Impact of edge cooling on current profile evolution and resistive wall tearing stability in JET

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Abstract

Edge cooling preceding disruptions can significantly modify the current density profile, potentially destabilizing tearing modes. In this work, we investigate the influence of current density evolution on resistive wall tearing mode (RWTM) stability using a newly developed linear solver benchmarked against JOREK–STARWALL and CASTOR3D. The validated framework is subsequently applied to a realistic JET discharge in which edge cooling was observed prior to the disruption to study the evolution of the current profile and the onset of MHD activity.

1 Introduction

Disruptions in tokamaks are often preceded by magnetohydrodynamic (MHD) activities associated with changes of the plasma current density profile [1]. In part of JET discharges, strong edge cooling has been observed prior to disruption onset, leading to substantial redistribution of the plasma current and the appearance of low-n MHD modes, where n is the toroidal harmonic mode number. Understanding whether these profile modifications can destabilize tearing modes, and how conducting structures surrounding the plasma influence this process, is important for disruption prediction in present-day devices and future reactors.

Recent theoretical work has emphasized the role of wall properties in the onset of MHD instabilities by introducing resistive wall tearing modes (RWTMs) [2] that are stable in the ideal-wall limit but become unstable when sufficiently high wall resistivity is considered. Such modes provide a possible mechanism linking gradual current profile evolution to pre-disruptive non-linear MHD activities. However, their role in realistic tokamak plasmas undergoing transient edge cooling remains largely unexplored.

In this work, a newly developed linear tearing-mode solver is first used to identify stability boundaries and quantify the influence of wall properties on tearing mode growth rates. The results are benchmarked against JOREK–STARWALL and CASTOR3D simulations. Building on this framework, JOREK simulations are performed for a realistic JET discharge in which edge cooling is introduced through impurity radiation. The impurity mixture is varied to reproduce the experimentally measured radiation and temperature evolution, providing experimentally realistic initial conditions for subsequent 3D MHD simulations of the observed MHD activity.

2 Linear stability analysis

To investigate the role of wall resistivity on tearing-mode stability, a semi-analytical linear solver has been developed based on cylindrical resistive-MHD theory shown in Ref. [3]. The solver evaluates the tearing mode stability parameter Δ' and the corresponding linear growth rate while consistently accounting for arbitrary wall distances and wall resistivity values. Extending previous approaches

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restricted to the ideal-wall and no-wall limits [2], the present model resolves the continuous transition between these regimes.

Systematic scans of current density profile shapes and wall properties reveal the existence of RWTM regimes in which a plasma stable in the ideal-wall limit becomes unstable when the wall resistivity exceeds a critical value. The stability boundary shown in Fig. 1(a) corresponds to the marginal tearing-mode stability condition, $\Delta' = 0$. The calculations show that wall resistivity (η_w) shift the marginal stability boundary between TM and RWTM regime toward a larger unstable TM region. The linear solver identifies a finite region of parameter space where RWTMs exist, providing guidance for selecting equilibria for nonlinear JOREK–STARWALL test-case simulations.

The predictions of the linear solver have been benchmarked against linear JOREK–STARWALL simulations and CASTOR3D calculations. Good agreement is obtained for both growth rates and mode structures over a broad range of wall resistivities and equilibrium parameters, as seen in Fig. 1(b). In addition, RWTM solutions are identified in both simulation frameworks, providing the first cross-code validation of these modes. These results establish confidence that the simplified model captures the essential physics governing wall-influenced tearing-mode stability and can therefore be used as a fast diagnostic tool for interpreting profile evolution in more realistic plasmas.

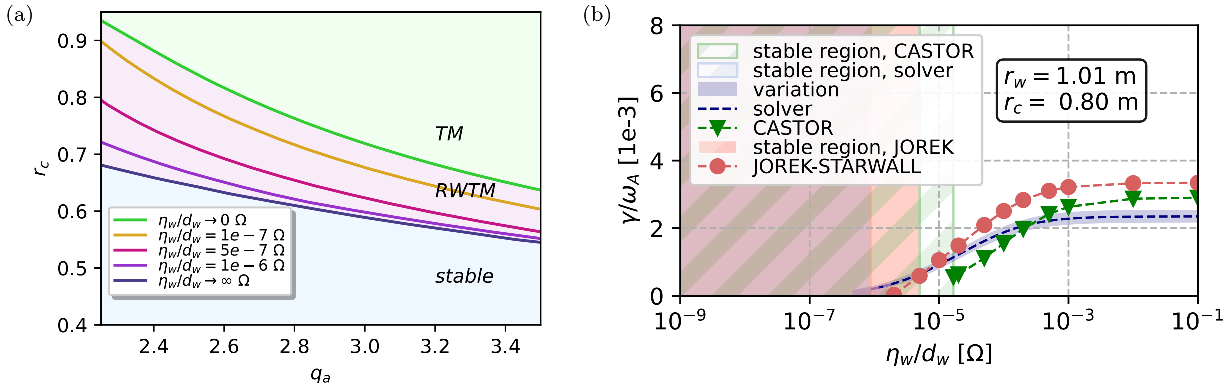

Figure 1: (a) Marginal stability diagram for $r_w = 1.01\,\mathrm{m}$. Three regimes are identified: stable configurations, conventional (TMs), and (RWTMs), which are stable with an ideal wall but become unstable above a critical wall resistivity. (b) Benchmark of the linear solver (blue) against JOREK–STARWALL (red) and CASTOR3D (green) for the 2/1 mode growth rate as a function of wall resistivity (the cutoff parameter for current denstiy profile is $r_c = 0.80\,\mathrm{m}$, $r_w = 1.01\,\mathrm{m}$). Shaded regions denote stable configurations.

3 Simulation of edge cooling in a JET discharge with JOREK

To investigate the physical mechanism leading to the observed pre-disruption MHD activity, simulations are being performed for a JET discharge that exhibited strong edge cooling and interesting locked mode characteristics prior to the disruption. Figure 2 summarizes the experimental observations preceding the disruption. Between 64.08 s and 64.14 s, total radiated power, following the increase of the electron density, while the electron cyclotron emission (ECE) measurements show an edge cooling front propagating inward. Following this cooling phase, a quasi-periodic locked mode develops and persists until the disruption. Meanwhile, $n = 1$ and $n = 2$ rotating modes are observed. The increase in radiated power suggests enhanced impurity radiation and consequent edge cooling during this time interval. Since the plasma resistivity increases with decreasing temperature, the cooling modifies the current diffusion and leads to a redistribution of the plasma current. Such changes in the current density profile, particularly in the current gradient near rational surfaces, may destabilize of current-driven (resistive wall) tearing modes.

The present work focuses on reproducing the edge-cooling phase (marked by the blue vertical lines in Fig 3) preceding the onset of MHD activity, while reproducing the experimentally observed

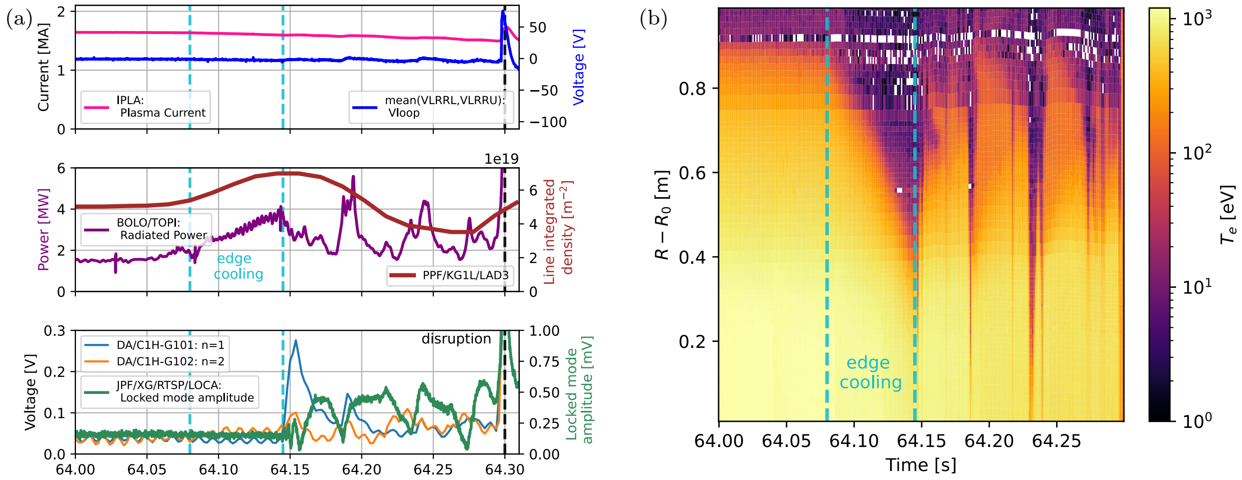

Figure 2: Experimental overview of JET discharge #81540. (a) Time evolution of (a.1) plasma current and loop voltage, (a.2) line-integrated density and total radiated power measured by the bolometer, and (a.3) locked-mode, $n = 1$ and $n = 2$ rotating mode signals. (b) Electron temperature evolution measured by ECE as a function of major radius. The vertical dashed lines indicate the beginning and end of the edge-cooling phase (blue) and the disruption time (black).

MHD evolution self-consistently is left for future work. 2D simulations are performed with JOREK by introducing impurity radiation, while the impurity species and concentrations are adjusted to reproduce the experimentally observed evolution of the radiated power and electron temperature. A major part of this work has been the determination of the impurity content such that both the total radiated power and the electron temperature evolution measured by ECE diagnostics are reproduced simultaneously.

Several impurity species have been investigated. Nickel and tungsten are intrinsic metallic impurities originating from plasma-wall interactions in JET, while residual carbon and oxygen have also been observed during ITER-like wall operation [4]. Oxygen was additionally considered because it can be present in JET plasmas depending on the vacuum conditions. Furthermore, its radiative cooling rate peaks at relatively low electron temperatures, making it particularly effective at reproducing the experimentally observed edge cooling while contributing comparatively little to radiation from the hotter plasma core [5]. The best agreement was obtained for an impurity mixture of $n_\mathrm{C} = 2 \cdot 10^{17}, \mathrm{m}^{-3}$, $n_\mathrm{Ni} = 1 \cdot 10^{16}, \mathrm{m}^{-3}$, $n_\mathrm{O} = 2 \cdot 10^{18}, \mathrm{m}^{-3}$, and $n_\mathrm{W} = 1 \cdot 10^{15}, \mathrm{m}^{-3}$, resulting in a total radiated power of approximately $P_\mathrm{rad} = 3.5$ MW, in good agreement with the bolometer measurements.

Figure 3 shows the comparison between the simulated and experimentally measured electron temperature evolution, together with the resulting evolution of the current density profile from JOREK. Although the simulated electron temperature profiles do not reproduce the ECE measurements exactly, the edge cooling is captured well. In particular, the edge temperature decreases significantly, with the cooling front propagating inward from approximately $R - R_0 \approx 0.9$ m to 0.75 m during the simulated time interval. Further improvement of the agreement with the ECE measurements is expected from a refined impurity composition, in particular by increasing the tungsten concentration.

The edge cooling has a clear impact on the current density profile. This demonstrates that the experimentally observed edge cooling can produce substantial modifications of the current density profile, supporting the hypothesis that it may provide favourable conditions for the destabilization of tearing modes. The obtained solution therefore represents a promising starting point for the subsequent three-dimensional nonlinear MHD simulations. These simulations are currently being extended to investigate whether the experimentally observed locked mode and the subsequent MHD evolution can be reproduced self-consistently from the edge-cooling-induced current profile evolution.

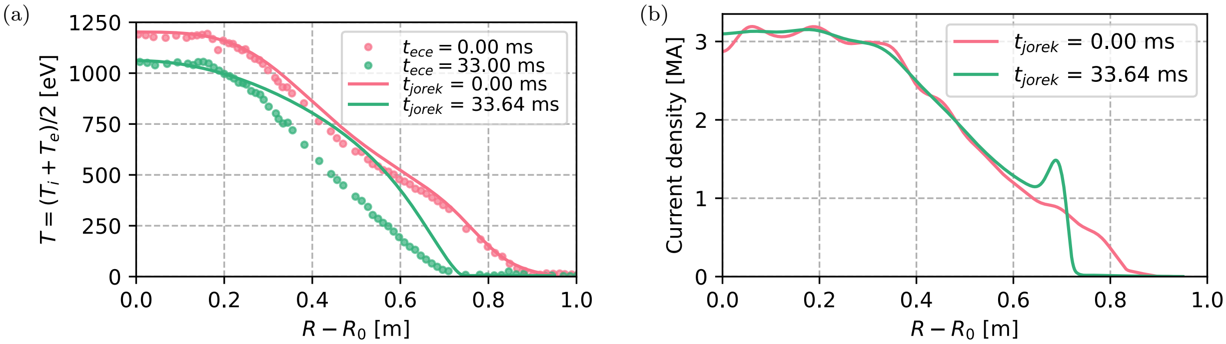

Figure 3: Comparison of the experimentally observed and simulated edge cooling for the best-fitting impurity mixture. (a) Comparison of electron temperature profiles measured by ECE and obtained with JOREK at selected times during the edge-cooling phase. (b)Toroidal current density profiles from JOREK at the beginning and end of the edge-cooling phase, illustrating the current redistribution induced by the decrease in edge temperature.

4 Conclusions

A linear tearing-mode solver has been newly developed and benchmarked against JOREK–STARWALL and CASTOR3D, demonstrating good agreement in the prediction of RWTM stability. This provides confidence in using JOREK-STARWALL for further RWTM studies with realistic tokamak plasmas. Moving to the initial modeling of pre-disruptive JET discharge with JOREK, the simulations reproduced the observed edge cooling and showed a significant redistribution of the plasma current. These results support the hypothesis that edge cooling can modify the current density profile sufficiently to promote tearing-mode destabilization. These simulations provide experimentally relevant initial conditions for ongoing three-dimensional nonlinear MHD studies with JOREK.

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