Preliminary Study of the Magnetic Perturbation Effects on the Edge Density Profiles and Fluctuations Using Reflectometers on EAST∗

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Abstract The resonant magnetic perturbation (RMP) coils have been successfully designed and installed on the Experimental Advanced Superconducting Tokamak (EAST). Using the reflectometer systems, the density profile and the density fluctuations during magnetic perturbations (MPs) phase have been investigated. During the experiments, two different cases are studied separately: steady MPs and rotating MPs. In both cases, a strongly density pump-out has been observed. In the steady MPs cases, an enhancement of the low frequency (<60 kHz) density fluctuations in H-mode phase has been observed. The plasma density boundary out-shifts ~ 5% caused by the MPs. The pedestal density gradient is reduced by 50%, while the radial location nearly stays unchanged. In the rotating MPs, the line-averaged density, the Dα emission at the divertor region and the spectrum of the density fluctuations are modulated. The results suggest that the low frequency (<60 kHz) density fluctuations may contribute to the strong density pump-out.

Keywords: magnetic perturbations, microwave reflectometer, density profile, density fluctuation, tokamak

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(Some figures may appear in colour only in the online journal)

1 Introduction

When the high-confinement (H-mode) [1] is achieved in a tokamak, quasi-periodical events, so called edge-localized modes (ELMs) [2], will eject transient heat and particle fluxes to the plasma facing components, which will cause erosion and damage to them. Considering the next generation device, such as ITER and CFETR [3], this issue will become more severe [4]. Various methods have been developed to actively control the ELMs [5,6], such as magnetic perturbations (MPs) using either in-vessel or external coil systems [7–11].

The reduction of the central line averaged plasma density, so called the density pump-out, is always observed in the RMPs experiments. The reduction of the pedestal density and pedestal density gradients is also observed in many tokamaks, such as DIII-D [12], JET [13,14], MAST [15,16] and KSTAR [10]. The change of the density profiles and the density fluctuations during the RMP experiments are investigated using reflectometers on DIII-D [17]. The spectrum of the edge density fluctuations is different with low and high pedestal collisionalities [18]. More measurements are needed to understand the mechanism of the ELMs mitigation by MPs.

The density pump-out is believed to be a thermal [19] and particle [20] transport enhancement due to the deformation of the magnetic boundary layers by MPs. The deformation of the separatrix, or last-closed flux surface (LCFS) by MPs can radially extend the structures near the X-point [21]. The radial displacements of the separatrix by MPs at the midplane of the tokamaks are also observed. In MAST, the radial three-dimensional displacement of the plasmas was analyzed using various toroidal located diagnostic [22]. In DIII-D, the plasma boundary radial displacement in the midplane was observed using beam emission spectroscopy [23], and then the experimental results were compared using the M3D-C code [24].
The consideration of three-dimension displacement is needed in developing models to understand the MPs’ effects on ELMs [16].

The RMP coils are designed and installed on EAST tokamak, and their commission campaign was carried out in the summer in 2014 [25,26]. The edge plasma density profile and the spectrum of the density fluctuations were measured using reflectometer systems [27–29] on EAST. This paper is organized as follows: the experimental setups of the reflectometer systems and the RMP coils system will be given in section 2. The experimental results of the n=2 steady MPs and n=1 rotating MPs will be presented in section 3. Discussions and conclusions will be given in section 4.

2 Experimental setups

EAST is a full superconducting toroidal device with a major radius (R) of 1.75 m and minor radius (a) of 0.45 m. The field at the magnetic axis is up to 3.5 T. The auxiliary heating power used in the experiments related in this paper is neutral beam injection (NBI) in the co-current direction, which is newly developed on EAST in 2014 [30]. The setups of the reflectometer systems and the RMP coils system are given in detail in the following subsections.

2.1 The reflectometer systems

On EAST, the density profiles and the fluctuations are measured with two separate reflectometer systems. The density profile reflectometer systems consist of Q-band (33–50 GHz), V-band (50–75 GHz) and W-band (75–110 GHz). Each of them is equipped with a fast frequency voltage controlled oscillator (VCO). The systems use separate antennas and single sideband modulators (SSBMs) which enables heterodyne measurements. The probe waves are X-mode polarized. The detailed description of the hardware systems has been given in Ref. [31]. The antenna of the launching wave is not shown in the equatorial plane, and the receiving antennas are placed above the launching antennas.

The density fluctuation reflectometers use low frequency synthesizers to generate microwaves at fixed frequencies, and the density fluctuations are detected at the cutoff layer of each launched microwave. The antennas of the microwaves are located below the EAST equatorial plane, and the tilt angle of the antennas is ∼5° [29]. The antennas of the systems are located outside the vacuum vessel. The chord view of the antenna systems is shown in Fig. 1.

2.2 The RMP coils systems

The RMP coil systems were designed and installed on EAST in 2014. The schematic diagram of the systems are show in Fig. 1 in Ref. [25]. The EAST RMP coil systems consist of two arrangements of coils beneath the passive plates, with up and down symmetry. Each array has eight coils, and each coil has four turns. The current in each turn can be up to 10 kA. Four power supplies, with the voltage output up to 600 V, are used in the coil systems. The coil configurations can be n=1–4 in non-rotating mode and n=1–3 in the rotating mode.

3 Experimental result

3.1 n=2 steady MPs

EAST shot 49033 is a typical MPs discharge, with the lower single null (LSN) configuration. The magnetic field is 2.0 T in the co-current direction. The safety factor at 95% flux surface (q95) is ∼5. Fig. 2 shows the waveforms of the shot. The current of the shot is 400 kA. MPs are applied at 5.5 s. The normalized beta reduces to ∼1.1 from ∼1.4 before the application of MPs. The normalized density decreases gradually from ∼0.56 to ∼0.46, which indicates a strong density pump-out. The amplitude of the Dα increases when MPs are applied, and frequency decreases gradually until finally H→L transition. The heating power keeps unchanged during the MPs application period.

In shot 49033, the current in the RMP coils is 2.5 kA and the toroidal number is n=2. The density profiles are shown in Fig. 3. The profiles are measured with reflectometers and an MTAHN method [33] is used to fit the profile. In Fig. 3(a), a strong reduction of the pedestal density is shown. The location of the average plasma boundary, r_p, is out-shifted from r_p/a = 1.04 to r_p/a = 1.09, where a is the tokamak minor radius. In other words, ∼5% radial displacement is observed after the application of the MPs. The maximum gradient of the density decreases to nearly half of the original value after application of MPs. No obvious change in the radial position of the maximum density gradient is...
observed. (Fig. 3(b)). The contour plot of the density profile between 5.4 s and 6 s is shown in Fig. 3(c), and the profile given in every 10 ms for clarity.

![Fig.2](image-url) Waveforms of EAST shot 49033. (a) the plasma current, (b) the signal indicating the application of RMP coils, (c) the line-averaged density normalized by Greenwald density limit ($n_G = I_p/\pi a^2$), (d) the normalized beta, (e) the $D_\alpha$ signal in the lower divertor region and (f) the NBI heating power in the co-current direction.

![Fig.3](image-url) The density profile measured with reflectometers. (a) the edge density profile at 5.42 s and 4.65 s, which are before and after MPs respectively. The circle represents the cutoff position of the microwave with the frequency of 60 GHz. The gray bar denotes the location of the LCFS calculated using EFIT code \[34\]. (b) the edge density gradient at the same time in (a). (c) the contour plot of the density profiles from 5.4 s to 6 s, and the value of the density is shown in the color bar on the right.

The edge density fluctuation is measured using the reflectometers with the probe wave frequency fixed at 60 GHz. The radial position of the cutoff layer is shown in Fig. 3(a), which is at the steep gradient region. In Fig. 4(c), the spectrum of the density fluctuation is shown, the low frequency (<60 kHz) turbulence is enhanced when the MPs are applied in H-mode. Fig. 4(d) and (e) show the power spectrum difference in the H and L-mode respectively. The density fluctuations signal is selected from 20% to 90% of each ELM cycle to exclude the ELM effects. These figures show that the low frequency density fluctuations are enhanced in the H-mode phase while the higher frequency turbulence is suppressed. In the L-mode case, the high frequency turbulence (>100 kHz) is enhanced and relatively low frequency turbulence is suppressed. The low frequency fluctuations in the H-mode MPs phase may cause extra electron transport which leads to the reduction of the plasma density in the core and pedestal region as well as the pedestal density gradient.

![Fig.4](image-url) The density fluctuation measured with the reflectometers with the frequency fixed at 60 GHz. (a) the RMP coils signal, (b) the $D_\alpha$ signal, (c) FFT spectrum of the measured density fluctuations, (d) and (e) the power spectrum of fluctuations with and without MPs in H-mode and L-mode respectively.

### 3.2 $n=1$ rotating MPs

Shot 52342 is a typical shot with rotating MPs applied. The magnetic field is 2.5 T in co-current direction. The configuration of the plasma is LSN. The safety factor at the 95% flux surface is 5.0. The waveforms of this shot are shown in Fig. 5. The MPs are applied at 3.2 s with a rotating frequency at 10 Hz, and the toroidal mode number of the RMP coils is $n=1$. The normalized density decreases from ~0.51 to ~0.47. The normalized beta decreases from ~1.35 to ~1.14. The density fluctuations at the pedestal region were measured with reflectometers with the launching wave frequency fixed at 60 GHz, and the cutoff layer was at the pedestal region. Fig. 5(e) shows the spectrum of the density fluctuations. The spectrum of the density fluctuations is modulated by the changing of the RMP coil phases. The NBI heating power keeps unchanged.
The detailed information of density fluctuation spectrums is shown in Fig. 6. The line-averaged density and the D\textsubscript{α} emission in the lower divertor region are also modulated by the MPs (as shown in Fig. 6(b) and Fig. 5(c)). The density decreases rapidly with application of MPs at 3.2 s. The D\textsubscript{α} emission increases suddenly, indicating an increasing number of the particles interacting with divertor plates. From 3.275 s to 3.325 s, the current in RMP coils changes sinusoidally from +2.5 kA to −2.5 kA, (‘−’ phase in Fig. 6(a)). In the ‘−’ phase, the density starts to decrease, with its rate following the current in the RMP coils. The D\textsubscript{α} emission increases continuously during the whole ‘−’ phase. The power of the low frequency (<60 kHz) density fluctuation increases ∼ 100%, while the power of the high frequency (>60 kHz) decreases ∼ 50%. In the following ‘+’ phase, the plasma density, following the RMP current, starts to increase and the D\textsubscript{α} emission decreases. The low frequency power of the density fluctuations decreases, while the high frequency power of the density fluctuations increases to the level without MPs. These behaviors of these signals repeat in the following few RMP periods. The power spectra of the density fluctuation during different ‘+’ and ‘−’ phases are shown Fig. 6(f). The density fluctuation signals are selected between 20% to 90% of each ELM cycle, i.e., the effects of the ELMs on density fluctuations are excluded. The power of the low frequency density fluctuations increases ∼ 50% and ∼ 100% in the ‘+’ and ‘−’ phases of MPs respectively. These signal behaviors indicate the low frequency fluctuations contribute to the density pump-out. No density profiles were measured in this shot.

**4 Conclusions**

Experiments have been carried out on EAST using RMP coils. The experimental results with \( n=2 \) steady MPs and \( n=1 \) rotating MPs have been shown in this paper. The density profiles in the non-resonant MPs case are measured with the reflectometers, and the density fluctuations are measured in both cases. Density pump-out is observed in the \( n=2 \) steady MPs case. The density in the pedestal top is reduced. A ∼ 5% out-shift of density edge is obtained, which indicates a deformation of the separatrix. This measurement is consistent with the MAST result [16]. The maximum density gradient in the pedestal region reduces to nearly half of the value when non-resonant MPs were applied with the radial location nearly unchanged. These results are consistent with JET [13] and DIII-D high collisionality resonant MPs case [18]. The pedestal electron collisionality is relatively high. Cases with low electron collisionality will be investigated after the upgrade of the heating power. The density fluctuations at the pedestal region is measured using reflectometers with the probe wave frequency of 60 GHz. An enhancement of the density...
fluctuations with frequency $< 60$ kHz is observed in H-mode phase when non-resonant MPs are applied, while in the L-mode phase, the high frequency ($> 100$ kHz) density fluctuations are enhanced. The low frequency density turbulence may cause extra particle transport and density pump-out accordingly.

Significant density pump-out is observed with the rotating MPs applied. The line-averaged density, $D_\alpha$ emission and density fluctuations are modulated by the applied MPs. When the low frequency ($< 60$ kHz) fluctuations are enhanced, the plasma density decreases and the $D_\alpha$ emission at the divertor region increases. The low frequency density fluctuations may enhance the particle transport from plasma core to divertor region and contribute to the density pump-out.

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**References**


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