PHYSICAL REVIEW A VOLUME 27, NUMBER 4 APRIL 1983

High-frequency Stark-effect measurements in emission spectroscopy

N. J. Wiegart
Institut für Experimentalphysik V, Ruhr-Universität, D-4630 Bochum, Federal Republic of Germany
(Received 20 October 1982)

The applicability of the high-frequency Stark effect in the diagnostics of turbulent plasmas is demonstrated by measurements of He I line profiles (4^1D-2^1P) in a turbulent linear discharge. The existence of electron plasma waves with field strengths of 6–9 kV/cm is confirmed spectroscopically. Competing effects—e.g., the emission of molecular lines—are discussed in detail and are shown to be negligible under our experimental conditions.

I. INTRODUCTION

The high-frequency Stark effect in helium atoms, which was first investigated theoretically by Baranger and Mozer,[1] has received great attention because of its usefulness in plasma diagnostics (for a review, see Griem[2]). The main application is the determination of the electric field of plasma oscillations in turbulent plasmas.

After the first experimental verification of the effect,[3] a great number of experimenters claimed to have found "satellites" on He I profiles. Some of the results were in excellent agreement with theory,[4,5] whereas others were hardly apt to increase confidence in the diagnostic method. The observation of satellite lines was reported under circumstances where turbulence could be ruled out with great certainty.[6,7] Drawin and Ramette[8] concluded that lines of helium molecules might be responsible for the structures on the observed line profiles. For a wide range of parameters the assumption could be proved wrong by Wiegart *et al.*[9] Piel[10] pointed out that H_2 lines may lead to misinterpretations of helium line profiles.

Although these difficulties can often be circumvented by applying laser resonance fluorescence techniques,[11] there are some cases where emission spectroscopy has to be used, e.g., when the lower level of the transition is weakly populated. It seems worthwhile to examine what information can then be won from measured line profiles. A careful interpretation requires the choice of the most suitable theoretical description and the exclusion of atomic, ionic, and molecular impurity lines. Clearly, the *complete* line profile should be considered. In some of the earlier investigations (e.g., Ref. 12) large portions of the profile remained unexplained. This, of course, may be one reason for discrepancies between experimental results and theoretical predictions.

II. EXPERIMENT

The experimental set up (Fig. 1) is similar to that of turbulent heating experiments: A linear discharge is operated between hollow electrodes (inner diameter 3 cm), spaced 80 cm apart. First, a tenuous plasma is generated by means of an rf transmitter; then a small capacitor (0.3 μF) is discharged across two coils (ten turns each), acting like a θ-pinch coil. The main discharge ($C=1.9\ \mu$F, $U=40$ kV, $T=5.2\ \mu$s) follows after a delay of 70 or 80 μs. The electron density at this time ($n_e \simeq 10^{13}$ cm^{-3}) is known from microwave cutoff measurements.[13]

At filling pressures below 20 mTorr, one finds characteristic features of a two-stream instability (Fig. 2): The dI/dt signal displays a strong dip, which coincides with a maximum in the voltage between the electrodes, i.e., the resistivity is drastically increased. At the same time x-ray emission occurs. This behavior of the plasma resembles that found in turbulent heating experiments, especially in the one by Amagishi *et al.*[14] One therefore expects to observe electron plasma waves and/or ion-acoustic turbulence.

The spectroscopic observation (mainly side-on) was carried out with a 1-m monochromator and a photomultiplier RCA 4526. The profiles were measured on a shot-to-shot basis, averaging over about nine discharges at each wavelength. The line profiles were scanned in steps of 0.01 nm for the most important portions and 0.02 nm otherwise. The instrumental width was 0.025 nm. Ideally, such measurements should be carried out with an optical multichannel analyzer in order to keep the influence of statistical fluctuations at a minimum. After a series of tests, however, we found that such a device was not suitable, first because at the low intensity level of our experiment the line wings were badly af-

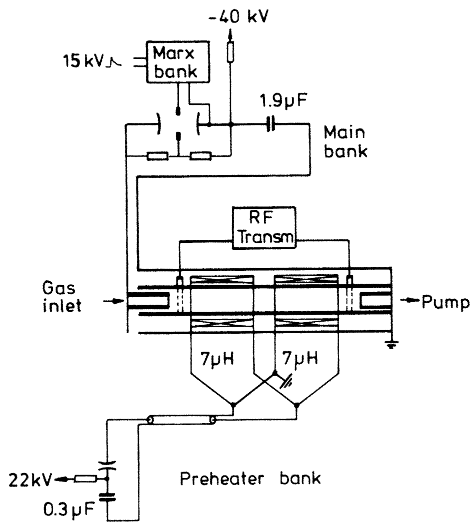

FIG. 1. Experimental setup.

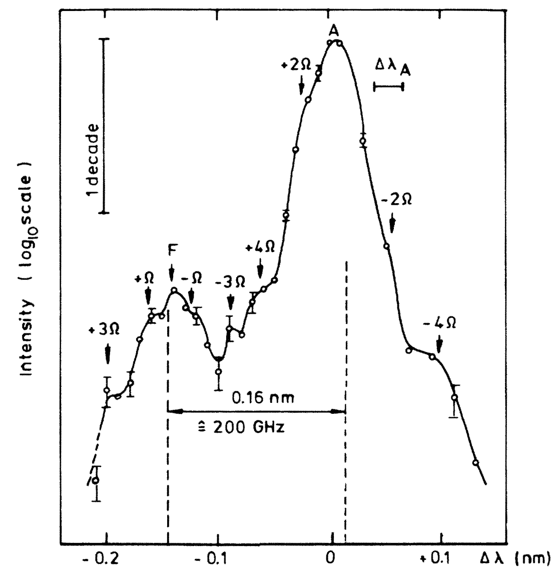

FIG. 3. Profile of the He I line at 492 nm 1.5 μs after the beginning of the main discharge (delay 80 μs); dashed lines are the positions of the satellite centers of the allowed and forbidden components; note that this figure and Fig. 5 do not give the correct relative intensities of the profiles at different times.

fected by noise and second because pulsing the multichannel analyzer resulted in a distortion of the profile. Only a specially selected photomultiplier tube allowed measurements of the line profiles over more than two orders of magnitude.

III. RESULTS AND DISCUSSION

As the emission of He I lines in the main discharge starts after the dip in the dI/dt signal, the large low-frequency field associated with the assumed ion-acoustic instability cannot be determined spectroscopically. There is, however, some indication of the existence of high-frequency turbulence in all the observed profiles of the He I line at 492 nm (4^1D-2^1P transition with a dipole forbidden component 4^1F-2^1P). A typical example is shown in Fig. 3.

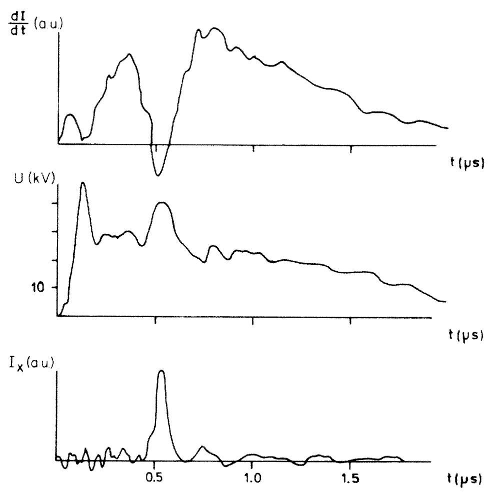

FIG. 2. Time derivative of the discharge current (Rogowski loop), voltage between the electrodes, and x-ray intensity (measured with a *p-i-n* diode with maximum sensitivity between 6 and 20 keV).

The question arises of how to interpret a complex profile like this one. Depending on the properties of the high-frequency field, one might expect to observe "satellites" or "dips." The latter possibility can be deduced from an extension of existing theories for hydrogen[15,16] to the case of helium,[17] where the Stark effect is generally in the intermediate range between the linear and the quadratic Stark effect. Under our experimental conditions, such dips would most probably not be observable because of their small width. In any case they would be situated on the line wings and would therefore not be able to produce the structure on the forbidden line.

It remains to be decided which satellite theory gives the closest approach to the effects that are present in the experiment. As the measured profile does not change considerably on a time scale typical of the growth or decay of electron plasma waves, the turbulence would have to be more or less stationary. Then the width of the frequency spectrum can be estimated to be small in comparison with the electron plasma frequency.[18] Thus the assumption of monochromatic waves seems justified. Furthermore, the electron plasma frequency ω_p ($\propto \sqrt{n_e}$) is much larger than the electron-impact width ($\propto n_e$) at low densities, and so the satellites may be treated as individual lines broadened by the usual mechanisms. As a consequence, calculations based on those by Hicks, Hess, and Cooper[19] are applicable. In addition to the satellites, one also expects a static forbidden component due to the Holtsmark field.

When higher-order satellites are present, the field frequency Ω can easily be determined, because the spacing of successive satellite peaks is 2Ω for the forbidden and allowed components. Obviously, the spectrum becomes very complex when several different frequencies are present. Fortunately, we find that the whole line profile can be explained assuming that just one frequency is present.

Once the frequency ($\nu=\Omega/2\pi=22.1$ GHz) is known, one can then relate satellites (e.g., 2Ω) and peak positions. The fact that all even satellites are shifted to the red by the same amount by which all odd satellites are shifted to the blue indicates that the assignment is correct.

Because of the inhomogeneity of the plasma, the allowed line and the static forbidden component contain contributions of turbulent as well as of nonturbulent regions. Therefore the field strength cannot be obtained from the relative intensity of a satellite with respect to the allowed line, as, e.g., in the simple case discussed by Baranger and Mozer.[1] For the same reason, the agreement of the calculated satellite pattern with the experimental one should mainly serve as a qualitative confirmation, but a more accurate value of the field strength can be derived from the shifts of the centers of the satellite features on the allowed and forbidden components (6 ± 0.7 kV/cm). The value for the level spacing 4^1D-4^1F without perturbation was taken from Martin.[20]

The time evolution (Fig. 4) should be regarded as a further proof that the peaks have correctly been assigned to satellites, because they change their positions in a consistent manner, i.e., at each time they form a satellite pattern as expected by theory, with the field frequency increasing slowly in time.

The electron density that corresponds to the satellite frequency varies from 4×10^{12} cm^{-3} at early times to 10^{13} cm^{-3} 750 ns later. These values are considerably lower than the average density estimat-

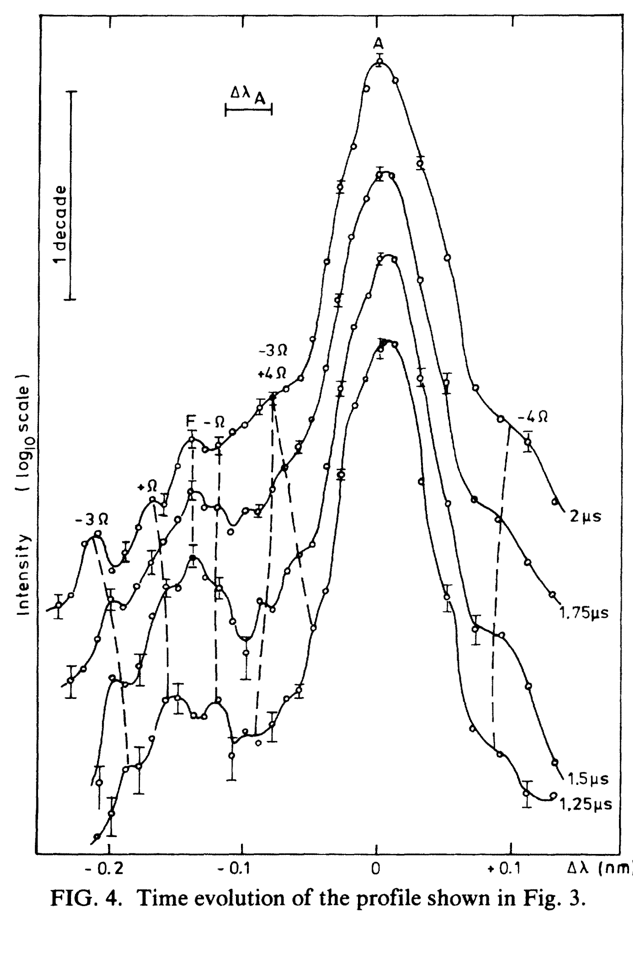

FIG. 4. Time evolution of the profile shown in Fig. 3.

ed from the ionization rate that can be inferred from the time behavior of He I and He II lines. Electron density and temperature cannot be determined by Thomson scattering here, because the amount of scattered light would be too small for detection. The estimated values are 6×10^{13} cm^{-3} for the electron density on the axis at the time of maximum emission of He I and 40—70 eV for the electron temperature. Thus the plasma oscillations seem to be located in a cold plasma layer near the wall. For the generation of the plasma waves, the following hypothesis is made: Fast electrons that have been accelerated in the cathode fall penetrate into the plasma. In the bulk of the plasma, their velocity does not suffice to overcome the threshold for an instability because there the thermal velocity is high. In a cold region, however, the threshold value is exceeded, and electron plasma waves or ion-acoustic waves are produced, depending on the ratio of beam electron density and plasma electron density. In the presence of an efficient loss mechanism (losses to the walls), the turbulence may become stationary.

When the initial conditions are slightly changed (70-μs delay instead of 80 μs), the contribution from the turbulent regions can be seen more distinctly because of the higher field strength (9.5 ± 0.7 kV/cm) (Fig. 5). The peaks marked $A1$ and $F1$ are assigned to allowed and forbidden lines originating from nonturbulent regions because they are nearly unshifted. The profile shows that for certain cases it is not at

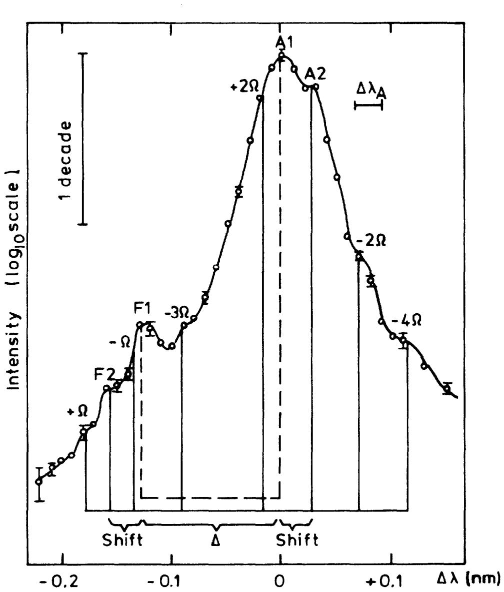

FIG. 5. Profile of the He I line at 492 nm 1.25 μs after the beginning of the main discharge (delay 70 μs); contributions from nonturbulent regions are marked with dashed lines.

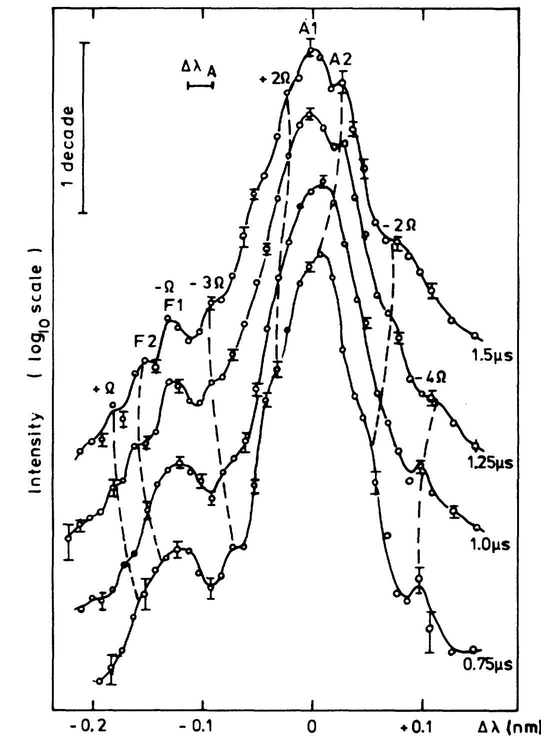

FIG. 6. Time evolution of the profile shown in Fig. 5.

all easy to recognize a satellite pattern. Again the time evolution of the profile (Fig. 6) shows a reasonable variation of satellite positions. As expected, the density at early stages is higher than in the first case. This time the density does not increase as much as before, but the satellites move according to the shift of the forbidden ($F2$) and allowed ($A2$) lines as the field strength varies. It cannot be excluded that part of the shift is caused by a low-frequency field accompanying the high-frequency field. Therefore the value for the field strength of the plasma waves may be somewhat lower than the one calculated from the total shift.

With regard to the small intensities, fluctuations are bound to have a detrimental effect on accuracy. On the far wings photon statistics does in fact give the main contribution to the error as can be estimated from the number of photons reaching the photomultiplier tube. For other parts of the profile, fluctuations in the discharge conditions are more important. In Figs. 3—6 error bars indicate the standard deviation of the mean value. For the sake of easy viewing only a few typical error bars are given.

For most of the peaks, errors are small enough to justify the assumption that the peak was not caused by fluctuations. On no account could fluctuations have produced the whole satellite pattern moving consistently with time. Apart from that, no satellites are observed when there is no indication of turbulence (e.g., when the filling pressure is raised).

Because of the growing skepticism towards this diagnostic method (e.g., Drawin[21]), extra care was taken to discriminate against competing effects. Impurity lines, e.g., constitute a potential source of misinterpretation. In our case, one would mainly expect atomic or ionic lines of copper and zinc (electrodes), of silicon and oxygen (walls), as well as of carbon (diffusion pump). Fortunately, the He I line at 492 nm is relatively free of impurity lines unlike the line at 447 nm which cannot be used here because of the oxygen lines in the wing of the forbidden component. In our case the most harmful impurity line would be a Fe I line coinciding with the forbidden line, but as other lines of the same multiplet are missing, its appearance becomes extremely unlikely. For similar reasons other lines can be excluded.

The number of helium molecules can definitely be said to be much too low for a disturbing influence on the He I line profiles. Not even the otherwise strongest band $e\,^2\Pi_g \rightarrow a\,^3\Sigma_u^+$ could be detected. Similarly, at the positions of strong H_2 lines, practically no intensity was found.

In principle, one has to beware of some less obvious sources of error, e.g., quasimolecular lines.[22,23] But as this is basically a high-density effect, it is thought to be of little importance here. Recently, a collision-induced intercombination line (He I 2^3P-3^1D) was observed.[24] For the He I line at 492 nm (4^1D-2^1P), an intercombination line (4^3D-2^1P) at 0.048 nm to the red of the allowed transition might appear. In our measured spectra, however, there is little indication of such a line, which is not amazing since the density is low. Even if there were an intercombination line it would only explain one peak (-2Ω), so the interpretation of the whole profile would not be questioned.

Finally, it may be argued that the line shape is changed drastically when a distribution of field strengths is present. We have carried out calculations for monochromatic fields with various amplitude distributions showing that the variation in shape is not really significant as long as the width of the distribution is—roughly speaking—smaller than the average field strength. It should be noted, however, that in such calculations the electric field is assumed to be linearly polarized. The application of this model in the case of a random distribution of field directions may lead to an additional error in the field strength. Furthermore, in all our calculations the quasistatic fields have been assumed to be much smaller than the high-frequency field and have therefore been neglected. Their inclusion into the formalism is possible from a mathematical point of view, but the difficulties in the numerical calculations are immense.

IV. CONCLUSION

The results presented in this paper demonstrate the applicability of the high-frequency Stark effect as a diagnostic method in emission spectroscopy. Information about field strength and frequency of turbulent fields in plasma may be won by the interpretation of measured spectra, provided sufficient care is taken to avoid or take into account unwanted side effects and to achieve the greatest possible accuracy. It seems essential to us to regard the time evolution of spectra as well as to interpret the total profile. In our opinion, higher-order satellites—as observed in this experiment—could also explain the additional peaks in the profiles measured by Davis[5] or Kawasaki,[12] e.g., if careful reinterpretations were made.

Nevertheless, in the majority of applications the use of resonance fluorescence techniques[11] is recommendable mainly because in emission spectroscopy one often faces intensity problems. Preferably, the method should be applied in combination with neutral-particle injection.[25]

ACKNOWLEDGMENTS

I wish to express my gratitude to Dr. H.-J. Kunze for his support and perpetual interest in this work. Also, I would like to thank Dr. H.R. Griem of the University of Maryland for useful discussions. This work was carried out under the auspices of the Sonderforschungsbereich No. 162 Bochum–Jülich.

[1]M. Baranger and B. Mozer, Phys. Rev. 123, 25 (1961).
[2]H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic, New York, 1974).
[3]H.-J. Kunze and H. R. Griem, Phys. Rev. Lett. 21, 1048 (1968).
[4]W. S. Cooper and R. A. Hess, Phys. Rev. Lett. 25, 433 (1970).
[5]W. D. Davis, Phys. Fluids 15, 2382 (1972).
[6]J. Ramette and H.-W. Drawin, Z. Naturforsch. 31a, 401 (1976).
[7]A. Sanchez and R. D. Bengtson, Phys. Rev. Lett. 38, 1276 (1977).
[8]H.-W. Drawin and J. Ramette, Z. Naturforsch. 33a, 1285 (1978).

[9]N. J. Wiegart, G. A. W. Lins, and H.-J. Kunze, J. Phys. B 12, 3495 (1979).
[10]A. Piel, in *Spectral Line Shapes,* edited by B. Wende (de Gruyter, Berlin, 1981), pp. 577–589.
[11]H.-J. Kunze, in *Spectral Line Shapes,* see Ref. 10.
[12]K. Kawasaki, J. Phys. Soc. Jpn. 43, 648 (1977).
[13]E. Dullni (private communication).
[14]Y. Amagishi, H. Iguchi, Y. Ito, T. Kawabe, A. Mase, and T. Tsukushima, Phys. Lett. 63A, 31 (1977).
[15]E. A. Oks and G. V. Sholin, Zh. Eksp. Teor. Fiz. 68, 974 (1975) [Sov. Phys.—JETP 41, 482 (1975)].
[16]A. I. Zhuzhunashvili and E. A. Oks, Zh. Eksp. Teor. Fiz. 73, 2142 (1977) [Sov. Phys.–JETP 46, 1122 (1977)].
[17]N. J. Wiegart (unpublished).
[18]V. N. Tsytovich, *Theory of Turbulent Plasma* (Plenum, New York, 1977).
[19]W. W. Hicks, R. A. Hess, and W. S. Cooper, Phys. Rev. A 5, 490 (1972).
[20]W. C. Martin, J. Phys. Chem. Ref. Data 2, 257 (1973).
[21]H. W. Drawin, in *Spectral Line Shapes,* see Ref. 10, pp. 527–576.
[22]R. C. Preston, J. Phys. B 10, 523 (1977).
[23]E. A. M. Baker and D. D. Burgess, J. Phys. B 12, 2097 (1979).
[24]D. D. Burgess and C. St. Q. Playford, J. Phys. B 13, L245 (1980).
[25]U. Rebhan, N. J. Wiegart, and H.-J. Kunze, Phys. Lett. 85A, 228 (1981).