Experimental study of density pump-out on EAST*

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Abstract
In the experimental advanced superconducting tokamak, density pump-out phenomena were observed by using a multi-channel polarimeter-interferometer system under different heating schemes of ion cyclotron resonant heating, electron cyclotron resonance heating, and neutral beam injection. The density pump-out was also induced with application of resonant magnetic perturbation, accompanied with a degradation of particle confinement. For the comparison analysis in all heating schemes, the typical plasma parameters are plasma current 400 kA, toroidal field 2 T, and line average density $2 \times 10^{19} \text{m}^{-3}$. The experimental results show that the degree of pump-out is concerned with electron density and heating power. Low density deuterium low confinement (L-mode) plasmas ($<3.5 \times 10^{19} \text{m}^{-3}$) show strong pump-out effects. The density pump-out correlated with a significant drop of particle confinement.

Keywords: density pump-out, particle confinement, ECRH, ICRF, NBI, RMP

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

1. Introduction

The phenomenon of density pump-out, also dubbed density flattening, has been observed on both tokamaks and stellarators. It indicates the particle depletion from the plasma core and thus leads to the degradation of particle confinement. In nuclear fusion, the confinement time and density are of great importance and are affected by density pump-out in some experimental observation [1–4]. The research on density pump-out has an important significance on improving particle confinement time and density profile control [5]. Moreover, it may provide an available tool for high-Z impurities pumped-out from the core plasma for achieving the goal that tokamak can operate steadily with long pulse and high-performance plasma.

Several explanations of the confinement degradation due to density pump-out have been given in different devices. In Tore Supra, these density redistributions are ascribed to an $E \times B$ convection process linked with rf sheaths in condition of ICRH [6]; in MAST, a possible explanation of the phenomenon would be an enhancement of the particle turbulent transport in the outer plasma due to the magnetic perturbation [7]; in CHS, density pump-out is possibly triggered by the production of the electrons accelerated perpendicularly to the magnetic field with ECRH [8]. Apart from these reasons for this phenomenon, the self-consistent electric fields in the region near the isolated island chains [9], neoclassical outward thermodiffusion [10],
and the decrease of the Ware pinch [11], have been put forward as well. But the underlying physics mechanism is still not well understood due to the difficulty of measuring the sources for particle transport with sufficient accuracy.

In the experimental advanced superconducting tokamak (EAST), density pump-out was observed clearly with ion cyclotron resonant heating (ICRF) [12], electron cyclotron resonance heating (ECRH), neutral beam injection (NBI) plasma. The density pump-out was also induced with application of resonant magnetic perturbation (RMP) on EAST, accompanied with a degradation of particle confinement. This paper presents the observation of the density pump-out and hence the confinement degradation on EAST. A brief description of the Far-infrared (FIR) polarimeter/interferometer system for density pump-out phenomena observation on EAST is presented in section 2. Section 3 describes the observation of density pump-out with ECRH, ICRF, NBI and RMP plasma on EAST. Then the statistical results of the relation between relative density drop and line-averaged density or heating power are shown in section 4. Finally, summary and discussions are presented.

2. FIR polarimeter/interferometer system on EAST

Density pump-out is mainly observed by HCN interferometer and polarimeter-interferometer (POINT), which can provide the density profile with high time resolution.

Since 2006, the HCN interferometer has been setup as the primary diagnostic system to measure density. The wavelength of HCN laser is 337 μm and output power is about 100 mW. Three-chord probing beams pass through the EAST in the vertical direction. The three beams are located at \( R = 1.64 \, m, 1.82 \, m, \) and \( 1.91 \, m \). \( R \) is major radius, as shown in figure 1. The details of the HCN interferometer are described in [13]. A double pass, radially-viewing, multi-channel FIR polarimeter/interferometer system is developed to measure the current density profile and electron density profile on EAST from 2014. There are three FIR lasers and each of them can generate more than 30 mW power by utilizing three 432.5 μm formic acid FIR lasers pumped by three CO₂ lasers. To determine the Gaussian beam propagation size along the laser beam path, the cube corner retro-reflectors are used behind the inner-wall tiles which can withstand 350 °C baking temperature and 1000 s discharge. In 2014, a five-chord POINT system was installed on EAST. The five chords were located at \( Z = -34 \, cm, -17 \, cm, \) 0 cm, 17 cm, and 34 cm along the horizontal direction. Then, an eleven-chord system was upgraded and routinely operated from 2015. Eleven chords were located at \( Z = -42.5 \, cm, -34 \, cm, -25.5 \, cm, -17 \, cm, -8.5 \, cm, 0 \, cm, 8.5 \, cm, 17 \, cm, 25.5 \, cm, 34 \, cm, \) and 42.5 cm, as shown in figure 1. Initial calibration indicated the electron line-integrated density resolution is less than \( 5 \times 10^{16} \, m^{-2} \). Detailed information about the POINT system is described in [14].

Figure 2 shows the operational region of EAST in 2014 and 2015. \( n_{gw} \) is the Greenwald limit, which is defined as \( n_{gw} = \frac{I_p}{\pi a^2} \), \( I_p \) is the plasma current, and \( a \) is the minor radius.

The density used in this paper is line-averaged density, while the density measured by POINT is line-integrated density, the chord length or the minor radius used to calculate line-averaged density is critical to density pump-out. We
should be aware and confirm that the minor given by the equilibrium fitting code is correct. The red circles in figure 2 represent the density pump-out discharges.

3. Density pump-out

3.1. Density pump-out induced by ECRH, ICRF, NBI

Here, the time evolution of the signals from the central chord of POINT and the density peaking factor, defined as the ratio of the central \((n_0)\) to the peripheral \((n_2)\) chord of the POINT signal, \(n_0/n_2\), as well as the signals of other diagnostics, are plotted in a short time window around some heating scheme switch-on, as shown in figures 3–5.

ECRH, and NBI caused the density and density peaking factor to be decreased, as shown in figures 3, and 5. But the ICRF caused the density to decrease and the density to peak a little increased, as shown in figure 4. After ICRF launched into plasma, the radiation, neutron production and \(D\alpha\) signal increased. Loop voltage decreased. The spectrogram of the mironov coil signals indicates that some MHD activity may
have occurred in ICRF plasma. The results are in agreement with most of the shots with density pump-out caused by ICRF in 2010, which was observed with ICRF heating during L-mode discharges at high electron density of \(4 \times 10^{19}\ \text{m}^{-3}\) [12]. Also, NBI caused the radiation, \(\beta_N\) and stored energy as well as the neutron production to increase. Next, ECRH induced density pump-out will be emphasized.

The effect of ECRH on the plasma density may become of high importance for future long-pulse or steady-state plasma operation, because it may provide a tool for density control. The impurity confinement is also affected by ECRH, which may provide a tool for impurity control [10]. Despite the obvious importance of the effect, there is still little understanding of the underlying physical process. On EAST, a new ECRH system has been routinely operated from 2015. With the application of ECRH, the central electron density decreased and density peaking also decreased, which means the density profile became flat. Figures 6(a) and (b) illustrate the electron density and temperature of L-mode plasma in steady conditions during the Ohmic phase (4.75 s), density decreasing phase (5.35 s) and after density decrease phase (6.55 s). The electron density in the plasma core decreased apparently while density increased in the edge, which is in accordance with the time evolution of density peaking that the density profile became flat. Density profile is obtained by combining the core profile from the POINT and edge profile from reflectometer. The line averaged density is \(2 \times 10^{19}\ \text{m}^{-3}\), providing a clear example of density pump-out on EAST caused by ECRH.

Figure 6(c) represents the values of inverse electron density gradient length \(1/L_d(\rho) = \nabla n_e(\rho)/n_e(\rho)\) profiles in a different heating phase. Obviously, the length profile is slightly changed after ECRH was applied in the domain \(\rho = 0.2–0.6\). While for large values of density gradient length, the dominant instability is a TEM and density gradients are a drive for TEMs [15], the ECRH density pump-out may be related to the TEM instability.

### 3.2. Density pump-out induced by RMP

Edge-localized modes (ELMs) are an important phenomenon of edge higher confinement mode (H-mode) and H-mode can maintain for a long time under good control due to ELM expelling impurities. ELM is a disadvantage for a facing plasma component because it can lead to energy being lost and this will have an effect on the operation of inner parts in tokamaks. RMP is a useful way to control ELMs and affect its frequency and size. But under some conditions, when RMP was used, density pump-out will happen, as seen in figure 8. There are not ELMs in this shot because the H mode was not obtained.

Different from radio frequency (RF) heating and NBI heating cases, RMPs mainly act on the plasma edge. From the time evolution of the density peaking plotted in figure 7(f), we can see the signal \(n_e/n_2\) increased after using RMP. This is because the peripheral density \(n_2\) dropped more than the central density. The electron temperature profile remained unchanged, which means the RMP cannot influence the temperature of the plasma core effectively, as seen in figure 8(b). The decreasing of the \(\beta_N\) and the stored energy is mainly due to the density pump-out.

Figures 8(a) and (c) show the density profile and the inverse electron density gradient length in different time. Density profile becomes flattening while the density gradient...
length remained nearly unchanged, which is slightly different with the ECRH induced density pump-out.

4. The statistical result of density pump-out

Quantities of shots with electron density pump-out were observed under specified conditions of heating method or magnetic perturbations. Nearly all of the shots with density pump-out are in L-mode with a low density of $1.5 - 3.5 \times 10^{19} \text{ m}^{-3}$. As is shown in figure 9, the relative peaking, defined as the ratio of the central ($n_c$) to the peripheral ($n_p$) chord of the POINT signal, and normalized to the value during the ohmic heating phase, decreased when some heating method was applied, which shows a strong density pump-out effect. This effect occurs at intermediate densities ($n_e \sim 4 \times 10^{19} \text{ m}^{-3}$), but there are few data available in this domain, and in L-mode no data can be obtained at larger densities. In AUG, the H-mode with higher densities shows a small but still significant pump-out at the lowest densities ($n_e < 4.5$), a very well documented and reproducible absence of pump-out at intermediate densities ($4.5 < n_e < 6.5$), while a small effect of pump-out appears again at high densities ($n_e > 6.5$) [15].

Figure 10 chooses two current platforms to study the relation between line-averaged density with the normalized line-averaged density drop. Obviously, larger densities have stronger density pump-out.

Most of the shots with obvious density pump-out were caused by application of NBI and ICRF. As shown in figure 11, all of the shots with density pump-out caused by ICRF and NBI were plotted. Figure 11(a) shows if the shots have lower density, the density pump-out becomes weaker with the increase of ICRF power. On the contrary, this phenomenon gets more obvious. Figure 11(b) shows the relative density drops less with the NBI power increase.

Figure 6. (a) Electron density profile, (b) electron temperature profile, (c) inverted electron density gradient length $1/L_n$ at 4.75 s (red marks), 5.35 s (green marks), and 6.55 s (blue marks).
Density pump-out is caused by ICRF, NBI and ECRH. When these heating methods are used, the line-averaged density decreased and density peaking also dropped. The density profile became flatter because the particle in the plasma core was expelled to the edge. Meanwhile, the electron temperature measured by Thomson Scattering increased apparently especially in the core due to the effective heating.

RMP is an effective way to control ELMs and it is responsible for the particle loss unavoidably, especially in the plasma edge. So the density peaking increased when the density dropped just because the particle in the edge lost more than in the core.

The statistical data gives the relation between the relative density change and density or the heating power. This change went up with the increase of line-averaged density and dropped with the increase of NBI power. But lower density has weaker density pump-out and higher density has stronger pump-out with the increase of ICRF power.

It is difficult to explain this phenomenon because of uncertainties of recycling coefficients and neutral density profiles and, as a result, the underlying physical processes are still not understood, even though several explanations have been proposed in past years. Among the proposed explanations for density pump-out, one is based on neoclassical outward thermodiffusion, involving locally trapped particles in the presence of MHD modes. The presence of MHD activity may be responsible for the observed striking difference between the peaking obeying the general scaling and peaking in discharges with pump-out [10]. Another result shows the central electron density pump-out is due both to the decrease of the Ware pinch (caused by the decrease of electric field) and to an increase of the diffusion coefficient. Besides,
Figure 8. (a) Electron density profile, (b) temperature profile and (c) inverted electron density gradient length $1/L_n$ at 3.2 s (red marks), 3.8 s (green marks), and 4.4 s (blue marks).

Figure 9. Line-averaged density as a function of relative peaking in L-mode.

Figure 10. Relative density drop as a function of line-averaged density.
simulations of the behavior of the electron density during ECRH showed that the observed central electron density pump-out could be explained by the combined effect of a decrease of the collisional inward (‘Ware’) pinch and an increase of the diffusivity in TFR [11]. In TEXT, the self-consistent electric fields in the region near the isolated island chains may explain the observed density pump-out and thus, $E \times B$ convection may be responsible for the enhanced particle transport [9]. On EAST, the conceivable mechanism is MHD activity, which can be seen from the time evolution of $dB/dt$ measured by mirror coils, caused by ICRF application, as shown in figure 5(b). Also, heating can make the impurity in the edge raised up and the core impurity did not drop from the time evolution of density pump-out induced by ICRF, ECRH and NBI in L mode plasma, which indicates that no obvious impurity elimination effect exists in L mode plasma. Thus the particles lost in the core are mainly deuterium. The density pump-out and hence the impurities pump-out after using the ECRH, ICRF etc will be focused on in the next step. The confinement evaluation after using RMP in ELMs H mode plasma will be another key issue of study on density pump-out in the near future.

References

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Figure 11. Relative density drop versus the power of ICRF (a) and NBI (b).