PLASMA AND THE CONTROLLED THERMONUCLEAR REACTION

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by
P. L. KAPITZA
Institute for Physical Problems of the Academy of Sciences, Moscow, USSR

The choice of the theme for my Nobel lecture presents some difficulty for me. Usually the lecture is connected with work recognized by the prize. In my case the prize was awarded for work in low temperature physics, at temperatures of liquid helium, a few degrees above absolute zero. It so happened that I left this field some 30 years ago, although at the Institute under my directorship low temperature research is still being done. Personally I am now studying plasma phenomena at those very high temperatures that are necessary for the thermonuclear reaction to take place. This research has led to interesting results and has opened new possibilities, and I think that as a subject for the lecture this is of more interest than my past low temperature work. For it is said, "les extremes se touchent".

It is also well recognized that at present the controlled thermonuclear reaction is the process for producing energy that can effectively resolve the approaching global energy crisis, resulting from the depletion of fossil fuels used now as our principal energy source.

It is also well known that intensive research on fusion is done in many countries and is connected with fundamental studies of high temperature plasmas. The very possibility of fusion is well beyond doubt, for it takes place in the explosion of hydrogen bombs. We also have a detailed theoretical understanding of nuclear fusion reactions that is in agreement with experiments. But in spite of the great effort and large sums spent up to now, it is impossible to conduct the process of fusion as to make it a useful source of energy. This certainly is a cause for some bewilderment.

One could expect that during the decades of experimental and theoretical plasma work in studying the conditions for fusion we would have reached a sufficient understanding of the various facts that hinder us from setting up a controlled thermonuclear reaction. It could be expected that we should have discovered and revealed the main difficulties that bar our progress. In this lecture I hope to clarify, what are these difficulties, and what are the chances that these difficulties will be resolved. I will also try to explain the divergence of opinions of different scientists on the practical possibilities for obtaining useful thermonuclear energy.

Before embarking into this subject I would like to speak on the practical importance of obtaining energy from nuclear sources.

The reality of the approaching global energy crisis is connected with the unavoidable lack of raw materials: gas, oil, coal. This is now generally appreciated. It is also known that the GNP (gross national product) that determines the wellbeing of people is proportional to the expenditure of energy. Energy resources depletion will inevitably lead to general impoverishment.

Two possible ways out of the approaching energy crisis are discussed. The first, maybe the more attractive, is to extensively use the inexhaustable sources of energy: hydroelectric power, the power of wind, solar energy, geothermal energy. The second way is to use nuclear energy discovered by man less than a hundred years ago. At present heavy element fission power is already cheaper than energy from some nonexhaustable sources.

It is well known that the main fuel in these reactors is uranium. It has been shown that as used at present there is enough uranium for only a hundred years. If in the future uranium will be more fully used in breeder reactors, it will last 50 times longer, for a few thousand years. Many consider that uranium dissolved in sea water may also be efficiently used for cheap energy production. Thus it may seem that the processes now used in modern nuclear reactions may resolve the approaching energy crisis. But there are important reasons against using uranium as a source of energy. These arguments are mainly connected with security.

In the first place, the use of uranium leads to accumulation of longlived radioactive wastes and the problem of safely storing a growing amount of these waste materials. This is a problem that at present has not been definitely solved.

In the second place, in a large energy-producing nuclear power plant a vast amount of radioactive material is accumulated, so that in a hypothetical accident, the dispersion of this material might lead to a catastrophe comparable in scale to that of Hiroshima.

I think that eventually modern technology will resolve these two dangers. But there is still a third hazard, even more grave. This is the danger, that the construction of great numbers of nuclear power stations will inevitably lead to such a huge amount of radioactive material disseminated around the world, that an efficient control on its proper uses will be practically impossible. In the long run not only a small country, but even a wealthy man or a large industrial organization will be able to build its own atomic bomb. There is at present no secret of the bomb. The necessary amount of plutonium, especially if breeders are to be widely built, will be readily available. Thus recently in India a small bomb was built and exploded. With the present system of international organizations there is nobody with sufficient authority that could execute the necessary control of the peaceful use of uranium as a source of energy. Moreover, it is not clear now how such an organization could be set up. This is the main reason why it is most important to obtain energy by the third way, through the process of thermonuclear fusion.

It is common knowledge, that this process will not lead to generation of large amounts of radioactive wastes and thus to a dangerous accumulation of radioactive material, and mainly it does not open any chances for a feasible nuclear explosion. This is the main reason why the solution of the scientific and technical problems involved in controlled thermo-nuclear fusion is considered of prime importance by many physicists.

The conditions for the thermonuclear reaction for energy production are well known and firmly established. There are two reactions of importance: the D + D and D + T process. The first one is the reaction between two nuclei of deuterium. The second occurs in the interaction of deuterium with tritium. In both cases fast neutrons are emitted, whose energy may be used. As a small amount of deuterium is present in water and is easy to extract, an abundant source of fuel is available. Free tritium practically does not exist in nature and tritium has to be produced, as it is usually done, through the interaction of neutrons with lithium.

The thermonuclear reaction is to take place in a high temperature plasma. So as to practically use the energy of neutrons the production of energy has to be greater than the power used to sustain the high plasma temperature. Thus the energy, obtained from the neutrons, has to be much greater than the bremsstrahlung radiation of the electron gas in the plasma. Calculations show that for useful energy production for the D + D reaction the necessary ion temperature is 10 times greater than in the case of the D + T reaction. Although the D + T reaction works at a lower temperature, it is hampered by the necessity to burn lithium, whose amount in nature is limited. Moreover, it seems that the use of lithium greatly complicates the design of the reactor. Calculations show that for obtaining useful energy the temperature of ions in a plasma for the D + D reaction should be about 10^9K and for the D + T reaction about 10^8K.

From research in plasma and nuclear physics it is thus known that for practical energy generation purposes, the technical problem of realising a controlled thermonuclear reaction is reduced to obtaining a plasma ion temperature at least 10^8K with a density 10^{13} - 10^{14} c m^{-3}. It is obvious that the containment of a plasma in this state by any ordinary vessel cannot be done, as there is no material that can withstand the necessary high temperature.

A number of methods for the containment of plasma and its thermal isolation have been suggested.

The most original and promising method was the "Tokamak" proposed in the Soviet Union and under development for more than a decade /(1) page 15/. The principle of its operation can be seen from the design shown in fig. 1. The plasma is confined by a magnetic field, generated in a toroidal solenoid. The plasma has the form of a ring of a radius R and a cross section of the radius a, placed in the coil. The plasma has a pressure of a few atmospheres. As it expands in the magnetic field, currents are excited that retard this expansion. The plasma is surrounded by a vacuum insulation, This is necessary to sustain the sufficiently high temperatures at which thermonuclear reactions take place. It is obvious that this method of confinement is limited in time. Calculations show that due to the low thermal capacity of the plasma, the energy for initial plasma heating, even in cases when the plasma exists for a few seconds, will be small as com-

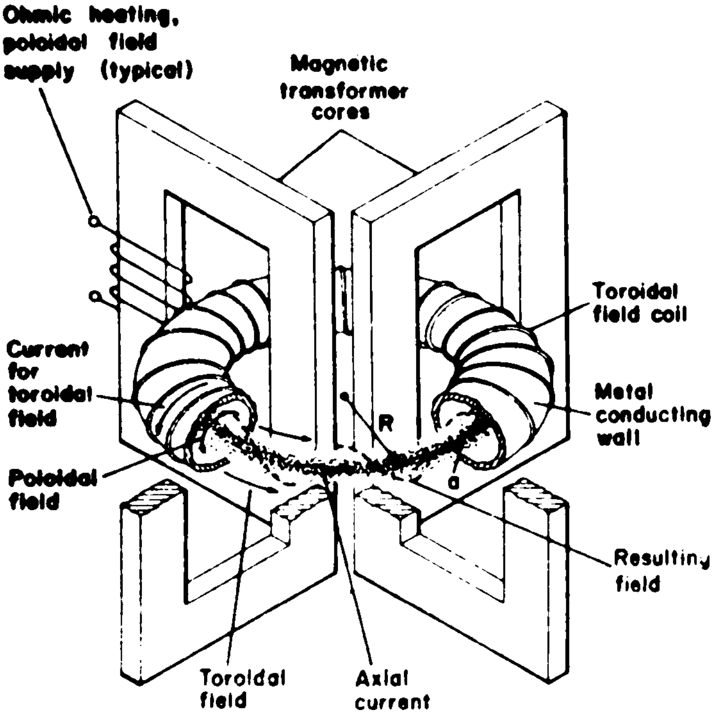

Fig. 1. Main features of a Tokamak

pared with the thermonuclear energy. Thus a reactor of this type may effectively work only in a pulsed mode. The Tokamak is started as a betatron: by discharging condensers through the coils of the transformer yoke. In practice plasma confinement by this method is not simple. In the first place there are difficulties in stabilising the plasma ring in the magnetic field. With the growth of the cross section radius a and moreover of the torus radius R, the ring loses its proper form and becomes unstable. This difficulty may be circumvented by choosing the appropriate ratio of R to a, and by properly designing the magnetic field, although at present the time for plasma confinement is only a small fraction of a second. It is assumed that with scaling the Tokamak up this time will be proportional to the square of the size of the machine.

But the main difficulty is due to reasons, not fully appreciated in the beginning. For the thermonuclear reaction one has to heat the D and T ions. The main difficulty in passing heat to them is due to the fact that the plasma is heated by an electric field. In this case all the energy is transferred to the electrons and is only slowly transferred to the ions because of their large mass as compared to the mass of the electrons. At higher temperatures this heat transfer gets even less efficient. In the Tokamak the plasma is heated by the betatron current induced through the condensor discharge. Thus, all the energy for heating the plasma is confined to the electrons and is transferred to the ions by collisions. To heat the ions to the desired temperatures the necessary time Δ t is much longer than the time during which we may maintain heating of the plasma by an electric current. The calculations that are usually done are complicated, as attempts were made to do them as exactly as possible, and so they lose in clarity. It is easy to estimate the lower time limit in which the ion heating may be made by the following simple formula /(2) page 24 expression 14/

$$\Delta t > -2.5 \cdot 10^{2} \frac{f}{\Lambda} \frac{T_e^{3/2}}{n} ln\left(1-\frac{T_i}{T_e}\right)$$

We assume that during heating the plasma density n,

$$n = \frac{7.3 \cdot 10^{21} P}{T_e},$$

the pressure P (atm) and the electron temperature $T_e$are constant.

The coefficient f is equal to the ratio of the ion mass to that of the proton, A is the well known logarithmic factor /2 in (4)/, T_i- the ion temperature. For modern Tokamaks, operating with the D + T reaction and at plasma temperatures T_i= $5.10^8$and n = 3.10^{13}cm-^{3}(with an initial electron temperature T_e. = 10^9K) the time necessary to heat the ions to nuclear process temperatures is more than 22 seconds, at least two orders of magnitude more than confinement times in the modern Tokamaks. The plasma confinement time may be made greater only by building a larger machine, as it seems that the time Δ t is proportional to the square of the size. From this formula it also follows that the time Δ t for the D + D reaction is greater by another two orders of magnitude and then Δt ~ 2.10^3 sec. The difficulties with the time for heating the ions is now fully recognized, although one cannot see how to shorten this time and how a Tokamak may work if, before the plasma ions have been heated, all the betatron energy from the condensers will be fully radiated by the electrons. That is why in the current Tokamak projects extraneous energy sources are envisaged that are greater than the energy of the betatron process, used only for initially firing the plasma.

Extra energy must be transferred to the ions by a more efficient way than Coulomb scattering of electrons on ions. There are two possible processes for this. The first /(1) page 20/ already used, consists in injecting into the plasma ring atoms of deuterium or tritium, already accelerated to temperatures necessary for the thermonuclear reaction. The second process of heating is through exciting radial Alfvèn magnetoacoustic waves in the external magnetic field by the circulating high frequency current. It is known /(3)/ that the energy dissipated by magnetoacoustic waves is directly passed into the ions and the transmitted power is sufficient to heat the ions and sustain their temperature for a sufficiently long time. Thus the problem of heating the ions may be solved, although the mode of operation of Tokamak will be more complicated than at first suggested. The design of the Tokamak becomes more complicated and its efficiency diminishes.

In all nuclear reactors the power generated is proportional to the volume of the active zone and the losses are proportional to its surface. Therefore the efficiency of nuclear reactors is greater for larger sizes and there exists a critical size for a nuclear reactor after which it may generate useful power. The practically necessary dimension is determined not by scientists but by the engineers who design the machine in general with proper choice of all the auxiliaries and the technology necessary for energy production. The following development is to a great measure determined by the talent and inventive ability of the design engineers. That is why the critical size of the Tokamak will be mainly determined by the proposed designs. Personally I think that the existing published design solutions lead us to a critical size for Tokamaks that make them unfeasible. But certainly life does show that the ingenuity of man has no limits and therefore one cannot be sure that a practically useful critcial size of Tokamaks may not be reached in the future.

One must note that although the main difficulty for obtaining a thermonuclear reaction in Tokamaks is the heating of deuterium and tritium ions, there is a difficulty of still another kind that does not have a well defined solution. In a Tokamak, for example, the plasma attracts and absorbs impurities extracted from the walls of the container. These impurities greatly lower the reaction rate. The plasma emits neutral atoms that hit and erode the wall. Moreover, the extraction of energy from neutrons also complicates the design of the Tokamak and leads to a larger critical size. Will we be able to bring the critical dimension of the Tokamak to a practically possible size? Even if it will eventually happen, of course we have no means to say when it will happen. Now we may only state that there are no theoretical reasons why in a Tokamak controlled thermonuclear reactions are not feasible, but the possiblity to release useful energy is as yet beyond the scale of our current practice.

Among other approaches to controlled thermonuclear fusion serious considerations should be given to pulsed methods without magnetic confinement /(1) page 33/. The idea is to heat a D + T pellet about 1 mm in diameter in a short time so as it will not have time to fly apart. For this very high pressures are necessary, that ensure intensive heat transfer between ions and electrons. It is assumed that in this way the thermonuclear reaction in a D + T pellet may fully take place. For this it is necessary to have a very powerful source of focussed laser light that should heat the pellet from all sides simultaneously in about a nanosecond. This heating is a complicated process, but using modern computers one may calculate all necessary conditions. If we illuminate a pellet by a well focussed laser beam, this may lead to a surplus of thermonuclear energy. But when one considers this process in detail, it is not clear how one can possibly resolve the technical and engineering difficulties. How, for instance, can one ensure uniform and simultaneous illumination and how can one usefully exploit the neutron energy?

In this case one may also say that the basic theoretical idea is sound, but the consequent engineering development with current technology is beyond our reach. Once again one cannot completely exclude a solution to this problem, although the design for laser implosion seems to me even less probable than the pulsed magnetic methods like the Tokamak.

The third approach to a thermonuclear reactor is based on continuously heating the plasma. Up to now this method has been developed only at our Institute. Our work was described 9 years ago /(4). Since then this type of reactor has been studied in detail, and now we see the main difficulties which we have to encounter. I will describe here in general terms what are the problems demanding a scientific solution.

As distinct from Tokamaks and the laser implosion method for producing conditions for the thermonuclear process, our method was not specially invented, but while developing a high power CW microwave generator accidentally we discovered a hot plasma phenomenon. We constructed an efficient microwave generator operating at 20 cm wave length with a power of a few hundred kW. This generator was called the "Nigotron" and its principles are described in (5) where full details of its construction with operating characteristics are given. In the process of its development beginning in 1950, during tests of our early model, high power microwave radiation was passed through a quartz sphere, filled with helium at 10 cm Hg pressure. We observed a luminiscent discharge with well defined boundaries. The phenomenon was observed only for a few seconds, as the quartz sphere in one place melted through.

These observations led us to the suggestion that the ball lightening may be due to high frequency waves, produced by a thunderstorm cloud after the conventional lightening discharge. Thus the necessary energy is produced for sustaining the extensive luminosity, observed in a ball lightening. This hypothesis was published in 1955 (7). After some years we were in a position to resume our experiments. In March 1958 in a spherical resonator filled with helium at atmospheric pressure under resonance conditions with intense H_{01} oscillations we obtained a free gas discharge, oval in form. This discharge was formed in the region of the maximum of the electric field and slowly moved following the circular lines of force.

We started to study this type of discharges where the plasma was not in direct contact with the walls of the resonator. We assume that this plasma may be at a high temperature. During a number of years we studied this interesting phenomenon in various gases and at different pressures, up to some tens of atmospheres at different power levels, reaching tens of kW. We also studied the effect of a magnetic field reaching 2,5 T in our experiments. This work is described in detail (4). A sketch of our setup is shown in fig. 2.

The plasma discharge has a cord-like form 10 cm long, equal to half the wavelength. Intense microwave oscillations E_{01} are excited in a cylindrical resonator (1). The cord of the discharge is situated at the maximum of the electric field and its stability along the longitudinal axis was due to the high

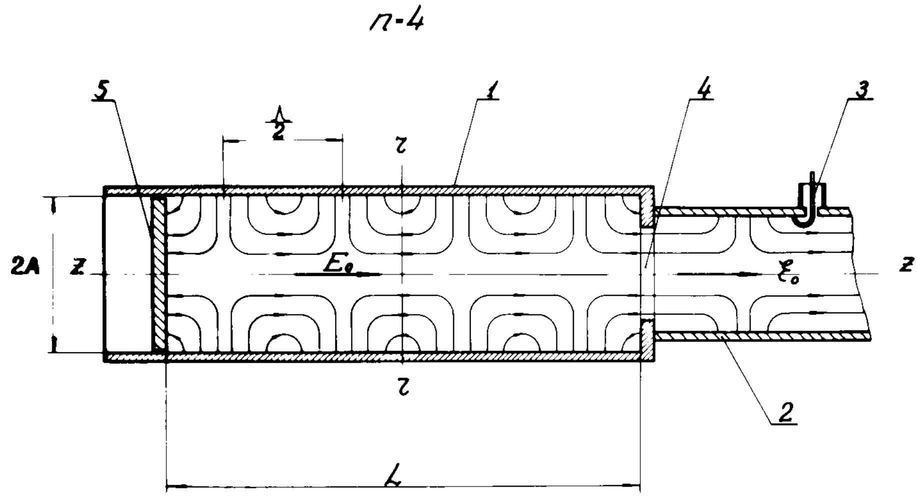

Fig. 2. Structure of the HF field in a resonator for E_{01} oscillations

frequency electric field. In a radial direction the stability was provided by rotating the gas. The discharge in hydrogen or deuterium was of great interest. At low powers the discharge did not have a well defined boundary and its luminosity was diffuse. At higher power the luminosity was greater and the diameter of the discharge increased. Inside the discharge a well defined filamentary cord-like nucleus was observed. In our initial experiments the power dissipated in the discharge was up to 15 kW and the pressure reached 25 atm. The higher the pressure, the more stable was the discharge with a well defined shape. A photograph of the discharge is shown in fig. 3. By measuring the conductivity of the plasma and by using passive and active spectral diagnostics we could firmly establish that the central part of the discharge had a very high temperature - more than a million K. So at the boundary of the plasma cord in the space of a few millimeters we had a discontinuity of temperature more than a million K. This meant that at its surface there was a layer of very high heat isolation. At first some doubt was expressed about the existence of such a layer. Various methods of plasma diagnostics were used, but they all and always confirmed the high temperature - more than a million K. Later we found out how it is possible to explain the physical nature of this temperature jump. It is easy to show that at these high temperatures electrons scattered at the boundary and freely diffusing into the surrounding gas will carry away a power of hundreds of kW. The lack of such a thermal flux may be explained by assuming the existence of electrons reflected without losses at the boundary of a double layer. The occurrence of a similar phenomenon is well known as such a layer exists in hot plasmas surrounded by dielectric walls, say, of glass or ceramics.

It is well known that in these conditions even at high pressures the electrons may have a temperature of many ten thousands of K and not

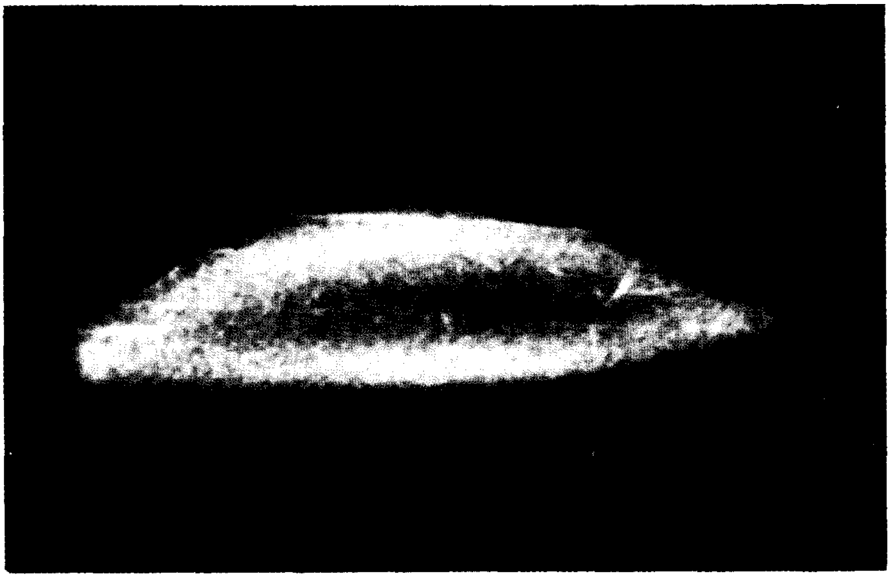

Fig. 3. Photograph of a cord discharge in deuterium with an admixture of 5 % argon at high power P = 14, 7 kW and high pressure p = 3,32 atm. Length of the discharge ~ 10 cm. The left edge of the discharge is blocked by the window. Oscillations of E_{01} type (1969)

markedly heat the walls. This phenomenon is well explained by the existence of a double layer on the dielectric surface. The mechanism leading to its formation is simple. When the electron hits the surface, due to its greater mobility it penetrates the dielectric to a greater depth than the ions and leads to the formation of an electric double layer, the electric field of which is so directed that it elastically reflects the hot electrons. The low electron heat conductance at the surface of plasmas is widely used in gas discharge lamps and the method of plasma heat insulation was first suggested by Langmuir. We assume that at a sufficiently high pressure a similar mechanism of heat insulation may take place in our hot plasma. The existance of a double layer in the plasma on the boundary of the cord discharge as a discontinuity in density was experimentally observed by us. This mechanism for a temperature discontinuity may obviously exist only if the ion temperature is much lower than the electron temperature and not much above the temperature at which the plasma is noticibly ionised. But this is only necessary at the boundary of the discharge. In the central part of the discharge the ion temperature may reach high values. As we will see further, the difference in temperatures inside the core and at the surface is determined by the value of the thermal flux and the heat conductivity of the ion gas. Usually the heat conductivity is high, but in a strong magnetic field the transverse heat conductivity may become very small. Thus we may expect that in a strong magnetic field the ion temperature in the core will not differ from the electron temperature and may be sufficiently high to obtain in a deuterium or tritium plasma a thermonucle-

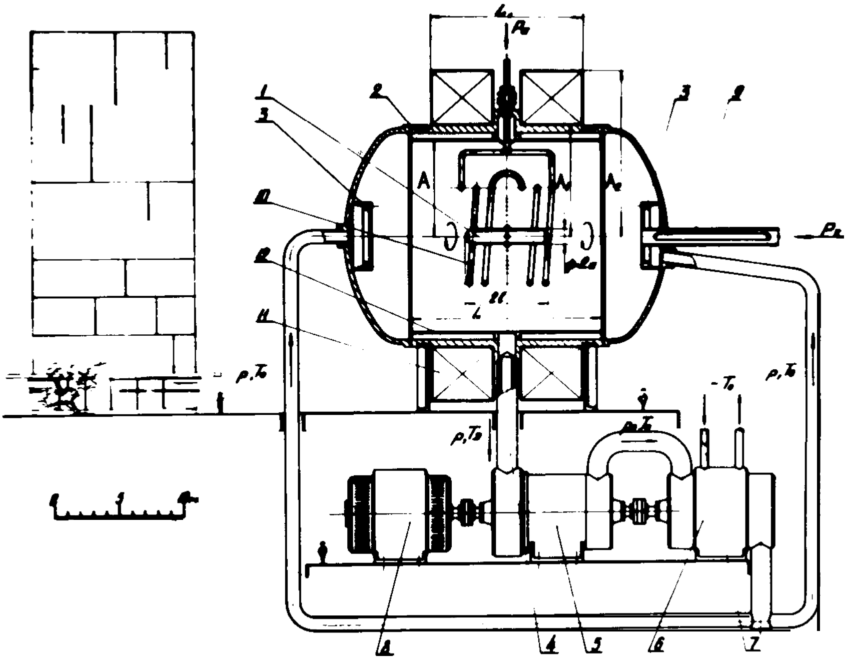

Fig. 4. Drawing of the construction of a thermonuclear reactor operating on a closed cycle. I - cord discharge, 2 - cylindrical container of the reactor, 3 - inclined nozzles, 4 - pipe connecting the container of the reactor with the gas turbine, 5 - gas turbine, 6 - isothermal compressor, 7 - cooling water, 8 - generator, 9 - coaxial waveguide, 10 - coil for the alternating magnetic field, 11 - solenoid, 12 - copper wall of the resonator, L - length of the resonator, L_1 - length of the solenoid, Pa - power of magnetoacoustic oscillations, P_r - high-frequency power, A - radius of the resonator, A_1 - internal radius of the winding, A_2 - external radius of the winding, 21 - length of the cord discharge, 2a - diameter of the cord discharge, h - distance between the wall of the container and the resonator.

ar reaction. This is the basis for designing a thermonuclear reactor to produce useful energy, and this has been worked out (8). The general outlay and the description of the reactor are shown in fig. 4.

The cord discharge (1) takes place in a confining vessel and resonator (2). The deuterium pressure is 30 atm, the magnetic field 1 T, produced by an ordinary solenoid. The design shows how the neutron energy is used. The gas heated by the neutrons passes through a gas turbine (5) where it adiabatically expands. Next it passes through a turbocompressor (6) and is isothermally compressed. The excess power is consumed in the generator (8). The cord discharge is heated by a high frequency field as it is done in cylindrical resonators (see fig. 2). The difference is in the coil surrounding the discharge and used to excite magnetoacoustic waves so as to raise the plasma ion temperature/(4) page 1003/. This design and pertinent calculations were published in 1970/(8) page 200/so as to demonstrate the expected parameters of our thermonuclear reactor, working with our plasma cord.

During the past time we have considerably increased our understanding of the processes in the plasma. We have mainly improved the microwave diagnostics and it is now possible to measure with 5% accuracy the radial density distribution, its dependence on the magnetic field, pressure and supplied microwave power. The necessary stability conditions have been established. All this has allowed us to raise the microwave power by many times and in this way increase the electron temperature up to 50 million K. If we could establish temperature equilibrium between the electrons and ions in this case even without the extra heating of the plasma by magneto-acoustic oscillations, we could have reached the D + T reaction. The design of the reactor is simpler and its size is smaller. In this case the thermonuclear reactor would be not only easier to build but the neutron energy is easier to convert to mechanical power. Thus we escape the main difficulties on the way to building pulsed thermonuclear reactors.

But still we have also some unresolved difficulties which merit most serious consideration, because they might make the whole problem unsolvable. The main difficulty is the following. Now we can obtain in our installation a high frequency discharge at a pressure of 25 atmoshperes and continuously maintain the electrons at a temperature of 50 million K, and going to a greater size of our discharge even more. At present the size is limited only by the power conveyed to it. Thus we have permanently an electron gas with a record high temperature, even higher than the electron temperature inside the Sun. The main problem is to heat the ions to the same temperature, for although the electron gas interacts with the ions in the entire volume of the discharge, it is not easy to raise this temperature in such a way.

The temperature equalisation proceeds in two steps. In the first step the energy is passed from the electrons to the ions. This is simply due to the collisions of electrons with ions, and in this case it is obvious that the heat transfer will be proportional to the volume. The next stage is the transfer of energy from the ion gas to the surrounding media. This flux will be proportional to the surface of the plasma cord. At a given thermal conductivity of the ion gas the temperature will increase for larger sizes of the cross section o the plasma cord. Thus at a certain heat conductivity there will be a critical size for the diameter of the plasma cord, when the ion temperature will reach a value close to that of the electrons and the required D + D or D + T reaction can take place. If we know the heat conductivity of the plasma, then it is easy to calculate the critical dimension. If, for example, we make this calculation for ordinary ion plasma in the absence of a magnetic field, when the heat conductivity is determined by the mean free path, we will find that the plasma must have an unrealizably large size of many km. One can lower this cross section only by decreasing the heat conductivity of the ion gas by placing it in a magnetic field as it is done in the reactor shown in fig. 4. The heat conductivity of an ion gas in a magnetic field is markedly decreased and it is determined not by the mean free path but by the radius of Larmor orbits the size of which is inversely proportional to the magnetic field. The thermal conductivity of ion gas in a magnetic field is easy to calculate.

It is thus seen that the critical diameter of the cord is inversely proportional to the magnetic field and at a field of a few tesla the diameter of the cord to get thermal neutrons will be 5-10 cm, that can readily be provided for. For this we need a plasma installation considerably greater than the one in which we at present study the nature of the electron gas in the plasma. In the conditions of our laboratory this installation is quite feasible and is now under construction.

It may be shown that the thermonuclear reactor we have described makes it possible to obtain conditions not only for the D + T reaction but also for D + D, if it were not for yet another factor that could eventually make the whole process unfeasible.

We determined the heat conductivity of the ion gas by considering the mean free path of the ion, assuming it to be equal to the Larmor orbit radius, having not taken into account the effect of convection fluxes of heat in a gas. It is well known that even in ordinary gases the convection heat transfer is much larger then the heat conduction due to molecular collisions. It is also known that unfortunately it is virtually impossible to calculate theoretically the heat transfer by convective currents even for the simple case of random turbulent motion in an ordinary gas. In this case we usually can, by dimensional considerations, estimate the thermal conductivity in a similar case and then generalize it for a special case, determining the necessary coefficients empirically. In the case of plasma the process depends on many more parameters and the problem of determining the convectional thermal conductivity is even more complicated than in an ordinary gas. But theoretically we may estimate, which factors have most influence on the rate of convection. To sustain convection one must supply energy. In a gas this energy is drawn from the kinetic energy of flow and leads to loss of heat.

In a quiescent plasma there is no such source of energy. But in an ionized plasma there may be another source of energy that will excite convection. This source is connected with temperature gradients and some of the thermal energy flux could produce convection. Quantitatively this process is described by internal stresses and was first studied by Maxwell (9). Maxwell had shown that internal stresses are proportional to the square of viscosity and derivative of the temperature gradient. In an ordinary gas they are so small that up to now they have not yet been experimentally observed. This is because the viscosity, which is proportional to the mean free path, at normal pressures equals to ~ 10^{-5} cm and so at low temperature gradients, the stresses are small.

In the plasma the mean free path of electrons and ions is of the order of cm and the temperature gradients are high. In this case the internal stresses following Maxwell's formula are 10 orders of magnitude greater than in a gas and we may expect both convection currents and turbulence. The presence of a magnetic field certainly can have effect on this phenomenon, and with additional effect of an electric field on convection it makes even a rough theoretical approach to estimating the magnitude of convection very unreliable. In this case there is only one alternative: to study these processes experimentally and this is what we are now doing.

In any case convectional thermal conductivity will lower the heating of ions and will lead to a greater critical cross section for the thermonuclear plasma cord. Correspondingly the size of the reactors for useful energy production will be greater.

If this size will be out of our practical reach, then we should consider methods to decrease convectional heat transfer. This may be done by creating on the boundary of the plasma a layer without turbulence, as it happens in fluids where we have the Prandtl boundary layer. This possibility has been theoretically considered /(4) page 1002/.

In conclusion we may say that the pulsed method used in Tokamaks can now be fully worked out theoretically, but the construction of a thermonuclear reactor, based on this method, leads to a large and complicated machine. On the other hand, our thermonuclear reactor is simple in construction, but its practical means of realisation and size depend on convection heat transfer processes, that cannot be treated purely theoretically.

The main attraction in scientific work is that it leads to problems, the solution of which it is impossible to foresee, and that is why for scientists research on controlled thermonuclear reactions is so fascinating.

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