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On resolving the optical spectra of the edge plasma radiation against a strong background of the divertor stray light

L I Ognev[1,3] **and V S Lisitsa**[1,2]
[1]National Research Centre "Kurchatov Institute", Moscow 123182 Russia
[2]National Research Nuclear University "MEPhI", Moscow, Russia

E-mail: liognev@gmail.com

Abstract. A method of detecting a weak radiation of the Balmer lines from the hydrogen isotopes in the edge plasma of a tokamak (SOL) on the strong optical background formed by reflection of the light emitted from the divertor plasma is proposed. The method is based on a parallel registration of the radiation from the optical dump and from the wall near the dump. Calibration of the attenuation of the stray light radiation by the optical dump is being performed in the course of the measurements, using the intensity of the high-frequency pulsations that are not correlated with the edge plasma emission. Statistical estimates show that a 20-fold attenuation of the light by the dump allows registration of the weak edge plasma radiation making down to 0.5% of the background intensity.

1. Introduction

The issue of registering the Balmer line radiation from the hydrogen isotopes in the edge tokamak plasma (SOL) has become particularly important after first assessments of the background formed by reflection of the powerful light radiation from the divertor plasma. The ratio of the divertor to the SOL radiation intensity in the H-alpha line in modern tokamaks (JET) is about an order of magnitude. Given the parameters of ITER, this ratio can reach a value of 10^2 [1].

2. Methods of detecting a weak radiation on a strong background

Several methods have been proposed to solve this problem [1, 2]. Utilisation of an optical light dump (an absorbing cavity in the wall) was proposed in [1]. The method [2] is based on a solution of the inverse problem of recovering the SOL signal using the data of measurements along different chords, including those viewing the divertor. Parallel detection of the radiation from the dump and wall ("double chords" scheme) improves the stability of the method.

2.1. The dump calibration method using high-intensity fluctuations of the background

In this paper we analyze the possibility of detecting a weak SOL signal on the background of a strong divertor radiation in the scheme with the light dump [2] ("double chords"), taking advantage of the statistical independence of the fluctuations of the signals from both sources. The typical frequencies of

[3] To whom any correspondence should be addressed

such fluctuations in modern tokamaks, according to the observations of the spectra of optical radiation from helium [3] and hydrogen [4], reach the values up to 100 kHz. In the method proposed, the high frequency part of the fluctuation spectrum is used to calibrate the optical dump.

This method is based on comparing the intensity of the radiation beams reflected from the attenuating dump I_2 and from the first wall without attenuation I_1 (figure 1). Both beams include, as a minor fraction, the radiation from the neutral atoms in the edge plasma (SOL), x_1 and x_2, respectively, which is registered without attenuation and is the useful signal to be resolved. The background radiation reflected from the vicinity of the dump, y_1, is not attenuated – unlike that reflected from the dump itself, y_2 (figure 2). Therefore, $x_1 \approx x_2 = x << y_1$, $y_2 = \alpha y_1$, $x_1 + y_1 = I_1(t), x_2 + y_2 = I_2(t)$, where α is the light attenuation factor in the dump. Now the intensity of the weak signal can be found as:

$$x = (I_2 - \alpha I_1)/(1-\alpha) \tag{1}$$

Diagnostic requirements for monitoring the H-alpha signal foresee the time resolution of 0.1 s. Therefore, the time-average values should be taken for the intensities I_1 and I_2 in equition 1. The intensity of the high frequency part of the fluctuation spectrum in the text below will be noted as $\tilde{I}$. So, in order to detect the weak signal on the strong background one needs to know the reflectivity of the light beam dump, which may vary in time over the measurement period of the signal T_1 = 0.1 s. Unlike the "double chords" [2], this method does not require detailed information about the shape of the line.

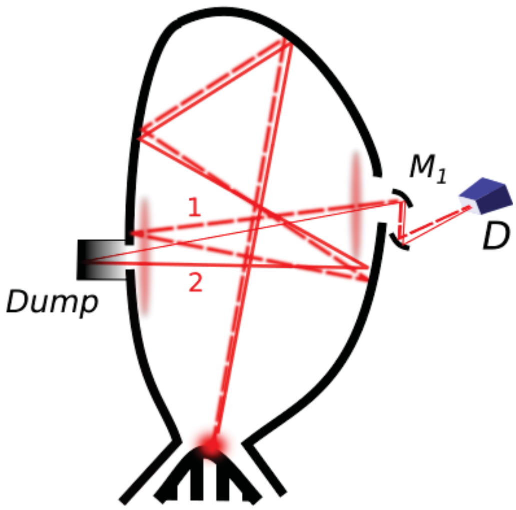

Figure 1. Scheme of the formation of the two-channel signal I_1 and I_2 by the reflection of the divertor stray light from the wall (chord 1) and from the optical dump (chord 2) with the addition of the radiation contribution of the edge plasma. M_1 is the first diagnostic mirror, D the detector with separate registration of the channels. The radiation zones are shadowed.

The reflectivity of the light dump can be calculated from the time-averaged power of the fluctuations of the high intensity divertor radiation in the light beams reflected from the dump and from the chamber wall as

$$\alpha(t) = \sqrt{\langle \tilde{y}_2^2 \rangle} \Big/ \sqrt{\langle \tilde{y}_1^2 \rangle} \approx \sqrt{\langle \tilde{I}_2^2 \rangle} \Big/ \sqrt{\langle \tilde{I}_1^2 \rangle} \tag{2}$$

since, due to the statistical independence, $\langle \tilde{I}_i^2 \rangle = \langle \tilde{y}_i^2 \rangle + \langle \tilde{x}_i^2 \rangle$ and $\langle \tilde{x}_i^2 \rangle << \langle \tilde{y}_i^2 \rangle$.

2.1.1 Statistical accuracy of the dump effectiveness and the bandwidth of the background fluctuations. High intensity fluctuations of the H-alpha line are collected in a frequency band [ω_2, ω_3] and subjected to quadratic detecting followed by isolation of the low-frequency signal components $\langle \tilde{I}_i^2 \rangle$ in the diagnostic range [0, ω_1]. We will use the relation between the dispersion of the current through the quadratic detector squared and the frequency ranges used for registration of the high- and low-frequency signals in the model of the white noise with the Gaussian statistics [5]:

$$\frac{<(\delta<\tilde{I}_i^2>)^2>}{(<\tilde{I}_i^2>)^2} = \int_0^{\omega_1} S_f(\omega)d\omega \Big/ \int_0^{\omega_1} S_0(\omega)d\omega = \frac{4(<\tilde{I}_2^2>)^2 \dfrac{\pi}{\Delta\omega}\cdot\omega_1}{(<\tilde{I}_i^2>)^2} = \frac{4\pi\omega_1}{\omega_3-\omega_2} \tag{3}$$

where $S_f(\omega)$ and $S_0(\omega)$ are the spectral densities of the fluctuations of the processed signal and its constant component. Since $\delta\alpha/\alpha \sim (1/2)\cdot\delta\left(\langle \tilde{I}_i^2 \rangle\right)/\langle \tilde{I}_i^2 \rangle$ from (3) one obtains $\delta\alpha/\alpha \sim (1/2)\cdot\sqrt{4\pi\omega_1/(\omega_3-\omega_2)}$

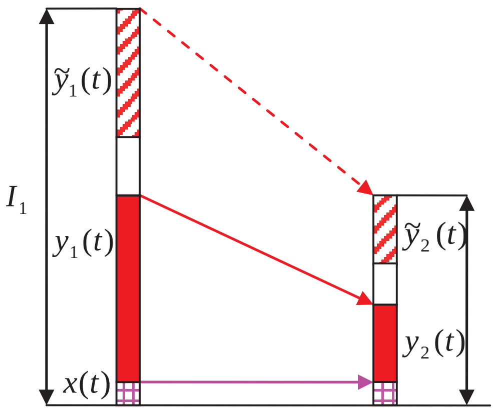

Figure 2. Schematics of the measurement of the optical radiation signal from the neutral hydrogen atoms (*x (t)*) on the background of the divertor stray light (*y (t)*). The total radiation intensity $I_1(t)$ and the total intensity of the radiation from the optical dump $I_2(t)$ is what is actually measured. The shaded areas correspond to the rapidly oscillating component of the radiation coming from the divertor.

The bandwidth of the high-frequency filter necessary to satisfy the accuracy $\delta\alpha/\alpha \le 0.1$ can be found from the relation $4\pi\omega_1/0.04 \le \omega_3 - 10\omega_1$. Hence $\omega_3 > (4\pi/0.04+10)\omega_1$, and for $T = 0.1$s, the frequency of the high-frequency pulsations used for the dump calibration $f = 3200$Hz is adequate for the dump calibration. This corresponds to the minimum reference time interval for the noise $\Delta t = 0.3\cdot10^{-3}s$. The required photon flux through the high-frequency filter in the interval of $\Delta t/2$ is $N/(\Delta t/2) = 100/(0.3\cdot10^{-3}s/2) = 7\cdot10^5$ph/s, and this can indeed be registered in experiment.

2.1.2 Sensitivity of the method. The uncertainty of the $\bar{x}(t)$ calculation is attributed to variations in the reflectivity of the dump $\alpha(t) = \bar{\alpha}(t) + \delta\alpha$. Let us express the variation through the partial derivative of $x = a(\alpha, I_2)$ with respect to α: $\delta x = (\partial x/\partial\alpha)\cdot\delta\alpha$. After substitution $I_2 = \alpha(t)\left[I_1(t) - x\right] + x$, taking into account the smallness of $x \ll I_1$ we obtain

$$\sqrt{\langle(\delta x)^2\rangle} \approx I_1\sqrt{\langle(\delta\alpha)^2\rangle}\Big/(1-\alpha) \tag{4}$$

Therefore, minimization of $\delta\alpha$, rather than the smallness of α itself, is important for improving the sensitivity. Assuming $\delta\alpha/\alpha \le 0.1$, if $\alpha \le 0.05$ [1], the minimum detectable signal-to-noise ratio $x_{\min}/I_1$ can be estimated as less than 0.005.

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