THE POSSIBILITY OF PRODUCING THERMONUCLEAR REACTIONS IN A GASEOUS DISCHARGE*

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Of foremost significance among the more important problems of modern engineering science is utilization of the energy of thermonuclear reactions. Physicists the world over are attracted by the extraordinarily interesting and very difficult task of controlling thermonuclear reactions.

Investigations in this field are being carried out by Academician Artsimovich at our Institute. A leading role in the theoretical investigations has been played by Academician M.A. Leontovich**.

As is known, thermonuclear reactions can arise if the temperature of matter is sufficiently high for atomic nuclei to surmount the forces of the Coulomb barrier with appreciable probability during thermal collisions. The excitation of thermonuclear reactions in deuterium or in a mixture of deuterium and tritium is especially interesting since in this case a noticeable effect should be obtainable at relatively low temperatures.

Physics is indebted to the founder of nuclear physics, Ernest Rutherford, for information regarding the interaction of deuterons. In one of his last investigations Rutherford studied the nuclear reactions that occur when two deuterons collide. It was difficult to suspect at that time that the new facts discovered by him would help realize our hope of mastering the energy sources of the hot interior of the sun and distant stars that shine overhead.

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

Some idea of the conditions under which thermonuclear reactions should be experimentally observable can be obtained by considering several concrete cases. In deuterium at densities equal to that of a solid body under normal conditions, a temperature of 2×10^5 °C would be required to obtain 1 neutron/sec/g of deuterium. In highly rarefied deuterium with a concentration of about 10^{13} atoms/cm^3 a temperature of about 5×10^5 °C would be required to produce the same 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 should be an almost totally ionized plasma.

The amount of energy that 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 raise the temperature of 1 g of deuterium to 10^6 °C equals only a few kilowatt-hours. This is about the same amount of energy required to boil water in a large family samovar.

Therefore, if one were able to devise 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 $T^{5/2}$. If matter is heated to a temperature of only several tens of thousand degrees in the absence of thermal insulation, the losses will be so great that further increase of temperature will be practically impossible.

*Lecture given April 26, 1956 at the British Atomic Energy Research Establishment at Harwell, England.

**Some works of L.A. Artsimovich and M.A. Leontovich appear in this issue.

There is another obstacle that arises when dense substances are heated: one must overcome the enormous mechanical forces that result from increase of the pressure with temperature. On heating initially solid or liquid deuterium we find that already at $T = 10^5$ °C the pressure exceeds 10^6 atmos. Therefore, thermonuclear reactions can be induced only during a very short period of time in dense substances and such a process will always resemble an explosion (which, however, may not be dangerous) or a brief pulse.

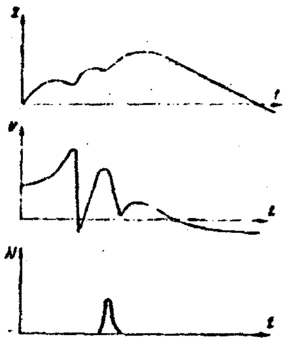

Fig. 1. The general form of the variation of the current and voltage in pulse discharges, and the neutron pulse that accompanies the discharge.

On considering the various ways of generating intense controllable thermonuclear processes one finds that there is a number of directions that can be taken in attempting to solve this problem.

On the one hand, there are the approaches that lead to stationary thermonuclear reactions, and on the other hand, those that 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 insulation of the plasma, which is heated to a high temperature, 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 sufficient for the particles to have a good chance to react 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 move freely only along the lines of magnetic force. In a plane normal to these lines of force the particles will move along circles of small radius. The positions of the centers of these circles can vary only as a result of collisions, each collision displacing the center 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 the processes taking place in completely ionized plasma indicates that at high field strengths H and high temperatures the transverse thermal conductivity coefficient is inversely proportional to H^2 and is many orders of magnitude less than the value found in the absence of a magnetic field. However, under these conditions radiation losses must be considered.

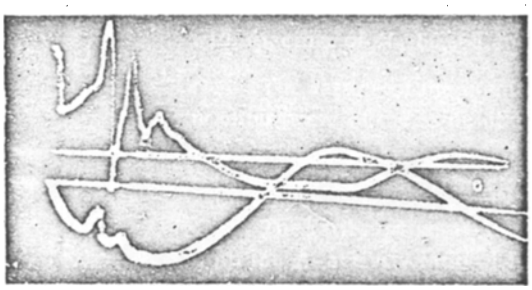

Fig. 2. Oscillogram of current and voltage in a discharge in deuterium, V_0 = 40 kv, P_0 = 0.2 mm Hg.

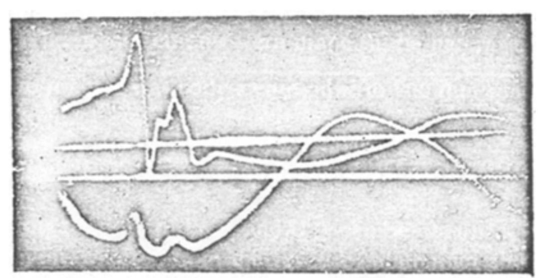

Fig. 3. Oscillogram of current and voltage in a discharge in deuterium, P_0 = 0.2 mm Hg, V_0 = 40 kv.

The magnetic field required to provide the thermal insulation can 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 that occur when intense currents pass through a plasma.

We shall first examine the principal theoretical concepts that 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 the plasma temperature should follow. If a contracted column of the plasma is detached from the vessel wall as a result of electrodynamic contraction ("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 increase proportionally to the square of the current. As is known, if the electrons and ions are in thermal equilibrium the plasma temperature can be expressed by the equation:

$$T = I^2/4Nk$$

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

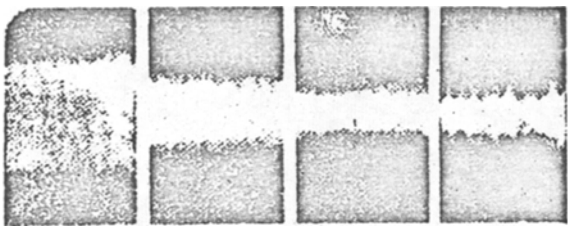

Fig. 4. Frames of a moving picture of a pulse discharge.

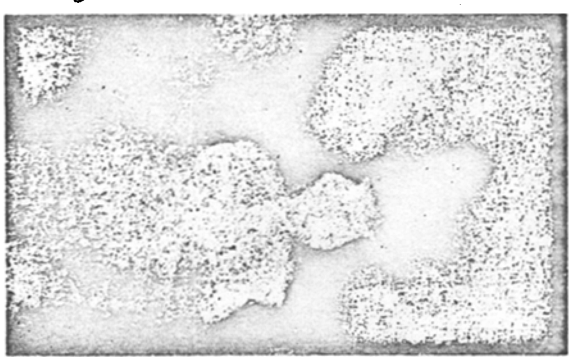

Fig. 5. Photograph of the development of discharge in deuterium for a pressure $P_0 = 10$ mm Hg. The electrodes are hemispheres. The interelectrode spacing is 45 mm. The scale of the photograph is 1 μsec = 18 mm. $I_{max} = 1.2 \cdot 10^6$ amps. T/4 = 9.5 μsec. The diameter of the chamber is 180 mm.

A contracted plasma column detached from the walls can exist only while the discharge 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 periodically heat the plasma 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 interactions for 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 pulse discharges of very short duration through deuterium if the current was sufficiently large. Theoretical calculations indicated that even a current of 300 kiloamps should be sufficient to produce an observable emission of neutrons of thermonuclear origin. At currents of several million amperes the emission should be very intense. Such were the theoretical predictions that preceded the experimental work.

Further development of concepts 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 intense pulse discharges. These results completely altered the character of the picture created by the initial theoretical efforts.

Experimental investigation of intense pulse discharges was carried out in 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 content were studied. The measurements were carried out at initial gas pressures ranging from 0.005 mm Hg to 1 atmosphere. The basic experiments were performed with straight discharge tubes. The length of the discharge gap varied from several centimeters up to 2 m and the diameter from 5 to 60 cm. The discharge was produced by a voltage of several tens of kilovolts. The peak current varied from 100 kiloamps up to 2×10^6 amps, the rate of build-up of the current lying between 10^{10} amp/sec and 10^{12} amp/sec. The maximum instantaneous power released in the plasma in these experiments was as much as 40×10^6 kw.

*In England, pulsed discharges in gases have recently been investigated by J.D. Craggs and his collaborators, S.W. Cousins and A.A. Ware, and others.

Banks of high-voltage condensers were used to produce the discharges. The leads that carried the current from the condenser to the discharge gap were designed to keep the parasitic inductance of the electric circuit to a minimum since this factor restricted the magnitude of the current and its rate of growth. For a voltage of 50 kv and total capacity of the condenser bank of several hundred μf, the parasitic inductance of the circuit and switch was only 0.02-0.03 μh (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 these were used to study the intense pulsed discharges. Besides oscillography, ultra-high-speed moving-picture cameras (up to 2×10^6 frames/sec) were used as well as photography by 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 the aid of piezoelectric elements, and also of the instantaneous magnitude of the 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 that could be placed at various points within the discharge vessel.

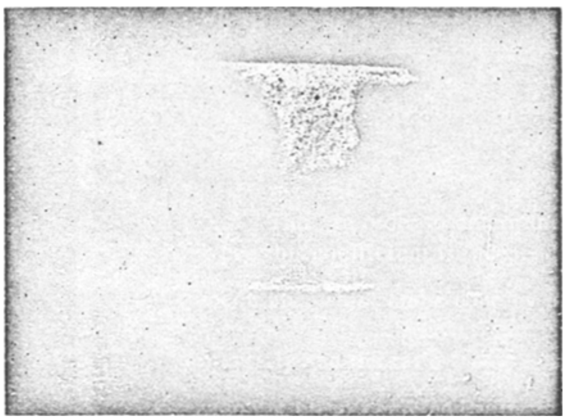

Fig. 6. The instant of contraction of the discharge column. The exposure time is 0.2 μsec. The discharge is in deuterium at a pressure $P_0 = 1$ mm Hg. The interelectrode distance is 45 mm, and the chamber diameter is 180 mm.

Fig. 7. Photograph of deuterium discharge made with Kerr cell 2.2 μsec after discharge began. Exposure 0.2 μsec. Initial pressure 1 mm Hg; distance between electrodes, 40 mm.

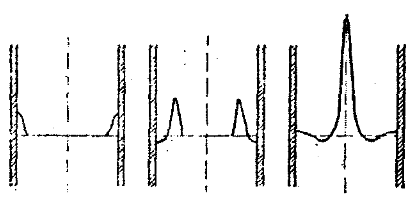

Fig. 8. Distribution of current density across the discharge tube at various times.

Space limitations do not permit me to give a detailed account of the numerous results obtained in this series of experiments. I will therefore report only a small part of this 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 μsec. At the beginning of the discharge, after breakdown of the gas, a smooth increase of the 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 Fig. 1, which illustrates the general nature of time variation of the current and voltage; see also Figs. 2 and 3). After the first drop the voltage began to increase rapidly and then dropped sharply again. This second voltage decrease was paralleled by the appearance of a new kink on the current oscillogram. In some cases, three consecutive sharp changes in the otherwise smooth variation of the current and voltage were observed at the first stage of the discharge.

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

When the rate of current build-up is of the order of 10^{11} amp/sec, the interval between breakdown of the gas and appearance of the first voltage drop is 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 gas mass per centimeter length of the discharge gap.

Inductive reactance is much larger than ohmic resistance 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. An analysis of this type shows that in all cases the very first stage of the process is featured 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 instant when the kink on the current oscillogram appears and a sharp drop in the potential is observed, the inductance begins to decrease. This means that this time corresponds to maximum contraction of the plasma filament. This situation is followed by a rapid expansion of the plasma filament. If a few kinks are observed on the current oscillogram, it means that successive contractions and expansions of the column take place.

These conclusions, which were obtained by analyzing current and voltage oscillograms, are confirmed by data obtained by applying ultra-high-speed cinemaphotography of pulse discharges in tubes with transparent walls. On Fig. 4. are shown four successive frames of a moving picture of a pulse discharge in deuterium at a pressure of 0.1 mm Hg and peak current of about 200 kiloamp. These pictures were taken at intervals of 0.5 μsec and refer to only a very small period of development of the process, which corresponds to the time of the current and voltage break. The plasma-column minimum diameter corresponds exactly to this time (the moving picture frames were synchronized with the current and voltage oscillograms).

Figure 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 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 10^6 amperes. The initial gas pressure was 10 mm Hg. The time of maximum contraction and the further development of the process are clearly visible.

Photographs of the contracting plasma column obtained with a Kerr cell are shown in Figs. 6 and 7.

Valuable data on the main physical processes occurring in intense pulse discharges can be obtained by measuring magnetic and electric field strengths in the plasma. Magnetic-field measurements permit one to draw the following picture of current distribution in the plasma: 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 toward 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 time 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 is several dozen times greater than the mean current density over the cross section of the tube. On subsequent expansion and contractions the current density remains very high in a central region of several centimeters in diameter although fluctuations are appreciable.

The current density distribution over the cross section of the discharge tube at various times 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 time at which the current was 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.

The velocity of the ionized gas is the quantity directly characterizes the dynamics of a pulse dics 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

$$v = cE/H$$

Measurements of E and H indicate that in a pulse discharge with rapid growth of current the radial velocity of the plasma may be very high. In the experiments described here the maximal velocity during contraction and expansion of the plasma column in rarefied gases was found to reach hundreds of kilometers 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 intense pulse discharge in light gases is the appearance of penetrating radiation. In 1952, soon after experiments with pulse 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 when the peak discharge current is 400-500 kiloamp 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 blaced 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; however, control experiments did not confirm this explanation.

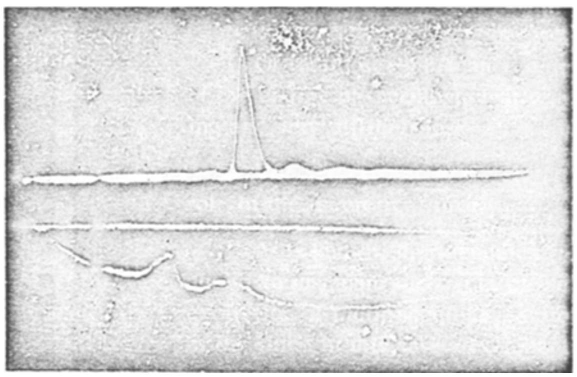

Fig. 9. Oscillograms of the current and the neutron pulse for a discharge in deuterium with $V_0 = 40$ kv and $P_0 = 5 \cdot 10^{-2}$ mm Hg.

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

In subsequent experiments the neutrons were recorded with a scintillation counter fed to an oscillograph. 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 subjected 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 tenths of microseconds. The chief results of the oscillographic investigations were not consistent with the initial assumption that the neutron emission is the result of quasi-stationary heating of the plasma during which the temperature increases proportionally to the square of the current.

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

It was found that not only neutrons but hard X-rays as well were produced in pulse 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 spurts. 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 that occur in the plasma of a pulse discharge oscillating under the action of electrodynamic forces is still at such a 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 quasi-stationary processes characterized by equilibrium between the external and internal pressures.

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

At the initial stage of the discharge the internal pressure in the plasma is very low; thus the electrodynamic forces 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. At 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 will move with the same velocity irrespective of sign, the kinetic energy acquired by the ions will be quite large, whereas that of the electrons will remain effectively constant because of their small mass. 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 that begins to move therefore gradually increases and the total amount of ions and electrons in the plasma increases rapidly.

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 $(M/V_0^2)^{1/4}$, where M is the mass of gas per unit length of discharge tube and V_0 is the initial voltage. This dependence is exactly what one finds experimentally for the interval between breakdown and 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 instant a great part of the energy of ordered motion changes into heat and the pressure and plasma temperature sharply increases. During maximum contraction, the plasma temperature may be of the order of 10^6 °C. The nature of the processes occurring during maximum contraction is not very clear, but after maximum cumulation a diverging shock wave should appear to drive the plasma towards the walls. Inside the outgoing wave there should be a rarified zone. Under the action of elctrodynamic forces that tend to compress the current, the outgoing wave should be decelerated rapidly 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 that are favorable for accelerating in the longitudinal electric field 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 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 repeatedly will be reflected, their energy increasing after each reflection. Acceleration of ions and electrons in the longitudinal electric field near the discharge axis is possibly the explanation for the appearance of neutrons and penetrating X-rays. The electric field strength during the second contraction may be very high. It can exceed the instantaneous external voltage applied to the discharge tube by a large factor.

However, it must be mentioned that not everything in this acceleration mechanism is yet clear. Under certain conditions acceleration of ions in a longitudinal electric field may also be possible outside the central zone of the discharge due to the presence of space charges. Some types of instability that 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 of spontaneous creation of a longitudinal magnetic field in the plasma as a result of spiraling of the plasma column.

If the second contraction is followed by the few 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, however, is that the plasma may begin to interact with the discharge-tube walls with the result that the wall material begins to evaporate and appreciable amounts of foreign gases appear in the volume.

We considered here some features of the phenomena that accompany the passage of intense pulse 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. However, there are serious reasons to believe that this cannot be achieved.

On appraising the various approaches to the problem of obtaining intense thermonuclear reactions, we do not deem it possible to completely exclude further attempts to attain this goal by using pulse discharges. However, other possibilities must also be carefully considered. Especially interesting are those in which stationary processes may be used.

An English translation of this report was distributed at Harwell by the Soviet scientists visiting England. This translation has been verified by the Consultants Bureau Staff. and some slight modifications made.

The Kurchatov lecture, together with comments by American and British physicists and government officials, was published in Nucleonics. June, 1956.