

Active divertor flux control by the supersonic molecular beam injection with magnetic perturbations induced by lower hybrid waves on EAST

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Introduction

A serious challenge for high-power long-pulse operations of the tokamak is how to prevent damage to the plasma-facing components by particles from the edge plasma. Experiments on the EAST tokamak showed that lower hybrid waves (LHWs) can change the magnetic topology by inducing helical current filaments (HCFs) flowing along magnetic field lines in the scrape-off layer (SOL) [1, 2]. Such flexible magnetic perturbations have already shown their powerful abilities for controlling edge localized modes and the heat load in past experiments.

Recently, the redistribution of the divertor heat flux is observed on EAST by combining LHW-induced magnetic perturbations with the fueling technique, namely, the supersonic molecular beam injection (SMBI). This measurement has already been used to help EAST achieve a new record duration of steady-state H-mode discharge over 100 seconds in the 2017 campaign. To better understand the physical mechanism behind, some simulations using the EMC3-EIRENE [3, 4] code are performed in this paper.

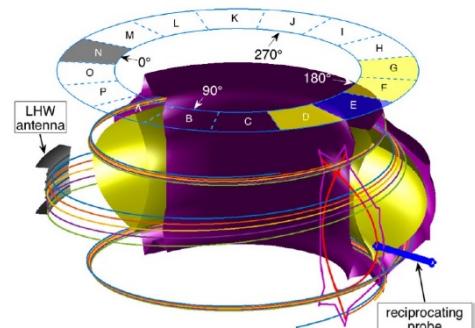


Fig.1. Sketch of LHW-induced HCFs.

First 3D edge plasma transport simulations with LHW-induced magnetic perturbations

In this section, a double-null configuration plasma equilibrium in the #41618 discharge at 3.05 s reconstructed by the EFIT code is utilized in the following analysis [5]. The plasma shape at this moment and the HCFs induced by the 2.45 GHz LHW system are shown in Fig. 1. The positions of HCFs are modeled by tracing field lines start in front of the LHW antenna with a certain distance from the last closed flux surface (LCFS).

The grid generation for EMC3-EIRENE has been improved to be capable of taking into account the LHW-induced HCF effects. After completing the grid generation, some boundary conditions including input power of the SOL and the cross field transport coefficients, are necessary to solve the transport equations in the EMC3-EIRENE. Due to much stronger parallel field transport compared with cross field diffusion, the 3D magnetic topology structure is reflected clear in the plasma properties. Several lobes of field lines can be regarded as the additional plasma transport channel to reach the divertor targets, thus resulting in strike point splitting as shown in Fig.2.

For the divertor heat flux footprint, there is only one split striation, because the dominant toroidal mode number of LHW-induced perturbations is one. Fig.3 also shows a good agreement between the simulation and the experiment. Combined with experimental observations, the simulations strongly support that the total current amplitude of LHW-induced HCFs is increased with an increase in LHW input power. This can further deepen the penetration depth of the additional transport channel by extending the stochastic edge layer, and influence the ratio of heat (or particle) flux between the striated and original strike line on the divertor targets.

EMC3-EIRENE simulations with the synergy of SMBI and magnetic perturbations

The influence of SMBI pulses with LHW-induced magnetic perturbations on the divertor heat flux has been measured by an infrared camera as shown in Fig.4. In this experiment, the plasma with a lower single-null configuration was established by the 2.45 GHz LHW system with the input power of ~ 1.2 MW and the ICRH with ~ 0.7 MW. The 10 Hz SMBI pulse with the pulse length of 8 ms is mainly used to sustain the line-averaged plasma density in $4 \times 10^{19} \text{ m}^{-3}$. As can be seen, the peak heat flux located at the split strike point (SSP) is increased immediately after each SMBI pulse, while the peak heat flux near the original strike point (OSP) is reduced. Then both of them will revert to their previous states.

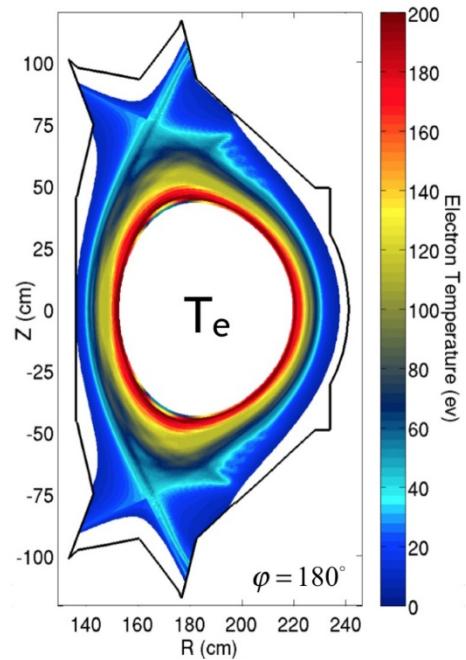


Fig.2. The poloidal cross-section of the simulated electron temperature at a toroidal position of φ_i .

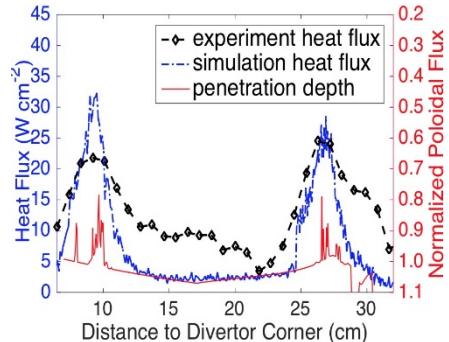


Fig.3. The profiles of simulated and experimental heat flux on the lower outer divertor.

Such divertor flux redistributions are studied by a series of simulations using the EMC3-EIRENE code [6]. In these simulations, an upper single null-configuration plasma with LHW-induced magnetic perturbations in the discharge #64784 at 4.15 s is utilized in generating a 3D computation grid. The current of LHW-induced HCFs is assumed as 2 kA. Note that, only 4.6 GHz LHW system located at E-port is used in this discharge. Fig.5 shows the heat and particle flux footprints simulated by the EMC3-EIRENE on the upper outer divertor. There is one split striation with four arms in footprints. The arm number equals to the number of the 4.6 GHz LHW antenna rows.

Fig.6 indicates the simulated particle and heat flux footprints during the SMBI with LHW-induced magnetic perturbations. Here are the input conditions of the SMBI according to the experimental calibrations. The position of the SMBI is at the mid-plane in the lower field side of J-port. The injected materials are deuterium molecules with temperature about 300 K. The injected velocity is sampled from a truncated Maxwellian density distribution shifted by 1200 m/s. The polar angle of source particles against the injected direction is sampled from a Gaussian distribution with the standard deviation three degree. The injection rate is assumed as 4.682×10^{21} molecules s⁻¹. Similar to the experimental observations with the SMBI, a slight detached state is appeared at the OSP. For the SSP, two reasons contribute to the increased divertor flux. One is that the higher divertor flux from the core plasma by LHW-induced additional transport channel. Another is that the interaction between the plasma and injected particles in the SOL. By the field line tracing technique as shown in Fig.6, it is found that the charged particles originating from the ionization of injected neutral particles in the SOL, flow along the magnetic flux tube towards the divertor, thus directly increasing the heat and particle flux on the SSP.

Using the multi-lobe structure of the magnetic topology with the density feedback control by the SMBI, a method to actively steer the divertor flux is proposed by adjusting the SMBI position or the phase of magnetic perturbations. The LHW-induced magnetic perturbations form the multi-lobe structure of field lines with a long connection length near the LCFS. The multi-lobe structure can be regarded as several groups. The lobe number in each group is same

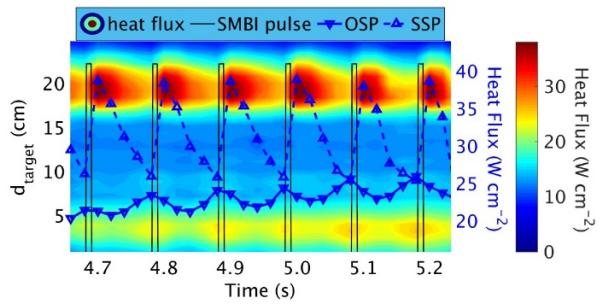


Fig.4. The heat flux on the lower outer divertor in the discharge #41828 influenced by the SMBI and LHW-induced magnetic perturbations. Here, d_{target} is the distance to the divertor corner. The blue lines show the heat flux on the OSP and SSP.

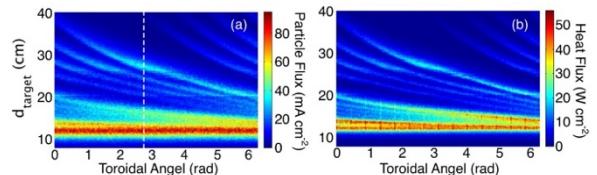


Fig.5. The simulated footprints of divertor flux without the SMBI on the upper outer divertor.

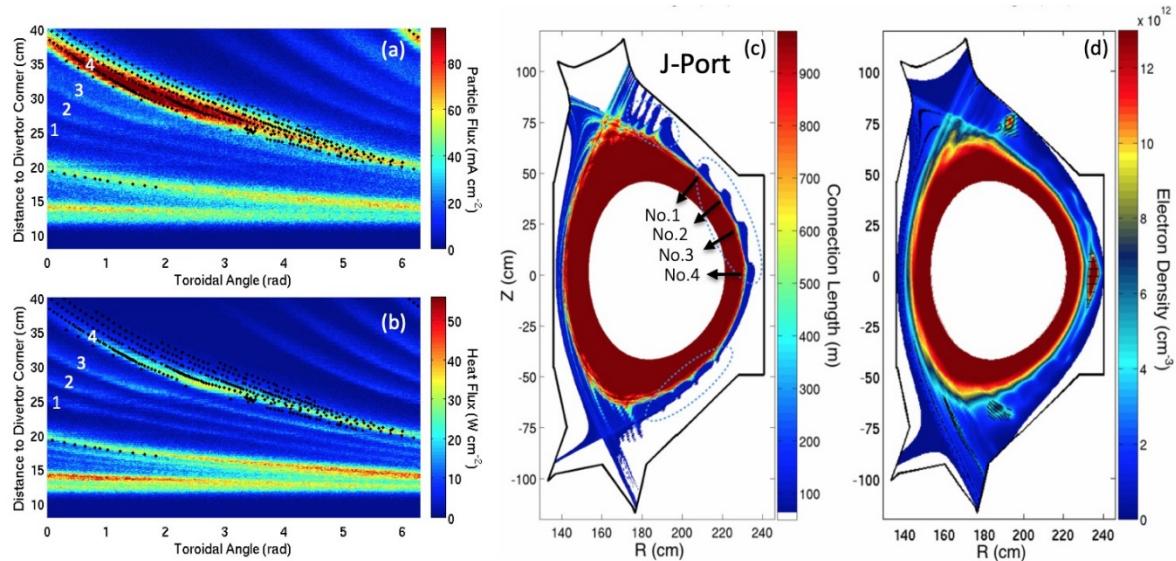


Fig.6. The simulated footprints of (a) particle flux and (b) heat flux with the SMBI on the upper outer divertor. The poloidal cross-sections of (c) the connection length and (d) electron density at the same toroidal position with the SMBI. Every dashed ellipse in Fig. (c) marks a group of the multi-lobe structure of the edge magnetic topology. The black points in Fig. (a, b, d) represent the positions of the field lines traced from the SMBI-induced higher density region.

to the number of LHW antenna rows. In above simulation, the SMBI position corresponds to the No.4 lobe, so more divertor flux is increased near the No.4 arm in footprints. If the SMBI position corresponds to other lobe, more divertor flux will change to the corresponding arm in footprints. This method can be regarded as an actuator to control the deposited portions of plasma flow power among the split arms, thus averaging out the non-toroidally uniform erosion on the divertor target.

Conclusion

In summary, first EMC3-EIRENE simulations with LHW-induced magnetic perturbations show good agreements with the experiments. Based on the good performance of the EMC3-EIRENE code, the divertor flux redistribution caused by magnetic perturbations with the SMBI has been reproduced for the first time in qualitative simulations. Due to the low SMBI divergence and the multi-lobe structure of edge magnetic topology, active control of the divertor flux can be realized by adjusting the SMBI position or the phase of magnetic perturbations.

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