SPECTROSCOPIC INVESTIGATION OF A TOROIDAL DISCHARGE

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A spectroscopic investigation is carried out of the plasma glow in the "Beta" installation (under various experimental conditions) and a study is made of the time dependence of the line intensities due to ions of different degrees of ionization. The results are interpreted on the basis of corresponding variations in the electron temperature of the plasma.

INTRODUCTION

THE installation "Beta" belongs to the class of toroidal chambers with a weak magnetic field, such as "Alpha" and "Zeta." In contrast to the other two installations a considerably higher current density is produced in "Beta."

It was of interest to carry out a spectroscopic investigation of the radiation from the discharge and, first of all, to study the variation with time of the intensity of the lines due to ions of different degrees of ionization (oxygen, fluorine, carbon and others) as the conditions of the discharge were varied.

As an interesting feature of the discharge we note that observation of the time dependence of the total radiation from the discharge by means of a photoelectric element with a "uviol" window (for the range 2200 — 6000 A) has shown that the intensity of the light passes through a minimum at the instant when the current reaches its maximum (Fig. 1).

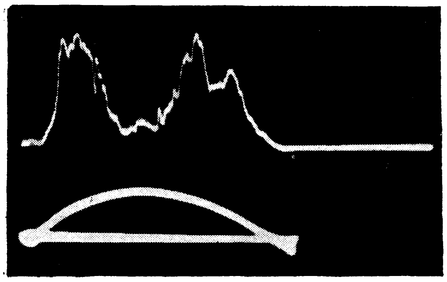

FIG. 1. Time dependence of the intensity of the spectroscopically unanalyzed light (in the range 2200-6000 A) (top) and of the magnitude of the discharge current (bottom).

DESCRIPTION OF THE EXPERIMENT

The installation "Beta" has the following parameters: principal diameter of the toroid 750 mm, diameter of the discharge chamber 210 mm, diameter of the external shell 250 mm, working pressure of hydrogen $(3-5)\times 10^{-3}$ mm Hg, maximum energy stored in capacitors 22 kilojoules, duration of the discharge 670 μsec, intensity of the longitudinal magnetic field 200 — 1100 oe, maximum discharge current with 1.5 kv initially applied 120 kamp, maximum current density evaluated for the total cross section of the discharge chamber 400 amp/cm^2, maximum conductivity of the discharge evaluated for the total cross section of the chamber (at a longitudinal magnetic field intensity of 640 oe) 4×10^{14} cgs esu.

The light was observed through a quartz window situated parallel to the plane of the large cross section of the discharge chamber. By means of a system of mirrors light from the same portion of the discharge was made to fall on the entrance slits of two monochromators ZMR-2 (Fig. 2), and this permitted simultaneous observation of the time dependence of the intensities of two different spectral lines.

At the exit of each monochromator there was placed an FÉU-18 photomultiplier, signals from which were applied to the input of two identical amplifiers of the OK-24MKB oscillograph.

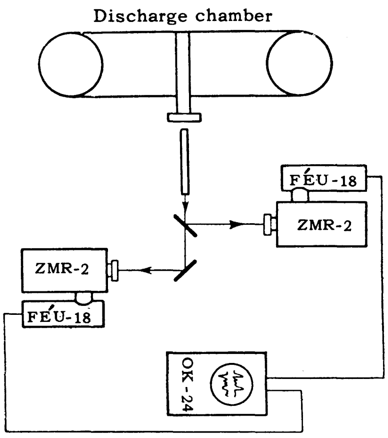

FIG. 2. Optical block diagram of the experimental arrangement.

Each photomultiplier had its own independent VS-9 rectifier. The photomultipliers and the connecting lines were carefully screened from all possible induction effects associated with the powerful gas discharge. The current in the discharge was measured by means of a Rogowski belt, the signal from which was integrated and applied to the input of an OK-17M oscillograph.

The voltage was measured by means of a turn of wire situated on the discharge chamber parallel to its axis. The voltage signal was applied to the second input of the OK-17M oscillograph.

EXPERIMENTAL RESULTS

1. Time dependence of the intensity of the spectral lines. Displays were obtained of the time dependence of the intensity of the spectral lines of oxygen, fluorine, nitrogen, carbon and helium. The wavelengths, the spectroscopic notations for all the lines, and the energies of the upper levels are shown in the table.

Line	λ, Å	Transition	Energy of the upper level, ev
OV	2781	$3s^3S_1—3p^3P_2$	81
OIV	3063	$3^2S_{1/2}—3^2P^0_{3/2}$	48
OIII	3047	$3s^3P^0_2—3p^3P_2$	37
FV	2707	$3s^4P^0_{7/2}—3p^4D_{9/2}$	81
FIV	2826	$3s^3P^0_2—3p^3D_3$	56
FIII	2994	$3s'''\,^6S^0_{5/2}—3p'''\,^6P_{7/2}$	53
NV	4945	$6^2G—7^2H^0$	91
NIV	3485	$3^3S_1—3^3P^0_1$	50
CIII	4650	$3^3S_1—3^3P^0_1$	32
He II	4685	$3^2D—4^2F$	51

The oscillograms exhibit the following phenomena:

1. The glow due to the ions of different degrees of ionization begins after different lapses of time from the beginning of the discharge: lines due to ions of higher degree of ionization (OV, FV) appear later than lines due to ions of lower degrees of ionization (OIII, FIII).

2. All the observed lines have a minimum intensity in the neighborhood of the maximum of the discharge current. The width and depth of this "dip" in the intensity depends on the degree of ionization of the emitting ion.

3. In contrast to the lines due to OIII and OIV, which have well defined intensity maxima at the beginning and at the end of the discharge, the line due to OV has a weakly pronounced second maximum at the end of the discharge, and sometimes the line due to OV does not get excited at all at the end of the discharge.

4. The time dependence of the intensities of the lines due to NV, NIV, CIII in its general behavior agrees with the time dependence of the lines due to OIII, OIV, FIII and FIV.

2. Effect of the initial conditions of the discharge. An investigation of the effect on the time dependence of the intensity of the spectral lines of the initial conditions of the discharge has shown that the appearance of the "dip" in the intensity of the lines is very sensitive to the variation of such parameters as the initial pressure, the discharge current and the initial longitudinal magnetic field.

It was established by means of preliminary experiments that the resistance of the plasma also depends on the variation of these three parameters, and it is possible to select such values of these parameters as to make the conductivity of the plasma a maximum. The corresponding values of the pressure p, of the maximum discharge current I_{max} and of the longitudinal magnetic field H_z have been chosen by us for the operating values and in future shall be referred to as "optimum" values [$p = (3.5 - 4.5) \times 10^{-3}$ mm Hg, $I_{max} = 120$ kamp; $H_z = 640$ oe].

It was found that a deviation of the longitudinal magnetic field from its optimum value by 150 — 200 oe in either direction leads to a change in the form of the time dependence of the intensity: to a diminution and even to a complete disappearance of the "dip" and to the appearance of strong fluctuations of intensity.

The same applies to the variation in initial pressure. The range of pressures for which a "dip" in the intensity of light is observed is $(3.5 - 4.5) \times 10^{-3}$ mm Hg. Outside this range a gradual smearing of the minimum is observed, accompanied by considerable fluctuations in the intensity of the glow.

The form of the time dependence of the lines due to OIII and OV for different values of the discharge current is shown in Fig. 3 (the longitudinal magnetic field and the pressure have been chosen equal to their optimum values).

It can be seen from the figure that a decrease in the discharge current leads to a decrease in the depth of the intensity minimum and to a complete disappearance of the minimum. We should particularly note the cases when a small dip in the intensity of the line due to OIII was observed while there was no such dip (Fig. 3d) in the line due to OV.

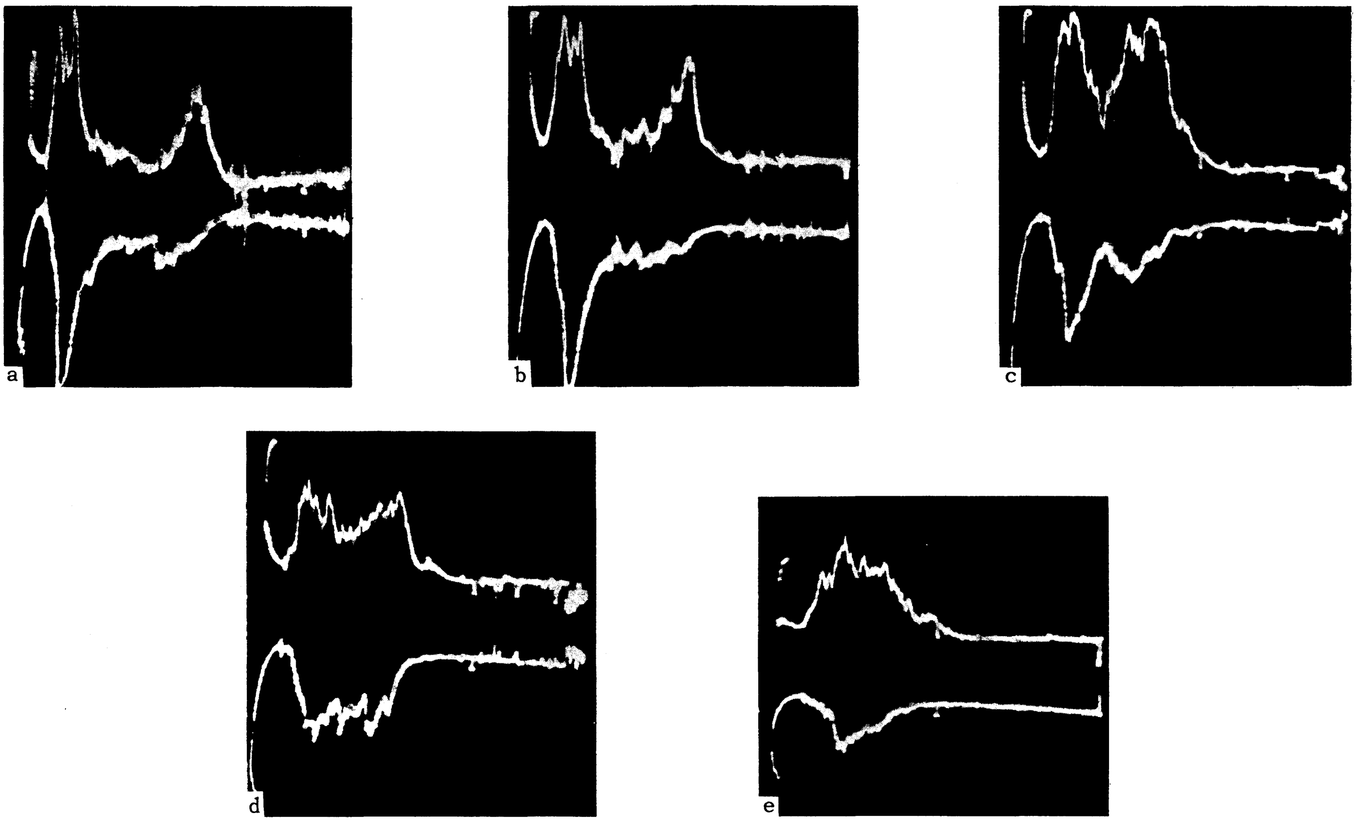

FIG. 3. Time dependence of the intensities of the OIII lines (upper trace) and OV lines (lower trace) for different values of the maximum discharge current: a – I_{max} = 120 kamp, b – 95 kamp, c – 75 kamp, d – 65 kamp, e – 50 kamp.

If we assume that the decrease in the intensity of the lines in the sequence from OII to OIV and OV is due to the transition of all the ions into a state of higher degree of excitation, then we can say that in the case of Fig. 3d we are observing by means of the line from OII the transition of the ion O^{++} into O^{+++}, while the ion O^{++++} (the line OV) does not have time to become ionized.

The oscillograms which give the dependence of the current on the voltage, and which were obtained under optimum conditions for the discharge, exhibit the well-known displacement (shift) of the current curve with respect to the voltage curve. This shift, as well as the dip in the light intensity, depends on the initial conditions of the discharge. But, the range of variation in the initial conditions within which the dip in the light intensity is preserved is considerably narrower than the range of variation in conditions within which the shift is preserved. For example, the values of the initial pressure, for which a dip in intensity is observed, lie within the range $(3.5 - 4.5) \times 10^{-3}$ mm Hg, while a shift is observed within the pressure range $(1 - 6) \times 10^{-3}$ mm Hg. Apparently, the dip in the intensity of the light is a very sensitive parameter characterizing the discharge.

3. Effect of impurities. The investigations which we have carried out on the effect of helium and argon impurities introduced into the discharge gave the following results:

1. The discharge in the presence of a 50% addition of He, and also in pure He, practically does not differ from the discharge in pure hydrogen. A dip in the light intensity is observed under optimum conditions of the discharge.

2. On the other hand, the discharge in the presence of an Ar impurity differs sharply from the "pure" discharge. Numerous sparkovers occur in the discharge chamber and as a result of this the pressure increases, and both the shift of the current with respect to the voltage mentioned earlier and the dip in the light intensity disappear.

The lines are excited only during the first half of the discharge, the time of emission of the OIII line does not exceed 200 μsec.

DISCUSSION OF RESULTS

At least two explanations are possible for the existence of the dip in the time dependence of the intensity of the lines.

As the electron temperature of the plasma increases the degree of ionization is increased and transitions occur, for example, OIII → OIV → OV → OVI etc. Naturally, in this case the lines due to all ions of lower degree of ionization will exhibit a dip in intensity.

On the other hand, owing to instabilities arising in the discharge the plasma can touch the walls and in this way become cooled. This leads to a fall in the electron temperature and, correspondingly, also to a dip in the light intensity.

The weakness of the second explanation is immediately apparent. After the appearance of the instability and the cooling of the plasma at the moment of the maximum of the discharge current it is not very probable that the plasma will have time to be heated again towards the end of the discharge. And yet towards the end of the discharge all the observed lives due to OIII, OIV, FIII, FIV, NIV, and sometimes even OV exhibits a second light intensity maximum. Moreover, experiment shows that at sufficiently low currents the dip in the intensity disappears and this, in accordance with the second explanation, ought to indicate an increase in the stability of the discharge.

But experiment shows that at such low currents the radiation from the discharge becomes unstable, the reproducibility from discharge to discharge is strongly reduced, i.e., the discharge becomes less stable.

Both these circumstances support the first assumption. Indeed, the presence of the second intensity maximum at the end of the discharge denotes that as the plasma cools and its electron temperature falls a deionization process occurs in accordance with OVI → OV → OIV → OIII etc.

The dependence of the depth of the "dip" on the value of the discharge current shows that as the current decreases the electron temperature of the plasma falls, and in agreement with this the dip in the intensity decreases and disappears completely.

Apparently, we can assume that the reason for the appearance of the dip in the light intensity is an increase in the electron temperature of the plasma at the instant when the current is maximum. If we adopt this hypothesis, then from the time dependence of the intensity of the lines due to ions of different degrees of ionization we can attempt to evaluate the time dependence of the electron temperature and its maximum value.

Unfortunately, we could not investigate the intensity of the OVI line situated in the vacuum region of the spectrum. By utilizing data obtained only from the OIII, OIV, OV lines we can evaluate the time dependence of the electron temperature at the beginning and at the end of the discharge and its lower limit at the instant when the current is maximum.

As is well known, in the case of plasma of not excessively low density the main processes leading to the ionization of atoms are collisions with electrons. The inverse process of deionization also occurs in binary collisions with electrons (the probability of a triple collision is negligibly small at an electron density of $\sim 10^{14}$ cm^{-3}) and is accompanied by radiation (photorecombination).

In the steady state, the number of both kinds of effective collisions must be the same.

If we denote by S_i the ionization cross section, and by α_i the photorecombination cross section, then the ratio of the densities of ions of degrees of ionization $i+1$ and i will be given by:

$$n_{i+1}/n_i = \langle S_i v\rangle / \langle \alpha_{i+1} v'\rangle,$$

where v and v' are respectively the velocities of the ionizing and the recombining electrons, while the brackets denote the averaging of the cross sections over the electron velocity distribution. If the velocities have a Maxwellian distribution, then the ratio n_{i+1}/n_i is a function of the electron temperature T_e.

Ions are also excited in collisions with electrons, and deexcitation occurs by radiation as a result of low particle density. In such a case the intensity of a spectral line is given by

$$I = I_0 n_i n_e \langle S^* v\rangle.$$

Here n_e is the electron density, n_i is the density of the emitting ions, $\langle S^*v\rangle$ is the excitation cross section averaged over the electron velocity distribution. The constant I_0 includes all the numerical coefficients.

We have utilized the values of the cross sections S_i and α_i averaged over the Maxwellian velocity distribution given in McWhirter's paper.[1] We have assumed the value of S^* to be equal to S_i at a potential equal to the excitation potential of the line under consideration. The last assumption will not lead to any appreciable error since we need only the relative values of the cross sections.

We have calculated the dependence of the relative intensities of the oxygen and fluorine lines on the electron temperature on the assumption that the total number of oxygen and fluorine atoms does not change in the course of the discharge. The results of the calculation using oxygen lines are shown in Fig. 4.

By utilizing the time dependence of the intensity of the OIII, OV, FIII, FIV, FV lines obtained by us we have measured the time intervals from

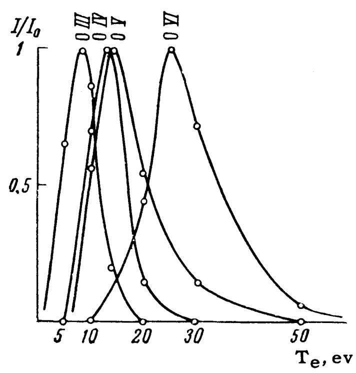

FIG. 4. Calculated dependence of the relative intensities of the OIII, OIV, OV, and OVI lines on the electron temperature of the plasma (wavelength of the OVI line is equal to 1036 A).

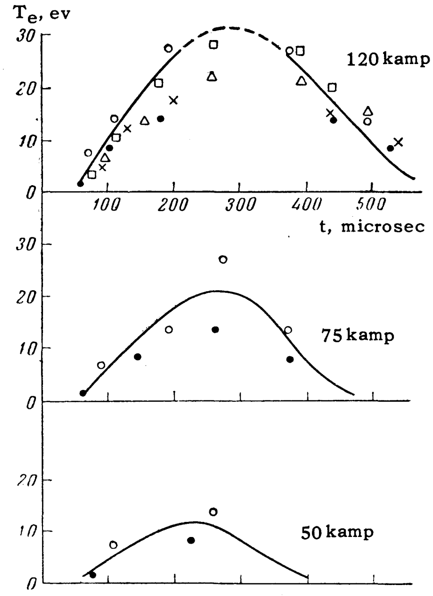

FIG. 5. Time dependence of the electron temperature for different values of the maximum discharge current determined from different lines: o – OV, ● – OIII, □ – FV, △ – FIV, × – FIII.

the instant of the beginning of the discharge to the instant when the first maximum of the lines is attained; to the instant when the intensity of these lines is equal to 20% of maximum intensity; to the instant when the same intensity is attained after the dip; and, finally, to the instant when the second maximum in the intensity is attained. The measured time intervals were averaged over three or four oscillograms. Each such point can be assigned a corresponding value of the electron temperature.

The time dependence of the electron temperature obtained in this manner for three different values of the discharge current is shown in Fig. 5. In making the transition from the variation of the line intensity with time to the variation of electron temperature we have not taken into account the change in the electron density after the lines have reached the first intensity maximm. Since by the time the current maximum is reached a simultaneous pinching of the discharge can occur, the electron density can increase by a factor of several fold during a time from 100 to 200 μsec after the beginning of the discharge. This must mean that the intensity attains not 20% of the maximum value, but an appreciably lower value, i.e., the electron temperature attains even greater values than shown in the figure.

The difference in the values of the electron temperature obtained from lines corresponding to different degrees of ionization is apparently associated with the fact that the discharge is observed over the whole cross section so that on the radiation coming from the hot central region consisting of light supplied by the "hot" OV and FV lines there is superimposed radiation coming from the colder external layers where the light is supplied by the OIII, FIV, FIII, etc lines. The existence of such stratification of the plasma has been established by Kaufman [2] using the "Sceptre" apparatus.

As is shown in Fig. 5, corresponding to the greatest value of the discharge current (I_{max} = 120 kamp) the electron temperature attains a value not less than 25 — 30 ev after a lapse of time of 200 μsec after the beginning of the discharge. During the next 100 μsec the current continues to increase, and this can lead to a further increase in the electron temperature. After the current has passed through its maximum the electron temperature probably also begins to decrease and attains the value of 25 — 30 ev again after a time interval of 370 — 400 μsec after the beginning of the discharge, while after a lapse of 500 μsec it falls to a value ~ 10 ev.

At a discharge current of 75 kamp the electron temperature attains a value of 25 — 30 ev after a lapse of 300 μsec after the beginning of the discharge, and this high value of the electron temperature is apparently preserved only during 50 μsec. At a current of 50 kamp the maximum electron temperature does not exceed 14 ev.

It should be noted that in the first two cases when the OV line exhibits a dip in intensity the value of the electron temperature determined from the decrease in intensity gives a lower limit for the electron temperature. In the last case when there is no dip in the OV line the value of 14 ev is the upper limit on the electron temperature.

The electron temperature of the plasma can be estimated by utilizing the value of the plasma conductivity σ. For $\sigma = 4 \times 10^{14}$ cgs esu we obtain $T_e \sim 10 - 15$ ev. However, this value is without any doubt too low since the conductivity has been evaluated corresponding to the whole cross section of the discharge chamber. If we take pinching into account T_e can be increased by a factor of several fold.

Very recently communications have appeared in the literature on the observation of a "dip" in the time dependence of the intensities of spectral lines in installations where "slow" processes occur. In the "Alpha" installation two maxima in the intensity of the NIV line are observed corresponding to the greatest value of the capacitor bank voltage.[4] In the case of the "Tokamak" installation only the first intensity peak is observed[5] for the CIII line, $\lambda = 4651$ A.

In these two cases, apparently, we have the same mechanism as that described earlier.

In the same way Breton and Herman[6] attempt to explain the time dependence of line intensities in the TA-2000 installation. However, judging by the figure given in their paper, the intensity of the CIII line goes through a minimum twice during one half period of the current, and at the instant when the current reaches its maximum they observe not a minimum, but a second intensity maximum, and this is followed by a third one at the end of the half period of the current. It is doubtful that such a variation of intensity can be associated with a variation of the electron temperature of the plasma, it is more likely that it is due to some kind of instabilities of the discharge.

A similar dip in light intensity was observed[3] in the "Scylla" installation, where at the instant when the current reached its maximum a peak in the intensity of the OVII line was observed and a dip in the intensity of the OVI line. The authors working with "Scylla" explain such a time dependence of the line intensity by an increase in the electron temperature of the plasma and by a transition of all the O^{5+} ions into the O^{6+} state.

CONCLUSIONS

1. Spectroscopic measurements show that the intensity of radiation from a plasma in the range 2200 – 6000 A obtained in a toroidal discharge in a weak magnetic field passes through a minimum at the instant when the discharge current passes through a maximum.

2. The electron temperature of the plasma attains a value of not less than 30 ev for a maximum discharge current of 120 kamp. Such a value of the temperature persists for approximately 100 μsec.

3. The rate of growth of the temperature and its maximum value depend on the value of the discharge current. At a current of 50 kamp the electron temperature of the plasma does not exceed 14 ev at the time of maximum current.

4. For an exact determination of the maximum electron temperature under optimum conditions of the discharge it is necessary to investigate the time dependence of the intensities of the OVI, FVI, and, if possible, of the OVII lines.

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