Dynamic Stark Effect on Line Shapes in Laboratory and Fusion Plasma*)

Ibtissem HANNACHI[1,2], Roland STAMM[1], Joël ROSATO[1] and Yannick MARANDET[1]
[1]Aix-Marseille Univ. and CNRS, PIIM, 13397 Marseille, France
[2]University of Batna 1, PRIMALAB, Department of Physics, Batna, Algeria

(Received 29 July 2024 / Accepted 5 September 2024)

Different forms of the Stark effect can affect the emission of line shapes in a plasma. Alongside the fluctuating microfield created by plasma ions and electrons, one often observes the fingerprints of oscillating electric fields. All these dynamic Stark effects result from random and collective motion of the particles but also from oscillating fields applied from outside the plasma by radiofrequency or laser sources. We here use a computer simulation to accurately capture the complex dynamics affecting the emission of a hydrogen atom in a laboratory or fusion plasma.

Keywords: Stark broadening-periodic electric field-numerical simulation-Zeeman effect-polarization

DOI: 10.1585/pfr.20.2401001

1. Introduction

Atoms and ions emitting in a plasma are often subject to periodic electric fields which can affect the emitted line shapes. In laboratory settings and magnetic fusion devices, radio frequency waves (RF) are employed for heating and diagnosing the plasma. In the realm of magnetic fusion, numerous projects are delving into the physics of toroidal plasmas, as observed in tokamaks (ASDEX U, EAST, WEST, JT-60SA, DIII-D), heliotrons (LHD) or stellarators (WENDELSTEIN 7-X). Investigations across these facilities contribute invaluable insights for the forthcoming operations of the international ITER tokamak, currently under construction in France. Spectroscopic measurements of regions heated by the RF field are crucial for enhancing our understanding of wave-plasma coupling mechanism [1]. Additionally, diagnosing the periodic fields arising from non-thermal effects and instabilities, such as wave generation in tokamaks influenced by runaway electrons presents another layer of interest [2]. Notably, a spectroscopic diagnostic capable of early detection of runaway electrons is of interest for the ITER project.

Modeling the effect of periodic electric fields has a long history involving various line shape formalisms [3,4,5], and has often focused on a monochromatic and linearly polarized wave $\overrightarrow{E}_w \cos(\Omega t + \varphi)$, where φ is a random phase. In this study, we explore the utility of computer simulations in understanding the impact of the particle microfield and a concurrent periodic electric field on line shapes. By numerically solving the Schrödinger equation for a hydrogen emitter, we accurately capture the complex dynamics of our physical system [6]. Several groups employ such computer simulations today, and a recent comparison of the outcomes from their codes has been performed for hydrogen lines in a periodic electric field [7], which will be briefly reviewed here. We will also examine the influence of the magnitude E_w and the frequency Ω of the wave, and present the application of the simulation to the conditions of different laboratory and fusion plasmas, particularly in the presence of a magnetic field.

2. Computer Simulation for the Line Shape

The electric field resulting from the motion of the charged particles can be obtained by summing the field of a large number of particles moving in a cubic box. We here assume that the particles move on straight lines in the cubic box, and retain the screening effects by a Debye potential. In the calculations presented we can simulate both the ions and electrons, or 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 numerically solve the Schrödinger equation for the emitter evolution operator $U(t)$:

$$i\hbar \frac{dU(t)}{dt} = \Big[H_0 - \overrightarrow{M} \cdot \overrightarrow{B} - \overrightarrow{D} \cdot \left(\overrightarrow{E}_i + \overrightarrow{E}_e \right) - \overrightarrow{D} \cdot \overrightarrow{E}_W \cos(\Omega t + \varphi) \Big] U(t), \quad (1)$$

where H_0 is the Hamiltonian of the unperturbed emitting atom, $\overrightarrow{M}$ and $\overrightarrow{D}$ are respectively the magnetic moment and the dipole operator of the emitter, $\overrightarrow{B}$ is the magnetic field, $\overrightarrow{E_i}$ and $\overrightarrow{E_e}$ the ion and electron electric fields, and E_W the magnitude of the oscillating electric field. If we use an impact model for ϕ_e, the Griem-Kolb-Shen [8] collision oper-

author's e-mail: ibtissam.hannachi@univ-batna.dz
*) This article is based on the presentation at the 26th International Conference on Spectral Line Shapes (ICSLS2024).

ator provides a good approximation:

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

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 [8]. 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:

$$C(t) = Tr\left\{\vec{D}\;U^{+}(t)\vec{D}U(t)\right\}. \tag{3}$$

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

3. Line Shape Codes Comparison

The Spectral Line Shapes in Plasma (SLSP) workshop has been created in 2012 with the aim of comparing the line shapes obtained by the many analytical and numerical approaches developed in the last decades [9]. A comparison of the different obtained results allows one to identify the main physical mechanisms at work for a specific case. If it is possible to compare with experimental spectra, one can also estimate the accuracy of the spectroscopic diagnostic. For SLSP 6, which took place in 2022, four cases concerned the effect on hydrogen lines of a periodic field $E_w\cos(\omega_p t+\varphi)$ oscillating along the z axis at the plasma frequency $\omega_p = \sqrt{N_e e^2/\mathrm{m}\varepsilon_0}$, with e and m the electron charge and mass, and ε_0 the permittivity of free space. A recent paper [7] recalls the main features of the five line shape codes, and reports about the good overall agreement observed between these codes which all use a simulation of the plasma particle motion, and a numerical integration of the Schrödinger equation. We present in Fig. 1 Hβ line shapes for a density $N_e = 10^{22}\,\mathrm{m}^{-3}$, a temperature $T = 1\,\mathrm{eV}$, and a magnitude of the periodic electric field $E_w = 10\,F_0$, where F_0 is the Holtsmark field defined by:

$$F_0 = \frac{e}{\varepsilon_0}\frac{1}{2}\left(\frac{4}{15}\right)^{2/3}N_e^{2/3}. \tag{4}$$

The results of five line shape codes (ERIP [10], HSTRKII [11], MyWave [12], SimU [13], Xenomorph [14]) are here compared in units of the oscillation frequency ω_p. For the plasma conditions of Fig. 1, all these codes predict the appearance of a central component, and on each side of three satellites located close to multiples of the plasma frequency. There is a good overall agreement between the different calculations, with differences that can be attributed to the numerical methods employed. The code HSTRKII uses a line shape formalism which does not assume a stationary process [15], in contrast with the other approaches. This results in a slightly different distribution of intensity between the central part of the line and the wings.

4. Line Shapes in Periodic Electric Field and a Static Magnetic Field

We present in the following the hydrogen line shapes Balmer alpha (Hα) and Balmer β (Hβ) calculated with the MyWave code, in the conditions of edge plasmas in magnetic fusion devices, with the oscillating electric field and static magnetic field both along z, and the line of sight perpendicular to z ($\theta = \pi/2$). The periodic field magnitude E_w is compared to the mean plasma microfield E_m, which is about 3.4 F_0 in a weakly coupled plasma, where F_0 is the Holtsmark field. Figure 2 shows Hα in a magnetic field $B_z = 6\,\mathrm{T}$ and an electric field oscillating at the cyclotron frequency $\omega_c = \mathrm{e}B/\mathrm{m}$ with a magnitude E_m and 3 E_m. Significant changes occur for $E_w = 3\,E_m$, with satellites of the central π component (corresponding to $\Delta m = 0$ transitions, with m the magnetic quantum number) visible at multiples of ω_c. For this alpha line and the conditions used, the σ component ($\Delta m = \pm 1$) is weakly affected by the oscillating electric field.

Figure 3 illustrates how an oscillating electric field at frequency 1.5 ω_c replicates both the π and σ components

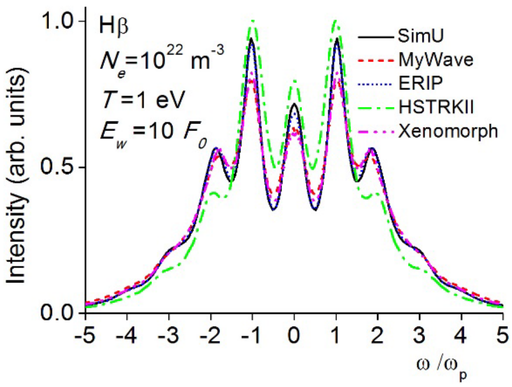

Fig. 1 Hβ calculated with five different codes for an oscillating electric field magnitude $E_w = 10\,F_0$.

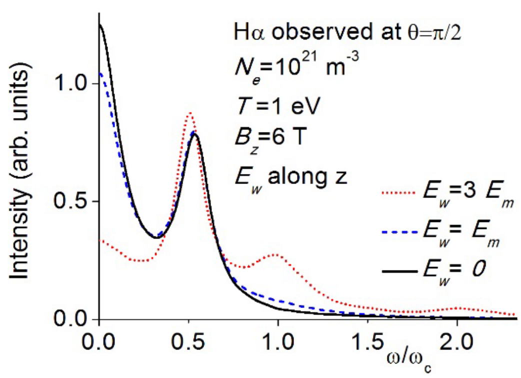

Fig. 2 Hα line calculated in a magnetic field $B_z = 6\,\mathrm{T}$, and $E_w =$ 0, 1 and 3 E_m.

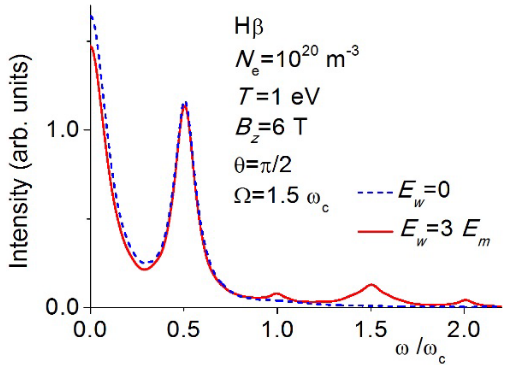

Fig. 3 Hβ line in a magnetic field $B_z = 6\,$T, and an electric field oscillating at 1.5 ω_c, with $E_w = 0$ and 3 E_m.

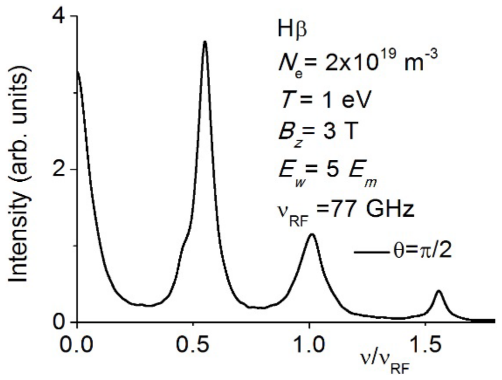

Fig. 4 Hβ line in a magnetic field $B_z = 3\,$T, and an electric field oscillating at $\upsilon_{\mathrm{RF}} = 77\,$GHz, with $E_w = 5\ E_m$.

for the Hβ line. Since both the σ and π components are affected by the oscillating electric field, a replica of the Lorentz triplet centered at the oscillation frequency is observed for $E_w = 3\ E_m$.

We consider in Fig. 4 the effect of a radio frequency field at $\upsilon_{RF} = 77\,$GHz, with an oscillation along z, and a magnetic field $B_z = 3\,$T. A replica of the Lorentz triplet is visible centered at the oscillation frequency, with a σ minus component appearing as a shoulder in the σ plus component of the main triplet. The oscillation frequency is chosen equal to a radiofrequency field used in the large helical device (LHD) at NIFS. Our calculations show that a large oscillating field magnitude of about 5 E_m allows a clear observation of the Lorentz triplet replica.

Figure 5 shows the effect of an oscillating electric field at the upper hybrid frequency ω_{UH} with a magnitude E_w of 2 and 5 E_m, and edge plasma conditions expected for ITER (density $N_e = 10^{21}\ \mathrm{m}^{-3}$, temperature $T = 1\,$eV). As in the previous figures, both the oscillating electric field and the magnetic field are along z, and the line of sight is transverse to z. Such magnitudes E_w could be generated by the presence of a beam of runaway electrons, and according to our calculations might be detected early by a survey of Hβ. The line calculated for $E_w = 2\ E_m$ already shows a

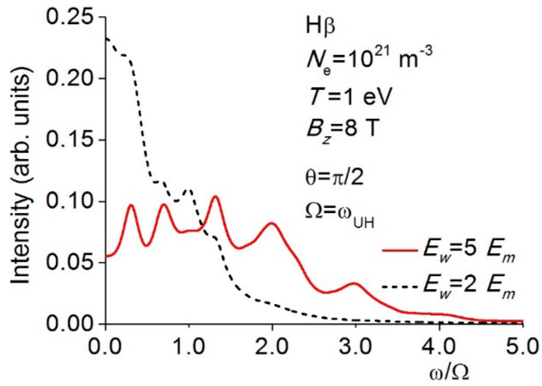

Fig. 5 Hβ line shape for ITER edge plasma conditions and a magnitude of the electric field $E_w = 2$ and 5 E_m, with an oscillation frequency equal to ω_{UH}.

small triplet structure around ω_{UH}. For $E_w = 5\ E_m$ the line is strongly modified. A first replica of the triplet is visible around ω_{UH}, but with a weak π component, and three other replica without a clear structure can be observed at multiples of ω_{UH}.

5. Conclusion

We have developed a computer code for calculating the line shapes emitted in the presence of a magnetic field and an oscillating electric field. Our calculations show that an accurate simultaneous diagnostic of the plasma and wave properties is possible. The periodic electric field transfers the central intensity of the hydrogen lines to replicas centered close to multiples of the oscillation frequency. Possible applications concern the spectroscopic diagnostic of the coupling of radiofrequency fields to the plasma [1], and the early detection of runaway electrons in magnetic fusion devices [2]. Prospects for this model are the use of Stokes parameters to obtain the direction of oscillation of the electric field, and the use of other emitting atoms and ions than hydrogen.

[1] C. Klepper *et al.*, Phys. Rev. Lett. **110**, 215005 (2013).
[2] W. Bin *et al.*, Phys. Rev. Lett. **129**, 045002 (2022).
[3] M. Baranger and B. Mozer, Phys. Rev. **123**, 25 (1961).
[4] V. Lisitsa, *Atoms in plasmas* (Springer, Berlin, 1994).
[5] E. Oks, *Plasma Spectroscopy* (Springer, Berlin, 1995).
[6] R. Stamm *et al.*, Phys. Rev. A **30**, 2039 (1984).
[7] I. Hannachi *et al.*, Atoms **12**(4), 19 (2024).
[8] H.R. Griem *et al.*, Phys. Rev. **116,** 4 (1959).
[9] E. Stambulchik, High Energy Density Phys. **9**(3), 528 (2013).
[10] M. Gigosos *et al.*, Phys. Rev. A **31**, 3509 (1985).
[11] S. Alexiou, Atoms **9**, 30 (2021).
[12] I. Hannachi *et al.*, Adv. Space Res. **71**, 1269 (2023).
[13] E. Stambulchik and Y. Maron, J. Quant. Spectrosc. Radiat. Tranfer **99**, 730 (2006).
[14] P. Cho *et al.*, ApJ **927**, 70 (2022).
[15] S. Alexiou, Atoms **12,** 17 (2024).