Quantifying physical parameters in an outer divertor region using Balmer line spectroscopy

T. Nishizawa[1], M. Cavedon[2], F. Reimold[1], R. Dux[2], and the ASDEX Upgrade Team[2]

[1] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 17491 Greifswald, Germany*

[2] *Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, D-85748 Garching, Germany*

Mitigating head load on the divertor target is considered one of the critical challenges in achieving a commercial fusion reactor. Fortunately, both density and temperature at the divertor target can be reduced significantly through a process called "detachment", leading to tolerable heat flux. However, our current understanding of the detachment process is mostly based on empirical laws and qualitative descriptions, and the extrapolation of the current detachment behavior to future reactors is not reliable. Balmer line spectroscopy is a non-intrusive diagnostic technique for characterizing plasma parameters in cold divertor regions, helping us further understand detachment. While this technique has successfully provided useful information at various devices[1, 2], the interpretation of the measurements is not always straightforward due to line-integration effects. A new analysis technique for the Balmer line spectroscopy that enables quantitative particle source and sink measurements is discussed herein.

Figure. 1 (b) describes plasma parameter profiles along the red line of sight shown in Fig. 1 (a). The profiles, which resemble ASDEX Upgrade(AUG) plasmas, are calculated by SOLPS simulations. In general, spatial variations of plasma parameters are not negligible in the outer closed-divertor at AUG, and a simple uniform plasma slab is not an appropriate approximation. In order to account for line-integration effects, a simplified profile model shown in Fig. 1 (c) is introduced. The model has six parameters: $\hat{T}_{e,1}$ (lower electron temperature corresponding to a private flux region), $\hat{T}_{e,2}$ (higher electron temperature corresponding to a SOL region), $\hat{n}_e$ (average electron density), $\hat{n}_0$ (uniform neutral density), $\hat{l}$ (FWHM of the triangular electron density profile), and $\hat{\alpha}$ (asymmetry factor that defines the peak position of n_e).

In this analysis, only Balmer lines D_ε, and D_δ are considered. For these two lines, the line emission coefficient is given by:

$$i_X(n_e, T_e, n_0) = n_e^2 \mathrm{PEC}_X^{\mathrm{rec}}(n_e, T_e) + n_e n_0 \mathrm{PEC}_X^{\mathrm{exc}}(n_e, T_e), \tag{1}$$

where $X = \varepsilon$, δ. The letters, $\mathrm{PEC}_X^{\mathrm{rec}}$ and $\mathrm{PEC}_X^{\mathrm{exc}}$ are photon emission coefficients, provided by ADAS[3]. The first and second terms on the right hand side are recombination emission and excitation emission, respectively. For plasma parameter profiles specified by $\theta = [\hat{T}_{e,1}, \hat{T}_{e,2}, \hat{n}_e, \hat{n}_0, \hat{l}, \hat{\alpha}]$,

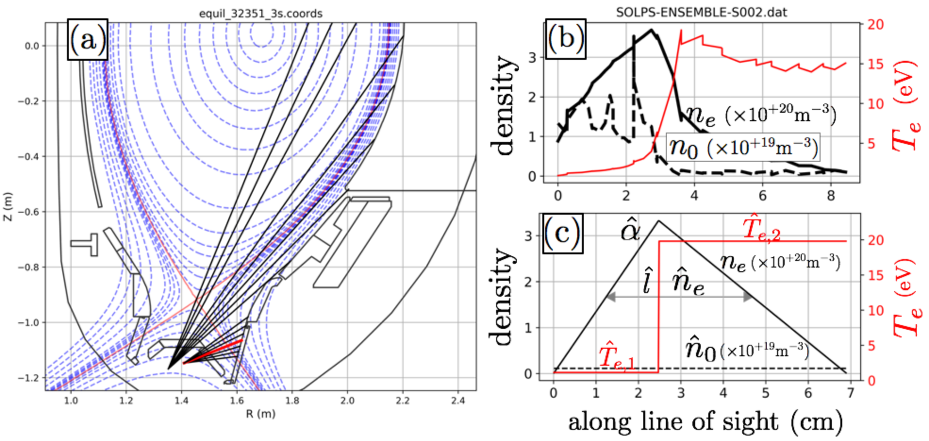

Figure 1: (a) Lines of sight for the outer divertor in AUG. (b) An example of plasma parameter profiles along the red line of sight shown in (a). (c) A simplified profile model. n_e has a triangle profile. T_e has two steps. n_0 is uniform. The parameter $\hat{\alpha}$ specifies the peak position of n_e.

the measured spectral radiance of both lines can be calculated using the following equation:

$$I^{\text{model}}_{X,\lambda_X} = \int d\lambda H_{\lambda_X} \int dl i_X L_X, \tag{2}$$

where

$$L_X(\lambda, n_e, T_e) \propto \frac{1}{(\lambda - \lambda_{0,X})^{5/2} + (c_X \frac{n_e^{a_X}}{T_e^{b_X}})^{5/2}}, \tag{3}$$

which is appropriate for the cold divertor regions in AUG[1], and H_{λ_X} is an instrument function of the wavelength channel λ_X.

Probability distributions of θ that reproduce experimental measurements are calculated by using the Bayes' theorem[4]. Assuming that errors in the measurements follow a Gaussian distribution, the likelihood is given by:

$$p(D|\theta, I) = \prod_{\lambda_\varepsilon} \frac{1}{\sqrt{2\pi\sigma^2_{\lambda_\varepsilon}}} \exp\left(-\frac{(I^{\text{data}}_{\varepsilon,\lambda_\varepsilon} - I^{\text{model}}_{\varepsilon,\lambda_\varepsilon})^2}{2\sigma^2_{\lambda_\varepsilon}}\right) \prod_{\lambda_\delta} \frac{1}{\sqrt{2\pi\sigma^2_{\lambda_\delta}}} \exp\left(-\frac{(I^{\text{data}}_{\delta,\lambda_\delta} - I^{\text{model}}_{\delta,\lambda_\delta})^2}{2\sigma^2_{\lambda_\delta}}\right), \tag{4}$$

where $I^{\text{data}}_{X,\lambda_X}$ is the experimentally measured intensity of the wavelength channel λ_X, and σ_{λ_X} is the uncertainty of $I^{\text{data}}_{X,\lambda_X}$.

The validity of the simplified profile model in the particle source and sink measurements is tested by using synthetic data. Effective ionization and recombination rates for given n_e and T_e are also provided by ADAS[3]. Once a probability distribution is calculated in the θ space, the distribution can be mapped onto probability distributions of line-integrated ionization and recombination rates. A set of synthetic spectral data of D_ε and D_δ is generated from the results of

SOLPS simulations, and the Bayesian framework with the simplified profile model is applied to calculate line-integrated ionization and recombination rates. The data set includes H-mode and L-mode discharges in both attached and detached cases. The lines of sight shown in Fig. 1 are used. Figures 2 (a) and (b) show the results of recombination and ionization rate measurements. It can be seen that recombination rates are measured with reasonable precision. However, the ionization rate measurements suffer from large uncertainties. While the Stark-broadening of D_ε strongly constrains $\hat{n}_e$, the probability distribution of $\hat{n}_0$ is typically broad. The uncertainty of $\hat{n}_0$ propagates to the ionization rate. On the other hand, the recombination is independent of n_0, and can be more strongly constrained. With the current diagnostic capability of AUG, only D_ε and D_δ can be measured simultaneously using the same line of sight. However, if a signal from one optical fiber is split and fed to two different spectrometers, the four Balmer lines D_ε, D_δ, D_γ and D_β can be measured simultaneously without sacrificing wavelength resolution. Since D_γ and D_β are more sensitive to excitation, adding these two lines effectively excludes the choices of θ that reproduce the experimental data with only recombination emissions. The results of ionization rate measurements when D_γ and D_β are included are shown in Fig. 2 (c). The uncertainties are significantly reduced compared with Fig. 2 (b). Optical fiber splitters are now being constructed, and the simultaneous measurements of the four Balmer lines will be possible in the near future at AUG.

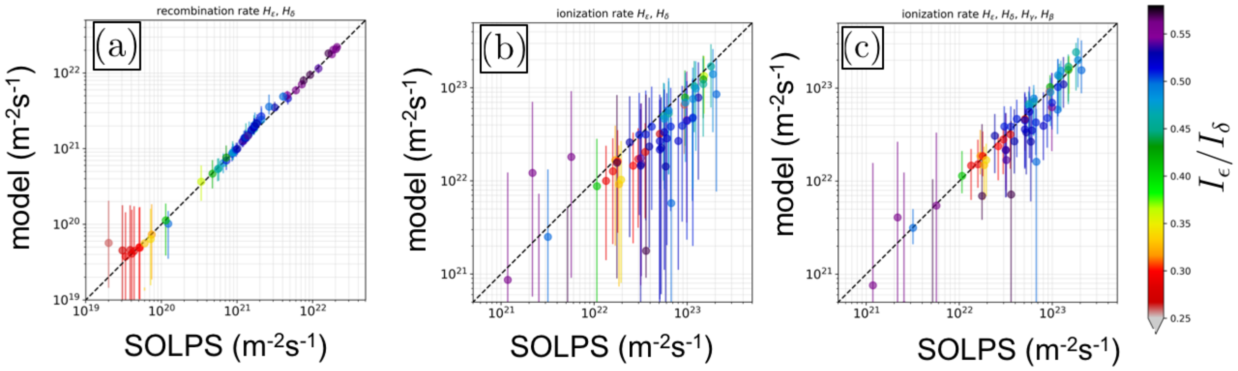

Figure 2: (a) Recombinaion rate calculated from D_ε and D_δ. (b) Ionization rate calculated from D_ε and D_δ. (c) Ionization rate calculated from D_ε, D_δ, D_γ, and D_β. The x axes are the true ionization and recombination rates calculated directly from the SOLPS results. The color represents the emission intensity ratio of D_ε to D_δ. The higher the ratio, the more contribution from recombination emission than excitation emission. The errors show the 68 % of confidence level.

The analysis technique for particle source and sink measurements is also applied to an L-mode discharge with N_2 seeding and a density ramp. Basic discharge parameters are shown in

Fig. 3 (a) and (b). At $t = 1.6$ s, N_2 seeding starts, and the D_2 puff amount increases at $t = 2.5$ and 3.5 s stepwise, leading to a gradual increase both in the core and edge n_e. Figure 3 shows the total recombination and ionization rates in the outer-divertor volume, which are calculated by assigning appropriate integration volumes for each line of sight. While the total ionization rate has large errors bars, its ranges agree with the total ion flux on the target. The total recombination rate plays a minor role in the particle flux balance. These observations are consistent with our current understanding of the high-recycling regime.

In summary, the new Balmer line analysis technique based on the Bayesian framework is presented. The simplified profile model for an outer divertor plasma is able to measure recombination rates (particle sinks) with reasonable precision. While particle source (ionization rate) measurements have large errors, the precision can be significantly improved if additional Balmer lines are included. This analysis technique will be useful in characterizing divertor plasmas relevant to fusion reactors.

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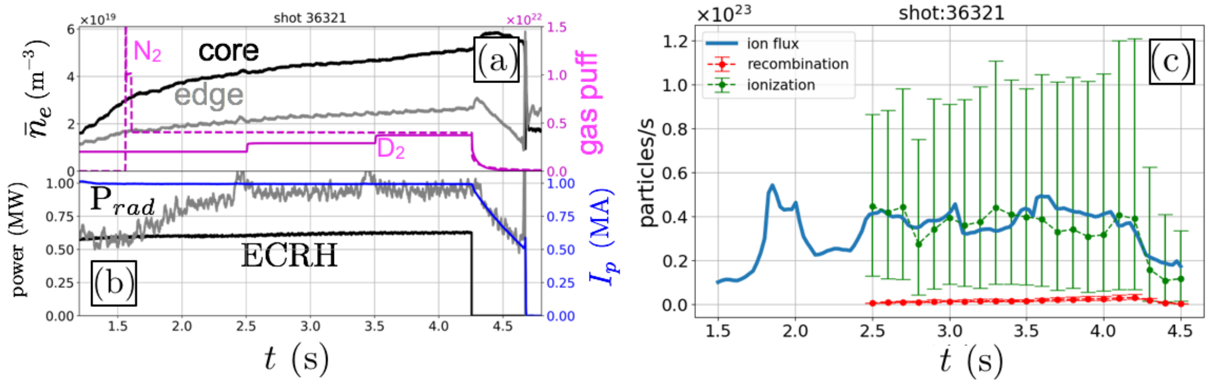

Figure 3: (a) Time evolutions of line-averaged n_e and gas puff rates. (b) Time evolutions of ECRH power, radiated power, and the plasma current. (c) Volume-integrated recombination and ionization rates and a total ion flux at the target. For this discharge, sufficient signal levels of D_ε and D_δ are available after $t = 2.5$ s.

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