Spectroscopic Measurement of Neutral Particle Influx Ratio on EAST∗

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Abstract The spectra of HeI (587.6 nm), Hα (656.28 nm) and Dα (656.1 nm) of the helium discharges as well as the normal deuterium discharges have been measured with two optical spectroscopic multi-channel analysis (OMA) systems on the experimental advanced superconducting tokamak (EAST). The influx ratio of the sum of H and D to He spectral lines and the influx ratio of H to D are given. In this way the ratio of the hydrogen/deuterium ion \((S/XB)_{H/D}\) to \((S/XB)_{He}\) as well as \((S/XB)_{H/D}\) is not very sensitive to the variation in the edge density and temperature. The low-density helium discharges are operated in order to reduce the recycling hydrogen fluxes; however, the effect is not obvious. The possible reason is that the number of helium discharges is not enough and the content of hydrogen in the wall is still very abundant, which is caused by frequent wall conditionings and the vacuum leakage. The \(H/(H+D)\) ratio decreases quickly after one lithium coating and reduces to less than 10% using several accumulated lithium wall conditioning. It is found that the deposited He atoms on the carbon wall will remain at a low level after several \(D_2\) discharges.

Keywords: optical spectroscopic multi-channel analysis (OMA), influx, helium discharges, lithium

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1 Introduction

Retention and recycling of impurities and hydrogen from the plasma facing component (PFC) affect the fuelling efficiency, plasma density control and density of neutral hydrogen at the plasma boundary. This in turn affects particle and energy confinement [1∼4]. In a deuterium plasma, the ratio of \(H/(H+D)\) is essential for the understanding of hydrogen retention and recycling [5]. Moreover, the \(H/(H+D)\) ratio is a critical factor which decides whether the ion cyclotron resonance frequency (ICRF) auxiliary heating with \(H\) as the minority species can be realized in the deuterium discharges [6]. The \(H/(H+D)\) ratio can be inferred from the \(D_α(H_α)\) spectrum measured by spectroscopic means. Thus, spectroscopic measurements of radiation emitted by impurities and hydrogen are important in order to understand and minimize the effects on plasma performance.

On EAST, a variety of wall conditioning techniques have been developed and applied for impurities and hydrogen removal [7∼10], such as baking, glow discharge cleaning (GDC), as well as ion cyclotron wall conditioning (ICWC) technique, boronization, siliconization, lithium coating, and so on. He glow discharge is one very effective method to remove hydrogen from the wall, limiter and divertor plates on EAST [11]. During the fifth and sixth cycle (2010) experimental campaigns of EAST, in order to reduce the \(H/(H+D)\) ratio and achieve the optimum ratio to realize RF heating on hydrogen minority, He discharges and lithium coating were operated. It is important to measure the effects and aftereffects of such wall conditionings. Two optical spectroscopic multi-channel analysis (OMA) systems have been successfully implemented on EAST to routinely monitor the bulk ion and impurity ion spectral lines. The OMA systems are mainly used to monitor hydrogen isotopes and He influxes in the He discharges. At other times during the various operation periods of the tokamak, the OMA systems monitor the main impurities (C, O, etc.) as well as bulk ion lines.

The paper is organized as follows. Following the introduction in section 1, the experimental layout and a description of the optical spectroscopic multi-channel analysis (OMA) systems are given in section 2. In section 3, the principle of neutral particle flux measurement is described. The experimental results are analyzed in section 4. Finally, a summary is given in section 5.

2 Experimental setup

EAST is the first fully superconducting tokamak with an advanced configuration [12,13]. The main oper-
ational parameters in this experimental campaign are the plasma current $I_p = 100 \sim 1000 \text{ kA}$, the line averaged density $\bar{n}_e = (0.5 \sim 4) \times 10^{19} \text{ m}^{-3}$, the toroidal magnetic field $B_T = 2 \sim 3 \text{ T}$, a value of the edge safety factor of $2 \sim 10$, the edge electron temperature $T_e(a) = 10 \sim 30 \text{ eV}$, and the edge plasma density $n_e(a) \sim < 1 \times 10^{19} \text{ m}^{-3}$, the power of the lower hybrid wave (LHW) in the range of $50 \sim 1000 \text{ kW}$, and the typical pulse length of $3 \sim 100 \text{ s}$ under L-mode discharge conditions.

The schematic spatial arrangement of sightlines of the OMA systems in the poloidal cross-section of EAST is described in Fig. 1. Two OMA systems are used. OMA1 is equipped with an Acton Research Spectrometer (SP300i, $f = 300 \text{ mm}$) and a liquid nitrogen-cooled CCD detector (1340 × 400 pixels). It is equipped with three gratings (300 gr/mm, 1200 gr/mm and 2400 gr/mm) mounted on a turret. The 300 gr/mm grating with a spectral dispersion of 0.2 nm/pixel can be tuned and cover a wide spectral range spanning from 200 nm to 700 nm. The 300 gr/mm grating was adopted in this work. OMA1 is usually used to measure the impurities as well as bulk ion spectral lines. OMA2 is a high-resolution Action Research Spectrometer (SP750, $f = 750 \text{ mm}$) equipped with a back-illuminated ICCD (1024 × 1024 pixels). The 1800 gr/mm grating provides a high spectral dispersion of 0.0069 nm/pixel, which is adequate to measure the $D_\alpha$ ($\text{H}_\alpha$) spectral line shape. The two systems utilize essentially identical optical systems and cover the same spatial range to measure the light from intrinsic emission of the plasma. The two optical arrays view the plasma from $Z = -94.3 \text{ cm}$ to $-48.9 \text{ cm}$ below the tokamak midplane and between $Z = 16 \sim 64.6 \text{ cm}$ at $R = 1.75 \text{ m}$. The channel-to-channel distance of the OMA1 system is about 60 mm. The spatial resolutions of the OMA2 system are better than OMA1, by about 30 mm.

![Fig.1 Schematic spatial arrangement of sightlines for the OMA systems in the poloidal cross-section of EAST (color online)](image)

The light is imaged from the plasma onto two bundles of bifurcated quartz fibers and transmitted to the SP300i or SP750 spectrometer. The optical and mechanical component assemblies for the OMA systems are shown in Fig. 2. Two collection lenses (one for upper space viewing and one for the inner leg of the divertor viewing through a reflection mirror) are mounted outside of the EAST vacuum vessel with a focal length of 87 mm and 137 mm, respectively (Fig. 2(a) and (b)). The left end of the fiber bundles (shown in Fig. 2(c)) is attached to the entrance slit of the spectrometer. At the other end, the fibers are divided into four groups, labeled as A, B, C, and D. Only two ends A and C or B and D are used, each group consists of 15 closely spaced 100 µm optical fibers for SP750 and 8 closely spaced 200 µm optical fibers for SP300i. The adjacent fibers are crossed on the CCD detector. The front surface of the optical fibers array is thoroughly polished to increase the transmission.

![Fig.2 The optical and mechanical component assemblies for the OMA systems (color online)](image)

### 3 Measurements of particle influx ratio

Neutral hydrogen isotopes and impurities entering the plasma are ionized in a narrow shell at the plasma periphery. The neutral particle influx $\Gamma_0$ is proportional to the ionization rate and can be derived from the line-of-sight intensity of the absolute line emission $I_0$ [14] by assuming negligible recombination:

$$\Gamma_0 = 4\pi \frac{S}{XB} \frac{I_0}{h\nu},$$  \hspace{1cm} (1)

where $S$ is the ionization rate coefficient, $X$ is the excitation rate coefficient, $B$ is the corresponding branching ratio, $h\nu$ is the photon emission energy. The quantity $S/XB$ is called the ionization events per photon, which is needed for calculating the neutral influxes.

In the case where hydrogen and deuterium can be resolved, the ionization and excitation rate coefficients of hydrogen and deuterium are assumed to be the same ($\frac{S}{XB}_H = \frac{S}{XB}_D$ [15]), so the $H/(H+D)$ ratio can be simplified as follows:

$$\frac{\Gamma_H}{\Gamma_H + \Gamma_D} = \frac{I_H}{I_H + I_D},$$  \hspace{1cm} (2)

where $I$ is the $H_\alpha/D_\alpha$ light emission intensity which can be obtained through the SP750 system.
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For hydrogen/deuterium and helium, the influx ratio of the sum of H and D to He, $H'/(H'+He)$ is expressed as

$$\frac{\Gamma_{H'}}{\Gamma_{H'}+\Gamma_{He}} = \frac{I_{H'}/(\frac{S}{XB})_{H'/D}+I_{He}/(\frac{S}{XB})_{He}}{I_{H'}/(\frac{S}{XB})_{H'/D}/(\frac{S}{XB})_{He}+I_{He}}$$

where $\Gamma_{H'} = \Gamma_{H} + \Gamma_{D}$ which is the sum of H and D flux. $I_{H'} = I_{H} + I_{D}$ and $I_{He}$ are the line emission intensities of hydrogen isotopes and Hel, respectively. The SP300i system with a 300 gr/mm grating can cover a wavelength range from 515 nm to 785 nm at a 650 nm central wavelength in one scanning which includes $D_{\alpha}/H_{\alpha}$ and some HeI spectral lines simultaneously, and H and D spectral lines are unresolved.

Fig. 3 gives the typical raw spectrum with the central wavelength of 650 nm in one plasma shot with the SP300i. The spectral range includes lines of hydrogen isotopes, CIII, LiI, LiII, OII, and Hel. The existence of Li spectral lines is the result of lithiumization. It can be seen in Fig. 5(a) that the dependence of the $S/XB$ values for the $H_{\alpha}/D_{\alpha}$ line on the electron temperature is actually weak over the range of 20–100 eV. However, the electron density dependence becomes considerably large when the density is greater than $1 \times 10^{19}$ m$^{-3}$, whereas the ionization events per photon for $H_{\alpha}/D_{\alpha}$ emission have been generally used as a constant because the edge plasma density for the normal plasma is lower than $1 \times 10^{19}$ m$^{-3}$.

The ionization events per photon $S/XB$ for $H_{\alpha}/D_{\alpha}$ and Hel lines are shown in Fig. 5 as a function of the electron density ($n_e$) at six different electron temperatures ($T_e$). The data $S/XB$ are taken from the OPENADAS database [18]. It can be seen in Fig. 5(a) that the dependence of the $S/XB$ values for the $H_{\alpha}/D_{\alpha}$ line on the electron temperature is actually weak over the range of 20–100 eV. However, the electron density dependence becomes considerably large when the density is greater than $1 \times 10^{19}$ m$^{-3}$, whereas the ionization events per photon for $H_{\alpha}/D_{\alpha}$ emission have been generally used as a constant because the edge plasma density for the normal plasma is lower than $1 \times 10^{19}$ m$^{-3}$.
fixed temperature. The dependence on $T_e$ is still considerably obvious. In most EAST discharges, the edge electron temperature is about $10\sim30$ eV and the error of the temperature dependence is estimated to be below 20% for the ratio.

Fig. 6 The $n_e$ dependences of ratio of hydrogen/deuterium ion ($S/XB)_H$ to ($S/XB)_{He}$ for several $T_e$ values (color online)

4 Experimental results

In the He discharges on EAST, two methods were adopted. One was the He plasma with $D_2$ prefill. The other was the pure He discharge (prefill+gas puff) with the injection of the LHW power for pre-ionization. Without the help of the lower hybrid current drive (LHCD), the pure He discharge was hardly maintained on EAST.

A time behavior of the $H'/(H'+He)$ and $H/(H+D)$ ratio in a typical He plasma with $D_2$ prefill is shown in Fig. 7. The discharge was initiated with a $D_2$ prefill, and He gas was puffed during the discharge to build up the density to the desired level and maintain it until the end of the discharge. In this shot, the main plasma parameters were as follows: line-averaged density $n_e \approx 2 \times 10^{19}$ m$^{-3}$, $I_p = 250$ kA. It was noted that the first value of the $H'/(H'+He)$ ratio is up to about 86%, which is because $D_2$ was the prefill gas. Then the $H'/(H'+He)$ ratio arrived at and remained about 35% when entering the flat-top phase. The $H/(H+D)$ ratio remained fairly constant at about 30% which demonstrated that the hydrogen and deuterium recycling was stable. Fig. 8 shows the time evolution of the $H/(H+D)$ and $H'/(H'+He)$ ratio in a typical pure helium discharge with $P_{LHCD} = 600$ kW. The line-averaged density $n_e = 1.6 \times 10^{19}$ m$^{-3}$, $I_p = 300$ kA. The $H'/(H'+He)$ ratio decreased from 60% initially to about 20% quickly after the injection of the LHW. The lower temperature and density in the initial ionization phase resulted in a higher $H$ and He influx ratio. The probable reason was that the injection of the LHW hastened the ionization of He and increased the plasma density which made the $H'/(H'+He)$ ratio lower. The $H/(H+D)$ ratio was high, up to 60%, which was probably caused by the enhancement of plasma-wall interactions due to the injection of the LHW.

Fig. 7 The temporal evolution of shot 24802 in a He plasma with $D_2$ prefill (color online)

Fig. 8 The evolution of $H/(H+D)$ and $H'/H'(H'+He)$ in a pure helium discharge with the injection of LHW (shot 24501) (color online)

The dependence of the $H/(H+D)$ ratio on the line-averaged densities during the pure He discharges is indicated in Fig. 9. The plasma density was $0.2 \times 10^{19} \leq n_e \leq 2 \times 10^{19}$ m$^{-3}$, the plasma current $I_p = 250 \sim 300$ kA, magnetic field $B_T \sim 2$ T. It

Fig. 9 The variation of $H/(H+D)$ versus plasma density during the He discharges
was observed that the H/(H+D) ratio decreased with the plasma density, probably because the lower density was more beneficial to the release of hydrogen than deuterium in the He discharges. By comparing the H/(H+D) ratio before and after the He discharges, it was observed that this ratio decreases a little, from about 45% to 33%, probably because the shot number of helium discharges is not enough and the content of hydrogen in the wall is still very abundant, which is caused by frequent wall conditionings and the vacuum leakage.

The shot-by-shot He/(He + H′) ratio evolution in the D2 discharges is given in Fig. 10. The D2 discharges were operated at $n_e = 0.3 \sim 1 \times 10^{19}$ m$^{-3}$ and $I_p \sim 250$ kA. Shot 24929 was the first D2 discharge after stopping the He discharges. It can be seen that the ratio reduced monotonically and rapidly, and finally maintained a low level at about 7% after some shots accumulation of D2 discharges. This meant that the retention of helium was very low, and the He atoms deposited on the tokamak wall could be continually removed and replaced by deuterium. However it was also found that a low constant He level was maintained in the following discharges, which was due to erosion/deposition equilibrium [19].

Another technique, lithium coating, worked as the major method for wall conditioning during the sixth cycle experiment campaign on EAST. The main results are given as follows.

Two typical spectral lines for two Ohmic discharges before and after lithium are presented in Fig. 11, as measured by the SP750. These two shots had nearly the same central line averaged electron density $n_e \sim 1.8 \times 10^{19}$ m$^{-3}$ and $I_p = 250$ kA and the toroidal field was 2.2 T. A polarizer was placed in the front of the collection lens and used to eliminate ±σ components. The direction of the polarizer was not accurately determined, which probably resulted in the wavelength difference between the two shots, as shown in Fig. 11. The data clearly indicate that the spectral line intensities of carbon and hydrogen were reduced to a low level following lithium.

Fig. 12 is the evolution of the H/(H+D) ratio as a function of the discharge number after a series of lithium coating. The ratio remained at above 60% before the lithium coating. From this figure, it can be seen that the H/(H+D) ratio was higher initially and about 40%, which was caused by the vacuum leak, and the ratio reduced to about 10% or less quickly, which was due to the accumulation effect of lithium coating afore. In the steady wall state and low edge recycling with lithium coating, the efficient minority ion heating of ICRF was realized and the first H-mode plasma on EAST was accessed at shot 32525 under the LHW injection.

5 Summary

Two optical spectroscopic multi-channel analysis (OMA) systems have been used to simultaneously measure H, D, He as well as other impurity lines on EAST. The $S/XB$ value needed for the calculation of the particle influx ratio is available from the OPENADAS database. In order to reduce the H/(H+D) ratio, two methods which include the helium discharges and lithium coating are adopted. The low-density helium discharges are operated. In the helium discharges, the low discharge density is more beneficial to the release of hydrogen than deuterium. However, the final
effect is not satisfied. Compared to the He discharges, the lithium coating plays a very effective role in decreasing the H/(H+D) ratio, which drops rapidly after one lithium coating and reduces to less than 10% using several accumulated lithium wall conditionings. Those data indicate the effectiveness of lithium coating to lower the H/(H+D) ratio and edge recycling. The retention of helium is very low and can be continually removed by some repetitions of the deuterium discharges. However, a low constant He level will be maintained because of the erosion/deposition equilibrium.

References