ANALYSIS OF STARK LINE PROFILES FOR NON-EQUILIBRIUM PLASMA DIAGNOSIS

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One of the most commonly used methods to do plasma diagnosis is the analysis of the Stark broadened line profiles emitted by the atoms or ions in the plasma. The shapes of these lines strongly depend on the density of charges in the plasma. This permits to use some of the line characteristics, as its width at half maximum, as a diagnostic tool to obtain the plasma electron density. It's more, the dependence of the line shapes is more important when the Stark effect is linear, as for hydrogen or hydrogenic ions, what has been a reason of the wide use of these elements in plasma diagnosis. In fact, the determination of the plasma electron density from the hydrogen Balmer beta full width at half maximum (FWHM) is a well-established diagnostic method [1-3].

In many cases plasma diagnosis has been done using only the FWHM of an experimentally recorded line. However, more information on the plasma state can be obtained from the measured profiles, as the shapes of many lines strongly depend on the kinetics of the emitter and the heavy perturbers in the plasma. This kinetics, that gives rise to what is known as ion-dynamics effects, alters not only the line widths but the shape of the full line. The emitter and heavy perturbers velocities depend on their masses and on their temperatures, that may be different from the electron temperature if the plasma is not in kinetic thermodynamic equilibrium. Then, the comparison of the measured profiles with calculated profiles obtained taking into account ion-dynamics effects, as well as non-equilibrium effects can become a more sophisticated diagnostic method to obtain plasma conditions.

One of the theoretical methods that allow to consider those kinetics effects readily are computer simulations. This simulations, although may require a considerable cost of calculation, are considered as the most efficient method to obtain spectral line shapes [2,4]. Besides, the consideration of non equilibrium effects in these calculations can be done without additional cost.

Calculated Stark profiles are obtained from the Fourier transform of the emitter dipole moment autocorrelation function averaged on a ensemble of emitters. Every emitter evolves perturbed by the local dynamic electric microfields due to the charged particles that surround it. These are the local electric microfields that give rise to the Stark effect. In the calculation one must obtain the evolution of the emitter atom perturbed by the dynamic electric field and then take the average on a representative sample of perturber configurations. This requires to solve the time dependent Schrödinger equation for the emitter suffering the local electric field. This is the aim of the computer simulation used by our group.

The plasma physical model employed in our simulations, based on the “classical path approximation” [5-9] considers that the plasma is weakly coupled, globally neutral, homogeneous and isotropic. In this model, the ions and free electrons are considered as independent classical point particles that move inside the plasma creating a electric field on the emitter atom. In the simulations the velocities distributions for the particles are obtained according to a Maxwell-Boltzmann distribution assuming thermal equilibrium. Numerical simulation permits to consider
sets of particles with different temperatures. This is done, for example, for perturber electrons and ions independently, so that it is not difficult to study a plasma with two different kinetic temperatures for the two species.

In the analytical calculations ---not in the simulations--- the spectral profile is calculated [10] from an average on the plasma parameters (impact parameter, particle velocity, impact parameter passing time, ...) that characterize the collisions suffered by the emitter. For some calculations the integrals over those parameters lead to divergences. On the contrary, in our simulations no divergences of this kind appear and the correct statistics on all the perturbers parameters naturally arise.

In the simulations shown in this work the emitter atoms are neutral, do not suffer interactions with other emitters and evolve due to the electric microfields created in the plasma by the charged perturbers. This evolution is calculated using a dipolar interaction Hamiltonian.

Extensive and detailed descriptions of the numerical treatment used in the simulations described here can be found in [11,12]. Some interesting details discussed in those works are the stability of the statistical distributions, the effects due to the finite size of the simulation volume and the particles reinjection method, and the numerical integration of the differential equations that give the emitter evolution as well as the numerical quality of the solutions. In order to guarantee the accuracy of the solution of the differential equations that give the time evolution operator a small enough temporal step is taken in the simulations. In this way, under the physical model considered, the simulations give an exact solution of the emitter evolution. On the contrary, analytical treatments based on the same plasma and emitter physical models are forced to do mathematical approximations, mainly to obtain the statistical averages on the collisions parameters or in the perturbative development of the time evolution operator. These approximations are not necessary in the simulations. As a consequence, the differences in the results of computer simulations and analytical calculations based on the same physical model are due to the mathematical or numerical approximations needed in the last ones. The drawback of this higher precision in the simulations is, obviously, that computer simulations are a much slower method to obtain line shapes than the analytical calculations.

As mentioned above some line shape parameters are noticeably dependent of the plasma temperature and of the state of equilibrium in the plasma. A line of special interest of study, due to its broad use as a diagnosis tool, is the hydrogen Balmer beta line. Although the width of this line hardly depends on the plasma temperature its central structure strongly varies with the dynamics of the heavy perturbers in the plasma. This two facts, together, represent a high advantage in the use of this line as a diagnostic tool. On the one hand its width can give good measurement of the plasma electron density while and analysis of its center can determine the state of equilibrium in the plasma or even the existence of gradients in the plasma. Simulations of the Balmer beta line have been done for wide ranges of electron density and temperature as well as of degree of equilibrium between the electrons and ions in the plasma. Figure 1 shows results for a pure Hydrogen plasma with electron density, $N_e = 10^{22}$ m$^{-3}$ and electron temperature, $T_e = 10000$ K. In that figure the depth of the characteristic central dip of the Balmer beta line has been represented versus the temperature of the ions in the plasma, $T_i$. As it's well known and can be clearly seen in the figure, this parameter is very sensitive to the conditions of equilibrium in the plasma, changing noticeably in the analyzed range. As a consequence, the discrepancies in the comparisons of the central parts of calculated and measured Balmer beta profiles can be a good indication of the existence of cold layers in the plasma that alter the central part of the emitted profiles.
In many cases it is not possible to use Stark broadened Hydrogen profiles as a diagnostic tool. For those conditions alternative diagnosis methods are required [13]. One of those methods is the analysis of helium lines with forbidden components. These lines have been extensively studied and relations between electron density and different parameters of the lines are broadly used in practical applications [13]. In this work we have also done calculations of two of those lines, namely the 447.1 and 471.3 nm lines, and the dependence of some characteristics of the lines on plasma conditions has been studied. Figure 2 shows some results for the full width at half maximum of the allowed component of the 447.1 nm line for a constant electron density and different electron temperatures as a function of the ionic perturbers temperature. As can be seen in that figure, this parameter noticeably changes for the conditions studied here, what shows its applicability as a diagnostic tool to detect equilibrium conditions in the plasma.

Figure 3 shows another result for this same line. In this figure, results of the dependence of the depth of the dip between the allowed and forbidden components of the He I 447.1 line with the
heavy perturbers temperature are shown. Results for three different electron temperatures are shown together for the same value of plasma electron density. It can be clearly seen there that the changes in this parameter due to non-equilibrium conditions are noticeable enough to be used as a check of equilibrium conditions in the plasma.

![Fig. 3](image)

**Fig. 3** Depth of the dip between the allowed and the forbidden component of the He I 447.1 nm line as a function of the ionic perturbers temperature in a He-H\(^+\) plasma for an electron density \(N_e=10^{22}\) m\(^{-3}\) and different electron temperatures, \(T_e\).

**Reference**