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Addressing the effect of oscillating electric fields on Stark profiles by computer simulations

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Abstract. Oscillating electric fields are present in many different kinds of plasmas and can modify the radiated line shape. An accurate characterization of their effect is difficult since they act simultaneously with the fluctuating microfield of the electrons and ions. We propose to address these simultaneous effects by a computer simulation of the plasma particles motion coupled to a numerical integration of the Schrödinger equation. We discuss here the role of ion dynamics on the effect of oscillating fields, and the different situations which can be investigated by this approach: fixed or sampled oscillating electric field magnitude, fixed direction or randomly oriented oscillating field.

1. Introduction

Oscillating electric fields can change the radiative properties of plasmas, with in particular changes in the line shape. Such fields may be generated by an external source, as e.g. a microwave generator or laser radiation, with the aim of diagnosing or heating the plasma. They may also be created inside the plasma, resulting from a nonthermal effect driven by a plasma instability. For this case a current interest is the diagnostic of energetic particle beams in tokamak edge plasmas, with the potential use of line shape changes [1] due to the generated Langmuir waves. The effect of oscillating fields on spectral line shapes has been studied since several decades by using approaches based on kinetic theory and retaining the quantum effects of the emitting particles [2,3,4]. We study here the simultaneous effect of ion dynamics and oscillating electric fields on hydrogen Stark profiles. Ion dynamics is well known to affect the central region of the first Lyman and Balmer lines e.g. for plasma densities of 10^{19} to 10^{23} m⁻³ and temperatures of the order of the eV or larger, corresponding to many laboratory, fusion and astrophysical plasmas. Reliable models for ion dynamics are based on computer simulations coupled to a numerical integration of the Schrödinger equation for the emitter evolution operator [5]. We discuss here some of the features of the models required in the different situations considered: fixed or sampled oscillating electric field magnitude, fixed direction or randomly oriented oscillating field.

2. Computer simulation for the line shape

The electric field resulting from the motion of the charged particles may be obtained by summing the field of a large number of particles moving in a cubic box. We assume here that the particles move on straight lines in the cubic box, and retain the screening effects by a Debye potential [5]. In the calculations presented we simulate only the ions and retain the effect of the electrons by a collision operator ϕ_e . The oscillating electric field is supposed to have a single frequency Ω and a random phase φ . We solve numerically the emitter Schrödinger equation for the emitter evolution operator $U(t)$:

$$i\hbar \frac{dU(t)}{dt} = [H_0 + i\hbar\phi_e - \vec{D} \cdot \vec{E}_i - \vec{D} \cdot \vec{E}_W \cos(\Omega t + \varphi)]U(t), \quad (1)$$



where H_0 is the Hamiltonian of the unperturbed emitting atom, \vec{D} is the emitter dipole operator, \vec{E}_i the ion electric field, and E_w the magnitude of the oscillating electric field. We use the Griem, Kolb, Shen [6] collision operator:

$$\phi_e = C \frac{N_e}{v_e} \vec{D} \cdot \vec{D} \left[1 + \int_{y_{min}}^{\infty} \frac{e^{-y}}{y} dy \right], \quad (2)$$

where C is a constant, N_e is the electronic plasma density, v_e the electronic thermal velocity, and y_{min} the square of the ratio of the Weisskopf radius to the Debye length [6]. The evolution operator is calculated for each history of the ion and oscillating electric field, and the dipole autocorrelation function is obtained by averaging the following expression over a large number of histories:

$$C(t) = Tr\{\vec{D} U^+(t) \vec{D} U(t)\}. \quad (3)$$

A numerical Fourier transform of $C(t)$ then gives the line shape.

3. Results

In the following we calculate the effect of a Langmuir wave oscillating at the plasma frequency defined by $\omega_p = \sqrt{N_e e^2 / m \epsilon_0}$, with e and m the electron charge and mass, and ϵ_0 the permittivity of free space. We compare the mean or fixed oscillating electric field magnitude E_w to the mean plasma microfield $E_m \approx 3.4 E_0$ [7], where $E_0 = e / 4\pi\epsilon_0 r_0^2$, with the average distance between particles defined by $r_0 = \sqrt[3]{3/4\pi N_e}$. Our model provides the shape of Lyman and Balmer lines of hydrogen using n, l, m quantum numbers, thus neglecting fine structure effects. We first investigate the simultaneous effects of ion dynamics and oscillating electric field. Since ion dynamics mainly affects the first lines of the series, we focus here on the line shape of Ly- β ; for a density $N_e = 10^{22} \text{ m}^{-3}$ and a temperature $T = 10000 \text{ K}$. Line structures such as dips or peaks observed in the static ion approximation (dashed line) are smeared out by ion dynamics (solid line). However for an oscillating field with a magnitude $E_w = 3 E_m$, both the static and dynamic ion profiles plotted in figure 1 exhibit satellites, with intensities similar to that of the central part of the line for the satellite at the plasma frequency.

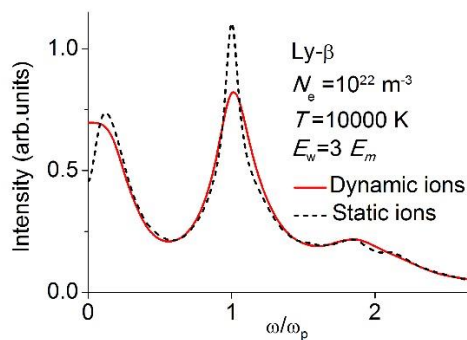


Figure 1. Ly- β for $E_w = 3 E_m$ with static and dynamic ions.

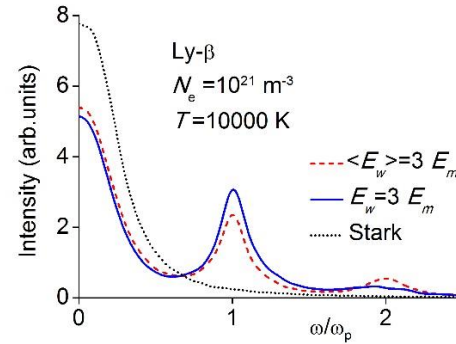


Figure 2. Ly- β pure Stark profile and for $E_w = 3 E_m$ with or without sampling.

Figure 2 illustrates for $N_e = 10^{21} \text{ m}^{-3}$ how the intensity of the central part of the line (dotted line) is reduced by one third and transferred to satellites as an oscillating field with magnitude $E_w = 3 E_m$ is applied (solid line). Using sampled magnitudes E_w distributed along a half Gaussian PDF (dashed line) only slightly reduces the transfer, but favors the appearance of new satellites.

As can be seen in figure 3, the transfer of intensity is increased with the density and the magnitude of the oscillating electric field. For a density $N_e = 10^{23} \text{ m}^{-3}$, about 20% of the central intensity is transferred

to one satellite for $E_w=E_m$, but more than three quarters of the central intensity are transferred to three satellites for an oscillating field $E_w=3 E_m$. Figure 4 shows the effect of an oscillating field assumed to be in a fixed direction, along the z axis. The Stark effect resulting from an electric field in a fixed direction and magnitude allows to distinguish between the π components corresponding to $\Delta m=0$ transitions and the σ components corresponding to $\Delta m=\pm 1$. The intensities of π and σ components have a different intensity variation when one changes the observation angle θ with the z axis. Only a part of this dependence on the angle θ is observed in figure 4, since the emitter is also submitted to the randomly oriented field of the ions which rotates the atomic dipole during the time of interest. For a density $N_e=10^{21} \text{ m}^{-3}$ and a temperature 10^4 K , the difference in intensity in the central part of the line compared to that of the first satellite ranges from 50% to 15% as the observation angle varies from $\theta=0$ to $\theta=\pi/2$.

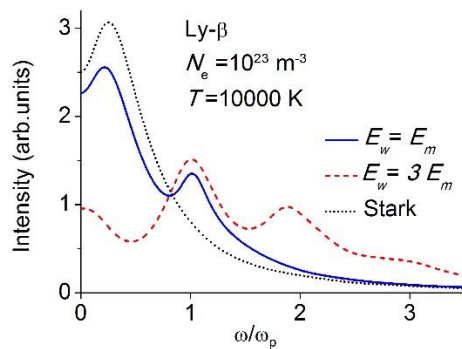


Figure 3. Ly- β pure Stark profile and for $E_w=E_m$ and $E_w=3 E_m$.

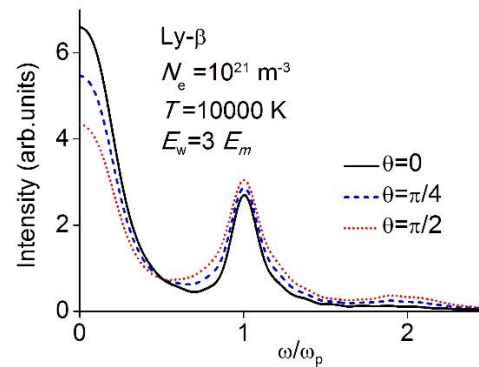


Figure 4. Ly- β for $E_w=3 E_m$ with a fixed direction and for 3 angles of observation.

4. Conclusion

We have applied a computer simulation approach to the study of the simultaneous effects of ion dynamics and an oscillating electric field on hydrogen line shapes. For magnitudes of the oscillating electric field of the order of or larger than the mean plasma microfield, we observe a transfer of intensity from the central part of the line to one or more satellites. The role of ion dynamics is to smear out the structures appearing in such satellites. Our model allows one to study the changes in the line shapes e.g. by a sampling by an arbitrary PDF instead of the use of a fixed magnitude. It also allows to investigate the changes in the line shape as the angle between the line of sight and a fixed direction of the oscillating electric field is assumed. This simulation calculation can be easily extended to include other physical effects, such e.g. the effect of a magnetic field [8].

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