Observation of turbulence suppression after electron-cyclotron-resonance-heating switch-off on the HL-2A tokamak

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The formation of a transient internal transport barrier (ITB) is observed after the electron-cyclotron-resonance-heating (ECRH) switch-off in the HL-2A plasmas, characterized by transient increase of central electron temperature. The newly developed correlation reflectometer provided direct measurements showing reduction of turbulence in the region of steepened gradients for the period of ITB formation triggered by the ECRH switch-off. Furthermore, the reduction of core turbulence is correlated in time with the appearance of a low-frequency mode with a spectrally broad poloidal structure that peaks near zero frequency in the core region. These structures have low poloidal mode number, high poloidal correlation, and short radial correlation and are strongly coupled with high-frequency ambient turbulence. Observation indicates that these structures play important roles in the reduction of the core turbulence and in improvements of the core transport after the off-axis ECRH is turned off.

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I. INTRODUCTION

Discharges with internal transport barriers (ITBs) have been widely investigated in recent times to compile an international database that will help researchers understand the conditions which lead to and the parameters which allow control of ITBs. Many experiments have been performed on various devices to clarify the formation of the transport barrier with reduced transport triggered by localized heating and fueling, such as pellet injection, supersonic molecular beam injection (SMBI), high-Z impurity injection, and electron cyclotron resonance heating (ECRH) [1–7]. There are two types of explanations relating to these phenomena [5–7]. One is relevant to the current profile, the magnetic shear or plasma rotation. The other one is relevant to the so-called nonlocal effects, for which theories have not been well developed so far. In the off-axis ECRH experiments, observations in T-10 and TEXTOR suggest that the necessary condition to reduce the core transport after ECRH switch-off is relevant to the appearance of the low value of $dq/d\rho$ near rational surfaces [4,5]. A large increase on the central electron temperature is induced by off-axis ECRH in DIII-D, which was modeled in terms of a significant heat pinch and suppression of heat diffusivity [3]. However, previous off-axis ECRH experiments were mostly carried out around $r/a \sim 0.4$ [4–6], and the core turbulence study is not sufficient. The links among the improved confinement, the ECRH power deposition, and the core turbulence are still unclear.

In this paper, we concentrate on the results with far-off-axis ECRH switch-off on the HL-2A tokamak to explore the physics of the underlying processes in the formation of ITB.

II. EFFECT OF ECRH SWITCH-OFF ON ELECTRON TRANSPORT

The ECRH system on the HL-2A consists of six gyrotrons [8] with total output power up to 2.5 MW. At present, we cannot steer the ECRH poloidally because of technical reasons, so experiments with various ECRH deposition positions were carried out by changing the toroidal field. The parameter ranges were as follows: density, $(1–1.5) \times 10^{19}$ m$^{-3}$; plasma current, 160–180 kA; and ECRH frequency, 68 GHz, with power up to 1 MW in this study. The toroidal field is scanned from 1.22 T for on-axis heating to 1.45 T for off-axis heating shot by shot to adjust the ECRH deposition position. One aspect of this investigation that deserves attention is the effect of the variation in the magnetic field. We discuss the response of plasma to ECRH switch-off by contrasting discharges that have dissimilar values of the plasma $\beta$ due to the scan of the toroidal field (but somewhat similar values of the ECRH power). Figure 1 shows time evolutions of the core and the edge temperatures after ECRH switch-off in three typical shots with different ECRH deposition positions. In the case of on-axis ECRH, the core and the edge temperatures have simultaneous responses to the ECRH switch-off; that is, they start to drop almost at the same time. As the ECRH deposition position moves outward to $r/a \sim 0.2–0.4$, a delayed drop of the central temperature is observed. When the ECRH deposition position moves further outward to $r/a \sim 0.6–0.7$ (far-off-axis ECRH, near the $q = 2$ surface), an increased central temperature after ECRH switch-off is observed while the edge temperature always simultaneously drops. The central temperature increases for several tens of milliseconds before it starts to drop.

Figure 2 shows that a steep electron temperature-gradient zone appears around $r = 10$ cm (near $q = 1$ surface) in a typical far-off-axis ECRH discharge (13593), in which the 740-kW ECRH is deposited at $r = 27.8$ cm ($r_{\text{dep}}/a \sim 0.69$). The electron temperature gradient arises because the central (within $r < 9$ cm) electron temperature increases for about 20 ms and then decays to equilibrium state after the off-axis ECRH switch-off, while the temperature at $r = 17$ cm falls as indicated by the time evolution of the electron temperatures on the right of the figure. This corresponds to the formation of an ITB as a well-localized narrow layer with low heat diffusivity (3.5 m$^2$/s compared with 5 m$s^{-1}$ in the Ohmic case) in the plasma. The current

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