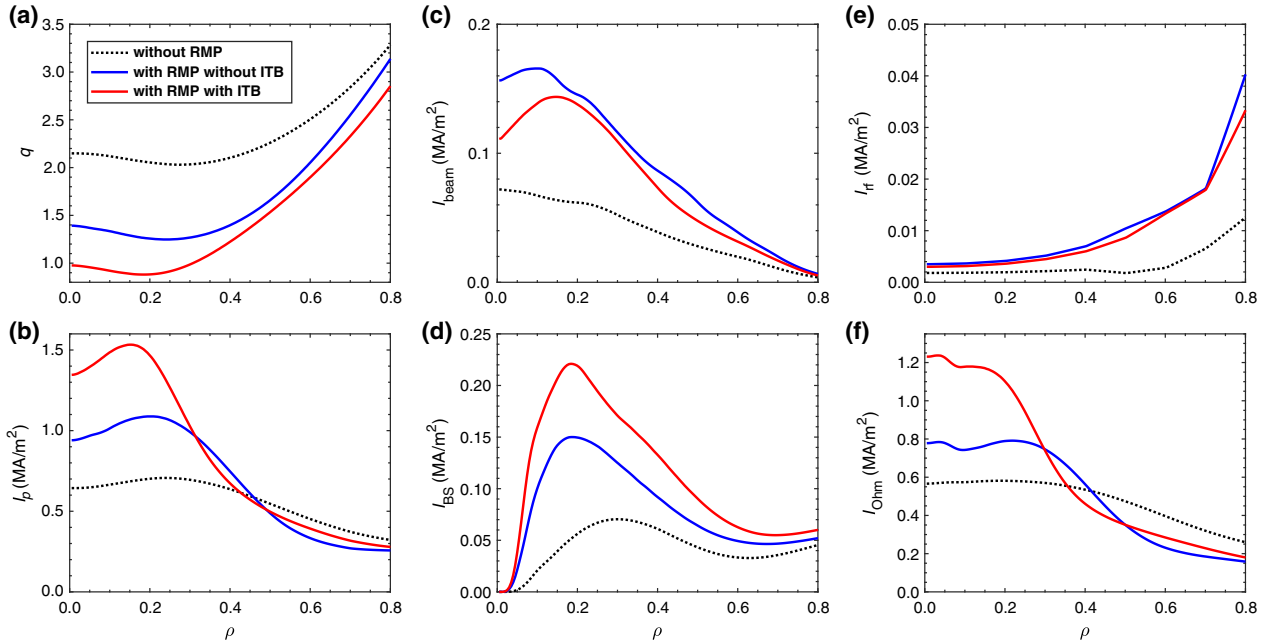


FIG. 10. Plasma radial profiles in the case without RMPs (black), with RMPs but without an ITB (blue), and with RMPs and an ITB (red). Radial profiles of (a) the safety factor q , (b) the plasma current, (c) the neutral beam current, (d) the bootstrap current, (e) the lower hybrid current, and (f) the Ohmic current from equilibrium reconstruction and modeling using NUBEAM [51], ONETWO [50], and CQL3D [52] plus GENRAY [53].

APPENDIX B: EXTENDED PROFILES AND COMPARISONS

The typical profiles of the W impurity, electron density, and electron temperature are shown in Fig. 9. Without RMP application, the W impurities tend to accumulate severely in the core during these discharges. It should be noted that this is a relative distribution, and similar distributions have been observed for the W impurities with charge states ranging from W^{26+} to W^{45+} . The RMPs can suppress W impurity accumulation effectively, and this suppression can be maintained during the ITB phase. As shown in Fig. 9(c), the electron temperature in the core region is very low without RMPs due to W impurity accumulation, generally lower than 1 keV. With the reduction of W impurity concentration induced by RMPs, the electron temperature can be significantly increased, generally reaching approximately 2 keV. The formation of the ion ITB has minimal effect on the electron temperature. The evolution of the electron density profile for discharge 91548 is shown in Fig. 9(b). With RMP application, the density drops significantly before ITB formation but recovers notably during the ITB phase. However, it is worth noting that the density does not always recover during the ITB phase.

The q profiles of discharge 91471, obtained from an equilibrium reconstruction with polarimeter-interferometer constraints and calibrated with use of the sawtooth and fishbone phases, are shown in Fig. 10(c). It is clear that the safety factor in the plasma core decreases with RMP application and is characterized by slightly reversed shear. The reconstructed q and current profiles for multiple discharges are similar. Calculations with NUBEAM [51], CQL3D [52] plus GENRAY [53], and ONETWO [50] show that the beam current and lower hybrid current drive increase with the increase of the electron temperature. The efficiency of NBI-driven current I_{beam} is proportional to T_e/n_e . With RMP application, the density is reduced and the electron temperature is increased. Therefore, I_{beam} increases with RMP application. The central bootstrap current increases in the phase with the ion ITB.

The effect of the core resonant and nonresonant $n = 2$ RMPs on the ITB is shown in Fig. 11. The difference between these two discharges is the current and $\delta\phi_{\text{UL}}$ of the RMP. The RMP current of discharge 79029 is fixed at 3.5 kA with $\delta\phi_{\text{UL}} = 0^\circ$. The RMP current of discharge 79024 ramps up from 1.5 to 3 kA with $\delta\phi_{\text{UL}} = 180^\circ$. For discharge 79024 with core resonant $n = 2$ RMPs, the ion ITB forms at around 4.7 s. However, it is disrupted when the $n = 2$ RMPs penetrate the core region, as evidenced by a sudden increase in the radial magnetic perturbations. In contrast, the ITB can be triggered and sustained for core nonresonant $n = 2$ RMPs even with a higher RMP current. Before ITB formation, the ion temperature and rotation in the core region are comparable for these two discharges.

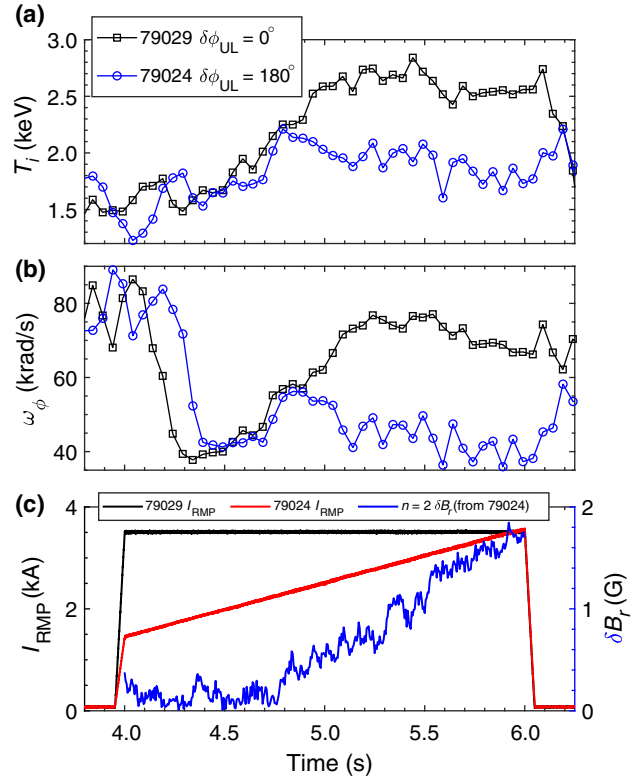


FIG. 11. Temporal evolution of (a) core ion temperature, (b) core toroidal rotation, and (c) measured $n = 2$ radial magnetic perturbations in EAST discharges 79029 ($\delta\phi_{\text{UL}} = 0^\circ$, black line) and 79024 ($\delta\phi_{\text{UL}} = 180^\circ$, red line) with application of $n = 2$ RMPs.

Following ITB formation, however, the ion temperature and rotation in the core region are much stronger for discharge 79029 than for discharge 79024.

- [1] J. Ongena, R. Koch, R. Wolf, and H. Zohm, Magnetic-confinement fusion, *Nat. Phys.* **12**, 398 (2016).
- [2] A. H. Boozer, Physics of magnetically confined plasmas, *Rev. Mod. Phys.* **76**, 1071 (2005).
- [3] ITER Physics Basis Editors, ITER Physics Expert Group Chairs and Co-Chairs, and ITER Joint Central Team and Physics Integration Unit, Chapter 1: Overview and summary, *Nucl. Fusion* **39**, 2137 (1999).
- [4] F. Wagner *et al.*, Regime of improved confinement and high beta in neutral-beam-heated divertor discharges of the ASDEX tokamak, *Phys. Rev. Lett.* **49**, 1408 (1982).
- [5] J. W. Connor, T. Fukuda, X. Garbet, C. Gormezano, V. Mukhovatov, M. Wakatani and (ITB Database Group), ITPA Topical Group on Transport and Internal Barrier Physics), A review of internal transport barrier physics for steady-state operation of tokamaks, *Nucl. Fusion* **44**, R1 (2004).
- [6] K. Ida and T. Fujita, Internal transport barrier in tokamak and helical plasmas, *Plasma Phys. Control. Fusion* **60**, 033001 (2018).

- [7] S. Ding *et al.*, A high-density and high-confinement tokamak plasma regime for fusion energy, *Nature* **629**, 555 (2024).
- [8] H. Zohm, Edge localized modes (ELMs), *Plasma Phys. Control. Fusion* **38**, 105 (1996).
- [9] A. Loarte, G. Saibene, R. Sartori, D. Campbell, M. Becoulet, L. Horton, T. Eich, A. Herrmann, G. Matthews, N. Asakura, A. Chankin, A. Leonard, G. Porter, G. Federici, G. Janeschitz, M. Shimada, and M. Sugihara, Characteristics of type I ELM energy and particle losses in existing devices and their extrapolation to ITER, *Plasma Phys. Control. Fusion* **45**, 1549 (2003).
- [10] T. Evans, R. A. Moyer, K. H. Burrell, M. E. Fenstermacher, I. Joseph, A. W. Leonard, T. H. Osborne, G. D. Porter, M. J. Schaffer, P. B. Snyder, P. R. Thomas, J. G. Watkins, and W. P. West, Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas, *Nat. Phys.* **2**, 419 (2006).
- [11] J.-K. Park, Y. Jeon, Y. In, J.-W. Ahn, R. Nazikian, G. Park, J. Kim, H. Lee, W. Ko, H.-S. Kim, N. C. Logan, Z. Wang, E. A. Feibush, J. E. Menard, and M. C. Zarnstorff, 3D field phase-space control in tokamak plasmas, *Nat. Phys.* **14**, 1223 (2018).
- [12] Y. Sun *et al.*, Nonlinear transition from mitigation to suppression of the edge localized mode with resonant magnetic perturbations in the EAST tokamak, *Phys. Rev. Lett.* **117**, 115001 (2016).
- [13] Y. Koide, M. Kikuchi, M. Mori, S. Tsuji, S. Ishida, N. Asakura, Y. Kamada, T. Nishitani, Y. Kawano, T. Hatae, T. Fujita, T. Fukuda, A. Sakasai, T. Kondoh, R. Yoshino, and Y. Neyatani, Internal transport barrier on $q = 3$ surface and poloidal plasma spin up in JT-60U high- β_p discharges, *Phys. Rev. Lett.* **72**, 3662 (1994).
- [14] F. M. Levinton, M. C. Zarnstorff, S. H. Batha, M. Bell, R. E. Bell, R. V. Budny, C. Bush, Z. Chang, E. Fredrickson, A. Janos, J. Manickam, A. Ramsey, S. A. Sabbagh, G. L. Schmidt, E. J. Synakowski, and G. Taylor, Improved confinement with reversed magnetic shear in TFTR, *Phys. Rev. Lett.* **75**, 4417 (1995).
- [15] E. J. Strait, L. L. Lao, M. E. Mauel, B. W. Rice, T. S. Taylor, K. H. Burrell, M. S. Chu, E. A. Lazarus, T. H. Osborne, S. J. Thompson, and A. D. Turnbull, Enhanced confinement and stability in DIII-D discharges with reversed magnetic shear, *Phys. Rev. Lett.* **75**, 4421 (1995).
- [16] C. Gormezano *et al.*, Internal transport barriers in JET deuterium-tritium plasmas, *Phys. Rev. Lett.* **80**, 5544 (1998).
- [17] O. Gruber, R. C. Wolf, R. Dux, C. Fuchs, S. Gunter, A. Kallenbach, K. Lackner, M. Maraschek, P. J. McCarthy, H. Meister, G. Pereversev, F. Ryter, J. Schweinzer, U. Seidel, S. Sesnic, A. Stabler, J. Stober, and ASDEX Upgrade Team, Stationary H-mode discharges with internal transport barrier on ASDEX Upgrade, *Phys. Rev. Lett.* **83**, 1787 (1999).
- [18] T. Sarazin, M. Bécoulet, P. Beyer, X. Garbet, Ph. Ghendrih, Y. C. Hender, E. Joffrin, X. Litaudon, P. J. Lomas, G. F. Matthews, V. Parail, G. Saibene, and R. Sartori, Edge issues in ITB plasmas in JET, *Plasma Phys. Control. Fusion* **44**, 2445 (2002).
- [19] R. Dux, C. Giroud, K.-D. Zastrow, and JET EFDA contributors, Impurity transport in internal transport barrier discharges on JET, *Nucl. Fusion* **44**, 260 (2004).
- [20] R. A. Pitts, S. Carpentier, F. Escourbiac, T. Hirai, V. Komarov, A. S. Kukushkin, S. Lisgo, A. Loarte, M. Merola, R. Mitteau, A. R. Raffray, M. Shimada, and P. C. Stangeby, Physics basis and design of the ITER plasma-facing components, *J. Nucl. Mater.* **415**, S957 (2011).
- [21] K. Ida, S. Inagaki, R. Sakamoto, K. Tanaka, H. Funaba, Y. Takeiri, K. Ikeda, C. Michael, T. Tokuzawa, H. Yamada, Y. Nagayama, K. Itoh, O. Kaneko, A. Komori, and O. Motojima (LHD experimental group), Slow transition of energy transport in high-temperature plasmas, *Phys. Rev. Lett.* **96**, 125006 (2006).
- [22] P. Mantica, D. Van Eester, X. Garbet, F. Imbeaux, L. Laborde, M. Mantsinen, A. Marinoni, D. Mazon, D. Moreau, N. Hawkes, E. Joffrin, V. Kiptily, S. Pinches, A. Salmi, S. Sharapov, A. Thyagaraja, I. Voitsekhovitch, P. de Vries, and K.-D. Zastrow, Probing internal transport barriers with heat pulses in JET, *Phys. Rev. Lett.* **96**, 095002 (2006).
- [23] K. Ida, Y. Sakamoto, H. Takenaga, N. Oyama, K. Itoh, M. Yoshinuma, S. Inagaki, T. Kobuchi, A. Isayama, T. Suzuki, T. Fujita, G. Matsunaga, Y. Koide, M. Yoshida, S. Ide, and Y. Kamada (JT-60 team), Transition between internal transport barriers with different temperature-profile curvatures in JT-60U tokamak plasmas, *Phys. Rev. Lett.* **101**, 055003 (2008).
- [24] Y. Liang *et al.*, Active control of type-I edge-localized modes with $n = 1$ perturbation fields in the JET tokamak, *Phys. Rev. Lett.* **98**, 265004 (2007).
- [25] A. Kirk, E. Nardon, R. Akers, M. Bécoulet, G. D. Temmerman, B. Dudson, B. Hnat, Y. Liu, R. Martin, P. Tamain, D. Taylor, and MAST team, Resonant magnetic perturbation experiments on MAST using external and internal coils for ELM control, *Nucl. Fusion* **50**, 034008 (2010).
- [26] W. Suttrop, T. Eich, J. C. Fuchs, S. Günter, A. Janzer, A. Herrmann, A. Kallenbach, P. T. Lang, T. Lunt, M. Maraschek, R. M. McDermott, A. Mlynek, T. Pütterich, M. Rott, T. Vierle, E. Wolfrum, Q. Yu, I. Zammuto, and H. Zohm (ASDEX Upgrade Team), First observation of edge localized modes mitigation with resonant and non-resonant magnetic perturbations in ASDEX Upgrade, *Phys. Rev. Lett.* **106**, 225004 (2011).
- [27] Y. M. Jeon, J.-K. Park, S. W. Yoon, W. H. Ko, S. G. Lee, K. D. Lee, G. S. Yun, Y. U. Nam, W. C. Kim, J.-G. Kwak, K. S. Lee, H. K. Kim, and H. L. Yang (KSTAR team), Suppression of edge localized modes in high-confinement KSTAR plasmas by nonaxisymmetric magnetic perturbations, *Phys. Rev. Lett.* **109**, 035004 (2012).
- [28] R. Nazikian *et al.*, Pedestal bifurcation and resonant field penetration at the threshold of edge-localized mode suppression in the DIII-D tokamak, *Phys. Rev. Lett.* **114**, 105002 (2015).
- [29] T. F. Sun, Y. Liu, X. Q. Ji, Y. Q. Liu, R. Ke, J. M. Gao, N. Wu, W. Deng, M. Xu, and X. R. Duan, Edge-coherent oscillation providing nearly continuous transport during edge-localized mode mitigation by $n = 1$ resonant magnetic perturbation in HL-2A, *Nucl. Fusion* **61**, 036020 (2021).

- [30] Y. Liu, A. Kirk, and E. Nardon, Full toroidal plasma response to externally applied nonaxisymmetric magnetic fields, *Phys. Plasmas* **17**, 122502 (2010).
- [31] C. Paz-Soldan, R. Nazikian, S. R. Haskey, N. C. Logan, E. J. Strait, N. M. Ferraro, J. M. Hanson, J. D. King, M. J. Lancot, R. A. Moyer, M. Okabayashi, J.-K. Park, M. W. Shafer, and B. J. Tobias, Observation of a multimode plasma response and its relationship to density pumpout and edge-localized mode suppression, *Phys. Rev. Lett.* **114**, 105001 (2015).
- [32] X. Yang, Y. Sun, Y. Liu, S. Gu, Y. Liu, H. Wang, L. Zhou, and W. Guo, Modelling of plasma response to 3D external magnetic field perturbations in EAST, *Plasma Phys. Control. Fusion* **58**, 114006 (2016).
- [33] R. Fitzpatrick and A. O. Nelson, An improved theory of the response of DIII-D H-mode discharges to static resonant magnetic perturbations and its implications for the suppression of edge localized modes, *Phys. Plasmas* **27**, 072501 (2020).
- [34] Q. M. Hu, R. Nazikian, B. A. Grierson, N. C. Logan, D. M. Orlov, C. Paz-Soldan, and Q. Yu, Wide operational windows of edge-localized mode suppression by resonant magnetic perturbations in the DIII-D tokamak, *Phys. Rev. Lett.* **125**, 045001 (2020).
- [35] D. M. Yao, G. N. Luo, Z. B. Zhou, L. Cao, Q. Li, W. J. Wang, L. Li, S. G. Qin, Y. L. Shi, G. H. Liu, and J. G. Li, Design, R&D and commissioning of EAST tungsten divertor, *Phys. Scr.* **2016**, 014003 (2015).
- [36] B. Wan *et al.*, Recent advances in EAST physics experiments in support of steady-state operation for ITER and CFETR, *Nucl. Fusion* **59**, 112003 (2019).
- [37] Y. Sun, Y. Liang, J. Qian, B. Shen, and B. Wan, Modeling of non-axisymmetric magnetic perturbations in tokamaks, *Plasma Phys. Control. Fusion* **57**, 045003 (2015).
- [38] A. Loarte *et al.*, Progress on the application of ELM control schemes to ITER scenarios from the non-active phase to DT operation, *Nucl. Fusion* **54**, 033007 (2014).
- [39] Y. Sun *et al.*, First demonstration of full ELM suppression in low input torque plasmas to support ITER research plan using $n = 4$ RMP in EAST, *Nucl. Fusion* **61**, 106037 (2021).
- [40] M. Jia *et al.*, Integrated ELM and divertor power flux control using RMPs with low input torque in EAST in support of the ITER research plan, *Nucl. Fusion* **61**, 106023 (2021).
- [41] Y. Y. Chang, Y. W. Sun, H. Sheng, X. T. Yan, H. H. Li, P. C. Xie, W. M. Zhang, J. Guo, S. F. Mao, Y. Q. Liu, L. Zhang, Y. M. Duan, Y. Y. Li, Q. Zang, and M. Y. Ye, Tungsten transport due to the neoclassical toroidal viscosity induced by resonant magnetic perturbation in the EAST tokamak, *Phys. Plasmas* **30**, 122301 (2023).
- [42] H. Sheng *et al.*, Simultaneous reduction of tungsten and rotation in the core region induced by RMP, *Nucl. Fusion* **65**, 016009 (2024).
- [43] A. C. C. Sips *et al.*, An international database for the study of the formation of ITBs in tokamaks, *Plasma Phys. Control. Fusion* **44**, A391 (2002).
- [44] X. Gao, L. Zeng, M. Wu, T. Zhang, Y. Yang, T. Ming, X. Zhu, Y. Wang, H. Liu, Q. Zang, G. Li, J. Huang, X. Gong, Y. Li, J. Li, Y. Wan, and EAST team, Experimental progress of hybrid operational scenario on EAST tokamak, *Nucl. Fusion* **60**, 102001 (2020).
- [45] R. E. Bell, F. M. Levinton, S. H. Batha, E. J. Synakowski, and M. C. Zarnstorff, Poloidal rotation in TFTR reversed shear plasmas, *Phys. Rev. Lett.* **81**, 1429 (1998).
- [46] E. Joffrin, R. Wolf, B. Alper, Y. Baranov, C. D. Challis, M. de Baar, C. Giroud, C. W. Gowers, N. C. Hawkes, T. C. Hender, M. Marachek, D. Mazon, V. Parail, A. Peeters, K.-D. Zastrow, and Contributors to the EFDA-JET Workprogramme, $q = 1$ advanced tokamak experiments in JET and comparison with ASDEX Upgrade, *Plasma Phys. Control. Fusion* **44**, 1203 (2002).
- [47] M. W. Shafer, G. R. McKee, M. E. Austin, K. H. Burrell, R. J. Fonck, and D. J. Schlossberg, Localized turbulence suppression and increased flow shear near the $q = 2$ surface during internal-transport-barrier formation, *Phys. Rev. Lett.* **103**, 075004 (2009).
- [48] C. Angioni, Impurity transport in tokamak plasmas, theory, modelling and comparison with experiments, *Plasma Phys. Control. Fusion* **63**, 073001 (2021).
- [49] Y. Sun, Y. Liang, K. C. Shaing, H. R. Koslowski, C. Wiegmann, and T. Zhang, Neoclassical toroidal plasma viscosity torque in collisionless regimes in tokamaks, *Phys. Rev. Lett.* **105**, 145002 (2010).
- [50] W. W. Pfeiffer, R. H. Davidson, R. L. Miller, and R. E. Waltz, ONETWO: A computer code for modeling plasma transport in tokamaks, Technical Report (General Atomic Co., San Diego, CA (USA), 1980).
- [51] A. Pankin, D. McCune, R. Andre, G. Bateman, and A. Kritz, The tokamak Monte Carlo fast ion module NUBEAM in the National Transport Code Collaboration library, *Comput. Phys. Commun.* **159**, 157 (2004).
- [52] Y. V. Petrov and R. W. Harvey, A fully-neoclassical finite-orbit-width version of the CQL3D Fokker-Planck code, *Plasma Phys. Control. Fusion* **58**, 115001 (2016).
- [53] A. Smirnov and R. Harvey, The GENRAY ray tracing code, CompX Report CompX-2000-01 (2001).