High-current Pulse Discharges


Pulsed gas discharges may be called “fast” if the inertial forces arising during the accelerated motion of the gas are important. In these discharges the time for the current to rise to the first peak or break in the curve $i(t)$ is comparable with the time of gas contraction towards the axis of the discharge chamber. Several papers dealing with the discharges of this kind have been published. This paper presents results of the study of the phenomena that occur when such a powerful pulse discharge passes through gas. The experiments were conducted under the following conditions: capacitor voltage was 20 to 120 kv; maximum current was 200 to 1600 ka; rate of current rise at the beginning of the process was from $10^{11}$ to $10^{12}$ amp/sec; energy stored in the capacitor bank was up to $5 \times 10^8$ joules. Mainly discharges in deuterium were studied. Some experiments were performed with discharges in other gases.

At large energy densities, where more than 10 joules are given off per square centimeter of chamber surface during the process, the subsequent development of the process may be effected by the gas given off by the ceramic walls even during the first stages of the powerful pulse discharge. It was found in the experiments that metal-walled chambers give off less gas, but the character of the pulse gas discharge in them differs greatly from that in chambers with non-conducting walls. The development of magnetic and electric phenomena inside the column of the gas discharge will be described for chambers having both non-conducting and conducting walls. Detailed studies of neutron radiation and high-energy electrons in chambers with conducting walls are presented in the last two parts of this paper, by separate authors given there.

DISCHARGES IN CHAMBERS WITH NON-CONDUCTING WALLS

Current and Voltage Oscillograms

The general character of the gas discharge can be derived from the current and voltage oscillograms. If the experiment is carried out under sufficiently pure conditions, contamination of the gas by particles from the chamber walls being prevented, then two or more transients are found in the voltage oscillogram at certain values of the initial pressure and voltage, while breaks are seen in the current oscillogram at the corresponding moments. These oscillograms indicate that the inductance of the gaseous gap changes periodically; that is, the plasma column contracts periodically. The inductance of the gaseous discharge gap can be determined from the current and voltage oscillograms, and from this inductance the effective column radius can be found, as a function of time and the rate of contraction. The data obtained in this way agree with that obtained by other methods and will be given below.

More detailed information concerning the development of the discharge can be obtained by measuring the magnetic field inside the discharge by means of minute coil-type magnetic probes. If the magnetic field distribution is found then the current density distribution along the section of the chamber, the magnetic field energy, and the inductance of the gaseous gap can be determined as a function of time. In our experiments the magnetic field was measured simultaneously at four points inside the discharge. Current, voltage and the neutron pulse (for discharges in deuterium) were also registered. Symmetry of the gaseous column was checked beforehand, and all calculations were fulfilled up to the moment when the symmetry still existed.

Figure 1 shows curves for the inductance of the gaseous gap during a typical discharge. They were calculated in two ways: from the current and voltage traces $I(t)$, $V(t)$ (neglecting resistance)

$$L^*(t) = \int_0^t V(\tau) d\tau / I(t);$$

and from the values of the magnetic field inside the discharge

$$L(t) = l \times 10^{-8} \int_0^\pi H_\phi(r, t) dr / I(t).$$

Thus, the assumption that the resistance may be ignored in our process is verified because these two curves coincide well enough.
HIGH-CURRENT DISCHARGES

349

The effective plasma column radius variation is given in this figure as well. This plot was calculated from the values of inductance. Figure 2 gives the results of calculation of the energy introduced into the discharge and the magnetic field energy. The current density distribution over the cross-section of the discharge column at different moments at the same discharge conditions is shown in Fig. 3.

Magnetic field measurements show that after the plasma column has separated from the wall (this occurs some time after the process has begun), a considerable part of the pinched current is concentrated within a cylindrical sheath 3 to 5 cm thick. If we assume that the thickness of this sheath is determined by skin-effect, the gas conductivity at this stage of the discharge must be taken equal to \(10^{12} - 10^{14}\) cgs units. This conductivity corresponds to an electron temperature of not greater than 10 eV. The rate of contraction, computed from the moments when the magnetic field begins to be registered by the probes located at various distances from the axis of the chamber, rises from \(3.5 \times 10^6\) cm/sec at the beginning of the process to \(7-8 \times 10^6\) cm/sec at the end of the first contraction. The same rates can be obtained from the time variation of the inductance. These figures are for a discharge in deuterium at \(p_0 = 0.05\) mm Hg and \(V_0 = 40\) kv. At other initial pressures \(p_0 = 0.01\) mm Hg and \(p_0 = 3\) mm Hg, and the same initial voltage \(V_0 = 40\) kv, the maximum rate of contraction is equal to \(10^7\) and \(2 \times 10^6\) cm/sec, respectively. (At initial pressures above 0.3-0.4 mm Hg the current reaches the axis of the chamber during the second quadrant of the period, while at 10 mm Hg no magnetic field in the central zone is registered at all. The initial voltages here are equal to 40 kv.)

By the time of the first voltage transient the current reaches the center of the discharge chamber. Then, the current begins to rise rather sharply near the walls of the chamber while it continues to increase in the central zone. This redistribution of current results in a lower inductance of the gap and in a corresponding drop in voltage and rise in total current.

A similar redistribution of current occurs at the time of the second voltage break. During the time interval between the first and second voltage transients, the current in the central zone rises somewhat at first, then falls, and rises again. Some time after the second or third voltage transients the current in the central zone vanishes and does not reappear there until the very end of the process. By the time of the second voltage transient, the instabilities characteristic of this type of gas discharge become essential.

The part of the total energy that increases the energy of the particles can be found from the difference between the curves of Fig. 2 at \(p_0 = 0.05\) mm Hg and \(V_0 = 40\) kv. Consideration of the possible energy losses to the walls during this stage of the process shows that there is no evidence that they are large, although there is no direct experimental proof of this point.

Two cases must be considered in estimating the possible temperature, \(T_e < T_i\) and \(T_e > T_i\). If equilibrium between the electrons and the ion gas is
not as yet established, practically all of the energy stored in the gas is that of heavy particles. In this case the average energy of the deuterons is 200 ev at the instant of maximum contraction, assuming that all of the particles were involved in the pinch process. If equilibrium between the electrons and the ion gas has already been established by the time of the maximum contraction, the average energy per particle amounts to 100 ev, which corresponds to a temperature of 70 ev. Non-uniform contraction of the plasma column and cumulative effects may lead to local heating. Therefore, the above estimates are not in contradiction with the temperature of one million degrees that was obtained from the spectroscopic measurements.  

**Pressure Measurements**

The compression of the particles at the central axis and their temperature rise should be accompanied by a sharp increase in the pressure at the central zone. This pressure rise was studied by means of piezoceramic pickups set at various points inside the discharge. The design of the pickup is schematically shown in Fig. 4a. A diaphragm detector shown in Fig. 4b was designed to determine the sensitivity of the pickup. It enables the pickup to be calibrated under conditions similar to those in the gas discharge. Time-position curves for two diaphragms of different mass are plotted in Fig. 4c; these were drawn up after the treatment of the experimental data. The scale of the pressures recorded by the pickup can be obtained by comparing the area under a pulse on the trace of the pickup signal with that of the pulse received with the diaphragm.

Oscillograms of pressure pulses, which are synchronized with the full current flowing through the chamber, are shown in Fig. 5 for different positions of the pickup. With the pickups set radially the pressure rise from the outside of the cylinder to the center can be seen as the plasma column contracts towards the axis of the discharge, and then the pressure wave spreads in the opposite direction. Pickups set axially record only a small pressure rise in the outer regions of the discharge chamber during the contraction. A sharp pressure rise was recorded near the axis during the last phase of contraction, the pulses received by the axial and radial pickups being about the same. As the discharge column expands, the axial pickups near the perimeter also record a marked pressure rise. These experiments show that during the first stage of contraction the radial velocities of the particles directed inwards to the chamber axis dominate. At the instant of maximum contraction and when the plasma column expands, the other velocity components are essential as well.

When a magnetic probe, which measured the time derivative of the magnetic field at a fixed point, was set near the piezoceramic pickup (Fig. 5), it was found that the pressure pulse appeared somewhat later than the time derivative of the magnetic field during the contraction of the discharge column.

The concentration of particles at the pickup can be calculated from the measured values of the pressure pulse, the particle velocity and the time during which the pressure acted on the pickup. For the experimental conditions listed in Fig. 5 the calculated concentration of particles in the region near the chamber axis is about 100 times greater than the initial one. Knowing the pressure and particle density in the compressed state, it is possible to estimate the temperature by means of the formula $p = 2nkT$. In the experiment we now consider the initial density of atoms was equal to $7 \times 10^{15}$ particles/cm$^3$; the final density was found to be about $7 \times 10^{17}$ particles/cm$^3$. At this moment, the pickup registered a pressure of about 100 atmospheres. The temperature obtained from these values of pressure and particle density is a very rough estimate, $T = 50 - 100$ ev.

**Heavy Gases**

Let us briefly consider some characteristic features of the development of the discharge in heavy gases such as xenon, for example. By comparing results of
Figure 5. Diagram and results of measurements with a piezoceramic pickup.
measurements at pressures for which the masses of xenon and deuterium within the chamber are the same we find the general character of the current density distribution along the discharge cross section to be similar. The rate of contraction for xenon, however, is somewhat larger than for deuterium. Moreover, for discharges in deuterium the maximum magnetic field in the central zone is 3 to 4 times larger than that near the walls, while for discharges in xenon the magnetic field amplitude is almost the same along the entire discharge cross-section. Therefore the current concentration at the chamber axis is much less for discharges in xenon than in deuterium.

It is interesting to note, for an initial pressure of the xenon of 0.1 mm Hg, that during the second half-period the current sheath formed at the walls is also seen to move towards the center just as in the first half-period, provided cylindrical symmetry is not disturbed throughout the entire process.

All oscillograms for discharges in xenon-deuterium mixtures containing 1% of xenon atoms are similar to oscillograms for pure xenon. This character of the discharge in pure xenon and in mixtures agrees with data on the X radiation which accompanies the discharges in these gases.

### Longitudinal Electric Field

In addition to the magnetic field inside the discharge, the longitudinal electric field $E_z$ was measured by means of magnetic probes of a somewhat different construction. The idea of this method of measurement is as follows. Let us consider a contour ABCDEA in Fig. 6. We can write

$$\int E_z dl = -\frac{1}{c} \int \dot{H}_\phi dS. \quad (3)$$

Neglecting the voltage drop across the parts of the contour running along metal conductors, and assuming that the column has cylindrical symmetry, and that $E_z$ and $E_r$ do not depend on $z$, we obtain

$$E_z = \frac{V}{l} - \frac{1}{c} \frac{\partial}{\partial t} \int_r^R H_\phi dr \quad (4)$$

where $V$ is the voltage applied to the divider.

The time derivative of the magnetic flux in the right-hand side of Eq. (4) was measured by an elongated loop set along the radius (Fig. 6). The longitudinal electric field was determined simultaneously at four points at different distances from the chamber axis. The results for the most typical discharge are given in Fig. 7. The electric field in the central region of the discharge is equal to zero during the first stages of the process, then it rises and attains a value of 500 to 700 v/cm by the time the voltage transient occurs. At the time of the voltage transient, the electric field becomes negative over the entire cross-section of the discharge chamber, and its value in the central region reaches 1000 v/cm. By the
time the neutron pulse appears, the electric field recorded lies between 100 and 600 v/cm. Our method does not permit the measurement of local electric fields, which may attain large values due to the development of various forms of instability.

The ohmic voltage drop across the discharge column may be calculated from the longitudinal electric field. Calculations show it is valid to neglect the ohmic voltage drop as we have done.

The longitudinal electric field is associated with the current density and the magnetic field intensity by

\[ j_z = \sigma \left( E_z + \frac{V_r H_\phi}{c} \right). \]  

(5)

If the ohmic voltage drop can be neglected,

\[ V_r = - \frac{\varepsilon E_z}{H_\phi}. \]  

(6)

The radial velocity of the particles during the contraction calculated in this way agrees well with the velocity of the internal current boundary given above.

At the moment of the voltage transients \( E_z \) is negative, while \( H_\phi \) and \( j_z \) are positive. Therefore, \( V_r \) is positive, that is, the particles fly out from the central zone. The corresponding radial velocity is greater than \( \frac{\varepsilon E_z}{H_\phi} \). During a discharge at \( p_0 = 0.05 \) mm Hg and \( V_o = 40 \) kv, the radial velocity of the particles is greater or equal to \( 1.5 \times 10^7 \) cm/sec in the central zone and drops off in going away from the center of the discharge chamber.

**Increased Rate of Current Rise**

Let us pass to the question of how the discharge process changes when the initial rate of current rise is increased. For this purpose experiments were carried out on an apparatus having a chamber of 40 cm in diameter and 50 cm in height. The 64 \( \mu \)f capacitor bank was charged to a voltage from 40 kv up to 120 kv. The initial rate of current rise varied from \( 3 \times 10^{11} \) amp/sec to \( 10^{12} \) amp/sec, the discharge energy being much larger than that in the apparatus described before.

The current and voltage oscillograms with \( V_o = 40 \) kv do not differ from those described above. At voltages above 80 kv, only one peak remains on the voltage oscillogram. A sample oscillogram is shown in Fig. 8. The same series of measurements were made as described above for voltages across the chamber to 100–120 kv. Only a few measurements were made with magnetic probes at maximum voltages due to the experimental difficulties. Some characteristic features for discharges at voltages of 80 to 120 kv are listed below:

1. The current at the walls of the discharge chamber comprised a considerable part of the full current (about 50%) during all stages of the discharge process. This greatly influences the discharge inductance. Therefore, the rate of contraction found from the inductance curves is 1.5–2 times less than that found by means of magnetic probes.

2. Since the current at the walls is large, it is difficult to prevent contamination of the chamber with the wall material.

3. The magnetic field in the central zone continues to rise at the time of the voltage transients, and exists for several microseconds, attaining 14 kilo-ersteds at 5 cm from the discharge chamber axis \( (V_o = 100 \) kv).

4. The energy of the particles at the highest voltages (120 kv) cannot be estimated by the method described above since the magnetic field could not be measured because of the experimental difficulties. Taking the total energy introduced into the discharge up to the time of the first transient and subtracting the 35% from it that is allotted for the magnetic field according to theoretical calculations, we obtain 500 ev per particle (including electrons).

**Hard Radiation**

We shall now describe the hard radiation that accompanies a powerful pulse discharge in deuterium. At voltages not larger than 60 kv neutron radiation appears at the instant of the voltage transients (this is usually after the second peak, when instabilities develop). Simultaneously a hard X-ray pulse appears (of the same duration as the neutron pulse); the discussion of this pulse will be given later on. Neutron radiation at voltages above 80 kv is recorded as long as the compressed state exists, that is, from 2 to 3 microseconds. A typical oscillogram of this
neutron pulse, which was obtained by means of a scintillation counter, is given in Fig. 8. Discharges in hydrogen with the same initial mass of the gas were accompanied by hard X radiation; however, this radiation lasted for not more than 0.3 microseconds. The appearance of an X-ray pulse in the region of the first current break indicates that there is an acceleration process which can result in the neutron radiation. However, since the X-ray pulse is much shorter in time than the neutron pulse, it is suggested that some neutrons may emerge due to a non-accelerated process as well.

It is not difficult to estimate the possible contribution of the thermonuclear reactions to the neutron effect observed by making use of the experimental data available and assuming a 50-fold compression of the plasma column (this follows directly from optical data and measurements of the compression density by the piezo-ceramic pickup). This estimate gives a neutron yield of $5 \times 10^8$ neutrons (at a temperature of 330 ev). This calculation, however, is very sensitive to the number of particles over which the energy is distributed. If we assume that the energy is not imparted to all of the particles in the discharge chamber, it must be assumed that only 40% of the total number of particles should be heated up in order to explain the entire neutron yield ($5 \times 10^8$) by thermonuclear processes. These considerations indicate that a part of the neutron yield observed may be due to thermonuclear reactions.

For an initial voltage of 60 kv the temperature in the compressed state at the time of the first maximum contraction does not exceed 100 ev. Neutron radiation is noticed at the time of the second contraction and may be explained by the presence of deuterons accelerated to high energies in the discharge. These deuterons (having energies up to 200 kev) were found in direct experiments (see below), and also in recording the neutrons using the recoil protons obtained in nuclear emulsions (the method described in Ref. 6).

**STUDY OF FAST CHARGED PARTICLES**

In 1953, after detecting hard X radiation accompanying powerful discharges in hydrogen and deuterium, the upper bound of the energy spectrum was estimated. It was established that there exist in the spectrum quanta having energies of several hundred kev at a discharge tube voltage of 15 to 20 kv. However, the gradual falling off of the spectrum made it difficult to establish the energy limit of the radiation under study.

Cloud Chamber Studies

A cloud chamber method of measuring the energy of quanta was employed to determine more accurately the energy of the X-ray quanta. The main advantage of using a cloud chamber in studying short bursts of X radiation is that the device has a comparatively short sensitive time and electromagnetic obstacles do not effect its operation.

In order to determine the electron energy, the lengths of the electron tracks formed in the cloud chamber were measured. The well-known method for determining the electron energy from the track curvature in the magnetic field was not suitable for the conditions of the experiment, since at electron energies of about 200 kev the mean dispersion angle greatly exceeds the maximum value at which it would be still possible to measure the track curvature in the magnetic field.

In determining the energy of the X-ray quanta using the electron energy, it is necessary to determine whether these electrons are formed as a result of the photo-electric effect or the Compton effect. The Compton mechanism of electron formation by quanta having energies above 200 kev was found to be more probable under the conditions of the experiment. The calibration experiments in which a stream of X rays of known energy was directed into the cloud chamber from an X-ray tube proved this estimation to be correct.

All these experiments were conducted with a porcelain discharge chamber 100 cm long and 17.6 cm in diameter at an initial hydrogen pressure of 0.06 mm Hg (corresponding to maximum hard X-ray yield), a discharge voltage of 40 kv and a maximum discharge current of about 200 ka. A 36 μf capacitor bank was used.

It is difficult to follow on the photographs the long tracks formed in the cloud chamber, which correspond to high-energy electrons, because of the large number of short tracks there. To determine the character of the spectrum in the high-energy range the Wilson chamber was shielded from the discharge tube with lead 15 mm thick (which greatly absorbed the soft part of the X-ray spectrum). Oscillograms of the scintillation counter pulses were obtained at the same time as the tracks were photographed. If there was no pulse on the oscillogram, the corresponding photograph of the tracks was not developed.

Since one camera was used to photograph the tracks, the picture on the photographs is the projection of the electron traces onto a plane perpendicular to the optical axis of the camera. When projecting a sufficiently winding track on a plane, the length of its projection is $\pi/4$ of its actual length. Winding electron tracks were studied in Ref. 11, where it was shown that the above factor could be used with high enough accuracy.

The electron energy was determined from the range-energy curve drawn up on the basis of known experimental data.

In order to take into account the background contribution, the cloud chamber was expanded after each time the traces of the electrons formed by the X-ray pulse were photographed, and then the tracks were photographed without any discharge. A histogram of the energy spectrum for the electrons formed by X-ray pulses accompanying a discharge in hydrogen is given in Fig. 9. The spectrum of the electrons formed by the background is given in the same figure. The same number of photographs were treated to construct the histograms for the effect studied and for the background. Out of a total of 500 photographs,
189 were chosen to be treated in accordance with the criterion indicated above.

**Calibration Measurements**

Figures 10 and 11 show the calibration histograms for electron comparison spectra. They were obtained while X-irradiating the cloud chamber from an X-ray pulse generator. The voltage pulses on the X-ray tube amounted to 240 and 285 kv. As seen from the histograms, the maximum energies of the electron spectra in these cases amounted to 120 kev and 140 kev, respectively.

As follows from the elementary theory of the Compton effect, the maximum energy of the Compton electrons corresponding to X-ray quantum energies of 240 kev and 285 kev are equal to 116 kev and 145 kev, respectively. These values agree with the experimental results within measurement accuracy. The maximum energies of photoelectrons knocked out from the glass at the same X-ray quantum energies amount to 200 kev and 265 kev (the highest ionization potential of the K shell is about 20 kv).

Thus, the data presented show that under the conditions of the experiment at energies above 200 kev it is much more probable for the Compton effect to occur than for the photo-effect.

According to the histogram of Fig. 9, the energy spectrum limit for the electrons in the cloud chamber is estimated at 180 kev for discharges in hydrogen. Assuming that the electrons in the high energy region of the spectrum are formed due to the Compton effect, we can find the energy of the X-ray quanta.

**Results of Cloud Chamber Studies**

Calculations show that a powerful discharge in hydrogen at an initial capacitor bank voltage of 40 kv is the source of quanta of radiation having an energy of 320 kev. Analysis of this experimental data permits us to assert that the number of X-ray quanta with an energy above 320 kev does not exceed 0.1% of the total number of quanta in the discharge, on the average.

The measurement error on the calibration tube does not exceed 5%. However, it should be remembered that the value of the maximum energy of the spectrum was obtained by averaging the spectra of a large number of pulses. Therefore, it is possible that several quanta may exist in the spectrum with a higher energy.

**Thompson Parabola Studies**

Thompson's parabola method was used for direct measurements of the deuterium ion velocities. By emitting a narrow beam of charged particles from the discharge gap (a porcelain tube 80 cm long and
17.2 cm in diameter) into a special chamber, the ions may be analyzed according to their velocities and values of $e/m$. The width of the beam was set by two inlet diaphragms, $d_1 = 1$ mm and $d_2 = 0.5$ mm. In order to maintain a high vacuum in the chamber, the first diaphragm was shut with a high-speed electromagnetic valve.

Each discharge took place in pure deuterium at a pressure of 0.02 to 0.06 mm Hg, a discharge voltage of 40 kv and a discharge current peak of $1.5 \times 10^5$ amps.

The photograph plates were exposed for not more than several microseconds during one pulse discharge (about one half-period, which was equal to 8 microseconds). All plates were exposed when neutron radiation was present (on the average there were $10^8$ neutrons per pulse).

The velocities of the deuterons emerging from the plasma (perpendicular to the discharge axis) were measured. Just noticeable traces of parabolas were obtained after the plate had been exposed for 80–100 pulses.

The stream of particles was much more intense in experiments with charged particle beams emitted along the discharge axis through an outlet in the cathode (Figs. 12, 13). Faintly noticeable parabola traces appeared in the plates after one pulse discharge.

Exposures of 3–5 pulses resulted in parabolas that were quite distinct. In the sections of the parabolas from 80 kev and higher on some photo plates there are black spots of 1 mm in diameter with clear-cut boundaries. These spots are evidence of good focusing in a very narrow velocity band for small groups of deuterons.

There is much scatter in the experiment results at the same operating discharge parameters. The maximum energies of the deuterons usually lie between 80 and 170 kev, and more rarely from 170 to 200 kev.

Upon increasing the exposure to 10–15 pulses there appear parabolas of negative deuterium ions with energies from 4 to 120 kev. These fast negative ions are evidently formed by charge exchange with fast positive ions; that is by the appearance of fast neutral particles and subsequent electron capture. Here the direction of the fast-particle velocity remains almost the same. The maximum velocities for the negative ions of deuterium have a sharp boundary but they are less than those of the deuterons on the same plate. The direction of the negative deuterion ion velocity coincides with that of the deuterons; therefore, they move towards the cathode in the retarding electric field, losing part of their energy.

Upon increasing the exposure (to 25 and more pulses), in addition to $D^+$ and $D^-$ parabolas, parabolas corresponding to the ions of $D_2^+$, $D_2^-$ and electrode and tube materials appeared on the photo plates. Parabolas of $H^+$ and $H^-$ were obtained in experiments with hydrogen. From 5 to 10% of helium was added to the deuterium to obtain a reference parabola.

By charging the capacitors at reversed polarity, it is possible to analyze the charged particle beam emitted through the outlet in the anode. No signs of parabolas were discovered on photographic plates exposed for 50 pulses. Therefore, fast deuterons arise only during the first half-period of the current discharge. Furthermore, the electric fields in which the deuterons are accelerated to high energies are of the same polarity as that from the applied discharge voltage. The stream of fast deuterons is directed along the axis of the discharge tube towards the cathode with slight dispersion toward the walls.

Thus, applying the parabola method for measuring ion velocities in a powerful pulse discharge in deuterium, it was found that deuterons exist having energies right up to 200 kev. The existence of deuterons with energies five times greater than the discharge voltage indicates that acceleration processes develop in the discharge.

Figure 12. Ion energy analysis by Thomson parabola method. $B = 900$ gauss; $E = 950$ v/cm; $V_p = 40$ kv; $P_0 = 0.04$ mm Hg. 6 pulse discharges; $D^+$ parabola to the left and downwards; $D^-$ parabola to the right and upwards. Horizontal line: $E = 0$

Figure 13. Ion energy analysis by Thomson method. $B = 1500$ g; $E = 1850$ v/cm; $V_p = 40$ kv; $P_0 = 0.04$ mm Hg; photographs for two different directions of $H$. 7 pulse discharges. $D^+$ parabola upwards (slightly blackened), $D^-$ parabola downwards.
Summary

The basic experimental facts known to date regarding the hard radiation from a gas discharge in porcelain chambers at pulse voltage up to 50 kV show:

1. The neutron and X radiation during the discharge process appear at the same time.
2. Deuterons responsible for the appearance of neutrons during discharges in deuterium are accelerated towards the cathode, while the maximum intensity of X radiation appears in the region near the anode.
3. Both types of radiation always appear in the same well-defined range of gas pressure in the discharge tube.
4. The energy of the X-ray quanta (and, therefore, of the electrons which create them) was experimentally determined to be 300 keV, while the deuteron energy determined was 200 keV. These values coincide well with each other within the limits of experimental error.

Experimental facts prove that hard X radiation from powerful pulse discharges is of the same character as the neutron radiation which arises in deuterium discharges. The radiation is most likely due to the electric fields directed along the tube axis which accelerate the charged particles (electrons and ions). As has been pointed out previously, these electric fields may arise from a redistribution of currents while the radius of the discharge column is changing. An electric field of the order of a few hundred volts per centimeter arises at the time of the X-ray pulse. This corresponds to a potential difference of tens of kilovolts. Local electric fields that appear in this process may attain extremely large values if certain types of instabilities develop.

DISCHARGES IN A METAL-WALLED CHAMBER

Experiments were carried out with metal-walled chambers in the discharge circuits, which were similar to those with ceramic-walled chambers. (Some of this work is discussed in Ref. 13, vol. 4, p. 170, 182, 201.) A schematic view of the metal-walled chamber used in most of the experiments is shown in Fig. 14. Experiments showed that the discharge process in metal-walled chambers develops differently than in ceramic ones.

Evolution of the Discharge

Measurements with magnetic probes have shown that the discharge process begins with a breakdown from the electrodes to the metal wall of the chamber. Here, the discharge process, which is symmetric about the longitudinal axis of the chamber, only takes place near the positive electrode. The discharge subsequently develops as shown in Fig. 14. The dashed lines show how the current gradually spreads toward the chamber axis. The zone of maximum compression is situated near the positive electrode surface, and becomes smaller in extent along the chamber axis with larger initial gas pressures.

This type of metal chamber may be used to obtain a highly pinched discharge at relatively large initial pressures (up to 4–30 mm Hg). This phenomenon was not observed in ceramic chambers with discharge circuits of similar parameters.

The high contraction may be obtained because only a relatively small part of the gas filling the chamber participates in the discharge. The larger the initial pressure, the smaller this amount of gas.

Since it is possible to work at high initial pressures and since the metal walls do not give off much gas, a large number of discharges can be carried out and well-reproducible results may be obtained without changing the gas in the chamber.

Neutron Production

Just as in the case of ceramic chambers, the oscillograms for the full discharge current through the chamber and the voltage across its electrodes indicate that the inductance of the discharge gap increases when the discharge column pinched (see Fig. 14). At the time of the maximum gas contraction to the chamber axis, intense neutron radiation is observed over a wide range of pressures. Localization of neutron radiation was studied in two ways by means of collimator devices.

(a) A scintillation detector with a naphthalene-anthracene crystal was placed in a paraffin block with a collimator slit (Fig. 15). By moving this device longitudinally and transversely with respect to the chamber axis, the sources of neutron radiation were discovered. They were located in the region of
maximum discharge contraction, which was determined by means of magnetic probes (point A on Fig. 14).

(b) Considerable intensity of neutron radiation (up to $3 \times 10^9$ neutrons per discharge) made it possible to carry out quantitative measurements by means of another collimator device, which is shown in the left side of Fig. 15. A paraffin block in a cadmium jacket was placed in a tank of water. This block slowed the neutrons that fell on it through a flat slit formed in the water shield by a hermetically sealed tin box. The slowed-down neutrons activated the silver foil ($\text{Ag}^{109}$) which enclosed a $\beta$ counter, whose pulses were counted by an ordinary scale device. The collimator slit was moved inside the tank and pointed at the selected region in the chamber. The readings of the collimator counter were compared with those of an unprotected monitor placed near the discharge chamber. The data of a large number of experiments for determining the longitudinal and transverse distribution of neutron radiation were treated and the results are given in the drawing of the chamber (Fig. 15).

Experiments with nuclear emulsions, prior to those of a subsequent part of this paper, also showed that the source of neutron radiation is located close to the positive electrode near the chamber axis. After treating a large number of proton tracks in the emulsions (which were placed at the cathode and anode of the chamber), it may be seen that less anisotropy is observed here than in the similar case with ceramic chambers at voltages not exceeding 40 kv. The energy spectrum obtained for the neutrons is given in Fig. 16. The location of the cassettes with the nuclear emulsions is shown in this figure as well.

Even when adding large amounts of xenon to deuterium (500–600% by mass), the intensity of neutron radiation, in contradiction to the case with ceramic chambers, was reduced only by several times, the time of current maximum contraction to the chamber axis being a little more comparing with a discharge in pure deuterium. However, the characteristic pinch of the discharge was not observed when the chamber filled with the same amount of pure xenon.

**THE THEORY OF PLASMA COLUMN CONTRACTION AND OSCILLATION AT HIGH RATES OF CURRENT RISE**

Due to magnetic forces the plasma column formed by passing a powerful current pulse through a cylindrical discharge chamber is pinched with a rate which is determined by the compressing forces and the plasma inertia.

The qualitative theory for the contraction process was developed by Leontovich and Osovets. Later on Braginskii and Migdal qualitatively considered the problems connected with increasing plasma conductivity, ionization, the neutral gas sweep by the charged particles, the shock waves, cumulation effects and the growing mass of the moving gas with time. It is extremely difficult to calculate the contraction and pulsation of a plasma column in detail taking into account all of these factors. Only a magnetohydrodynamic approximation was used, in which the plasma was considered to be a monatomic ideal gas having a constant conductivity $\sigma$.

This model does not account for ionization and the energy loss through radiation, as well as unfully sweeping of the neutral particles by charged ones which are directly effected by electromagnetic forces. The free path of the particles is considered to be small. Let the pressure be $P_0 = 0.2$ mm Hg for example. For a cross section of $3 \times 10^{-16}$ cm² the mean-free path is equal to 0.2 cm. Assuming a compression ratio of

![Figure 15. Experiments on neutron collimation. Apparatus on the left: 1, water; 2, cadmium; 3, slit; 4, $\beta$ counter; 5, paraffin. Apparatus on the right: 6, paraffin; 7, scintillator; 8, lead; 9, slit; 10, photomultiplier. Experimental curves: 11, ratio of readings of collimated and non-collimated counters minus the background at corresponding positions of the slit; 12, relative difference in amplitudes of the scintillator pulses with the slit open and closed at corresponding positions of the collimator.

![Figure 16. The neutron energy spectrum $\rho_0 = 2$ mm Hg; $V_0 = 30$ kv; solid curve for anode (1); broken curve for cathode (5).]
HIGH-CURRENT DISCHARGES

30, full ionization, and ion temperature of 100 ev the mean-free path of the ion amounts to approximately 0.1 cm, and the time of heating the electron by the ions to approximately $10^{-7}$ sec. It is believed that the adopted model correctly accounts for the main mechanical and electrodynamical effects, e.g., inertia and gas motion, heating in the shock wave and skin effect.

The constant value for the electrical conductivity may be justified in part by the fact that the electron temperature is almost constant (several ev) as long as the ionization is incomplete. Even this schematic formulation of the problem leads to a complex set of non-linear partial differential equations. This set of equations was solved numerically on an electronic computer under the supervision of I. M. Gelfand and R. P. Fedorenko.

The equations for the region inside the plasma in dimensionless variables are as follows:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial r} + \frac{\partial \rho v}{\partial r} = 0, \]
\[ \frac{\partial \rho v}{\partial t} + \frac{\partial \rho v}{\partial r} + \frac{1}{r} \frac{\partial \rho v}{\partial r} = \frac{\partial \rho H}{\partial r}, \]
\[ \frac{\partial \rho H}{\partial t} = \rho E, \]
\[ \frac{\partial \rho H}{\partial r} = K_{\rho}(E + vH), \]
\[ T = \frac{\rho}{\rho}, \]

where \( \rho \) = density, \( v \) = velocity, \( \rho \) = pressure, \( T \) = temperature, \( E \) = electric field along the axis, \( H \) = magnetic field. The density of the undisturbed gas is taken as unit of density and the radius of the discharge chamber \( a \) is taken as unit of length. The units of measurement of the other quantities are as follows: \( t \) is the unit of time.

\[ v_1 = \frac{a_0}{t_1}; \quad p_1 = 9.6 \times 10^2; \quad E_1 = \frac{v_1}{c} H_1; \]
\[ H_1 = 4 \times 10^2 v_1; \quad T_1 = M v_1^2, \]

where \( M \) is the average particle mass. The following dimensionless quantity is also introduced:

\[ K_{\sigma} = \frac{4 \pi a_0^2 \sigma}{\epsilon^2 t_1}. \]

The initial and boundary conditions are as follows:

\[ \rho = 1; \quad v = 0; \quad \rho = 0; \quad H = 0 \quad \text{at} \quad t = 0; \]
\[ \rho = 0; \quad H = 0 \quad \text{at} \quad r = a, \]

where \( a(t) \) is the coordinate of the edge of the column determined in the process of integration. Outside the column \( \rho = 0 \); therefore, instead of Eq. (8f) we may write the following for the magnetic field:

\[ H(t, r) = \frac{1}{r} H(t, 1) \quad a < r < 1. \]

The current is excited by a capacitor \( C \) which is charged to an initial voltage of \( V_0 \), and is discharged through a gap of length \( l \) in series with some external inductance \( L_e \).

The corresponding electrical equations may be used as the boundary conditions for Eqs. (8). In dimensionless form they are

\[ K_{e} \frac{dV}{dt} = -H(t, 1) \quad E(t, 1) + K_L \frac{dH(t, 1)}{dt} = V \]

where the following quantities are chosen as units:

\[ V_1 = V_0; \quad E_1 = V_0 / l; \quad H_1 = (c t_1 / a_0) E_1 = (c t_1 / a_0) (V_0 / l), \]
\[ t_1 = \left( \frac{1}{V_0} \right)^{1/4} \times a_0 \left( \frac{l}{V_0} \right)^{1/4} \]

and the following designations are adopted:

\[ K_{e} = \frac{2e}{c t_1^2}; \quad K_L = \frac{L_e}{2l}. \]

When \( t = 0 \) we have

\[ V = 1. \]

Using Eqs. (8) and (12) we derive the law of conservation of energy in dimensionless form:

\[ \int_0^a \left( \frac{P}{\gamma - 1} + \frac{\rho \rho^2}{2} + H^2 \right) 2 \rho dr 
+ \left( \ln \frac{1}{a} + K_L \right) H^2(t_1) + K_L V^2 = \text{const}. \]

The following values of the dimensionless variables were adopted for purposes of integration:

\[ \gamma = 1.66; \quad K_L = 1; \quad 1/K_{e} = 0.46; \quad K_{\sigma} = 8; 64; 512 \]

Figures 17, 18 and 19 give some results of numerical integration for \( K_{\sigma} = 64 \) and also corresponding experimental curves for a discharge chamber 40 cm in diameter and 90 cm long at \( V = 40 \) kv and \( C = 83 \) \muF. The scales for quantities having dimensions relate to a pressure of \( p_0 = 0.2 \) mm Hg. The ratio \( K_L = L_e/2l \) for this chamber is near unity; \( 1/K_{e} = 0.46 \) at pressure of \( p_0 = 0.2 \) mm Hg. Under these conditions the units of time, temperature and pressure are equal to \( t_1 = 2.62 \times 10^{-4} \) sec, \( T_1 = 120 \) ev and \( p_1 = 2.8 \) kg/cm$^2$ respectively. The value of \( K_{\sigma} = 64 \) corresponds to an electric conductivity \( \sigma = 3 \times 10^{23} \) absolute units.
Figure 17. Current vs. time curves. Solid curve: theoretical. Broken curve: experimental.

Note that for a pressure $p_0 = 0.05$ mm Hg, the units will be as follows: $t_x = 1.85 \times 10^{-6}$ sec, $t_x = 240$ ev, $P_1 = 1$ kg/cm$^2$, and $1/\kappa = 0.23$. In calculating $t_x$, the average mass of a particle $M$ is taken equal to the mass of the deuterium atom, which means neglecting the electrons.

The first contraction of the string occurs when $t = 1.9$ (dimensionless quantity); the shock wave reaches the center at 1.7. The density is increased up to 50 times during contraction, the average increase taken over the area of the cross section is about 30 times. The dimensionless pressure reaches 21 during the contraction, which corresponds to 60 kg/cm$^2$ for $p_0 = 0.2$ mm Hg, and 30 kg/cm$^2$ for $p_0 = 0.05$ mm Hg. The dimensionless temperature averaged over the area of the cross section reaches 0.54 during the first contraction. This corresponds to 65 ev for $p_0 = 0.2$ and 130 ev for $p_0 = 0.05$ mm Hg, when neglecting the electrons. If the electron and ion temperatures are the same, the corresponding figures are 32 ev and 65 ev. The temperature is 20% higher during the second contraction. The temperature greatly increases ("cumulative effects") near the axis when the second shock wave impinges. The central part of the gas, comprising one-tenth of the total mass, has a temperature 1.5 times the mean temperature.

It is convenient to relate the mean temperature to the current at the instant of maximum contraction by means of an equation that is similar to the usual equilibrium relationship between temperature, current, and number of ions $N$ per unit length:

$$T = \frac{\eta I^2}{2z^2N} = 3.12 \times 10^{12} \frac{\eta I^2}{N} [\text{kev}]. \quad (17)$$

The coefficient $\eta \approx 2.7$ during the first contraction and $\eta \approx 2.1$ during the second.

The control sum in Fig. 19 deviates from a constant value due to the errors introduced when solving the equations numerically.

The results of integration are similar for $K_v = 512$, but the skin effect is much more pronounced, and the column is pinched somewhat more greatly. For $K_v = 8$ the string expands up to the "wall" ($r = 1$) after the first contraction.

The following discrepancies between the theoretical and experimental results should be pointed out:

The compression is somewhat greater and the current somewhat less in the experiment than in the calculations. The expansion observed after the first contraction is less than that following from the calculations and afterwards the oscillations are observed to decay quickly. This is an indication that the elasticity of the plasma column in reality is less than the value adopted for the magnetohydrodynamic model, which does not account for energies expended on ionization, excitation and radiation, as well as the influence of various kinds of instability.
inductance causes the current curve on the oscillogram to rise more rapidly after passing through its minimum value than would be expected on the basis of calculations.

The calculations, of course, do not account for a certain initial delay of the current near the chamber walls, which is connected with the formation of plasma dense enough to sweep the neutral gas.

NUCLEAR EMULSION STUDIES

Neutron radiation in high-current pulse discharges in deuterium has been detected in experiments both in chambers with non-conducting walls and in chambers with conducting walls. The energy spectrum of neutron radiation in discharges in chambers with non-conducting walls has been studied by a number of authors. In the present work the neutron radiation accompanying pulse discharges in deuterium in a chamber with conducting walls was investigated by means of nuclear emulsions. All the investigations were carried out for the two polarities of the voltage applied to the electrodes of the chamber. It was shown that the sources of the neutrons are mainly concentrated in a small region near the anode. As a result of a study of the angular distribution of the neutrons, a second (appreciably weaker) source near the cathode was also hypothesized. On the basis of studies of neutron spectra obtained on five plates placed in different positions in relation to the chamber, a conclusion was reached about the accelerator mechanism producing the main body of the neutron radiation. The maximum energy of the deuterons was approximately 200 kev. The results of the present work are compared with data obtained in chambers with non-conducting walls.

Description of Experiments

In the experiments, a capacitor bank of 145 microfarad capacity was discharged through the chamber filled with deuterium at a pressure of 2 mm Hg. The initial voltage $V_0$ of the bank was 30 kv.

Soviet nuclear plates, NIKFI [Cinematographic and Photographic Scientific Research Institute] type K, with an emulsion thickness of 100 microns, were used in the work. The emulsions used were calibrated by irradiation with 2.52 Mev. The location of the plates in relation to the discharge chamber is shown in Fig. 20. The plates were exposed to about 50 discharges through the chamber giving a total neutron intensity of $\sim 10^{10}$. They were also exposed for both polarities of the chamber electrodes. In all, about 8000 tracks of recoil protons were scanned. Simultaneously, unexposed controls from the same batch of emulsion were examined to determine the number of background tracks. It appeared that there were practically no background protons.

Results

After the plates had been scanned it became clear that for each plate there was a clearly defined preferential angle of incidence of the neutrons. In Fig. 20, $\phi$ denotes the angle between the direction from which the neutrons from the discharge chamber strike the plate and the axis of the chamber, measured clockwise from the cathode ($\phi = 0^\circ$) to the anode ($\phi = 180^\circ$). It follows from consideration of the values of $\phi$ that the sources of the neutron radiation are located on the axis of the chamber, chiefly in the neighborhood of the anode, which agrees with the results obtained by the method of collimating counters.

The “center of gravity” of the sources lies at a point 3-4 cm from the anode. It should be observed that all the plates were completely scanned for each of the two polarities of the voltage across the chamber electrodes. Here, results are given only for one polarity, indicated on Fig. 20 (the anode is the upper electrode). Similar results were obtained when the polarity was reversed (allowing for the spatial change in the direction in which the angle $\phi$ is read off; i.e., $\phi$ is measured from the cathode to the anode in both cases).

Figure 21 shows the energy spectra of the neutrons obtained for all five plates with various values of $\phi$. For ease of comparison, the spectra are standardized: values of $f_n$, the percentage ratio of the number of neutrons in a given energy interval to the total number

---

1 Work performed in 1958. This part is by M. M. Sul- kovskaya, N. V. Filippov and V. A. Khabrov.
of neutrons, are plotted as the ordinates. The energy of the neutrons is determined to an accuracy of ± 50 kev. The maxima of the cathode and anode spectra are displaced by approximately 200 kev towards the end corresponding respectively to energies larger and smaller than those of “thermonuclear” neutrons. It must be pointed out here that in the work described in Ref. 14 and briefly above a neutron energy spectrum was obtained (Fig. 16 above and Fig. 5 in Ref. 14) that had been obtained in the course of preliminary experiments where no special steps were taken to reduce the effect of the scattering of the neutrons. As a result, the cathode spectrum maximum was somewhat displaced towards the low-energy end; this, as was explained subsequently, led to the erroneous conclusion that the shift between the maxima of the cathode and anode spectra obtained in a chamber with conducting walls is less (see above) than that obtained in a chamber with non-conducting walls.\(^6\)\(^{15}\)\(^{16}\) In the present work, the neutron energy spectrum is the result of experiments carried out under conditions which eliminate the effect of scattering so far as possible, although some 20–30% of the neutrons are still scattered.

The form of the spectra obtained indicate the existence of an accelerating mechanism producing neutron radiation in chambers with conducting walls (just as in the case of chambers with non-conducting walls).\(^6\)\(^{15}\)\(^{16}\) The acceleration of the deuterons occurs in a small region near the anode; and the velocity of the main body of fast deuterons is directed along the axis of the discharge chamber from anode to cathode.

From the spectra obtained it is possible to calculate (allowing for straggling) that the maximum energy of the accelerated deuterons must be about 200 kev.

In examining the spectra of neutrons leaving the chamber at different angles \(\phi\) (Fig. 21), a shift of their maxima towards the lower-energy end as \(\phi\) increases is noticeable. Figure 22 shows the relationship between the angle \(\phi\) and the neutron energy at the maxima of the neutron spectra (the calculated curves are represented by broken lines). It is clear from Fig. 22 that deuteron energies of 25–50 kev correspond to the maxima of the neutron spectra.

Assuming, as a first approximation, that the neutron source is a point situated 3.5 cm from the anode, we plotted the angular distribution of the neutrons. This showed that, for the lateral and anode plates (\(\phi = 45°–180°\)), the experimental results are in satisfactory agreement with the angular distribution of neutrons corresponding to a deuteron energy of \(\sim 50\) kev. In the case of the cathode plate (\(\phi = 0°\)) it was found that the intensity of neutrons leaving the chamber in the direction of the cathode was \(\sim 3\) times that of neutrons radiated in the direction of the anode (whereas, even at the maximum deuteron energy of 200 kev, it should have been only 1.5 times as great). The ratio could come out at \(\sim 3\) only if the energy of the accelerated deuterons was taken as 1.5–2 Mev, which completely contradicts the results of other experiments. This contradiction can be disposed of if we assume the existence of a second neutron point-source not more than 5 cm from the cathode with an intensity not exceeding 10% of that of the main source. This second source can make a
substantial contribution only to the neutron flux falling on the nearest (cathode) plate.

The cathode and anode neutron spectra obtained in the present work were also compared with the corresponding spectra for chambers with non-conducting walls. In Fig. 23, 1-4 are neutron spectra obtained respectively in the present work and in that described in Refs. 15 and 16. In this diagram, the cathode spectra of the neutrons are shown in dotted lines and the anode spectra in full lines.

It is noticeable that in anode spectra 1 and 4 there is a relatively large quantity of neutrons with energies approaching the "thermonuclear". Nevertheless, all four spectra are extremely similar to one another despite the fact that they were obtained for neutron radiation produced under different initial conditions (type of wall, dimensions of chamber, pressure, voltage, etc.) and have a different longitudinal distribution of the sources of the radiation. However, we do not have sufficient grounds for giving a definite answer to the question: Is there, or is there not, the same accelerating mechanism for chambers with conducting and those with non-conducting walls?

Conclusions

The following deductions can be made from the results obtained here:

1. The sources of the neutron radiation are concentrated along the axis of the chamber, chiefly (\(\sim 90\%\) of the total intensity) in a small area not more than 6-7 cm long in front of the anode. The center of gravity of the sources is situated 3-4 cm from the anode.

2. On the basis of the observed angular distribution of the neutron radiation, the existence was assumed of a second neutron source, with an intensity not exceeding 10% of the total intensity, situated not more than 5 cm from the cathode.

3. The main body of the neutron radiation is dependent upon the existence of some sort of mechanism for accelerating deuterons. The maximum energy of the latter is 200 kev, and the deuteron energy corresponding to the maximum of the neutron energy spectra is 20-50 kev.

4. Comparison with the results of other experiments \(6, 15, 16\) shows that the general form of the energy spectra of neutron radiation is identical for chambers with conducting and for those with non-conducting walls, and is affected to only a small extent by changes in the discharge conditions (shape and dimensions of the chamber, initial voltage, pressure of the deuterium, etc.).

Electrons Causing the Hard X Rays

The work here described was devoted to the measurement of the energy of the electrons responsible for the emission of hard X-ray quanta. The experiments were carried out under the conditions described in Part 3. During the work the presence of X-ray pulses was checked by means of a scintillation counter connected to a pulsed oscilloscope.

In accordance with the hypothesis that the electrons are accelerated along the axis of the discharge chamber, a hole was made in the center of the electrode which is positive at the moment at which the voltage is applied; this hole was covered with aluminum foil \(6\ \mu\) thick. Behind the aluminum window was mounted a flat vacuum chamber situated between the pole-pieces of an electromagnet run off a pile of batteries. Hyper-sensitized X-ray plates, prepared at NIKFI [Cinematographic and Photographic Scientific Research Institute], were used to monitor the electrons.

When a slit diaphragm was interposed between the aluminum foil and the plate in the absence of a magnetic field, a sharp image of the slit field appeared when the plate was exposed to 5-10 discharges. When a weak magnetic field \((H = 20\ \text{gauss})\) was applied, one end of the image of the slit became diffuse. This diffuseness could only be explained by negatively charged particles impinging upon the plate. The blackening observed could not have been caused by penetrating electrons of energy \(W = 40\ \text{kev}\) originating at the start of the discharge, since when

---

1. To facilitate comparisons we have reduced spectra 2, 3 and 4 to the form \(I_n(E_n)\) used in the present work.
2. This part is by I. M. Podgorny, N. G. Kovalsky and V. E. Palchikov.

---
the initial pressure of the hydrogen was reduced to 1.5 × 10⁻⁴ mm Hg, the intensity of the initial X rays increased sharply but no pulse of (hard) X rays were recorded by the oscillograph, and there was no blackening of the plate. These facts show beyond doubt that the electrons responsible for the generation of hard X rays are accelerated along the axis of discharge.

To determine the energy of these electrons, the plate was exposed in the absence of the magnetic field and then, without being changed, was subjected to several tens of discharges under a magnetic field (H = 230 gauss). This method enabled us to obtain on the same plate blackening due both to the energy spectrum of the electrons and to the line corresponding to the undeflected beam of electrons. This line was used for determining the position of the plate in the spectrograph. The plates thus obtained were scanned with an MF-4 microphotometer.

To obtain the spectrograph dispersion curve, the electron tracks were plotted graphically. This called for thorough study of the topography of the magnetic field. Using the dispersion curve, and measuring on the microphotograph the distance between the base line and the boundary of the blackening caused by the electrons deflected by the magnetic field, it is easy to obtain the value of the maximum energy acquired by the electrons while moving along the axis of discharge.

As has been indicated, the curve of the energy spectrum of hard X rays falls sharply on the high-energy side. Hence the position of the boundary of the energy spectrum of electrons responsible for hard X rays might be expected to vary with the exposure. To confirm this, a series of experiments was carried out in which the exposure varied from 20 to 90 discharges. Comparison of the corresponding microphotograms showed that, beginning with an exposure of 50 discharges, the boundary of the blackening ceases to be displaced directionally towards the base line (i.e., towards the high-energy side). It should, however, be pointed out that as the exposure increases the curve of blackening near the boundary becomes less steep, which makes it easier to determine the maximum energy. Processing of the experimental results obtained showed the maximum energy of the electrons to be 500 kev.

A 100-kev electron beam was used to confirm the accuracy of the plotting of the electron tracks. The electron source was placed inside the porcelain chamber; in addition, the geometry of the test corresponded in every detail to that used in the experiments described in this paper. The energy of the electrons as determined by measuring the potential difference agrees to within 3% with that obtained by plotting the dispersion curve. Allowing for the spread in the results of individual experiments, the authors consider that the results obtained are accurate to 5-6%.

Thus it has been shown by direct experiment that the electrons responsible for the generation of hard X rays accompanying high-current pulse discharges in hydrogen are accelerated along the axis of the discharge chamber. The maximum recorded energy of the electrons was 300 ± 20 kev, a figure which agrees well with the results obtained by measuring the boundary energy of the X-ray spectrum.

REFERENCES

3. L A Artsimovich, A M Andrianov, E I Dobrokhотов, S IU Luk'ianov, I M Podgornyi, N V Filipov, Atomnaya Energi, 7, No 3, 84 (1956)
4. S IU Luk'ianov and V I Simtsm, Atomnaya Energi, 7, No 3, 88 (1956)
5. S IU Luk'ianov and I M Podgornyi, Atomnaya Energi, 7, No 3, 97 (1956)
7. S Berglund, R Nilson, P Ohlin, K Sieglin, T Sundström and S Svennerstedt, Nucl Instr., 7, 233 (1957)
12. S IU, Luk'ianov and V I Simtsm, Spectroscopic Investigations of High-Temperature Plasmas, P/2228, Vol 32, these Proceedings