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ELM SUPPRESSION BY ECCD-CONTROLLED BENIGN MHD MODES IN THE KSTAR TOKAMAK

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Abstract

Stationary suppression of edge-localized modes (ELMs) has been observed in KSTAR through the amplification of a benign core magnetohydrodynamic (MHD) mode via electron cyclotron current drive (ECCD). The amplified core mode induced a magnetic island at the plasma edge, resulting in ELM suppression. Diagnostic measurements reveal core-edge coupling, connecting the kink-mode in the core to the magnetic island at the edge. Notably, ELM suppression was obtained without electron density reduction, thereby preserving electron particle confinement. However, during the ELM-suppressed phase, significant accumulation of carbon impurities and enhanced toroidal rotation damping were observed. The underlying physics is discussed in terms of modified pedestal transport and neoclassical toroidal viscosity. These findings suggest a promising operational scenario for future fusion devices, utilizing MHD modes for ELM control.

1. INTRODUCTION

The high-confinement mode (H-mode) is a baseline operational scenario for future fusion devices such as ITER, as it significantly improves plasma energy confinement. This improvement is attributed to the formation of a steep pressure gradient at the plasma edge, known as a pedestal. However, the steep pressure gradient drives periodic bursts known as edge-localized modes (ELMs). Large ELMs lead to the expulsion of significant particle and heat fluxes onto plasma-facing components (PFCs), which can severely damage and limit the lifetime of divertor components in future large-scale devices [1]. Therefore, the development of effective ELM control techniques is a critical issue for the successful operation of ITER.

In this work, we present experimental results from KSTAR demonstrating a stationary ELM suppression regime. The suppression is observed when a benign core magnetohydrodynamic (MHD) mode is amplified via electron cyclotron current drive (ECCD). This amplified core mode subsequently induces a magnetic island at the plasma edge, leading to complete ELM suppression. Diagnostic measurements reveal a core-edge coupled structure in which the core kink-mode is connected to the edge magnetic island. Notably, the electron density increases during the ELM suppression; however, this favorable behavior is accompanied by significant accumulation of carbon impurities. In addition, enhanced toroidal rotation damping is observed. This paper investigates the physical characteristics of this ELM control scenario, the mechanisms underlying the core-edge coupling, and the implications for impurity transport and plasma rotation in future fusion devices.

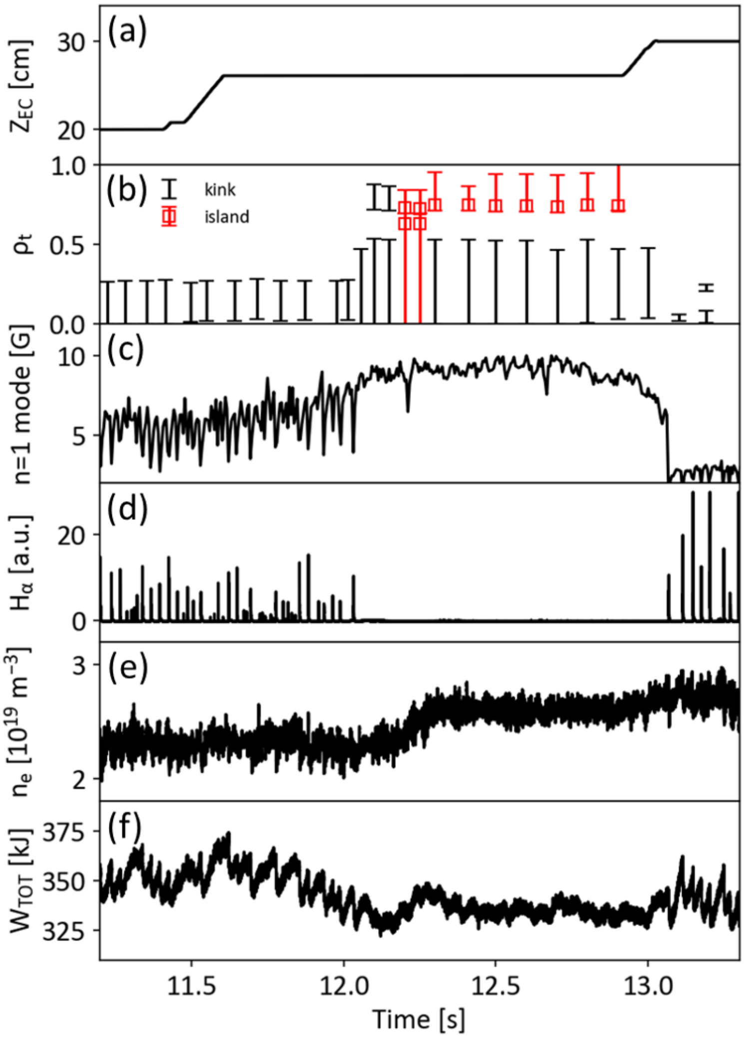

FIG. 1. Time evolution of plasma parameters for KSTAR discharge #23879. (a) Vertical target position of the EC wave (Z_{EC}). (b) Radial position of the core kink-mode (black) and edge magnetic island (red) determined from electron cyclotron emission (ECE) radiometer measurements in normalized toroidal flux coordinate (ρ_{t}). (c) $n = 1$ mode amplitude. (d) Divertor H_α. (e) Line-averaged electron density. (f) Total stored energy.

2. EXPERIMENTAL RESULTS

2.1. Overview of the ELM suppression discharge

The experiments were conducted in KSTAR with a plasma current $I_{\text{p}} = 675$ kA and a toroidal magnetic field of $B_{\text{t}} = 1.9$ T. Figure 1 shows the time evolution of key parameters for discharge #23879 during a scan of the vertical ECCD target location. At this B_{t}, the electron cyclotron (EC) resonance layer is located at the plasma axis (major radius $R = 1824$ mm). A benign MHD mode with toroidal mode number $n = 1$ was already present in the plasma core at the start of the period shown. ECCD was maintained at a vertical position of $Z_{\text{EC}} = +20$ cm until $t = 11.5$ s.

At $t = 11.5$ s, Z_{EC} was adjusted to $+26$ cm, resulting in notable amplification of the pre-existing core mode. As the core mode amplitude increases, a magnetic island structure forms at the plasma edge. With the growth of this coupled core-edge mode structure, ELM activity is completely suppressed. During the ELM-free phase, the line-averaged electron density is observed to increase while the stored energy decreases.

The ELM-suppressed state is stably maintained until $t = 13.0$ s, when Z_{EC} is subsequently moved to $+30$ cm. Fol-

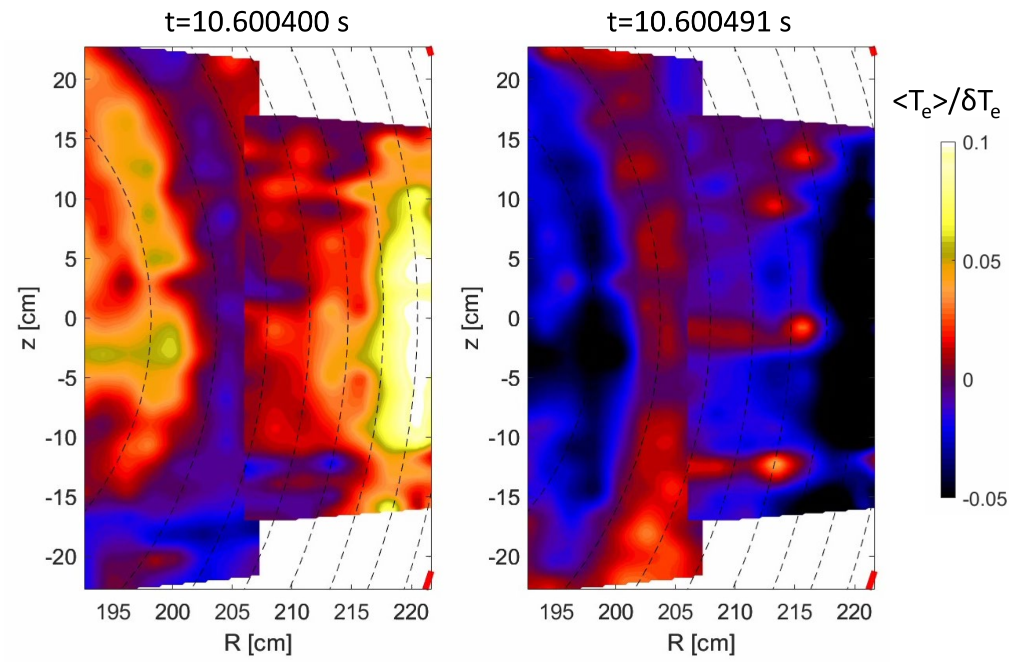

FIG. 2. ECEI measurements of normalized electron temperature (T_e) fluctuation during ELM suppression in discharge #23878.

lowing this change, the mode amplitude decreases, the edge island structure disappears, and the plasma promptly returns to an ELMy H-mode state. This demonstrates a clear correlation between the core-edge coupled MHD structure and ELM suppression.

2.2. MHD mode structure and characteristics

To understand the physical mechanism underlying ELM suppression, the spatiotemporal structure of the MHD mode was investigated using ECE imaging (ECEI) diagnostics. Figure 2 shows ECEI measurements from discharge #23878, which exhibits similar ELM suppression behavior to #23879. The ECEI images reveal the presence of both the core mode and the edge island structure, demonstrating a core-edge coupled structure.

2.3. Confinement and impurity behavior

The preservation of electron particle confinement is a key characteristic of this ELM suppression method. As seen in Figs. 1(e) and 1(f), during the ELM-suppressed phase, the line-averaged electron density slightly increases, while the stored energy shows only a minor reduction compared to the preceding ELMy H-mode.

However, a significant change in impurity behavior is observed during ELM suppression. At the time of these experiments, all PFCs in KSTAR were carbon-based, making carbon the dominant impurity species in the plasma. The carbon density profile is measured by the charge exchange spectroscopy (CES) diagnostic [2]. Figure 3 compares the carbon density profiles at three key time points: the initial ELMy phase, the ELM-suppressed phase, and the post-suppression ELMy phase. During ELM suppression, the carbon density increases substantially across the entire profile compared to the initial ELMy state. Notably, the pedestal gradient becomes steeper. After the mode amplitude decreases and ELMs return (at $t \approx 13.0$ s), the carbon density shows a decrease but remains higher than the initial level.

2.4. Toroidal rotation damping

A significant damping of toroidal rotation is observed during the transition to the ELM suppression. Figure 4 presents the rotation damping in two distinct phases. In the initial ELMy phase, the core mode amplitude gradually increases and the rotation decreases across the entire radial profile over approximately 400 ms. In the subsequent phase, when the edge magnetic island forms and ELMs are suppressed, a rapid collapse of rotation occurs over approximately 60 ms. The damping is particularly pronounced at the plasma edge.

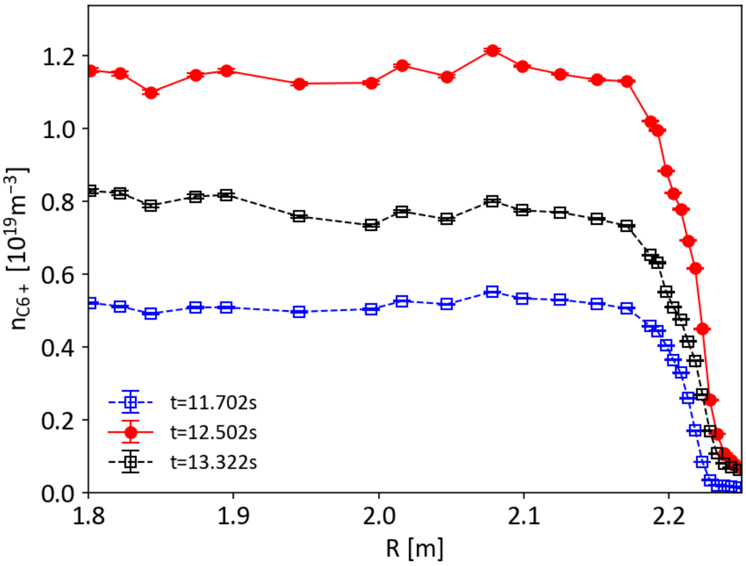

FIG. 3. Comparison of carbon density profiles during the initial ELMy phase ($t = 11.702$ s, open blue squares with dashed line), the ELM-suppressed phase ($t = 12.502$ s, closed red circles with solid line), and the post-suppression ELMy phase ($t = 13.322$ s, open black squares with dashed line).

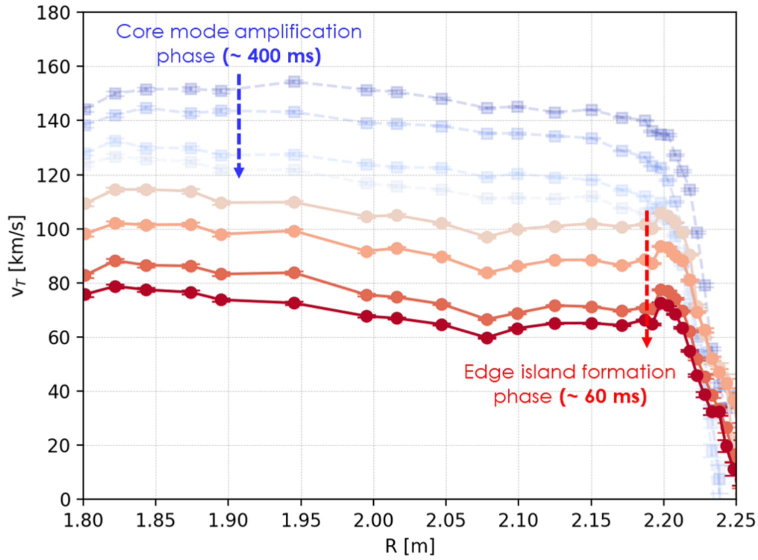

FIG. 4. Time evolution of toroidal rotation profiles during the transition to the ELM suppression in discharge #23879. Profiles are color-coded from light to dark shades to indicate temporal progression. The blue dashed arrow marks the core mode amplification phase (∼ 400 ms, ELMs still present), and the red dashed arrow marks the edge island formation phase (∼ 60 ms, ELM suppressed)

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3. DISCUSSION

The mechanism by which the core-edge coupled structure suppresses ELMs remains under investigation and requires detailed stability analysis. The observed changes in impurity behavior and toroidal rotation, however, provide insights into the plasma response during this regime.

3.1. Carbon impurity transport

The ELM-suppressed phase is characterized by complex changes in transport. A notable observation during the ELM-suppressed phase is the simultaneous increase of both the line-averaged electron density and the carbon impurity density. The formation of an edge magnetic island is generally expected to enhance radial particle transport. This observation points to a regime with improved particle confinement despite degraded energy confinement, likely associated with a reduction in plasma temperature.

Under these conditions, the significant accumulation and steepening of the carbon density gradient suggest that impurity transport is governed by mechanisms distinct from those of the main plasma. While the absence of ELM flushing contributes to the overall increase, the steepened gradient points to a fundamental change in the impurity transport coefficients within the pedestal. This implies either an enhancement of the inward pinch velocity or a reduction of the outward screening effects.

Two primary hypotheses are considered. First, the formation of an induced magnetic island at the plasma edge may alter the plasma-wall interaction, potentially leading to enhanced physical sputtering of carbon. This analysis is particularly relevant given KSTAR's carbon-based PFCs during these experiments. However, with KSTAR's recent upgrade to a tungsten divertor and plans for a full tungsten wall [3], understanding impurity transport in this ELM-suppressed regime is critical for future operations.

Second, the transition from an ELMy to an ELM suppression fundamentally alters impurity transport dynamics. The transport of impurities is determined by a balance between the outward neoclassical temperature screening effect, which is driven by the main ion temperature gradient, and inward forces from friction and pinch. The inferred reduction in plasma temperature, particularly if it leads to a flattening of the temperature gradient in the pedestal, could weaken the temperature screening effect. A shift in the balance of forces, favoring net inward convection, would lead to the observed accumulation of carbon ions.

3.2. Toroidal momentum transport

The two-stage damping of the toroidal rotation, shown in Fig. 4, is consistent with the theory of neoclassical toroidal viscosity (NTV) [4]. NTV arises from the breaking of toroidal axisymmetry by non-axisymmetric magnetic perturbations, which creates a viscous drag on the plasma.

The initial slow, global damping is attributed to the NTV torque generated by the amplified core kink-mode. As the core mode grows, it breaks the toroidal symmetry of the core plasma, initiating a global viscous drag. The second, more rapid damping phase coincides with the formation of the edge magnetic island. This suggests that the formation of the edge island, a significant non-axisymmetric perturbation, dramatically increases the NTV torque, leading to a strong and fast braking of the plasma rotation, especially in the region where the island is located. The magnitude of the NTV torque is known to be strongly dependent on the size of the magnetic perturbation, which is consistent with the observation that the flow damping is strongest when the coupled mode structure is fully developed.

4. CONCLUSIONS AND FUTURE WORK

A new ELM suppression regime has been established in KSTAR by using ECCD to actively control a benign core kink-mode, which in turn induces an edge magnetic island. This method achieves a quiescent edge while avoiding the strong particle confinement degradation often seen in ELM control scenarios. ECEI diagnostics have provided direct evidence of a core-edge coupled structure. The suppression mechanism appears to modify the edge stability boundary, possibly through changes in the edge current profile or via non-linear mode interactions, rather than simply by reducing the pressure gradient.

Associated with this new regime are observations of increased carbon impurity density and toroidal flow damping. The increased carbon gradient points to a change in pedestal impurity transport, potentially linked to a reduction in temperature screening. The toroidal flow damping is consistent with the onset of NTV due to the axisymmetry-breaking coupled structure.

These findings open a promising path for developing ELM-free scenarios in future reactors. Future work will focus on detailed stability analysis to distinguish the roles of edge current modification and non-linear mode coupling in ELM suppression. Furthermore, dedicated experiments and transport modeling are required to elucidate the cause of the modified carbon impurity transport, including the dynamics of its accumulation and subsequent slow decay. Such studies are essential for qualifying this operational scenario for future KSTAR campaigns with its full tungsten interior and for informing ITER operations.

ACKNOWLEDGEMENTS

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