Investigation of the $H\alpha$ line in dense plasmas

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The $H\alpha$ line is analyzed in a dense plasma of $N_e \approx 10^{18}$ cm^{-3} produced in a z-pinch discharge. The line is shifted by up to 9 Å to the red, and the profile is strongly modulated. This modulation is attributed to the effect of collective fields of different frequency distributions, one being of the order of ω_{pi}. The shift is density dependent and agrees with available theoretical calculations.

I. INTRODUCTION

In plasma spectroscopy, hydrogen lines are widely used for density determination since they have been studied over a wide range of conditions both theoretically and experimentally. At very high densities, however, i.e., electron densities higher than 10^{18} cm^{-3}, the linewidth becomes so broad that only the lines $L\alpha$, $L\beta$ and $H\alpha$ remain isolated. All other hydrogen lines merge with the free-bound continuum. For electron densities of the order of 10^{18} cm^{-3}, the half-width of $H\alpha$ is already of the order of 100 Å; this allows the investigation of details of the line profiles which are of the order of a few percent of the half-width only. In this paper, we report on detailed studies of the profile of the $H\alpha$ line at these high densities.

It is instructive to compare the mean particle-electric-field strength $\overline{F}_p$ to the average electric field $\overline{F}_W$ due to thermally excited longitudinal plasma waves. For a plasma of $N_e \approx 10^{18}$ cm^{-3} and $kT_e \approx kT_i \approx 10$ eV, one obtains[1]

$$\overline{F}_p \approx 8.8\, e N^{2/3} \approx 1.3\times 10^6 \text{ V/cm}$$

and

$$\overline{F}_w \approx (kT/3\pi\lambda_D^3)^{1/2} = 1.1\times 10^5 \text{ V/cm}.$$

This reveals that, for a thermal plasma of these parameters, the collective wave field reaches already 10% of the mean interparticle field, and it can be even increased by current driven turbulence. It is conceivable, therefore, that the line profile of $H\alpha$ is influenced by collective effects even in thermal equilibrium.

II. EXPERIMENT

The investigations of the $H\alpha$ line were done on a dense plasma produced in a z-pinch device. Details of the experiment have been described before.[2,3] Here, we summarize only some results which are relevant to the following measurements. All spectroscopic observations were done side-on along a diameter in the midplane of the discharge tube. The analysis of the continuum intensity and of the optical thickness of the plasma column as well as Schlieren measurements showed that plasmas with electron densities between 5×10^{17} and 7×10^{19} cm^{-3} can be produced rather reproducibly. The electron temperature is $kT \approx 4$ eV for the higher electron densities and $kT \approx 10$ eV for the lower ones, the duration of the dense phase varying between 1 and 0.1 μsec for these cases. The plasma column has a diameter of about 1 cm and displays a rather flat density profile with a sharp boundary for the times considered.[3] The pinch itself is driven by an electrical current with a maximum value of 1 MA. It is striking that the β value of the plasma is of the order of 1, which indicates that the current mainly flows at the boundary of the plasma column. The ratio of electron-drift velocity to thermal-ion velocity is there typically of the order of 1. It cannot be excluded, therefore, that the electrical current drives turbulences of the modified two-stream instability type.[4]

Two different discharge tubes were used. In the first part of this paper, in which properties of the entire $H\alpha$ profile are described, a quartz tube had been installed, and in the second part, where only the center of the profile is considered, a glass vessel was used. The different wall materials influence the plasma in so far as a glass wall produces a considerably higher impurity level than quartz. Therefore, the effective z value and the continuum radiation near $H\alpha$ is higher by a factor of about 1.5–2 in this case. In addition, the high-Z ions radiate such an amount of energy that the plasma temperature decreases from $kT \approx 8$–15 eV in the case of a quartz wall to $kT \approx 5$–10 eV for a glass wall.

From discharge to discharge, the glass wall increasingly eroded and soon acted like a ground glass, whereas the transmission of quartz remained unchanged. For the spectroscopic observations, the glass tube had to be provided with long sidearms, therefore, where now absorption could take place. For this reason, the center of

$H\alpha$ exhibited stronger self-reversal in the case of the glass vessel than with the quartz tube.

The spectral range covered for $H\alpha$ was 350 Å, and the relative calibration of the spectroscopic setup was done using a tungsten-strip lamp. The 1-m monochromator was equipped with a holographic grating and a photomultiplier at the exit slit. In the first series of measurements, the spectrum was scanned from discharge to discharge. For the second series, a good correlation over the spectrum was desired, and an eight-channel polychromator was built by attaching a glass-fiber system to the exit slit of the monochromator. The width of each channel corresponded to 0.2 Å. The different channels were calibrated relatively to each other using the tungsten-strip lamp and, *in situ*, the continuum radiation of the plasma, both methods giving consistent values.

When measuring spectral lines emitted from dense plasmas, the optical thickness of the line must be checked. For a given pinch plasma, this can be done rather easily. The earlier measurements revealed[3] that the continuous light emission in the visible spectral region grows with increasing filling pressure until the intensity reaches the value determined by the blackbody radiation. The plasma temperature decreases slightly with the increasing filling pressure. Therefore, if one compares the maximum light intensity of the $H\alpha$-line contour at the filling pressure of interest with the intensity value at higher filling pressures where the plasma radiates as a blackbody the theory of Bartels[3,5,6] allows an estimate of the optical thickness τ from the ratio of these two values.

This method yields an upper limit for τ since the change in temperature was neglected. For the plasma conditions which are treated in the following, we find a value of $\tau \simeq 0.07$ at the maximum of the line contour, when working with the quartz vessel, and $\tau \simeq 0.15$ when using the glass tube. This indicates that self-absorption can be neglected for the main part of the line up to the line shoulder. The self-absorption dip in the center of the line is not treated in this paper.

III. GROSS PROPERTIES OF THE $H\alpha$-LINE PROFILE

In the first series of measurements, the gross properties of the $H\alpha$ line profile were studied. On the wings, the intensities were measured in 5- or 10-Å, near the line center in 2-Å steps. The typical time development of the profile is shown in Fig. 1 for a filling pressure of 0.5 Torr; we see the spectral intensity distribution at 800 nsec (a), 600 nsec (b), 400 nsec (c), 200 nsec (d), and 0 nsec (e) before reaching maximum compression. Intensity and half-width of the line grow as expected. The absorption at the center is deeper at the early times and less marked, e.g., at maximum compression. It is at the central wavelength of $H\alpha$.

When regarding the line more carefully, one finds that the red wing of the line is higher and broader than the blue one, the line being shifted to the red side of the spectrum. The quantitative determination of the half-width and of the red shift, however, becomes difficult because of several "structures" on the line. In the second part of this paper these structures are investigated in more detail. The goal is to verify whether they are caused by poor statistics or are real.

For the comparison of experimental and theoretical profiles a chi-squared fit procedure was used. The theoretical function had the form

$$f(\lambda)=A\,\lambda^{-2}+B\,\lambda^{-6}G(N_e\,;\lambda-\lambda_0),$$

where the parameters A, B, N_e, and λ_0 had to be fitted. The first term on the right-hand side describes the continuum radiation which varies as $I_\lambda\,d\lambda \sim \lambda^{-2}\,d\lambda$; the second term represents the line profile; $G(N_e,\lambda)$ is a spline representation of $H\alpha$ for the values given by Griem.[1] The factors A and B are proportional to the continuum and the line emissivity, respectively; N_e is the electron density; and λ_0 the red-shifted center of the line. The parameters A, B, N_e, and λ_0 were found by minimizing the modified chi-squared function

$$\chi^2=\sum\frac{1}{n}\;\frac{[I(\lambda)-f(\lambda)]^2}{\sigma^2(\lambda)}\;.$$

$I(\lambda)$ is the measured intensity at the wavelength λ; $\sigma(\lambda)$ is the variance of the measured intensity at λ; and n is the degree of freedom, i.e., the number of spectral points minus the number of parameters to be fitted. Figure 2 shows the value of N_e as a function of time obtained in this way. During the first phase of the discharge, the electron density—probably in the piston—increases only slowly until about 200 nsec before maximum compression, when the plasma collapses on the axis of the pinch. A maximum value of 2×10^{18} cm^{-3} is reached. Similar to the electron density, the line shift grows from about 4 Å at the beginning to 9 Å at maximum compression. The red shift of the line could be caused by two effects: the movement of the plasma towards the axis results in a Doppler shift which can be estimated to a maximum value of 1 Å at the beginning of the discharge; later, at maximum compression, the Doppler shift should decrease to zero. Moreover, since the plasma column is observed symmetrically along a diameter, the Doppler shift is both positive and negative and results in a broadening

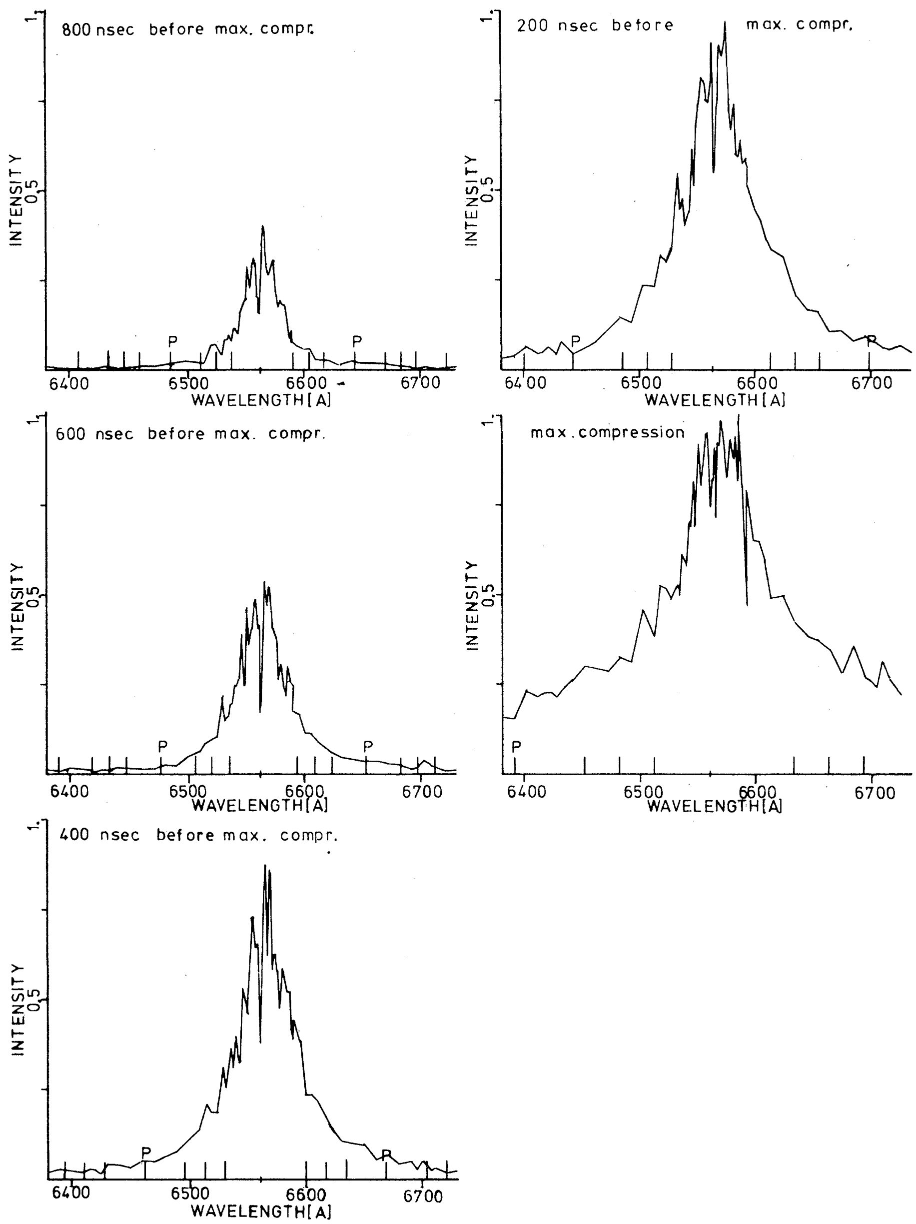

FIG. 1. Profile of the $H\alpha$ line for different times during the discharge. The vertical lines indicate the positions where "dips" are expected after Oks and Sholin. The letter P denotes the positions $\Delta\lambda = (\lambda^2/c)\nu_{pe}$.

rather than in a shift of the line. The observed shift must therefore be a high-density effect. This effect is neglected in most line-broadening theories of hydrogen lines. Only a few calculations predict such shifts[7-9] supported by a few experimental observations on $H\alpha$.[10,11] In the calculation of Bacon,[7] the shift arises from the impact operator ϕ. He included the contributions from all multipoles in the free-electron–atom interaction and time ordering. The calculated red shifts are $\Delta\lambda = 0.3$ Å for $T_e = 2\times10^4$ K and $N_e = 10^{17}$ cm^{-3}, and $\Delta\lambda = 1.9$ Å for $N_e = 10^{18}$ cm^{-3} and the same temperature. The shift increases nearly proportional with density and temperature. In Fig. 3, our measured shifts are plotted versus the electron density; the values found agree with the theory of Bacon if a temperature of about 10 eV is adopted which also follows from other measurements. In addition, shifts obtained by Birkeland (B) and Wiese (W) are indicated, though they were measured at lower temperatures in arc experiments.

Finally, Sholin[8] and Demura and Sholin[9] developed a theory for the asymmetry of the Stark profiles of hydrogen lines in high-density plasmas and

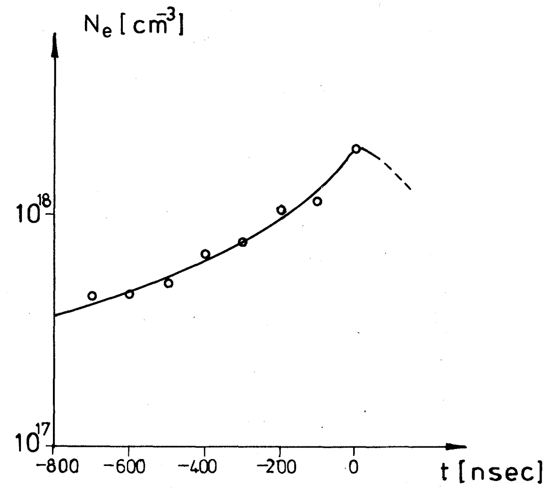

FIG. 2. Electron density as a function of the time.

found that the asymmetry results essentially from the electric-ion-field inhomogeneity. Their line shift derived for $H\alpha$ is $\Delta\lambda = 7\times10^{-18} N_e$ Å, and the dashed line DS in Fig. 3 indicates this relation. The experimental values yield $\Delta\lambda = 6.4 \times 10^{-18} N_e$ Å.

From the density values of Fig. 2, the frequencies of the plasma resonances can be calculated. Since the field strength of the collective oscillations is nearly comparable to the mean particle field one would expect "satellites" at a wavelength $\Delta\lambda_s = (\lambda^2_{H\alpha}/c)\,\nu_{pe}$ from line center. In Fig. 1, the positions have been marked, where such satellites are expected (letter P). In most cases, there are indeed structures in the vicinity of these positions, and, especially at early times, where drift turbulences probably occur, one may identify satellites. At later times, the structures become so complex that any identification would be doubtful.

The strong "structures" on the lines resemble those predicted by Oks and Sholin.[12] As described

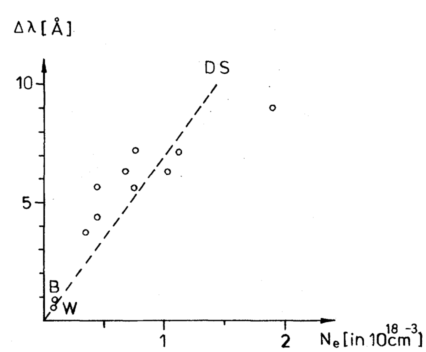

FIG. 3. Relation between electron density and red shift.

there, one typically finds a valley with one hill on each side. However, the strongest "structures" are not at spectral positions corresponding to the plasma resonance but rather at positions between $\frac{1}{4}\omega_{pe}$ and $\frac{1}{2}\omega_{pe}$. The calculations of Oks and Sholin predict similar structures not only at the resonance frequency but also at some harmonics and subharmonics, i.e., at $\frac{1}{2}n\omega_{pe}$ with $1 \leq n \leq 8$; $n \neq 7$ for $H\alpha$. The predicted positions are marked in Fig. 1. Because of the uncertainty in the density determination and therefore of the value of ω_{pe}, we cannot decide at present whether the observed line contour corresponds indeed to the model of Oks and Sholin.

If we would assume, however, that this model describes our plasma, we can test another prediction, that the half-width of the valley is a measure of the turbulent electrical field strength. With the numerical values given by Zhushunashvili and Oks,[13] we would calculate for the observed typical valley half-width of 10 Å a field strength of about 4×10^5 V/cm. This value for the high-frequency collective fields seems not unreasonable.

It remains crucial to prove that these structures are not simply caused by statistical or systematic errors. Let us therefore now assume that they are produced by statistics and try to reject or verify this. If the measured intensities obey Poisson statistics the deviation from the mean value should be proportional to the square root of the intensity; we define a quantity $\Delta(\lambda)$ as

$$\Delta(\lambda) \equiv [I(\lambda) - f(\lambda)]/[f(\lambda)]^{1/2} \equiv \delta/\sqrt{f}\ ,$$

where $I(\lambda)$ is the measured intensity, and $f(\lambda)$ the value of the fitted curve. For purely statistical distributions, the mean value of Δ should be constant for a given experimental arrangement, and it should not depend on the intensity. For the analysis, we divide each spectrum in two parts, one containing all values outside the half-width of the line and the other one containing the points inside, but excluding the absorption dip. For each line profile, both parts contain approximately the same number of spectral points, i.e., about 30.

We define a mean value of $\overline{\Delta^2}$ for each part by

$$\overline{\Delta^2} = \frac{1}{N}\sum_{n=1}^{N} \Delta^2(\lambda_n)\ .$$

Figure 4 shows the values of $\overline{\Delta^2}$ thus obtained as well as the best-fit regression lines. At early times, the difference between the value of $\overline{\Delta^2}$ for both parts of the line profile is not significant, but at later times $\overline{\Delta^2}$ becomes considerably larger inside. This indicates that the structures on the line grow significantly with time and that the hy-

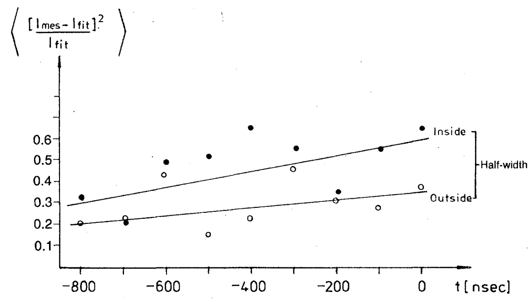

FIG. 4. Mean square deviation from the $H\alpha$ line as a function of time.

pothesis must be rejected that they are solely caused by statistical effects. The increase of Δ^2 with time outside the half-width indicates that the contribution of the line wing relatively to the continuum increases and influences Δ^2.

We can also rule out that systematic effects such as changes in density and temperature from discharge to discharge produce these structures. This was shown by monitoring the continuum intensity.

IV. PROPERTIES OF THE CENTRAL PART OF THE LINE PROFILE

The central part of the line profile from 6540 to 6572 Å was investigated in detail using an eight-channel polychromator. Figure 5 shows the results of these measurements at four times [300 nsec (a), 200 nsec (b), 100 nsec (c), and 0 nsec (d) before maximum compression]. A somewhat "noisy" spectrum with a deep absorption dip at the center of $H\alpha$ can be seen. As discussed earlier, the dip is very deep here because the use of long sidearms had been necessary. It is also apparent that the red part of the line is higher than the blue one, indicating the red shift or asymmetry discussed above. The shift, indicated by the asymmetry in the self-absorption dip is consistent with the earlier results. Obviously, "structures" are present in the spectrum with very different wavelength scaling: short-scale fluctuations are superimposed on long-scale fluctuations, and it seems difficult to distinguish between noise and true structures. A Fourier analysis of the spectrum was carried out, therefore.

In order to reduce the weight of the lowest Fourier components, parabolas were fitted to the spectrum. They are drawn in Fig. 5. The power spectrum of the fluctuations around the parabolas, $P(k)=(A_k^2+B_k^2)^{1/2}$, is shown in Fig. 6 (A_k and B_k are the Fourier coefficients). The Fourier component k represents a perturbation on the line profile with a scale length of $\Delta\lambda = 30$ Å$/k$. The highest amplitudes are found for the Fourier components $k=2$–4; the minimum for $k=7$ is followed by a smaller maximum at $k=8$–9. To higher k values, the power spectrum decreases with slight modulation. An analysis reveals that the first maximum is mostly caused by the absorption dip, the rest of the power spectrum being not characteristically changed when this part of the line profile is omitted; especially, the second maximum at $k=8$–9 remains unchanged in this case. We neglect, therefore, the first maximum in the following. The value $k=8$ in Fourier space corresponds to a modulation of the line profile according to a wavelength $\Delta\lambda = 30$ Å$/k = 3.75$ Å. If this modulation is interpreted as "satellites" arising from plasma waves, the frequency of these waves should be about $\nu \approx 2.6\times10^{11}$ Hz. The only characteristic frequency of the plasma close to this value is the ion plasma frequency for an electron density of 1.5×10^{18} cm^{-3}. This density corresponds indeed rather well to the density derived from the half-width of the line. It seems justified, therefore, to interpret the small-scale fluctuations as being caused by the low-frequency part of the collective wave spectrum. The upper limit of these waves corresponds to the dip in the power spectrum at $k=7$. This indicates that the line

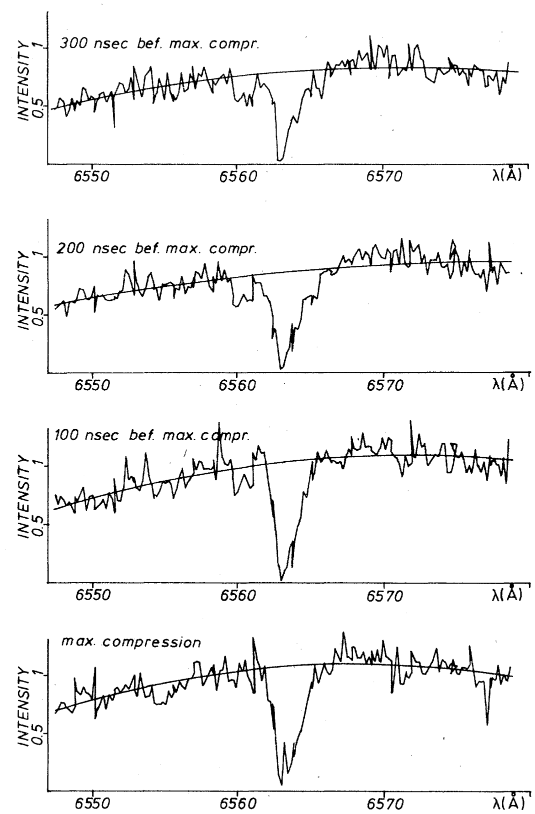

FIG. 5. Central part of the $H\alpha$ line for different times.

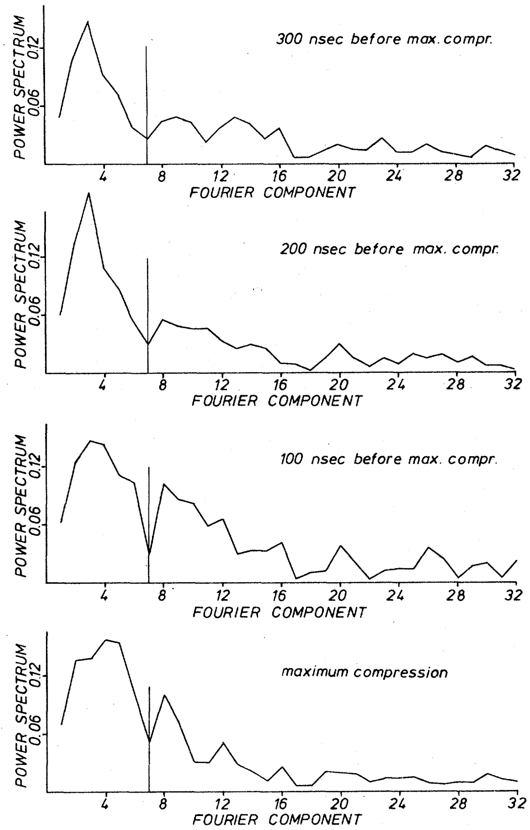

FIG. 6. Power spectrum of the central part of $H\alpha$.

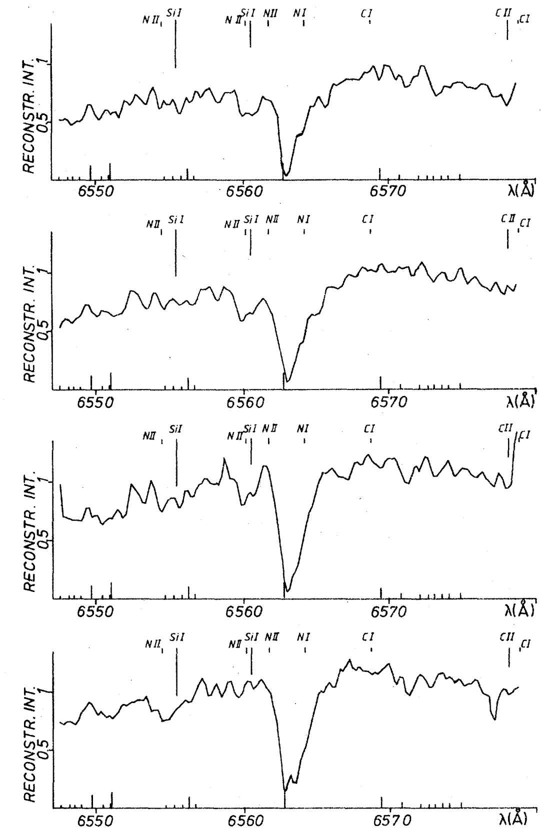

FIG. 7. Filtered central part of $H\alpha$. The vertical lines at the bottom indicate the positions of H_2-molecule lines, the lines at top of each picture impurity lines.

profile is modulated with pertubations of different scale lengths, i.e., by broad structures arising from electron plasma waves and by these small-scale structures arising from ion waves.

The absolute value of the power spectrum $P(k)$ of the low-frequency perturbation yields the corresponding modulation depth of the line profile. The low-frequency waves produce a modulation of about 5%. For values of k higher than 20, the power spectrum remains smaller than 1%. We assume that this part is essentially determined by noise. In order to eliminate this noise from the spectrum, we apply an "optimum filter procedure" as described by Brault *et al.*[14] This is done in Fourier space. The Fourier coefficients are multiplied with the filter function $F(k)$:

$$F(k) = P_0^2(k)/[P_0^2(k) + P_n^2(k)]\,,$$

where $P_0(k)$ is the power spectrum of the true function and $P_n(k)$ that of the noise. The application of this technique is straightforward if a clear distinction between noise and true spectrum is possible, if not an estimate suffices in many cases. The error from the uncertainty in the proper choice of $P_n(k)$ is not serious because small deviations from the optimum function influence the result only slightly.

For Fig. 7 the filter function was chosen to

$$F(k) = \begin{array}{l} 1, \quad k < 20 \\ 1 - (k-20)/60\,, \quad 20 \leqslant k \leqslant 80 \\ 0, \quad k \geqslant 80\,. \end{array}$$

It is obvious that the noise is strongly reduced by suppressing the higher Fourier components, and the low-frequency satellites become distinctly visible on the line profile.

The reconstructed spectrum of Fig. 7 also shows the strongest lines of the H_2 molecule (at the bottom). Their relative intensity after Crosswhite[15] is indicated by the length of the bars. Because of the large number of lines, it is not surprising that some minima on the $H\alpha$ line coincide with molecular absorption lines, but a systematic coincidence between molecular lines and the observed structures on $H\alpha$ cannot be found. A similar argument also holds for impurity lines[16] which are indicated at the top of each subpicture. This shows that the observed spectrum is probably not much perturbed by impurities or molecules.

V. CONCLUSION

We have found that in dense plasmas the $H\alpha$ line is shifted to the red side of the spectrum and that the line is strongly modulated.

The shift is density dependent and agrees with existing theoretical calculations. Measurements at different temperatures would be desirable in order to verify or to exclude the temperature dependence suggested by the calculations of Bacon.

The modulation is caused by collective fields of two typical frequencies: a high one of the order of the electron plasma frequency and a low one of the order of the ion plasma frequency. The amplitude of the line perturbation is stronger for the high-frequency field than for the low-frequency field. If the model of Oks and Sholin is correct for the description of the observed profile, one has to conclude that the collective fields, even the ion fields, cannot be treated adiabatically in the line-broadening theory for these dense plasmas.

With the exception of the interpretation of for instance, Zhuzhunashvili and Oks for thin, strongly turbulent plasmas, we found no examples where a similar line modulation is described for dense plasmas. In most experiments in which hydrogenlike lines are investigated in dense plasmas, the spectra are either poorly resolved or show so many impurity lines, that they yield no information on a line modulation. Some recent laser-pellet experiments, however, display structures on lines of hydrogenlike ions located symmetrically to the center of the line at a distance corresponding to ω_{pe} (see Fig. 2 of Ref. 17, Fig. 4 of Ref. 18, Fig. 3 of Ref. 19, and Fig. 5 of Ref. 20.) It must be stated, of course, that the noise on the photographs is high and the number of suitable examples is too small in order to be able to substantiate this interpretation without any doubt. We think, however, that it is useful to look for this effect in future experiments. Unfortunately, similar structures, even rather symmetric ones, can be caused by transitions of the type $1snl - 2l'nl)$ as shown by Boiko *et al.*[21] These satellites, however, depend only on atomic properties and not on the electron density. A distinction between both effects should be possible, therefore.

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