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ON THE POSSIBILITY OF PRODUCING THERMONUCLEAR REACTIONS IN A GAS DISCHARGE*

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AMONG the more important problems of modern engineering science, utilization of the energy of thermonuclear reactions stands out as one of the foremost significance. Physicists all over the world are attracted by this extraordinarily interesting and difficult task of controlling thermonuclear reactions.

Investigations in this field are being carried out under the direction of Academician L. A. ARTSIMOVICH at our Institute. A leading role in the theoretical investigations was played by Academician M. A. LEONTOVICH.†

As is well known, thermonuclear reactions can occur if the temperature of matter is sufficiently high for the atomic nuclei to have an appreciable probability of surmounting the Coulomb barrier during thermal collisions. The excitation of thermonuclear reactions in deuterium or in a mixture of deuterium and tritium is especially interesting, as in this case a noticeable effect should be obtainable at relatively low temperatures. Physics is indebted to the founder of nuclear science, ERNEST RUTHERFORD, for the earliest information regarding the interaction of deuterons. In one of his last investigations RUTHERFORD studied the nuclear reactions which occur when two deuterons collide. It was difficult to suspect at that time that the new facts which he discovered would make more realistic our hope of mastering thermonuclear energy—the source of power which has so far existed only in the remote parts of the sun and distant stars which shine above us.

The intensity of thermonuclear reactions in deuterium should greatly increase with the temperature up to temperatures of several billion degrees.

Some idea of the conditions under which thermonuclear reactions should be experimentally observable can be obtained by considering specific cases.

In deuterium of density equal to that of a solid body under normal conditions, a temperature of $2 . 10^5$ degrees would be required to obtain one neutron per second per gram of deuterium. If the deuterium were a highly rarified gas with a concentration of about 10^{13} atoms per cm^3 a temperature of about $5 . 10^5$ degrees would be required to produce some effect in a gram of deuterium, which would occupy a volume of 30,000 m^3.

Thus, even to approach the threshold for production of thermonuclear processes the temperature of matter must be raised to a very high level. At such temperatures and under stationary conditions the deuterium would be an almost totally ionized plasma.

The amount of energy which must be concentrated in the plasma to raise its temperature to a level sufficient for the production of intense thermonuclear reactions should be comparatively small. Thus, the amount of thermal energy necessary to

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† Papers by L. A. ARTSIMOVICH, M. A. LEONTOVICH and others appear in this issue of *Atomnaya Energiya*.

raise the temperature of one gram of deuterium to 10^6 degrees equals only a few kilowatt hours. This is about the amount of energy required to boil water in the family samovar.

Therefore, if one were able to invent a method of heating the plasma with practically no thermal losses, even a low power energy source could be used to induce intense thermonuclear processes. The main problem is to exclude heat losses, which rapidly increase with the temperature since the thermal conductivity of the plasma is proportional to $T^{5/2}$.

When matter is heated to a temperature of only several tens of thousand degrees the losses in the absence of thermal insulation will be so great that further increase of temperature will be practically impossible.

There is another obstacle which arises when dense substances are heated: one must overcome the enormous mechanical forces which result from increase of the pressure with temperature. On heating initially solid or liquid deuterium we find that already at $T = 10^5$ degrees the pressure exceeds a million atmospheres. Therefore, thermonuclear reactions can be induced only during a very short period of time in dense substances, and such a process will always have the character of a brief pulse, resembling an explosion (which, however, may not be dangerous).

On considering the possible ways of generating intense controllable thermonuclear processes one finds that there are quite a number of directions which may be followed in attempting to solve this problem.

On the one hand there are the approaches which lead to stationary thermonuclear reactions; and on the other, those which are based on the idea of utilizing an instantaneous temperature rise in transient processes of very brief duration. However, irrespective of the way the investigation is carried out there is one problem that is inevitably encountered, namely, the isolation of the hot plasma from the walls of the vessel in which it is confined. In other words, a means must be found to keep the fast particles within the plasma over a period sufficiently long for the particles to have a good chance of reacting with each other.

One of the ideas proposed in connection with this problem was that of using a magnetic field for thermal insulation of the plasma. Academicians SAKHAROV and TAMM were the first to point out this possibility in 1950. In a sufficiently strong magnetic field, electrons and ions can freely move only along the lines of force. In a plane normal to the lines of force the particles will describe circles of small radius. The positions of the centres of these circles can vary only as a result of collisions, each collision displacing the centre by a distance of the same order of magnitude as the radius of curvature of the particle trajectory. If the radius of curvature of the trajectory is small compared to the mean free path, diffusion of the particles and thermal conductivity of the plasma in the plane normal to the magnetic field will be greatly diminished. The theory of processes taking place in a completely ionized plasma indicates that at high field strengths H and at high temperatures, the transverse thermal conductivity coefficient is inversely proportional to H^2, and is smaller by many orders of magnitude than the value found in the absence of a magnetic field. Under these conditions, however, radiation losses must be taken into account.

The magnetic field required to provide the thermal insulation may be produced by passing a sufficiently intense current through the plasma. The current will also heat the plasma as a result of Joule losses and of the work of electrodynamic forces. These considerations were the basis for carrying out theoretical and experimental studies of the physical processes which occur in a plasma on the passage of intense currents.

Let us first examine the principal theoretical concepts which preceded the experimental work. When a current is passed through a plasma, the latter should contract under the action of electrodynamic forces (attraction of parallel currents). An increase of plasma temperature should follow. If a contracted column of the plasma is detached from the vessel wall as a result of electrodynamic contraction (the "pinch" effect) its temperature may be estimated from the condition that the pressure of the ionized gas is balanced by the electrodynamic forces. A simple computation shows that in such quasi-stationary contraction processes the plasma temperature should be proportional to the square of the current. It is well known that if the electrons and ions are in thermal equilibrium the plasma temperature can be expressed by the equation:

$$T = \frac{I^2}{4Nk}.$$

Here I is the current expressed in electromagnetic units, N is the number of particles of a given sign per centimetre length of discharge tube and k is the Boltzmann constant. Investigation of the conditions of thermal equilibrium showed that for $N \sim 10^{17}$ the electron and ion temperatures should be practically identical. At appreciably lower values of N only the electron temperature will increase.

A contracted plasma column detached from the walls can exist only as long as the current is building up. If the current is constant the column will disintegrate and come in contact with the walls.

It is evident that a thermonuclear reaction with a constant yield over an appreciable period of time cannot be produced by passing a current through a plasma. In principle it should be feasible to heat the plasma periodically and induce thermonuclear reactions in phase with the peak current. Calculations of the expected thermonuclear effect led to the following result, which at first glance may seem paradoxical. It was found that during a single heating cycle the total number of elementary nuclear interaction events pertaining to a given value of the peak current should be independent of the duration of this cycle. Thus, it seemed that it should be possible to excite very intense thermonuclear reactions by sending pulsed discharges of very short duration through deuterium, on the condition that the current was sufficiently large. Theoretical calculations indicated that a current of only 300 kA should be sufficient to produce an appreciable emission of neutrons of thermonuclear origin. At currents of several millions of amperes the emission should be very intense. Such were the theoretical predictions which preceded the experiments.

Further development of our ideas regarding the nature of the processes occurring in a plasma during the passage of an intense current was profoundly influenced by the new facts discovered during experimental investigation of powerful pulsed discharges. These results completely altered the picture which had been created by the first spurts of theoretical effort.

Experimental investigation of intense pulsed discharges was carried out over a broad range of the parameters characterizing the initial discharge conditions.*

Discharges through hydrogen, deuterium, helium, argon, xenon and gas mixtures (deuterium-helium, deuterium-argon, deuterium-xenon) of various relative contents were studied. The measurements were carried out at gas pressures ranging from 0·005 mm Hg to one atmosphere. Most of the experiments were performed with straight discharge tubes. The length of the discharge gap varied from several centimetres up to two metres and the diameter from 5 to 60 cm. The discharge was produced by a voltage of several tens of kilovolts. Peak current varied from 100 kA up to two million amperes, the rate of buildup of the current lying between 10^{10} A sec^{-1} and 10^{12} A sec^{-1}. The maximum instantaneous power released in the plasma in these experiments attained as much as 40 million kilowatts.

Banks of high voltage condensers were used to produce the discharges. The leads which carried the current from the condenser to the discharge gap were designed in such a manner as to keep the parasitic inductance of the electric circuit down to a minimum, since this factor restricted the magnitude of the current and its rate of growth. For a voltage of 50 kV and a total condenser bank capacity of several hundred μF, the parasitic inductance of the circuit and switch was only 0·02–0·03 microhenry (in those cases when the current growth was maximal).

Oscillographic methods of measurement of the main parameters characterizing the state of the plasma during passage of a current were developed, and were used to study the intense pulsed discharges. Besides oscillography, ultra-high-speed moving-picture cameras (up to 2 million frames per second) were used as well as photography by the aid of Kerr cells supplied with special electroexplosive types of shutters.

In addition to the discharge current and voltage, oscillograph records were also made of the intensity of separate spectral lines from the plasma, of the neutron and X-ray intensity, of the magnitude of pressure pulses measured with aid of piezo-electric elements, and also of the instantaneous magnetic and electric field strengths at various points within the plasma. The magnetic and electric fields were measured with small probes in the form of miniature coils, loops or needle electrodes of various shapes which could be placed at various points within the discharge vessel.

Limitations of space do not permit me to give here a detailed account of the numerous results obtained in this series of experiments. It is possible to report only a small part of the available experimental material.

Of greatest interest is the first phase of the discharge, during which the plasma current rises from zero to the peak value. In the experiments discussed here this phase lasted from 3 to 30 microseconds. At the beginning of the discharge, after break-down of the gas, a smooth increase of current and voltage in the discharge gap takes place. After a certain period of time a sharp decrease of the voltage occurs. At the same time a more or less pronounced kink can be seen on the current oscillogram (see Figs. 1, 2, and 3). After the first drop the voltage began to increase rapidly and then sharply dropped again. This second voltage decrease was paralleled by the

* In England pulsed discharges in gases have been investigated in recent years by J. D. CRAGGS and his collaborators, S. W. COUSINS, A. A. WARE, and others.

appearance of a new kink on the current oscillogram. In some cases three consecutive sharp changes in the otherwise smooth variation of current and voltage were observed in the first stage of the discharge.

These characteristic features of high-current pulsed discharges are especially pronounced when the discharge takes place in gases of low atomic weight (hydrogen, deuterium, helium) and at low initial pressures.

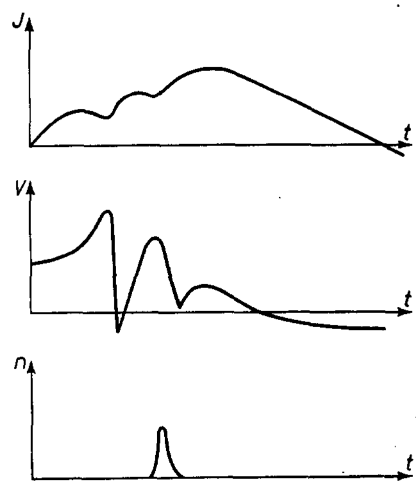

FIG. 1.—Diagrammatic representation of the time variation of current and voltage in a pulsed discharge, showing also the burst of neutrons.

When the rate of current buildup is of the order of 10^{11} A sec^{-1} the interval between breakdown of the gas and the appearance of the first voltage drop comprises several microseconds. This time interval is a regular function of the parameters characterizing the initial conditions of the discharge. For a given discharge tube diameter it varies approximately as the fourth root of the mass of gas per centimetre length of the discharge gap.

The inductive resistance is much larger than the ohmic one in pulsed discharges in which the current increases at a high rate. Thus by using current and voltage oscillograms one may find the time dependence of the inductance of the plasma column and hence determine how the radius of the column changes at various stages of the process. An analysis of this type indicates that in all cases the very first stage of the process is characterized by an increase of the inductance due to contraction of the plasma towards the discharge tube axis. The speed of constriction of the plasma increases with the initial current build-up rate (that is, with the derivative dI/dt), and decreases with the gas density. At the moment when the kink on the current oscillogram appears and a sharp drop in the potential is observed the inductance begins to decrease. It follows that this moment corresponds to maximum contraction of the plasma filament. This situation is followed by a rapid expansion of the filament. The appearance of several kinks on the current oscillogram signifies that consecutive contractions and expansions of the column take place.

These conclusions, which were obtained by analysing current and voltage oscillograms, are confirmed by data obtained by applying ultra-high-speed cine-photography to pulsed discharges in tubes with transparent walls. On the accompanying photograph

(Fig. 4) are shown four successive frames of a moving picture of a pulsed discharge in deuterium at a pressure of 0·1 mm Hg having a peak current of about 200 kA. These pictures were taken at intervals of 0·5 microseconds and refer to only a very small period of development of the process which corresponds to the current and voltage break. The moving picture frames were phased with the current and voltage oscillograms, and it was shown that the minimum plasma column diameter corresponds exactly to the moment of maximum contraction.

The next photograph (Fig. 5) was obtained by using a moving picture camera for continuous photography. In this method a narrow slit perpendicular to the axis of the discharge tube subtends a small segment of the discharge gap whose image is swept across the film with a high speed. As a result, a continuous picture of the variation of the diameter of a small segment of the plasma column was obtained on the film. The photograph shown here was obtained for a discharge in deuterium with a peak current of about one million amperes. The initial gas pressure was 10 mm Hg. The moment of maximum contraction and the further development of the process are clearly visible.

A photograph of the contracting plasma column obtained with the aid of a Kerr cell is shown in Fig. 6.

Valuable data on the main physical processes occurring in intense pulsed discharges can be obtained by measuring the magnetic and electric field strengths in a plasma. Magnetic field measurements permit one to draw the following picture of current distribution. Directly after breakdown, the current conducting region is a thin cylindrical layer adjacent to the discharge tube walls. The inner boundary of this layer moves at first slowly and then more rapidly towards the axis. After a certain interval of time the current fills the whole tube as a result of movement of the inner current boundary. The moment at which the current reaches the axis practically coincides with the time of appearance of the first kink on the oscillogram.

The current density near the discharge axis at this time exceeds the mean current density over the cross-section of the tube by several tens of times. On subsequent expansions and constrictions the current density remains very high in a central region of several centimetres in diameter although appreciable fluctuations are observed.

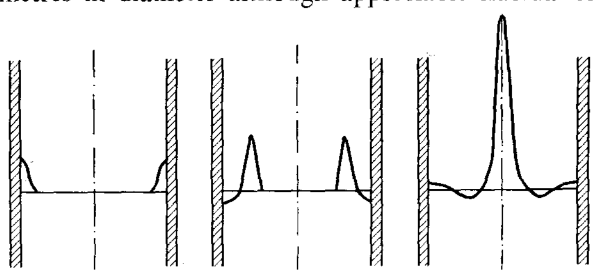

FIG. 8.—Current density distribution across the discharge tube at different times.

The current density distribution over the cross-section of the discharge tube at various periods of time is shown schematically in Fig. 8. The current density distribution at the very first stage of the discharge is shown in the left figure. The second one refers to the moment when the current is moving towards the axis. The distribution after the first contraction of the plasma column is illustrated in the right figure. An interesting feature of this stage of the process is that in a certain zone of the discharge the current reverses its direction.

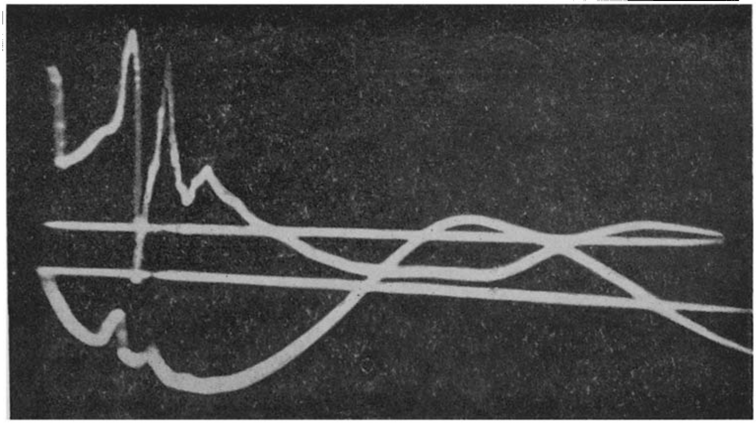

FIG. 2.—Oscillogram of current and voltage for a discharge in deuterium at $V_0 = 40$ kV and $P_0 = 5 \, . \, 10^{-2}$ mm Hg.

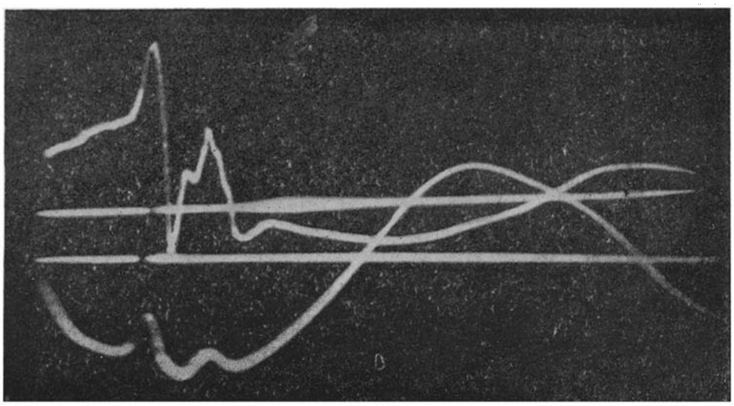

FIG. 3.—Oscillogram of current and voltage for a discharge in deuterium at $V_0 = 40$ kV and $P_0 = 0{\cdot}2$ mm Hg.

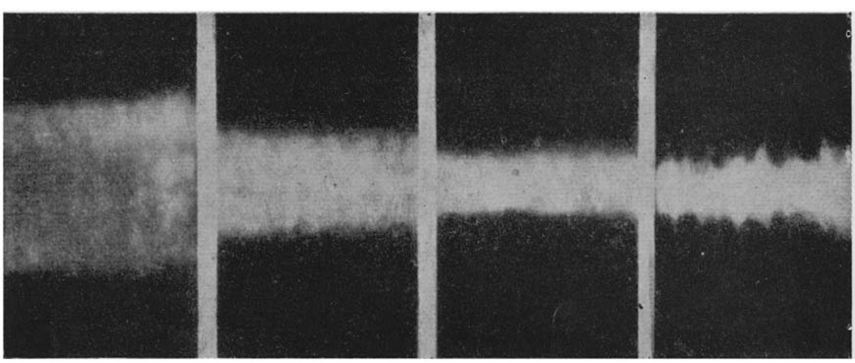

FIG. 4.—Motion-picture frames of a pulsed discharge.

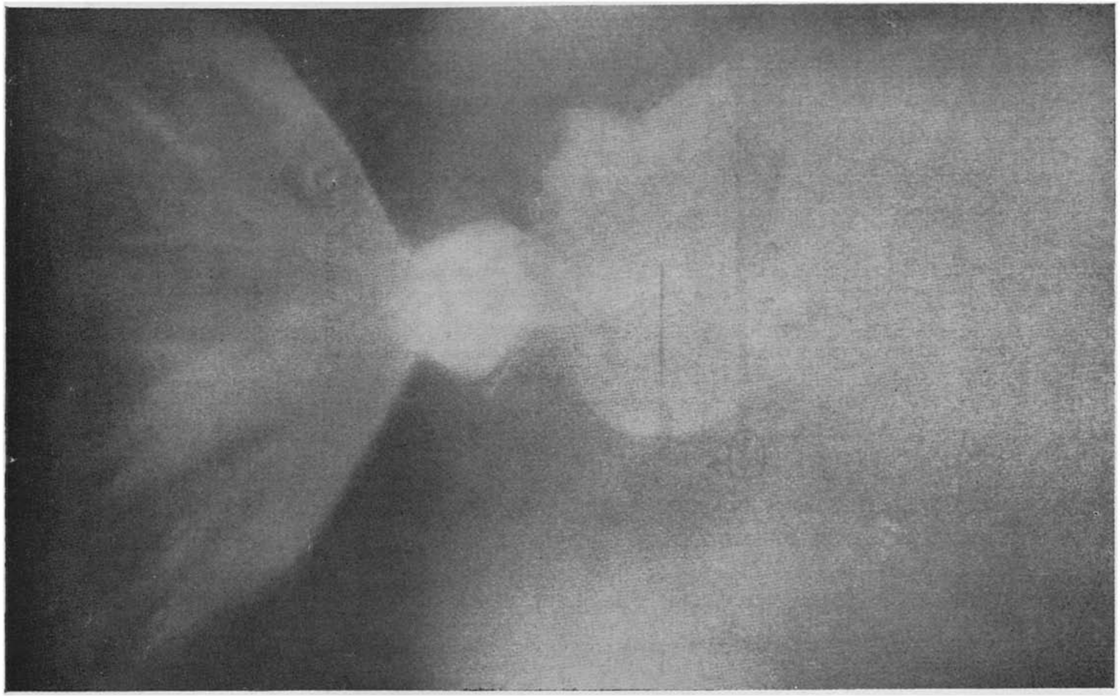

FIG. 5.—Photographic sweep of a discharge in deuterium at a pressure of $P_0 = 10$ mm Hg. Hemispherical electrodes were held 45 mm apart in a 180 mm diameter chamber. $I_{max} = 1{\cdot}2 \times 10^6$ amps, $T/4 = 9{\cdot}5\ \mu$sec. Scale: 18 mm = 1 μsec.

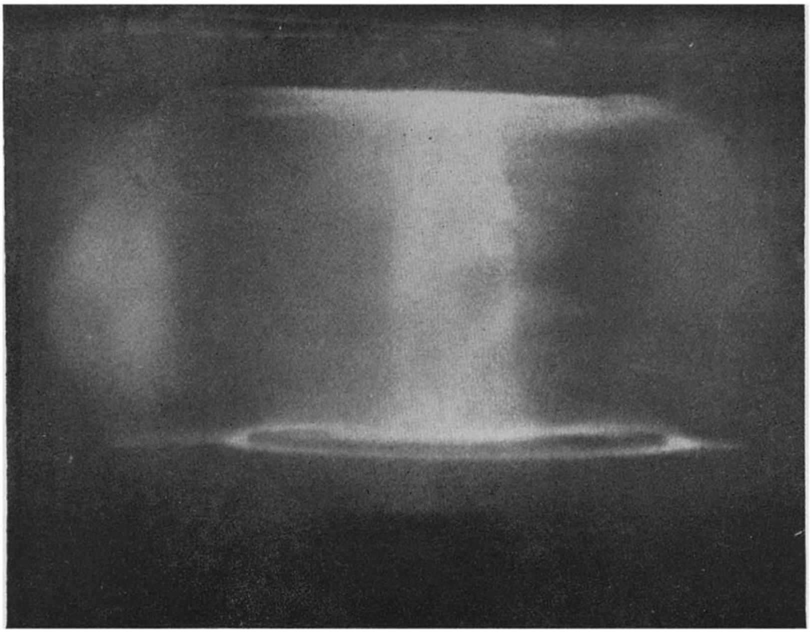

FIG. 6.—Moment of contraction of the discharge column. Exposure 0·2 μsec, made with Kerr cell. Discharge in deuterium at pressure $P_0 = 1$ mm Hg. Distance between electrodes 45 mm, diameter of vessel 180 mm.

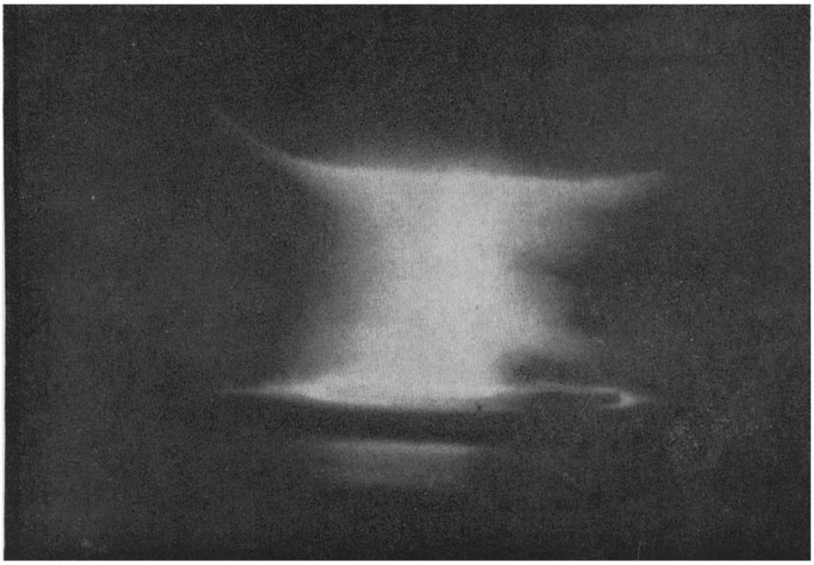

FIG. 7.—Photograph made with Kerr cell, 2·2 μsec after commencement of discharge in deuterium. Exposure 0·2 μsec. Initial pressure $P_0 = 1$ mm Hg. Distance between electrodes 40 mm.

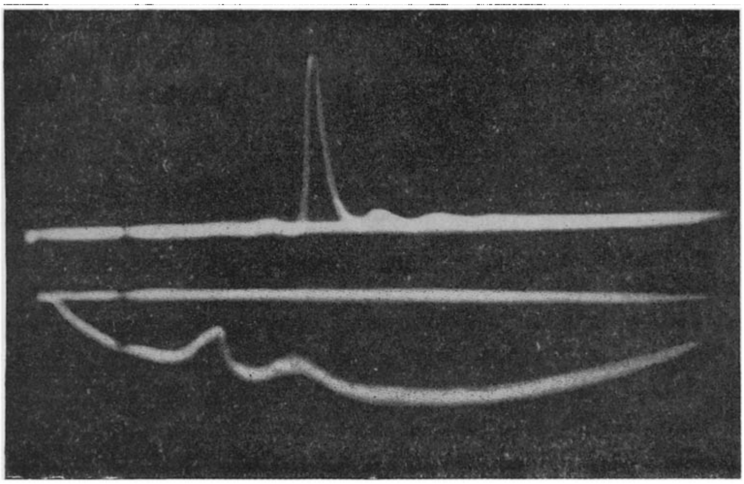

FIG. 9.—Oscillogram of current and neutron pulse for a discharge in deuterium at $V_0 = 40$ kV and $P_0 = 5 \cdot 10^{-2}$ mm Hg.

The velocity of the ionized gas is the quantity which directly characterizes the dynamics of a pulsed discharge.

In a plasma of sufficiently high conductivity this velocity is determined by the ratio between the longitudinal electric field strength E and the magnetic field strength H:

$$v = \frac{cE}{H}.$$

Measurements of E and H indicate that in a pulsed discharge with rapid growth of current the radial velocity of the plasma may be very high. The maximum velocity during contraction and expansion of the plasma column in rarefied gases was found to reach hundreds of kilometres per second. This signifies that the kinetic energy of the drift of the plasma ions is of the order of several hundred electron volts.

One of the most interesting effects observed in the intense pulsed discharge in light gases is the appearance of penetrating radiations. In 1952, soon after experiments with pulsed discharges were started, it was found that at sufficiently high currents the discharge in deuterium becomes a source of neutrons.

The first experiments performed with the aim of studying this phenomenon showed that neutrons appear under conditions when the peak discharge current is 400–500 kA and the initial deuterium pressure is about 0·1 mm Hg. The neutron emission was observed in a relatively narrow pressure range and its intensity rapidly increased with increase of the applied voltage, i.e. with increase of the peak current. In these first experiments the radioactivity induced in a silver target embedded in a paraffin block near the discharge tube served as the neutron detector. A possible explanation of this phenomenon was that the neutron emission resulted exclusively from collisions between the accelerated deuterons and deuterium adsorbed by the electrodes on tube walls; control experiments, however, did not confirm this explanation.

In the early stages of the investigation it was quite natural to assume that the neutrons resulted from thermonuclear reactions in the high temperature plasma. This was exactly what was expected from the beginning; and the fact that the phenomenon was detected under conditions which completely corresponded to the *a priori* theoretical predictions seemed to speak in favour of this interpretation. The behaviour of the neutron radiation (its dependence on pressure and current) observed in the first experiments qualitatively concorded with the assumption that the phenomenon was due to a thermonuclear mechanism. However, very soon, serious doubt about the correctness of this assumption began to appear. This happened after it was found that neutrons can be observed at comparatively small discharge currents, of the order of 150 kA. According to the initial calculations the intensity of the thermonuclear reaction at currents of 150 kA should be practically zero.

In subsequent experiments the neutrons were recorded with a scintillation counter fed to an oscillograph. This technique made it possible to find the relation between the discharge properties and the moment of appearance of neutrons. It was found that the neutrons were always emitted when the second kink appeared on the current oscillogram, i.e. at the moment when the plasma was subject to the second contraction (Fig. 9). No neutrons were produced during the first contraction. The neutrons were always emitted as short pulses with a steep front. The rise time of the pulses was several tens of microseconds. The chief results of these oscillographic investigations were not consistent with the initial assumption that the neutron emission is the result of quasistationary heating of the plasma during which the temperature increases proportionally to the square of the current.

Further investigation yielded new and interesting facts pertaining to the plasma neutron radiation. It was established, in particular, that in specially designed discharge tubes the neutrons could appear at fairly high deuterium densities, as much as several tens of millimetres of initial pressure. This fact signified that the neutron emission was certainly not a trivial effect.

It was found that not only neutrons but also hard X-rays were produced in pulsed discharges. Penetrating X-rays were found when large currents were passed through hydrogen, deuterium and helium. The radiation produced by discharges in deuterium always consisted of short bursts. The pulses due to the neutrons and X-ray quanta always appeared simultaneously on the oscillograms. The energy of the X-ray quanta produced in pulsed electrical processes in hydrogen and deuterium reached 300–400 keV. It is noteworthy that at the time of emission of such high energy quanta the voltage applied to the discharge tube was only about 10 kV.

Theoretical analysis of the complex phenomena which occur in the plasma of a pulsed discharge oscillating under the action of electrodynamic forces is still at such an early stage that quite a number of facts remain to be explained. However, the general picture of the process is gradually becoming clear, and some of the peculiarities of the phenomenon seem to have been sufficiently elucidated.

It is now clear that contraction and expansion of the plasma are not quasistationary processes characterized by equilibrium between the external and internal pressures.

In the equations describing the dynamics of a pulsed discharge the main term is that which accounts for momentum changes in the ionized gas due to magnetic pressure. The kinetic energy of the ordered motion should at some stages of the process therefore greatly exceed the thermal energy concentrated in the plasma.

At the initial stage of the discharge, the internal pressure in the plasma is very small and the electrodynamic forces therefore produce acceleration along the radius towards the discharge tube axis. Thus, the work of the electrodynamic forces is not expended in raising the temperature but in imparting kinetic energy to the converging plasma layer. During this stage the discharge tube operates as a peculiar type of accelerator in which the particles are driven by the magnetic field. Since charged particles, irrespective of sign, will move with the same velocity, the kinetic energy acquired by the ions will be quite large, whereas the kinetic energy of the electrons will virtually not change by reason of the small mass of these particles. From the viewpoint of gas dynamics the contraction process should be considered as a phenomenon in which a cylindrical shock wave converging towards the axis is produced in the plasma. At first, the gas located before the inner wave front is not ionized. When the wave begins to move, the gas is carried along together with the charged particles of the plasma and its atoms simultaneously become ionized. The amount of matter which begins to move gradually increases and the total number of ions and electrons in the plasma rapidly increases. The duration of the contraction phase can be determined by calculating the velocity acquired by the contracting gas. It was found to be approximately proportional to $\sqrt[4]{\frac{M}{V_0^2}}$, where M is the mass of gas per unit length of discharge tube and V_0 is the initial voltage. This is exactly what one finds experimentally for the interval between breakdown and the appearance of the first kink in the current oscillogram.

The final stage of cumulative contraction sets in when the plasma, accelerated by the magnetic field, reaches the axis. At this moment a great part of the energy of ordered motion changes into heat, and the pressure and plasma temperature sharply increase. Under maximum contraction the plasma temperature may be of the order of a million degrees. The nature of the processes occurring during maximum contraction are not very clear, but apparently after maximum cumulation a diverging shock wave must appear which drives the plasma towards the walls. Inside the outgoing wave there should be a rarified zone. Under the action of electrodynamic forces which tend to compress the current the outgoing wave should be abruptly decelerated and a new phase of contraction should ensue. This stage differs from the first in that the density in the inner region of the discharge is small and the gas in this region is probably almost completely ionized. As a result, during the second contraction conditions are produced which are favourable for the acceleration in the longitudinal electric field of a certain group of ions and electrons located near the discharge axis, i.e., in the region in which the magnetic field is small. One may note here a certain analogy with the accelerating mechanism proposed by FERMI in his theory of the origin of cosmic rays. A plasma of high conductivity will move together with its magnetic field; and with respect to particles located in the inner zone it will be equivalent to a converging magnetic wall from which the enclosed electrons and ions will repeatedly be reflected, their energy increasing after each reflection.

Acceleration of ions and electrons in the longitudinal electrical field near the discharge axis is possibly the explanation of appearance of neutrons and penetrating X rays. The electric field strength during the second contraction may be very high. It may exceed the instantaneous external voltage applied to the discharge tube by many times.

However, it must be said that not all in this acceleration mechanism is yet clear. Under certain conditions it is possible that ions may also be accelerated in the longitudinal electric field outside the central zone of the discharge, due to the presence of space charges. Some types of instability which are peculiar to the column may play an important role in accelerating particles in the plasma. In particular, one type of instability observed experimentally may be of importance for the acceleration of electrons. It consists in the spontaneous creation of a longitudinal magnetic field in the plasma as a result of a spiralling of the plasma column.

If the second contraction is followed by more radial oscillations of the plasma column the acceleration of the particles may be repeated several times. Experimentally, not more than three successive oscillations have been observed. A possible explanation of this is that the plasma may begin to interact with the discharge tube walls, with the result that wall material begins to evaporate and appreciable amounts of foreign gases appear in the volume.

We have considered here some features of the phenomena which accompany the passage of intense pulsed discharges through rarefied gases. The success of further work in this direction will greatly depend on the possibility of creating conditions under which the plasma column will experience multiple oscillations during build-up of the current, without coming into contact with the walls. There are serious reasons for believing that this cannot be achieved.

On appraising various approaches to the problem of creating intense thermonuclear reactions, it would seem that the prospect of attaining this goal by use of pulsed discharges cannot be altogether dismissed at the present time. However, other possibilities must also be considered carefully; and among these, particular interest attaches to methods in which stationary processes may be employed.