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Observation of deuterium molecule emission spectra under an active feedback control of H-mod plasma divertor detachment experiment on the EAST tokamak*

Wei Gao(高伟)†, Juan Huang(黄娟), Jichan Xu(许吉禅), Liang Wang(王亮), Jing Zhang(张静), Jianxun Su(宿建勋), Yingjie Chen(陈颖杰), Wei Gao(高伟), Zhenwei Wu(吴振伟), and the EAST Team

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Based on neon gas puffing, an active feedback control of H-mod plasma divertor detachment experiment was successfully operated on the EAST tokamak. During the feedback control discharge, the plasma was detached by puffing neon gas and the strike point splitting phenomenon on divertor target was also clearly observed by divertor probes diagnostic. In boundary region, many neutral particle processes (atom and molecule) were happened and accompanied by their emission spectra under the detachment discharge. By studying these emission spectra, it is helpful for us to understand the role of atoms and molecules in boundary recycling, which is important for studying the physical mechanism of divertor detachment. For the Fulcher-α system ($d(3p)\,^3\Pi_u^{\pm} \rightarrow a(2s)\,^3\Sigma_g^+$), D_2 emission spectra in the range from 601 nm to 606 nm were observed, identified and fitted in the detachment experiment for the first time on the EAST, and the spectra in the $Q(0–0)$ band ($d\,^3\Pi_u^- \rightarrow a(2s)\,^3\Sigma_g^+$) in the Q branch of the Fulcher-α system were used for detailed analysis to acquire the boundary region temperature T_e (below 5 eV), which could not be provided very well by other diagnostics on the EAST. An electronic version deuterium molecular spectral line database was established to identify the spectral lines and a multi-peak fitting program was developed to fit and analyze the observed spectra.

Keywords: plasma, detachment, molecular spectrum, deuterium

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1. Introduction

One of the most critical issues for high power and long pulse steady-state H-mod plasma operation on the EAST is how to deal with the high divertor power, particle fluxes and related plasma–wall interaction (PWI). It is also important for the future International Thermonuclear Experimental Reactor (ITER) and the China Fusion Engineering Test Reactor (CFETR). Currently, the divertor detachment operation offers one of the most attractive means of addressing the heat load on divertor plates, which has been used on many fusion devices and even will be used on the ITER and the CFETR. Under the detachment, there are many neutral particle processes (atoms and molecules) in the boundary, which could be studied to acquire the boundary recycling information. It would be helpful for us to understand the physical mechanism of divertor detachment discharge. The hydrogen molecules and its isotopes in the edge plasma of a tokamak are of high interest under the detachment in current research. Because they affect the energy and particle balances in the edge plasma, participating in reactions of excitation, ionization, dissociation and recombination. The explanations of the role of the complicate molecular processes are still insufficient, so it is necessary to observe and study the vibrationally excited molecule emission spectrum to understand the effect of them in the boundary recycling at the edge region directly. The emission spectra of hydrogen molecule isotopes are distributed in the entire visible band and blended with their atom lines of the Balmer series. Because their emission spectra have the rotational structures, it is necessary to analyze the molecular spectra with the electron-vibrational-rotational transitions in studying the processes in edge plasmas, and it has been carried out on some tokamaks (TEXTOR, DIII-D, JET, T-10 etc).[1–5] In previous studies, much attention paid to the molecular spectra is about the proportion to the total flux in the recyling,[2–10] because the charged particles of the total flux coming into the plasma could be significantly underestimated when atomic component is considered to be the only item.

However, the similar works have not been performed on the EAST tokamak. In last campaign (2018), an active feedback control divertor detachment experiment by puffing neon gas was successfully operated for the first time on the EAST. During detachment discharge, the deuterium molecule emission spectra of the Fulcher-α system ($d(3p)\,^3\Pi_u^{\pm} \rightarrow a(2s)\,^3\Sigma_g^+$) in visible band (601–606 nm) were also observed in boundary region by a high resolution optical spectroscopic multichannel analysis (OSMA) system. Under the detachment, other diagnostics cannot provided the temperature T_e in the boundary on the EAST when it was below 5 eV. Here the spectroscopic methodology was used to acquire the temperature T_e

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by analyzing observed D_2 emission spectra. First, the spectra were recognized and fitted by an electronic version deuterium molecular spectral lines database and a multi-peak fitting program which were established and developed by our group. By analysis of the molecular spectrum structure, the rotational temperature of the upper excited state $(d\,^3\Pi_u^-)T_{rot}^*$ and the ground state $(X\,^1\Sigma_g^+)T_{rot}^0$ can be acquired by Boltzmann distribution.[5,11–14] Then, the temperature of the neutral deuterium gas T_{gas} in boundary region can be acquired from the temperature T_{rot}^*. It can be used as a reference for the temperature T_e in detachment experiment. The spectral lines in the $Q(0–0)$ band of the Q branch were used for detailed analysis and discussion in the present work.

The paper is organized as follows. The experimental setup and diagnostic performance are introduced in Section 2. An active feedback control of H-mod plasma divertor detachment experiment and the detailed analysis of the deuterium molecular emission spectra are discussed in Section 3. Finally, Section 4 summarizes our results.

2. Experimental setup and diagnostic performance

The EAST is a fully superconducting tokamak which can create a spiralling magnetic field configuration with an ITER-like D-shaped cross section. The range of the major radius R is 1.7–1.9 m, the minor radius a is 0.4–0.45 m, the triangularity δ is 0.4–0.7 and the elongation k is up to 1.9. The plasma current I_p can be 1 MA with the toroidal magnetic field currently operated in the range of $B_t = 1.2–3.5$ T. A flexible PF control system with separate power supply for each PF coil is used to accommodate both upper/lower single null (USN/LSN) and double null (DN) divertor configurations. The lower and upper divertors were covered by graphite tiles. In recent upgrade, the upper graphite divertor has been replaced with an ITER-like tungsten (W) monoblock divertor, by which the capability of total auxiliary heating has been enhanced, with the source power over 20 MW with rf heating dominant. The OSMA system is used to observe the atomic and molecular emission spectra in boundary region on the EAST. It consists of an SP750 spectrometer and a ProEM Electron-Multiplying charge coupled device (EMCCD) 1024B camera. The focal length of the spectrometer is 750 mm, which features a triple grating turret and triple indexable gratings (2400 g/m@600 nm, 1200 g/m@500 nm, 1200 g/m@300 nm). It includes a direct digital grating scan mechanism with full wavelength scanning capabilities in visible band. The ProEM EMCCD is a back-illuminated, thermoelectrically cooled pixels (1024×1024) CCD with the size of 13 μm × 13 μm, which has a dynamic range of 16 bits. The EMCCD is cooled below −75 ℃ and has a lot of advantages, such as high sensitivity, extremely low etaloning, baseline active stability engine, EM and non-EM modes for lowest noise and the best linearity. The slit width of the spectrometer can be adjusted from 10 μm to 3000 μm. The schematic diagram of the experiment is shown in Fig. 1. One array of 13 viewing chords were used to observe the molecular emission spectra in the upper divertor regions. The spot diameter of the view chords is about 2.2 cm and the angle between the adjacent chords is about 2°. The spatial resolution of the OSMA system is less than 5.5 cm near the divertor target. Here the detector array was binned into 13 channels of 60 rows each for the viewing chords. In the experiment, the deuterium molecular emission spectra were observed in the upper divertor region. On the EAST or other tokamaks, the intensity of the molecular spectra is always too weak to observe, the signal-to-noise ratio is always terrible and the spectral lines are blended with each other, which makes it complicated and difficult to distinguish from each other. In order to obtain a better signal-to-noise ratio and higher spectral resolution, the exposure time was set at 100 ms, the width of slit was adjusted to 100 μm, and 2400 g/m grating was used to observe the molecular emission spectra under the divertor detachment experiment. These made it possible to record the spectra with the width about 5 nm in one discharge. The wavelength resolution (FWHM) was about 0.013 nm and the instrument function of the OSMA system was about 0.0105 nm.

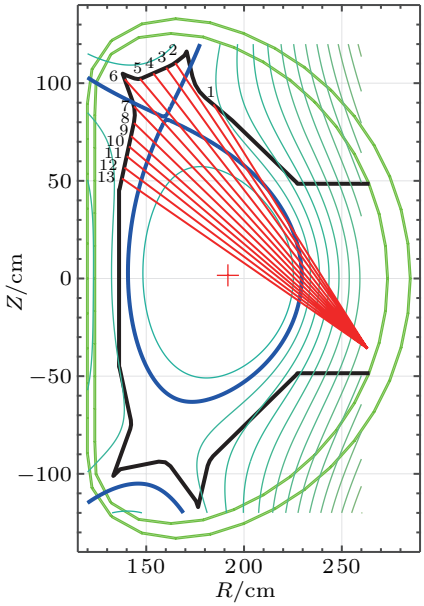


Fig. 1. Schematic of the EAST poloidal section with viewing lines for the OSMA system.

3. Discussion

3.1. Active feedback control of divertor detachment

In the present work, the analyzed divertor detachment discharge was conducted in upper single null divertor configuration with top W divertor with ion gradient drift $B \times \nabla B \uparrow$, and it was successfully operated by neon gas puffing feedback control in NBI dominated H-mod plasma discharge in 2018

campaign, also utilizing the divertor particle flux control module. It shows that neon is one of the most suitable impurity species for increasing edge radiation without significant decrease of core plasma performance compared with the argon and nitrogen on the EAST.[16,17] For the top W divertor of the EAST at the present time, it is not very good for impurity screening, so the neon seeding was performed using the mixture with D_2, and the ratio of Ne to D_2 was selected from 5% to 20%. The discharge conditions are presented in Fig. 2. During the detachment discharge, the plasma parameters are as follows: (a) the plasma current I_p was about 400 kA. (b) The line-averaged electron density n_e at the core was about 4.48×10^{19} m^{-3}. (c) The LHCD, NBI and ECRH were used as auxiliary heating, and the power values were about 1.2 MW, 3.2 MW and 0.8 MW, respectively. (d) The plasma stored energy W_{MHD} was about 180 kJ. (e) The radiation power was presented here. (f) The target J_{sat}/J_{roll} value was set at 0.5 (red line), and the real time signal of J_{sat}/J_{roll} was acquired in feedback control phase (pink line). (g) The neon gas was puffed in the plasma from $t = 4$ s, and the signal of puffing gas was presented in figure. During the feedback control phase, the radiation power was maintained almost stably. This means that the neon gas was well exhausted during the discharge. The W_{MHD} slightly increased rather than decreased while the plasma line-averaged density was maintained quite stably, which was a surprise to us and the underlying physics needed to be further studied in detail. From $t = 4.5$ s, the detachment could be observed clearly by the divertor probes diagnostic in Fig. 3 and discussed below.

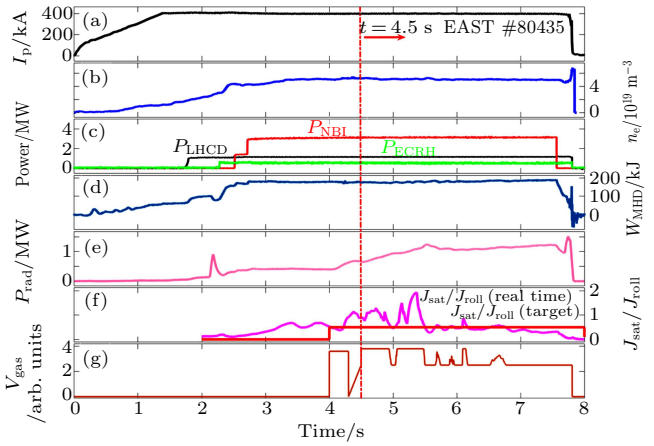


Fig. 2. Discharge conditions of the active feedback control of divertor detachment experiment shot #80435 on the EAST.

Figure 3 shows the signal of particle flux measured by the divertor probes on the upper out divertor region at D port and O port during the detachment feedback control discharge by puffing neon gas from $t = 4$ s with Ne: $D_2 = 5\%$. From the figure, it could find that the particle flux was significantly reduced when the feed-forward neon gas was puffed, and then reduced when the divertor plasma was went into detachment in the discharge. During the feedback control phase, the plasma line-averaged density was maintained quite stably. From $t = 4.5$ s, the splitting of strike point on the divertor target was clearly observed by divertor probes in the discharge, and meanwhile the peak temperature of the upper out W divertor was reduced from 470 ℃ to 320 ℃ measured by infrared camera diagnostic. By using the neon gas puffing feedback control, the plasma was successfully went into the detachment, and the particle and heat flux were reduced at the same time. It would be helpful for us to achieve the high-power and long-pulse high performance H-mode steady-stable plasma on the EAST, even on the future ITER and CFETR.

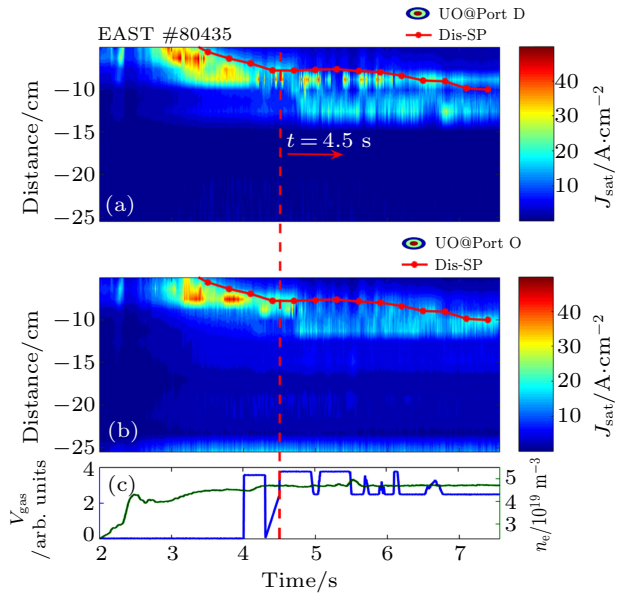


Fig. 3. Active feedback control of H-mode detachment via the divertor particle flux controller with divertor neon gas puffing in an H-mode plasma. The 2D contours of upper outer (UO) particle fluxes and strike point (SP) movements, i.e., distances from the UO diverotor corner, at port D and O are given in (a) and (b), respectively.

3.2. Measured D_2 emission spectra

Under the detachment experiment, the deuterium molecular emission spectra in the wavelength range from 601 nm to 606 nm (Fulcher-α system, $d(3p)\,^3\Pi_u^{\pm} \rightarrow a(2s)\,^3\Sigma_g^+$) were observed by our OSMA system. The plasma parameters $I_p = 400$ kA, $T_e = 3.8$ keV, $n_e = 4.48 \times 10^{19}$ m^{-3} (at the core of the plasma) and the detail of discharge conditions are given in Section 3.1. It should point out that the Q branch ($d\,^3\Pi_u^-$) of the Fulcher-α system of D_2 is the brightest in this band, so it is usually used for analysis in most of the researches. In the present work, the rotational structure of the spectra was clearly observed by the OSMA system with high resolution and good signal-to-noise ratio, which could be distinguished from other spectral lines in the observed band. According to the Refs. [21] and [22], an electronic version deuterium molecular emission spectral line database was firstly established, and then the D_2 emission spectra of the Fulcher-α system of Q,

P, R branches of bands Q(0–0), P(0–0), and R(1–1) (v'–v''), where v' and v'' are vibrational quantum numbers of the upper and lower states) were identified and marked in Fig. 4. It is also found that the emission spectra (d(3p)$^3\Pi_u^{\pm} \rightarrow$ a(2s)$^3\Sigma_g^+$) were blended by other recognized emission spectral lines in g(3d)$^3\Sigma_g^+ \rightarrow$ c(2p)$^3\Pi_u^{\pm}$ (0–0: P, Q, R branches, 1–1: P, Q, R branches, 2–2: R branch) and i(3d)$^3\Pi_g^{\pm} \rightarrow$ c(2p)$^3\Pi_u^{\pm}$ (for $^3\Pi_g^+$ 2–2: P branch, 3–3: P, Q branches, 4–4: R branch, for $^3\Pi_g^-$ 0–0: P branch, 2–2: P branch, 3–3: P, Q branches) system according to the database. The spectra were fitted by a multi-peak fitting program which was developed based on nonlinear least squares method. In the present work, the measured spectra were considered to be mainly broadened by the Doppler broadening and the instrument broadening ($\gamma_{\text{inst}} = 0.0105$ nm). Both the factors are of Gaussian lineshape, so the two-Gaussian-lineshape convolution equation is used as the fitting function. The fitting function could be expressed as follows:

$$F(\lambda) = y_0 + \sum_{k,j=1}^{N} a_j w_j A_k W_k \sqrt{\frac{\pi}{4\ln 2(w_j^2 + W_k^2)}} \times \exp\left[-4\ln 2\frac{(\lambda-\lambda_k)^2}{(w_j^2+W_k^2)}\right]. \quad (1)$$

Here $F(\lambda)$ is the final equation of two-Gaussian-lineshape convolution, y_0 is the background level, a_j and w_j are the amplitude and FWHM of the instrument function, A_k, λ_k and W_k are the amplitude, center wavelength and FWHM of spectral line k. The instrument function was measured by a He–Ne laser lamp. The detail of the fitting method can be found in our previous work.[15] Here 52 spectral lines were fitted, of which 49 could be identified based on the established database, and 3 unrecognized were added to make the fitting better. The fitting result and residual are shown in Figs. 4(a) and 4(b).

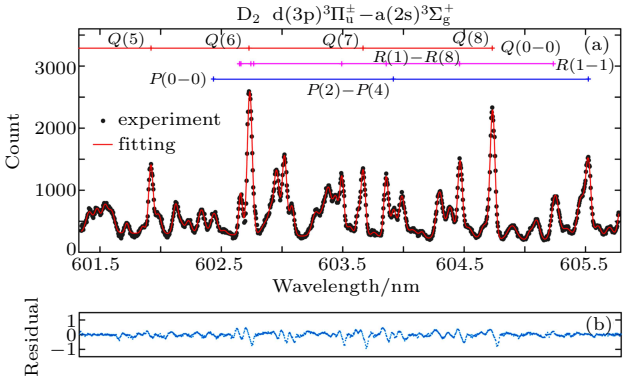


Fig. 4. Fitting of the spectra of deuterium molecular emission spectra of the Fulcher-α system (601–606 nm).

For high resolution and good signal-to-noise ratio of D_2 emission spectra, the main fitting errors are from the blending of spectral lines of other branches for the complexity of the molecular spectra and part of unrecognized impurity spectral lines in this band for kinds of impurities in plasma boundary.

Due to the 2400 g/m grating used for acquiring high resolution, the scan range of the OSMA was only 5 nm (601–606 nm) in one discharge. Therefore, only the spectral lines $Q(5)$–$Q(8)$ in the Q(0–0) band were observed and used for the analysis under the absolutely same discharge parameters. Under the detachment, the temperature T_e in the boundary was less than 5 eV, which could not provide diagnostics on the EAST, so we needed to use other methods to acquire the information of temperature data based on observed deuterium molecular emission spectra. In this work, the rotational temperature of the ground X $^1\Sigma_g^+$ and the excited d $^3\Pi_u^-$ states were estimated by D_2 emission spectral lines in the Q(0–0) band, in which the molecules over the rotational levels were a Boltzmann distribution. Thus, the intensities of the rotational lines to the rotational temperature could be expressed as follows:

$$\ln\left(\frac{I_{J'\rightarrow J''}}{v^4_{J'\rightarrow J''}\cdot S_{J',J''}}\right) = -\frac{hc}{kT^*_{\text{rot}}}\cdot E(J') + \text{const.}, \quad (2)$$

where $I_{J'\rightarrow J''}$ is the intensity of the rotational line corresponding to J'–J'' transition, $v_{J'\rightarrow J''}$ is the radiation frequency of this transition, $S_{J',J''}$ is the Hönl–London factor which can be calculated with the Hönl–London formula,[11,18,19] $E(J')$ is the energy of the upper level in units of cm^{-1}, h is Planck's constant, k is Boltzmann's constant, c is the velocity of light in vacuum, and T^*_{rot} is the rotational temperature of the upper excited state. The plot of the $\ln[I_{J'\rightarrow J''}/(v^4_{J'\rightarrow J''}\cdot S_{J',J''})]$ versus the rotational level energy term values $E(J')$ gives a so-called Boltzmann plot. The rotational temperature of the upper excited state (d $^3\Pi_u^-$)T^*_{rot} can be obtained from the slope of this plot. Based on T^*_{rot}, the rotational temperature of the ground state (X $^1\Sigma_g^+$)T^0_{rot} can be acquired by the equation $T^0_{\text{rot}} = T^*_{\text{rot}}(B^0_e/B^*_e)$, where B^0_e and B^*_e are the rotational constants of the ground and excited states. Here the rotational constant of the ground state is twice that of the excited state. According to Ref. [20], the T^0_{rot} could be assumed to be equal to the transition temperature of the gas T_{gas} in the discharge. Therefore the temperature of the neutral deuterium gas T_{gas} in boundary region can be acquired under the divertor detachment, and used as a reference value for the boundary temperature T_e. The Boltzmann plot for the observed D_2 emission spectral lines of Q(0–0) branch of the Fulcher-α system are given in Fig. 5. According to the linear regression equation fitting, the rotational temperature of the upper excited state T^*_{rot} is about 1255 K, so the temperature of the ground state T^0_{rot} and the neutral deuterium gas T_{gas} in the boundary region is about 2510 K.

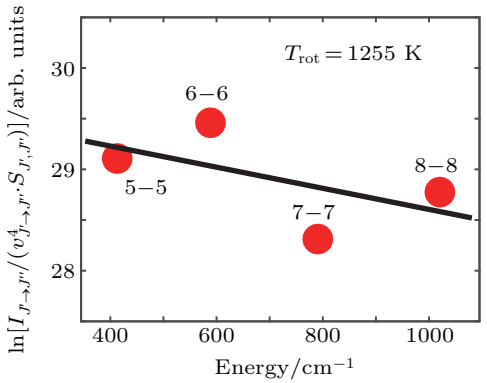


Fig. 5. Determining the rotational temperature of the upper excited state $D_2(d\,^3\Pi_u^-)$.

During the divertor detachment discharge, an interesting phenomenon was also observed, and the measured D_2 emission spectra at three time points ($t = 4$ s, 4.5 s, 5.5 s) were compared, as shown in Fig. 6. The intensity of the most of spectral lines increases first and then decreases with the increase of the rotational temperature $T^*_{\rm rot}$. However, the intensity of the spectral lines with higher values of the quantum number corresponding to other electron transitions ($g(3d)\,^3\Sigma_g^+ \to c(2p)\,^3\Pi_u^\pm$, 0–0 band near 603 nm) decreases first and then increases with the increase of the temperature. This means that the population on the (0–0) band of the $g(3d)\,^3\Sigma_g^+ \to c(2p)\,^3\Pi_u^\pm$ system decreases first and then increases. These could be explained as follows: When the temperature is lower, the electrons in the energy-level states are mainly distributed at lower levels for steady state. When the temperature increases, their energy increases and they will be distributed at higher levels for maintaining steady state. Therefore the intensity of spectral lines with higher values of the quantum number will increase, and with lower values of the quantum number will decrease. This reflects that the distribution of the population on rotational energy level charged at the rotational temperature $T^*_{\rm rot}$ follows the Boltzmann distribution under the current plasma discharge conditions.

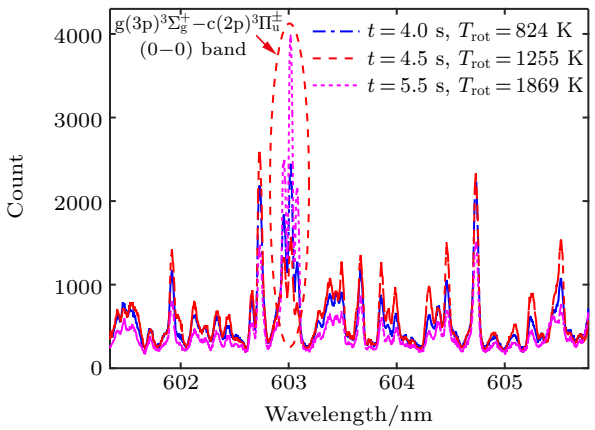


Fig. 6. Temperature dependence of the D_2 emission spectra.

4. Conclusion

An active feedback control of H-mode divertor detachment by neon gas puffing experiment was operated and succeeded for the first time on the EAST tokamak. By neon gas puffing, the plasma was successful detached, and the strike point splitting was clearly observed by diagnostic of divertor probes on the upper out divertor region at D port and O port. During the detachment discharge, the emission spectra of deuterium molecular of the Fulcher-α system ($d(3p)\,^3\Pi_u^\pm \to a(2s)\,^3\Sigma_g^+$) (601–606 nm) were observed and fitted for the first time on the EAST. Using the Boltzmann plot, the spectral lines in the Q(0–0) band were analyzed to acquire the rotational temperatures of the upper excited $(d\,^3\Pi_u^-)T^*_{\rm rot}$ and ground state $(X\,^1\Sigma_g^+)T^0_{\rm rot}$ for obtaining the neutral deuterium gas $T_{\rm gas}$ in boundary region, which was used as a reference value for temperature T_e. In the future, we will use two spectrometers to observe the deuterium atomic and molecular emission spectra under the divertor detachment discharge. One is for the the deuterium atom emission spectra ($D_{\alpha,\beta,\gamma,\ldots}$) and the other is for the Fulcher-α system of deuterium molecules in the wavelength range from 590 nm to 640 nm. By analyzing measured atomic and molecular spectra in one discharge, it would be possible to analyze the dynamics of the atomic and molecular components in the boundary recycling and to estimate the charged particles coming into the plasma in the form of atoms and molecules of deuterium. It will be good for us to study the physical mechanism of divertor detachment on the EAST and even for the future ITER and CFETR.

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