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Impurity control in a tokamak edge plasma by a method of Doppler-free spectroscopy

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ABSTRACT

The laser-induced fluorescence (LIF) technique is proposed to use for local determination of an effective ionic charge in a plasma edge of large fusion devices. The method is based on non-linear phenomenon of saturation of an optical transition of hydrogen atom excited by means of an intense laser light with a small spectral width. It is demonstrated that measurements of a slight Stark broadening without Doppler-broadened background are possible under conditions typical of tokamak plasma. One of approaches for evaluation of an effective ionic charge from the homogeneous Stark width is discussed in detail.

1. Introduction

The impurity control is one of the remaining critical problems for development of fusion devices. The effective ionic charge Z_{eff} is a means to estimate the global impurity content of tokamak plasma. The method widely used to determine this value is based on measurements of the visible bremsstrahlung emission in many viewing lines with subsequent Z_{eff} profile reconstruction, e.g. [1]. In the plasma edge, lines radiation, pseudo continua from molecular bands and thermal radiation from hot parts of the plasma facing components dominate the bremsstrahlung background. As a result unphysical high Z_{eff} values may be obtained.

The methods of Doppler-free spectroscopy are free from shortcomings of the passive spectroscopic diagnostics and provide really local measurements of the homogeneous Stark width of spectral lines, which depends on the electric field created by the surrounding charged particles (H^+ or D^+ and impurity ions). The theoretical bases of one of these methods were stated in paper [2]. It was shown that homogeneous Stark width and effective ionic charge are coupled by simple relation. Further the method was developed and successfully implemented in practice in the TV-1 tokamak by means of LIF technique [3], where the homogeneous width of the hydrogen H_α line was measured locally by recording the fluorescence line profile. The theoretical calculations carried out in the present paper and experimental results obtained earlier form the foundations for application of this method to the plasma edge of large fusion devices.

2. Method description

In high-temperature plasmas typical of tokamaks a broadening of hydrogen line mainly originates from the Doppler effect. A homogeneous Stark broadening Γ may be imperceptible against the background of the Doppler broadening. In order to extract a small value of a Stark broadening the methods of Doppler-free laser spectroscopy are applied. The method proposed is based on non-linear phenomenon of a saturation of an optical transition of hydrogen excited by means of an intense laser beam with the spectral width, which is significantly smaller than the Doppler one.

The probability of a laser-induced transition from the lower level n to the upper one n' is [4]:

$$\langle W_{nn'} \rangle = \frac{G\Delta\omega_r}{2\sqrt{\pi}\Delta\omega_D} \int_{-\infty}^{\infty} \exp\left(-x^2 \frac{\Delta\omega_r^2}{\Delta\omega_D^2}\right) \frac{y\sqrt{\pi}U(x,y)dx}{1 + y\sqrt{\pi}U(x,y)G}, \qquad (1)$$

where $x = 2(\ln 2)^{1/2}(\omega_r - \omega_0 - \mathbf{kV})/\Delta\omega_r$, $y = \Gamma(\ln 2)^{1/2}/\Delta\omega_r$, $U(x,y)$ is the Voigt function, $\Delta\omega_D$ is the full width at half maximum (FWHM) of the Doppler-broadened line, $\Delta\omega_r$ is the FWHM of the laser line, $(\omega_r - \omega_0)$ is the deviation of laser frequency ω_r from the centre of the atomic line ω_0, $\boldsymbol{k}$ is the direction of laser beam, and $\boldsymbol{V}$ is the velocity of atom. The probability is normalized to a value of 0.5. The expression (1) is written under the assumption that the atoms have a Maxwellian distribution on velocities, and the laser line is not monochromatic and has a Gaussian spectral profile. The probability $\langle W_{nn'} \rangle$ depends on the saturation parameter $G = (p_{nn'}E/\hbar)^2\tau_{\mathrm{eff}}/\Gamma$, also. Here $p_{nn'}$ is the matrix element of the transition dipole moment, E is electric field strength of the laser beam, τ_{eff} is the effective relaxation time of the levels n and n'. The value $p_{nn'}E/\hbar$ represents the transition speed of a particle between the levels and, hence, results in a spectral line broadening caused by the intense field of laser light (energy broadening). If the laser radiation

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is monochromatic the contour widened by the light field has a dispersion shape with a half-width Γ_B, which is connected with a homogeneous Stark broadening Γ by the non-linear relation [5]:

$$\Gamma_{\mathrm{B}} = \Gamma\sqrt{1+G}. \tag{2}$$

Thus a spectral line shape observed contains both the Doppler-broadened thermal profile and the profile formed by the energy broadening.

The average probabilities $\langle W_{23}\rangle$ calculated for laser-induced transition of hydrogen atom from level $n = 2$ to level $n' = 3$ are presented in Fig. 1 as functions of the value of $G\Gamma$ for various Γ. The theoretical dependences are the saturation curves obtained for two important cases. The solid curves correspond to the cold plasma containing neutral atoms produced at the plasma facing components, e.g. the plasma being in a vicinity of X-point of a divertor configuration. In this case the electron and atom temperatures are about 1 eV and the Doppler width $\Delta\lambda_D = 0.05$ nm. The dashed curves are plotted for hotter plasma in which most of the neutrals are born as a result of charge-exchange reaction. The electron and atom temperatures are chosen about 100 eV and $\Delta\lambda_D = 0.5$ nm for these calculations. In both cases the electron density is 10^{20} m^{-3}, the wave length of the laser radiation coincides with a centre of the atom transition and the FWHM of the laser line $\Delta\lambda_r = 0.01$ nm.

At weak saturation ($G \ll 1$) the field of a light wave interacts with a small part of atoms. Because of the Doppler-frequency shift these are only those atoms, which are under the resonance condition $v = (\omega_r - \omega_0)c/\omega_0$, i.e. have quite certain projection of the velocity v in the direction of the laser beam, where c is the speed of light. The deficiency of atoms at the lower level appears in the velocity distribution. It is so-called Bennet's 'hole' with width 2Γ and the centre corresponding to a resonant frequency. Scanning a narrow laser line within a Doppler-broadened spectral line contour it is possible to measure a Doppler width and then deduce a temperature of radiating atoms.

When the intensity of the laser radiation increases the velocities range of atoms interacting with the field of the light wave is expanded, and the energy broadening of a spectral line becomes comparable to the Doppler broadening. In the strong fields ($G \gg 1$) the whole Doppler contour is covered. This significant enhancement of the width of the dispersive component allows us to extract it from the observed Voigt profile and determine the homogeneous Stark width of the spectral line using relation (2).

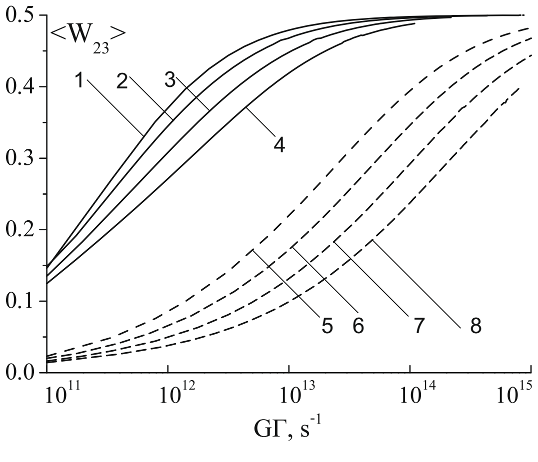

Fig. 1. Average probabilities $\langle W_{23}\rangle$ of laser-induced transition from level $n = 2$ to level $n' = 3$ calculated for hydrogen atom as dependences on the value of $G\Gamma$ under following conditions: $\lambda_r = \lambda_0$, $\Delta\lambda_r = 0.01$ nm. Solid lines ($\Delta\lambda_D = 0.05$ nm): 1 – $\Gamma = 0.02$ nm, 2 – $\Gamma = 0.01$ nm, 3 – $\Gamma = 0.005$ nm, and 4 – $\Gamma = 0.0025$ nm. Dashed lines ($\Delta\lambda_D = 0.5$ nm): 5 – $\Gamma = 0.02$ nm, 6 – $\Gamma = 0.01$ nm, 7 – $\Gamma = 0.005$ nm, and 8 – $\Gamma = 0.0025$ nm.

Under conditions typical of the plasma edge the Stark broadening of spectral lines is formed by collisions of radiating hydrogen atoms with the major plasma component and impurity ions. The contribution of electrons to this broadening is negligible. Under ion impact broadening a homogeneous Stark width is found as a result of summation of contributions from all of the perturbing particles [6]:

$$\Gamma = \frac{32}{3}\cdot\frac{\hbar^2}{m_0^2} I(n,\, n') \sum_i \frac{Z_i^2 N_i}{\langle V_i\rangle}\left(\ln\frac{\rho_D}{\rho_{0i}} + 0.215\right), \tag{3}$$

where m_0 is mass of an electron, N_i, $\langle V_i\rangle$, ρ_{0i} and Z_i are density, relative thermal velocity, Weisskopf radius, and charge of the particles of species i respectively, ρ_D is Debye lenght and the factor $I(n, n')$ depends on the principal quantum numbers of the levels of the radiative transition. The relative velocity of particles is always determined by the velocity of the lightest particles, therefore $\langle V_i\rangle$ can be replaced by the thermal velocity of the hydrogen ions $\langle V_H\rangle$. Moreover, the quantity $\ln(\rho_D/\rho_{0i})$ has a very weak dependence on Z_i, therefore $Z_{\rm eff}$ can be used instead of Z_i in Weisskopf radius definition while the summation over i is performed. Then

$$\Gamma \approx \frac{32}{3}\frac{\hbar^2}{m_0^2} I(n,\, n')\frac{n_e}{\langle V_H\rangle} Z_{\rm eff} \ln\frac{\rho_D}{\rho_0},$$

$$\text{where } Z_{\rm eff} = \frac{\sum_i Z_i^2 N_i}{n_e}. \tag{4}$$

In this case a value of $Z_{\rm eff}$ is easily deduced from the homogeneous Stark broadening Γ measured with help of proposed technique if independent data on electron density n_e, ion T_i and electron T_e temperatures are available. The possibility of this method implementation has been demonstrated in the TV-1 tokamak.

3. Experimental set-up

The TV-1 tokamak has a major radius $R = 0.235$ m and a limiter radius $a_L = 0.035$ m. The tokamak operates under the following discharge conditions: a plasma current $I_p = 4$–5 kA, a toroidal magnetic field $B_T = 1.4$ T, and a discharge duration $\tau = 7$ ms. The core plasma parameters were taken from the Thomson scattering diagnostic (an electron density $n_e = (1$–$2)\ 10^{19}$ m^{-3} and temperature $T_e = 200$–300 eV).

The intensities of the fluorescence and H_α (656.3 nm) spectral line profiles were measured in the conventional arrangement. The linearly polarized laser radiation passed from below upwards through the centre of the plasma core. The scattered light was collected at the right angle to the direction of the probing beam. A tunable dye laser with flash lamps pumping was used as a source of the exciting light. Two Fabry–Perot interferometers with baselines of 5 and 100 μm were placed in the resonator to tune the laser and to generate a spectrally narrow line in the H_α region. The laser generated 2 μs pulses with the energy of 0.01–0.03 J. The laser line had a Gaussian profile with a half-width $\Delta\lambda_r = 0.010 \pm 0.001$ nm.

Each fluorescence line profile was recorded over a series of reproducible tokamak discharges when the laser wavelength was consecutively tuned in the vicinity of H_α line with the step of 0.01 nm. The fluorescence signals were measured both during startup and during the flattop phase of the discharge. The most of the measurements were carried out during excitation of the π-component of the Zeeman structure of H_α transition.

4. Results of the measurements

The extracting of the Doppler and energy broadenings from experimental data obtained was made by the following two ways.

In the first case two fluorescence line profiles for different power densities of laser radiation P_r corresponded two different values of saturation parameter G were measured. The π-component of H_α line profiles observed are shown in Fig. 2 as the dependence of the fluorescence signal I_{fl} on the wavelength detuning of the dye laser from the centre of this hydrogen line (λ_r–λ_0). The line profiles obtained were compared with calculated ones. In the calculations the expression (1) was used. The line shape described by this expression may, in general, be quite different from a Voigt line shape, but as the saturation parameter G increases the wings of the function $U(x,y)$ begin to make a progressively greater contribution to this line shape. At G » 10 the line shape (1) tends towards a Voigt contour. It thus appeared to be possible to use the tables for Voigt function or the simple approximate relations that connect the FWHM $\Delta\lambda$ of the line profiles observed with $\Delta\lambda_D$ and Γ_B.

In the second case only one fluorescence line profile was recorded at rather low power density of laser radiation, i.e. far from saturation of the transition. Further, the fluorescence signal was measured when the laser excited the centre of the line and a laser power density was sufficient to saturate the transition of the radiating atoms. These results were used to determine the experimental probability of the transition of the hydrogen atom from its lower level $n = 2$ to the upper level $n' = 3$. The probability was found as the ratio of the fluorescence signals measured far from saturation and at saturation. The values of probability $\langle W_{23} \rangle$ and the power density of laser radiation being proportional to product $G\Gamma$ allowed to determine a single set of the unknown values $\Delta\lambda_D$ and Γ. For these purposes the saturation curves as in Fig. 1 calculated at plasma parameters typical of TV-1 tokamak as nomograms using the formula (1) along with the corresponding relationships for the FWHM of the Voigt contour were used.

The FWHM of Doppler broadening $\Delta\lambda$ and energy broadening Γ_B are depicted in Figs. 3 and 4 accordingly as the dependences on the power density of the laser beam P_r. The values found for $\Delta\lambda_D$ do not depend on P_r, while Γ_B naturally shows a strong dependence. The figures at the left (a) are related to startup phase of the discharge ($\tau = 0.3$ ms) but figures at the right (b) are concerned the flattop phase of the discharge ($\tau = 3$ ms). As a result the following values were determined for a discharge current plateau at the plasma centre: $\Delta\lambda_D = 0.045 \pm 0.007$ nm, $\Gamma = 0.009 \pm 0.002$ nm. Besides, the densities of atomic hydrogen in the ground state $n_1 = (3.7 \pm 0.2) \times 10^{15}\ \mathrm{m}^{-3}$ and in the excited state $n_2 = (1.1 \pm 0.1) \times 10^{13}\ \mathrm{m}^{-3}$ were routinely deduced from the fluorescence signal obtained at the saturation.

5. Discussion and conclusion

The observed narrow hydrogen H_α profiles have demonstrated that the emission of the charge-exchange neutrals was negligible in comparison with the emission of neutral atoms produced at the plasma facing components as walls and limiters. The Doppler width measured corresponded to hydrogen atoms with kinetic energies about 1 eV. These atoms could be produced in processes similar to Franck–Condon decay of hydrogen molecules, which leave the surface in an excited state and dissociate into atoms with such energies. The existence of a large contribution of 'slow' atoms with kinetic energies below 1 eV have been confirmed also in TEXTOR plasma edge, in which the velocity distributions of the recycled atoms have been recorded [7]. Moreover the contribution to the H_α line radiation from atoms with energies in the order of some eV exceeds 90% [8,9].

As mentioned above it is possible to obtain information on presence of impurities in plasma from the homogeneous Stark width measured. The reliability of this information is contingent upon the ion impact broadening (IIB) theory used. In frames of the standard theory of IIB the homogeneous Stark width is a linear function of Z_{eff} [2]. Following this paper the approximate expression (4) can be applied to determine the effective charge. In TV-1 tokamak a

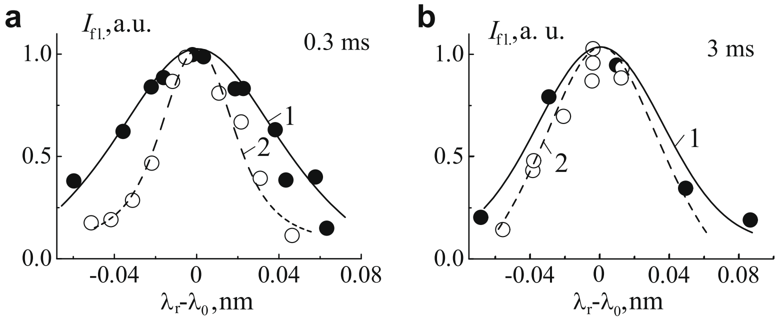

Fig. 2. H_α line profiles (π-component) measured for various laser light power densities P_r: (a) during startup phase of the discharge: 1 – $P_r = 0.12$ kW/cm^2 (dashed line and open circles), 2 – $P_r = 1.7$ kW/cm^2 (solid line and circles); and (b) during the flattop phase of the discharge: 3 – $P_r = 0.14$ kW/cm^2 (dashed line and open circles), 4 – $P_r = 1.2$ kW/cm^2 (solid line and circles). The lines represent the fitting by Voigt functions.

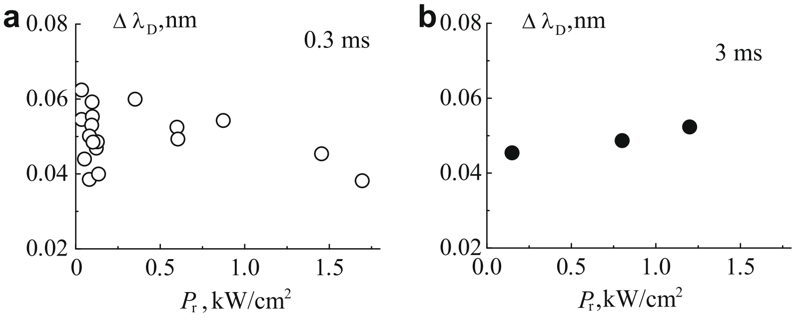

Fig. 3. FWHM of the H_α line Doppler broadening versus the power density of the laser light: (a) $\tau = 0.3$ ms (open circles); and (b) $\tau = 3$ ms (solid circles).

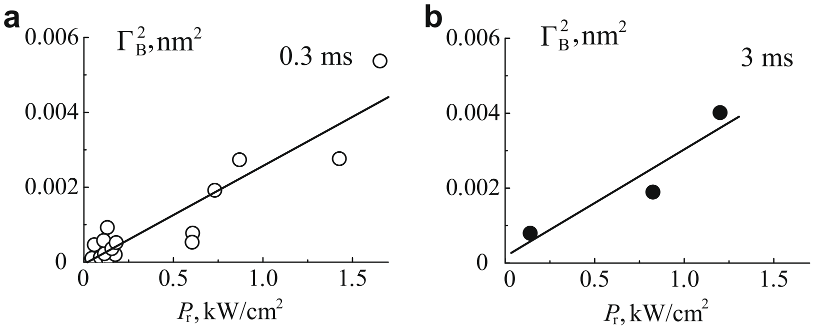

Fig. 4. FWHM of the H_α line energy broadening versus the power density of the laser light: (a) τ = 0.3 ms (open circles); (b) τ = 3 ms (solid circles). The lines represent the linear fits.

large fraction of the hydrogen atoms had energy that was much less than the proton energy (T_i = 30–60 eV). Therefore the effective charge was calculated from more general expression (3), which allowed for the relative impurity velocities accurately. As a result it was found Z_{eff} = 1.5–2.0. The generalized theory of IIB in high-temperature magnetized plasmas [10] finds some restrictions of the technique mentioned above. In particular, the dependence of the spectral line width on parameters of a sort of perturbing ions is more complicated under strong magnetic fields. However, in this case the Stark width allows us to estimate the density of the impurity prevailing in plasma. Moreover, the width of the π-component of the L_α is a function of Z_{eff}. The LIF measurements of L_α line profile of atomic deuterium were performed in TEXTOR [7] by laser system with pulse frequencies of 25 Hz. Unfortunately, the power of this system was almost one order of magnitude away from the saturation. In TV-1 tokamak the power density of the laser light that was sufficient for the saturation of hydrogen H_α line was about 1 kW/cm^2. The lasers available in the present time can produce much higher power and saturate the H_α Doppler contour observed in plasma edge of large tokamaks.

To measure accurately the contour of the laser fluorescence line in the presence of the fluctuations of H_α radiation from the plasma, the density of neutral hydrogen atoms should be higher than 10^{15} m^{-3}. The system for laser-induced fluorescence measurements installed on TEXTOR-94 has the same detection limit. Such density of hydrogen is typical for the plasma edge, also.

Thus, the laser-induced fluorescence of the hydrogen spectral lines can be employed to measure an effective charge locally. At the further development of the experimental technique this spectroscopic Doppler-free diagnostic will find the application in the plasma edge of large-scale devices.

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