Low-
$n$
 global ideal MHD instabilities in the CFETR baseline scenario

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Abstract

This article reports an evaluation on the linear ideal magnetohydrodynamic (MHD) stability of the China Fusion Engineering Test Reactor (CFETR) baseline scenario for various first-wall locations. The initial-value code NIMROD and eigen-value code AEGIS are employed in this analysis. Despite the distinctly different approaches in modeling the scrape off layer region, the dominant growth in each of the low-
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$\mathbf{n}$(\mathbf{n}=1−10) modes are consistent between the two codes. The higher-
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$\mathbf{n}$ modes are dominated by ballooning modes and localized in the pedestal region, while the lower-
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$\mathbf{n}$ modes have more prominent external kink components and broader mode profiles. The influence of the plasma-vacuum profile and wall shape are also examined using NIMROD. In the presence of a resistive wall, the low-
n ideal MHD instabilities are further studied using AEGIS. For the designed first-wall location, the \(n=1\) resistive wall mode is found to be unstable, which could be fully stabilized by uniform toroidal rotation above the 2.9% core Alfvén speed.

Keywords: CFETR, ideal MHD, global instability, RWM, rotation, NIMROD, AEGIS

1. Introduction

Besides being a partner in the International Thermonuclear Experimental Reactor (ITER) [1], China has recently proposed to design and potentially build the China Fusion Engineering Test Reactor (CFETR) [2]. The goal is to address the physics and engineering issues essential for bridging the gap between ITER and DEMO (the DEMOnstration Power Station), including achieving a tritium breeding ratio (TBR) > 1 and exploring options for DEMO blanket and divertor solutions [3, 4]. A conceptual engineering design for CFETR, including different coils and remote maintenance systems was prepared at the beginning [5]. The initial design parameters of CFETR are based on a 0-D analysis [2], and were later optimized using several 1.5D transport codes [3]. To achieve the staged goals, the CFETR has been designed for two steady-state scenarios - baseline and advanced scenarios [4]. The baseline scenario is designed for moderate fusion power (200 MW) with a fully non-inductive current drive, giving more importance towards a challenging annual duty factor of 0.3 – 0.5. The advanced design is aimed at higher fusion power with a substantial challenging fraction of bootstrap current drive.

In the baseline scenario, the current drive sources are deposited on the far off-axis, and as a result there is a reversed magnetic shear with the minimum safety factor \(q_{\text{min}} > 2\) located at an outer radius [6]. Fully non-inductive operation requires...
at least 36% of the bootstrap current fraction (see table-1 of [7]), which leads to high pedestal pressure gradient and peaked edge current. Such a configuration is expected to be unstable to both ballooning and external kink modes [8]. In principle, the external kink modes, which have the potential to lead to plasma disruptions, are dominantly low-\(n\) modes and may have strong interactions with the first-wall [9, 10]. The high-\(n\) modes are more dominated by the peeling-balloonning modes that are localized near the edge. The edge-localized modes (ELMs) are less dangerous, but the repetitive expulsion of stored plasma energy and particles due to ELMs would degrade plasma confinement and damage the divertor and first-wall components.

To provide a physics base for the engineering design on the optimal choice of the first-wall position of CFETR, a thorough evaluation of \(n = 1 – 10\) modes is performed in this paper. Assuming the plasma is surrounded by a conformal and perfect conducting first-wall, the dependence of growth rates for \(n = 1 – 10\) modes on the wall position are evaluated using the initial value extended-magnetohydrodynamic (MHD) code NIMROD [11] and the eigenvalue code AEGIS [12]. With a perfect conducting wall located at the designed wall position, the most dangerous \(n = 1\) mode is found to be stable. Considering in practice that the first-wall is not perfectly conducting, the \(n = 1\) ideal MHD mode would be actually the resistive wall mode (RWM), which grows in the wall-resistive time scale. In last two decades, toroidal plasma rotation has been found to have stabilizing effects on RWMs [13–16]. We employ AEGIS code to evaluate the rotational stabilizing effects on RWMs in the CFETR baseline scenario. The rotation threshold where the \(n = 1\) RWM growth can be fully suppressed is found.

This paper is organized as follows. In section 2, the equilibrium profiles of the baseline scenario are introduced. Section 3 describes the resistive single-fluid MHD model in NIMROD and AEGIS codes. Section 4 reports the calculations for low-\(n\) ideal MHD modes in the presence of a perfect conducting wall using both NIMROD and AEGIS codes. Effects of more realistic plasma-vacuum profiles and wall shape are discussed in section 5. In section 6, rotational effects towards the stabilization of RWMs are presented. Conclusions and discussions are given in section 7.

2. Equilibrium of CFETR baseline scenario

The equilibrium of the CFETR baseline scenario considered in our calculation was generated through integrated modeling in the OMFIT framework [7]. The plasma size is slightly smaller than ITER, with a major radius of 5.7 m and a minor radius of 1.6 m. The toroidal magnetic field (5 T) and the plasma current (10 MA) at the magnetic axis are listed in table 1 of reference [7], among others. Since the baseline case is not designed for demonstrating high fusion gain, the normalized \(\beta_N\) is set to 1.88. Both density (figure 1(a)) and temperature (figure 1(b)) profiles show an edge pedestal region inside the last closed flux surface (LCFS). The safety factor (\(q\)) profile has a strong reverse shear region (figure 1(c)) with \(q_{\text{min}} > 2\). The current density profile has highly peaked edge current due to a high fraction of bootstrap current (figure 1(d)).

3. MHD model in NIMROD and AEGIS

The MHD equations used in our NIMROD calculations are:

\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times [\eta \mathbf{J} - \mathbf{u} \times \mathbf{B}] 
\]

where \(\mathbf{u}\) is the center-of-mass flow velocity with particle density \(N\) and ion mass \(m\), \(\mathbf{J}\) is the plasma current, \(\mathbf{B}\) is the magnetic field, \(p\) is the plasma pressure, \(\eta\) represents the resistivity, \(\Pi\) is the ion viscous stress tensor, \(\gamma\) is the adiabatic index, and \(\mu_0\) is the permeability of free space. The initial value NIMROD code has been consistently used in studying different macroscopic phenomena in both fusion and space plasmas [17–19].

The AEGIS code solves the ideal MHD eigenvalue equation employing the adaptive shooting method along the radial direction and the Fourier decomposition in the poloidal and toroidal directions. This code has been applied before in evaluating the stability of ideal MHD modes in the presence of either conducting or resistive wall for ITER [15, 20]. In AEGIS, the ideal MHD model is used for the plasma region within separatrix, and the scrape off layer (SOL) region extends from the separatrix to the first wall. AEGIS code considers the SOL (‘halo’) region as a pure vacuum, whereas in NIMROD code the same region is modeled with low-temperature halo plasma that is vacuum-like.

A thorough convergence check has been performed for the numerical calculation results in this study. Using NIMROD, growth rates of all \(n = 1 – 10\) modes are found to reach numerical convergence for all below cases with the following parameters: the radial grid number is 96, poloidal grid number 240, time step \(5 \times 10^{-8}\) s and polynomial degree 6. The radial grids are packed near the plasma-vacuum boundary and the poloidal grids are packed near the X-point (figure 2(a)). In AEGIS, up to 1356 radial shooting grids are used for calculating the \(n = 10\) eigenfunction. The radial grids are compacted at the rational surfaces and pedestal region in the AEGIS code (figure 2(b)), which are specified by the truncation surface near the plasma edge and the corresponding cutting-off safety factor \(q_a\) value (\(q_a = 4.156\)).
Figure 1. Profiles of (a) electron density, (b) ion temperature, (c) safety factor and (d) current density in CFETR baseline equilibrium. $\psi_N$ is the normalized poloidal flux function.

4. Dominant low-n ideal MHD instabilities in presence of perfect conducting wall

For the purpose of benchmark and comparison, a step-like hyperbolic tangent resistivity profile is adopted in NIMROD to model the ideal core plasma and the vacuum-like halo region, where the Lundquist number (defined as $S = \tau_R / \tau_\lambda$) of core plasma region $S_{\text{plasma}} \sim 10^{10}$ and halo region $S_{\text{halo}} \sim 10^2$ (figure 3). Here, $\tau_R = \mu_0 a^2 / \eta$ is the resistive diffusion time with $a$ being the minor radius and $\tau_\lambda = R_0 \sqrt{\mu_0 \rho_0 a / B_0}$ the Alfvén time with $R_0$ being the major radius of the magnetic axis, $B_0$ and $\rho_0$ the values of magnetic field and mass density at magnetic axis respectively. $S_{\text{plasma}}$ and $S_{\text{halo}}$ have been scanned to identify their asymptotic values of ideal MHD regime respectively, where the two codes should agree (figure 4).

Employing this resistivity model, we are able to study the $n = 1 - 10$ ideal MHD modes using NIMROD. In figure 5(a), the $n = 1, 3, 5, 8$ ideal MHD growth rates are calculated for a range of perfect conducting wall locations ($r_w$), from being close to LCFS to $r_w = 2a$. We find that the growth rates of all $n$ modes reach the no-wall limit at a close proximity to LCFS, suggesting a weak dependence on the conducting wall position. This finding differs from AEGIS, where the ideal wall limit is reached only far away from plasma boundary, especially for lower-$n$ modes (figure 5(a)). For the designed wall location $r_w = 1.2a$, AEGIS (NIMROD) finds $n = 1$ mode stable (unstable). However, good agreement is achieved for growth rates of all $n = 2 - 9$ modes between AEGIS and NIMROD (figure 5(b)). We note that whereas the separatrix is included in the NIMROD computation domain, the AEGIS computation domain only considers the truncated plasma region inside the separatrix. As demonstrated in [21], the calculated growth rates from AEGIS depend on the cutting-off safety factor value $q_a$ at the edge truncation, which may contribute to the remanent discrepancy from NIMROD. In
addition, the disagreement on the continuity of current profile at the LCFS, as captured by the different domains and models around the LCFS in the two codes, may further confound the validation exercise.

The variations in mode structure for different toroidal numbers $n$ are also consistent between NIMROD (figure 6) and AEGIS (figure 7). Whereas both plasma and SOL (‘halo’) regions are included in the NIMROD computation domain, the AEGIS computation domain only covers the truncated plasma region inside the separatrix. Nonetheless, within the same plasma region inside the separatrix, the mode structures from the two codes agree with each other. In particular, such agreements are evident from the contours of the perturbed radial velocity $V_r$ in the plasma region inside the separatrix from NIMROD and the perturbed radial displacement $\zeta$ from AEGIS for the $n=1$ mode at $r_w = 1.35a$ (figure 8(a)-(b)).
Figure 4. Growth rates of $n = 2, 4, 8$ modes for the step-like hyperbolic tangent function resistivity model as functions of (a) plasma Lundquist number ($S_{\text{plasma}}$) with fixed $S_{\text{vac}} \sim 10^2$ and (b) vacuum Lundquist number ($S_{\text{vac}}$) with fixed $S_{\text{plasma}} \sim 10^{10}$.

Figure 5. (a) Ideal MHD growth rates as functions of the perfect conducting wall location for $n = 1, 3, 5, 8$, from NIMROD and AEGIS calculations. (b) Ideal MHD growth rates versus toroidal number $n$ with perfect conducting wall at position $r_w = 1.2a$ from NIMROD and AEGIS calculations. 

as well as the poloidal mode structures on the $q = 3.94$ flux surface and the LCFS for $V_r$ and $\xi$ from the two codes, respectively (figure 8(c)–(d)). The mode poloidal numbers, widths, and phases are found to be consistent between the results from the two codes, except for the X-point region in the NIMROD computation domain which is absent in the AEGIS results.

For the perturbed magnetic field and velocity from NIMROD calculations, the mode structures in the poloidal plane are apparently different between the low $n$ modes and the high $n$ modes. The $n = 1, 2$ mode structures are broader and the magnetic field and velocity perturbations extend well into the SOL region across separatrix, whereas the $n = 8$ mode structure is much narrower and localized in the pedestal region inside separatrix (figure 6). For the perturbed radial displacements from AEGIS calculations, the two dominant components $m = 4, 5$ ($m = 8, 9$) of the $n = 1$ ($n = 2$) mode are peaked near the edge region, and the $m = 5$ ($m = 9$) component has the typical profile of an external kink mode. For $n = 8$ mode, all $m$ components are localized in the pedestal region near edge.

5. Effects of realistic plasma-vacuum profile and wall shape

The stability of $n = 1 − 10$ modes has been re-evaluated using NIMROD after considering the more realistic resistivity profile based on the Spitzel model (figure 3), i.e. $\eta = \eta_0(T_{e0}/T_e)^{3/2}$, where $T_{e0}$, $\eta_0$, $T_e$ denote the electron temperature, the resistivity at magnetic axis and the electron temperature profile respectively. The same $\eta_0$ is used for both the Spitzer model and the step-like resistivity profile. The gradient of the resistivity profile in the plasma-vacuum interface in the Spitzer model is smaller than the steep step-like model. The gradient of resistivity of is known to give rise to the rippling instability [22]. Thus the step-like resistivity
profile is expected to be more unstable. The normalized ideal MHD growth rates of \(n = 1, 2, 3, 5, 8, 10\) are plotted in figure 9 with a self-similar wall position varying from close to separatrix to \(r_w = 1.8a\). A particular wall position \(r_w = 1.04a\) is identified where no mode is found unstable inside. The growth rates of all modes increase rapidly until the wall position \(1.2a\) is reached. Afterwards, they gradually approach their corresponding no-wall limit values. The wall positions for all modes transitioning to the no-wall limit are basically the same, and the growth rate at the no-wall limit increases monotonically with mode numbers from \(n = 2\) to \(n = 10\). The presence of the Spitzer resistivity profile stabilizes the \(n = 1\) mode which is found to be unstable using the hyperbolic tangent resistivity profile (figure 9 and 5(a)). This finding is consistent with earlier studies using NIMROD in the context of other tokamaks such as NSTX and JT-60U [18, 23].

All the above numerical results from both the NIMROD and AEGIS calculations are based on non-uniform density profiles with high gradient in pedestal region. The density pedestal gradient has driven the \(n = 2 - 10\) modes to become more unstable than the uniform density case (figure 10(a)). The higher the toroidal mode number, the stronger the influence of the density pedestal on growth rate. Here, the level of uniform density is kept the same as the value of density profile at the magnetic axis, therefore the normalizing Alfvén time scale (\(\tau_A = 6.627 \times 10^{-7}s\)) is the same for both density cases. The modification to the local Alfvén velocity modifies the mode growth rate. For \(n \leq 4\), the mode structures locate more into the SOL region outside the separatrix, therefore the modification to the local Alfvén speed due to non-uniform density profile inside the separatrix has less impact on these modes. In contrast, the growth rates of modes with \(n > 4\) are affected more by the non-uniform density profile since they are located more towards plasma edge inside the separatrix.

The growth rate calculations of different modes have also been carried out after considering recently proposed real first-wall configuration of CFETR (shown in figure 12 as the boundary of contour). The designed first-wall position is near
Figure 7. Real component of radial displacements for (a) $n = 1$ ideal MHD modes with perfect conducting wall at position $r_w = 1.35a$, (c) $n = 2$ with $r_w = 1.2a$, and (e) $n = 8$ with $r_w = 1.2a$, respectively, and color contours of radial displacements for (b) $n = 1$, (d) $n = 2$, and (f) $n = 8$, respectively. The domain boundary is the plasma boundary used in AEGIS code.

the wall location of $r_w = 1.2a$, but the shape is different from the self-similar wall often used in MHD stability calculations. A stabilizing effect of a real first-wall shape is noticed for higher-$n$ modes, whose growth rates are close to those with the self-similar wall at $r_w = 1.08a$, whereas for low-$n$ modes, their growth rates are similar to the self-similar wall at $r_w = 1.2a$ (figure 10(b)).

All unstable modes have radial structure only localized at the edge pedestal region, close to the inside of separatrix which is indicated by black lines of poloidal flux contour (figures 11–12). The positions and shapes of mode structure of these two different wall shapes are essentially the same. The spatial structure of the $n = 10$ mode is more radially localized than that of the $n = 3$ mode.
6. Rotational stabilization on resistive wall mode

$\beta_N$ in the baseline scenario is 1.88, well below the no-wall $\beta$ limit expected from the experimental scaling law $\beta_{N, no-wall} \sim 4l_i = 2.52$, where $l_i$ is the plasma inductance [24]. However, the above results from both NIMROD and AEGIS suggest that at the no-wall limit, the long-wavelength $n = 1$ mode in the CFETR baseline scenario could be unstable. This is contrary to the expectation that normally such a low $\beta_N$ would help this equilibrium to lie within the stability limits of global ideal MHD modes. The strong reversed shear in the core region could be the main reason for the difference between the expectation from the scaling law and our calculation results in terms of the no-wall $\beta$ limit. For example, in experiments on DIII-D and JET [25, 26], it is found that for a reversed or near reversed shear $q$ profile, the no-wall $\beta$ limit is approximately $\beta_{N, no-wall} \sim 2.5 l_i$. In the previous theoretical study, the $\beta_{N, no-wall}$ of the $n = 1$ mode is found to be significantly lower in the reversed shear $q$ profile case than the monotonic $q$ case [27].

The linear growth rate of $n = 1$ RWM is calculated using AEGIS code with the assumption of a thin, conformal wall. The resistive diffusion time of the wall $\tau_w = \mu_0 \bar{r}_w d/\eta_w \sim 10$ ms is used for normalizing the RWM growth rates, where $\bar{r}_w$ is the average minor radius of the wall, $d$ is the wall thickness, and $\eta_w$ is the wall resistivity. In the case of a static equilibrium, the growth rate monotonically increases with the wall position from the plasma boundary to $r_c = 1.31a$ (the blue dashed line in figure 13). This $r_c$ is the critical wall position (vertical dashed line) where the mode turns into a fast growing ideal-wall mode.

Long term steady-state operation requires stabilization of $n = 1$ RWM. The toroidal rotation may open a stable window for the RWM near the critical wall position. The width of the stable window is determined by rotation
Figure 9. Low-n global mode growth rates as functions of the perfect conducting wall location for different toroidal numbers using plasma-vacuum profiles of (a) Spitzer and (b) step-like hyperbolic tangent function resistivity models, respectively, from NIMROD calculations.

Figure 10. Growth rates of ideal MHD modes as functions of toroidal mode number \(n\) (a) with perfect conducting wall at position \(r_w = 1.2a\) for uniform and non-uniform density profiles, and (b) for different shapes of perfect conducting wall.

speed \([13, 15, 28, 29]\). Such results for CFETR are summarized in figure 13 for uniform plasma rotation with frequency from \(\Omega = 0\) to \(\Omega = 3.5\%\Omega_A\), where \(\Omega_A\) is the Alfvén frequency evaluated at magnetic axis. For the designed wall configuration \(r_w = 1.2a\), full stabilization can be achieved at \(\Omega = 2.9\%\Omega_A\). The global mode structure becomes more localized to the edge region as \(\Omega\) increases from 0 to 2.9\%\(\Omega_A\) (figure 14). In the CFETR baseline scenario, the rotation frequency is around 15 – 80 krad/s (~1% – 5\%\(\Omega_A\)), slightly larger than the prediction for ITER (10 – 20 krad/s, ~0.7% – 1.5\%\(\Omega_A\)) in \([6, 30]\).

7. Summary and discussions

In summary, despite the distinctly different approaches between the eigenvalue code AEGIS and initial value code NIMROD in modeling the SOL region, our linear stability analysis of the CFETR baseline scenario has found that the dominant growth in each of the low-n \((n = 1 – 10)\) modes are consistent between the two codes. The external kink component, which leads to the global mode structure in these low-n modes, gradually reduces as \(n\) increases. All the growth rates approach the corresponding no-wall limits when the wall is moved sufficiently far away. The effects of different plasma-vacuum profile models and wall shapes are examined. The Spitzer resistivity profile and the designed wall geometry are found to be more stabilizing, whereas the presence of an edge density pedestal tends to be destabilizing.

For the resistive wall, the \(n = 1\) mode is found to be unstable for a wall location \(r_w < 1.31a\). The toroidal rotation required for full suppression of the \(n = 1\) RWM with a wall location \(r_w = 1.2a\) is determined to be \(\Omega = 2.9\%\). The effects of
Figure 11. Dominant linear mode structures in presence of Spitzer resistivity profile and self-similar conducting wall at position $r_w = 1.2a$ as shown in the color contours of the radial components of: (a) perturbed $B_r$ of $n = 3$ mode, and (b) perturbed $V_r$ of $n = 3$ mode, and (c) perturbed $B_r$ of $n = 10$ mode, and (d) perturbed $V_r$ of $n = 10$ mode. The location of separatrix is indicated by black contour lines of poloidal flux.
Figure 12. Dominant linear mode structures in presence of Spitzer resistivity profile and the proposed real first-wall as shown in the color contours of the radial components of: (a) perturbed $B_r$ of $n = 3$ mode, and (b) perturbed $V_r$ of $n = 3$ mode, and (c) perturbed $B_r$ of $n = 10$ mode, and (d) perturbed $V_r$ of $n = 10$ mode. The proposed real first-wall configuration is shown as the boundary of the contours.
Figure 13. The $n = 1$ RWM growth rates as functions of wall position for different toroidal rotation frequencies. The critical wall position for ideal-wall external kink mode is plotted as the vertical dot-dashed line.

Figure 14. Real component of the radial displacements for the unstable $n = 1$ RWM (a) in absence of rotation and (b) in presence of toroidal rotation (frequency $\Omega = 2.9\%\Omega_A$) with the wall position $r_w = 1.2a$, respectively.

trapped and energetic particles [31, 32], as well as diamagnetic drift [20] may further reduce the rotation threshold for RWM stabilization. These additional passive stabilizing mechanisms are next to be included in stability analysis for the CFETR baseline scenario.

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