The Influence of Neutral Beam Injection on the Heating and Current Drive with Electron Cyclotron Wave on EAST*

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Abstract Both neutral beam injection (NBI) and electron cyclotron resonance heating (ECRH) have been applied on the Experimental Advanced Superconducting Tokamak (EAST) in the 2015 campaign. In order to achieve more effective heating and current drive, the effects of NBI on the heating and current drive with electron cyclotron wave (ECW) are analyzed utilizing the code TORAY and experimental data in the shot #54411 and #54417. According to the experimental and simulated results, for the heating with ECW, NBI can improve the heating efficiency and move the power deposition place towards the inside of the plasma. On the other hand, for the electron cyclotron current drive (ECCD), NBI can also improve the efficiency of ECCD and move the place of ECCD inward. These results will be valuable for the center heating, the achievement of fully non-inductive current drive operation and the suppression of magnetohydrodynamic (MHD) instabilities with ECW on EAST or ITER with many auxiliary heating methods.

Keywords: ECRH, NBI, EAST, TORAY

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

1 Introduction

In order to achieve a high performance in a tokamak, some effective auxiliary heating methods have been developed, such as electron cyclotron resonance heating (ECRH), neutral beam injection (NBI), low hybrid wave (LHW), and ion cyclotron resonance frequency heating (ICRF). Compared with other methods, the heating and current drive with ECW is highly localized and easier to control. Thus, electron cyclotron wave (ECW) is applied for plasma starting up, control of the current profile [1,2], and suppression of magnetohydrodynamic (MHD) instabilities [3,4]. NBI is also an effective heating and current drive method in a tokamak [5]. As an important auxiliary heating facility and a tool for non-inductive current drive, the ECW and NBI have been widely applied in all kinds of tokamaks, such as DIII-D [6,7], NSTX [8,9], JT-60U [10,11].

An electron cyclotron heating and current drive code TORAY has been used to investigate their features and optimize schemes of ECRH and electron cyclotron current drive (ECCD) on the Experimental Advanced Superconducting Tokamak (EAST) [12,13]. Moreover, experimental analysis and simulations of neutral beam current drive, heating efficiency, and beam shine-through power are illustrated [14,15]. However, the synergy effect between NBI and ECRH on EAST is not clear, which is important for more effective heating and current drive by ECW and NBI. In particular, the accurate position of ECCD is crucial for the control of the neoclassical tearing mode during the experiment with NBI and ECW on EAST. Thus, the influence of NBI on ECW should be investigated.

In this paper, the engineering and physical parameters of ECW and NBI and TORAY code are briefly presented in section 2. Section 3 is devoted to a detailed description of the influence of NBI on heating efficiency, deposition position, and current drive of ECW on EAST. Finally, the conclusion and discussion are offered in section 4.

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2 NBI/ECRH system and TORAY code

EAST is a full superconducting tokamak device with an anion-circular cross-section. The typical background plasma parameters are: major radius $R = 1.85$ m, minor radius $a = 0.45$ m, elongation $\kappa = 1.9$, triangularity $\delta = 0.5$, toroidal magnetic field on axis $B_0 = 2.3$ T. EAST is equipped with four neutral beam sources housed in two beamlines, with adjustable beam energy between 50 keV and 80 keV at beam powers between 2 MW and 4 MW and pulse duration between 10 s and 100 s. As shown in Fig. 1, NBI1 and NBI2 are injected in the co-current and counter-current direction, respectively. The ECW system has a beam installed on EAST with a maximum of 4 MW power and a wave frequency of 140 GHz. In this paper, a linear code TORAY $^{[16,17]}$ was used to simulate the ECRH and ECCD on EAST. The second harmonic and weakly relativistic Matsuda–Hu model was used as the wave absorption model, and the Lin–Liu model was been chosen for the current drive efficiency $^{[18]}$. Fig. 2 illustrates the definitions of the toroidal angle $\varphi$ and poloidal angle $\theta$ in TORAY. For ECW on EAST, the toroidal incident angle $\varphi$ is variable from 160 degrees to 205 degrees. The poloidal incident angle $\theta$ can change from 65 degrees to 90 degrees. In this paper, the equilibrium data were reconstructed with EFIT code. The profiles of electron density $n_e$, electron temperature $T_e$ with normalized minor radius $r$ are achieved from the electron cyclotron emission (ECE) diagnostic.

![Figure 1](image1.png)  
**Fig.1** A sketch map of EAST-NBI with NBI1 (co-) and NBI2 (counter-)

![Figure 2](image2.png)  
**Fig.2** The angle and launch point of ECW in TORAY: (a) Poloidal angle $\theta$ in the poloidal cross-section of tokamak, (b) Toroidal angle $\varphi$ in the toroidal cross-section of tokamak

3 The simulation analysis ECW with TORAY

In our simulations, EAST discharges #54411 and #54417 are investigated. Only ECW (420 kW) in #54411 and both ECW (420 kW) and NBI (1.6 MW) in #54417 are applied. Fig. 3 displays the time evolution of the corresponding plasma parameters. The electron temperature is achieved from the ECE diagnostic. As seen in Fig. 3(e), the improvement of the stored energy due to ECW is 7 kJ in shot #54411. However, after NBI, the implement of ECW on EAST increases the stored energy by about 15 kJ in shot #54417. Thus, the implement of ECW following NBI enhances the ECW heating efficiency. In the following part, the power absorption and driven current due to ECW will be deeply investigated with the code TORAY.

![Figure 3](image3.png)  
**Fig.3** Time evolution of (a) Plasma current $I_p$, (b) ECW power $P_{ECW}$, (c) NBI power $P_{NBI}$, (d) Electron temperature in the core $T_e$, (e) Plasma stored energy $W_p$ for shot #54411 (black line) and #54417 (red line)
3.1 The power absorption of ECW

Table 1 offers the parameters in the simulation with TORAY for #54411 and #54417 at 3.7 s. The power deposition efficiency and deposition place of ECW are presented in Fig. 4. According to the integral of the power deposition shown in Fig. 4, the total absorption efficiency $\eta$ (the ratio of the absorbed power to the total injected power) in shot #54411 and shot #54417 are 65% and 85%, respectively. Thus, according to the above power absorption efficiency and the experimental data in Fig. 3(e), the injection of neutral beam before the ECW improves the power deposition of ECW.

According to the theory of ECRH in the hot plasma, the wave absorption of ECW can be expressed in terms of the optical depth $\tau = \ln(1/(1-\eta))$. For X2-modes, including the effects of the hot plasma [1],

$$\tau = \pi^2 n_{X2} \frac{n_e}{n_{O1}} \frac{T_{e,keV}}{\Omega_e} \frac{L_B}{\lambda} \sin^2 \varphi \left(1 + \cos^2 \varphi \right) \left(\frac{6-g}{6-2g}\right)^2.$$  

(1)

Where $g = \omega_p^2/\Omega_e^2$, $\omega_p$ is the plasma frequency, $\Omega_e$ is the electron cyclotron angular frequency, $n_{X2}$ is the index of refraction for X2 mode, $n_{O1}$ is the cutoff density of O1 mode. $\varphi$ is the angle between the wave vector and the magnetic field. $L_B = B/(\partial B/\partial s)$ is the characteristic length along the ray over which the magnitude of the magnetic field changes and $\lambda$ is the free-space wavelength, and where the optical depth for the X2-mode is evaluated for quasi-perpendicular propagation such that $80 < \varphi < 100$. From formula (1), we can know that the electron temperature $T_e$, electron density $n_e$, magnetic structures and incident angles can affect the absorption efficiency of ECW. Therefore, for the similar $n_e$, the optical depth $\tau$ increases with the improvement of the electron temperature $T_e$. Therefore, the experimental observations in Fig. 3(e) agree with the theory results. Furthermore, the absorption efficiency $\eta$ for different $n_e$ and $T_e$ is illustrated in Fig. 5. Scans of $n_e$ and $T_e$ show that the improvement of the electron density $n_e$ and electron temperature $T_e$ can increase the absorption efficiency $\eta$ of ECW, which offers the more effective method to achieve the higher temperature plasma during the experiment with NBI and ECW on EAST or ITER.

On the other hand, the variation of the ECW absorption position with NBI or not is also displayed in Fig. 4. From the Fig. 4, we can find that the ECW deposition position moves towards the center of the plasma. Usually, the Doppler shifts and relativistic effects can affect the ECW deposition position. Considering the both effects, the resonance condition of ECW at the $n$’th harmonics can be expressed by the following equation [1]

$$\omega = \frac{n_e \omega_c}{\gamma} + k_\parallel v_\parallel.$$  

(2)

Where, $\omega$ is the wave frequency, $\omega_c = eB/m_e$ is the electron cyclotron frequency, $\gamma = 1/\sqrt{1-(v^2/c^2)}$ is the relativistic factor, $k_\parallel v_\parallel$ is the Doppler effects term. According to the Eq. (2), $\gamma$ is important for the ECW deposition position and the width of the absorption line. Also, the relativistic factor $\gamma$ has relationship with the electron temperature and electron density [19]. Thus the electron temperature can affect the ECW deposition place. Moreover, Fig. 6 shows...
the ECW deposition position by scanning the electron density and electron temperature. As seen in the Fig. 6, the ECW deposition position moves inward with the improvement of the electron temperature for the similar electron density \(n_e\). The increase of the density makes the deposition position move outward once the electron temperature is constant. Thus, according to the Figs. 4 and 6, the NBI before ECW makes the ECW deposition position shift towards inside, which is a benefit for the center heating of a tokamak.

![Fig.6](image)

**Fig.6** The normalized deposition position contour by scanning \(T_e\) and \(n_e\) with TORAY for \(P_{ECW} = 420\) kW and \((\phi, \theta) = (200, 85)\)

### 3.2 A comparison of ECCD with NBI, or not

The current drive efficiency profiles for shot #54411 and #54417 with the ECW power \(P_{ECW} = 420\) kW are displayed in Fig. 7. According to the Fig. 7, the total driven current \(I_{ECCD}\) are respectively 3.5 kA and 6.6 kA for shot #54411 and #54417 by the integral. Then, the corresponding driven current efficiency \(\gamma_{ECCD}\) (the ratio of ECCD to the total injected power) are, respectively, 8.4 kA/MW and 15.7 kA/MW. According to the theory of the current drive with ECW \(^{12}\), the ECCD efficiency \(\gamma_{ECCD}\) can be written as the form:

\[
\gamma_{ECCD} = \frac{I_{ECCD}}{P_{ECW}} = \xi \times \frac{T_e}{n_e R (Z_{eff} + 5)},
\]

where \(\xi\) is the normalized CD efficiency, which depends on the wave parameters of ECW and ECCD geometry, \(R\) is the major radius, and \(Z_{eff}\) is the effective charge. According to Eq. (3), the electron temperature and electron density have great effect on the ECCD. For the similar electron density \(n_e\), the driven current efficiency \(\gamma_{ECCD}\) increases with the rise of the background electron temperature \(T_e\). Fig. 8 offers the contour map of the driven current efficiency \(\gamma_{ECCD}\) for different \(n_e\) and \(T_e\) with TORAY. From Fig. 8, we can know that \(\gamma_{ECCD}\) is enhanced with the improvement of the electron temperature and the decrease of the density. This conclusion agrees with the theoretical result from the Eq. (3). Also, the direction of ECCD in shot #54411 and #54417 is counter-clockwise with the same direction of the plasma current. Therefore, according to the simulations and theoretical results, the injection of the neutral beam before ECW in the physical experiment can improve the driven current efficiency of ECCD, which is valuable for the enhancement of the non-inductive current in a tokamak. Moreover, Fig. 7 shows that the position of ECCD moves towards the center of the plasma with NBI in shot #54417. This is benefit for the accurate suppression of MHD instabilities with ECW in the physical experiment on EAST of ITER.

![Fig.7](image)

**Fig.7** The current drive efficiency profiles as a function of a normalized radius \(r\) simulated with TORAY for \(P_{ECW} = 420\) kW and \((\phi, \theta) = (200, 85)\), where the dash lines show the current drive place

![Fig.8](image)

**Fig.8** The contour map of ECCD by scanning \(T_e\) and \(n_e\) in TORAY for \(P_{ECW} = 420\) kW and \((\phi, \theta) = (200, 85)\)

### 4 Conclusion and discussion

The analysis of the shot #54411 and #54417 has allowed us to investigate the influence of NBI on the ECRH and ECCD with experimental data and the code TORAY. The corresponding theories of ECRH and ECCD are considered. According to the experimental, simulated and theoretical conclusion, the injection of neutral beam before the ECW can improve the heating
efficiency of ECRH by increasing the optical depth of ECW and enhance the efficiency of ECCD. On the other hand, the NBI makes the ECW deposition position and current drive place move towards inside of the plasma. These results are valuable for the center heating and suppression of MHD instabilities with ECW in the experiment.

In future work, more experimental data with NBI and ECW are needed. The relationship of the NBI power with the value of the shift of power deposition place and ECCD needs to be investigated.

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References


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