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Active control of divertor heat and particle fluxes in EAST towards advanced steady state operations

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ABSTRACT

Significant progress has been made in EAST towards advanced steady state operations by active control of divertor heat and particle fluxes. Many innovative techniques have been developed to mitigate transient ELM and stationary heat fluxes on the divertor target plates. It has been found that lower hybrid current drive (LHCD) can lead to edge plasma ergodization, striation of the stationary heat flux and lower ELM transient heat and particle fluxes. With multi-pulse supersonic molecular beam injection (SMBI) to quantitatively regulate the divertor particle flux, the divertor power footprint pattern can be actively modified. H-modes have been extended over 30 s in EAST with the divertor peak heat flux and the target temperature being controlled well below 2 MW/m^2 and 250 °C, respectively, by integrating these new methods, coupled with advanced lithium wall conditioning and internal divertor pumping, along with an edge coherent mode to provide continuous particle and power exhaust.

1. Introduction

Steady-state operations under high performance plasma conditions are essential for today's tokamaks and next-step fusion devices such as ITER and DEMO [1]. A critical issue that arises is the excessive high heat load on the divertor targets [2,3], which will cause intense plasma-wall interactions and, eventually, lead to an unacceptable erosion of the target materials, especially for the tokamaks with a very narrow heat flux channel, as expected for ITER [4,5]. Significant progress has been made in actively controlling edge neutral recycling, transient ELM and stationary divertor heat and particle fluxes in the Experimental Advanced Superconducting Tokamak (EAST) since the last PSI conference. Many innovative techniques and physics approaches towards heat and particle flux control have been developed, such as lithium (Li) wall conditioning, upgrade of plasma facing components (PFCs) from graphite to molybdenum, ELM mitigation/suppression/pacing with lower hybrid current drive (LHCD) [6,7], supersonic molecular beam injection (SMBI) into the pedestal region [8,9], ELM pacing by lithium/deuterium pellet injection [10,11], real-time Li powder injection during long pulse plasma [12], and the combination of LHCD and multi-pulse SMBI to actively modify the stationary power footprint pattern by regulating the divertor conditions. By integrating these new methods, coupled with internal divertor cyro-pumping, a new long-pulse high-confinement (H-mode) regime of over 30 s has been achieved reproducibly [13,14], in which the peak heat flux on the divertor target was controlled well below 2 MW/m^2, along with an edge coherent mode (ECM) in the steep-gradient pedestal region at f = 20–90 kHz to provide continuous particle and power exhaust [15]. The pedestal collisionality may be a key factor for the ECM. In EAST the ECM has been found in high collisionality regime presently (ν_e^* = 0.5–5), being different to the edge harmonic oscillation (EHO) observed in quiescent H-mode operation of low collisionality in DIII-D [16].

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2. Experimental setup and divertor heat/particle flux diagnostics

EAST is a fully superconducting tokamak with ITER-like divertor configuration and RF-heating scheme [17,18]. The major and minor radii of EAST are $R = 1.7–1.9$ m and $a = 0.4–0.45$ m, respectively. The maximum toroidal field and plasma current that have been achieved are $B_t = 3.5$ T and $I_p = 1$ MA, which can be extended to 1.5 MA by reducing the temperature of the superconducting magnets from 4.5 to ~3.8 K. The key divertor heat/particle flux diagnostics are triple Langmuir probe (LP) arrays embedded in the target plates [19], and the infra-red (IR) camera [20] whose view-field covers the divertor region. In the work reported in this paper, the poloidal spatial resolution of LPs along the outer target plates is 10 mm, with a temporal resolution of 20 μs. The heat fluxes measured by LPs are calculated using the standard sheath model [21], i.e., $q_t = \gamma n_t C_{st} T_t \sin\theta$, where θ is the grazing angle between the field line and the target plate, n_t and T_t are the electron density and electron temperature at the target, respectively. The ion sound speed $C_{st} = \sqrt{2T_t/m_i}$, assuming $T_i = T_e$ and the sheath heat transition factor $\gamma = 7$. The divertor particle flux measured by triple LPs is directly related to the ion saturation current density, j_s, as $\Gamma_{ion} = n_t C_{st} = j_s/e$, i.e., Γ_{ion} $(\mathrm{m^{-2}\,s^{-1}}) = 6.24 \times 10^{22} j_s$ $(\mathrm{A\,cm^{-2}})$. The IR camera measures the surface temperature of divertor target plates directly, and a 2D finite element code called DFLUX is used to calculate the target heat flux, q_t, from the surface temperature. The spatial resolution of the IR camera along the divertor targets is 8 mm poloidally, while the temporal resolution related to the data of this paper is 20 ms, which is not ELM-resolved. Currently, the upper divertor LPs have been upgraded successfully in the actively water-cooling, cassetted, ITER-like tungsten monoblock divertor, while the IR camera has also been successfully upgraded to be ELM-resolved.

3. Lithium wall conditioning to control edge recycling and impurity influx

Li wall coating, developed in collaboration with Princeton Plasma Physics Laboratory (PPPL), has been proven to be the most effective wall conditioning technique in EAST to control edge recycling, impurity influx, and thus facilitates plasma density maintenance and ICRF heating coupling. In the last two EAST campaigns, Li coatings by evaporation were performed as a routine wall conditioning method [22]. By upgrading the EAST Li coating systems, Li area coverage increased from ~35% in 2010 to ~85% in 2012. As a result, carbon, oxygen and molybdenum impurities were decreased to extremely low levels. In addition, hydrogen concentration was further decreased with the H/(H + D) ratio falling to as low as 2.5%. Fig. 1 shows the effect of total lithium accumulation on carbon, oxygen impurity suppression and H/(H + D) reduction with a series of sequent shot numbers. The effective recycling coefficient decreased significantly to ~0.89 with fresh Li coating [23] and remained below unity for ~100 discharges. This allowed for effective feedback control of the plasma density. The wall retention rate increased from 55% to 75%, owing to stronger pumping of deuterium particles with increased Li coverage. With increased Li coverage, H-mode plasmas were generally easier to obtain and the EAST operating space was broadened.

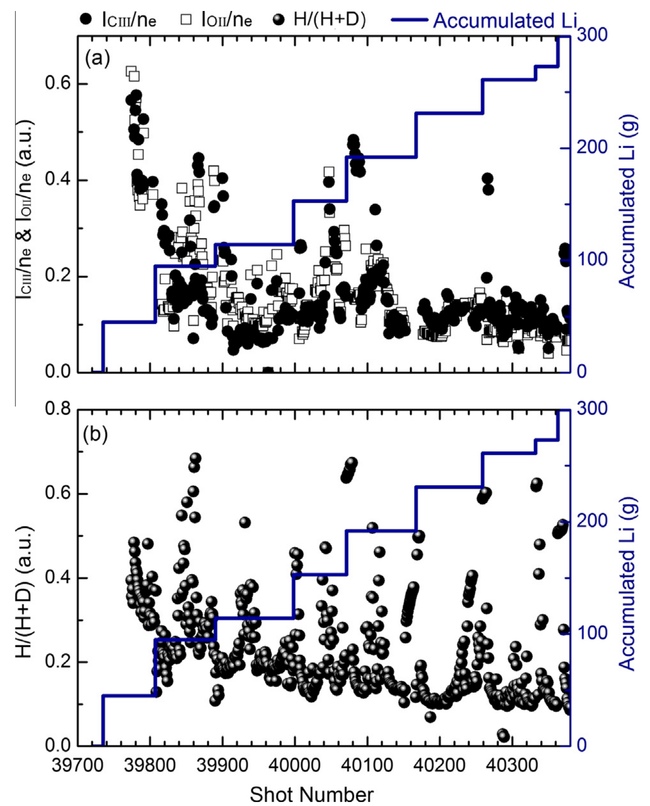

Fig. 1. The evolutions of impurity C_{III} (467.7 nm), O_{II} (386.4 nm) luminosity, and H/(H + D) ratio with total accumulated lithium for a series of EAST shots. The intensity of C_{III} and O_{II} were both normalized to the central line average density.

4. Divertor heat flux control by LHCD

4.1. Edge magnetic topology change induced by LHCD

The EAST experiments with LHCD have demonstrated the formation of helical radiation belts in the scrape-off layer (SOL), which are well aligned with the LHCD antenna array once they pass the mid-plane [6]. The radiation belt appears to be in the SOL as they stay on the low field side (LFS) in a double-null (DN) plasma configuration. Those helical radiation belts are only observed if LHCD is applied, especially in high-density plasmas, and become more pronounced with additional helium puffing.

The helical current filaments (HCFs) driven by LHCD along SOL field lines produce additional fields, leading to a profound change in edge magnetic topology, similar to resonant magnetic perturbations (RMPs) by in-vessel or external magnetic perturbation coils [24]. The ergodization of the edge magnetic fields opens new lobes for divertor particle and power exhaust, as shown in Fig. 2(a) by incorporating the magnetic perturbation of HCFs in the magnetic topology with modeled SOL field lines [25]. The modeled magnetic connection length clearly shows the splitting of outer strike points. Fig. 2(b) and (d) illustrate the particle fluxes measured by the divertor LP arrays on the upper outboard and lower outboard divertor target plates in a helium DN discharge heated dominantly by LHCD. Both the experimental and calculated results show strong modifications of the plasma edge magnetic topology due to the application of LHCD, resulting in the splitting of the strike point. The predicted footprint patterns are in agreement with experimentally observed particle flux profiles in the divertor region. More detailed comparison of the modeling with divertor heat and particle fluxes at different toroidal angles are shown in Ref. [25]. Note that the splitting of outer strike point immediately disappears when the LHCD is switched off, while the plasma configuration remains in DN until the end of the discharge.

4.2. ELM mitigation/suppression/pacing by LHCD

Strong mitigation and suppression of ELMs have been demonstrated in EAST when LHCD is applied to the H-mode plasmas with