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*FREE PLASMA FILAMENT IN A HIGH FREQUENCY FIELD AT HIGH PRESSURE**

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The main experimental results obtained in the course of an investigation of plasma in a filamentary high frequency discharge floating in the middle of a resonator are presented. An experimental arrangement for obtaining a stable discharge is described; stabilization is obtained by rotation of the gas. The investigations are carried out primarily in an atmosphere of deuterium at a pressure of several atmospheres. For an input power up to 20 kW the length of the discharge attains a value of 10 cm. Spectrometric investigations and their theoretical interpretation lead to the conclusion that the discharge consists of an internal cylindrical region filled with hot plasma at an electron temperature of the order of 10^6 °K and of a cloud of partially ionized plasma ($T = (7-6) \times 10^3$ °K) surrounding it. It is shown that the existence of such a high temperature is possible due to a temperature discontinuity at the plasma boundary; an explanation is proposed that this discontinuity arises as a result of a double layer at the boundary. The effective heating of the filament by HF current takes place due to the anomalous skin effect.

Such an interpretation of plasma processes is experimentally confirmed by experiments on the effect on the discharge of a constant magnetic field (up to 25 kOe). A study is made of the ion temperature. The observed emission of neutrons is insufficient for the determination in terms of them of this temperature and cannot even be sufficiently reliably investigated in order to establish its thermonuclear nature. Other methods so far also do not give a reliable result for determining the ion temperature. The problem is considered as to how one could by means of magnetoacoustic oscillations and magnetic thermal insulation raise the ion temperature up to the level required for the production of a reliable thermonuclear reaction. Some preliminary experiments in this direction are described.

The investigations reported here have been carried on for over ten years by the staff of the Physics Laboratory of the Academy of Sciences of the U.S.S.R.

1. INTRODUCTION

IN the course of development of high frequency (HF) generators of high and continuous power we have constructed in 1950 a planotron [[1], p. 115], which emitted power of several kilowatts at a wavelength in the neighborhood of 10 cm. When we passed this radiation through a quartz sphere of 10 cm diameter filled with helium at a pressure of 10 cm of Hg a discharge was ignited in it which had a well defined boundary. The whole phenomenon was observed for several seconds since the walls of the quartz sphere became rapidly heated and melted at one spot. This observation led to the thought that spherical lightning is a discharge which is produced by HF radiation arising in storm clouds after ordinary lightning. Thus, a source of energy is provided which is required to support luminosity of long duration accompanying ball lightning. This hypothesis was published in 1955.[2] Several years later after we had constructed a more powerful generator of continuous radiation which we have called a "nigotron [[3,4], p. 7], we returned to the possibility of producing a free HF discharge in helium. Indeed, in March of 1958 we succeeded in obtaining in a spherical resonator, in which intense continuous oscillations of the H_{01} type occurred with a wavelength in the neighborhood of 19 cm and which was filled with helium, a freely floating gas-

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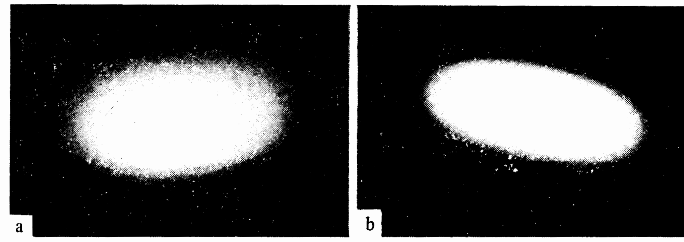

FIG. 1.1. Diffuse discharges in helium stabilized by gas circulation: a—p = 1.8 atm, P_a = 1.3 kW, b—p = 3.5 atm, P_a = 1.2 kW. Oscillations of E_{01} tye (1963).

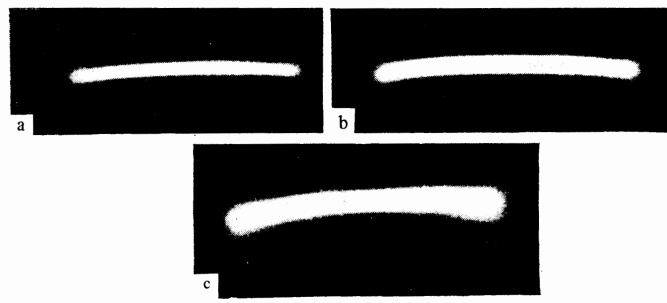

FIG. 1.2. Filamentary discharges in deuterium without stabilization by gas circulation, a—P_a = 2.9 kW; b—P_a = 4.5 kW; c—P_a = 6.4 kW, oscillations of H_{01} type (1961).

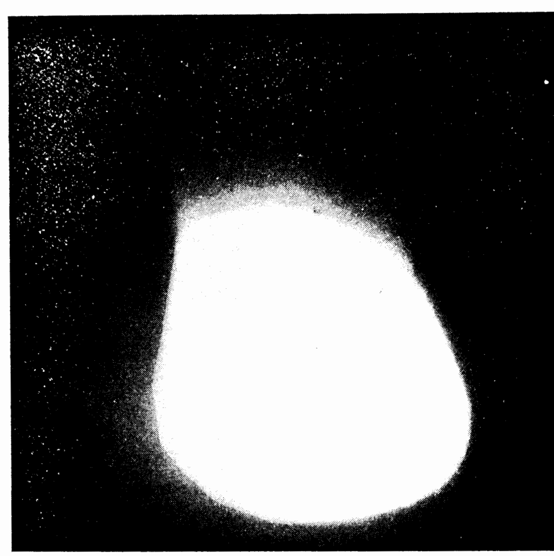

FIG. 1.3. Diffuse discharge with an admixture of acetone without stabilization by gas circulation. p = 200 mm Hg, P_a = 0.6 kW, H_{01} (1960).

eous discharge visually of oval shape. This discharge was produced in the region of a maximum of the electric field and moved slowly along a circle coincident with a line of force. Sometimes the discharge stopped along this line. Discharges of this type in helium could be observed up to a pressure of 9 atm. A further increase in pressure was limited by the strength of the resonator walls. We have also obtained such floating discharges in argon, in carbon dioxide, and in air.

It was most convenient to carry out the experiments in helium and the discharge had a good brightness, was easily "ignited" and, what is most important, no chemical reaction occurred in inert gases, while in air nitric oxide was produced in the discharge which reacted with the resonator walls. A photograph of the discharge in helium is given in Fig. 1.1. In the course of a further study of the discharge it was found that in actual fact the discharge does not always have a shape close to spherical, but can also occur in the form of a thin filament several millimeters in diameter and of length up to 4–6 cm surrounded by a luminous cloud. It turned out that the spherical shape of the luminosity of the cloud, which we observed initially, owes its origin to a large extent to impurities in the gas. But if we take purer helium, then the spherical luminosity almost disappears and one obtains a filament of ellipsoidal shape similar to the discharge in deuterium as can be seen in the photograph of Fig. 1.2. All the impurities which we tried increased the luminosity of the cloud with the exception of hydrogen and deuterium. These gases, on the contrary, aided the production of the filamentary form of the discharge. The strongest influence on the luminosity of the cloud was observed when 1–2 cm^3 of acetone was mixed in with the helium. Then the discharge assumed the shape of a sphere having a bright blinding white luminosity similar to ball lightning (photograph in Fig. 1.3). After such experiments the walls of the resonator turned out to be covered with soot. In subsequent investigations it was established that even in a pure gas there exist two forms of the discharge. At low power input the discharge was of oval shape with poorly defined boundaries, and glowed not very brightly emitting diffuse light (Fig. 1.1). Then as the power input was raised the discharge rapidly went over into the filamentary form (Fig. 1.2). This phenomenon was observed most clearly in hydrogen and in deuterium at high pressures.

As the level of the HF power was raised (it was supplied to the resonator from below through a round quartz window) the length of the discharge increased, it began to float upwards in the helium into the upper part of the resonator sphere, and here a closed ring could be formed of 8–10 cm diameter, which floated in a stable manner in the upper portion of the resonator. A photograph of such a discharge is given in Fig. 1.4. But more frequently, as is shown in Fig. 1.5, it stuck to the wall of the resonator.

From the very beginning of the investigations a high degree of stability to the filamentary discharge was observed. For example, if an intense circulation of the gas was produced, the discharge underwent fanciful convolutions but did not go out, and the filamentary nature of the discharge was not altered. A simple visual study of the spectrum of the filament already gave interesting results. First of all, it turned out that the spectral lines were narrow and not smeared out, and, secondly, an intense continuous spectrum was observed. As is well known, in a plasma the ratio of the brightness of the line spectrum to the brightness of the continuous spectrum of bremsstrahlung depends on the electron temperature T_e, and by measuring this ratio it is possible to make an estimate of this temperature. The higher is this temperature the more intense is the continuous spectrum compared to the line spectrum.[5,6]

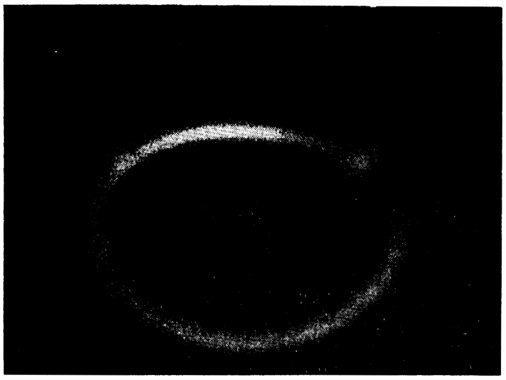

FIG. 1.4. Ring discharge in helium without stabilization by gas circulation. The reflection of the ring in the resonator wall can be seen. $p = 1$ atm, $P_a = 1.8$ kW, H_{01} (1960).

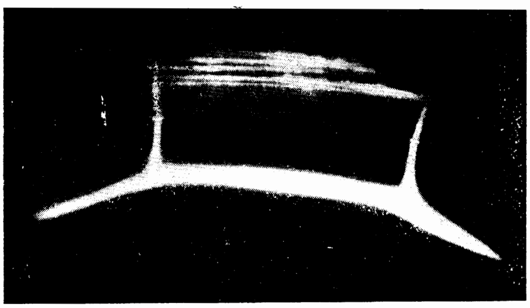

FIG. 1.5. Filamentary discharge in deuterium whose legs have stuck to the resonator wall where its reflection can be seen. $p = 1.8$ atm, H_{01} (1961).

A quantitative study of this ratio gave interesting results. At first we began to measure this ratio by examining photometrically the photographs of the spectrum, then we began to do this in a simpler and more accurate manner by projecting the spectral line on the screen of a vidicon and by measuring the brightness in terms of the spread out image on a cathode ray oscillograph. These measurements have shown that in accordance with the theoretical calculations the electron temperature in the helium could not be less than 5×10^5–3×10^5 °K. We then went on to the study of a gas which is simpler for theoretical calculations—hydrogen. Experiments on the measurement of the ratio of the intensity of the bremsstrahlung and of the lines of the Balmer series continued to show that the electron temperature must be greater than half a million degrees. The possibility of the existence of such a high temperature led us to replace hydrogen by deuterium in order to see whether neutrons might not be observed.

The method of measurement consisted of having two counters constructed of a number of tubes filled with enriched BF_3. Each of the counters was in turn placed for 20 min near the resonator containing the filamentary discharge. Both counters were mounted on a common frame in such a way that by rotating the frame one could either raise them or move them sideways by about a meter and a half. For each counter separately the difference was taken between the number of counts in the near and the far positions. Experiments showed that a difference in counts was reproducibly observed which indicated the presence of neutrons. The effect over a day of observation amounted to ~5%. This was insufficient in order to study in a reliable manner the regularities in the radiation, but the existence of the effect was established with statistical reliability. It is evident that if the neutrons were of thermonuclear origin then their number should increase very rapidly with the temperature of the ions in the plasma. It is natural to assume that the plasma temperature would increase with the power supplied. In order to increase the neutron flux we began to increase the power supplied to the filament. Experiments showed that as the power was increased the electromagnetic forces stabilizing the position of the filament in the resonator in its freely floating condition turned out to be no longer sufficient. They could not balance the force of buoyancy and the filament began to float upwards and to stick to the resonator walls. Then we replaced the spherical resonators by horizontal cylindrical ones in which the oscillations were also of the form H_{01}. With the aid of small air blowers (taken from a vacuum cleaner) a rotary motion of the gas was set up in the cylinder. Owing to the circulation that was set up the filamentary discharge ceased sticking to the resonator walls, increased in size and the power supplied could be raised up to 20 kW. Experiments showed that in the course of this the filament underwent strong convolutions and began to break up into two parts. But the intensity of neutron emission did not increase significantly. Thus, it turned out that the neutron emission is not affected by the amount of power supplied, and we concluded that the processes occurring in the plasma of the filament could be understood only by a study of the structure of the filament.

In experiments on increasing the power input great stability of the discharge itself was observed and, just as in the rotating gas, the filament underwent convolutions and coiled in a most fanciful manner, but did not break up and was not extinguished. Of course, it was not possible to study the structure of the filament in view of its chaotic motion, and, therefore, the apparatus for the production of the filamentary discharge was altered in a radical manner. In a cylindrical resonator the oscillations produced were not of the H_{01} but of the E_{01} type. This led to the fact that the stable position of the filament coincided with the axis of the resonator cylinder; in this case the stabilizing rotation of the gas did not lead to large chaotic displacements of the filament, it almost did not undergo convolutions and preserved well a shape close to that of an ellipsoid of revolution.

In order to realize such an arrangement it became necessary to develop a transformer of the oscillations of the H_{01} type generated by the nitrogen, into oscillations of E_{01} type which were fed into the resonator. Since the impedance of the filament changed as its dimensions were increased it was necessary to develop variable coupling between the transformer and the resonator in order to achieve efficiency in supplying large amounts of power to the filament. The transformer was of the spider type. The theory and the construction of such a transformer have already been described by us [[7], p. 7]. The "spiders" utilized here differed from those previously described only by the fact that they had rotatable legs and this enabled variable coupling to be achieved. The development of this whole experimental arrangement (it is described in the second part of Sec. 2) required more than two years, and after this it became possible not only to supply to the discharge a high level of power, but also to carry out more reliably and accurately measurements of the dimensions of the plasma filament (of its length $2l$ and of its diameter $2a$). A further significant improvement in our investigations was the development of an apparatus by means of which the image of the filament could be stabilized on the slit of the spectrograph, which was achieved by rotating a mirror controlled by photocells. This enabled us to make a detailed study of the emission spectrum of the filament. In this manner we succeeded to measure in a more accurate manner the width of the spectral lines in the different portions of the filament. They were narrow (not greater than 3–4 Å) and this according to the Stark effect corresponded to a plasma density of $10^{14}-10^{15}$ cm^{-3}. If we assume that the plasma is completely ionized, then at normal pressure such a density corresponds to an electron temperature of the order of 10^6 °K, and this agrees with the already described preliminary observations on the relative intensity of the continuous and the line spectra.

It is known from theory that the value of the electron density which we observe in the plasma can be explained in two ways. The first—and it would appear the more natural explanation—is that the plasma in the filament is cold, and its equilibrium temperature lies in the range from 6000 to 7000°K. This in accordance with the Saha expression gives a degree of ionization of 10^{-3} – 10^{-4}, and this corresponds to the observed electron density. Another possible explanation consists of the fact that the plasma is not and is therefore completely ionized, its temperature corresponds to its density and lies in the range from 10^6 to 10^7 °K. This explanation at first appeared to be very improbable, since it led to a number of theoretical difficulties. A further experimental study of the filamentary discharge confirmed ever more strongly the presence in the filament of hot plasma. It also turned out that the contradictions with the theory could be resolved.

As is described below in Sec. 5, by measuring the coupling between the nigotron and the discharge it is possible to determine the absolute value of the field in the resonator and, by assuming that the filament is a conducting ellipsoid, it is possible to determine the current in it. Measurements have shown that the value of the current lies in the range 20–50 A. Here a significant difficulty arises in explaining the mechanism of the skin-resistance in the usual manner. According to the measurements on the filament the power absorbed amounts to several kilowatts; then, according to the measured value of the current, the skin-resistance of the filament should be equal to a few ohms, but it turns out that this value of the resistance is considerably greater than the value which is calculated theoretically for an electron gas on the basis of Coulomb collisions.

We explained this contradiction by the fact that a so-called anomalous skin-resistance occurs in plasma. A similar mechanism for the absorption of the surface current is well known in metals at low temperatures, it is possible only at high frequencies, when the thickness of the skin-layer is considerably smaller than the electron mean free path. Applying the theory of this process to plasma we obtain a value for the skin-resistance which is in agreement with that experimentally measured. These calculations are given in Sec. 6. Thus, we arrive at the conclusion that the existence of a free filamentary discharge of the type observed by us is possible only due to the existence of the anomalous skin-resistance. Calculations have shown that in a cold plasma at the observed values of the current both for a constant current and at lower frequencies such a high absorption of power cannot take place.

Another essential difficulty in explaining the existence of a hot plasma consists in the presence at the boundary of the plasma filament of a large temperature discontinuity. It is not difficult to calculate that electrons striking the boundary with an energy corresponding to a temperature of 10^6-10^7 °K on penetrating diffusely into the surrounding gas would give rise to a thermal power flux of the order of 10^3 kW per cm^2. Therefore, in order to explain the absence of such a powerful heat transfer one must assume that elastic reflection of electrons occurs in the boundary plasma layer. The existence of such elastic reflection of electrons in nature is already well known, it occurs in gas discharge tubes and has a simple explanation. Electrons hitting the tube walls from the inside penetrate into the glass to a greater depth than ions, and as a result of this a double layer is formed on the surface the electric field of which reflects electrons from the walls without losses. We assume the existence of such a double layer at the boundary of our plasma filament. In our experiments the gas which surrounds the filament has a density three orders of magnitude higher than the plasma itself and can be regarded in comparison with it as a medium which exists as if in a different state. A description of the structure of such a layer and a quantitative study of the possibility of existence of such boundary conditions are given in Sec. 4.

A further study of the filamentary discharge confirms that the discharge consists of an interior region of hot plasma at a temperature of the order of 10^6 °K and of a relatively cold region surrounding it which we shall refer to as a "cloud." Such a structure of the filament can be seen in its photograph in Fig. 3.6 (cf., below) taken at high values of the power and of the pressure.

Experiment shows that in such powerful discharges it is not possible to make a determination of the temperature of the hot plasma in terms of the Stark broadening of the Balmer lines. It is well known that as the temperature of the hot plasma is raised the intensity of the radiation from it diminishes. The cloud of cold plasma surrounding the hot plasma inside the filament is at a constant temperature and glow equally brightly, and this makes it impossible to study spectrographically the interior less bright region of the discharge in the visible domain. It turned out to be possible to overcome this difficulty by measuring the temperature of the electrons inside the plasma in terms of its radiation in the microwave domain ($100\,\mu$). It is well known that in this part of the spectrum it is possible to determine the proper plasma frequency in terms of the threshold frequency for emission, and in terms of it the density and, since the plasma is hot, to determine its temperature.

A confirmation of the fact that the plasma is indeed hot is also given by the intensity of its radiation in the extreme ultraviolet region ($\lambda \approx 1000$ Å). Measurements show that bremsstrahlung (cf., Sec. 3) is particularly intense in this domain, and is higher by a factor of at least 10^8 than it would be if the plasma were cold.

There exists a number of other factors which establish the high temperature of the plasma. The most significant of them is the effect of a magnetic field on the shape of and on the radiation from a filamentary discharge. When the filamentary discharge was placed in a magnetic field of intensity up to 25 kOe, it remained stable but a change occurred in its structure: it became longer and the diameter of its cross section reduced to as low as 30%, while the intensity of the radiation from it increased. These experiments are described in Sec. 7. The basic theoretical concepts of plasma processes show that such phenomena can take place only in a hot plasma. There exists also another set of observations which cannot be explained by phenomena occurring in a low temperature plasma. For example, the homogeneity of the temperature, the stability of the shape of the filament, the less intense radiation from the interior region of the plasma as can be seen from the photograph of Fig. 3.6 (cf. below).

It turned out to be possible to investigate by the methods which we have employed, in a sufficiently complete manner, the electron structure of the filament and its density, and to determine the electron temperature, but until now we have not succeeded in determining experimentally with a sufficiently high degree of accuracy the temperature of the ions. In order to determine this temperature one could utilize two methods. The first, and the most reliable one, is based on the partial pressure of the ions. This partial pressure is the difference between the total gas pressure in the resonator and the partial pressure due to the electrons, which is determined in terms of the density of the electrons and their temperature. Therefore, if one knows how to determine sufficiently accurately the temperature of the electrons and their density, then it is possible to determine the ion ion temperature. Since this quantity is determined as a difference, one requires good accuracy in determining the density and the temperature of the electrons, which we have not yet attained. We expect to attain it in experiments involving increased dimensions of the filamentary discharge. Another method of determining the ion temperature is in terms of the neutron radiation. The count of neutrons carried out by us could have given us, if they were of thermonuclear origin, reliable information on the ion temperature.

In going over to resonators with oscillations of the E_{01} type and to the resultant increase in the power input to the filamentary discharge we continued our neutron count, but, as before, it did not increase significantly. We later constructed an apparatus involving a toroidal resonator in which stabilization of the filament, as before, was produced by rotation of the gas, and with its aid we obtained an increase in the power supplied to the filament. In this apparatus we had considerably lengthened the filamentary discharge and raised the power input to 40 kW. Because of the small dimensions of the toroidal apparatus it turned out to be impossible to set up a gas circulation sufficiently well ordered to produce a discharge which did not undergo great convolutions. We give a summary of the results for the toroidal resonator. During the whole time of counting of 500 hours they were as follows: the first counter recorded 143 698 pulses, the excess in the close position was 4380; in the case of the second counter there were 160 442 pulses with an excess of 4842. Thus, the excess in the number of counts lies outside the limits of statistical error, but we were unable to correlate it with the processes in the filament. Not a single change in the conditions for the existence of the discharge affected the difference in the counts in a sufficiently noticeable manner. If the observed emission of neutrons were of thermonuclear origin, then calculations have shown that it would have corresponded to a temperature from 6×10^5 to $8 \times 10^5\,^\circ$K. This temperature is not higher than the electron temperature and is therefore quite possible. But, based on the scale of the phenomenon and on the impossibility of relating it quantitatively to conditions under which the discharge occurs, it is not yet possible to regard that the thermonuclear origin of this emission has been proven, and one should for the time being regard its nature as not having been established. We have so far been able to determine the lower possible limit for the ion temperature only by means of theoretical calculations (cf., Sec. 4). It is estimated as $10^5\,^\circ$K.

At the present stage in our investigations we assume that the plasma obtained by us is hot and that the electron temperature in it is of the order of a million degrees, while the temperature of the ions is probably considerably lower. It is natural to pose the question of the possibility of raising the ion temperature in a filamentary discharge to a level required for the reliable realization of a controlled thermonuclear reaction.

It is well known that the principal difficulty in obtaining a high temperature in a plasma is the heat loss the main part of which is due to electrons since their mass is small and they have a greater mobility than the ions. In a plasma under the conditions of our filamentary discharge the heat loss due to electrons is small because of the existence of a double layer, and, therefore, one of the principal difficulties of obtaining a high temperature plasma disappears. Two other difficulties remain: overcoming the heat losses from the ions and the supply to them of the energy required in order to raise their temperature. Apparently both these difficulties can be resolved by placing the filament in a longitudinal magnetic field. From theoretical investigations it is well known that for a sufficiently intense field when the radii of the cyclotron orbits of the ions are less than the radius of the filament and when the time between collisions of the ions is great the heat losses in the plasma can become so small that the ion temperature can attain high values.

Energy can be supplied to the ions in two ways: either by means of a collective interaction with the electrons, or by the generation of magnetoacoustic oscillations. These oscillations arise in a plasma in the presence of a magnetic field when a high frequency component is superimposed on it. Both these processes have received little study theoretically and experimentally. The theory of magnetoacoustic oscillations and the experiments that have already been carried out are described in Sec. 8

and give us a basis for assuming that it is possible to achieve in the hot plasma of the filamentary discharge conditions for obtaining ions of a temperature required for the production of a thermonuclear reaction, but for this it is necessary to increase in a significant manner the dimensions of the filamentary discharge. A priori it may be seen that since the heat losses are proportional to the surface of the filament while the power supplied by magnetoacoustic oscillations is absorbed in a volume, then as the dimensions are increased the ion temperature will be increased. In this case it is necessary to adjust the intensity of the magnetic field to the dimensions of the filament since for a given magnetic field the ion orbits attain a value which is close to the cross section of the filament and the input of energy by acoustic waves will not produce any further increase in the temperature. In determining the magnetic field this limiting ion temperature is proportional to the square of the diameter of the filament. In order to obtain a reliably measured thermonuclear effect the ion temperature should be greater than $10^6\,{}^\circ$K. In order to obtain this temperature it is necessary to increase the linear dimensions of our apparatus by a factor of 3–4. The possibility of utilizing a plasma filament for the realization of a thermonuclear reactor will be investigated in another paper.

The aim of our further investigations is to increase the dimensions of the apparatus in order to raise the ion temperature to that required for the production of thermonuclear neutrons and thus to carry out a further check of the correctness of the interpretation adopted by us for the phenomena observed in a filamentary discharge.

Until now in our investigations we have not increased the dimensions of the apparatus since the main difficulty was development of the apparatus itself for obtaining a stable easily observable filamentary discharge and development of methods for measuring its parameters. Such development consisted of finding the correct construction of resonators, an efficient supply of HF power, etc.

Work of such an exploratory nature is associated with construction of a large number of experimental arrangements and with their modification. In a small research institute such as ours work of this nature proceeds faster if it is carried out on a small scale. Now, when the methods of observation have been found and the construction of the resonators in which the discharge takes place has been developed, one can undertake experiments on a larger scale with a sufficient degree of reliability.

The investigations described here have been carried out over several years and a group of scientific workers, constructors and mechanics has participated in them.

A number of investigations the results of which we shall mention here only briefly will be published in the near future with a more detailed description of the experimental methods in the form of separate papers by individual members of our group.

The creation of all the apparatus and the experimentation was carried out together with S. I. Filimonov; the optical investigations were carried out together with É. A. Narusbek, assisted by Yu. F. Igonin; investigations in the microwave domain were carried out together with É. A. Tishchenko, and also with the creative aid of a number of comrades; the work involving counters was carried out by D. B. Diatroptov, the investigation of oscillations by L. A. Prozorova. V. I. Chekin, N. I. Kondrat'ev, A. G. Nedelyaev, N. I. Milyukov and A. V. Lebedev participated in carrying out the experiments. Constructors A. I. Degal'tsev, Yu. E. Saprykin, V. I. Tsvetkov and A. D. Nikulin participated in the construction of experimental apparatus. A. N. Vetchinkin and K. A. Zhdanov participated in constructing electronic apparatus. All the apparatus was made in the machine shop of the Institute. Master mechanics V. V. Aref'ev, A. M. Goncharov, V. V. Khristyuk and S. A. Smirnov participated creatively.

I am grateful for aid in theoretical developments to Comrades L. P. Pitaevskiĭ, L. A. Vaĭnshteĭn, and in the initial stages to A. A. Abrikosov and L. P. Gor'kov. A number of calculations and estimates were carried out by B. É. Meĭerovich and G. P. Prudkovskiĭ.

2. EXPERIMENTAL SETUP

The most laborious part of the investigations of the properties of a freely floating plasma filament was the design and construction of the apparatus itself for obtaining a stable filamentary discharge of large size. For this a high level of HF power was required. Therefore, the first problem was the construction of a continuous HF generator. We developed such a generator of the magnetron type to which we have given the name of nigotron. The theory and the design of this type of generator have been described by us in detail [[3, 4], p. 7]. The nigotron which we are now using to obtain a plasma filament has a continuous power reaching 175 kW. It generates oscillations of H_{01} type at frequencies corresponding to a wavelength of 19.3 cm.

As we have already indicated in the Introduction, we began our investigations with a study of discharges in resonators in which oscillations of the H_{01} type were excited. These resonators were either spherical or cylindrical; in them the filamentary discharge at high power "floated" in a sufficiently stable manner and not very fast along a circle in that region of the electric field where it had its maximum value. As the power input was increased the dimensions of the filamentary discharge increased until it lost its stable position in the resonator. In this case the filament simply floated upward and assumed the shape of an arc which stuck to the wall and at the point of contact heated the surface until it melted. A photograph of such a filament stuck to the wall is given in Fig. 1.5. In order to ensure stability of the position of the filament we utilized circular circulation of the gas since under these conditions the lighter heated gas in the filament had a tendency to position itself along the axis of rotation. In order to realize effectively such systems of stabilization we had to go over to resonators in which oscillations of the E_{01} type were excited. In order to achieve this we developed a wave transformer of the spider type. The theory and the calculations for such transformers have been described in [7]. A further increase in the power of the filamentary discharge was made difficult by the nature of the load of the filamentary discharge, since the power absorbed in it was proportional to the intensity of the electric field E, and this does not correspond to the most advantageous load characteristic for a nigotron. If the nigotrom is used over a wide range of power, then the power absorbed must be proportional to E^2. Therefore, we had to develop an apparatus which enabled us to establish variable coupling between the generator and the resonator. This was realized by the same spider transformer which was so constructed that the legs of the "spider" could be simultaneously rotated. In this case the greater was the angle between the directions of the legs and the radius, the greater became the coupling.

A study of the plasma structure of the discharge showed that a study of the effect on the discharge of a constant magnetic field was of considerable interest. With this aim in mind we constructed a solenoid with a diameter of the opening sufficiently large to accommodate a resonator which had an inner diameter of 20 cm. A description of and the construction of such a solenoid but of somewhat smaller dimensions are given in [8]. With a power input of 500 kW we could obtain in it fields up to 25 kOe.

We shall give a detailed description of our apparatus in a number of subsequent papers together with a description of the experimental investigations. Here we shall restrict ourselves to giving only the schematic diagram of the apparatus which is shown in Fig. 2.1.

The power input at a voltage of 18 kV is delivered to the nigotron 1. It is situated in the solenoid 2 which produces a homogeneous field required for the generation of HF oscillations. In the resonator 3 in which the nigotron is situated oscillations of H_{01} type are produced with a wavelength $\lambda = 19.3$ cm. These oscillations are transformed by the spider 4 into ones of E_{01} type and they enter the wave guide 5 which cuts off oscillations of the H_{01} type. In the load-resonator 6 in which the plasma discharge 7 is formed a number of standing waves of wavelength Λ is produced. The coupling between the resonator 6 and the feeder waveguide is realized through the window 8 made of two concave discs of optical quartz. One of them is sealed into the wave guide 5 in such a manner as to guarantee a vacuum in it. The second quartz disc closes the entrance aperture into the resonator 6. Such an arrangement of two discs is associated with the necessity of cooling them by a stream of gas; otherwise they can become strongly

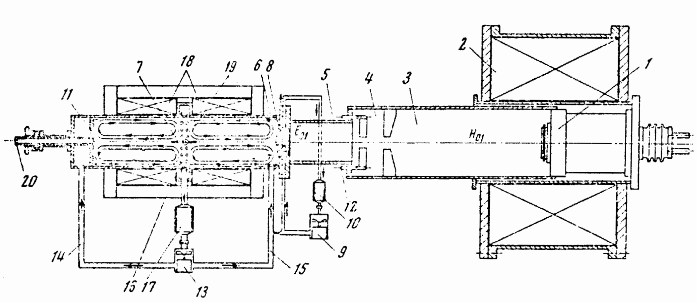

FIG. 2.1. Schematic diagram of the apparatus for the study of a filamentary discharge. 1—nigotron, 2—solenoid, 3—resonator, 4—spider transformer, 5—waveguide, 6—load resonator, 7—filamentary discharge, 8, 19, 20—windows, 9, 13—centrifugal air blowers, 10, 17—heat exchanger, 11—piston, 12—legs of the "spider," 14, 15—tubes, 16—a number of apertures for the passage of gas, 18—solenoid.

heated both from the high frequency of the field, and also from contact with the hot gas circulating within the load. Circulation of the gas for cooling the quartz window is brought about by a centrifugal air blower 9 into which gas is admitted that had been previously cooled in the heat exchanger 10.

The load resonator 6 is tuned to the frequency generated by the nigotron by moving the piston 11. A reliable contact between the piston and the walls of the resonator is guaranteed by a device which we have developed and to which we have given the name of a hydroseal. This is a thin walled copper tube which is placed in a somewhat collapsed state into a channel machined in the piston. The tube is filled with oil. When subsequently additional oil is pumped into it pressure is generated, the tube straightens out and presses tightly against the walls of the resonator; in this way a good contact is formed between them.

The magnitude of the coupling between the resonator and the generator is determined by the identical rotation of the legs 12 of the "spider" transformer. Special channels are provided in the walls of the resonator, the piston and the waveguide; in them for cooling purposes, there is continuous circulation of distilled water which, in turn, is cooled in a heat exchanger by tap water. By measuring the consumption and the temperature changes of the circulating water we determine that part of the power which goes from the discharge to the walls of the resonator. Another part of the HF power input is absorbed in the heat exchanger 17 which cools the gas circulating in the resonator. As we have already pointed out, circulation of the gas in the resonator serves by means of rotary motion to stabilize the position of the filament. The gas is set in rotation in the following manner: by means of the air blower 13 the gas is directed along the two tubes 14 and 15 into both ends of the resonator 6. At the ends of the cylinder along its circumference there is situated a number of inclined nozzles, and, therefore, the gas entering through them acquires a rotational motion. Near the central section of the resonator a number of openings 16 is situated through which the gas leaves the resonator and then returns back to the air blower through the heat exchanger 17. Naturally, in streaming through the resonator the gas in addition to the rotational motion around the longitudinal axis also acquires a certain vortex motion with a radial component as is shown in Fig. 2.1 by thin lines with arrows. In practice it has turned out that a more stable position of the filamentary discharge is achieved when the circulation of the gas in these vortices in the region where the filament is situated has a direction from the periphery towards the center as is shown in the diagram. At first we utilized in our apparatus air blowers from ordinary vacuum cleaners, but later it turned out that the carbon brushes of the motors introduce undesirable carbon dust which on penetrating into the discharge burns up and contaminates the gas in the resonator. For example, if the gas is hydrogen then methane is formed. We now use air blowers of a special type with alternating current motors which have no brushes. In Fig. 2.1 we have also shown the outline of the solenoid mentioned by us.

Observation of the spectrum and of the shape of the discharge was made through a number of windows 19 made in the wall of the resonator 6. These windows have a diameter of 2–2.5 cm and are usually made of optical quartz discs of 5 mm thickness. Several such windows are situated in the central cross section of the resonator. For longitudinal observation of the discharge window 20 has been provided. In order to be able to look through this window the rod for moving the piston is made hollow. If necessary an endoscope can be inserted in it.

The configuration of the HF field in the resonator is shown below in Fig. 5.1. The axial component E_z of the electric field along the axis varies sinusoidally. The maxima of the field are separated from one another by distances of the waveguide half-wavelengths $\Lambda/2$ (cf., Sec. 5). If the load resonator is tuned by moving the piston 11, then for a sufficiently intense generation in the nigotron a breakdown occurs in the gas and at one of these maxima of the field a filamentary discharge lights up. In order to guarantee that the discharge would occur at the center of the resonator opposite the windows we constructed a special device which we have called a lighter. It consists of a thin quartz rod at the end of which a thin tungsten wire of length 2–2.5 cm is attached to form a T. With relatively small oscillations, but close to resonance, the quartz rod of the lighter is introduced through one of the windows 19 in such a way that the tungsten wire is at the center of the resonator and is situated perpendicular to the electric field. Then the rod is rapidly turned through 90° in such a way that the wire becomes parallel to the field, and then oscillations appear in it. If the HF field is sufficiently intense, then corona discharge appears at its ends and the filament lights up. After this the rod is again rapidly rotated into its initial position and is taken away. Such precautions are necessary so as not to melt the tungsten wire. The lighter is moved inside the sealed enclosure by means of a permanent magnet.

The resonator, the whole gas conducting system attached to it and the heat exchangers were so constructed that the gas pressure could be raised up to 5 atm. Experiment shows that at this pressure the filamentary discharge can exist freely and so far no indications have been observed that a further increase in pressure could limit the existence of filamentary discharges. We have carried out our investigations usually with deuterium since it has the advantage over hydrogen that it has a lower heat conductivity and, therefore, the discharge requires less power. Experiment shows that bcth in hydrogen and in deuterium the filamentary type of discharge arises more easily and shows greater stability than in other gases. In Sec. 9 a brief description is given of experiments on obtaining discharges in gas mixtures. It was found that a small admixture of hydrogen to a number of gases facilitates the existence of a filamentary discharge. The gas which fills the resonator is purified. If it is deuterium, hydrogen, or helium, this purification is carried out by means of passing it through a trap of activated charcoal cooled by liquid nitrogen. When in the case of some spectrographic investigations it was required to have in the resonator exceptionally pure deuterium and hydrogen, the gas filling the apparatus was subjected to continuous circulation through a cooled trap. This device is not shown in Fig. 2.1. In the apparatus described above a filamentary discharge could "burn" for a long time continuously and the experiments could last for hours.

We have adopted the power P_a absorbed in the discharge as the principal characteristic of a filamentary discharge. This power was measured by the heating of the water which served to cool the resonator 6 and the circulating gas in the heat exchangers 10 and 17. The quantity of the circulating water was measured by consumption meters, and the temperature change was measured by thermocouples. After each measurement a check was made of the consistency in the balance between the supplied and the measured power; usually this was realized within limits of 5%. The power P_a was determined with approximately the same accuracy. We determined the structure and the temperature of the discharge by observing the radiation from it. The methods of measurement and the results obtained will be described below.

In order to carry out these investigations successfully it was necessary that the discharge should be stationary as far as possible. For a number of investigations the circular circulation of the gas could not guarantee the required lack of mobility in the position of the discharge. Therefore we have developed a special device which could stabilize the image of the filament. A detailed description of this stabilizer will be given in the course of describing our optical experiments, while here we shall give only the principle according to which it operates. Schematically the stabilizer is shown in Fig. 2.2. The optical system of the stabilizer consists of two lenses and two mirrors. A ray from the filamentary discharge 1 passes through the lens 2, then undergoes two reflections from mirrors 3 and 4 set at an angle of 45° to the direction of the ray and gives an image of the filament 8 on the slit of the spectrograph. One of the mirrors 4 can be rotated about a horizontal axis. The purpose of this device consists of ensuring the automatic rotation of this mirror in such a manner that as the filament moves within the resonator its im-

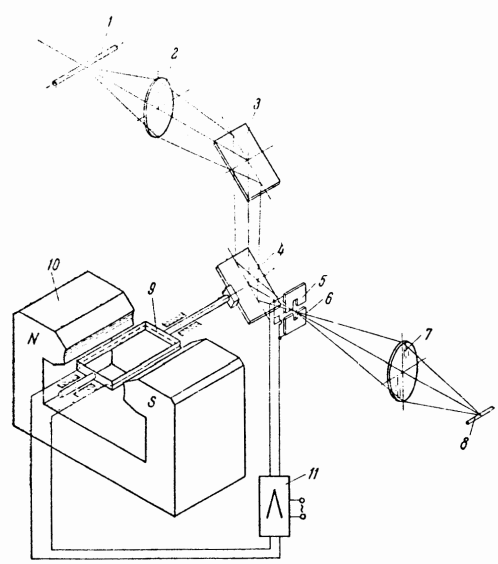

FIG. 2.2. Schematic diagram showing the principle of the stabilizer of the image of the discharge on the slit of the spectrograph. 1—discharge, 2, 7—lenses, 3, 4—mirrors, 5, 6—photoresistors, 8—image of the filament, 9—frame, 10—magnet, 11—control unit.

age should remain motionless both on the aperture between the photoresistors 5 and 6, and on the spectrograph slit. It is evident that as the image moves in the plane of the photoresistors one of them will be illuminated more strongly. As can be seen from the circuit shown in Fig. 2.2 usual for this kind of devices, this will result in a current appearing in the winding of the frame 9 situated on the axis of the mirror 4. Since the frame is situated in the field of the magnet 10 it begins to turn together with the mirror in such a direction that the image of the filament returns to a position symmetric with respect to the photoresistors 5 and 6. If the image of the filament moves over to the other photoresistor then, evidently, a reverse motion of the frame will occur and, as a result, the image of the filament will tend to remain motionless on the spectrograph slit. By means of such a stabilizer it is possible to hold the filament sufficiently motionless on the spectrograph slit that the filament diameter of 2–2.5 mm can be measured with an accuracy of 5–10%. The spectrograph used for our investigations was ISP-51 with a camera UF-90; at a wavelength of 4861 Å it had a linear dispersion of approximately 4 Å/mm.

The collimator slit can be slowly moved vertically and horizontally in the plane of the image of the spectrum by means of a micrometer. Its motion is transmitted by means of potentiometer to a two-coordinate recorder and causes the motion of the recorder pen along the abscissa. The vertical deflection of the recorder was determined by the intensity of the light passing through the slit and falling on the cathode of a photomultiplier. The horizontal motion of the vertical collimator slit determined the distribution of intensity of the spectral lines. The slit could be replaced by a small aperture. Then one could measure the profile of the spectral line at different sections of the filament. The collimator could also be provided with a horizontal slit which had a vertical motion; in this manner one could measure the distribution of intensity of monochromatic radiation across the filament. A sample of such a record is given in Fig. 2.3. Both curves represent the intensity of emission of the D_β line for a filamentary discharge of power $P_a \sim 8$–8.7 kW in deuterium at a pressure of p = 1.4 atm. Curve 1 was obtained for a magnetic field of 1.6 kOe, curve 2 for a field of 21.7 kOe. We determine the width of the filament from such a curve by the half-height denoted by 2a and adopted as the external diameter of the filament. If the filament is regarded as a cylinder of homogeneous intensity then the true diameter $2a_0$ would be equal to

$$2a_0 = \sqrt{2}\cdot 2a. \tag{2.1}$$

The dependence of the measured diameter along the middle of the filament on the power P_a is shown by the curves of Fig. 2.4. The measurements were carried out at different pressures p. As can be seen, it has a relatively small effect on the value of the diameter of the filament. The accuracy of these measurements is to a large extent determined by the degree of perfection of the operation of the stabilizer.

The length of the filamentary discharge was determined by different methods: either the filament was simply photographed, or it was projected through pinhole apertures onto the screen of a vidicon and was reproduced on the screen of a television set where its length was measured. The latter method has the advantage that it enables one to trace the oscillations in the position of the filament which are due to the fluctuations of the circulating gas, and this gives us the possibility of observing and choosing such a gas circulation that the filament in the resonator should be in its most quite state. The dependence of the length of the filament on the pressure and on the power input is given in Fig. 2.5. As can be seen, the length of the filament reaches a limiting value as the power is increased, while the pressure has little effect on the length of the filament.

The most difficult problem was to ensure the axial stability of the filament, in particular when it attained

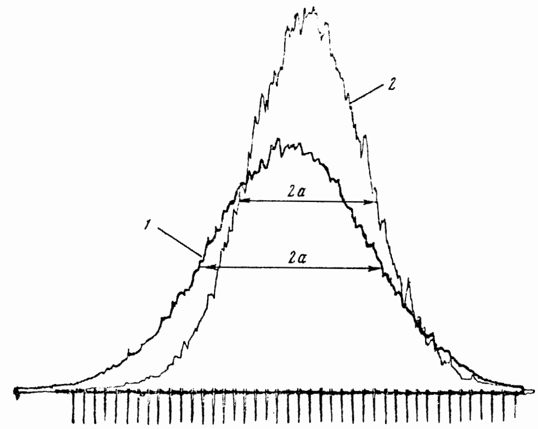

FIG. 2.3. A sample record of the intensity of emission of the D_β line for a filamentary discharge across a diameter. Deuterium, p = 1.4 atm. Curve 1—P_a = 8.0 kW, H = 1.6 kOe; curve 2—P_a = 8.7 kW, H = 21.7 kOe.

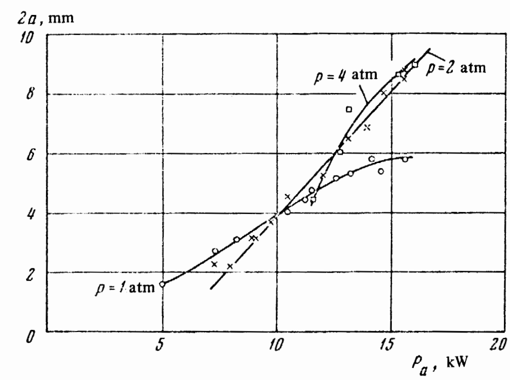

FIG. 2.4. Curves of the dependence of the diameter of a filamentary discharge in deuterium on the power input.

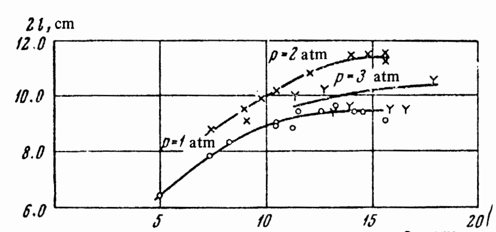

FIG. 2.5. Variation in the length of a filamentary discharge in deuterium as a function of the power input.

limiting dimensions close to half a wavelength. From Earnshaw's theorem it is well known that the electric forces acting on a dipole cannot hold it in a state of stable equilibrium. This theorem has been proven for static fields, but if the length of the filament is small compared to a wavelength then it is applicable to its position of equilibrium in the resonator. It can be easily seen that in our case for oscillations of E_{01} type the filament will not be stable with respect to radial motion, but will have stability in the axial direction tending to become situated in the region of maximum electric field. Therefore, in order to guarantee radial stability in our case it was necessary to introduce stabilization by means of rotation of the gas. As has been noted already, the rotational motion of the gas is also needed in order to prevent the floating of the filament upwards which occurs due to the fact that the heated gas in the filament is of lower density than the gas surrounding it. If one produces a rotational motion of the gas with an angular velocity Ω_g, then in the case of an inhomogeneity in its density centripetal forces appear in the radial direction which per unit volume of the gas are equal to

$$dF_{\Omega g} = -\Omega_g^2 r \frac{\partial \rho}{\partial r} dr, \tag{2.2}$$

where ρ is the gas density.

Since the plasma in the filament has a higher temperature and a lower density than the surrounding gas, then under the influence of the force F_{Ω_g} the gas will move towards the axis of the cylinder. Owing to radial electric forces, the filament itself will be attracted towards the walls and will move somewhat in that direction radially, but, on the other hand, owing to the rotation of the gas, it will be returned towards the center by the stream of gas "blowing" on the filament in such a direction as to return the discharge to the center of the cylinder. Such will be the mechanism of radial stability of the filament created by the rotary motion of the gas surrounding it. The buoyant force arising in this case will be equal to:

$$dF_g = \sigma \frac{\partial \rho}{\partial r} dr, \tag{2.3}$$

where g is the acceleration of gravity.

In order not to have the filament floating upwards it is necessary that this force should be balanced by the centripetal force. Equating the last two expressions we obtain the following:

$$r = g / \Omega_g^2. \tag{2.4}$$

This expression gives the value of the displacement of the filament due to the force of gravity. The displacement occurs in the horizontal direction and the stability of the position of the filament arises due to the "blowing" on it from above downwards. Experiment shows that there is no difficulty in creating a rotation of the gas which would guarantee the radial stability of the filament.

The experimentally observed stable position of the filament along the axis of the resonator can be explained only to a certain extent by the stable position of a dipole in the electric field, since in our case the forces acting on a dipole will hold it in those regions of the actual field where it has its maximum value. If the power input to the filament is increased its length and diameter grow. When the length of the filament begins to approach half a wavelength then the magnetic field will also begin to influence the stability of its position as well as the electric field. When the electric field reaches a value for which the length of the filament is close to half a wavelength of the oscillation (in our case this is approximately 10 cm) resonance occurs and the energy of the magnetic field surrounding the filament becomes equal to the electrical energy. Then the value of the current in the filament will be determined only by its active impedance. In this case the angle between the phase of the oscillation of the electric and the magnetic field surrounding the discharge and the phase of its own field will change to 90° and the force of interaction between the filament and the field in the resonator will be absent. But if the filament could continue to increase in length and to pass through resonance, then the forces of interaction would change sign and the position of the filament would lose its longitudinal stability and would acquire radial stability.

A gradual development and improvement of the system of gas circulation enabled us recently to raise considerably the power input to the filament, to practically double it and to increase the length of the filament to 10 cm, which corresponds to a dipole with oscillations equal to half a high frequency wavelength. Experiment has shown that on reaching this length the filament ceases to increase in length as the power input is increased. Its diameter continues to grow but up to a definite limit after which the filament begins to break up into two parts. Under these conditions it is observed that its longitudinal stability becomes less, and it more easily jumps over along the axis of the resonator from one maximum to another, but still there was enough stability that the filament could remain for a long time at the middle cross section of the resonator. The retention of the stability of the filament in the resonator cannot be ascribed due to the electromagnetic forces. It also cannot be explained by the vortices formed in the circulation of the gas, since in Fig. 2.1 it can be seen that the axial flow of gas produced by the vortex is directed from the middle of the filament towards the ends of the resonator, and could much more easily give rise to instability in its position. We consider the following explanation to be the most natural one: the place at which the energy is supplied to the filament is situated in that region of the filament where the greatest current flows, and this region coincides with the one where the electric field has a maximum along the resonator axis. If the filament moves along the axis then one of its ends moves into a region of low electric field and therefore less heat is supplied to it and it behaves as if it were being extinguished. The other end of the filament arrives at a region of strong fields and, conversely, grows. In this manner the filament is retained within the regions of maximum electric field.

Supporting the validity of this mechanism is the fact that in those resonators where the waveguide wavelength Λ is much greater than the free wavelength λ and, therefore, a high degree of homogeneity of the field is produced along the filament, the longitudinal stability of the filament decreases. Experiment confirms that it is not possible to obtain stable long filamentary discharges when the diameter of the resonator is small. Conversely, by increasing the diameter of the resonator and decreasing the waveguide wavelength Λ, we achieved greater longitudinal stability of the discharge and thus obtained a filament with a diameter of its cross section much greater than at the beginning of these experiments.

3. SPECTRAL INVESTIGATIONS OF THE PLASMA IN THE FILAMENT

The principal problem in the study of the plasma in the filament is the determination of the electron density N_e, the ion density N_i and the neutral atom density N_0, and also of their temperatures T_e, T_i, T_0. In view of the fact that in our case the plasma is not an equilibrium one these temperatures can be different. Since our plasma is neutral and of high density we have the equality

$$N_e = N_i. \tag{3.1}$$

For such a plasma the usual relationship exists between the temperature, density and pressure. If the partial pressure of the electrons p_e, of the ions p_i and of the neutral atoms p_0 is expressed in atmospheres, then we have

$$p_e = 1.35\cdot 10^{-22}\, N_e T_e \text{ atm},\quad p_i = 1.35\cdot 10^{-22}\, N_i T_i \text{ atm},$$

$$p_0 = 1.35\cdot 10^{-22}\, N_0 T_0 \text{ atm},\qquad p = p_e + p_i + p_0, \tag{3.2}$$

where p is the gas pressure in the resonator.[1)] When the plasma is hot, i.e., when it is fully ionized, we have

$$T_e + T_i = 7.4\cdot 10^{21}\, p/N_e,\qquad N_0 = 0. \tag{3.3}$$

If the temperature of the ions T_i is much lower than the electron temperature T_e, then expression (3.3) assumes the form

$$T_e = 7.4\cdot 10^{21}\, p/N_e,\quad T_e \gg T_i. \tag{3.4}$$

The first fundamental problem of spectral investigations is to determine the value of the electron density N_e. In the visible part of the spectrum this is accomplished most simply by means of the Stark effect by measuring the broadening of the spectral line. In the emission spectrum of the filament we selected for this purpose the hydrogen line H_β and the deuterium line D_β. If we determine the broadening $\Delta\lambda$ and separate out that part $\Delta\lambda_S$ which is due to the Stark effect [[6], p. 225], then we have

$$N_e = 3.5\cdot 10^{14}\Delta\lambda_S^{3/2}, \tag{3.5}$$

where $\Delta\lambda_S$ is expressed in Å.

As has been already described in the preceding section the determination of the broadening of spectral lines is carried out by means of an automatic recorder which records the intensity of emission as a function of the wavelength. A sample of such a record of the D_β line is given in Fig. 3.1. For comparison we have also recorded there the H_β lines from a gasotron. On the curves of Fig. 3.2 we have given the broadenings $\Delta\lambda$ for D_β taken at different gas pressures as a function of the power input to the filament. From these curves it can be seen that the value of the broadening $\Delta\lambda$ is not great and does not exceed 4 Å. The observed broadening is somewhat greater than the Stark broadening, since a part of it should be ascribed to the apparatus effect, which for our spectrograph was estimated to be equal to $\Delta\lambda_p \approx 0.3$–$0.4$ Å. Further, line broadening can occur due to the Doppler effect [[6], p. 221], which for the D_β lines is equal at half height to

$$\Delta\lambda_D = 2.5\cdot 10^{-3}\sqrt{T_0}. \tag{3.6}$$

The temperature of the deuterium plasma in the filament cannot be less than 7000–6000° since according to this expression the Doppler broadening will always be greater than 0.2 Å. Therefore, in order to obtain Stark broadening we must subtract from the observed broadening $\Delta\lambda$ the quantity $\Delta\lambda_p + \Delta\lambda_D$, which is equal to 0.5–0.6 Å.

As long as the power input to the filament in our experiments did not exceed 9–10 kW the observed Stark broadening was not less than 2 Å, which according to (3.5) corresponds to an electron density of $N_e \approx 10^{15}$. Then, considering that the plasma is hot, the electron temperature is estimated by us in accordance with ex-

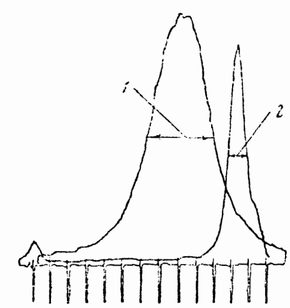

FIG. 3.1. A sample record of the D_β line in deuterium (curve 1); $\Delta\lambda_\beta$ = 1.53 Å, P_a = 12 kW, p = 1.6 atm. Also reproduced is the record of the H_β line of the hydrogen gasotron (curve 2); $\Delta\lambda_\beta$ = 0.4 Å.

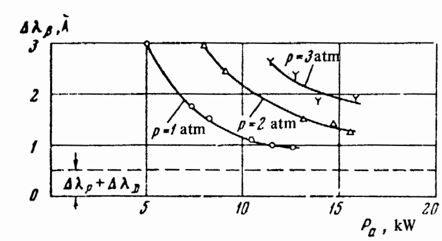

FIG. 3.2. The width of the D_β line as a function of the power input to the discharge in deuterium.

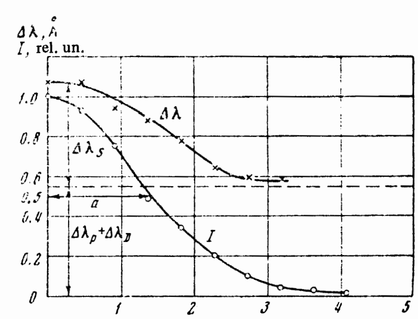

FIG. 3.3. Distribution of the Intensity I and of the width $\Delta\lambda$ of the D_β line as a function of the radius of a discharge in deuterium. P_a = 6.5 kW, p = 1 atm.

1)Everywhere, unless stated otherwise, the temperature is expressed in degrees Kelvin, and the pressure in absolute atmospheres.

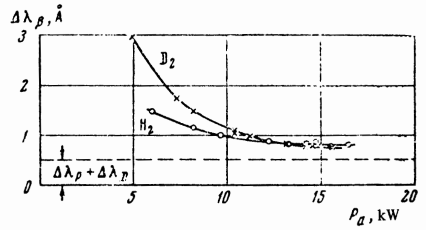

FIG. 3.4. Widths of the D_β and H_β lines as a function of the power input to the discharge.

pressions (3.4) and (3.5) to be in the neighborhood of 10^7 °K. In doing so it is assumed that the high frequency current flows at a small depth along the exterior surface of the filament and, consequently, the temperature over the whole cross section of the filament will be the same and the intensity of emission over the whole volume of the plasma must also be the same.

If this is so, then the curves recorded by the automatic recorder of the distribution of intensity across the diameter must coincide with half of an ellipse. In Fig. 2.3 we have already given a sample of the record of the distribution of intensity of emission across a diameter of the filament for the D_β line. In Fig. 3.3 we have also given the distribution of the total intensity for the line D_β, measured across a diameter of the filament. From these two curves it can be seen that the distribution of intensity along the diameter differs from an ellipse. We ascribe this discrepancy as being due to insufficient stabilization of the image of the filament on the spectrograph slit. In the initial stages of our investigations we considered this agreement to be sufficiently good.

The insufficiency of such a method for the determination of electron temperature became apparent when, as we have already stated, during the last half a year we have succeeded in considerably increasing the power input to the filament having raised it up to 15–17 kW. The high power domain both in the case of deuterium and in the case of hydrogen has been studied by us more closely. The results are shown in Fig. 3.4. As can be seen from the curves, the broadening of the H_β and D_β lines diminishes to 0.8 Å. This left for the Stark broadening only 0.2–0.3 Å, and this corresponds to an electron density of $N_e = 3\times10^{13}$ and to an electron temperature $T_e = 3\times10^8$ °K. It can be easily understood that such values are not real since, as simple calculations show, such a plasma could not be realized by a high frequency current in view of the fact that at such a low electron density the corresponding skin-resistance would make it impossible to feed in large amounts of power.

In order to resolve this contradiction two possible explanations were proposed. The first is that this is a cold equilibrium plasma with a low degree of ionization. In order to have the observed electron density in accordance with the Saha expression their temperature T_e must be in the neighborhood of 6×10^3 °K and $N_0 = 10^{18}$. As will be shown below, such a cold plasma cannot explain a number of the observed properties of the plasma filament, for example, such as its electrical conductivity, the effect of a magnetic field on the structure of the filament, the high intensity of emission in the deep ultraviolet, the weaker emission from the interior region of the filament and a number of other phenomena. The second possible explanation of this phenomenon, which, as will be shown, is completely satisfactorily confirmed also by other observations, consists of the fact that in reality the filament consists of two regions: in addition to the external region of diameter 2a, there exists an internal region of diameter 2b. The plasma confined in this region is hot. It is completely ionized, and therefore, $n_0 = 0$, and the electron density is homogeneous and equal to n_e. The cloud of diameter 2a surrounding the filament forms a cold sheath of electrons which by the brightness of its radiation appears to mask the radiation from the internal region of the filament. Therefore the density N_e which we determine in accordance with the Stark effect refers to the electrons of the cloud and the density N_0 of neutral atoms corresponds to the temperature of the cold plasma lying in the range 6000–7000°. The electron density in the cloud is low, the resistance is great, and therefore there is practically no HF absorption in it, the oscillations penetrate inside and the current flows along the surface of the interior region of the filament of diameter 2b. The fact that inside the plasma filament the charge density was higher than on the periphery was observed from measurements of the broadening of the spectral line D_β inwards along the filament radius. In order to do this, as we have described in the preceding section, the slit of the collimator of the spectrograph was replaced by a small aperture which was moved along the spectral line in different regions of the cross section of the filament. The results of these measurements are shown in Fig. 3.3. From these curves it can be seen that the Stark broadening $\Delta\lambda_S$ is greater by a factor of several fold at the center compared to that on the periphery.

The most accurate measurement of the electron density inside the filament turned out to be possible in terms of the emission in the far infrared region of the spectrum in the range of wavelengths from 100 to 500 μ. We have utilized an already well-known method of plasma diagnostics [[6], p. 329]. This method is based on the fact that plasma cannot emit oscillations whose frequency is lower than the proper plasma frequency (the Langmuir frequency). The latter in our case lies in a region corresponding to wavelengths in the range from 100 to 500 μ. The relationship between the electron density n_e and the proper plasma frequency ν_0 is determined by the well-known expression:

$$n_e = 1.12\cdot10^{13}\nu_0^2, \tag{3.7}$$

where the frequency is given in reciprocal centimeters. The investigations are made difficult by the fact that the intensity of emission by the plasma in this region of the spectrum is low and one requires a spectrograph with a sensitive detector. There is no standard equipment for this, and a special Fabry–Perot spectrometer using reflectors constructed from metal grids was developed. As filters we have utilized pressed polyethylene gratings. A carbon bolometer maintained at liquid helium temperature served as the detector. The curves of Fig. 3.5 give in arbitrary units the reduced data of the measurements of the intensity of emission by the filamentary discharge at different frequencies ν. The curves shown there refer to a plasma filament at pressures of p = 1 atm and p = 2 atm. From these curves it can be seen that as the frequency is reduced beyond a certain frequency ν_0, to which we shall refer as the limiting frequency, the intensity of emission begins to fall off sharply. We consider this limiting frequency ν_0 to be equal to the proper plasma frequency and in accordance with (3.7) we determine the electron density n_e in the filament. If the filament were of homogeneous density [6], p. 331], the falling off of intensity at the limiting frequency would be somewhat sharper than observed by us. This shows that in our case, as should be expected in accordance with the model of the filament adopted by us, the plasma density is not homogeneous—it increases from the periphery towards the center, and the measured electron density is situated in the hot region of the filament. The reliability of the results obtained by our equipment was checked by replacing the filament in the resonator by its "model" in the form of a heated carbon rod which radiated as a black body. In this case the measured intensity of radiation must be proportional to the quantity $T\nu^3$ multiplied by the magnitudes of the external surface of the rod and by the figure of merit $\Delta\nu/\nu$ of our spectrograph. Experiment has confirmed that in the frequency region investigated by us the intensity measured by our spectrometer follows this law.

The data obtained on the temperatures and densities of plasma filaments are shown in the Table. We have also presented there data of other measurements obtained for the same filaments. From the assembled data, for example, it can be seen that in the filament for p = 1 atm and for a power input of P_a = 12.4 kW the electron density inside the plasma filament is $n_e = 7.3 \times 10^{15}$ cm^{-3} and is greater by a factor of about 50 than $N_e = 1.4 \times 10^{14}$ cm^{-3} determined by means of the Stark effect. Knowing the density n_e inside the filament one can estimate the electron temperature in accordance with expression (3.3). In order to do this accurately one must also know the ion temperature T_i, and this, as will be seen from subsequent discussion, until now has been achieved only by means of calculations of low reliability. But since the ion temperature is in any case lower than the electron temperature, we can from expression (3.3) determine within a factor of two the limits within which T_e lies. From subsequent discussion it will be seen that the ion temperature is considerably lower than the electron temperature and, therefore, the upper limit on the temperature T_e should be regarded as being closer to reality.

P_a, kW	p, atm	$2a$, cm	ν_0, cm^{-1}	n_e, 10^{15} cm^{-3}	$n_e/10^{15}\,p$	T_e, 10^6 °K ($T_i = 0$)	$\Delta\lambda$, Å	N_e, 10^{14} cm^{-3}
8.8	1	0.8	23.5	6.2	6.2	1.2	1.6	4.6
12.4	1	0.9	25.5	7.3	7.3	1	1.35	1.4
12.4	2	0.75	32.0	11.5	5.8	1.3	1.93	6.6

Some information about the plasma can be obtained by studying the intensity of the emission over the spectrum. The intensity in the range $\Delta\lambda/\lambda$ of the continuous bremsstrahlung is determined by the following well-known expressions [9], p. 330]:

$$q = 2.6 \cdot 10^{-14} n_e^2 \left(\frac{\varepsilon}{kT_e}\right)^{1/2} e^{-hc/\lambda kT_e} S \Delta l \frac{\Delta\lambda}{\lambda}, \quad \frac{hc}{\lambda kT_e} \gg \sqrt{\frac{kT_e}{\varepsilon}},$$

$$q = 1.4 \cdot 10^{-14} n_e^2 \left(\frac{\varepsilon}{kT_e}\right)^{1/2} g S \Delta l \frac{\Delta\lambda}{\lambda}, \quad \frac{hc}{\lambda kT_e} \ll \sqrt{\frac{kT_e}{\varepsilon}}, \quad (3.8)$$

where g is Gaunt's logarithmic factor, ϵ is the ionization energy, q determines the number of photons emitted by a filament of cross section S along a length Δl of the filament.

A study of the intensity of emission in the short wave region confirms that inside the filament the plasma is hot.

We adopt the already described model of our discharge, but in further calculations for the sake of simplicity we shall regard it as a cylinder which inside consists of a volume of radius b filled completely by ionized plasma of electron temperature T_e and ion temperature T_i, and of density n_e which we determine from emission in the microwave region.

We shall assume that the filament is surrounded by a cloud with an electron ion density N_e and a neutral atom density N_0 (the values of these densities are estimated in terms of the Stark broadening, expression (3.5)), with a cloud temperature which varies but little and lies in the range 6000–7000°. Since this plasma is partially ionized, the density N_e in the cloud, as can be seen from Fig. 3.5, can fall off appreciably as we proceed from the center towards the periphery.

The intensity of emission Q_b per unit surface of the internal region can be determined with an accuracy up to a logarithmic term by means of (3.8). This quantity will be proportional to:

$$Q_b \propto b n_e^2 / T_e^{1/2}. \quad (3.9)$$

If we take into account expression (3.4), then we have

$$Q_b \propto b p^2 / T_e^{2.5}, \quad T_e \gg T_i. \quad (3.10)$$

The current flows over the surface of this region, the skin-layer is thin and the electron heat conductivity is great, and, therefore, we can assume that the temperature T_e within the cylinder of radius b is homogeneous and the emission per unit volume is also homogeneous.

The intensity of bremsstrahlung from the surface of the cloud surrounding the internal region will be proportional to

$$Q_a \propto (a - b) N_0 N_e p^2, \quad T_0 = \text{const}. \quad (3.11)$$

Experiment shows that for small diameters of the filament and a low power input P_a the surface emission from the core of the filament Q_b is somewhat greater than Q_a—the emission from the external cloud, and this, as we suppose, is the reason for the fact that at low power we observe a distribution of intensity which differs from an ellipsoid, with an increased value in the middle, as we have indicated at the outset, and as can

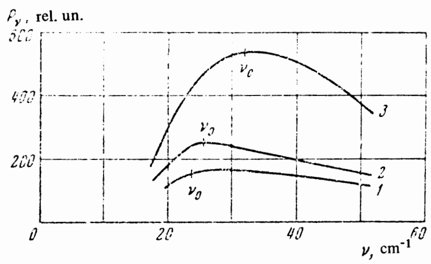

FIG. 3.5. Intensity of emission from a filamentary discharge in deuterium in the far infrared region of the spectrum. Curve 1—p = 1 atm, P_a = 8.8 kW; curve 2—p = 1 atm, P_a = 12 kW; curve 3—p = 2 atm, P_a = 14.7 kW.

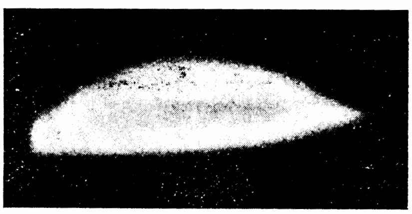

FIG. 3.6. Photograph of a filamentary discharge in deuterium with an admixture of 5% argon at high power P_a = 14.7 kW and high pressure p = 3.32 atm. Length of the discharge ~10 cm. The left edge of the discharge is blocked by the window. Oscillations of E_{01} type (1969).

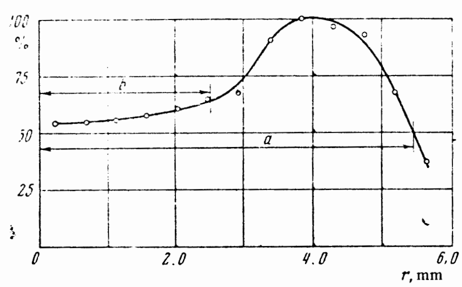

FIG. 3.7. Distribution of the volume intensity of emission (λ≈ 5800 Å) along the radius of a high power discharge in deuterium calculated from the curve of Fig. 3.8. P_a = 14.3 kW, p = 1 atm.

FIG. 3.8. Sample record of the intensity of monochromatic radiation along the diameter of a high power discharge in deuterium. P_a = 14.3 kW, p = 1.0 atm, 2a = 9.9 mm, λ = 5800 Å.

be seen in Fig. 3.3. But the same experiment also shows that as the power input is increased the temperature T_e also increases. The intensity of the surface emission of the filament, since it is inversely proportional to $T_e^{2.5}$, falls off rapidly. In this case the surface intensity of the exterior emission is of a more constant nature, since N_eN_0 varies but little. It turns out that at high values of power and pressure conditions are created under which the surface emission from the core of the filament may become less than that from the external cloud; then when the distribution of intensity is measured along a filament diameter one can observe a minimum at the center. This minimum can be seen in the photographs of the filament, for example, in Figure 3.6. Similar reduced intensity in the volume emission of the middle portion of the filamentary discharge can be seen in the curve of Fig. 3.7; it is calculated from a record of the intensity of emission made along the diameter for a filamentary discharge of high power. A copy of the original of this record is reproduced in Fig. 3.8.

From the photograph reproduced here one can estimate the ratio of the thickness of the cloud to the radius of the filament:

$$\gamma = (a - b) / a. \tag{3.12}$$

From the photograph of Fig. 3.6 and the curve of Fig. 3.7 this quantity can be determined only very approximately: we take it to be equal to γ = 0.6.

One of the checks on the correctness of the model of the filament adopted by us can be a determination of the absolute value of the intensity of emission of the filament in the microwave region (expression (3.4)), since it can be obtained from a comparison with the emission of a black body of the same shape as the filament placed in the resonator. The surface emission of the plasma in this frequency range is the sum of the emission from the cloud and from the filament. According to the calculations using (3.8) it is by approximately a factor of 10 greater than the emission of a black body at a temperature of 880°K. Within the limits of experimental error this is confirmed by experiment.

Of great interest is the study of the intensity of emission in the far ultraviolet region, since in accordance with the model adopted in this region the intensity of emission from the cloud compared to the intensity of emission from the hot plasma in the filament must become lower. The possibility of studying the plasma in this region is greatly limited by the fact that in the resonator the filament is surrounded by hydrogen or by deuterium at high pressure which very strongly absorb the ultraviolet radiation. This absorption, starting with λ = 860 Å, attains exceedingly high values. Thus, in our apparatus over the distance from the filament to the counter this absorption can attain values of 10^{-400} of emission from the plasma [9, p. 359]. Experiment shows that the intensity of emission from the plasma can be reliably measured by counters with lithium fluoride windows only for wavelengths not less than 1040 Å. For a hot plasma of temperature $T_e = 10^6$ °K we obtain in accordance with (3.8) for these wavelengths that the emitted number of photons is equal to:

$$q = 5.5\cdot 10^{17} e^{-ch/\lambda kT_e} p^2 \pi b^2 \Delta l \frac{\Delta\lambda}{\lambda}, \quad \lambda \approx 50\text{Å}$$

$$q = 4.5\cdot 10^{17} p^2 \pi b^2 \Delta l \frac{\Delta\lambda}{\lambda}, \quad \lambda \approx 1000\text{Å}. \tag{3.13}$$

It is of interest to carry out a study of this radiation over a narrow range of wavelengths, and, therefore, we began by utilizing special counters which transmitted radiation selectively from 1050 to 1175 Å, which corresponds to $\Delta\lambda/\lambda$ = 0.1. These counters had a counting efficiency of 1%. The first experiments showed a high intensity of emission in this region. The counter was situated at a distance of 15 cm from the filament, but its window had to be stopped down by a diaphragm to an aperture of 2.3×10^{-6} cm^2, otherwise it was saturated. Under these conditions the counter gave more than 1000 counts per second, and this corresponds to a number of photons emitted by the filament in the range of $10^{15}-10^{16}$ per second. Such high emission from the plasma in this extreme ultraviolet region enabled us to go over to measuring it by a selectively sensitive ionization chamber. We used an ionization chamber filled with nitric oxide, with a lithium fluoride window with a quantum yield of 0.3 [[9], p. 221]. Such an ionization chamber was sensitive only within the wavelength range from 1050 to 1350 Å. The window of the ionization chamber has a diameter of 0.8 cm and is situated at a distance of 15.4 cm from the filamentary discharge. The window in the resonator restricted entry of radiation from the filament over a length of Δl = 3 cm. Into the path of radiation on its way to the chamber one could insert a fluoride filter which limited the radiation up to 1240 Å or a quartz filter which limited the radiation up to 1400 Å. The photocurrent from the ionization chamber attained values of 10^{-7} A and could be measured well. On the insertion of the quartz filter the current eased. This indicated that the photocurrent comes from radiation in a region 300 Å in extent in the wavelength range from 1050 to 1350 Å. The observed radiation increased greatly as the deuterium was purified. As was indicated in Sec. 2, purification of deuterium was achieved by its continuous circulation through a trap at liquid nitrogen temperature. Without such purification the measured radiation in this region of the spectrum was less by a factor of several tens of times and attained its greatest value only after an hour and a half or two hours of purification by circulation. We explain such a great influence of impurities in deuterium by their great absorptive power, which is well observed in the case of an oxygen impurity. This is experimentally demonstrated when only 1 cm^3 of heavy water is introduced into the deuterium in the apparatus which has a volume of 60 liters. In this case the current through the ionization chamber is reduced by a factor of several tens of times.

We further observe that the introduction of the fluoride filter reduces the current through the ionization chamber to approximately one-third of its initial value. This shows that the average intensity of emission in the wavelength range from 1050 to 1250 Å differs but little from the intensity of emission in the range from 1250 to 1350 Å. Since in this range deuterium has no lines in its atomic spectrum, the observed radiation must be ascribed to bremsstrahlung. This assumption was confirmed when a spectrum was taken with a vacuum spectrograph. The spectrogram showed the existence of a continuous spectrum and at the position of the Lyman α line (1215.7 Å) an absorption band was seen.

It is of interest to note that in the hot part of the plasma we so far have been unable to observe any line spectrum, even when an admixture of oxygen, argon or helium is present in the deuterium. The emission from our filament in the range 1050–1250 Å under the conditions shown in the Table was approximately 5×10^{15} photons. We calculate the number of photons q by means of of (3.13) in accordance with the data in the Table. We take 2a = 0.9 cm, and then according to (3.12) we have 2b = 0.36, Δl = 3 cm, and for $\Delta\lambda/\lambda = 0.2$, $T_e = 10^6$ °K and p = 1 atm we obtain the value 2×10^{16} which is approximately by a factor of four greater than the observed value. Such a discrepancy both in terms of sign and in terms of magnitude is quite acceptable considering the approximate nature of the quantities utilized in this quantitative comparison. If the plasma were cold, then at a temperature of $T_0 = 6.5 \times 10^3$ °K in accordance with (3.13) it would emit in this spectral region a number of photons which would be less by a factor of at least 10^8. Thus, this experiment practically excludes the possibility of explaining the observed radiation as bremsstrahlung from a cold plasma.

It would be of interest to extend these investigations further into the domain of still shorter wavelengths, but this turns out to be impossible due to the absorption of the short wavelength radiation in its passage through the gas surrounding the filament. At wavelengths shorter than λ = 860 Å the absorption of the radiation by the deuterium at a distance of 15 cm between the counters and the filament attains a value of $\exp(-3000\,p)$, where p is the gas pressure. For still shorter wavelengths the absorption diminishes rapidly and at a wavelength of λ = 50 Å becomes equal to $10^{-2.6p}$. At an electron temperature in the plasma of $T_e = 10^6$ emission from the plasma in the filament could be observed from the "Maxwellian tail" if it were not restricted by the transparency of the window through which the radiation enters the counter.

In order to transmit the radiation this window must be thin, but at the same time it must be sufficiently strong to withstand a pressure of several atmospheres. The only material suitable for this purpose so far is a lavsan polyester film of thickness from 5 to 7 μ. The main disadvantage of such a window consists of the fact that the elements N, O, C which enter into the composition of lavsan have a strong selective absorption in the region starting with λ = 45 Å and shorter. This narrows the range of transmission down to $\Delta\lambda$ = 5–8 Å. The absorption in our lavsan films is estimated as $10^{-2.5}$.

In order to shield the counter from very intense radiation in the longer wavelength region $\lambda > 860$ Å (the absorption edge for hydrogen itself), the lavsan has to be coated with a layer of aluminum of thickness not less than 0.4 μ. We estimate the absorption of such an aluminum layer as being equal to $10^{-2.5}$. Nevertheless, we still carried out an experiment with such a counter. In this case we had a high background—several counts per second, which, apparently, was due to the fact that the aluminum layer had very small pinholes and, therefore, could not completely shield the counter from radiation in the longer wavelength region. The counting rate was very uneven and insufficient for quantitative conclusions.

The calculations we have made have shown that under the conditions under which the experiments have been carried out, i.e., with an absorption on the way to the counter of 10^{-12} of the emitted photons, the experiments cannot be reliable.

A more detailed analysis shows that a quantitative investigation of the filamentary discharge surrounded by hydrogen or deuterium at a pressure of several atmospheres by means of studying soft X-ray emission by the method of counters or photomultipliers can be carried out reliably only when the electron temperature is not less than 10^7 deg.

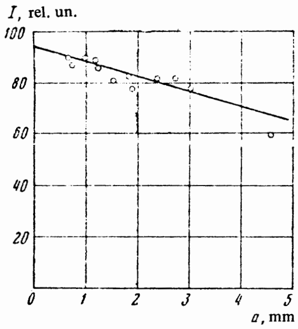

FIG. 3.9

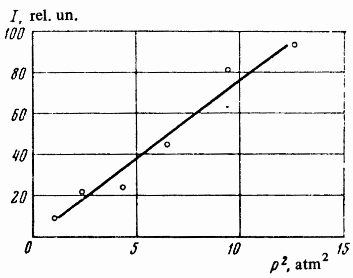

FIG. 3.10

FIG. 3.9. Intensity of monochromatic emission per unit volume of a discharge in deuterium as a function of the radius. $\lambda \approx 4730$ Å, p = 1 atm, 3.7 kW < P_a < 12 kW.

FIG. 3.10. Intensity of monochromatic emission per unit volume of a discharge in deuterium as a function of the square of the gas pressure. $P_a \approx 13$ kW.

Measurement of the intensity of emission opens up a number of possibilities for the study of the properties of the filamentary discharge.

In Fig. 3.9 we have shown in arbitrary units the value of the intensity I, measured on the basis of the current from a photomultiplier in a small spectral interval situated at a sufficient distance from the emission lines H_β and D_β, as a function of the radius of the discharge. The curve of Fig. 3.10 represents the same quantity I as a function of the square of the pressure p^2. Only limited possibilities exist for the interpretation of these results since the observed emission is the sum of the emission from the interior region containing the hot plasma and the emission from the cloud. From the curve of Fig. 3.9 obtained at a constant pressure of p = 1 atm it can be seen that the value of I shows only a small decrease as the radius increases and for a general discussion of the properties of the filament it can be taken as constant. This shows that the intensity of emission per unit volume of the filament diminishes as its diameter increases. From this it follows that the temperature of the hot plasma increases with increasing dimensions of the filament. From the curve of Fig. 3.10 it follows that the value of I is proportional to the square of the pressure. Since from the curves of Fig. 2.4 one can assume that the diameter of the filament 2a for a given power level P_a is independent of the pressure, then the intensity of emission per unit volume is proportional to the square of the pressure. This indicates that the electron temperature T_e does not depend strongly on the pressure. More reliable information should be given by a measurement of the intensity of bremsstrahlung in the ultraviolet, since it is completely due to the hot portion of the plasma. We carried out measurements of the intensity of the spectrum in the ionization chamber that has already been described which is filled with nitric oxide. The difficulty in interpreting these results is associated with the fact that in this region we cannot stabilize the image of the filament as we did in the visual domain by means of the stabilizer shown in Fig. 2.2. If we assume that the diameter of the filament of hot plasma 2b is proportional to diameter of the cloud 2a, then we obtain that the temperature of the hot electrons T_e is proportional to a power of the diameter somewhat smaller than unity, and also does not increase strongly with pressure. We expect to develop a method for the measurement of radiation with the aid of which it will be possible to determine with a greater degree of accuracy the relationship between the temperature T_e and the pressure p, the diameter 2a and the power P_a.

We have also carried out experiments using mixtures of gases. From the outset a curious phenomenon was observed here. The argon lines are completely absent in our photographs, while the deuterium Balmer lines can be seen perfectly although with a reduced brightness. In the same gas mixture, but in a Geissler tube, the spectral lines of Ar are quite pronounced. In experments with an admixture of He, Ne, Ar and Kr gases we have also observed a similar complete absence of the lines of their spectra in the filamentary discharge. Only when Xe was admixed a trace of its lines appeared. The most natural explanation of this phenomenon consists of the fact that in a hot plasma the atoms are multiply ionized and neutron atoms are practically absent. Thus, the emission spectrum must be displaced into the region of shorter wavelengths. The absence of line spectra of admixed atoms in the glow of the cold cloud can be explained by their higher ionization potential than that for deuterium. In this case only Xe glows for which the ionization potential is lower.

Finally, the reduced intensity of glow can be ascribed to the fact that in a hot plasma the number of ions decreases. Since they carry a larger number of positive charges a smaller number of ions is required to neutralize the electron gas.

A study of the spectra of impurities in the extreme ultraviolet (λ = 1050–1350 Å) which has now been started also shows a complete absence of line spectra of the impurities in the hot portion of the plasma. The absence of lines from multiply ionized atoms precludes the possibility of using them for plasma diagnostics in terms of the Stark or Doppler effect, and therefore the spectral radiation of the plasma in the extreme ultraviolet until now has opened up no new possibilities for determining the temperatures of the ions and of the electrons in the plasma.

4. HEAT LOSSES FROM THE FILAMENTARY DISCHARGE

As has been pointed out in the Introduction, the most noteworthy feature of the filamentary discharge is the fact that although in the interior region of the filament the electron temperature exceeds a million degrees, nevertheless, the heat flux in this case into the surrounding gas is small—one or two kilowatts per centimeter of the filament. It is not difficult to calculate that if the electrons striking the boundary of the filament at these temperatures simply diffused into the surrounding gas they would have carried away with them hundreds of kilowatts of power. We explain such thermal insulation by the fact that at the boundary of the hot plasma a double layer is formed from which the electrons are reflected without significant losses. The existence of an analogous phenomenon has been known for a long time. It occurs in cases when the plasma is bounded by walls of a dielectric substance, for example, like glass or porcelain. It is well known that under such conditions even at appreciable pressures the electrons in the plasma can have a high temperature without heating the walls strongly. This phenomenon has been explained long ago by the creation on the surface of the dielectric of a double layer. The mechanism for the production of the double layer is simple. It consists of the fact that because of their great mobility the electrons on striking the surface penetrate into the dielectric deeper than the less mobile ions. The volume charge of the electrons is formed in the dielectric deeper than the volume charge of the ions, and this creates an electric field directed in such a way that electrons are elastically reflected from it. The poor heat conductivity between the plasma and the walls is utilized in gas discharge type of light sources at high pressure.

We assume that a similar phenomenon of thermal insulation also occurs at the boundary of the hot plasma in the filament, but with the difference that in place of the dielectric wall the double layer is formed at the boundary between the plasma and the gas. In such a case a discontinuity is created between the temperature T_0 of the surrounding gas and the electron temperature T_e in the plasma.

Calculation of the structure of the double layer and of the processes occurring in it represents a complex problem. Moreover, a number of quantities required for this which determine the collision processes between atoms, ions and electrons is, as yet, poorly determined. Therefore, we limit ourselves to an approximate consideration which has for its aim only to demonstrate the reality of the possibility of the existence of such double layers at the boundary between the gas and the hot plasma.

A model for the structure of the central cross section of the filament is shown in Fig. 4.1. Inside the cylinder of radius b is filled with hot plasma. Experimentally we determine the density of its electrons n_e (cf., Table). The radii b and a can be estimated from the darkened portion in the photograph of the filament in Fig. 3.6. Since the power in the filament is supplied to the electrons at the surface of the hot plasma in the skin-layer, while the electron thermal conductivity in the hot plasma is great, the electron temperature T_e is higher than the ion temperature T_i. Therefore, the electron temperature can be determined in accordance with (3.4) in terms of the density n_e.

The heat losses suffered by the power input to the filament P_a occur in two ways. A considerable fraction of the electrons is reflected without losses from the double layer, but still a portion of their energy will be utilized to make up the losses occurring in the boundary layer as a result of the diffusion and the recombination of the ions. We denote the power spent in maintaining the double layer by $P_a \varphi$. The other part of the power $P_a(1-\varphi)$ is transmitted to the hot plasma by the heat exchange between the electrons and the ions, raises the ion temperature up to T_i and then by means of the ordinary heat conductivity is transferred to the surrounding gas.

We assume that the double layer begins at the boundary of the plasma filament of radius b. We denote the

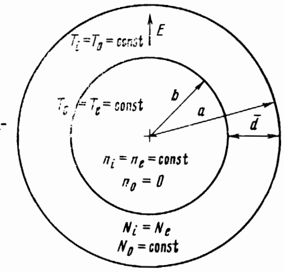

FIG. 4.1. Diagram showing the distribution of the temperatures and the densities of ions and of electrons across a section of the discharge.

electron density in the double layer by N_e. This layer also consists of neutral atoms of density N_0 and of temperature T_0 and of ions of density N_i at the same temperature. The electrons in the double layer will primarily undergo elastic collisions with ions and with neutral atoms which alter their direction of motion, but due to the large difference in the masses the transfer of kinetic energy will be small, and we neglect it in our calculations. For example for $T_e = 100$ V the cross section $q < 10^{-17}$ cm^2 [[10], p. 150, Fig. 4.1.9]. Therefore, we assume that the electrons in the double layer retain a temperature T_e close to the one which they have inside the filament. Thus, the electrons moving in the electric field E of the double layer will only change their density N_e, but not their temperature. We treat the processes in the double layer as a plane problem. We denote the distance from the boundary of the hot plasma by x. Also in order to simplify the problem we assume the filament to be in the shape of a cylinder. As can be seen from the Stark broadening (Fig. 3.3) the distribution of the electron density in the cloud has the nature of an exponential function. We therefore assume

$$N_e = n_e e^{-e\bar{E}x/kT_e}, \tag{4.1}$$

where n_e is the density of the electrons in the hot plasma, $\bar{E}$ is the average value of the field E in the double layer. Since the field E is created by volume charges one can assume that its value is proportional to N_e, and we assume

$$E = E_0 e^{-e\bar{E}x/kT_e}, \tag{4.2}$$

where E_0 is the field at the boundary of the hot plasma at $x = 0$. The difference in the density of the electrons N_e and of the ions N_i creates the electric field E of the double layer. In accordance with the Poisson equation we obtain

$$\frac{\partial E}{\partial x} = 4\pi e (N_i - N_e). \tag{4.3}$$

Since the quantity $eN_i\bar{d}$ is large, while the field E is small, we can practically take

$$N_i = N_e. \tag{4.4}$$

The partial pressure created by the electrons at the boundary will be transmitted through the electric field to the ions, and, therefore, in accordance with (4.1) and (4.2) we have

$$p_e = e\int_0^\infty N_e E\,dx = \frac{E_0}{2\bar{E}} n_e k T_e. \tag{4.5}$$

Since we also have $p_e = n_e k T_e$, then

$$E_0 = 2\bar{E}. \tag{4.6}$$

We determine the average thickness of the double layer:

$$\bar{d} = \frac{1}{\bar{E}} \int_0^\infty E_0 e^{-e\bar{E}x/kT_e}\, dx = \frac{2kT_e}{e\bar{E}}. \quad (4.7)$$

The electric field E pushes the electrons from the double layer back into the plasma, while the ions move in the gas in the opposite direction until they recombine with the electrons. This process of the motion of the ions in the gas is associated with liberation of heat, and this basically represents the expenditure of the power $P_a\varphi$ which is utilized to maintain the double layer. We evaluate this power. In moving through the gas an ion after a time interval τ_i undergoes a collision with neutral atoms. The average increase in the velocity which the ion has acquired during this period is given by

$$\overline{\Delta x} = \frac{eE}{2m_i}\tau_i, \quad (4.8)$$

where m_i is the mass of the ion. The value of τ_i is equal to

$$\tau_i = 1 / q_0 N_0 v_i, \quad (4.9)$$

where q_0 is the cross section of the neutral atom. The energy required to maintain the double layer is equal to the work done as the ions move in the electric field E. Then the power expended after taking into account the preceding expressions is equal to

$$\frac{P_a\varphi}{2l} = 2\pi b \int_0^\infty \overline{\Delta x} N_i eE\, dx = 2\pi \frac{b}{\bar{d}} \frac{2n_e (kT_e)^2}{3N_0 v_i m_i q_0}. \quad (4.10)$$

In this expression one can estimate all the quantities. Let us take the example which we have already considered (cf., Table). For deuterium we have b = 0.18, $T_e = 10^6$, $n_e = 7.3\times10^{15}$, $N_0 = 10^{18}$, $T_0 = 6.5\times10^3$, $v_i = 7.4\times10^5$. According to the photograph of Fig. 3.6 one can take the average thickness $\bar{d}$ of the double layer to be equal to $\bar{d} = 0.2$ cm. The least well determined quantity is q_0—the value of the cross section for the collision of neutral atoms with ions. This cross section is the sum of two quantities: q_p—the cross section for a collisions in which charge exchange between the ion and the atom occurs, and q_D—the cross section for a collision in which the energy is equalized. Both these quantities (cf., [10], pp. 150, 285) increase rapidly with decreasing temperature. No measurements are available for such low temperatures as exist in a cloud with T_0 = 6500 deg.

Extrapolating known data one can estimate that q_0 lies within the limits $q_0 = (1-3)\times10^{-14}$. We then obtain $P_a\varphi/l$ = 2–0.7 kW/cm, which does not contradict the experimental values of $P_a/2l$ referred to the middle of the filament which lie within the limits 2.5–1.5 kW.

It is of interest to determine the value of $\bar{d}$—the average thickness of the double layer—in terms of α—the recombination coefficient for the ions and the electrons. The recombination coefficient is defined by the following relation:

$$\frac{\partial N_i}{\partial t} = -\alpha N_e^2. \quad (4.11)$$

If we consider the element dx in the double layer and determine the material balance, then we have

$$\frac{\partial \overline{\Delta x} N_i}{\partial x} = \frac{\partial N_i}{\partial t}. \quad (4.12)$$

Treating α as a constant quantity and utilizing expressions (4.8), (4.9) and (4.12), we obtain

$$\frac{\partial eEN_i}{\partial x} = -2\alpha q_0 m_i v_i N_i^2. \quad (4.13)$$

Utilizing expressions (4.1), (4.2), (4.3) and (4.7) and differentiating we find

$$\bar{d} = \sqrt{\frac{8kT_e}{\alpha q_0 m_i v_i N_0 n_e}}. \quad (4.14)$$

From this expression, according to the experimental data quoted above we obtain $\alpha = 1.6\times10^{-10}$–$4\times10^{-11}$. These values are close to the calculated ones [[11], p. 667]; thus for a temperature of $T_0 = 6500°$ and $N_e = 7.3\times10^{15}$ we have $\alpha = 3\times10^{-10}$. For a plasma subject to our conditions the value of α is poorly known both experimentally and theoretically. In accordance with the theoretical paper by Gurevich and Pitaevskiĭ,[11] at high gas pressure α depends on the gas density and on its temperature:

$$\alpha \infty N_0 / T^{9/2}. \quad (4.15)$$

If such relations actually hold, then from (4.10) and (4.14) one can see that the power which is expended in maintaining the double layer does not depend strongly on the temperature, but increases with the pressure.

The double layer has a surface tension S which is equal to the energy of the electric field:

$$S = \frac{1}{8\pi}\int_0^\infty E^2 dx. \quad (4.16)$$

Utilizing expressions (4.2), (4.6), and (4.7) we obtain

$$S = \frac{1}{2\pi \bar{d}}\left(\frac{kT_e}{e}\right)^2. \quad (4.17)$$

This quantity is not large and, apparently, should not exert any appreciable influence on the structure of the filament.

The investigations which we have carried out show that as yet there is no possibility of carrying out a complete numerical estimate of the processes in the double layer, but the adopted model for the structure of the filament agrees with the experimental data obtained in the course of our study of the plasma in a filamentary discharge.

We consider the process for the removal from the hot plasma of the other part of the power $P_a(1-\varphi)$. For this it is first necessary to calculate the heat transfer between the ions and the electrons. This heat exchange can occur in two ways: the first is the well known mechanism of Coulomb collisions; the second is the heat transfer involving a collective interaction, but no method of calculating it has yet been found. But the transfer of energy between charged particles in virtue of their Coulomb interaction can be reliably calculated. At the basis of this calculation lies the quantity τ_{eq} which defines the average time for the redistribution of energy in a collision of two types of charged particles of masses m_1 and m_2 characterized by different temperatures T_1 and T_2. The time τ_{eq} required for equalizing the temperature of the mixture is given by the following expression,[12], p. 135:

$$\tau_{eq} = \frac{3}{8\sqrt{2\pi}}\frac{m_1 m_2 k^{3/2}}{n_i e^4 Z_1 Z_2 \Lambda}\left(\frac{T_1}{m_1}+\frac{T_2}{m_2}\right)^{3/2}, \tag{4.18}$$

where Z_1 and Z_2 are the charges of the ions, while Λ is a logarithmic term. In the hot plasma of the filament interaction occurs between electrons and ions. The mass of electrons is small compared to the mass of deuterium ions, while the electron temperature is usually much higher than the ion temperature, and, therefore, expression (4.18) can be simplified in the following manner:

$$\tau_{eq} = \frac{1}{6.7}\frac{m_i (kT_e)^{3/2}}{e^4 \sqrt{m_e}\Lambda n_e}, \quad Z_1 = Z_2 = 1, \quad m_i \gg m_e. \tag{4.19}$$

The power $P_a(1-\varphi)$ which is transferred from the electrons to the ions in the central section of the cylindrical filament is equal to

$$\frac{P_a}{2l}(1-\varphi) = \pi b^2 \frac{n_e(T_e - T_i)k}{\tau_{eq}\cdot 10^{10}}[\text{kW}]. \tag{4.20}$$

Under the condition $T_i \ll T_e$ we have

$$\frac{P_a}{2l}(1-\varphi) = \pi b^2 \frac{6.7 n_e^2 e^4 \sqrt{m_e}\Lambda}{10^{10} m_i (kT_e)^{1/2}}[\text{kW}]. \tag{4.21}$$

As an example we consider the same experimental data from the Table for the filament p = 1 atm, $P_a = 12.4$ kW, b = 0.18 cm, $T_e = 10^6$ °K, $n_e = 7.3 \times 10^{15}$. (We have used these data also in considering the processes in the boundary layer.) We find that the power which can be transferred from the electrons to the ions is equal to

$$P_a(1-\varphi)/2l = 2 \text{ kW/cm}. \tag{4.22}$$

Since in the central portion of the filament we have $P_a/2l$ approximately equal to 3 kW/cm, then a significant portion of the power can be transferred to the ions.

We evaluate the temperature T_{i0} of the ions at the center of the cross section of the filament. We consider first the general problem of radial heat transfer in a cylinder. We assume that over the whole cylindrical volume the power transferred from the electrons to the ions is the same; then the equation for the heat transfer is given by

$$\frac{\partial}{\partial r}\left(r\mathcal{K}\frac{\partial T_i}{\partial r}\right) = -\frac{P_a(1-\varphi)}{2l}\frac{r}{\pi b^2}. \tag{4.23}$$

Since the heat conductivity depends on the temperature we assume:

$$\mathcal{K} = CT^{\varkappa}. \tag{4.24}$$

Then, integrating (4.23), we obtain

$$\mathcal{K}T_{i0}\left[1-\left(\frac{T_i}{T_{i0}}\right)^{\varkappa+1}\right] = \frac{\varkappa+1}{4\pi}\frac{P_a(1-\varphi)}{2l}\frac{r^2}{b^2}, \tag{4.25}$$

where T_{i0} is the temperature at the center, while T_i is the temperature at a distance r from the center. The heat conductivity for the ions is equal to (cf., [13], p. 192):

$$\mathcal{K} = 4.7\cdot 10^{-32}\frac{n_e T_i}{m_i}\tau_i, \tag{4.26}$$

where

$$\tau_i = \frac{1.3\cdot 10^{13}}{\Lambda}\frac{T_i^{3/2}\sqrt{m_i}}{n_e}. \tag{4.27}$$

From this we obtain

$$C = \frac{6.2\cdot 10^{-19}}{\Lambda\sqrt{m_i}}, \quad \varkappa = 2{,}5. \tag{4.28}$$

If we set r = b and assume that the temperature of the ions at the center T_{i0} is considerably greater than T_{ib} at the boundary of the hot plasma which we assume to be equal to the gas temperature, we then have

$$T_{i0} = \left[\frac{\varkappa+1}{4\pi C}\frac{P_a(1-\varphi)}{2l}\right]^{1/3,5}. \tag{4.29}$$

For the example under consideration we obtain under the condition (4.22)

$$T_{i0} = 9\cdot 10^4\ {}^\circ\text{K}. \tag{4.30}$$

The temperature of the ions in the plasma obtained in this manner is considerably lower than the electron temperature and increases slowly with increasing power input.

An experimental determination of the ion temperature in the hot region of the plasma in the filament is of considerable interest. The most reliable determination of the temperature T_i could be realized by determining the partial pressure p_i due to the ions. From expression (3.3) it may be seen that for this it is necessary only to determine with sufficient degree of accuracy the temperature T_e and the density N_e. Until now we cannot measure these quantities in the plasma of the filament with an accuracy required for this purpose, although with an increase in the scale of the experiment this will apparently become possible.

A second experimental method for determining the ion temperature is in terms of the emission of neutrons by the filament. As has been pointed out in the Introduction, such emission is observed and it corresponds to a temperature of the ions in the plasma of (6–8) $\times 10^5$ °K. This temperature is lower than the electron temperature, and, therefore, it is possible to attain it, but since in our experiments the number of neutrons emitted is small compared with the background (from 3 to 5%), the accuracy of the experiment does not permit us to associate this emission quantitatively with the state of the plasma. Therefore it does not appear to us to be possible to treat the available data as a basis for determining the ion temperature.

There exists still another interesting experimental possibility for estimating the ion temperature, even though it is of an indirect nature. We have experimentally studied the thermal diffusion of ions in the filament. In order to do this we have compared the intensities of the H_β and D_β lines in the spectra of hydrogen and deuterium. For high power input to the filament these lines are sufficiently narrow and well separated, so that from their relative intensity we could determine sufficiently accurately the composition of an H and D mixture. The most detailed study we have made was of a mixture of 50% deuterium and 50% hydrogen. The recorded curve for these lines is given in Fig. 4.2. As can be seen, no difference (larger than ± 3%) was observed in the intensity and width between the H_β and D_β lines. Experiments were carried out at different values of the power and for other concentrations of hy-

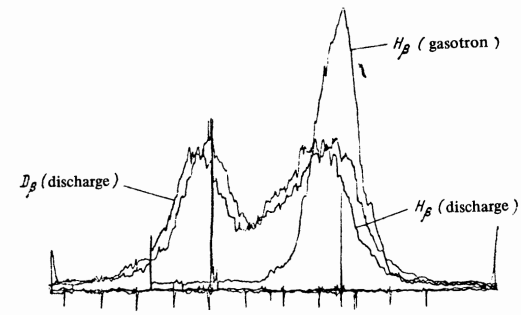

FIG. 4.2. Record of the D_β and H_β lines in a mixture of 50% D and 50% H. P_a = 13 kW, p = 1 atm. The spectrum of the discharge has been recorded twice.

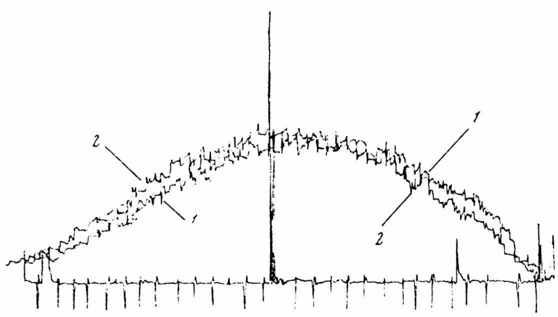

FIG. 4.3. Record of the distribution of intensities of the D_β (curve 1) and H_β (curve 2) lines along the diameter of the filament for the same mixture as in Fig. 4.2; P_a = 13 kW, p = 1 atm.

drogen and deuterium. In all these experiments the relative intensity of the H_β and D_β corresponded to the prepared mixture and did not vary with the power input to the discharge. We also measured the intensity of the H_β and D_β lines across a diameter of the filament. The record is reproduced in Fig. 4.3. As can be seen, in the mixture of 50% H and 50% D the distributions of intensity of H_β and D_β coincide within the limits of accuracy of the record. This shows that over the whole cross section of the filament the ratio of the densities of deuterium and hydrogen remains constant. Thus, we could discover no excess of hydrogen at the center of the filament due to thermal diffusion in the plasma in spite of the fact that with the ratio of the masses of the hydrogen ions to the deuterium ions equal to two, and for a temperature gradient determined from expression (4.25), one might expect in the hot region of the plasma a well pronounced difference in the densities of deuterium and of hydrogen. This contradiction apparently indicates that the mechanism adopted by us for the heat exchange processes of the ions differs from the actual one. It is possible to attain in two different ways the result that within that part of the filament where the H_β and D_β lines are emitted the ions should have a temperature gradient. The first way of achieving this is that the ion temperature should in general be much lower than the one determined from the Coulomb interaction (expression (4.29)). This explanation encounters great difficulties in the fact that the factors considered by us such as, for example, the collective interaction, should increase the heat exchange between the electrons and the ions and, consequently, should increase their temperature. Another possibility to remove this contradiction is to assume, conversely, that in this region the ion temperature is close to the electron temperature, $T_i \approx T_e$. In this case in the hot plasma there would again be no temperature gradient for the ions, and the ion temperature would be sufficiently high to be able to explain the observed neutron flux.

Such an explanation also encounters great difficulty, since for this one must assume that at the boundary of the hot plasma a temperature discontinuity exists for ions as well as for electrons. To justify the possibility of the existence of such a second discontinuity appears to be difficult, and this explanation for the time being appears to be of low probability. Thus, on the basis of available experimental data and theoretical concepts it does not appear to be possible for the time being to determine the ion temperature and its distribution across the diameter of the filament. We expect that it will be possible to solve this problem as the scale of the experiments is increased.

5. THE ELECTRIC CHARACTERISTIC OF A FILAMENTARY DISCHARGE

In this section we describe the method for the experimental determination of the current, of the skin-resistance and of the other parameters of the filamentary discharge which determine the electrodynamic processes occurring in it.

The resonator in which the discharge takes place is shown in Fig. 5.1. We denote the length of the cylinder 1 of the resonator by L and its radius by A. In the resonator, n half-wavelengths Λ of E_{01} type will be set up. We denote the wavelength of the eigenoscillations by λ_0, and the critical wavelength by λ_c. There exists the well known relationship

$$\lambda_0^{-2} = \lambda_c^{-2} + \Lambda^{-2}. \tag{5.1}$$

For small changes ΔL in the length of the resonator L the wavelength of its eigenoscillations λ_0 will be altered by $\Delta\lambda_0$:

$$\Delta\lambda_0 = \gamma\Delta L,$$

where

$$\gamma = \frac{2}{n}\left(\frac{\lambda_0}{\Lambda}\right)^3, \quad \Delta\lambda_0 \ll \lambda_0 \tag{5.2}$$

We denote the variable electric field at the center along the axis of the resonator by E_0, and its amplitude by $\hat{E}_0$, and then the high frequency field in the resonator will be given by the following well known expressions:

$$\begin{gathered} E_z = \hat{E}_0 J_0(k_c r)\cos\frac{2\pi}{\Lambda}z, \quad H_z = 0, \\ E_r = -\hat{E}_0\frac{\lambda_0}{\Lambda}J_1(k_c r)\sin\frac{2\pi}{\Lambda}z, \quad H_r = 0, \\ E_\varphi = 0, \quad H_\varphi = i\hat{E}_0 J_1(k_c r)\cos\frac{2\pi}{\Lambda}z, \\ k_c = 2\pi/\lambda_c, \quad \lambda_c = 2.61\,A. \end{gathered} \tag{5.3}$$

The oscillations occur with a frequency ω and a wavelength λ_0. We denote the length of the filamentary discharge by $2l$, the total current in an arbitrary cross section by I, and the density of the electric charge along the filament by δ. From the law of conservation of the quantity of electricity we have the relation

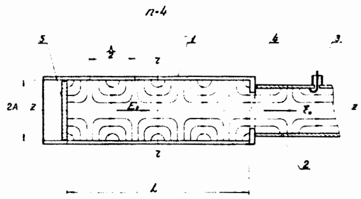

FIG. 5.1. Structure of the HF field in a resonator for E_{01} oscillations.

$$\frac{\partial I}{\partial z} = \frac{d\delta}{dt} = i\omega\delta. \tag{5.4}$$

By denoting by q the quantity of electricity carried across a cross section we have

$$I = \frac{dq}{dt} = i\omega q. \tag{5.5}$$

We denote all the variable quantities referring to the central section of the filament $z = 0$ by the subscript zero; then for the amplitude we have

$$I_0 = \dot{q}_0 = i\omega q_0 = i\omega \int_0^l \hat{\delta}\, dz, \quad I_0 = \hat{I}_0 e^{i\omega t}. \tag{5.6}$$

For the description of oscillatory processes in our system we choose as independent variables the intensity of the electric field at the center of the resonator E_0 and its time derivative $\dot{E}_0$, and also q_0 and $\dot{q}_0 = I_0$ over the central cross section of the filament. We write down the Lagrangian:

$$\mathcal{L} = \frac{1}{2} D_m \dot{E}_0^2 - \frac{1}{2} D_e E_0^2 + \frac{1}{2} f I_0^2 - \frac{1}{2}\frac{1}{c_p} q_0^2 - M_e q_0 E_0 + M_m \dot{q}_0 \dot{E}_0, \tag{5.7}$$

where the first four terms represent the electric and the magnetic energy of the resonator and of the filament, and the two last terms respectively their mutual energy. The term $D_e E_0^2/2$ represents the energy of the electric field; it is equal to

$$\frac{1}{2} D_e \hat{E}_0^2 = \frac{n}{8\pi} \int_0^A \int_c^{\Lambda/2} (\hat{E}_r^2 + \hat{E}_z^2) 2\pi r\, dr\, dz. \tag{5.8}$$

Utilizing (5.3) we obtain after integration

$$D_e = \frac{LA^2}{8} \left(\frac{\lambda_c}{\lambda_0}\right)^2 J_1^2(k_c A),$$

where

$$J_1(k_c A) = J_1(2{,}61) = 0{,}486. \tag{5.9}$$

At resonance the electric and the magnetic energy in the resonator are equal, and, therefore, we have

$$D_e = \Omega_0^{-2} D_m, \quad \Omega_0 = 2\pi c / \lambda_0, \tag{5.10}$$

where Ω_0 is the eigenfrequency of the resonator and λ_0 is the wavelength corresponding to it. We assume that the mutual energy between the field in the resonator and the filament is brought about only via the electric forces, and we neglect the magnetic coupling M_m. This is permissible when the length of the filament $2l$ is small compared to half a wavelength $\lambda_0/2$, and the filament is situated along the axis of the resonator ($r = 0$, $H_\varphi = 0$).

The mutual electric energy between the filament and the field is determined by the manner in which the charge is distributed along the length of the filament and is equal to

$$M_e q_0 E_0 = \int_{-l}^{l} \delta E_z z\, dz. \tag{5.11}$$

When in our experiments the length of the filament is small compared to $\Lambda/2$, then one can take the electric field E_z to be constant along the filament, and we then have:

$$M_e q_0 = \int_{-l}^{l} \delta z\, dz, \quad \Lambda \gg 2l, \quad E_z = E_0. \tag{5.12}$$

We denote the eigenfrequency of the oscillations of the filament by Ω_p. We then have

$$\Omega_p = c^2 / f c_p. \tag{5.13}$$

Differentiating the Lagrangian we obtain two fundamental equations for the oscillations:

$$\begin{gathered} \left[\frac{1}{c}\left(1 - \frac{\omega^2}{\Omega_p^2}\right) + i\omega R\right] q_0 + M_e E_0 = 0, \\ D_e \left[\left(1 - \frac{\omega^2}{\Omega_0^2}\right) + \frac{i}{Q}\right] E_0 + M_e q_0 = \beta \mathcal{E}_0, \end{gathered} \tag{5.14}$$

where $\beta \mathcal{E}_0$ is the force giving rise to the forced oscillations, $\mathcal{E}_0$ is the field in the feeder waveguide. Here we have also added terms with an imaginary coefficient which determine the dissipation of energy in the filament and in the resonator. The quantity Q is the quality factor for the oscillations in the resonator, while R is equivalent to the ohmic resistance of the filament.

Equations (5.14) enable us to determine the fundamental value of interest to us of the current I_0 in the central cross section of the filament. For this one has to determine the absolute value of the quantity $\beta \mathcal{E}_0$. This is carried out in the following manner. The intensity of the field $\mathcal{E}_0$ of the oscillations in the waveguide 2 from the supply generator is measured by the loop 3 (Fig. 5.1) by means of a detector or a thermocouple situated sufficiently far from the quartz window 4 through which the coupling with the generator takes place. The reading on the scale of the instrument is proportional to the intensity of the supply field $\mathcal{E}_0$. The coefficient β determines the degree of coupling between the resonator and the generator. We begin the determination of the quantity β by exciting oscillations in the resonator without a discharge for the same value of $\mathcal{E}_0$ twice: at first for a natural wavelength of the resonator λ_0', and then after a small retuning of the resonator for an eigen wavelength λ_0''. Then in accordance with expression (5.2) we have

$$\Delta\lambda_0 = \lambda_0' - \lambda_0'' = \gamma \Delta L, \tag{5.15}$$

where ΔL is the change in the length of the resonator which is produced by moving the partition 5 (Fig. 5.1). We then measure at the center of the resonator the absolute values of the corresponding magnitudes of the electric component of the field E_0' and E_0''. In carrying out the measurements it is also necessary to measure the frequencies of the generator itself. Let the corresponding wavelengths be λ' and λ''. We denote their difference by

$$\Delta\lambda = \lambda' - \lambda''. \tag{5.16}$$

For a high quality factor for the resonator and for small values of $\Delta\lambda$ and $\Delta\lambda_0$ by setting $q_0 = 0$ we can obtain from expression (5.14) with a high degree of accuracy the following values for $\beta\mathscr{E}_0$:

$$\beta\hat{\mathscr{E}}_0 = 2D_e\left(\frac{1}{\hat{E}_0'} - \frac{1}{\hat{E}_0''}\right)^{-1}\frac{\Delta\lambda_0 + \Delta\lambda}{\lambda_0},$$
$$\Delta\lambda \ll \lambda_0, \quad \Delta\lambda_0 \ll \lambda_0. \tag{5.17}$$

In this expression D_e and $\Delta\lambda_0$ are evaluated from (5.10). The values of $\Delta\lambda_0$ and $\Delta\lambda$ are calculated according to (5.2) and are determined directly from the oscillations of the resonator by measuring the wavelengths. We carried out a determination of the intensities of the electric field $\hat{E}_0'$ and $\hat{E}_0''$ in absolute units by measuring the deflections of a small hollow conducting sphere suspended near the center of the resonator. The method is described in detail in a previous paper [[7], p. 206]. In subsequent measurements the value of E_0 was determined from the deflection of a galvanometer connected to the loop 3 (Fig. 5.1) with a coefficient which determines its absolute value.

The following experimental observation simplifies further measurements in an essential manner. Experiment shows that when the discharge is struck for a constant value of $\mathscr{E}_0$ in the waveguide the field intensity in the resonator $\hat{E}_0$ is dimished by a factor of several tens. Thus, at resonance one can assume with a sufficient degree of accuracy that $\hat{E}_0$ is small and the quality factor Q is large; then from expression (5.14) by setting $\lambda = \lambda_0$ we obtain the simple relation

$$M_e q_0 = \beta\mathscr{E}_0. \tag{5.18}$$

This relation gives a direct connection between the current in the filament of the discharge and the supply field. In accordance with expression (5.5) the current in the central section of the filamentary discharge will be given by

$$\hat{I}_0 = \frac{\omega}{M_e}\beta\hat{\mathscr{E}}_0. \tag{5.19}$$

It now remains only to determine the value of the coupling coefficient. But in order to determine M_e, as may be seen from (5.12), one must know how the charge δ is distributed over the length $2l$ of the filament. For this it is necessary to know the distribution of capacitance and self inductance over z. For an approximate calculation it is possible to assume with a sufficient degree of reliability, as may be seen from the photograph of the filament in Fig. 3.6, that the boundaries of the plasma represent an elongated ellipsoid of revolution with semi-axes b and l. In terms of cylindrical coordinates r, z this ellipsoid is described by the equation

$$r^2 = b^2(1 - z^2/l^2). \tag{5.20}$$

We further assume that the ellipsoid is homogeneously electrified with a field $\mathscr{E}$ inside; then the charges do not penetrate into the filament and only on its surface charges appear whose linear density is equal to δ. We denote the cross section by S, and then have

$$\mathscr{E}dS = 4\pi\delta dz, \quad b \ll l. \tag{5.21}$$

Since the cross section is given by $S = \pi r^2$, utilizing (5.20) we obtain approximately

$$\delta = -\frac{\mathscr{E}}{2}\frac{b^2}{l^2}r, \quad b \ll l. \tag{5.22}$$

The quantity of electricity q_0 flowing across the central cross section will be given in accordance with the preceding expression by

$$q_0 = \int_0^l \delta\, dz = -\frac{\mathscr{E}}{4}b^2. \tag{5.23}$$

From the last two expressions we have

$$\delta = \frac{2q_0}{l^2}z. \tag{5.24}$$

On the other hand, in accordance with (5.12) and (5.22) we have

$$M_e q_0 = \int_{-l}^{l}\frac{\mathscr{E}}{2}\frac{b^2}{l^2}z^2\, dz = \frac{\mathscr{E}}{3}b^2 l. \tag{5.25}$$

From the last two expressions we obtain that for the ellipsoid the coefficient M_e of the mutual energy between the filament and the field in the resonator is equal to[2)]

$$M_e = {}^4/_3 l \tag{5.26}$$

From this expression and from (5.19) we obtain

$$\hat{I}_0 = \frac{3}{4}\frac{\omega}{l}\beta\mathscr{E}_0 \tag{5.27}$$

All the quantities on the right hand side can be measured. The absolute value of the quantity $\beta\mathscr{E}_0$ is determined by the method described above in terms of the deflection of a galvanometer connected to the loop 3 (Fig. 5.1). The frequency ω is measured by means of a wavemeter, the length of the discharge $2l$ can be determined as described in Sec. 2. Thus, one can determine the amplitude of the current $\hat{I}_0$ in the middle of the discharge. Experimental results for determining the average current I_0 as a function of the power P_a in a filamentary discharge in deuterium at a pressure in the range from 1.37 to 1.86 atm are given in Fig. 5.2. These results are obtained for a power P_a not exceeding 4 kW. At these power levels the length of the filament is considerably smaller than half a wavelength $\lambda_0/2$, and, therefore, it is permissible not to take into account the magnetic coupling between the filament and the field in the resonator. As can be seen from Fig. 5.2 we obtain a linear relationship between the power and the current. In order to determine the value of the current at high values of the power we extrapolate this linear dependence in accordance with the expression $P_a = 1.4 + 0.28\, I_0$.

The average power dissipated in the discharge is equal to

$$\bar{P}_a = {}^1/_2 R I_0^2. \tag{5.28}$$

This power is sufficiently high and could be determined calorimetrically in terms of the heating of the water which cools the resonator. For example, in the case when deuterium was used at pressures from 1 to 10 atm the power in the discharge P_a was in the range from 1 to 20 kW and could be, as indicated in Sec. 2, measured with an accuracy up to 3–8%. Having determined the power P_a and the value of the current I_0 in accordance with (5.27) we can determine the resistance R.

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2)This expression, which does not take into account coupling through the magnetic field, is an approximate one. More exactly we have: $M_e = {}^4/_3\, l(1-4l^2/\lambda^2)^{-1}$.

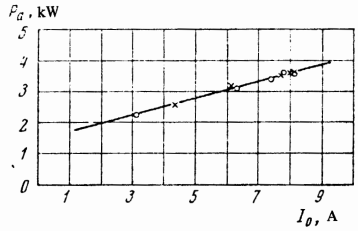

FIG. 5.2. Dependence of the current I_0 in the filament on the power input P_a determined from the experimental data for short filamentary discharges in deuterium. O–p = 1.37 atm, X–p = 1.86 atm, $P_a = 1.4 + 0.28\, I_0$.

For studying properties of plasma in the discharge we are interested in the skin-resistance ρ_s of the discharge. In order to determine it we assume that the discharge has along its length a circular cross section of radius b which varies as in an elongated ellipsoid. Then from (5.4) and (5.24) we obtain for the current in any cross section

$$I = -i\omega \int \frac{2q_0}{l^2} z\,dz = i\omega q_0\left(1 - \frac{z^2}{l^2}\right),$$
$$I = 0, \quad z = l. \tag{5.29}$$

According to expression (5.5) we have

$$I = \hat{I}_0(1 - z^2/l^2). \tag{5.30}$$

Experiments on the spectral investigation of the filament show that its temperature and density remain constant over the whole volume of the hot plasma. Therefore, we assume that the skin-resistance ρ_s remains constant over the whole length of the filament; then, utilizing (5.20), we find that the time average of the power dissipated in the segment dz will be given by

$$d\bar{P}_a = \frac{1}{2}\rho_s \frac{\hat{I}^2}{2\pi r}dz = \frac{\hat{I}_0^2\rho_s}{4\pi b}\left(1 - \frac{z^2}{l^2}\right)^{3/2} dz. \tag{5.31}$$

After integration we obtain

$$\bar{P}_a = \frac{3}{16}\frac{l}{b}\rho_s\overline{I_0^2}, \quad \overline{I^2} = \hat{I}_0^2/2, \tag{5.32}$$

from where, after comparison with expression (5.28), we find

$$\rho_s = \frac{16}{3}\frac{b}{l}R. \tag{5.33}$$

If we substitute into (5.32) the value of $\hat{I}_0$ from (5.19) and take into account (5.26), we obtain

$$\bar{P}_a = \frac{27}{512}\omega^2\frac{\rho_s}{bl}(\beta\mathscr{E}_0)^2. \tag{5.34}$$

Since, as is shown by experiment, as the intensity $\mathscr{E}_0$ supplied to the resonator is increased the length of the filament $2l$ and b both increase and the skin-resistance can also vary, the absorbed power will not be proportional to the square of $\hat{\mathscr{E}}_0$, but, as is shown by experiment, has a linear dependence. The experimental data given in Fig. 5.2 indicate a linear dependence of the current I_0 on the power input P_a. On the other hand, in accordance with expression (5.27) $\mathscr{E}_0$ is proportional to I_0, and, therefore, between $\mathscr{E}_0$ and the power a linear relationship should also hold. This linear relationship leads to the fact that in supplying the resonator from a high frequency generator in order to maintain high efficiency and not to overload the generator it becomes necessary as the power level is raised to increase the magnitude of β, i.e., to increase the coupling between the generator and the resonator as has been described in Sec. 2.

From expression (5.14) it can be shown that in order to obtain for a given value of $\beta\mathscr{E}_0$ the greatest current in the filament one must satisfy the condition

$$D_e\left(1 - \frac{\omega^2}{\Omega_0^2}\right)\left(1 - \frac{\omega^2}{\Omega_p^2}\right) = M_e^2; \tag{5.35}$$

in this case the current in the filament will be given by

$$\hat{I}_0 = \frac{\beta\hat{\mathscr{E}}_0}{RD_e(1 - \omega^2/\Omega_0^2)}. \tag{5.36}$$

Thus, for the optimum extraction of power from the generator into the resonator the latter must be somewhat detuned. This is essential when the length of the filament $2l$ is great, while the resistance R is small. Therefore, in practice one needs to tune the resonator by means of a small movable piston 11 (Fig. 2.1). It should be noted that for large lengths of the filament one can no longer neglect the magnetic coupling between the filament and the resonator. All the calculations have been carried out on the assumption that the current in the filament is entirely determined by the capacitance, i.e., it is reactive. To check this hypothesis we determine the active and the reactive impedance of the filament.

We calculate the value of the field E_0 produced at the center of the ellipsoid by the charges δ:

$$E_0 = 2\int_0^l \delta\frac{z\,dz}{(r^2 + z^2)^{3/2}}.$$

In accordance with expression (5.20) we take

$$r^2 + z^2 \approx b^2 + z^2, \quad b/l \ll 1,$$

and, utilizing (5.24), we obtain

$$E_0 = \frac{4q_0}{l^2}\int_0^l \frac{z^2\,dz}{(b^2 + z^2)^{3/2}} \approx \frac{4q_0}{l^2}\left(\ln\frac{2l}{b} - 1\right), \quad \frac{b}{l} \ll 1. \tag{5.37}$$

Utilizing (5.5) we obtain the reactive impedance of the filament:

$$Z_r = \frac{E_0}{I_0} = \frac{4}{l^2\omega}\left(\ln\frac{2l}{b} - 1\right). \tag{5.38}$$

Correspondingly the active impedance is equal to R and in accordance with (5.33) is given by

$$Z_a = i\frac{3}{16}\frac{l}{b}\rho_s. \tag{5.39}$$

Experimental data show that Z_r is by an order of magnitude greater than Z_a. The electrical field E_0 acts on the charge and stretches the filament. The stretching force in a homogeneous field is given by

$$F_z = E_0 q_0. \tag{5.40}$$

Utilizing expressions (5.5) and (5.39) we obtain

$$F_z = \frac{4I_0c^2}{l^2\omega^2}\left(\ln\frac{2l}{b} - 1\right). \tag{5.41}$$

The calculations carried out above are valid only in the case when the length of the filament is considerably smaller than half a wavelength. When the length of the filament approaches half a wavelength resonance occurs. In our type of resonator we could not obtain in a stable manner a filament length greater than half a wavelength. If this could be successfully accomplished, then the current would be determined not by the capacitance but by the inductance of the filament, and the phase of the current with respect to the field would be changed by an amount π.

6. THE STRUCTURE AND THE SHAPE OF THE FILAMENTARY DISCHARGE

In accordance with the structure of the filamentary discharge adopted by us the plasma is heated by the HF current when it flows in the layer at the boundary of the inner region of hot plasma. The skin-resistance of this layer is determined by the frequency of the current ω and by the condition of the plasma. Between the mean depth of penetration δ and the skin-resistance there exists the well-known relation:

$$\delta = \frac{c^2}{2\pi\omega}\rho_s\,[\mathrm{cm}]. \qquad (6.1)$$

In future we shall denote the skin-resistance by ρ_S and the specific resistance by η_S. The quantities ρ_S and η_S are related by the well-known expression

$$\rho_s = \eta_s/\delta = \frac{1}{c}\sqrt{2\pi\omega\eta_s}. \qquad (6.2)$$

The specific resistance of the plasma is in the general case determined by the following expression:[12]

$$\eta_s = \frac{m_e c^2}{e^2}\frac{\nu}{N_e}, \qquad (6.3)$$

where N_e is the density of the electrons, ν is the frequency of collisions between electrons and atoms, which is equal to $\nu = 1/\tau$, where τ is the time during which the electrons lose the directionality of the momentum acquired in the electric field. If the gas is not completely ionized then ν is the sum of frequencies of two types of collisions: ν_0 with a neutral atom and ν_i with an ion

$$\nu = \nu_0 + \nu_i. \qquad (6.4)$$

The frequency of collisions with neutral atoms is determined from the expression

$$\frac{\nu_0}{N_e} = \sqrt{\frac{2k}{m}}\frac{N_0}{N_e}T_e^{1/2}q_0, \qquad (6.5)$$

where q_0 is the cross section for collisions of neutral atoms with electrons. This quantity is determined experimentally. For deuterium it can be taken equal to $q_0 \approx 2.5 \times 10^{-16}\ \mathrm{cm}^2$ [[10], p. 150]. Collisions between electrons and ions are determined by the Coulomb interaction. Then for the specific resistance of the plasma we will obtain

$$\eta_s = \frac{\sqrt{m_e}c^2}{e^2}\left[\sqrt{2}\frac{N_0}{N_e}(kT_e)^{1/2}q_0 + \frac{1}{2}\left(\frac{\pi}{2}\right)^{1/2}\frac{e^4\Lambda}{(kT_e)^{3/2}}\right]. \qquad (6.6)$$

The skin-resistance evaluated from this expression in accordance with (6.2) as a function of the electron temperature is shown in Fig. 6.1 by the segment of the curve which is called the ordinary skin-resistance. On the same curve we have also taken into account the further reduction in the usual skin-resistance which begins at a plasma temperature in the neighborhood of 10^5 °K and which occurs when the frequency ν of the collisions of electrons becomes considerably lower than the frequency of the HF current in the plasma.

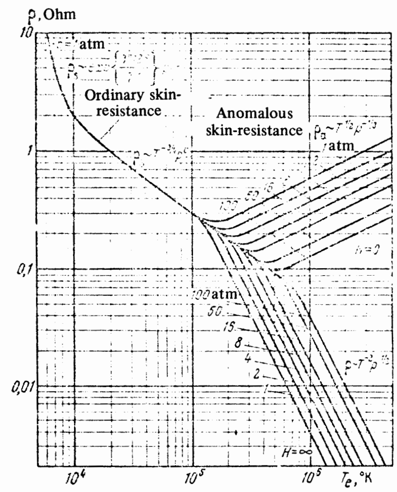

FIG. 6.1. Total skin-resistance as a function of the temperature of the electrons in the plasma calculated for a frequency $\omega = 10^{10}$.

From expression (6.6) it may be seen that at low degrees of ionization, when the ratio N_0/N_e is large, the resistance of the plasma is determined by collisions with neutral atoms. In our case this occurs in a cloud surrounding the hot plasma, where the value of N_0/N_e is greater than 10^3. Here the resistance of the plasma is high and the depth of penetration δ of the HF field is correspondingly large. If the height of the cloud $\bar{d}$ is less than δ, then the HF field will penetrate to the surface of the hot plasma without any appreciable absorption.

The specific resistance of the hottest plasma, since there are no neutral atoms present in it ($n_0 = 0$), is determined by Coulomb scattering. From the curve of Fig. 6.1 it can be seen that also in a hot plasma at an electron temperature of $T_e = 10^6$ °K the skin-resistance will turn out to be so small that for currents in the filament amounting to tens of amperes no heating of the filament will occur. We, therefore, assume that in a plasma there must exist also another more powerful mechanism for dissipating the ordered velocities of electrons arising due to the passage of a current. It is associated with the fact that at a high frequency ω and for large thermal velocities the electrons may leave the skin-layer and thereby destroy the ordered motion brought about by the current. This phenomenon was discovered at low temperatures and for HF fields in the investigation of metals. It was discovered by Pippard. Such a skin-resistance turned out to be much greater than the usual one, and was called anomalous. It can be easily seen that the mechanism giving rise to the anomalous skin-effect in metals is also applicable to plasma. We need only replace the Fermi-velocity of the electrons by their mean thermal velocity in the plasma; at the same time the expression itself determining the skin-resistance remains the same.

We give a simple derivation of the expression determining the anomalous skin-resistance in a plasma, since it shows in a graphic manner how this phenomenon arises when the mean free path of the electrons is large compared to the thickness of the skin-layer.

At the boundary of the plasma (Fig. 6.2) in a layer of thickness δ a current I flows which is equal to

$$I = \frac{e}{c} n_e \delta \Delta v, \tag{6.7}$$

where n_e is the electron density while Δv is the increment in their velocity in the alternating electric field. When the mean free path for an electron is greater than δ, the electron will freely leave this layer with a velocity v_x normal to the boundary, and will carry away the kinetic energy $m_e(\Delta v)^2/2$ acquired in the electric field. If there is no specular reflection of electrons at the outer surface of the plasma then the power lost over both boundaries will be equal to

$$P_s = n_e v_x \cdot {}^1\!/_2 m_e (\Delta v)^2. \tag{6.8}$$

The power lost in this manner is equal to the ohmic losses, while the velocity v_x normal to the layer is

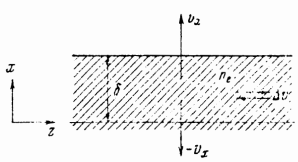

FIG. 6.2. Schematic diagram for calculation of the anomalous skin-resistance.

equal after averaging to one-half of the average thermal velocity. From the preceding expression we obtain

$$\rho_a I^2 = {}^1\!/_4 n_e v_e m_e (\Delta v)^2, \tag{6.9}$$

where ρ_a is the anomalous skin-resistance. Substituting into this expression the value of the current from (6.7) we obtain

$$\rho_a = \frac{1}{4} \frac{m_e c^2}{e^2 n_e} \frac{v_e}{\delta^2}. \tag{6.10}$$

Taking into account in accordance with (6.1) the relationship between the skin-resistance and the depth of penetration we introduce the plasma frequency for the electrons:

$$\Omega_e^2 = 4\pi n_e e^2 / m_e. \tag{6.11}$$

Then from (6.10) we obtain the skin-resistance expressed in ohms:

$$\rho_a = 30 \left[4\pi^3 \left(\frac{\omega}{\Omega_e} \right)^2 \frac{v_e}{c} \right]^{1/3}. \tag{6.12}$$

The expression for the skin-resistance of the plasma derived rigorously in a manner analogous to [14] is given by

$$\rho_a = 30\sqrt{3}\pi^{1/6} \left[\left(\frac{\omega}{\Omega_e} \right)^2 \frac{v_e}{c} \right]^{1/3}. \tag{6.13}$$

As may be seen, this expression gives a skin-resistance which is only 20% lower than the approximate one. The dependence on the pressure, the frequency and the temperature of both expressions is the same:

$$\rho_a \propto \omega^{2/3},\ T^{1/3},\ p^{-1/3}. \tag{6.14}$$

According to (6.6) the usual skin-resistance in the hot plasma is due to collisions between electrons and ions and has the following dependence:

$$\rho_a \propto \omega^{1/2},\ T^{-3/4},\ p^0. \tag{6.15}$$

Thus, the anomalous skin-resistance increases with the temperature while the ordinary one diminishes. In Fig. 6.1 are given curves for the dependence on T_e of the total skin-resistance calculated in accordance with (6.2), (6.6), and (6.13) at a frequency of $\omega = 10^{10}$. As can be seen, up to a temperature of $T = 10^5$ °K the resistance is determined by the ordinary skin-resistance, but above that temperature already by the anomalous one.

We determine the skin-resistance for hot plasma in the filament according to the data given in the Table (Sec. 3). For $P_a = 12.4$ kW, p = 1 atm, a = 0.45 cm and $T_e = 10^6$ °K we obtain from the curves of Fig. 6.1 $\rho_a = 0.59$ ohm.

From (5.32) we have the following expression for the current in the central cross section of the filament:

$$I_0 = \frac{4}{\sqrt{3}} \sqrt{\frac{P_a b}{l \rho_s}}. \tag{6.16}$$

If we take the length of the filament to be $2l = 10$ cm and in accordance with (3.12) b = 0.18 cm we then obtain for the current $I_0 = 63$ A. But if we determine the same current by extrapolating experimental data, obtained in the course of a direct measurement of the current and shown in Fig. 5.2, we then obtain $I_0 = 39$ A. Taking into account the approximate nature of the comparison the agreement may be considered to be satisfactory.

As can be seen from the experimental data quoted above, the power P_a which is dissipated in the filament attains values up to 18 kW. In the final analysis it is carried away by the heat flux through the gas from the filament towards the walls of the resonator. Let us consider the process of heat transfer from the filament. In photographs of the filament it can be seen that at a distance of two–three radii from the axis of the filament the gas no longer glows, and this shows that starting with this value practically no ionization is present, and one can assume that from this point the gas has the ordinary heat conductivity. We denote the temperature in this region by T_n. For deuterium this is 6000–7000°. We denote by a_n the radius of the region starting with which normal heat transfer begins. We consider the heat taken away from the ellipsoid of rotation of radius a_n and of the same length $2l$ as the filament. We denote the temperature in the gas surrounding this ellipsoid by T, and its heat conductivity by $\mathscr{K}$ [W/deg]. We assume that $\mathscr{K}$ depends on the temperature in the following manner:

$$\mathscr{K} = \mathscr{K}_0 (T/T_0)^{\varkappa}, \tag{6.17}$$

where $\mathscr{K}_0$ is the heat conductivity at the normal temperature of 273°K. It is well known that for a gas where the molecules can be regarded as hard spheres the index is $\varkappa = 1/2$. In actual fact, due to the dependence of the distance of closest approach of molecules in a collision on the value of the kinetic energy, the quantity $\varkappa$ is somewhat greater than $1/2$. If in the surrounding medium there are no sources of absorption or liberation of heat except for the filament itself, then according to the classical theory of heat transfer the temperature satisfies the equation

$$\operatorname{div} \mathcal{K} \operatorname{grad} T = 0. \tag{6.18}$$

Substituting the value for $\mathcal{K}$, we obtain

$$\nabla^2 T^{\varkappa+1} = 0. \tag{6.19}$$

The heat flux $P_{\mathcal{K}}$ created by the heat conductivity will be given by

$$P_{\mathcal{K}} = \iint \mathcal{K} \frac{\partial T}{\partial n} dS, \tag{6.20}$$

where the integral is taken over the surface of the ellipsoid. From this expression on introducing the value of $\mathcal{K}$ from (6.17) we obtain

$$P_{\mathcal{K}} = \frac{\mathcal{K}_0}{(\varkappa+1)\, T_0^{\varkappa}} \iint \frac{\partial T^{\varkappa+1}}{\partial n} dS. \tag{6.21}$$

Since it follows from (6.20) that $T_n^{\kappa+1}$ is a harmonic function, we can write by analogy with the electrostatic problem

$$P_{\mathcal{K}} = \frac{4\pi}{\varkappa+1} \frac{\mathcal{K}_0}{T_0^{\varkappa}} C T_n^{\varkappa+1}, \tag{6.22}$$

where T_n is the temperature of the surface of the filament, T_0 is the temperature of the resonator walls, while C is numerically equal to the capacitance of the filament with respect to the resonator. In our case when the filament is small compared to the resonator and is situated far from its walls C may be taken equal to the capacitance of a free ellipsoid of revolution with axes equal to a_n and l. We then have the well-known expression for the capacitance of an ellipsoid:

$$C = \frac{2l\varepsilon}{\ln[(1+\varepsilon)/(1-\varepsilon)]}, \quad \varepsilon^2 = 1 - \left(\frac{a_n}{l}\right)^2, \tag{6.23}$$

where ϵ is the eccentricity. Since our ellipsoid is elongated we have

$$C = \frac{l}{\ln(l/a_n)}, \quad a_n \ll l. \tag{6.24}$$

Thus, for a filament of radius a_n and long axis l we finally have

$$P_{\mathcal{K}} = \frac{4\pi}{\varkappa+1} \frac{\mathcal{K}_0}{T_0^{\varkappa}} \frac{l}{\ln(l/a_n)} T_n^{\varkappa+1}. \tag{6.25}$$

We calculate, as an example, the thermal flux for a filament in deuterium with parameters given in the Table (Sec. 3): P_a = 8.8 kW, $2l$ = 9.4 cm, a_0 = 0.4 cm. The radius a_n from the normal heat transfer begins we will take to be equal to three times the value of $a_0 : a_n$ = 1.2 cm. For dissociated molecules at a temperature of T_0 = 273°K we assume the heat conductivity to be $\mathcal{K}_0 = 2.16 \times 10^{-3}$ W/deg. For the temperature of the unionized gas we can take $T_n = 7 \times 10^3$ °K. Then on setting $\kappa = 1/2$, we obtain

$$P_{\mathcal{K}} = 4.5\,\text{kW}, \quad P_a / P_{\mathcal{K}} = 2. \tag{6.26}$$

Thus, only one half of the total power is removed through the heat-conducting surrounding gas.

Consequently, there exists another mechanism for taking heat away from the filament, and it is natural to assume that near the filament such a mechanism could be provided by the convection of the gas, which, as is well known, is often the main component of heat transfer in a gas.

The main temperature drop is near the filament, and therefore, to increase the heat flux in this region one must increase the heat conductivity in that neighborhood. Due to the fact that near the filament the gas temperature is high its density is less than the normal density by a factor of approximately 20, and, consequently, its volume heat capacity is small. Therefore, convection at ordinary velocities is not effective. Estimates show that both convective and turbulent methods of heat transfer are insufficient to explain the observed discrepancies between P_a and $P_{\mathcal{K}}$. The absence of any appreciable effect due to turbulence and convection is confirmed by experiment. If for a constant regime of the power input to the filament from a high frequency source one alters the velocity of rotation of the gas by a factor of several fold, it turns out that this has little effect both on the shape of the filament and on the value of the power input.

The increased heat conductivity of deuterium and of hydrogen in the high temperature domain which occurs in our experiments should possibly be explained by a heat transfer mechanism which was first pointed out by Nernst.[15] At the temperature of the surrounding gas the molecules become dissociated and molecular vibrations occur in them. This gives rise to an additional energy of the molecules the magnitude of which depends on the temperature. The diffusion transfer of this energy along the temperature gradient is what is responsible for the additional thermal conductivity. Theoretically it has been studied for hydrogen[16] and it was shown that by this method in the temperature range which happens to be close to the one possessed by the gas surrounding the plasma filament, this "portable" heat transfer may exceed the ordinary one by a factor of several fold. Numerical calculations of heat removal from the filament taking this "portable" heat transfer into account turn out to be a complicated computational problem, but estimates show that it can explain the increased heat removal from the filament which is observed in our experiments.

At the present stage of our investigation of the plasma filament we can assume that under all conditions the power taken away will be determined by the shape of the filament and will have a form analogous to the one given by expression (6.25):

$$\frac{P_a}{l} = \frac{f(T_n, p)}{\ln(l/a)}, \tag{6.27}$$

where $f(T_n, p)$ is a function of the temperature T_n at the surface of the filament, while p is the gas pressure. From this expression we obtain

$$\gamma = l/a = \exp(fl/P_a), \tag{6.28}$$

from where it can be seen that a small change in the indices strongly affects the ratio l/a. From this expression it follows that the ratio of the radius of the filament to its length is to a large extent determined by the conditions of heat removal which, thus, plays an important role in determining the shape of the filament.

It has been pointed out already that the filament can be stretched by the electric forces created by the HF field. The stretching force is equal to F_z, and its magnitude is given by expression (5.41). For our filaments its magnitude is of the order of 10^2 dyn.

The next force which acts on the filament is the compression of the filament by the so-called pinch effect. It is brought about by the fact that when a current flows over the surface of the filament and the magnetic field does not penetrate inside a normal pressure arises. Its value averaged over time is equal to

$$p_H = \overline{H_\varphi^2} / 8\pi \tag{6.29}$$

where $\overline{H_\varphi^2}$ is the average square of the magnetic field tangent to the surface of the filament. This field is determined by the density of the surface current:

$$\overline{H}_\varphi = 4\pi I / 2\pi r = 2I / r, \tag{6.30}$$

where I is the total current. Assuming that the radius of the cross section varies along the filament in accordance with (5.20) as in the case of an ellipsoid, we obtain by using (5.30) for the distribution of pressure along the filament

$$p_H = \frac{I_0^2}{2\pi b^2}\left(1 - \frac{z^2}{l^2}\right). \tag{6.31}$$

From this expression it can be seen that the pressure p_H which compresses the plasma has the greatest value at the middle of the filament and falls to zero at the ends of the filament. For large currents which occur in ordinary filamentary discharges between electrodes of capacitors this pressure, as is well known, can be many times greater than the pressure of the gas surrounding the plasma. Then the phenomenon of pinching occurs. But in our case, when the current is not great, the pressure at the middle section of the filament is of the order of 10^2 dyn.

In addition to magnetic forces electric forces can also affect the shape of the filament. They arise due to the fact that at the surface of the filament charges δ appear (5.24) which give rise to electrical forces normal to the surface. They produce a negative pressure in the plasma at the ends of the filament. Averaged over time it is equal to

$$p_e = \overline{E_n^2} / 8\pi, \tag{6.32}$$

where E_n is the amplitude of the normal component of the intensity of the electric field equal to

$$\overline{E}_n = 2\delta / r. \tag{6.33}$$

Substituting the value of r and δ from (5.20) and (5.24) and using (5.5) we obtain

$$p_e = \frac{2 I_0^2 c^2}{\pi b_0^2 l^2 \omega^2}\left(\frac{z}{l}\right)^2\left[1 - \varepsilon^2\left(\frac{z}{l}\right)^2\right]^{-1}. \tag{6.34}$$

In the derivation of (5.22) we have used an approximation for δ which is not valid at the ends of the ellipsoid; here the formula has been made more precise. This has led to the eccentricity ϵ appearing in (6.34). From this expression it can be seen that the force at the ends attains large values, and, therefore, it is not possible to use as a model for the plasma an ellipsoid which has a sharp boundary at the ends. But still the negative pressure at the ends will be greater than the magnetic compression. From this it follows that if the shape of the filament were determined by the pressure which is exerted on its surface by electromagnetic forces, then the filament would have the greatest diameter near the ends while its center would be compressed.

But in actual fact this does not occur. In the photograph of the filament (Fig. 3.6) it can be seen that it has the greatest cross-section in the middle. It is, therefore, clear that the electrical and magnetic forces in our case do not exert any appreciable influence on the shape of the filament and, consequently, cannot lead to an instability of its shape as is the case in the usual filamentary discharges.

As has been shown in Sec. 4, the high temperature of the electrons in the hot plasma of the filamentary discharge is possible due to the existence at the boundary of a double layer from which electrons are reflected elastically. Expression (4.17) gives the value of the surface tension of the double layer which could affect the shape of the filament, but, as has been noted already, its magnitude is too small for this.

Taking into account the estimate of the forces given above which act on the filamentary discharge and observing the behavior of the filament we think that the following simple mechanism explains sufficiently well why the filament has a shape close to that of an elongated ellipsoid, and why this shape is stable and does not depend on the electromagnetic forces which act upon it. The photograph 3.6 of the filament shows that there exists a sufficiently well defined boundary surface for the hot plasma; at such a boundary a temperature discontinuity must occur since the gas surrounding the hot plasma has a low temperature at which it has no appreciable electrical conductivity. In order for the gas surrounding the plasma to have a well defined temperature it is natural to assume that the radius of the cross section of the filament is the larger the more heat has been liberated at that point. The distribution of energy liberated along the filament is given by expression (5.31). One can foresee that a simple relationship between the energy liberated and the cross section of the filament is what determines the shape of the filament to be similar to an ellipsoid of revolution. At the present stage of our investigations an exact solution of this problem not only presents considerable mathematical difficulties but, primarily, requires a more detailed understanding of the mechanism of heat transfer between the plasma and the gas surrounding it.

With such a picture for the formation of the filament the mechanism providing its stability is apparently trivial. If at any point along the filament an expansion occurs, then the density of the surface current diminishes and likewise the liberation of heat. At the same time removal of heat increases due to the increase in the surface. All this leads to a cooling of the plasma and the expansion disappears. Converse phenomena occur in the case of an accidental contraction of the cross section of the filament: the surface current increases and this again leads to a smoothing out of the cross section. The nearness of the shape of the discharge to elliptical and the fact that its long axis is parallel to the electric field in the resonator are also from this point of view associated with stability, since only in this case when the current flows parallel to the length of the filament is complete homogeneity of the current density guaranteed everywhere on the surface.

As has been noted already at the end of Sec. 2 in the course of investigating the longitudinal stability of the discharge in the resonator, it can be seen from analogous considerations that the filament will tend to move to that region in the resonator where the electric field has a maximum value. This will occur because on that side of the plasma in the filamentary discharge where the higher field exists a greater density of the surface current will also occur, the heat influx from that side will increase and the amount of plasma in this direction will grow. Thus, a filament shape will result which is analogous to the shape of a flame. In the case of a filament its shape is determined by the supply of energy from the high frequency field, and in a flame it depends on the introduction of a fuel mixture. If this mechanism in fact determines the shape of the filamentary discharge its great stability must be preserved also when the dimensions of the filament are increased. Lately we have discovered an instability in the shape of the filament. This occurred in experiments in which we tried to obtain a discharge of the greatest possible cross section. This was achieved by increasing the input of HF power.

As has been already described in Sec. 2, as the power input was increased the length of the filament reached its limit which was equal to half a wavelength at the frequency of the input current. A further increase in power led to an increase in the cross section of the discharge without an increase in its length (cf., Figs. 2.4 and 2.5). It turned out that after a certain diameter has been attained the filament begins to be flattened and then to break up into two parts. In place of one filament two filaments were formed emanating from one point at a small angle, both somewhat shorter and thinner than the initial one.

A natural explanation of this phenomenon consists of the fact that when the filament attains its limiting length, the value of the HF current in it is determined, as always at resonance, by the active resistance, i.e., by the skin-resistance. Therefore, an inhomogeneity in the heating of the surface of the filament and the inhomogeneity caused by this in the value of the skin-resistance can give rise to a redistribution of the current density over the surface of the plasma, and this can lead to an unstable shape of the filament.

Thus, for a given frequency of the supply current apparently there exists not only a limiting length for the filamentary discharge but also a limiting diameter.

One of the principal difficulties in the experimental study of the shape of the plasma itself inside the filament is its small cross-section. Only with a transition to larger dimensions will it be possible to establish with greater confidence the mechanism which determines the shape of the discharge and its limiting dimensions.

7. INFLUENCE OF A MAGNETIC FIELD ON THE FILAMENTARY DISCHARGE

The mechanism for the effect of a magnetic field on plasma processes consists of the fact that between collisions electrons and ions move not along straight lines, but along circles with a Larmor frequency equal to

$$\omega_e = \frac{e}{m_e c} H = 1.76 \cdot 10^7 H,$$

$$\omega_i = 9.6 \cdot 10^3 Z \frac{m_p}{m_i} H, \tag{7.1}$$

where m_p is the proton mass and Z is the charge of the ion. If the time between collisions is τ and the velocity of the particles is v, then in the absence of the field the mean free path λ is equal to

$$\lambda_e = \tau_e v_e, \quad \lambda_i = \tau_i v_i. \tag{7.2}$$

The radii of the Larmor orbits are respectively equal to

$$r_e = v_e / \omega_e, \quad r_i = v_i / \omega_i. \tag{7.3}$$

In order that the magnetic field could introduce a noticeable change into the motion of particles in the plasma it is necessary that $\lambda \gg r$ and, consequently,

$$\tau_e \omega_e \gg 1, \quad \tau_i \omega_i \gg 1. \tag{7.4}$$

If this condition is not satisfied then the magnetic field has no effect on the gas kinetic processes in the plasma.

In studying the filamentary discharge we are interested in the effect of the magnetic field on the ion heat conductivity of hot plasma. The magnitude of the ion heat conductivity of a plasma in a magnetic field is theoretically determined. It is an isotropic, and while along the field it has the usual value already quoted by us in Sec. 4 (expression (4.26)), at right angles to the direction of the field it is equal to:[13]

$$\mathscr{K}_\perp = 1.3 \frac{k^2 n_i T_i}{m_i \omega_i^2 \tau_i}, \tag{7.5}$$

where τ_i—the time between collisions of ions—is given as before by expression (4.27). Comparing this heat conductivity in (7.5) with the heat conductivity in the absence of a field one can see that it is less by a factor of $(\omega_i \tau_i)^2$.

We consider the same problem which we solved in Sec. 4 for the radial heat conductivity in cylinders, but in the presence of a magnetic field directed along the axis of the cylinder. Utilizing expressions (4.24) and (4.27) we obtain

$$\mathscr{K}_\perp = C T_i^{\varkappa}, \quad C = 2.6 \cdot 10^{-15} \frac{n_e^2 \Lambda}{m_i^{1/2} \omega_i^2}. \tag{7.6}$$

In determining the temperature T_i we consider two limiting cases. The first is when the density n remains constant inside the cylinder. This is the case when the electron temperature T_e is considerably higher than the ion temperature T_i. Then, setting $\kappa = \frac{1}{2}$ according to (4.25) with the boundary condition $T_i = T_0$ we have for r = b:

$$T_i = \left[\frac{1}{8\pi} \frac{q}{C} \left(1 - \frac{r^2}{b^2} \right) + T_0^{1/2} \right]^2,$$

$$T_e = \text{const}, \quad n_i = n_e = \text{const}, \quad T_e \gg T_i, \tag{7.7}$$

where q is the power input per unit length of the cylinder. The process of heat removal proceeds in a somewhat different manner when the ion temperature is higher than the electron temperature. In this case the density of the plasma determines the ion temperature:

$$n_i = n_0 T_0 / T_i, \quad T^{\varkappa} = 1 / T^{2.5}. \tag{7.8}$$

Substituting these values into (7.6) we obtain $\kappa = -2.5$,

$$T_i = \left[T_0^{-3/2} - \left(1 - \frac{r^2}{b^2} \right) \frac{3}{8\pi} \frac{q}{C} \right]^{-2/3}, \quad T_i > T_e. \tag{7.9}$$

From this expression it may be seen that for a certain radius $r = b_m$ the temperature T_i becomes infinitely great. Setting the expression in square brackets equal to zero we obtain

$$\left(\frac{b_m}{b}\right)^2 = 1 - \frac{8\pi}{3}\frac{C}{qT_0^{5/2}}, \quad T_i = \infty. \tag{7.10}$$

The calculations described above have been made without taking into account the finite dimensions of the Larmor orbits, but in both cases considered above there exists a limitation on the increase of the temperature T_i which is imposed by the condition that a Larmor orbit with its center at the radius r must be contained within a cylinder of radius b, and consequently, $v_i \leq (b - r)\omega_i$, from where we obtain the value of the ion temperature at the boundary:

$$T_i \leqslant \frac{e^2H^2}{2m_ik}(b-r)^2. \tag{7.11}$$

The heat conductivity in a magnetic field given in (7.5) is derived on the assumption that in the interval between collisions the Larmor orbits remain motionless. But in actual fact it is sufficient for small fluctuations of the electric field to be present in order to make the centers of the Larmor orbits acquire a chaotic or, as it is said, a turbulent motion which increases the heat conductivity by a large factor. In order to take into account the effect of this turbulent motion in the filament we give a simple derivation of heat conductivity in a magnetic field which brings out well the physical nature of these processes.

As is well known,[17] the amount of heat transferred by the heat flux in a gas along the x axis is determined by the following general expression:

$$q_x = D_x \frac{\partial \varepsilon}{\partial T_i}\frac{dT_i}{dx} = \mathscr{K}_x \frac{dT_i}{dx}, \tag{7.12}$$

where the diffusion coefficient is given by

$$D_x = V_x \lambda. \tag{7.13}$$

Here λ is the mean free path, n is the particle density, V_x is the average velocity along the x axis as a result of thermal motion, equal to $|v_i|/3$, the quantity ϵ is the energy of the particles. In the case of a completely ionized gas the energy of the particles is equal to their kinetic energy:

$$\varepsilon = n_i k T_i. \tag{7.14}$$

If the hot plasma is situated in a magnetic field under the condition which is given by expression (7.4) then the mean free path between collisions will be determined by the diameter of a Larmor orbit. The distances between points at which collisions occur can be determined by any two points on the orbit. The orbit has a radius r_i; then the average distance $2\bar{r}_i$ between two points of the orbit will be given by

$$2\bar{r}_i = \frac{2r_i}{\pi/2}\int_0^{\pi/2} \cos\alpha \, d\alpha = \frac{4}{\pi} r_i. \tag{7.15}$$

Thus we obtain

$$\lambda = 2\bar{r}_i = \frac{4}{\pi}\frac{|v_i|}{\omega_i}. \tag{7.16}$$

Since during a time τ_i a particle on the average travels a distance $2\bar{r}$ then the velocity of its motion in the plasma in the direction of the x axis will be given by

$$V_x = \frac{1}{3}\frac{2\bar{r}}{\tau_i} = \frac{4}{3\pi}\frac{|v_i|}{\omega_i \tau_i}. \tag{7.17}$$

Substituting the values of ϵ, λ, V_x, D_x into expression (7.12) and taking into account $v_i^2 = 2kT_i/m_i$ we obtain

$$\mathscr{K}_\perp = \frac{32}{3\pi^2}\frac{n_i k^2 T_i}{m_i \omega_i^2 \tau_i}. \tag{7.18}$$

This expression agrees with the already well-known expression (7.5), but due to the simplified derivation the numerical coefficient in (7.18) is less by 20% than in the case of the rigorous derivation. We now assume that within a certain region of the plasma Δb greater than a Larmor diameter there arises due to fluctuations in the density of ions and electrons an alternating electric field E. Then the ions in this whole region will start moving along the radius with the velocity

$$V_r = cE_\varphi / H,$$
$$\Delta b < 2r_i, \quad V_r < v_i, \tag{7.19}$$

where E_φ is the component of the electric field normal to the radius and to the magnetic field. Therefore, the diffusion coefficient along the radius will consist of two parts:

$$D_r = \frac{1}{3}\left(\frac{4}{\pi}\right)^2 \frac{|v_i|^2}{\omega_i^2 \tau_i} + \tau_i V_r^2. \tag{7.20}$$

Approximate calculations show that at high values of heat conductivity it is sufficient to have quite small field fluctuations in order to bring about a large increase in the diffusion coefficient and, consequently, also in the heat conductivity. The only region in which the heat conductivity retains its low value is near the stationary boundary of the cylinder since here we have

$$V_r = 0, \quad r = b. \tag{7.21}$$

We determine the width of the boundary layer Δb in which fluctuations of the field have no appreciable effect on diffusion. If such a layer exists it must be not thinner than $2r_i$—a diameter of a Larmor orbit. Each ion can be regarded as a particle of cross section πr_i^2. The smallest possible monatomic layer will have a thickness $2r_i$. Therefore one can assume

$$\Delta b > 2r_i. \tag{7.22}$$

Then from (7.3) we obtain

$$\Delta b = \rho \frac{2}{\omega_i}\sqrt{2kT_i/m_i}, \tag{7.23}$$

where $\rho > 1$.

We further assume that due to the large turbulent heat conductivity in the central section of the cylinder from $r = 0$ to $r = b - \Delta b$ the temperature in it is uniform and equal to T_i. In a boundary layer of thickness Δb the heat removal will be determined by the heat conductivity $\mathscr{K}_\perp$, so that

$$q = 2\pi b \frac{T_i - T_0}{\Delta b}\mathscr{K}_\perp. \tag{7.24}$$

Using expressions (7.5) and (7.24) and assuming $T_i \gg T_0$ we obtain

$$q = 1.3\pi b \frac{k^2 n_i T_i^2}{\rho m_i \omega_i \tau_i \sqrt{2kT_i/m_i}}. \quad (7.25)$$

From this expression it can be seen that the heat conductivity in the plasma for large values of ω_i, in contrast to expression (7.5), falls off with the first power of the intensity of the magnetic field and in this is similar to the empirical expression proposed by Bohm [[12], p. 47].

The proposed picture of the phenomenon of heat transfer in a plasma reminds one of the process of heat conductivity which occurs in the flow of gas in pipes. Here also, when turbulence occurs, the temperature drop is concentrated across the boundary layer where the laminar flow is not much disturbed. The thickness of the laminar layer is what determines the magnitude of the heat transfer.

Setting $b/\Delta b = \rho_c$ we can determine the lowest critical value of ρ_c for which no turbulence arises in the plasma. From (7.23) we obtain its value:

$$\rho_c^{-1} = \frac{1}{b\omega_i}\sqrt{\frac{2kT_i}{m_i}} = \frac{r_i}{b}, \quad \rho_c > 1. \quad (7.26)$$

Very likely it will be possible to determine the quantity ρ_c only experimentally, as is the case with Reynolds critical number.

From expression (7.25) it is possible to show that even when the plasma goes over into a turbulent state the heat removal from a filament in a magnetic field remains small.

The magnetic field can also affect the heat conductivity which is due to electrons, but in our case we do not take it into account. As we have already indicated, the thermal insulation properties of the boundary layer are so great that a decrease in the heat conductivity brought about by the magnetic field cannot significantly affect the distribution of the temperature of the electrons in the plasma. As we have already noted, we consider the temperature T_e inside the filament to be constant.

It is well known that a magnetic field by acting on the motion of the electrons alters the specific ohmic resistance of the plasma. The conditions required for such an effect are the same as those that are given by expression (7.4). The time τ_e between collisions of electrons is determined by the following expression:[13]

$$\tau_e = \frac{0.28}{\Lambda}\frac{T_e^{3/2}}{n_e}. \quad (7.27)$$

It has been shown theoretically that for the case of a current flowing along a magnetic field the ordinary resistance is not altered, it is increased only when the current flows at right angles to the field but even then by not more than a factor of two.

It is not difficult to see that a magnetic field affects the anomalous skin-resistance strongly and results in its being reduced. The nature of this effect can be seen from the derivation of the anomalous skin-resistance given in Sec. 6. As can be seen in Fig. 6.1 the ohmic losses are due to the fact that the electrons in the course of their thermal motion leave the skin-layer δ and carry away with them the increment in the momentum $m_e\Delta v$ which produces the current. The bending of the electron trajectories in the magnetic field hinders this removal of the momentum, and ohmic losses are reduced. This process becomes effective when the magnetic field attains such a value for which the diameter $2r_e$ of the Larmor orbit is close to the thickness of the layer:

$$\delta \gtrsim 2r_e. \quad (7.28)$$

Utilizing expressions (6.1), (7.1), and (7.3) we obtain

$$H \gtrsim 4\pi\omega m_e / ce\rho_a. \quad (7.29)$$

From the picture given above it follows that the magnetic field affects the skin-resistance when it is directed parallel to the plane in which the current is flowing. It can be shown theoretically that as the field is increased the anomalous skin-resistance in the limit disappears completely and only the ordinary skin-resistance of the plasma remains. A quantitative determination of this effect presents certain difficulties, since it depends strongly on the conditions for the reflection of electrons from the boundary, and it has not as yet been established whether this reflection should be treated as specular or diffuse.

An experimental study of the filamentary discharge in a magnetic field was carried out using the solenoid described in Sec. 2. The magnetic field which it produced was parallel to the filament and attained a value of 22 kOe. So far the experiments have been restricted to measurements (for different values of the power and of the pressure up to p = 3 atm) of the external diameter 2a of the filament, of its length $2l$ and of the width $\Delta\lambda$ of the D_β line. In the course of this we have invariably noted in the magnetic field a decrease in the diameter 2a, a lengthening of the filament and an increase in $\Delta\lambda$. The experimental record of the D_β line in the filament in a magnetic field of 20 kOe is given in Fig. 2.3. The results of the measurements are shown in Figs. 7.1 and 7.2. The dependence of the narrowing of the filament and of $\Delta\lambda$ on the intensity of the field is shown in Fig. 7.3. As can be seen from these curves the external diameter of the filament in the magnetic field is decreased by 30%, while its length is increased by 10%, while the power input $P_a/2l$ remains constant. Therefore, in accordance with (5.34), since the experiments were carried out at a constant value of the intensity $\mathscr{E}_0$ in the supply resonator, it turned out that the resistance in the magnetic field was decreased to 30%. For a skin-resistance ρ_s = 0.59 ohm the depth of penetration according to (6.1) will be given by $\delta = 9.4 \times 10^{-3}$ cm. The diameter of a Larmor orbit in a field of 20 kOe for $T_e = 10^6$ °K and $v_e = 5.5 \times 10^8$ cm/sec is equal according to (7.3) to $2r_e = 6.3 \times 10^{-3}$ cm. Thus, according to (7.28) experimental data confirm the assumption that a decrease in the diameter of the filament is a result of the influence of the magnetic field on the anomalous skin-effect. A more exact quantitative investigation of this phenomenon is made difficult primarily by the lack of a possibility of measuring the internal diameter of the filament 2b. For the time being we sume that the internal diameter 2b is proportional to the external diameter 2a and is determined in accordance with expression (3.12).

In future we shall study this phenomenon in greater detail by utilizing measurements in the microwave and the extreme ultraviolet regions. An explanation of this phenomenon by any processes involving heat transfer by

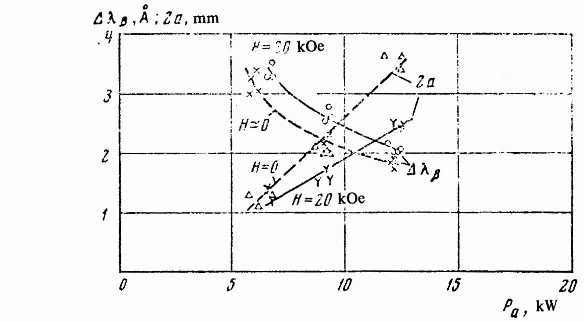

FIG. 7.1. Dependence of the diameter of the filament and of the broadening of the D_β line on the power in the discharge with a magnetic field and without it. Deuterium, 1.3 atm < p < 1.5 atm.

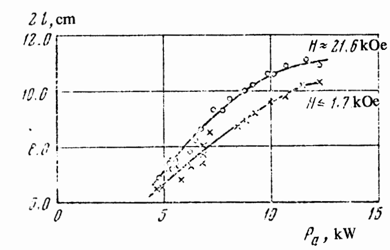

FIG. 7.2. Dependence of the length of the filamentary discharge on power input at low and high magnetic fields. Deuterium, 1.3 atm < p < 1.46 atm.

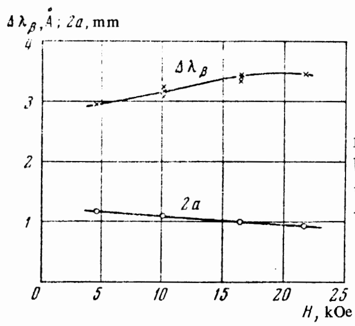

FIG. 7.3. Variation of the diameter of the discharge and line broadening as functions of the intensity of the magnetic field. Deuterium, p = 1.23 atm, 9.7 kW < 11.3 kW.

ions encounters a difficulty in the fact that according to our measurements the quantity $\omega_i \tau_i$ is close to unity and according to (7.4) the magnetic field cannot exert a strong influence on ionic processes.

If we attempt to explain this phenomenon on the basis of a cold plasma at a temperature of $T_e = 6500°$, then in this case no processes are known which reduce the specific resistance of the plasma. Moreover, such an explanation does not satisfy criterion (7.4) since the value of $\omega_e \tau_e$ is small. Thus, at the present stage we can explain the observed effect of a magnetic field on a filamentary discharge only by processes occurring in a hot plasma.

8. MAGNETOACOUSTIC OSCILLATIONS IN THE PLASMA OF THE FILAMENT

In this section we consider problems of increasing the ion temperature by magnetoacoustic oscillations. One of the characteristic properties of a hot plasma is the fact that as its temperature is increased the heat exchange between the ions and the electrons decreases. From expression (4.21) it can be seen that at a constant pressure and constant cross section of the filament πb^2 the electron density n_e is inversely proportional to the temperature T_e, and the power transferred to the ions will decrease as $T^{2.5}$.

The energy which is supplied to the filament all goes via the skin-resistance into heating the electrons. Thus, in order to increase the temperature of the ions it is necessary to supply power directly to them. The simplest and most direct method is to excite magnetoacoustic oscillations in the plasma the kinetic energy of which is produced by the oscillations of the ions. In our case this can be done if a magnetic field H is produced parallel to the filamentary discharge and an alternating field is superimposed in the same direction of amplitude ΔH and of such a frequency ω_a for which the field would not penetrate deeply into the plasma. Then near the surface of the filament a pressure arises equal to

$$\Delta p = \Delta H \cdot H / 4\pi. \tag{8.1}$$

For a field $H = 2 \times 10^4$ Oe the pulsing of the pressure will attain a magnitude of $\Delta p_n = 0.05$ atm.

We calculate the limiting power which could be directed across the boundary into the plasma of the filament. The electric field at the boundary of the filament will be given by

$$E = {}^1/_2 \Delta H \omega_a b, \tag{8.2}$$

where b is the radius of the filament. The average flux of power across the boundary will be determined by the Poynting vector. This is the limiting power; it is equal to

$$\frac{P}{2l} = \frac{\Delta H E}{8\pi} 2\pi b = \frac{(\Delta H)^2}{4} b^2 \omega_a. \tag{8.3}$$

For a value of ΔH = 30 Oe, a frequency of $\omega_a = 1.5 \times 10^8$ and b = 0.4 cm we have $P/2l$ = 500 W. If such additional power were absorbed in the filament it could be observed experimentally, and, therefore, we began to carry out experiments. For this purpose an apparatus was constructed which is schematically shown in Fig. 8.1. In essence this is our previous apparatus described in Sec. 2 and shown in Fig. 2.1. A magnetic field is produced in its resonator by the previously de-

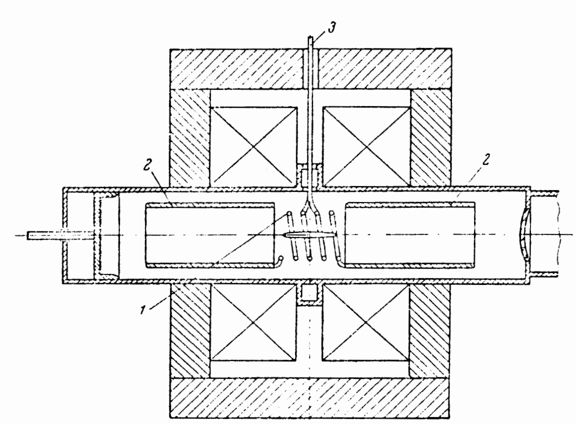

FIG. 8.1. Schematic diagram of the high frequency circuit for the excitation of magnetoacoustic oscillations in a filamentary discharge, 1–coil, 2–capacitors, 3–feeder line.

scribed solenoid with an iron yoke. The difference consists of the fact that a circuit consisting of the coil 1 of 2–3 turns and two cylindrical capacitors 2 serves to produce a variable magnetic field of amplitude ΔH. Such a construction enables one when the whole oscillatory circuit is placed within the resonator to obtain powerful oscillations of high frequency which reached values of $\omega_a = 1.5 \times 10^8$. The circuit is supplied by the line 3 which is connected to a fraction of the turns of the coil. The supply line was made of copper tubes through which water circulates and thus cooling of the circuit is achieved.

The principal difficulty in realizing such a system is associated with the choice of such dimensions and position of the circuit that it would not interfere with the main oscillations feeding the filament. The power input to the circuit in the feeder line 3 was measured in terms of the active component of the supply current. At an input power level of several kilowatts we attained an amplitude of $\omega H = 30$ Oe. The first experiments showed that, indeed, the filamentary discharge absorbs power. At first this phenomenon was interpreted by us as an effect on the plasma of acoustic oscillations, but this interpretation had to be abandoned, since it turned out that the absorbed power is considerably higher than that permitted by expression (8.3). Making a further study of this phenomenon we discovered that it is not even associated with the intensity of the oscillations of the magnetic field in the circuit. The matter was reduced to a simpler phenomenon. As can be seen from the construction of the oscillatory circuit shown in Fig. 8.1 in addition to the variable magnetic field ΔH in the region where the filamentary discharge is situated an axial alternating electric field is also produced by the capacitances 2 situated on the sides. It turns out that this field acts on the ionized gas surrounding the filamentary discharge and is strongly absorbed. When the circuit was replaced by another one in which this horizontal component of the field was absent, the absorption of power disappeared. Observations were carried out on the effect of the oscillation of ΔH in this circuit on the width of the discharge, on its length, on the intensity of emission of D_β and on $\Delta\lambda$. No appreciable effect on these quantities was observed. These experiments were carried out during that stage of our investigations when we assumed the radius a of the cloud to be the radius of the plasma in the filamentary discharge. Therefore, calculations of the power according to expression (8.3) were greater by a factor of 4–5.

A deeper investigation of the problem of the excitation of magnetoacoustic waves in the plasma showed that this is a difficult problem which, as will be seen, does not have a simple solution. First, it is difficult to excite acoustic waves by pressure because at the boundary the gas has a density which is by 2–3 orders of magnitude greater than that of the plasma. Therefore, in making calculations concerning radial high frequency oscillations the boundary should be regarded as a stationary one. Oscillations can be excited in the plasma only if the pressure Δp (expression (8.1)) is applied not at the boundary itself but somewhat deeper. We give an example of a possible mechanism for the excitation of oscillations in the following theoretical investigations.

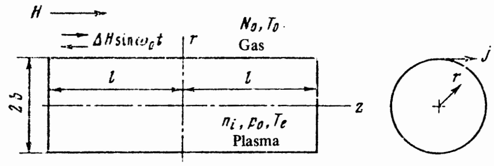

FIG. 8.2. Notation adopted for making calculations concerning radial magnetoactoustic waves in the plasma of the filament.

If the filament has a skin-resistance ρ_s [ohm], then the depth of penetration of the field δ is equal to

$$\delta = \frac{10^9}{2\pi\omega_a}\rho_s. \tag{8.4}$$

In the case that the plasma has a high conductivity this quantity can be small, but not smaller than the depth δ_0 which determines the density of electrons in the plasma. It is possible to make an estimate of this quantity from the relation $\delta_0 \approx (\lambda_l/2\pi)^2 b^{-1}$ where λ_l is the wavelength of the proper plasma oscillations.

At the surface of the filament an azimuthal current is produced with an amplitude equal to

$$j = \Delta H/4\pi, \tag{8.5}$$

which on interacting with the magnetic field H gives rise to a normal pressure $jH \sin \omega_a t$ which excites radial magnetoacoustic waves.

As has been noted already, the plasma is adjacent to a gas whose density is by a factor of 10^3 greater than the density of the plasma, and, therefore, we assume in our calculations that at the boundary at $r = b$ the plasma remains stationary:

$$\Delta r = 0, \quad r = b. \tag{8.6}$$

If the normal force Hj acting on the plasma were concentrated only at the boundary surface itself, then no oscillations could be generated in the plasma. But since the current penetrates to a certain depth oscillations will be generated even in the case of a stationary boundary.

Figure 8.2 represents a filament in terms of the coordinates adopted by us. For the sake of simplicity we assume the filament to be a cylinder. We denote the wave number by $k = 2\pi/\lambda_a$, the plasma density by $d_i = n_i m_i$ and the gas pressure by p_0. Then under the condition that the frequency is considerably lower than the plasma frequency Ω_e and greater than the cyclotron frequency ω_i we obtain the velocity of magnetoacoustic radial waves

$$V^2 = p\gamma/d_i, \quad V = \omega_a/k, \tag{8.7}$$

where

$$p = p_0(1 + H^2/4\pi\gamma p_0)$$

(γ is the adiabatic exponent). We consider the case of excitation of oscillations when the depth of penetration of the current δ is small compared to the radius of the plasma filament:

$$\delta \ll b.$$

Under this condition we can treat the process of the interaction between the current and the field at the boundary of the filament as a plane case. We denote the distance from the boundary by **x**. The normal force acting in the plasma will be equal to

$$F = \frac{Hj}{\delta} e^{-x/\delta} \sin \omega_a t. \tag{8.9}$$

We obtain the equation for the propagation of longitudinal waves in the usual manner by considering the equilibrium of the element dx:

$$\Delta \ddot{x} d_i + \frac{\partial \Delta p}{\partial x} = F, \quad \frac{\partial \Delta x}{\partial x} + \frac{\Delta p}{\gamma p} = 0; \tag{8.10}$$

from this equation and from expression (8.7) we obtain

$$\Delta \ddot{x} - V^2 \frac{\partial^2 \Delta x}{\partial x^2} = \frac{F}{d_i}. \tag{8.11}$$

Substituting the value of F from (8.9) we solve this equation under the boundary conditions (8.6). Utilizing (8.7) we obtain under the condition at the boundary $\Delta x = 0$, $x = 0$

$$\Delta x = -\frac{Hj\delta}{d_i [V^2 + (\delta\omega_a)^2]} [e^{-x/\delta} \sin \omega_a t + \sin (kx - \omega_a t)],$$
$$\Delta p = -\frac{Hj\delta\omega_a V}{V^2 + (\delta\omega_a)^2} \left[\frac{1}{\delta k} e^{-x/\delta} \sin \omega_a t - \cos (kx - \omega_a t) \right] \tag{8.12}$$

At a distance x from the boundary between the plasma and the gas when it is considerably greater than δ (the depth of penetration of the current) a progressive wave is formed which is determined by the expressions

$$\Delta \dot{x} = \frac{Hj}{d_i V} \frac{\beta}{1+\beta^2} \cos (kx - \omega_a t), \quad \Delta p_0 = Hj \frac{\beta}{1+\beta^2} \cos (kx - \omega_a t). \tag{8.13}$$

In this expression we have introduced the notation

$$\beta = \delta\omega_a / V = 2\pi\delta / \lambda_a. \tag{8.14}$$

Thus the quantity β is determined by the ratio of the depth of penetration of the current into the plasma to the wavelength of the magnetoacoustic wave in the plasma.

When the process of generation occurs at the surface of the plasma filament and the radius of the filament b is large compared to the depth of penetration δ, then the average power $\bar{P}_r$ which passes through the cylindrical surface of radius r will be given by

$$\bar{P}_r = 4\pi r l \frac{1}{T} \int_0^T \Delta p_0 \Delta \dot{r}_0 \, dt. \tag{8.15}$$

We set

$$x = b - r, \quad \Delta \dot{x} = -\Delta \dot{r}; \tag{8.16}$$

and obtain

$$\bar{P}_r = -2\pi b l \frac{(Hj)^2}{V d_i} \frac{\beta^2}{(1+\beta^2)^2}. \tag{8.17}$$

This expression has a maximum when $\beta = 1$; utilizing (8.7) we obtain

$$\bar{P}_{rm} = -\frac{\pi}{2} bl \frac{j^2 H^2}{\sqrt{p_0 d_i (1 + H^2/4\pi p_0)}},$$
$$\lambda_a = 2\pi\delta, \quad b > \delta, \tag{8.18}$$

for plasma $\gamma = 1$.

When the pressure $H^2/8\pi$ produced by the magnetic field is either small or large compared to the gas pressure p_0 we have two limiting cases:

$$P_{rm} = -\pi^{3/2} bl \frac{j^2 H}{\sqrt{d_i}}, \quad \frac{H^2}{4\pi} \gg p_0,$$
$$P_{rm} = -\frac{\pi}{2} bl \frac{j^2 H^2}{\sqrt{d_i p_0}}, \quad \frac{H^2}{4\pi} \ll p_0. \tag{8.19}$$

The propagation of an acoustic radial wave in a cylinder is, as is well known, determined by the following expression:

$$\frac{\partial \Delta p}{\partial r} = -d_i \Delta \ddot{r}, \quad \frac{\partial (r \Delta r)}{r \partial r} = -\frac{\Delta p}{\gamma p}, \tag{8.20}$$

where the velocity of propagation of the waves is determined as before by expression (8.7). For a wave progressing into the cylinder we have the following solution:

$$\Delta p_0 = A [J_0(kr) \sin (\varphi - \omega_a t) + N_0(kr) \cos (\varphi - \omega_a t)],$$
$$\Delta r_0 = \frac{A}{d_i V} [J_1(kr) \cos (\varphi - \omega_a t) - N_1(kr) \sin (\varphi - \omega_a t)], \tag{8.21}$$

where A and φ constants. It can be shown that this expression indeed corresponds to a progressive wave. We substitute these values into (8.15) and utilize the Wronskian:

$$J_0 N_1 - J_1 N_0 = -2/\pi kr. \tag{8.22}$$

We obtain that the average power of the wave flux will be constant and equal to

$$\bar{P}_r = -A^2 \cdot 4l / \omega_a d_i. \tag{8.23}$$

Equating this expression to (8.17) we determine the quantity

$$A = \sqrt{\frac{\pi}{2} bk} \, Hj \frac{\beta}{1+\beta^2}. \tag{8.24}$$

When the wave is propagated inwards from the surface of the plasma the energy density of the oscillation becomes infinite. The velocity $\Delta \dot{r}$ near the axis of the cylinder varies as

$$N_1 \to -2/\pi k r_n, \quad k r_n \ll 1, \tag{B}$$

and, therefore, we obtain from (8.21)

$$\Delta \dot{r}_0 = \frac{2A}{\pi \omega_a d_i} \frac{1}{r_n} \sin \omega_a t. \tag{8.25}$$

The kinetic energy of the ions in the plasma on the axis of the filament will be equivalent to the temperature:

$$T_i = \frac{\Delta \dot{r}^2 d_i}{2 k_0 n_i} = \frac{1}{2\pi k_0 n_i} \frac{b}{k r_n^2} \frac{(Hj)^2}{p_0 + H^2/4\pi} \frac{\beta^2}{(1+\beta^2)^2}, \tag{8.26}$$

where k_0 is the Boltzmann constant.

The smallest value of the radius r is apparently determined by that quantity of ions and electrons for which the plasma ceases to oscillate as a continuous medium. This quantity is determined by the Debye radius equal to

$$r_n^2 = k_0 T_e / 4\pi e^2 n_e, \tag{8.27}$$

where n_e is the electron density, T_e is the electron temperature. On reaching this radius the waves will be absorbed. Can one assume that as a result of this absorption their energy goes over into the thermal motion of the ions in the plasma? This is as yet an unanswered question, but it is a very important one, since for the heating of ions it is necessary that a significant fraction of acoustic oscillations would be absorbed by them. In the case of the method described above for the excitation of plasma oscillations ohmic losses in the skin-layer are also unavoidable. They can be estimated.

If, as before, we treat the filament as a cylinder of radius b and of length $2l$ then the average ohmic losses will be given by

$$\bar{P}_\rho = 2\pi l b \rho_s j^2. \qquad (8.28)$$

By using (6.1) in an approximate fashion we obtain in accordance with expression (8.14)

$$\rho_s = 2\pi \frac{V}{c^2} \beta, \qquad (8.29)$$

from which we have

$$P_\rho = 2\pi b l \frac{2\pi V}{c^2} \beta j^2. \qquad (8.30)$$

The ratio of the acoustic power to the power of the ohmic losses will be equal in accordance with (8.17) and (8.7) to

$$\chi = \frac{P_r}{P_\rho} = \frac{1}{2\pi} \frac{H^2}{p^2 + H^2/4\pi} \frac{\beta}{1+\beta^2} \qquad (8.31)$$

From here we obtain

$$\chi = \frac{2\beta}{1+\beta^2}, \quad \frac{H^2}{4\pi} \gg p. \qquad (8.32)$$

The maximum value will be $\chi = 1$ for $\beta = 1$. Thus, the ohmic losses can be equal to or greater than the power which is expended in maintaining acoustic oscillations.

If in our experiments described at the beginning we calculate in accordance with (8.17) the power input to the filament it will turn out to be in the range from 100 to 200 W for the whole filament, and in our experiments it does not appear to be possible to observe it. As can be seen from (8.3) the transfer of energy by magneto-acoustic oscillations increases with the square of the cross section and reaches a practical value when the dimensions of the filament are considerably greater than those which were realized in our apparatus.

The problem as to how to achieve effective heating of ions in the filament does not to date have a definite solution. The most promising direction is the excitation in the plasma of acoustic oscillations either radial or axial. Of great interest also is the action of the field on the cyclotron motion of the ions since here one might utilize resonance absorption. Of course, heating of the ions can also occur as a result of a collective interaction with electrons. As is well known, it has been observed, but so far there is no quantitative estimate of it. At this stage of the investigations of a filamentary discharge these problems must be regarded as some of the fundamental ones. For the time being their solution should be sought experimentally utilizing filaments of large dimensions.

9. CONCLUSION

The analysis of the experimental material presented in the preceding sections leads to the important result that the plasma at the center of the filament should be regarded as hot. This follows most convincingly from the intensity of its emission in the extreme ultraviolet (1000 Å) (Sec. 3) and also from the effect of a magnetic field on the shape of and on the emission from the filament (Sec. 7). According to present theoretical ideas these phenomena cannot occur in a cold plasma. The sum of the temperatures of the electrons and of the ions can be evaluated most reliably from (3.3) in terms of the limiting value of the frequency of emission in the microwave region (Fig. 3.6). If the temperature of the ions is low then in the hot region of the plasma in the filament the electron temperature is above a million degrees. The possibility of the existence of a plasma of such a high temperature is explained by us by analogy with gas discharge tubes in terms of the appearance at the boundary of the plasma of a double layer which reflects electrons elastically. Thus a discontinuity in the electron temperature is produced. Theoretical calculations of the structure of the double layer (Sec. 4) show that it is realizable and that its characteristics agree with the known experimental data which determine the interaction between ions and electrons. In the model of the structure of the filament adopted by us with an ellipsoidal region filled with hot plasma and surrounded by a cloud of cold plasma the high frequency current flows over the boundary of the ellipse in a skin-layer. In Sec. 5 a method is described for measuring the current and the results are given in Fig. 5.2. The high resistance of the boundary layer of the hot plasma is explained by analogy with metals by the existence of an anomalous skin-resistance. Numerical calculations confirm this well (Sec. 6).

The elliptic shape of the filament and its great stability are explained more simply than we had at first supposed. The filament is formed in that region of the electromagnetic field in which power can be supplied to it most efficiently. Thus, its shape and its stability are very similar to the stability of the flame of an ordinary candle, the shape of its flame is also determined by the supply of fuel from the wick and by the air flow on the outside. The length of the plasma filament is limited by half a wavelength of the high frequency field, because in such a case the greatest power input to the discharge is achieved. Experiment shows that after the plasma filament has attained this length a further increase in the power input leads to an increase in the cross section which also reaches a limiting value after which the filament begins to break up into two parts (Sec. 6). Thus, for a given frequency of the supply current there exists a limiting size of the filament. The investigations carried out by us have determined the electron structure of the filament sufficiently fully. The existing theoretical ideas concerning the properties of plasma enable us to give a quantitative interpretation of the observed phenomenon.

The ions have turned out to present the greatest difficulty for an experimental study. The determination of the density of ions in the discharge does not present any difficulty since it is equal to the electron density. But inside the filament the hot plasma is not in equilibrium, and the ion temperature T_i can be considerably lower than the electron temperature T_e. The most reliable method for determining T_i utilizes the partial pressure which the ions exert. As has been pointed out already, to achieve this one must in accordance with expression (3.3) make a sufficiently accurate determination of the plasma density N_e and the electron temperature T_e. The plasma density can be determined sufficiently accurately by the cutoff in the microwave region (the curve of Fig. 3.5), but so far there is no possibility of accurately measuring the electron temperature in terms of the bremsstrahlung. If one could find a reliable theory which quantitatively determines the effect of a magnetic field on the filamentary discharge which manifests itself in the experimental data described in Sec. 7, then this could give a very reliable method of determining T_e. But so far no such theory exists.

The method of determining the ion temperature in terms of the intensity of neutron emission is also sufficiently reliable and simple. But this emission becomes measurable only at an ion temperature above a million degrees. At lower temperatures this method is inapplicable. Therefore, for the time being we estimate the ion temperature by means of a calculation on the basis of the Coulomb interaction between ions and electrons. This interaction has been well studied theoretically, it gives simple numerical relationships. By this method we find that the temperature of deuterium ions at the center of the filament is in the neighborhood of 10^5 °K (cf. Sec. 4). This temperature is insufficient to explain the existence of the weak neutron emission observed by us which we described in the Introduction (Sec. 1) and which indicates a corresponding ion temperature in the neighborhood of 7×10^5 °K. One can draw conclusions regarding the temperature of the ions in an indirect manner by measuring the gradient of their temperatures. As is well known, this gradient determines the thermal diffusion processes in the plasma. Experiments on the thermal diffusion of hydrogen in deuterium described in Sec. 4 gave an unexpected result since they demonstrated its absence. Thus, determination of the ion temperature is at present one of the fundamental and most interesting problems in the study of a filamentary discharge.

In addition to the experiments described in the preceding sections we have observed in plasma a number of other phenomena which we have not as yet had time to study in detail, although a quantitative study of these phenomena will further deepen our understanding of plasma processes in a filamentary discharge.

We shall indicate the more interesting ones of them. We modulated the high frequency power supplied from the nigotron to the discharge, and observed variations in the intensity of emission from the filament in the visible region of the spectrum. Variations of intensity were observed only when the modulation frequency was not higher than 10^5 Hz. Approximate estimates have shown that this corresponds to the relaxation time for a hot plasma.

The diffuse form of the discharge was also investigated. As has been pointed out in the Introduction, it appeared at low power. Before assuming the shape of a filament the discharge had a diffuse shape of relatively low luminosity. It did not have a sharp boundary for the luminous cloud and the shape of the discharge was closer to oval than to filamentary. Experiment showed that this type of discharge is produced more easily at low pressures (below 1 atm). Under these conditions it can exist over a wider range of power. At pressures of 3–4 atm we did not succeed in producing such diffuse discharges in hydrogen and in deuterium. The power needed to maintain diffuse discharges is less than for a filamentary discharge and lies in the range of 2.5–3 kW. In the diffuse discharge the D_β line had a width of only 0.5 Å which corresponds to a degree of ionization of 10^{-4}–10^{-5}. It is natural to suppose that the diffuse state of the discharge in contrast to the filamentary state consists only of cold plasma.

A curious phenomenon was observed in experiments when the discharge was struck in helium which we took from a gas cylinder. In this case the shape of the discharge reminded one more of its diffuse state, although in the middle of the discharge one could nevertheless see a filament. Unexpectedly it turned out that the visible spectrum of this discharge does not contain a helium line, but only a hydrogen line, even though the content of hydrogen in the mixture was not greater than 1%. In order to obtain the purest possible helium we took it from evaporating liquid He. Only then did helium lines appear in the spectrum. In this case the hydrogen Balmer lines still did not disappear, but the discharge became even more diffuse and the filamentary structure at the center even less pronounced. These experiments have shown that the presence of even a small quantity of hydrogen creates favorable conditions for the production of a filamentary discharge. From the point of view of the model adopted by us as described in Sec. 4 it is natural to explain this phenomenon by the fact that hydrogen atoms have the most suitable properties for the establishment of a boundary layer. In accordance with expression (4.10) the large cross section q_p for charge exchange leads to small losses in the boundary layer. The recombination coefficient also affects the losses in the boundary layer. Possibly the value of these coefficients in the case of hydrogen atoms favors the creation of a boundary layer. We propose to make a more detailed study of this phenomenon. It is probable that a filamentary discharge can be produced in helium without an admixture of hydrogen only if the gas pressure is high.

Production of a filamentary discharge in pure argon also encounters difficulties. The discharge has a rather diffuse structure which is shot through with luminous threads randomly situated in it. A small admixture of hydrogen immediately facilitates the production of a filamentary discharge.

A more detailed study of these phenomena will most likely enable us to achieve a deeper understanding of the mechanism of the processes leading to the production of a filamentary discharge.

Further development of these investigations is at present limited by the scale of our present experiments. In our apparatus described in Sec. 2 the radius of the filament of hot plasma is not greater than 1.5–2 mm and and the double layer covering it is of approximately the same thickness. It is clear that with such small dimensions of the filament it is difficult to study its structure in detail. In the course of further developments of our investigations the scale of our experimental apparatus will be increased and consequently the cross section of the filament will be increased.

The difficulty in the study of the structure of the plasma filament is associated with the fact that the emission from the external cloud is superimposed on the emission from the hot plasma. Therefore, one should transfer the study into the domain of the extreme ultraviolet where there is practically no emission from the cloud. These investigations can be carried out with greater success when the electron temperature of the hot plasma is higher, and this, as has been shown in Sec. 3, is achieved by increasing the cross section of the filamentary discharge.

According to our ideas an increase in the dimensions of the filament will lead to an increase in the electron temperature. At the same time, as has been indicated in Sec. 4, the ion temperature will not necessarily increase, it could even decrease, since the power transferred from the electrons to the ions in accordance with expression (4.20) falls with an increase in their temperature. But an increase in the dimensions of the filament opens up a possibility of realizing an independent power input to the ions by means of magnetoacoustic oscillations in the plasma. As has been indicated already in Sec. 8 in order to excite magnetoacoustic oscillations one should produce in the filament a longitudinal magnetic field. This field will also reduce the radial thermal conductivity of the ion gas (cf., Sec. 7), and this will considerably raise the temperature of the ions in the internal portion of the hot plasma. Since at the boundary of the hot plasma the temperature will be the same as in the absence of a magnetic field, it is natural to assume that this increase in the temperature of the ions will not affect the shape and the stability of the filamentary discharge. As can be seen from expressions (8.3) and (8.17) the input to the ions of sufficiently high power in order to heat them appreciably can be achieved only with a sufficiently large diameter of the filament. The temperature T_i of the ions must be raised sufficiently that it should reach 1–2 millions of degrees. Then neutron emission will appear sufficiently intense for a reliable measurement of the ion temperature. The theory of excitation of magnetoacoustic oscillations which we developed in Sec. 8 and also the theory of thermal insulation for the ions given in expressions (7.7) and (7.25) enable us to calculate the dimensions of the filament needed to obtain such an ion temperature. The principal indefiniteness in these calculations is the fact that so far no theoretical solution has been found as to what fraction of the energy of the acoustic oscillations will be utilized to heat the ions, and what part will be used to heat the electrons. So far no account has been taken in these calculations of the collective interaction which will apparently also raise the ion temperature. The production and study of the thermonuclear process in the filament can, of course, also have a great practical significance for nuclear energy, but in addition to that a study of the filamentary discharge itself in which hot plasma exists continuously at exceptionally high temperatures and high pressures must lead to a deeper scientific understanding of a number of plasma processes.

[1] P. L. Kapitza, In the collection of articles "Elektronika bol'shikh moshchnosteĭ" (High Power Electronics) 1, Nauka, 1962.

[2] P. L. Kapitza, Dokl. Akad. Nauk SSSR **101**, 245 (1955).

[3] P. L. Kapitza, S. I. Filimonov, and S. P. Kapitza. In the collection of articles "Elektronika bol'shikh moshchnosteĭ (High Power Electronics) 3, Nauka, 1963.

[4] P. L. Kapitza, S. I. Filimonov, and S. P. Kapitza. ibid. 6, Nauka, 1969.

[5] V. I. Kogan. In the collection of articles "Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsiĭ" (Physics of Plasma and the Problem of Controlled Thermonuclear Reactions) 3, Published by Academy of Sciences, USSR, 1968, p. 99.

[6] Collection of articles "Diagnostika plazmy" (Plasma Diagnostics) (translations), Mir, 1967.

[7] P. L. Kapitza. In the collection of articles "Elektronika bol'shikh moshchnosteĭ" (High Power Electronics), 4, Nauka, 1965.

[8] P. L. Kapitza and S. I. Filimonov, Usp. Fiz. Nauk **95**, 35 (1968) [Sov. Phys.-Usp. **11**, 299 (1968)].

[9] A. I. Zaĭdel' and E. Ya. Shreĭder, Spektroskopiya vakuumnogo ul'trafioleta (Spectroscopy of the Vacuum Ultraviolet), Nauka, 1967.

[10] E. W. MacDaniel, Collision Processes in Ionized Gases (Wiley, 1964).

[11] A. V. Gurevich and L. P. Pitaevskiĭ, Zh. Eksp. Teor. Fiz. **46**, 1289 (1964) [Sov. Phys.-JETP **19**, 874 (1964)].

[12] L. Spitzer, Physics of Fully Ionized Gases, 2nd ed., 1965.

[13] S. I. Braginskiĭ, in the collection of articles "Voprosy teorii plasmy" (Problems of Plasma Theory) 1, Atomizdat, 1963.

[14] G. E. H. Reuter and E. H. Sondheimer, Proc. Roy. Soc. (London) **A195**, 336 (1948).

[15] L. Boltzmann, Festschrift, Leipzig **5**, 904 (1904).

[16] K. H. Riewe and L. Rompe, Z. Physik **103**, 478 (1937).

[17] J. H. Jeans, An Introduction to the Kinetic Theory of Gases, Cambridge, 1940, p. 186.

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