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*THE PROSPECTS OF INVESTIGATIONS OF THE PROBLEM OF CONTROLLED NUCLEAR FUSION**

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THREE main trends can at present be cited in the search for a solution of the above problem. The first of these is based on the use of open magnetic traps in which the plasma is contained by virtue of the reflection of the charged particles from regions of enhanced magnetic field. The second trend is connected with the use of ring plasma configurations enclosed in closed magnetic systems. In both cases we are dealing with quasistationary regimes in which the time of containment of the plasma exceeds by many orders of magnitude the time interval necessary for the particle to traverse the space of the magnetic trap. At the same time, the magnetic fields are either constant, or change relatively slowly in time.

In addition to systems of such a quasistationary type, work is also proceeding on devices intended for very fast constriction of the plasma by a magnetic field; in these devices a limiting concentration of energy is attained in a small volume for extremely short time intervals (installations of the "fast-pinch" type). In these installations the magnetic fields are pulsed. Their rise time is on the order of several microseconds.

High-intensity, high-frequency electromagnetic fields of the meter and decimeter band can in principle also be used to contain and thermally insulate hot plasma. Investigations in this field constitute an independent branch of the physics of high-temperature plasma.

During the very first stage of the investigations the main attention was given to fast compression processes. However, it soon became clear that to attain conditions required for a thermonuclear reaction with a positive energy yield in pulsed processes of the "fast-pinch" type requires the concentration and instantaneous release of an enormous energy ($\sim 10^{10}$ J). Thus the process must be in the nature of a powerful explosion (on a scale corresponding to the explosion of several tons of TNT).

It is therefore natural that the interests of the majority of physicists working on the problem of thermonuclear fusion were then transferred to the field of quasistationary processes. Until recently there has been a clear preponderance of work on open systems which have above all the advantage that they make it possible to try out the most diverse methods of producing a high-temperature plasma; injection of streams of fast particles or bunches, capture of plasma streams, high-frequency heating of cold plasma, production of fast ions in a cold plasma stream by way of certain plasma instability mechanisms, etc. We shall not dwell on a description and analysis of these methods, since we are interested mainly in the clarification of whether a thermonuclear reactor based on an open magnetic trap can in principle be constructed.

During the first stages (up to 1961) only open systems of the simplest type with magnetic mirrors at each end were used. In such magnetic traps the magnetic field strength increased along lines of force in both directions from the center and at the same time decreased in the radial direction. However in this

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variant it is impossible to achieve prolonged containment of a sufficiently dense plasma with hot ions. The lifetime of such a plasma at a concentration exceeding 10^7—10^8 particles per cubic centimeter does not exceed several dozen microseconds. It is limited because of the development of an instability caused by the fact that the plasma behaves like a diamagnet and moves readily along the force lines in the direction of weaker field. This instability, called flute instability, cannot be overcome in the simplest mirror traps without using means which affect sharply the thermal insulation of the plasma (bad vacuum, low-voltage arc within the space occupied by the plasma, etc.)

In 1961 M. S. Ioffe and his co-workers first carried out experiments at the Division for Plasma Research of the Atomic Energy Institute with an open magnetic trap in which the magnetic field increases in all directions from the region occupied by the plasma. Experiments showed that in such a system no flute instability is observed. In 1963—1964 experiments were carried out[2] on the new, more refined PR-5 installation and stable containment of a plasma with a concentration of 10^9—10^{10} particles/cm^3 with an ion energy of 3—4 keV was first achieved. The lifetime of the plasma attained was ~ 0.1 sec. An effective method of stabilization of one of the main instabilities of hot plasma was thus found. This method found further extensive application and was developed by a series of other investigators. At present it is considered practically generally accepted that for stable plasma containment open type magnetic traps should satisfy the "minimum-B" principle. After the first successful experiments on the PR-5 installation one could hope that the use of traps constructed in accordance with the principle of a minimum field in the region of the plasma would open the way to the final goal; however, these hopes turned out to be short-lived. Attempts to obtain a stable high-temperature plasma with a density appreciably exceeding 10^{10} encountered serious difficulties.[3] In a plasma enclosed within an open trap there appear at high density new types of instabilities caused by the nature of the particle distribution function in velocity space. Theory predicts several different mechanisms of such an instability. Apparently, most dangerous for open traps should be two types of kinetic instabilities which are accompanied by a build-up of ion oscillations and a sharp increase in the escape of particles along the lines of force of the magnetic field. The first type of instability is caused by a build-up in a homogeneous plasma of Langmuir oscillations of the ions transverse to the magnetic field (and by the longitudinal electron oscillations connected with these) as a result of the presence of a maximum in the distribution of the transverse-velocity components of the ions. A similar distribution is unavoidable for all traps with magnetic mirrors, since by virtue of the very principle of containing charged particles in them the plasma must always be deficient in ions with small transverse velocities owing to the existence of the so-called "loss cone." This instability, first considered by Rosenbluth and Post,[4] was therefore called the "loss-cone instability." It can develop in a sufficiently dense plasma with hot ions ($T_i > T_e$) when $\omega_{0_i} > \omega_{H_i}$ (ω_{0_i} and ω_{H_i} are the Langmuir and Larmor ion frequencies), and under the condition that the longitudinal dimension of the plasma L exceeds considerably the ion Larmor radius ρ:

$$\frac{L}{\rho_i} > C\left(1 + \frac{H^2}{4\pi n m_e c^2}\right)^{1/2}. \qquad (1)$$

Here C is a numerical factor which depends strongly on the specific velocity distribution function of the ions. Thus, according to the calculations of Rosenbluth and Post, for a maximum washed-out distribution which can occur as a result of Coulomb collisions in a trap with a "mirror ratio" F = 3*, $C \sim 10^2$, and for a distribution with a half-width $\Delta V = 0.25\ \bar{v}$, $C \approx 3$. The limitation imposed by the loss-cone instability on the length of the stably contained plasma turns out under conditions of practical interest to be extremely strong. For example, for $H_0 = 5 \times 10^4$ Oe, F = 3, and $n \sim 10^{14}$ cm^{-3} the length of the plasma should in the best case not exceed 100—150 Larmor radii. According to the conclusions of the theory this is a devastating instability: the lifetime of the plasma with this instability is no longer than the time of flight of the ions along the trap. Another instability is connected with the inhomogeneity of the distribution of the plasma density in a direction perpendicular to the magnetic field (this instability occurs even if only because of the limited cross section of the plasma pinch). In an inhomogeneous plasma there can occur because of the drift motion of ions a build-up of ion oscillations at frequencies close to the cyclotron frequency. The build-up condition for a washed out energy distribution of the ions is of the form

$$\frac{\rho_i}{a} > 0.4\left(\frac{H^2}{4\pi n m_i c^2} + \frac{m_e}{m_i}\right)^{2/3}. \qquad (2)$$

Here a is a quantity of the order of the radius of the plasma pinch. For $H = 10^4$, a = 50, and an energy of the deuterium ions of about 100 keV the plasma should be unstable if its concentration exceeds about 10^{11}. However, if it were possible to construct a trap of the same radius but with a 100 kG field, then this instability would occur in it, apparently, only for $n \sim 10^{15}$. But obtaining in a large open trap satisfying the "minimum-B" principle a 100-kOe field will be technically exceptionally difficult, since at the indicated field strength in the plasma fields of several hundred kilogauss will have to be produced in all surrounding regions.

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*$F = H_{max}/H_0$ where H_{max} is the maximum field strength in the region of the mirrors and H_0 is the field strength in the plasma region.

The main shortcoming of open systems, if one approaches them from the point of view of the prospects of their technical utilization in the far future, consists in the fact that even when all forms of instability are excluded such systems will be on the border of feasibility of a thermonuclear reaction with a positive energy yield. Therefore even a comparatively weak instability which leads to an increase in the loss of particles through the magnetic mirrors by a small factor compared with the ideal regime will completely eliminate the possibility of a technical utilization of open traps.

The question of the role which the development of open traps may play in the solution of the problem of thermonuclear fusion is of great interest. We should therefore dwell at least briefly on an analysis of the energy balance of such systems. A calculation of the energy balance of mirror traps for the ideal case of a completely stable plasma has recently been refined by D. V. Sivukhin.[5] We shall depend on certain results of his calculations. In the stationary regime an open-type trap thermonuclear reactor will produce energy if the energy losses due to the escape of particles along lines of force through the magnetic mirrors will be compensated with a surplus by the release of nuclear energy (we disregard here other energy losses). Let us denote the nuclear energy released per unit time per cm^3 by $W_{\rm nuc}$. It is proportional to the square of the concentration of the plasma particles and is a function of the ion temperature. The power which can be obtained after a conversion of nuclear energy into electrical energy (via thermal energy) will be $\eta_1 W_{\rm nuc}$ where η_1 is the efficiency of the conversion. In the stationary regime one must inject into the trap per unit time as many particles as are lost by escape along the lines of force. The flux of particles referred to a volume of 1 cm^3 is n/τ where n is the concentration and τ the mean lifetime of the particles in the trap. If the ion temperature is T_i, then the energy flux will be $(3/2)\, nkT_i/\tau$.* A portion of this energy escaping through the magnetic mirrors can be recouped, i.e., converted into electrical energy. One can assume that the highest coefficient of recovery η_m will be attained by using a magnetohydrodynamic method of converting the energy of the flux. With account of recovering the energy of the plasma flux, the total electrical power produced by the thermonuclear reactor will amount to

$$\eta_1 W_{\rm nuc} + \eta_m \frac{2}{3} nkT_i \frac{1}{\tau}\ .$$

In a technical thermonuclear reactor a portion of this energy should be used, after being converted in the injector device into kinetic energy of the ions, to cover energy losses. Let us denote the efficiency of the injector device by $\eta_{\rm inj}$. The condition under which the reactor will produce excess energy can obviously be written in the following form:

$$\eta_{\rm inj}\left(\eta_1 W_{\rm nuc} + \eta_m \frac{3}{2} nkT_i \frac{1}{\tau}\right) > \frac{3}{2} nkT_i \frac{1}{\tau}\,. \qquad (3)$$

We introduce the coefficient α which indicates by what factor the loss of particles along lines of force exceeds under real conditions the loss corresponding to the ideal case of a completely stable plasma. If τ_0 is the lifetime of particles in the trap for the ideal case, then $\tau = \tau_0/\alpha$. Condition (3) is equivalent to the relation

$$\eta_m > \frac{1}{\eta_{\rm inj}} - \frac{2}{3}\eta_1 \frac{W_{\rm nuc}\tau_0}{nkT_i\alpha}\,. \qquad (4)$$

Inasmuch as τ_0 is inversely proportional to n (with an accuracy up to a very slowly varying logarithmic term), and $W_{\rm nuc} \sim n^2$, the explicit dependence on n in the second term on the right-hand side practically drops out and it turns out (for a given η_1) to be a function of the composition of the nuclear fuel, of the temperature, and of the mirror ratio F. We are making use of the notation introduced in Sivukhin's work*:

$$\frac{2}{3}\frac{W_{\rm nuc}\tau_0}{nkT_i} = \frac{\lambda}{S}\,. \qquad (5)$$

Here λ is a coefficient which depends on F, and S is a function of the fuel composition and T_i. In the case of a Maxwellian distribution of the ion energies in the trap, λ can be approximated by $\lambda = \log F$. For a plasma with monoenergetic ions (δ-like energy distribution function) $\lambda = 3.3 \log F$. The values of S can be found with the aid of tables which have been compiled by Sivukhin. In the optimal case when working with a mixture of equal amounts of deuterium and tritium S reaches its smallest value of 0.72 for an ion temperature of 200 keV. It follows from (4) and (5) that

$$\eta_m > \frac{1}{\eta_{\rm inj}} - \frac{\eta_1\lambda}{S}\cdot\frac{1}{\alpha}\,. \qquad (6)$$

In order to calculate the minimum value of η_m, we assume that $\eta_{\rm inj} = 0.9$, $\eta_1 = 0.4$, $S = 0.72$, and $\lambda = 1.6$. The latter value corresponds to an assumption that the plasma into which the monoenergetic ions are injected is in a trap with a mirror ratio $F = 3$ (for $H = 100$ kOe, larger values for a system satisfying the "minimum-B" principle are unrealistic). With this choice of parameters the minimum acceptable value of η_m can be found from the expression

$$\eta_m > 1.1 - \frac{0.64}{\alpha}\,.$$

Hence it follows that even for $\alpha = 2$ the recovery coefficient should amount to about 80%, whereas for $\alpha = 3$ it must exceed 90%. Thus if the losses along the lines of force increase merely by a few times compared with the value corresponding to the usual

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*It is assumed that in a thermonuclear reactor the temperature of the electrons is at least several times lower than the ion temperature and therefore the energy flux carried away by the electrons is small.

*Atomnaya énergiya, issue of December, 1965.

Table I

Installation	Type of trap	Method of obtaining fast ions	Chamber diameter, cm	Distance between the mirrors, cm	W_i, keV	Injection current, mA	n	τ *
1. Ogra-I	Straight	Dissociation of H_2^+ in the gas	5 1.4 140	1200	80	150	10^8	$3\cdot10^{-4}$
2. Ogra-II	Minimum B	Lorentz ionization of neutrals	15 1.4 70	200	75	15	10^7	10^{-1}
3. PR-5	Minimum B	Ion magnetron, unstable plasma beam	5 1.6 40	120	0.5+1.0	—	10^{11} $5\cdot10^9$	$5\cdot10^{-5}$ 10^{-2}
4. DSKh-II	Straight	Dissociation of H_2^+ in a lithium arc	12 3.3 100	265	800	55	$8\cdot10^9$	$3\cdot10^{-2}$ ** $+3\cdot10^{-1}$
5. Alice	Minimum B	Lorentz ionization	8 1.7 45	60	20	50	$2\cdot10^8$	$5\cdot10^{-2}$
6. Phoenix II	Minimum B	Lorentz ionization	30 2.0	30	20	35	10^8	$3\cdot10^{-2}$
7. MTSE	Minimum B	Capture of a plasma bunch from a gun	5 1.8 20	70	2,5	—	$5\cdot10^{12}$	$5\cdot10^{-5}$
8. DECA II	Minimum B	Capture of a plasma bunch from a gun	10 12		1	—	10^{13} -- 10^{14}	$5\cdot10^{-5}$

*The value of τ is determined from time of decay of the plasma after the injecting device has been turned off.

**In the presence of a lithium arc.

mechanism of Coulomb pair collisions, then the realization of thermonuclear reactions with an excess energy yield becomes absolutely impossible*

Table I is a summary of parameters for a series of experimental installations with open type magnetic traps, intended for the production of plasma with fast ions. Of most interest are the last two columns which indicate the attained values of the concentration and the mean lifetimes determined from the decay rate of the plasma. It follows from this table that for concentrations exceeding 10^{10} it has been impossible to raise the lifetime of the ions above several dozen microseconds. Such is in general the rather unsatisfactory summary of the investigations which have been carried out in this field in various countries for over a decade.

However, it would at present be short-sighted to propose a total discontinuing of the development of open traps. It is not excluded that one can suppress the development of the most dangerous forms of the "cone" instability in open systems of the "minimum-B" type with sharply nonuniform fields in the entire region occupied by the plasma. It has not been proved a priori that one cannot in this way achieve conditions under which $\alpha = 1$, although this is not likely. One must continue investigations on the existing installations, but not be attracted by the construction of new, larger open systems, since their construction is at this stage unjustified.

Let us go over to consider closed magnetic traps. Investigations of the behavior of plasma in such systems had began even somewhat earlier than the development of open type plasma traps. Closed traps can be divided into three chief classes:

1. Toroidal systems in which the plasma is contained in equilibrium with the aid of the magnetic field of the current flowing in it, and a very strong longitudinal magnetic field is used to suppress the basic hydrodynamic instability of the plasma column. The intensity of this field H_z should exceed by a large factor the strength of the field H_I due to the current. An example of such installations are the Tokamak setups developed at the Division for Plasma Research of the Atomic Energy Institute.

2. Toroidal systems with an annular plasma current of the type of the English installation "Zeta" in which a weak longitudinal field smaller than that of the magnetic field of the current is used to stabilize the plasma ring.

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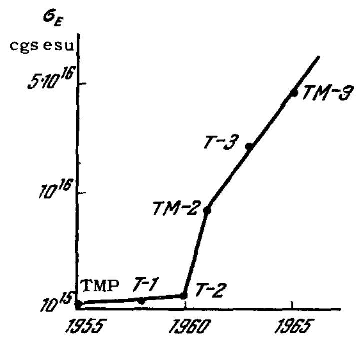
*It should be borne in mind that in the above calculation energy losses for supporting the magnetic field and various forms of radiation are not taken into account. In addition we underestimate the escape of particles, taking no account of the decrease in the value of the effective mirror ratio due to the fact that the plasma is positively charged with respect to the surrounding space. The positive potential of the plasma evens out the rate of escape of electrons and ions through the magnetic mirrors.

3. Stellarators in which the plasma column can be maintained in equilibrium with the aid of only one external field of complex structure with which there occurs a rotational transformation of the magnetic lines of force (they rotate continuously about the axis of the chamber if one moves along this axis). The investigation of the properties of plasmas in stellarators constitutes one of the most important elements of the work program on thermonuclear fusion in the USA.

Of the above three classes, systems indicated under 2 are at present only of limited interest, since numerous experiments have shown that a weak longitudinal field is incapable of performing the function of stabilizing a plasma column with a current. More hopeful (to use the terminology of an optimistic physicist) or less hopeless (to use the terminology of a pessimistic physicist) are the attempts to produce a thermonuclear generator based on the Tokamak and stellarator systems.

In the Tokamak devices the heating of the plasma is so far carried out only by means of the Joule losses of the current flowing through it, although in principle the use of other methods of heating is also possible (we shall speak of these somewhat later). The development of these installations has passed through several stages. Initially ceramic, quartz, or glass vacuum chambers were used in the experiments. Under these conditions one could not avoid contamination of the plasma with various impurities. Therefore the plasma temperature did not exceed several electron volts and full ionization of the gas could not be achieved. The situation improved considerably when in 1958—1959 the first installations with thin metal chambers were introduced; these could be outgassed by preliminary heating and conditioning in electrical discharges. In the new installations it became possible to raise the plasma temperature to 20—25 eV. The next important step was taken after attention had been drawn to the necessity of a careful correction of the magnetic fields. In installations with an improved magnetic-field geometry, one can at present heat a hydrogen plasma with a current to temperatures of 600—800 eV* with a longitudinal magnetic field up to 20—25 kG and a current density within the limits of 100—250 A/cm^2, the plasma concentration amounting to $\sim 10^{13}$ cm^{-3}.

The figure shows the gradual change of one of the basic parameters characterizing the properties of a plasma ring—the electrical conductivity σ_E—during the fifteen-year history of the Tokamak installations. The value of σ_E for a pure hydrogen plasma is $\approx 10^{13}\, T_e^{3/2}$ where T_e is the electron temperature of the plasma in electron volts. In the presence of an admixture of multiply-charge ions the electrical conductivity decreases appreciably, and therefore under the real conditions of the experiment the relation between σ_E and T_e may be of a more complex nature. However, the qualitative correlation between the change of both quantities remains.



As experiment shows, for a sufficiently large ratio H_z/H_I dynamic instabilities are suppressed in the plasma ring. However, the lifetime of charged particles in the plasma turns out nevertheless to be by several orders of magnitude shorter than would follow from classical diffusion theory. Thus, in addition to the mechanism of particle loss by ordinary diffusion which is due to pair collisions between the particles, there also exists a stronger "anomalous" diffusion mechanism. Anomalous energy losses are also connected with the anomalous diffusion. The relative portion of these losses in the energy balance of Tokamak installations amounts to 30–70% relative to the Joule heat. It depends on the concentration and temperature of the plasma, and also on the strength of the current and of the longitudinal magnetic field. Concerning the degree to which the anomalous losses of particles and energy in Tokamak installations affect the prospects of achieving the thermonuclear standard, we shall speak somewhat later.

We shall indicate now certain results of the theoretical analysis of such systems. The most important conclusion from this analysis is the necessary Kruskal-Shafranov criterion of magnetohydrodynamic stability. It is expressed by the relation

$$\frac{H_z}{H_I}\cdot\frac{a}{R}>1. \tag{7}$$

The quantity* $H_z a/H_I R$ is often referred to as the "stability margin." Below it will be denoted by q. It follows from the experiments that condition (7), being necessary, is nevertheless not sufficiently severe. As is well known, an arbitrary magnetohydrodynamic perturbation of the surface of a plasma column can be represented in the form of a superposition of spiral deformations of the simplest sinusoidal form which are classified by the number of their mode m

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*We are speaking here of the electron temperature T_e. The value of T_i is considerably lower and is no more than $T_e/3$.

*a is the cross-sectional radius of the plasma column, R is the radius of the toroid.

(the number of the mode is the number of revolutions about the plasma ring after which the deformation closes on itself). For $q > 1$ only the deformation with $m = 1$ is stabilized. If, on the other hand, q exceeds a certain integer m, then all modes from 1 through m are stabilized. To remove the sharply manifest magnetohydrodynamic instability, it is apparently quite sufficient to suppress the modes with $m = 1$ and 2*. The reasons for the anomalous energy losses which occur even with a large value of the instability margin were theoretically studied by B. B. Kadomtsev and his co-workers.[6] According to these investigations, a number of specific mechanisms of the development of instabilities should be responsible for the anomalous energy loss. Of these the most significant are:

1. The current-convective instability. It occurs because the plasma is not an ideal conductor and its conductivity is a function of the temperature.

2. The temperature-drift instability. It is connected with the circumstance that the temperature gradient over the cross section of the plasma column leads to drift of the ions which builds up ion oscillations of the plasma. In addition, in a low-density plasma an instability can also develop which is caused by the fact that a certain portion of the total number of particles in the toroidal system turns out to be enclosed between regions of strong field (on the inner side of a plasma ring the particles behave in the same way as in a trap with magnetic probes).

Kadomtsev gave estimates of the value of the coefficient of thermal conductivity of the plasma $\chi_\perp$ in the direction perpendicular to the magnetic field for instances corresponding to the development of instabilities of the first and second type, and also indicated conditions under which one must take into account the third type of instability. The thermal conductivity of a deuterium plasma caused by the temperature-drift instability is given by the expression

$$\chi_\perp \sim 10^{-12} \frac{nT_i^{3/2}}{aH_zH_I} . \qquad (7a)$$

Such a dependence of $\chi_\perp$ on the parameters of the system means that the azimuthal magnetic field of the plasma current H_I plays in this case the role of the main stabilizing factor. This is explained by the fact that the temperature-drift instability should weaken sharply in the presence of a so-called "shear." This term denotes such a structure of the helical magnetic field for which the magnetic lines of force are the more strongly twisted the further away they are from the axis of the plasma column. In Tokamak installations the "shear" is produced because of the current flowing in the plasma, and in stellarators because of the presence of an external helical winding. In rough comparative estimates of properties of various systems the ratios H_I/H_z for equal values of a can serve as a measure of the "shear."

Equation (7a) should be correct in the case when the temperature changes over the cross section of the plasma (in the radial direction) more rapidly than the density, i.e., if the condition

$$\left| \frac{d \ln T}{d \ln n} \right| > 1.$$

is fulfilled. It follows from (7a) that energy losses from the plasma due to the instability increase like $T_i^{5/2}$ and are inversely proportional to the strength of the longitudinal magnetic field H_z and the current field H_I. The numerical coefficient in the expression for $\chi_\perp$ can at present be estimated theoretically only with an accuracy within an order of magnitude, since it is very sensitive to the choice of the form of the distribution curves n and T along the radius, in particular with respect to the boundary conditions which remain rather indefinite. A certain arbitrariness in the choice of numerical coefficients is characteristic, generally speaking, of all formulas which are used to determine the anomalous energy losses caused by various instability mechanisms. Apparently, at the present stage of our knowledge one must reaffirm the inevitability of such an arbitrariness by introducing the general rule of the "admissible three," according to which in all calculations of the theoretical values of the energy losses and in their comparison with experimental data a discrepancy of less than a factor of three in any direction, i.e., by less than half an order of magnitude, is not admitted to have any significance.

At high temperatures the temperature-drift instability is the main source of energy losses from a hydrogen plasma. All other forms of losses are of relatively smaller significance.

The theory of the current-convective instability developed by B. B. Kadomtsev shows that the role of this mechanism in cooling a closed plasma ring is appreciable only up to temperatures not exceeding several hundred eV. With increasing T_e the coefficient of the anomalous thermal conductivity connected with the current-convective instability decreases as $T_e^{-5/4}$. The escape of plasma due to the instability on the enclosed particles begins to dominate according to Kadomtsev's calculations over the remaining escape mechanisms when

$$\frac{\lambda_e \rho_i}{a^2} > 10,$$

where λ_e is the mean free path of the plasma electrons. At present in individual experiments on Tokamak installations regimes are established for which $\lambda_e \rho_i / a^2$ exceeds 10: one can therefore expect additional energy losses because of the instability on the enclosed particles. However, for a sufficiently large plasma density the absolute value of these

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*However, this conclusion must not be considered to have been rigorously proved.

losses should not be large and it can be neglected in the energy balance of the plasma. In the proposed thermonuclear reactors of the future it will apparently be possible to remove this form of losses if the installations will be of sufficiently large dimensions. Let us now discuss the question of the development prospects of Tokamak installations within the general plan of solving the problem of controlled thermonuclear fusion. Statements which can be made on this subject are of course so far not sufficiently rigorous and convincing, but they are nevertheless useful, since they make it possible to grasp the nature of specific problems and difficulties in our path. Let us first assume that there are no anomalous energy losses from the plasma column. In this case the energy escapes from the plasma only in the form of electromagnetic radiation and of a thermal flux connected with the classical mechanism of thermal conductivity. The ratio of this flow to the energy lost in the form of x-ray bremsstrahlung is in order of magnitude $\sim 10^{12}q^2/a^2H_z^2$* where q is the stability surplus. For $q = 2$, $a = 100$, and $H_z = 10^5$ this ratio is only ~ 0.04. Thus one can neglect the classical conductivity in the energy balance of the thermonuclear generator. It is quite easy to explain why there should be such a striking difference between the behavior of a classical closed system and a classical mirror trap. In the latter the particle is lost in one collision, whereas in the former it must collide many times with other particles before it succeeds in diffusing a distance of the order of a across the lines of force. The number of such collisions is of the order of $(a/\rho_i)^2$ and it is precisely this factor which is the source of the difference between both types of magnetic systems. Thus under the condition of ensured stability of the plasma column one could utilize closed systems in the construction of thermonuclear generators without resorting to technical means beyond those already attained at present.

However, total stability can only be attained with thermodynamic equilibrium in a homogeneous plasma. In a hot plasma ring detached from the walls of the thermonuclear chamber the development of drift-gradient instabilities which lead to anomalous heat losses is inevitable. Let us clarify which parameters should be set for a Tokamak installation operating as a thermonuclear generator with a positive energy yield in the case where there are anomalous heat losses caused by the temperature-drift instability mechanism. Heat losses due to anomalous heat conduction per unit length of the plasma ring will amount to

$$Q \sim 2\pi\chi_\perp T_i \sim 10^{-11}\,\frac{nT_i^{5/2}}{aH_zH_I}\,. \tag{8}$$

They must be compensated by nuclear energy release. The compensation condition is of the following form:

$$\pi a^2 n_1 n_2 \overline{v_i\sigma}_{\mathrm{nuc}}\eta_1 W \sim 10^{-11}\,\frac{nT_i^{5/2}}{aH_zH_I}\,. \tag{8a}$$

Here $v_i\sigma_{\mathrm{nuc}}$ is the averaged value of the product of the ion velocity by the effective cross section for the nuclear reaction, n_1 and n_2 are the concentrations of the interacting components $n_1 + n_2 = n$, η_1 is the efficiency of utilization of nuclear energy, and W is the energy of the reaction. Let us consider the special case of a DT reaction in a mixture of equal amounts of deuterium and tritium. Here $\eta_1 W \approx 1.6 \times 10^{-5}$ (i.e., ≈ 10 MeV) and $n_1 = n_2 = n/2$. Energy losses due to bremsstrahlung can be neglected for $T_i > 4 \times 10^7$. Let $T_i = 10^8$ (i.e., ≈ 10 keV). The value of $\overline{v_i\sigma}_{\mathrm{nuc}}$ will then be $\sim 10^{-16}$. Taking the magnetohydrodynamic stability margin to be 2, we can at a given temperature write condition (8a) in the following form:

$$\frac{na^4H_z^2}{R} \sim 10^{30}. \tag{9}$$

In an installation of sufficiently large dimensions the ratio a/R can be made equal to $1/5$. Therefore to realize a regime with a positive energy yield, one must fulfill the condition $na^3H_z^2 > 10^{31}$. For $n = 10^{15}$ and $H = 10^5$ this condition will be fulfilled if the radius of the cross section of the plasma ring exceeds ~ 1 m. This estimate is apparently a little optimistic, since we have made no allowance for the fact that for a large temperature gradient intensive release of nuclear energy will take place only in a relatively small region of the cross section of the plasma column. Allowance for this fact can contribute to the estimated value in the right-hand part of (9) an additional numerical coefficient; this will make it necessary to increase accordingly the product $na^3H_z^2$. Neverthless, it appears that the main parameters required for a thermonuclear generator, although they are far beyond the possibilities of present-day technology, can with further technical progress be realized at most in several decades. The possibility of realizing in Tokamak installations in principle regimes with positive energy yield appears to raise hopes. However, there remains the question of whether it will be possible to heat the plasma to a temperature at which the release of nuclear energy will compensate for the thermal losses and leave a surplus.

So far we have heated plasma only by release of Joule heat. The limiting temperature which can be attained by this method is determined by the condition

$$\frac{I^2}{\pi a^2\sigma_E} \approx 2\pi\chi_\perp T_i. \tag{10}$$

To simplify the calculations for very rough estimates we can set T_e and T_i equal. Using (8), we obtain from (10)

$$T_i \approx 10^6\,\frac{aH_z}{(R^3q^3n)^{1/4}}\,. \tag{11}$$

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*If $T_i \approx T_e$.

It should be noted that T_i is not very sensitive to the choice of the numerical coefficient in the expression for $\chi_\perp$, since this coefficient enters in Eq. (11) as a fourth root.

Taking $a = 100$, $H_z = 10^5$, $R = 500$, $q = 2$, and $n = 10^{15}$, we find that $T_i \approx 10^7$. Consequently, it is impossible to reach the desired goal by means of ohmic heating alone. A gap with a ratio of the values of the order of 10 remains between the value which can be attained and the value which is required. One must seek other methods to bridge this gap. At present one of the natural ways of overcoming this difficulty appears the use of the method of external injection into the plasma of fast neutral particles. Such a flux can be quasistationary or it may consist of individual dense bunches which are successively fired into the toroidal chamber. So far almost nothing has been done to work out such a method for heating plasma, but possibly this is the method of the future. One must therefore assume that in the years to come the development of methods of realizing intense pulsed and quasistationary fluxes of neutral particles will occupy an important place in the general program of work on controlled fusion.

The available experimental material is so far unfortunately insufficient for asserting that there is good quantitative agreement between the above theoretical estimates of the heat conduction of the plasma and the experimental data on the energy balance obtained in experiments with the Tokamak installations. If we assume that the heating of the ions occurs mainly not because of the heat transfer in Coulomb pair collisions with electrons, but because of the mechanism of excitation of ion sound by the electron flux, then within the framework of the principle of the admissible three there is apparently no discrepancy between theory and experiment in determining the value of Q. However, two important questions remain unanswered:

a) Is the energy really carried away from the plasma by the ions?

b) Does the heating of the ions really occur not by means of the inefficient mechanism of heat exchange in pair collisions?

It should be noted that in the experimental regimes which are characterized by a large value of the magnetic field strength ($H_z > 2 \times 10^4$ Oe) and a high plasma temperature ($T_e > 10^6$) the energy losses from the plasma column under good vacuum conditions are many times smaller than those which are suggested by the well-known semi-empirical Bohm formula.* The ratios of the measured losses to the values calculated from this formula under optimal regimes on T-3 and TM-3 installations amount up 0.1, i.e., they are far outside the limits of the permitted indeterminacy. The lifetimes of the ions for such regimes in Tokamak installations amount to several milliseconds (for $a = 10$ cm and $n \sim 10^{13}$), and the energy efficiency of the process of ohmic heating (i.e., the ratio of the energy accumulated in the plasma to the integral of the Joule losses) amounts to 25—30%*. This result is the main basis for the cautious optimism with which we now view the future prospects of the development of this trend of the investigations.

The main advantage of the stellarator as a magnetic trap consists in the fact that the equilibrium of the plasma loop in this system can be ensured even in the absence of a longitudinal current in the plasma. However this advantage is bought at a high price. The "shear" in the stellarator turns out to be considerably smaller than in Tokamak installations. In addition, owing to the small value of the ratio of the radius of the plasma loop to its length, the limits of the magnetohydrodynamic stability of the system turn out to be very narrow. Experimental data obtained in Princeton (in particular on the large C stellarator) indicate that in a broad range of variation of the initial operational parameters of the stellarators (in the ohmic heating regime) strong anomalous diffusion occurs along with energy losses corresponding in magnitude to Bohm's formula. The mechanism of these losses cannot thus far be considered to have been finally explained. The losses occur not only in the ohmic heating regime of the plasma by a longitudinal current, but also under conditions when the energy enters the plasma from a high-frequency electromagnetic field which is used for resonance heating of the ions at the cyclotron frequency.

In stellarators the plasma temperature is commonly appreciably less than 50 eV, and therefore in the presence of a longitudinal current losses due to the current-convective instability can be of essential importance. In addition, it cannot be excluded that the plasma in the stellarator is unstable with respect to magnetohydrodynamic-type perturbations, since the magnetic system does not satisfy the "minimum-B" principle. With further temperature increase the behavior of the plasma column will be strongly affected by the drift-temperature instability which should for a small value of the "shear" lead to strong cooling of the plasma. In order to turn a stellarator into a trap capable of good containment of a high-temperature plasma, radical improvements must be introduced into the system; more precisely, one must take a further step and go over from the stellarator to new types of magnetic systems. Possibly it is precisely here that considerable success can result. It is in

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*According to this formula the mean lifetime of the charged particles in the plasma column is $3a^2eH/ckT_e$.

*In open systems the energy efficiency of injection does not exceed some tenths of a percent.

particular possible that success will be attained in going from the stellarator to closed systems of the minimum-B type. In this case it will at least be possible to ensure satisfactory magnetohydrodynamic stability of the plasma column. It should be noted that in Tokamak installations the minimum B occurs in practically all regimes of the process realized experimentally.*

The development of new types of closed magnetic traps with a field which satisfies the "minimum-B" principle can play an important role in changing the general state of the problem of controlled fusion.

In discussing the prospects of the main directions of investigation connected with thermonuclear fusion, one must not disregard the development of methods of short-duration plasma heating. Although these methods are apparently incapable of solving the main problem, they nevertheless are of considerable interest for attaining more modest goals. In installations where very fast compression of plasma takes place by electromagnetic forces during powerful direct discharges with large longitudinal currents (a so-called "noncylindrical pinch"), it is possible even now to attain record energy concentration in small volumes, and a plasma is thus produced with a density above 10^{19} and with a temperature on the order of 10^7 degrees (i.e., $\sim 10^3$ eV). The maximum gas-kinetic pressure of the hot plasma turns out in this case to be much higher than in experiments with theta-pinch systems where the compression of the plasma occurs in an increasing external field of the solenoid. At the same time one observes short but rather intense neutron radiation (up to $\sim 10^{10}$ neutrons per pulse in the experiments of Filippov and his co-workers at the Division for Plasma Research of the Atomic Energy Institute and analogous experiments by Maser in the United States). On further refinement of the method it will apparently be possible to increase appreciably the density and temperature of the plasma by more efficiently using the work of the forces of compression†. This opens the way to the construction of new forms of extremely powerful pulsed neutron sources. It appears very probable that it will be possible even during the next few years to attain a neutron yield at least of the order of 10^{12} per pulse in a discharge with pure deuterium and up to 10^{14} when operating with a deuterium-tritium mixture. The energy efficiency of the nuclear reactions will then reach 0.1 percent (for the DT mixture). As has already been said, one of the independent branches in the physics of high-temperature plasmas consists of work in which various methods of containing plasma and stabilization of plasma formations with the aid of high-frequency electromagnetic fields is investigated. Such investigations are carried out in a number of institutes in the USSR and in Saclay in France. In systems intended for plasma containment by a high-frequency field the gas-kinetic pressure is opposed by the average value of the electromagnetic pressure which is proportional to $\overline{H^2}$. The way is thereby open to the production of a whole series of interesting systems satisfying the principle of "minumum averaged H^2," At the present level of development of high-frequency techniques one cannot count on it that the methods in which high-frequency fields are used for plasma containment will lead in the next few years to tangible results as regards the obtaining of dense, high-temperature plasmas. The high-frequency field intensities attainable are very small even if the fields produced are of very short duration. It is possible that the development of new superconducting alloys will make it possible in the future to decrease the losses for supporting high-frequency fields to such an extent that the prospects of application of high-frequency traps for the maintenance of hot plasmas will look more hopeful. However, judging from the pace and results of the work, this will hardly occur earlier than in the course of a few decades. Such an estimate of the situation in this field is of course by no means equivalent to the conclusion that the carrying out of further physics investigations is to no purpose. On the contrary, one should consider the study of processes of interaction of plasma with fields with the aid of comparatively small experimental setups to be of interest not only from the purely scientific point of view, but also as preparing the ground for possible practical applications in the future. The same can also be said with respect to investigations in which high-frequency fields are used not directly for the purpose of plasma containment, but as an auxiliary means for removing instabilities. During recent years clear indications have been obtained in a number of experiments that large scale magnetohydrodynamic instabilities of a plasma column with current can be suppressed with the aid of high-frequency fields (such experiments have been carried out in the Division for Plasma Research of the Atomic Energy Institute and at the Sukhumi Physics Institute). Here too further progress is limited by the capabilities of radio technology.

A few words in conclusion. Investigations of the problem of controlled nuclear fusion have so far not shown us the way to a thermonuclear electrical power

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*In the case of toroidal systems of the type Tokamak and stellarator, the "minimum-B" condition requires special formulation. It is not equivalent to the requirement that on going away from the surface of the plasma loop the magnetic field strength should always increase. Instead of this requirement, which is not satisfied in this simple form, one must use some integral law. We shall not dwell here on the details of these formulations.

†At present only a very small fraction of the thermal energy accumulated by the plasma is in that small volume in which the matter has a very high temperature and density.

station. So far this is a matter of the future. However, if one aspires to hasten this future, one must not reduce the efforts made now, i.e., one must not refuse to carry out a sufficiently broad program of investigation of high-temperature plasma physics. It is of course essential that the scientific program be directed towards the working out of the most timely problems, and that it should not be overloaded by fragments of subject matter which has lost its significance and has been maintained through inertia. The distribution of effort over a broad front of theoretical and experimental studies should correspond to their scientific importance which requires from time to time reappraisal. In particular, most attention should at present be given to the development of closed magnetic traps.

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