Magnetic island formation and rotation braking induced by low-Z impurity penetration in an EAST plasma

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Abstract
Recent observations of the successive formations of the 4/1, 3/1, and 2/1 magnetic islands as well as the subsequent braking of the 2/1 mode during a low-Z impurity penetration process in EAST experiments are well reproduced in our 3D resistive MHD simulations. The enhanced parallel current perturbation induced by impurity radiation predominately contributes to the tearing mode growth, and the 2/1 island rotation is mainly damped by the impurity accumulation as results of the influence from high n modes.

Keywords: impurity radiation, tearing mode, magnetic island braking, higher-n mode, island formation

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

1. Introduction

The impurity radiation is long believed to play critical roles in setting the upper limits of energy confinement and stable operation regimes of tokamaks \cite{1}. The exact mechanism how the impurity radiation influence and govern the tokamak stability has remained a subject of continued interests.

Experiments have found some correlations between the impurity radiation and the tearing mode (TM) growth, ASDEX-Upgrade shows the low temperature and localized impurity radiation inside the growing magnetic island during the current contraction phase \cite{1}, and the similar connection between enhanced radiation and enlarged island width is observed in National Spherical Torus Experiment (NSTX) \cite{2}. Besides, EAST experiments demonstrate the $m = 2$ ($m$ is the poloidal mode number) island formation when the radiative cooling exceeds the ohmic heating \cite{3}. Those experimental observation contribute to supporting the impurity radiation as a driven mechanism of TM but without more detail, JET experiments show the TM onset induced by unstable shrinking (broadening) current profile as a consequence of temperature edge cooling (central hollowing) from radiation loss \cite{4}. In particular, Rijnhuizen tokamak uses the extended Rutherford model \cite{5} with a radiation term added to account for the observed mode exponential growth \cite{6}, although the data fitting is well it still remains some key parameters unknown due to the difficulties in diagnostic technologies. In addition,
the widely observed formation of impurity-induced helical ‘snake’ perturbation in tokamak plasmas emphasizes the role of impurity in magnetohydrodynamic (MHD) stability and particle confinement [7–9].

The idea of thermal instability induced mode growth was first proposed in [10], and a thermo-resistive TM model is developed later to describe the effect of impurity radiation on the magnetic island nonlinear evolution [11–13], which predicts the island growth once the local radiative cooling exceeds the Ohmic heating in the island interior. However, the model assumes the presence of a pre-existing small island or linearly unstable equilibrium to initiate the seeding required for the nonlinear island growth.

Recent EAST experiments observe the successive 4/1, 3/1, 2/1 and 3/2 island formation during the carbon impurity penetration from lower divertor into the plasma core region [14]. The 2/1 magnetic island, which propagates in electron diamagnetic drift direction, can be locked after the redistribution of carbon impurity concentration and the island width can reach approximately 5 cm from the electron cyclotron emission measurement. In addition, the ‘hysteresis effect’ between the impurity concentration and the 2/1 mode growth is found, namely the island width increases (decreases) and the rotation velocity decreases (increases) following the enhanced (reduced) impurity concentration in a hysteresis cycle.

In this work, we are able to use 3D resistive MHD code Non-ideal Magnetohydrodynamics with Rotation-Open Discussion (NIMROD) to simulate the process of impurity penetration from plasma boundary into central region and intend to reproduce the main features observed in the experiment. We demonstrate how the impurity radiation excites the TM growth and slows down the island rotation, even in absence of any external error field. This may help us understand the roles of impurity penetration leading to the potential degradation or disruption that threatens the steady state operation of tokamak.

The remainder of the paper is organized as follows. Section 2 gives a brief introduction to the simulation model and setup. Section 3 presents the simulation results about the 4/1, 3/1, and 2/1 magnetic island formation after the arrival of impurity radiation peak on the corresponding rational surfaces, where the radiation enhanced parallel current perturbation predominantly contributes to the TM growth. Section 4 reports the reproduced island rotation damping by the concentration of impurity and demonstrates the effects of higher toroidal harmonics. Section 5 concludes with a summary and discussion.

2. NIMROD/KPRAD model and simulation setup

This work is based on a single-fluid 3D resistive MHD model implemented in the NIMROD code [15], with a simplified module for impurity radiation adapted from the Killer Pellet RADiation (KPRAD) code [16], and the equations are as follows [17]:

\[
\begin{align*}
\frac{dn_i}{dt} + n_i \nabla \cdot \vec{V} &= \nabla \cdot (D \nabla n_i) + S_{\text{ion}/3-\text{body}} \\
\frac{dn_{\text{Z}=0-10}}{dt} + n_Z \nabla \cdot \vec{V} &= \nabla \cdot (D \nabla n_Z) + S_{\text{ion/rec}} \\
t_e \frac{dT_e}{dt} &= (\gamma - 1)[n_e \nabla \cdot \vec{V} + \nabla \cdot \vec{q}_e - Q_{\text{loss}}] \\
\vec{q}_e &= -n_e [\nu_e \vec{b} + \kappa_{\perp}(\vec{I} - \hat{b} \hat{b})] \cdot \nabla T_e \\
\frac{\partial \vec{B}}{\partial t} &= \nabla \times \left( \vec{V} \times \vec{B} \right) - \nabla \times \left( \eta \vec{J} \right)
\end{align*}
\]

Here, \(n_i\), \(n_e\), and \(n_Z\) are the main ion, electron, and impurity ion number density respectively, \(\rho, \vec{V}, \vec{J}, \) and \(p\) the plasma mass density, velocity, current density, and pressure respectively, \(T_e\) and \(\vec{q}_e\) the electron temperature and heat flux respectively, \(\nu\), \(\eta\), and \(\kappa_{\perp}\) the plasma diffusivity, kinematic viscosity, resistivity, and parallel (perpendicular) thermal conductivity respectively, \(\gamma = 5/3\) the adiabatic index, \(S_{\text{ion/rec}}\) the density source from ionization and recombination, \(S_{\text{ion}/3-\text{body}}\) also includes contribution from 3-body recombination, \(Q_{\text{loss}}\) the energy loss, \(\vec{E}(\vec{B})\) the electric (magnetic) field, \(\hat{b} = \vec{B}/B\), and \(\vec{T}\) the unit dyadic tensor. The source term \(S_{\text{ion/rec}}\) in equation (3) is from the impurity ionization and recombination, and the impurity radiation is calculated in the energy loss term \(Q_{\text{loss}}\) from the KPRAD module based on a coronal non-equilibrium model including ionization, recombination, bremsstrahlung, and line radiations. All particle species share a single temperature \(T = T_e\), which assumes instant thermal equilibrium between the plasma and the impurity species, and the plasma pressure \(p = \sum n_i T_e\), where \(j\) refers to particle species, includes impurity contributions. More details can be found in the appendix of [18].

A static MHD stable EAST L-mode equilibrium without any initial perturbations other than a localized impurity deposition is set up as the initial condition in simulations and some key parameters are listed in table 1. In the beginning of the simulation, we deposit an amount of neutral Neon impurity \(8.73 \times 10^{18} \text{ m}^{-3}\) at the bottom of the edge plasma region inside the plasma separatrix with a Gaussian distribution along both the poloidal and toroidal directions (figure 1). The impurity level is sufficiently low to avoid triggering the fast major disruption such as in a massive gas injection (MBI) process [19], while sufficiently high to excite the resistive tearing modes as in recent EAST experiments [14]. The impurity penetrates inward mainly through diffusion and convection as governed by equation (3). A constant isotropic diffusion coefficient \(D = 10 \text{ m}^2 \text{s}^{-1}\) is adopted in the simulation, which is larger than the typical EAST experimental value, i.e. \(0.1 - 1 \text{ m}^2 \text{s}^{-1}\), in order to accelerate the impurity inward penetration in simulations within the limit of affordable computational resource. The plasma and impurity are stationary at the beginning, i.e. \(V_0 = 0 \text{ m} \cdot \text{s}^{-1}\), to
Table 1. Key parameters in the simulation.

| Parameter                      | Symbol | Value | Unit   |
|--------------------------------|--------|-------|--------|
| Minor radius                   | a      | 0.45  | m      |
| Major radius                   | R0     | 1.85  | m      |
| Plasma current                 | Ip     | 0.38  | MA     |
| Toroidal magnetic field        | Br     | 2.267 | T      |
| Core value of safety factor    | q0     | 1.484 | Dimensionless |
| Edge value of safety factor    | q0s    | 9.768 | Dimensionless |
| Core electron number density   | ne,core| 2.3 x 10^19 | m^-3 |
| Core electron temperature      | T_e,core | 2.959 | keV |
| Edge electron temperature      | T_e,core | 3.875 | eV |
| Equilibrium velocity           | V0     | 0     | m s^-1 |
| The core resistivity           | η0     | 6.3316 x 10^-11 | ∇Ω m |
| Kinematic viscosity            | ν      | 27    | m^2 s^-1 |
| The core Lundquist number      | S0     | 6.413 x 10^9 | Dimensionless |
| Constant parallel thermal conductivity | κ∥ | 10^10 | m^2 s^-1 |
| Diffusivity                    | D      | 10    | m^2 s^-1 |

3. TM growth driven by impurity radiation

Our simulation results demonstrate the successive onsets and growth of the 4/1, 3/1, and 2/1 islands during the impurity inward penetration (figure 2(a)). The 4/1 and 3/1 island width increase and saturate first at ~0.5 cm and ~2.0 cm respectively, due to their proximity to the impurity source. The effect of impurity radiation on the island growth for the 2/1 mode is more significant, as shown in its sudden fast growth at \( t = 2.5 \text{ms} \) soon after the impurity radiation peak arrives on the \( q = 2 \) rational surface at \( t = 2.0 \text{ms} \) (figure 2(b)), along with a strong burst of radiation power on the same surface (figures 2(b) and (c)). The initial growth of the 2/1 mode during \( t = 0 - 2.5 \text{ms} \) is caused by mode coupling with the 3/1 mode as shown in the following section. Here the island width \( w = 4 \left( \frac{\tau_{\text{eff}}}{m q B_0} \right)^{1/2} \), where \( B_0 \) is the equilibrium poloidal magnetic field and \( B_0 \) is the \( m/n \) helical normal component of the perturbed magnetic field measured on the initial equilibrium rational surface \( r_n \). The impurity radiation peak stops around the \( q = 2 \) surface and does not penetrate inward further until after \( t = 4.5 \text{ms} \). Similar process has been observed to trigger MHD instabilities in Tore Supra experiments [20]. Such a close correlation between the impurity penetration and the
island growth indicates a crucial role of impurity radiation in triggering and driving the TM.

3.1. Current perturbations induced by impurity radiation

Impurity injection introduces two direct modifications to the equilibrium profiles (figure 3). On the one hand, the impurity radiation cooling leads to the temperature profile contraction; on the other hand, the impurity ionization increases the electron density at the impurity cold front, which is identified from the local peak of the electron density profile (figure 3(a)). As a consequence, the pressure profile steepens and its gradient is enhanced at the impurity cold front around the $q = 2$ surface (figure 3(b)). This local variation in pressure gradient is predominantly from the temperature profile change in the simulation case considered here.

Despite the dynamic nature of the impurity injection process, the profile evolution is quasi-static and the force balance $dp/dr \approx J \times B$ is well maintained (figure 4). The corresponding $n = 0$ component of the parallel current perturbation $\delta J_\parallel$ mainly comes from the perturbed Pfirsch–Schlüter (PS) current $\delta J_{\text{ps}} = -2 \frac{1}{r} \frac{dp}{dr} \cos \theta$ in the outer region on both sides of the $q = 2$ surface, which is induced by the pressure gradient perturbation $\delta p/dr$. However, the parallel current perturbation peaks around the $q = 2$ surface can not be accounted by the perturbed Pfirsch–Schlüter current $\delta J_{\text{ps}}$ alone.

The local positive current perturbation peak denoted by the red arrow correlates well with the local impurity radiation peak (figure 5). Similar skin current structure due to edge radiative cooling is also reported in previous studies [21–23]. The local current perturbation dip denoted by the blue arrow collocates with the surge of plasma resistivity in the cold region and is dominated by the current diffusion (figure 5). It is important to note that the location of impurity radiation peak is usually different from that of the enhanced plasma resistivity, because the impurity radiation is dominated by the line radiation, which is the strongest around $T_e \sim 10^2$ eV, whereas the resistivity
Figure 3. Radial profiles along the outboard mid-plane at $t = 1.5 \text{ms}$ (with the radial line cut denoted as orange line in the inset sketch). Here $r = R - R_0$ and same in all other figures. (a) Left axis: initial equilibrium $T_e$ (blue solid line) and dynamic $T_e$ (blue dashed line); right axis: plasma ion density $n_i$ (orange solid line), impurity ion density $n_{imp}$ (orange dashed line) and electron density $n_e$ (orange dotted line). (b) Right axis: initial equilibrium $p_0$ (orange solid line) and dynamic $p$ (orange dashed line); left axis: initial equilibrium pressure gradient $dp_0/dr$ (blue solid line) and dynamic pressure gradient $dp/dr$ (blue dashed line). (c) Pressure gradient perturbation $dp/dr$, where $p = nT_e$ (red solid line), pressure gradient perturbation with dynamic density and equilibrium temperature $dp_{n,T_e}/dr$, where $p_{n,T_e} = n_0T_e$ (blue dashed line), and pressure gradient perturbation with dynamic temperature and equilibrium density $dp_{T_e,n}/dr$, where $p_{T_e,n} = n_0T_e$ (green dotted line). The equilibrium $q = 4, 3, 2$ surface locations are denoted as black lines in all plots and same in all other figures.

3.2. Correlation between the current perturbations and TMs

The TM growth are driven by the parallel current perturbation as expected and confirmed from the correlation observed for the 2/1 as well as the 3/1 modes (figures 7(a) and (b)). Based on previous developed analytic theories on the nonlinear resistive growth of magnetic island including the interchange effects, the following modified Rutherford equation (MRE) may be introduced for discussion [24–27]

$$\frac{1}{\eta} \frac{\partial w}{\partial t} \sim \Delta' + \frac{\alpha_1 D_R + \alpha_2 E_{\phi0} \delta \eta_{m,n}}{\sqrt{w^2 + w_d^2}}$$

where $\Delta'$ is the tearing instability index, $\delta \eta_{m,n}$ is the $(m,n)$ helical component of the perturbed resistivity, and $E_{\phi0}$ is the toroidal electric field due to loop voltage. Here $D_R \approx \frac{e^2 B_p}{L \Delta} \left(1 - \frac{1}{q'} \right)$ is the resistive interchange parameter with $\epsilon_s = r_s/R_0$, $\beta_p = 2\mu_0 p/B_p^2$, $L_q = q/q' = r_s/s$, and $L_p = p/p'$, which is usually negative in a tokamak with monotonic safety factor $q$ profile [24], $w_d = 2\sqrt{2} \left(\kappa_{\perp}/\kappa_{\parallel}\right)^{1/4} (r_s R/\kappa_\parallel)^{1/2}$ is the finite thermal diffusion length scale [28], and the coefficients $\alpha_1$ and $\alpha_2$ may be determined from the more quantitative theory or fit from the corresponding simulation or experimental results. The overall time evolution of all key terms in equation (7) are summarized in figure 6, which we delineate further below in details.

For the 2/1 mode, the surface-averaged parallel current perturbation around the $q = 2$ rational surface $\langle \delta J_\parallel \rangle_{q=2}$ increases
Figure 4. Radial profiles along the (a) outboard and the (b) inboard mid-plane (with the radial line cut denoted as orange line in the inset sketch) for (left axis) pressure gradient \( \frac{dp}{dr} \) (red solid line) and radial Lorentz force \( J \times B \) (blue dashed line), (right axis) the \( n = 0 \) component of perturbed parallel current density \( \delta J_\parallel \) (cyan solid line), and perturbed Pfirsch–Schlüter current model \( \delta J_{ps} \) (magenta dashed line).

Figure 5. Flux-surface-averaged profiles of impurity radiation power \( P_{rad} \) (orange solid line), Ohmic heating power \( P_{ohm} \) (orange dashed line), plasma resistivity \( \eta \) (orange dotted line), and the \( n = 0 \) component of (a) parallel current perturbation \( \delta J_\parallel \) (blue solid line), (b) parallel current \( J_\parallel \) (blue solid line), respectively.

rapidly at \( t = 1.5 \) ms, and the 2/1 island width grows up thereafter at \( t = 2.5 \) ms (figure 7(a)). The parallel current perturbation \( \langle \delta J_\parallel \rangle_{q=2} \) is primarily induced by the enhanced impurity radiation, as indicated by its correlation with the local radiation power in figure 8(a). The \( m = 0 \), \( n = 0 \) component of the parallel current density perturbation \( \langle \delta J_\parallel \rangle \) drives the tearing growth through the \( \Delta' \) in the Rutherford equation, and the linear TM growth is just the results of major change to the current profile, i.e. \( \langle \delta J_\parallel \rangle \), which itself is induced by the impurity radiation. The helical current terms in the MRE (7) contribute to the nonlinear island growth, but not the trigger to the initial TM onset. In absence of any impurity deposition, the equilibrium adopted in the simulation is stable to the linear TM, i.e. \( \Delta' < 0 \). Only after the impurity deposition is introduced to the equilibrium and the subsequent penetration arrives at the corresponding rational surfaces, the spontaneous TM island growth are mainly driven by the now unstable parallel current profile with \( \Delta' > 0 \) as direct results of impurity radiative cooling. It is the impurity radiation effects on the current profile that triggers the linear growth of a TM. Once into the nonlinear stage, the thermal-resistive mechanism involving power balance between Ohmic heating and impurity radiations starts to contribute to the island development. The nonlinear island growth in our simulations here is not of neoclassical tearing mode (NTM) but the resistive tearing, since neither the neoclassical
Figure 6. The island growth rate $dw/dt$ (blue solid line), the linear tearing stability index $\Delta'$ (orange solid line), the resistive interchange parameter $D_R$ (orange dashed line), and the $m=2/n=1$ component of the perturbed plasma resistivity $\delta \eta_{2/1}$ (orange dotted line) as functions of time.

closure nor the bootstrap current is included in these simulations.

After $t=4.5$ ms, the current perturbation becomes dominated by resistive diffusion due to the enhanced plasma resistivity. The 1.0 ms delay ($t=1.5-2.5$ ms) in the mode growth may be due to the well-known stabilization effect from flux-averaged pressure gradient and magnetic curvature [24, 29], which reduces the cylindrical tearing instability parameter $\Delta'$ to an effective value [26], i.e. $\Delta'_\text{eff} = \Delta' + \sqrt{\frac{2\pi^3}{3}} D_R / w_d$. This derives from the fact that perturbed pressure leads to a parallel current perturbation outside the resistive layer through magnetic curvature, which contributes to the jump in the logarithmic derivative, i.e. the $\Delta'$. From figure 8(a), it is clear that the local pressure gradient is enhanced around 1.5 ms and decreases toward zero right before the mode growth ($t=2.5$ ms). More importantly, the absolute value $|D_R|$ indeed increases to a larger value right before the mode growth, which represents the stabilization effect, and drops rapidly once the mode begins to grow (figure 8(b)). With the impurity inward penetration, the current perturbations move along with the cold front and cross different rational surfaces to trigger TMs with multiple helicities.

4. Interaction between induced TM and impurity

4.1. The rotation of magnetic islands

A stationary equilibrium plasma framework is adopted in the simulations, i.e. $V_0 = 0$ ms$^{-1}$, to study the impurity effect on the rotation of magnetic islands alone, and the plasma equilibrium dose not start rotating without the impurity injection. A small perturbed toroidal velocity at the beginning of simulation is caused by the impurity injection, then it increases rapidly to its peak and decays slowly thereafter (figure 9). The mode frequency of the $n=1$ normal component of the perturbed magnetic field $B_t$ is slowly damped from beginning, and the magnetic islands become almost stationary after $t \gtrsim 4$ ms while the toroidal flow still remaining finite. The toroidal rotation frequency on the $q=2$ surface is approximate twice that on the $q=3$ surface, whereas the mode frequencies on these two surfaces are almost same during $t=0-4.0$ ms before locking. Such a mode excitation with finite frequency and the subsequent gradual damping and eventual locking is also observed in experiments, however, such a mode locking is previously attributed to the electromagnetic torque.
torque, through the increased island size by impurity radiation cooling as well as the reduction of rotation velocity itself [14]. Our simulation data indicates that the rotation in the subsequent simulation is induced first by the poloidal and toroidal pressure gradient as a direct result from the localized impurity radiative cooling. Once the impurity penetration reaches the rational surface where a TM island is driven to grow, the electromagnetic torque becomes the dominant driver for the island region plasma rotation, which can be seen from the time history of the poloidal components of the velocity, the pressure gradient, and the electromagnetic torque averaged over the \( q = 2 \) surface (figure 10). The electromagnetic torque includes contributions from both the diamagnetic current due to the change in radial pressure gradient and the inductive current due to the TM growth. The enhanced diamagnetic drift is equivalent to the enhanced diamagnetic current component of the electromagnetic torque, which contributes to the rotation change of the island region plasma rotation. The rotation eventually slows down after the impurity penetration induced pressure gradient and electromagnetic torque gradually decrease and vanish.

The impurity radial transport mainly depends on diffusion, and its penetration in the poloidal direction is dominated by the perturbed poloidal flow through convection. Meanwhile, the localization of the impurity density along with the radiation power not only lead to the island formation, but also correlates to the phase of the TM. As indicated by figure 11(c), the localization of the impurity radiation power corresponds to the \( O \)-point of the \( 2/1 \) island, which is widely observed both in experiments and simulations. The radiation leads to temperature cooling that enhances the plasma resistivity, thus reduces the current density and causes the \( O \)-point of the island. And the island may confine the impurity ions locally due to its magnetic structure. Therefore, the magnetic island rotates along with the impurity density in the poloidal plane, which is influenced by the perturbed poloidal flow, as identified by the correlation between the poloidal distribution of the radiation power, the perturbed poloidal flow, and the \( n = 1 \) mode phase evolution (figures 11(a) and (b)).

The island rotation amplitude can be measured by the integral of the perpendicular vortex associated with the mode in the poloidal plane, which decreases toward zero gradually (figure 12(a)). Whereas the island rotation velocity is a three-component vector with a 3D distribution in space, the integral of the perpendicular vortex \( \int U_S \cdot dS = \int \nabla_{\perp} \cdot \Phi dS \) is a single-valued global measure of the total degree of island rotation. The definition or the measurement of such a quantity does not rely on the presence or absence of a mode in the velocity field. Meanwhile, the impurity penetration front can be indicated by the local enhanced electron density peak, which sweeps inward in a step-wise manner across rational surfaces. The mode rotation amplitude rapidly shoots to its peak value in the beginning when the impurity is localized in the bottom region with a strong up-down asymmetric distribution, then gradually slows down as the impurity penetrates inward along with more uniform toroidal and poloidal spreading. This simulation results agree the experimental observation that the
modes can be locked following the redistribution of the low-Z impurity concentration [14], despite the fact that there is no error or external magnetic field at the perfectly conducting wall boundary in simulations. Similarly, Joint TEXT tokamak (J-TEXT) experiments demonstrate strong correlation between the 2/1 TM rotation and impurity distribution as well [30, 31].

4.2. The effect from higher-\( n \) modes

The inclusion of higher-\( n \) modes in simulation accelerates the mode rotation drop toward zero and the subsequent stationary state in the simulation (figure 12(b)). This suggests that the high-\( n \) helical structures may be able to introduce additional braking effects, likely through the electromagnetic torques from the magnetic island chains, as well as the coupling and overlapping of magnetic islands on the neighbouring rational surfaces.

Higher-\( n \) modes also significantly impede the impurity inward penetration and as a consequence the radiation peak stays longer upon the \( q = 2 \) surface (figure 12(c)), which could be due to a combined effects from the stochastic field [32] and the 2/1 magnetic island itself [33]. By contrast, in the simulation case with the \( n = 0 \) component only, the impurity front almost directly penetrates into the central region in absence of magnetic islands. This agrees with the observations that during an MGI experiment, the impurity penetration usually

Figure 9. Flux-surface-averaged toroidal velocity \( V_\phi \) (orange solid line) and normalized \( n = 1 \) normal component of perturbed magnetic field \( B_{r,n=1} \) (flushed color), which are measured on the \( q = m/n \) rational surface (denoted as the red circle in the sketch) for (a) the 2/1 mode and (b) the 3/1 mode as functions of time.

Figure 10. The poloidal velocity \( V_\theta \) (blue solid line), the Lorentz force \( (J \times B)_\theta \) (orange solid line) and the pressure gradient \( dp/\partial \theta \) (orange dashed line) in the poloidal direction measured on the \( q = 2 \) surface as functions of time.
Figure 11. Poloidal distribution of (a) impurity radiation power and (b) the normalized $n = 1$ normal component of perturbed magnetic field $B_{r,n=1}$ (flushed color), which are measured on the $q = 2$ surface (denoted as the red circle in the sketch), and the poloidal velocity $V_\theta$ (orange solid line) as functions of time. (c) The poincare plot (red dot) and impurity radiation power in the poloidal plane.
Figure 12. (a) The integral of perpendicular vortex $\int U_\perp dS = \int \nabla_\perp V dS$ in the poloidal plane (orange solid line) and radial location of the perturbed electron density peak $\max(\delta n_e)$ (blue solid line) as functions of time. (b) The integral of perpendicular vortex $\int U_\perp dS = \int \nabla_\perp V dS$ in the poloidal plane, and (c) the radial location of impurity radiation peak as functions of time for cases with different inclusions of toroidal mode numbers.

5. Summary and discussion

The successive formation of TMs observed during an impurity penetration process on EAST has been well reproduced in our 3D resistive MHD simulations using the NIMROD code with good agreement on several main features. The $4/1, 3/1$ and $2/1$ TMs grow in sequence after the arrival of impurity radiation peak on the corresponding rational surfaces, and the island rotation slows down gradually with the impurity accumulation. The surface-averaged component of current perturbation induced by the impurity penetration and radiation cooling is found to be responsible for driving the initial island growth. The perturbed Pfirsch–Schlüter current due to enhanced pressure gradient perturbation shows its stabilization effect, whereas after the island saturation, the corresponding helical current responsible for the island is mainly maintained by the plasma resistivity perturbation due to the radiative cooling. Higher-$n$ modes are found to introduce additional braking effects on the island rotation, and more importantly the impedance to the impurity inward penetration.

Whereas this work demonstrates the causal relation between the current perturbation induced by impurity radiation and the magnetic island growth, and in particular the roles of the higher-$n$ modes, more quantitative model and analyses are to be developed in future work. The correlation between impurity penetration and island growth is specific to the parameters of our particular simulation. Impurity radiation may not play a significant role in clean, high temperature plasmas as are needed for fusion reactors. Certainly the massive changes in current profile would not be seen under normal operational conditions, even though the designed level of impurity injection may be introduced and managed to initiate the TM growth and island rotation.
for the disruption mitigation or control purpose, among others.

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