Time-Resolved Profile Measurements of Impurity Lines in a Theta Pinch Discharge

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(Z. Naturforschg. **20 a**, 1375—1385 [1965]; received 14 August 1965)

Line profile measurements were carried out on a small theta pinch experiment in order to get information on the ion motions during the discharge. A FABRY–PEROT interferometer combined with a so-called Fafnir arrangement was used for measuring the shape of the investigated N V (4603 Å) and O VI (3811 Å) lines. The additional use of a polarizer and $\lambda/4$ plate made it possible to eliminate ZEEMAN splitting caused by a magnetic field present, which affects the line shape, and to measure the magnitude of the magnetic field strength at the site of line emission in the plasma. By means of a combined system comprising image converter and intensifier the emission regions of the investigated lines in the plasma could be identified. The experimentally obtained results are discussed considering the different influences leading to line broadening in the present experiment.

In experiments for producing a high-density hydrogen or deuterium plasma the presence of impurity ions often limits the obtainable electron temperature due to radiation losses. One of the aims of such experiments, therefore, is to decrease the impurity level as much as possible. In typical theta pinch discharges values of $0.1 - 1.0\%$ are attained, the impurities consisting mainly of oxygen but in some cases of carbon as well.

On the other hand, the line emission of such impurity ions affords possibilities of information on interesting plasma parameters. Spectroscopic studies, which have the advantage of not disturbing the plasma by the diagnostic method itself, have, therefore, frequently been carried out, mostly in order to derive values of the plasma electron temperature from the intensities of the impurity lines. The main interest of the present experiments, however, lies in the shape of the impurity lines, although by such measurements electron temperatures are obtained at the same time since the line intensity is then automatically recorded also.

Since information on the electron density distributions can be obtained more easily, for instance, from continuum measurements [1] spectral lines were used for which STARK broadening is negligible, i. e. their upper excitation levels were sufficiently below the ionization limit. The profiles of such selected lines are then determined by the ion temperature and the gross plasma movements, on the one hand, and by the magnetic field strength at the site of line emission, on the other. It is difficult to obtain information on these quantities by diagnostic methods other than spectroscopic ones, if ion temperatures of the order of 100 eV are to be expected and perturbations of the plasma by magnetic probes have to be avoided. The present investigations were carried out in order to check the possibilities of deriving the stated quantities from line profile measurements.

Introductory remarks on line profile measurements

Several difficulties arise in the determination of such line profiles and their interpretation. For one thing, the intensities of the lines suitable for the studies intended are often too weak for safe profile measurements if only the amount of impurity ions is used which is already contained in the investigated hydrogen or deuterium plasma as contaminations. To overcome this difficulty more of the species in question is added to the plasma. At the same time, however, the radiation losses of the plasma are increased by these additives and the electron temperature may be affected. The admissible amount of additives to the plasma, therefore, has to be estimated carefully. It can be calculated, for instance, that in a pure hydrogen plasma at a density of $10^{17}\,\text{cm}^{-3}$

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[1] A. EBERHAGEN and M. KEILHACKER, Compt. Rend. VIe Conf. Intern. Phenomenes Ionisation Gaz, Paris 1963, Vol. II, 573, 577.

and at a temperature of about 300 eV the energy emitted from the plasma within about 10^{-3} s by bremsstrahlung radiation corresponds to the thermal electron energy. This cooling time is considerably decreased by about two orders of magnitude if only 1% of oxygen is present in the plasma, mainly due to line emission of O VIII ions. The amount of additives to the plasma, therefore, has to be balanced for sufficient line intensity, on the one hand, and an admissible magnitude of radiation losses, on the other.

Further difficulties emerge in the interpretation of the experimentally determined line profiles. One is that the observed line emanates from all those plasma regions in which the excitation conditions are favourable to the emission of the line under consideration. This means that the measured line shape only represents a profile averaged over the total of these volume elements in which both the line broadening factors and the intensity of the emitted line can vary from place to place. This difficulty can be overcome, in principle, by measuring the line profile from small volume elements only. As already suggested by the foregoing remarks, however, the lines do not radiate strongly enough to allow the observed emission region to be kept sufficiently small. The intensity distribution of the line across the whole plasma volume actually observed should therefore be investigated, in addition, in order to establish at least those regions which predominantly contribute to the resulting line profile.

In interpreting the latter, further difficulties stem from the fact that the line shape may be influenced by the ion temperature, gross plasma movements and the magnetic field strength at the site of line emission all at the same time, especially if the line radiation from a theta pinch plasma, for instance, is under investigation, as was the case in the present experiments. By application of a polarizer and a $\lambda/4$ plate, however, the effect of the magnetic field on the line shape due to ZEEMAN splitting can sometimes be eliminated by measuring the line profile of only one individual ZEEMAN component. In this case, it is still necessary to estimate the contribution to the line shape arising from possible variations of the magnetic field along the line of observation since deviations from the average value cause different wavelength shifts. For this check the line intensity distribution across the observed plasma region is considered according to the foregoing remarks. Further consideration of the relative wavelength displacements of the different ZEEMAN components offers, in addition, an experimental method for measuring the magnitude of the magnetic field in the plasma, even if the separation of the ZEEMAN components is less than the line broadening due to the motion of the emitting ions [2].

Besides the stated contribution due to variations of the magnetic field along the line of observation, the line profile of an individual ZEEMAN component is determined by the motion of the emitting ions. Here the thermal velocity distribution has to be considered as well as gross plasma movements. Unfortunately, these two line-broadening factors often affect the line profile at the same time, but in different ways. The thermal ion velocity distribution causes a GAUSSian intensity profile, whereas gross plasma movements result in wavelength shifts of the line under consideration. Since fairly large plasma regions are always observed, as mentioned before, it may be quite difficult to separate from each other both influences on the resulting line profile when interpreting the latter. This is especially true when gross plasma movements are present at the same time directed both towards and away from the observer. This is sometimes the case, for instance, when the plasma oscillates or rotates or when such movements as turbulences occur in the plasma; these motions may even happen to feign a GAUSSian line profile. One remedy is to use in the plasma additives of different atomic mass [3]. This is because the line shape – besides the fact that the spectral lines compared appear at different wavelengths – should not be altered then if it is mainly due to gross plasma movements, whereas the half-widths of the temperarature profiles decrease according to the square root of the ion masses. This method, however, is often not applicable as no suitable lines exist in the available wavelength range from both different species. A meaningful interpretation of the line profile is then posible only if one of both broadening mechanisms makes the main contribution to the line shape.

[2] K. HÜBNER, Z. Naturforschg. **19 a**, 1111 [1964]. See also: F. C. JAHODA, F. L. RIBE, and G. A. SAWYER, Phys. Rev. **131**, 24 [1963].

[3] H. R. GRIEM, Plasma Spectroscopy, McGraw-Hill Book Co., New York 1964.

Summarizing these introductory remarks, it can be said that the investigation of line profiles in high-temperature and high-density plasmas seems to show promise in providing information on plasma parameters such as the ion temperature, gross plasma movements and the magnetic field inside the plasma. In addition, the electron temperature, too, is indicated automatically, whilst the line intensities are recorded. Because of insufficient intensities of the lines for profile measurements, however, the observed plasma regions should be relatively large. Only average values, therefore, can be expected. These, nevertheless, are of great interest in themselves.

In the following a description will be given of the optical arrangements used for measuring line profiles in a small theta pinch discharge and for the investigation of the line intensity distribution across the observed plasma region. The results obtained will be discussed in relation to the foregoing remarks.

Data of the theta pinch plasma used

The investigations were carried out on a 26-kJoule theta pinch apparatus which has already been described in greater detail [1]. Hydrogen gas was used at a filling pressure of .15 torr. A preceding fast theta pinch discharge was used to preionize the hydrogen up to about 50% before the main discharge was started. A bias magnetic field of .8 kG had been superimposed on the plasma by this time, its direction being parallel to that of the main discharge. The peak magnetic field was 55 kG, reached after 1.6 μs.

In previous investigations the electron density distributions at various distances along the discharge axis were measured [4]. It was shown that the plasma oscillates radially, and up to 13 maximum compressions of the plasma column could be identified. These radial gross plasma movements should therefore be allowed for when interpreting the line profile measurements from side-on observations, especially for the highly pronounced first two or three radial plasma oscillations. Another experimental result of these earlier investigations was the occurrence of a rarefaction wave moving from the ends of the discharge coil towards its midplane. Connected with it is a continuous outflow of plasma from the region inside the coil which attained a velocity of $.4 \times 10^7$ cm/s at the coil ends. These gross plasma movements should be taken into account for the end-on measurements of the line profiles.

Further previous studies were concerned with the time history of the plasma electron temperature [5]. These measurements were carried out for the plasma region close to the midplane of the discharge coil only. The information on the electron temperatures was obtained from the occurrence of different ionization stages of additives to the plasma as well as from profile measurements of laser light scattered by the plasma at an angle of 90°. The electron temperature resulted in values of about 25 eV at the moment of the first maximum compression. It then increased up to about 70 – 80 eV shortly before the moment of peak magnetic field. These values have been confirmed meanwhile by repeated light scattering measurements with an improved laser.

Additional plasma data obtained from previous measurements are [1, 4]: The electron density of the compressed plasma column was $1.0 - 1.5 \times 10^{17}\,\mathrm{cm}^{-3}$, but the line density (i. e. the total number of plasma particles in the cross section of the tube per 1 cm tube length) decreased from $1.65 \times 10^{17}\,\mathrm{cm}^{-1}$ in the midplane of the coil to $.8 \times 10^{17}\,\mathrm{cm}^{-1}$ near the coil ends. This decrease in line density was due to end losses during the preionization and during the main discharge itself. The internal magnetic field of the plasma had previously been measured only by magnetic probes inserted into the plasma. The reliability of such measurements, however, is doubtful since it was shown, at least in the case of an antiparallel trapped magnetic field, that the plasma is seriously affected by the presence of such probes [6].

For the present investigations oxygen, nitrogen and carbon additives to the plasma were used. The amounts were chosen so that the investigated lines were as strong as possible, but the electron temperature remained on the whole unaffected. To check whether the latter condition was sufficiently fulfilled, the time history of the line intensities was taken and comparison was made between a small and

[4] A. Eberhagen and H. Glaser, Z. Naturforschg. **20 a**, 1268 [1965].

[5] H. J. Kunze, A. Eberhagen, and E. Fünfer, Phys. Letters **13**, 38 [1964].

[6] A. Eberhagen and H. Glaser, Nucl. Fusion **4**, 296 [1964].

the higher amount of the additives. It was found in this way that 4% nitrogen or oxygen was admissible for the present plasma or 2% carbon. This was valid since the following lines of these additives were investigated: a) N V (4603 Å) which was emitted in the present plasma at an electron temperature of about 20 – 30 eV, b) O VI (3811 Å) at about 30 – 50 eV and c) C V (2271 Å) at about 60 – 90 eV. Any noticeable influence on the plasma electron temperature by the relatively high amount of nitrogen and oxygen additives at moments later than those when the interesting lines were emitted is, of course, of no interest for the present investigations.

Intensity distribution of the spectral lines investigated in the observed plasma region

The purpose of the present studies was to measure line profiles both in side-on and end-on observation. Both the radial and axial distribution of the intensities of the lines used have therefore to be known for all evaluated moments of the discharge. In previous studies an eight-light-pipe assembly was applied for this purpose [1, 4] which made it possible to determine the radial electron density distribution at variable distances along the discharge axis. The evaluation of the multiplier signals from this eight-light-pipe assembly, however, was laborious and since only the relative intensity distributions of the spectral lines were needed for the present investigations another method of determining them was tried.

A very convenient method is to study the time-dependent behaviour of a plasma column by means of smear cameras. The radial plasma oscillations, for instance, of a theta pinch discharge can readily be established by this technique when the plasma is observed side-on through a slit in the discharge coil perpendicular to its axis and the image of the plasma diameter on the recording film is swept perpendicularly along the direction of the discharge axis [4]. The exposures of such smear pictures, however, become unsufficient at the required time resolution if only monochromatic light from the plasma is to be used in order to study the plasma radiation of one individual spectral line from the different plasma volume elements. An image intensifier was therefore used which amplified the intensity of the smear picture appearing on the screen of the image converter. Hence, the plasma diameter was imaged on the entrance slit of a stigmatically focussing monochromator, its image on the exit slit of the latter in the light of the required wavelength was focussed on the photocathode of the image converter and then the smear picture of the plasma diameter on the screen of the image converter was imaged on the photocathode of the intensifier. The final smear picture on the screen of the image intensifier was recorded on Polaroid film. The combination of image converter plus intensifier has already been described in detail [7]. A six-stage intensifier, type P 829 A, with a minimum photon gain of 10^5 which was supplied by English Electric Valve Co., Ltd. was applied here. For the used combination consisting of image converter plus intensifier and including the necessary optical system the following figures were valid: gain 5×10^3 on the Polaroid film, resolution ten line pairs per mm, i. e. 250 line pairs across the whole screen of the image intensifier [8].

Several examples of intensifier smear pictures obtained in the way described are given in Fig. 1. All pictures were taken side-on at about 3 cm from the midplane of the discharge coil but with different exposures, depending on the varying sensitivity of the photocathodes at the different wavelengths.

For comparison, first a smear picture is shown of the radial distribution of the plasma continuum radiation at $\lambda = 4980$ Å and $\Delta\lambda = 16$ Å, Fig. 1 a. A photomultiplier trace of the identical plasma radiation is also given. The first five successive plasma compressions can be seen on the smear picture. The discharge axis seems to drift slightly downwards in this picture and in the following ones as well, but it was shown that this was due to inhomogeneities in the focussing magnetic field of the image intensifier.

The next smear picture, together with the photomultiplier trace shown, gives an example of the radial intensity distribution of the investigated N V (4603 Å) line, Fig. 1 b. The darkened line-spot in the middle part of the smear picture is due to

[7] A. Steinhausen, Compt. Rend. VIe Conf. Intern. Phenomenes Ionisation Gaz, Paris 1963, Vol. IV, 85.

[8] The authors are highly indebted to A. Steinhausen for providing the combined system consisting of image converter plus intensifier and the necessary optical system built up by him and his group and for supervising its operation in the present experiments.

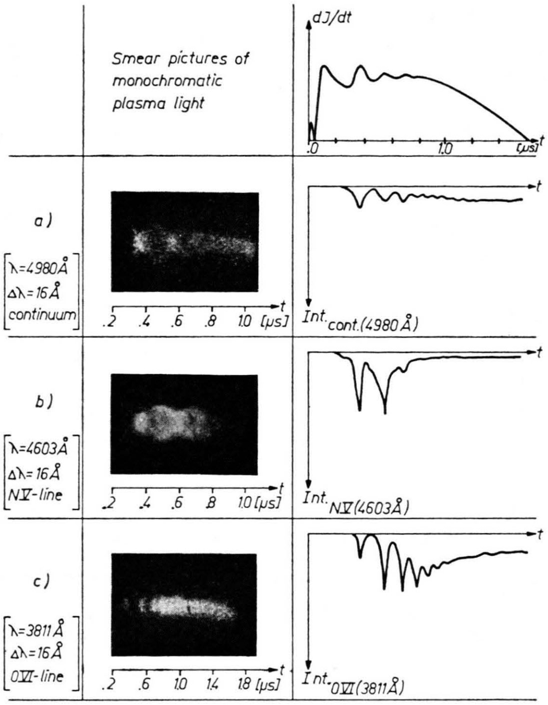

Fig. 1. Monochromatic smear pictures and photomultiplier traces from the plasma in side-on observation:
a) continuum: $\lambda=4980$ Å, $\Delta\lambda=16$ Å;
b) N V line: $\lambda=4603$ Å, $\Delta\lambda=16$ Å;
c) O VI line: $\lambda=3811$ Å, $\Delta\lambda=16$ Å.

damage in the photocathode of the image intensifier used here. The smear picture shows that the N V line is strongly emitted from the compressed plasma column for the first time at the moment of the first maximum compression. It again appears after the plasma column has expanded and it is then emitted continuously by the plasma with decreasing intensity until the third maximum plasma compression. After this moment the line becomes faint and the plasma radiation at this wavelength consists mainly of continuum radiation.

The last example of smear pictures and photomultiplier traces, Fig. 1 c, concerns the investigated O VI (3811 Å) line. Here the time sweep of the smear picture was reduced in order to cover the full time scale of the line appearance. It can be concluded from the smear picture that the O VI line is emitted mainly from the plasma when its column is being compressed. This is true at least up to the third maximum compression. Later on, however, the O VI line also appears during the other phases of the radial plasma oscillations, i. e. the line is also emitted from volume elements further from the discharge axis.

Similar intensified smear pictures and photomultiplier traces were taken for a further four distances from the midplane of the discharge coil along its axis inside and at 1 cm outside the coil. For the N V (4603 Å) line it could be shown in this way that it was emitted fairly homogeneously along the whole length of the coil, as shown by the example in Fig. 1, except that the intensity decreased slightly towards the coil ends, as did the diameter of plasma regions radiating at this wavelength. Emission of this line was also found at 1 cm outside the coil. For the O VI (3811 Å) line the decrease in intensity towards the coil ends was much more pronounced. Only about 50% of the intensity of the midplane region occurred inside the coil at 4 – 5 cm from its ends, no intensity being present outside, at about the moment of the fifth maximum plasma compression. This decrease in intensity of the O VI line is in agreement with the appearance of a rarefaction wave in this discharge moving from the coil ends towards its midplane. According to previous investigations, this rarefaction wave had moved inwards for about 7 cm at the moment in question of the discharge [4]. The radial distributions of the O VI line emission for various distances from the midplane of the coil were similar to those of the example in Fig. 1. At the earlier times of the discharge the plasma radiation at this wavelength was again most pronounced when the plasma column was compressed and its diameter decreased with increasing distance from the coil midplane.

Optical arrangement used for measuring the line profiles

Because of its greater light-gathering power and its favourable resolution a Fabry-Perot interferometer rather than a spectrograph was applied in the present experiments for the line profile measurements. Its silver-coated plates were kept at a distance of .394 mm by spacers consisting of precision stainless-steel balls [9]. The interferometer was placed in a small vacuum chamber which could be filled by propane gas in order to alter the refractive index.

[9] These were generously supplied by R. Meve, FOM-Instituut voor Plasma Fysica, Jutphaas, Netherlands.

The plasma radiation first passed an interference filter having a band pass of about 15 Å only at the required wavelength. After that the transmitted monochromatic light went through a polarizing assembly, which will be described later on. This was followed by the FABRY-PEROT interferometer and then an optical arrangement, consisting of lenses, mirrors and photomultipliers for separating from each other small wavelength ranges of the whole line profile under consideration and measuring them individually. This assembly, called "Fafnir" was constructed according to a proposal of HIRSCHBERG [10, 11] and is illustrated in Fig. 2. With it the

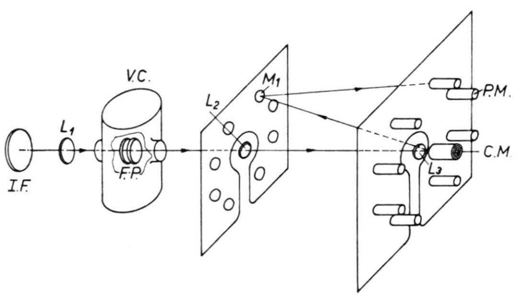

Fig. 2. Optical system of FABRY-PEROT interferometer and Fafnir arrangement: I. F.: interference filter, F. P.: FABRY-PEROT interferometer, V. C.: vacuum chamber, L_1, L_2, L_3: imaging lenses, C. M.: circular mirrors, M_1: adjustable concave mirrors, P. M.: photomultipliers.

central interference fringe of the FABRY-PEROT interferometer is focussed on a set of concentric, circular mirrors of equal area. These zone mirrors are slightly canted with respect to their common axis and consecutive wavelength ranges of the whole line profile are reflected to a set of mirrors and thence to the photomultipliers.

Of the spectral lines investigated the profiles of the N V (4603 Å) and O VI (3811 Å) lines were determined with this arrangement. The following data characterized the properties of the entire interferometer arrangement at the two different wavelengths present in the experiments: instrumental width .17 Å (at $\lambda = 4603$ Å) and .20 Å (at 3811 Å) respectively, wavelength range picked up by each photomultiplier channel .184 Å (at $\lambda = 4603$ Å) and .1525 Å (at $\lambda = 3811$ Å) respectively.

For the profile measurements of the C V (2271 Å) line this very useful Fafnir arrangement could not be applied because no suitable interference filters and coatings on the interferometer plates were available. Here a high-optical-speed, high-resolution monochromator was applied and small wavelength ranges of the total line profile were reflected by eight sufficiently narrow and increasingly bevelled mirrors to eight different photomultipliers. This arrangement and the optical system necessary in addition are described in [12]. It was possible with the total system used to resolve wavelength differences of .12 Å.

The relative calibrations of the different photomultiplier channels at the wavelengths of interest were done with the continuum radiation of the plasma for the Fafnir assembly. In the case of the monochromator arrangement the C V (2271 Å) line itself was used for this calibration by opening the monochromator slits sufficiently to afford full illumination of all eight reflecting mirrors with equal intensity of the C V line.

Elimination of Zeeman splitting of the line profiles by using a polarizing system

The polarizing system to be described was applied to eliminate the influence of ZEEMAN splitting by the magnetic field present in the plasma on the profiles of the N V (4603 Å) and O VI (3811 Å) lines. These lines originate from $^2S_{1/2}$-$^2P_{3/2}$ transitions of the respective ions and therefore develop anomalous ZEEMAN effect in a magnetic field. There occur two components which are polarized parallel to the magnetic field (π-components) and two stronger and two weaker ones which are circularly polarized (σ-components). Fig. 3 indicates the pattern of the

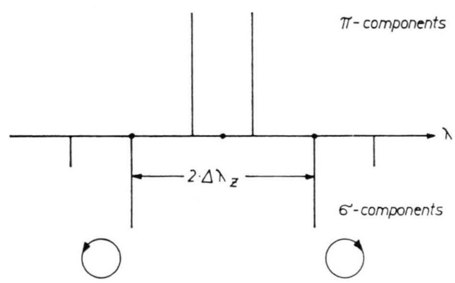

Fig. 3. ZEEMAN pattern for splitting of the $^2S_{1/2}-{}^2P_{3/2}$ transition in a magnetic field. The relative intensities of the individual components are indicated by the lengths of the bars.

[10] J. G. HIRSCHBERG, J. Opt. Soc. Amer. **50**, 514 [1960].

[11] J. G. HIRSCHBERG, C. BRETON, and R. CHABBAL, 3rd Symp. Engin. Probl. in Thermonucl. Res., Munich 1964.

[12] M. J. BERNSTEIN, Appl. Optics, to be published.

[13] E. U. CONDON and G. H. SHORTLY, The Theory of Atomic Spectra, Cambridge University Press, London 1964.

Zeeman splitting for the transition investigated [13]. The lengths of the bars give the relative intensities of the individual Zeeman components and the indicated wavelength separation $\Delta \lambda_Z$ is given by:

$$\Delta \lambda_Z = 4.67 \times 10^{-13} \cdot \lambda^2 \cdot H \quad [\text{Å}] \qquad (1)$$

(λ = wavelength of the investigated line in Å, H = magnetic field at the place of line emission in Gauss).

The rotation of the electrical vector is in opposite directions for the two pairs of σ-components.

The idea for measuring the line profile of one individual Zeeman component is based on this opposite rotation of the electrical vectors [14]. It can be applied by observing parallel to the magnetic field, i. e. for line profile measurements in a theta pinch discharge in end-on observation. The two π-components are not emitted in this direction as their electrical vector oscillates parallel to it. A $\lambda/4$ plate for the wavelength in question transforms the two pairs of circularly polarized components into two pairs which are polarized linearly but perpendicularly to each other. By application of a successive polarizer one of these two pairs of components can be selected.

Such a polarizing assembly was placed in the used optical arrangement behind the interference filter, as already mentioned. For the $\lambda/4$ plate a Soleil compensator was applied which is easy to adapt for different wavelengths.

As stated before, only a pair of σ-components could be selected in this way. Since for the transitions used, however, the separation of the two individual components of one pair, due to splitting in the magnetic field, is only one-third that of the two pairs and, furthermore, the weaker component is also only one-third the intensity of the stronger one – as can be seen from Fig. 3 – this resulted mainly in only a small apparent increase of the half-width of the line profile of the pair of components, compared with the case where only the stronger component of one σ-Zeeman pair is present. This influence on the experimentally determined line profiles of one Zeeman component could be accounted for by an estimate. An apparent increase of the half-width of about 10% was typical.

Another influence on the line profiles determined experimentally in this way was due to the possibility of the magnetic field strength deviating from its average value along the line of observation, as stated in the introductory remarks. This again influenced mainly the half-width of the line profile. As the plasma region from which the respective line was predominantly emitted could be identified by the mentioned smear pictures, an estimate was made of the possible deviations of the magnetic field in these regions and their influence on the line profile taken into account. For end-on observations of the O VI line profiles, for instance, evaluation was carried out only for the moments of maximum plasma compression. The smear pictures showed that the line was then emitted mainly from about two-thirds of the length of the whole plasma column. The magnetic field in this plasma region of O VI line emission, therefore, could be assumed to be fairly constant along the line of observation and deviations from its average value to be small in consequence. Allowing such deviations of up to 4 kG, i. e. about 20% of the measured average magnetic field at the plasma region of O VI line emission, results in an influence of about .05 Å for the half-width of the line profile, i. e. about 6% of it. For the N V line this influence on the line profile was assumed to be larger, since, according to the smear pictures, this line is also emitted strongly from plasma regions about the coil ends. Stronger deviations from the average magnetic field are therefore to be assumed and allowed here to range up to 8 kG, i. e. about 50% of the average magnetic field measured at the moment of N V line appearance. This results in an apparent half-width increase for the recorded line profiles of about .15 Å, i. e. about 20% of it.

For side-on observations of the line profiles the elimination of Zeeman splitting was more difficult as the σ-components are linearly polarized alike when observing perpendicularly to the magnetic field. The direction of the electrical vector, however, is perpendicular to that of the π-components which also appear now. With the use of a single polarizer both of the latter were selected here and the resulting line profile was compared with the unseparated one. This, however, was only possible in the present experiment for the line profile of the N V line because of insufficient intensity in the case of side-on observation of the O VI line. The profile of this line, therefore, was measured unseparated only.

[14] H. W. Babcock, Astrophys. J. **118**, 387 [1953]; Sci. Am. **202**, 53 [1960].

From the difference in half-width between the unseparated and the π-component separated line profile the total influence of the ZEEMAN splitting on the unseparated line shape was estimated for the N V line and, because of lack of additional information, also extrapolated on the O VI line profiles, with due allowance for the time dependence of the magnetic field as determined by end-on observation. For the N V line this difference resulted in .15 Å at the moment of the first maximum plasma compression (see Fig. 7). Considering that both the π-components had been measured at the same time and consulting Fig. 3 gave an apparent increase of the half-width of about .20 Å for the unseparated line profile, this being due to ZEEMAN splitting at this moment. For the extrapolation of this result to the O VI line profiles the quadratic wavelength dependence of the ZEEMAN splitting is to be considered as well as the varying magnetic field. Here the apparent increase of the half-width, therefore, is:

$$\Delta\lambda_{\mathrm{z, O\,VI, side\text{-}on}} = .01 \times H \text{ Å}$$

(H = magnetic field strength from end-on measurements in kG).

Final results from the line profile measurements

The results derived from line profiles obtained from end-on measurements are considered first. In Fig. 4 some examples of the experimentally determined line shapes are presented. They were obtained for the N V line at the moment of the first maximum plasma compression and show the profile of the unseparated line (Fig. 4 a) as well as the line shapes for both separated pairs of σ-components (Fig. 4 b). The points indicated are the values measured, each from a different photomultiplier channel. As the eight such channels available did not cover the whole line shape sufficiently, the propane gas pressure in the FABRY-PEROT interferometer was varied between the different discharges and the obtained parts of the total line profile were fitted together again afterwards, with due allowance for the change in refractive index. The intensity values in Fig. 4 are plotted in arbitrary units, comparing the unseparated profile (Fig. 4 a), on the one hand, and the separated ones (Fig. 4 b), on the other.

The shifts of the two different pairs of σ-components could clearly be observed, as seen from Fig. 4.

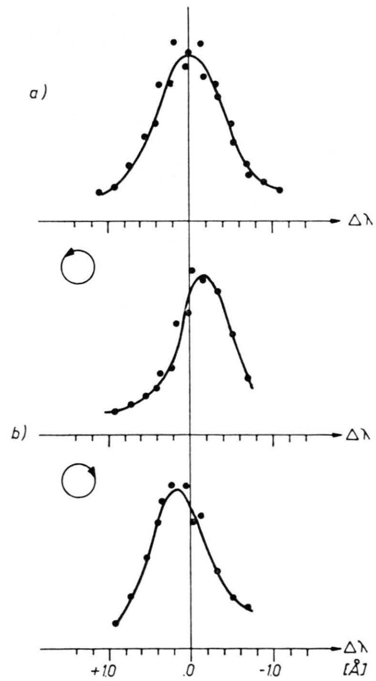

Fig. 4. Measured profiles of the N V (4603 Å) line in end-on observation: a) unseparated line shape, b) line shapes of the two pairs of σ-components.

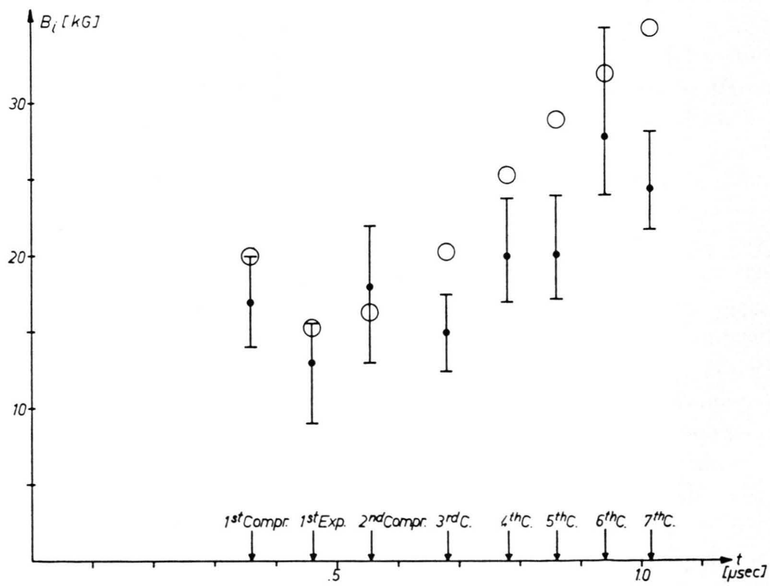

Fig. 5. Internal magnetic field of the plasma from line profile (solid circles) and probe (open circles) measurements.

Evaluating these shifts and the similar apparent shifts of the O VI lines at the later times of the discharge also afforded information on the size of the magnetic field inside the plasma. These results are given in Fig. 5. The first three items of information (i. e. for the times of the first and second maximum plasma compressions and the first expansion of the plasma column) come from the N V line profiles and the remaining six from the O VI line shapes. Also contained in Fig. 5 are the results of measurements with magnetic probes. These clearly indicate greater sizes of the internal magnetic field in the plasma for times later than the second maximum compression. These discrepancies are most probably due to perturbations of the plasma column caused by the presence of the probe. Similar effects on the plasma by probes, although then even much more drastic, were observed previously in the case of an antiparallel trapped magnetic field in the plasma [6]. According to the results shown, therefore, measurements of the internal magnetic field of a plasma, like those of a theta pinch discharge by means of inserted probes, are doubtful in either parallel or antiparallel magnetic fields, at least for times later than the second maximum compression of the plasma column.

As already stated in the introductory remarks of this report, further interpretation of the line profiles of individual Zeeman components is difficult as the two remaining line broadening factors can be effective at the same time. The one, namely the ion thermal velocity distribution, results in a Gaussian intensity distribution for the line shape with a half-width:

$$\Delta\lambda_D = 7.70 \times 10^{-5} \cdot (k\,T_i/M)^{1/2} \cdot \lambda \qquad (2)$$

(λ = wavelength of the line in Å, $(k\,T_i)$ = thermal energy of the emitting ion in eV, M = mass number of the ions [$M = 16$ for oxygen])

whereas the other line broadening factor, namely gross plasma movements, causes wavelength shift of the spectral line according to:

$$\Delta\lambda_S = \pm (v_i/c) \cdot \lambda \text{ Å} \qquad (3)$$

(v_i = velocity of the gross plasma movements parallel to the direction of observation. The negative sign is to be inserted for this velocity when it is directed towards the observer).

As gross plasma movements mostly occur in both directions at the same time in the observed plasma region, they produce an additional broadening in the line profile rather than a shift only.

In end-on observation of the plasma column gross plasma movements in the present experiments were to be expected mainly from the outflow of the plasma through the coil ends. The smear pictures mentioned showed that predominantly the N V line profile should have been influenced by the movements as the O VI line was only emitted weakly from the plasma regions involved in this plasma escape. The O VI line profiles in end-on observation, therefore,

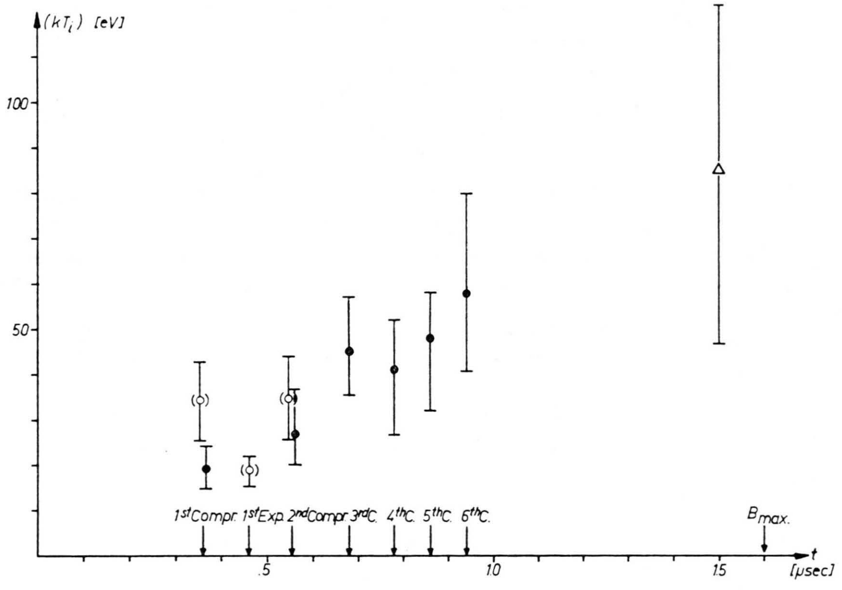

Fig. 6. Plasma ion temperature from measurements in end-on observation derived from N V (4603 Å) (open circles) O VI (3811 Å) (solid circles) and C VI (2771 Å) (triangle mark) line profiles.

were expected to yield fairly correct values of the ion temperature from their half-widths, whereas to the N V line profiles gross plasma movements also contributed.

In Fig. 6 the results obtained from the measured half-widths of the line profiles are shown, which are unfolded with respect to the instrumental width of the interferometer arrangement, corrected for inhomogeneities of the magnetic field and for one σ-component only, and then evaluated according to eq. (2), i. e. for considering the thermal ion velocity distribution only (circular marks). As can be seen from Fig. 6, the results for the N V line profiles actually yielded higher ion temperatures compared with those from the O VI line shapes, which could be derived both for two identical moments, namely for the first and second maximum plasma compressions. The marks for the ion temperature values for the N V line profiles, therefore, are given in brackets in Fig. 6 in order to indicate that account must be taken in this case of the influence of gross plasma movements on the line shape.

An additional item of information on the ion temperature indicated in Fig. 6 by the triangular mark was obtained from profile measurements of the C V (2271 Å) line which were carried out with the monochromator device already mentioned. This line developed an unseparated profile with a half-width of .72 Å, i. e. .68 Å when the instrumental width was taken into account. No information, however, was available from the experiment on the influence of ZEEMAN splitting on the shape of this line. If the magnetic field is assumed to be about 50 kG at the time evaluated the value noted in Fig. 6 by the triangular mark is obtained. It is, however, considered to be uncertain by about $\pm 50\%$, mainly due to the lack of more exact knowledge on the influence of the ZEEMAN splitting on this line profile in the present experiment.

As the equipartition times for collisions between the protons of the plasma and the ions of the additives are of the order of 10^{-8} s for the present experiment the values given in Fig. 6 can also be considered to be representative of the ion temperature of the protons.

These ion temperature figures for the present plasma at the different maximum compression times may be compared with the corresponding electron temperature values. Information on these is available from previous measurements [5] as well as from the present ones, the agreement between them being good. At the moment of the first and second maximum compressions of the plasma the N V line is radiated strongly and for the present plasma conditions this means an electron temperature of about $20-30$ eV, as already mentioned. Afterwards this line becomes faint and the O VI line was emitted mainly from the plasma, i. e. in the time interval between the second and about the sixth maximum plasma compressions, the electron temperature was estimated to range between $30-50$ eV here. Finally, for the single value measured from the C V line a corresponding estimate of the electron temperature of the plasma yielded about 70 eV. All these figures agree well with those of the ion temperature from the half-widths of the line profiles in Fig. 6. It can be concluded from this comparison, therefore, that within the error range of the measurements no marked difference could be detected between the electron and ion temperatures for the present discharge at any moment of maximum plasma compressions.

In side-on observations deriving information on the plasma parameters from line profiles was more complicated than in the end-on measurements. Here the radial plasma oscillations introduce considerable gross plasma movements. The line shapes to be expected for these cannot be calculated for the evaluated moments of maximum plasma compressions. Furthermore, the contribution of the thermal ion velocity distribution is superimposed on it. By way of provisional treatment, the half-widths of the line profiles unfolded with respect to the instrumental widths of the interferometer arrangement and measured in end-on observation were subtracted from those in side-on observation, likewise after being corrected for one individual π-component, in order to account for the ion temperature line profile. From the resulting differences velocities for the gross plasma movements by the radial plasma oscillations were then calculated according to eq. (3).

In Fig. 7 examples of the experimental line profiles are given for the N V line in side-on observation for the moment of the first maximum plasma compression. Above (Fig. 7 a) the whole unseparated line shape is presented and underneath (Fig. 7 b) the separated one in which only the two π-ZEEMAN components were recorded. As already mentioned the half-width of the latter is smaller by .15 Å.

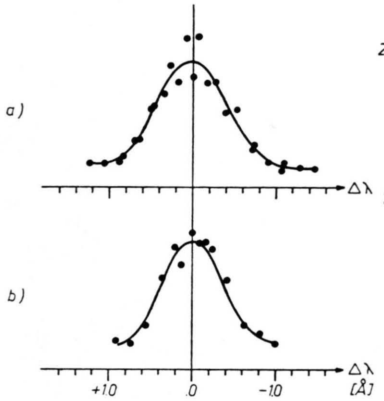

Fig. 7. Line profiles of the N V (4603 Å) line in side-on observation: a) unseparated line shape, b) line shape of the two π-components.

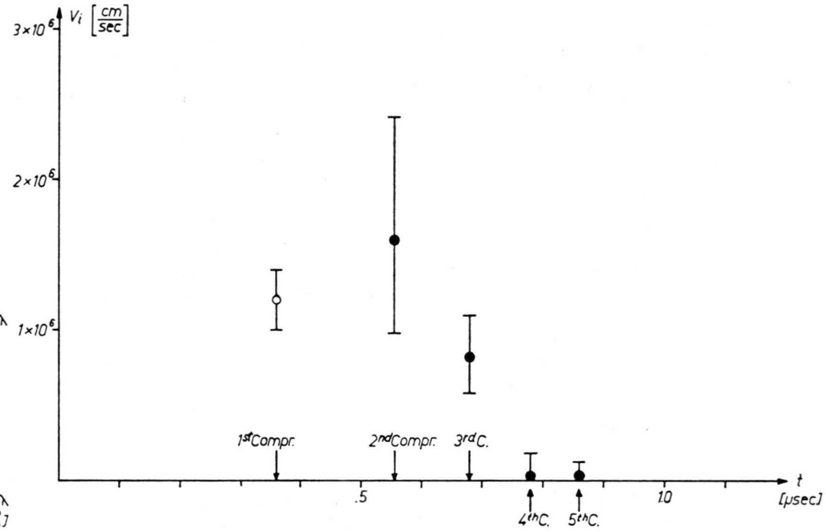

Fig. 8. Radial plasma velocities in side-on observation at the moments of maximum plasma compression from N V (4603 Å) (open circles) and O VI (3811 Å) (solid circles) line profiles.

In Fig. 8 the velocities of the radially oscillating plasma column are plotted according to the provisional treatment in evaluating the half-widths of the line profiles from side-on observations, as already explained. These afford values of the order of 10^6 cm/s for the moment of the first and the second maximum plosma compressions and a slightly smaller one for that of the third. For the fourth and the fifth plasma compressions a contribution of the gross plasma movements to the O VI line profile could no longer be detected, i. e. the half-width of the line shape was the same as that corresponding to the ion temperature in end-on observation. Compared with the maximum radial velocity values of the present plasma of about 10^7 cm/s, observed during the implosion and oscillation of the plasma column, the derived figure of about 10^6 cm/s seems to be rather small. It can, however, be considered valid for the moment of maximum plasma compression, i. e. the short time interval when the direction of the radial gross plasma movement is reversed. Unfortunately, a more detailed evaluation of the line profiles for moments before and after the time of maximum plasma compression had to be abandoned because of the sharp peaking of the line intensity at the moments of maximum plasma compression. Furthermore, it should be borne in mind that the statements made on the radial plasma velocity here are not as well-founded as the others of the present measurements, since evaluation of the line profiles from side-on observation could only be treated provisionally.

Summarizing the foregoing experimental results, which were intended as a check on the usefulness of impurity line profile measurements, it can be stated that careful consideration of all the different factors affecting the half-widths of the line shapes affords reliable information on the ion temperature of a plasma like that of a theta pinch discharge. Such measurements, furthermore, provide useful estimates of the electron temperature of the plasma at the same time and may also give values relating to the internal magnetic field. One requirement for line profile measurements, however, is a knowledge of the intensity distribution of the investigated lines across the observed plasma region. This was met in the present experiment by using a smear camera combined with an image intensifier.

Acknowledgements

The authors gratefully acknowledge the interest of Prof. E. Fünfer in the present experiments. They would also like to express their gratitude, in particular, to Dr. K. Büchl, who provided the Fabry-Perot interferometer for the measurements and made helpful suggestions. — This work was performed as part of the joint research program of the Institut für Plasmaphysik, Garching, and EURATOM.