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*PRESENT STATE OF RESEARCH IN CONTROLLED THERMONUCLEAR REACTIONS**

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THE conference ending today has demonstrated the wide range of research concerned with the problem of controlled thermonuclear fusion. More than 250 experimental and theoretical papers have been presented and a swiftly flowing stream of new scientific information has cascaded from this platform onto the heads of numerous listeners for more than thirty hours. The exchange of opinions and results in both the official and in the so-called "informal" discussions and individual conversations was extremely interesting; the cross-fertilization of scientific ideas was of fruitful, although sometimes perhaps of rather heated nature.

In summarizing the work of this conference we are forced to admit that after many years of intensive work we have only taken the first relatively small step on the path to the goal before us; we are still only approaching the main barrier that obstructs the entrance into the region of ultrahigh temperatures.

A plasma heated to a high temperature can very easily lose its accumulated thermal energy through the agency of various instability mechanisms. In experiments carried out up to the present time it has not been possible to maintain dense plasmas at appreciably high temperatures for time intervals greater than the order of hundreds of microseconds. The intensities of the so-called "real" plasma thermonuclear reactions are so small at the present time as to be completely masked by various acceleration processes. Satisfactory contact has not yet been established between experimental results and theoretical analyses. This is especially true for the important problem of plasma stability. As a result we have as yet not progressed very far in the development of methods of suppressing plasma instabilities.

The responsibility for this state of affairs obviously lies primarily at the door of experimentalists. However, the experimentalists have a strong justification. This justification is due to the special properties of the object under investigation, which make the formulation and execution of experiments extremely difficult. The task of producing a hydrogen or deuterium plasma of adequate purity is in itself not an easy one because the interaction of hot plasma with the walls of the vacuum chamber very rapidly leads to contamination by atoms and ions of impurity materials adsorbed on the wall surfaces; in turn contamination causes extremely high radiation losses. As an example, we may note that in toroidal pinch experiments intense impurity radiation is observed in every discharge, even after lengthy vacuum conditioning. This is one of the basic difficulties in trying to raise plasma temperatures in experiments of this kind. Investigations of the properties of a plasma in these circular pinches meet with many obstacles: a peculiar kind of uncertainty principle seems to operate in that purity of the experimental conditions is found to be irreconcilable with the application of diagnostic techniques. Because of its inaccessibility and extreme sensitivity to any contact, a pinch hidden behind metal walls and complicated windings is a singularly inconvenient object for investigation. Another difficulty arises in devices whose operation is based on the injection of fast particles in a magnetic field; because of the low efficiency of the source the particle flux is relatively low, so that long periods of time are required before the trap can be filled. During this time period even a relatively weak instability or an effect such as charge

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exchange on the residual gas can cause particles to escape from the working volume making it difficult, if not impossible, to obtain a plasma of appreciable density.

On the other hand, attempts to inject a plasma jet into a trap are faced with three problems that have not yet been solved: (1) how to trap the plasma; (2) how to convert the directed particle flow in the jet into bunches with a more or less isotropic velocity distribution; (3) how to eliminate the neutral gas emitted from the injector along with the plasma jet.

After these general remarks, which serve to some degree to indicate the relatively slow progress in our field of science, I would like to make a very brief, and necessarily superficial, survey of the basic results that have been obtained in work carried out in recent years.

On the whole the present status of the problem certainly shows great progress as compared with the situation at the Geneva Conference in 1958. At that time the exchange of scientific information consisted primarily of what might be called the proposal of ideas. In most cases these ideas were only slightly backed by rough and poorly verified experimental data, which were of more or less preliminary nature.

In contrast, in almost every division of the general thermonuclear program we now see a large number of carefully executed experiments and very valuable results which, in their totality, form a rather hopeful foundation, on which we can expect to accelerate the pace of research appreciably in the future. It is remarkable, however, that the reservoir of basic physical ideas has remained essentially unchanged—in the last three years no new important method of producing a high-temperature plasma has been proposed. There has also been an appreciable shift in the center of gravity of effort toward the development of particular approaches in the general program.

In the initial stages of development of the problem of controlled thermonuclear reactions a great deal of attention was given to the experimental investigation of the simplest method of producing high temperatures; the basis of this method is the linear pulsed discharge of high power and short duration (the so-called fast linear pinch). Even before the Geneva Conference investigations of the fast pinch indicated a rather clear characteristic pattern of effects in discharges of this kind, enabling us to determine the mechanism underlying the dynamics of the plasma pinch. As is well-known, this mechanism is essentially the acceleration of plasma by electrodynamic forces. One of the most interesting features of this process is the production of hard radiation: neutrons (in a deuterium plasma) and gamma rays. We now know that under typical experimental conditions the hard radiation is due to acceleration processes that originate in certain instabilities characteristic of high-current pinches. The primary mechanism responsible for the production of fast positive ions (and, consequently, neutrons) is the sausage instability; the fast electrons are produced by the screw instability, which stems from the tendency of the pinch to form a "force-free" configuration.

Although temperatures higher than a million degrees have been achieved in linear pinches, it is becoming increasingly evident that there is little hope that this method can be used in practice for obtaining intense thermonuclear reactions on a scale of technological interest. For this reason interest has naturally shifted toward the investigation of systems of a somewhat different type, in which rapid plasma compression is achieved by means of an external field that increases in time. Here we refer to the process known as the theta pinch. The theta pinch yields a maximum concentration of magnetic energy in small volumes. Compression of a plasma by an external field is thus a much more effective method of producing high temperatures than the linear discharge. The relative simplicity of the experimental apparatus and the alluring prospects in this field have brought about a situation in which the investigation of the theta pinch has, in recent years, become one of the most popular subjects in the controlled fusion research repertoire. The interest in this subject is indicated rather vividly by the large number of papers devoted to it at this conference (20 as compared with 2 or 3 at Geneva). If the present state of affairs continues we shall soon have "a theta pinch for every housewife."

The basic facts that have been established in theta-pinch devices are as follows: a trapped magnetic field is usually confined inside a dense cylindrical layer of plasma, which is in a state of rapid compression; the direction of this trapped magnetic field is opposite to that of the field at the outer surface of the plasma. In the initial stages of the process the work done by the magnetic compression force goes primarily into the acceleration of ions; on the other hand, the relaxation of the trapped internal magnetic field can make an important contribution to the heating of the electron component. The theta pinch is not a stable plasma configuration. This result has been demonstrated rather vividly in high-speed photographs of the optical emission from a plasma. In the plane perpendicular to the lines of force the contracting plasma object is reminiscent of an ink blot or a relaxed octopus with a hole at its center. We are dealing here with a typical sausage-type magnetohydrodynamic instability. This instability arises because the plasma undergoes a strong acceleration in the rapid compression and subsequent radial oscillations, and because the field configuration is unfavorable (convex outward). Although the agreement between the results reported by different authors is not satisfactory, it can still be said that in devices with limiting parameters built in Washington and Los Alamos it has been possible to obtain plasma bunches with densities of 10^{16} at temperatures of the order of 10^3 eV for times of the order of several microseconds. I do not wish to discuss here the nature of the neutron radiation observed in certain cases of rapid compression of a deuterium plasma since this problem is more or less academic. I might say, however, that if any one of the happy observers of this effect had brought to Salzburg a handful of the average number of pure neutrons produced in a single discharge there would still not be enough to offer one neutron as a souvenir to each one of the hospitable citizens of Austria.

In spite of the great number of valuable investigations of the properties of the theta pinch that have been carried out in England, the U.S.S.R., the U.S.A., and other countries, the nature of this process is still unclear in many respects (list here we might the mechanism by which the trapped field relaxes, the origin of the rotation of the plasma bunch, the loss of particles, and so on). Also, it is still not known whether it will be possible in the future to obtain a sufficiently stable hot plasma by fast compression without making fundamental changes in the shape of the magnetic field. In evaluating the future of this field of investigation we must take account of the fact that at the present time there is no method that produces hot plasma of higher density than that obtained in theta-pinch devices. For this reason one expects that in the foreseeable future the experimental investigations of ultrafast compression of plasma by a time-increasing field will continue in spite of the evidence that these devices will not be of practical use in terms of the thermonuclear program.

A traditional branch of the thermonuclear program is the investigation of so-called quasi-stationary or slow discharges in toroidal chambers. Two basic trends have developed in this field. The first of these proceeds from the idea of producing a paramagnetic plasma current pinch with a longitudinal self magnetic field of relatively low strength. This approach, as is well-known, has been realized in devices such as Zeta, Alpha, and Sceptre. The second trend is based on the idea of stabilizing a toroidal discharge by a longitudinal field many times stronger than the magnetic field produced by the current itself. Devices belonging to the Tokomak family represent an embodiment of this principle. This family also includes Stellarators in which ohmic heating is used.

To begin we consider the situation that has developed in the first field mentioned above. It was clear from reports given by workers at Harwell and Aldermaston at the Geneva Conference that a paramagnetic plasma pinch is also a victim of instability. Later work carried out in both England and the U.S.S.R. (on the Alpha device) verified these original conclusions. However, this finding ought not and in fact did not cause this work to be abandoned. The experiments were continued and gave a great deal of valuable information on the behavior of paramagnetic pinches and the properties of the plasmas formed therein. We shall indicate here only the most important results of this work.

Because of the low gas-kinetic pressure in a plasma pinch, a force-free magnetic-field geometry is produced, that is to say, the current everywhere flows precisely along the lines of the resultant magnetic field. We may note, among other things, that in the quasi-stationary mode this field-current configuration is formally equivalent to a limiting anisotropy of the electrical conductivity. The energy introduced into the plasma by the source of electrical power is dissipated in the form of impurity radiation when operation takes place at low power levels; at higher powers the energy is lost to the expulsion of particles from the walls. Spectroscopic measurements carried out on all three of the devices listed above indicate complete agreement on one point: the mean ion energy in a discharge is appreciably greater than the electron thermal energy. However, there is no clear cut agreement on the nature of the dependence of ion energy on charge Z and mass M. The measurements carried out at Harwell would seem to indicate that the ion energy increases linearly with M and is essentially independent of charge. The Alpha experiments give a completely different result, indicating that the energy of multiply charged ions is approximately proportional to Z^2 and not very sensitive to mass. The origin of the fast ions is still not clear. A very interesting effect has been found in Zeta: this is the anomalous plasma resistance, which is important in the general behavior of the device when the initial gas pressure in the chamber is low. The anomalous rise in plasma resistance can, a priori, be attributed to some kind of instability. However, this is far from an "explanation."

In spite of the great amount of important and interesting scientific information presented at the conference by workers from laboratories in which paramagnetic plasma pinches are being studied, one still gets the impression that this field of research is reaching the point at which no new data will be forthcoming.

In discussing the work carried out with Zeta devices one must also note that this work has stimulated the development of a whole series of new plasma diagnostic techniques. One of the most outstanding recent achievements in this field is a method of measuring plasma radiation at submillimeter wavelengths, which has been developed at Harwell. Another important technique is the one used for measuring the energy spectrum of plasma particles that has been developed at Leningrad and used with the Alpha device.

The study of ohmic heating processes in a plasma in a strong field is as yet just at its beginning stage. It has been established, however, that the external symptoms of marked instability disappear at sufficiently high values of the ratio H_z/H_φ (H_z is the longitudinal field and H_φ is the field due to the current). It has also been found that the diffusion of plasma across the lines of force in such systems is of anomalous nature. The observed diffusion coefficient is many orders of magnitude greater than the value obtained from classical theory, approaching the limiting value given by the heuristic Bohm formula. Anomalous diffusion results in a very rapid loss of particles from the pinch and limits lifetimes in existing devices to several hundredths of a microsecond at best. There are, however, certain experimental results which indicate that the measured particle-loss rates are characteristic of the peripheral regions of the plasma ring in a toroidal chamber; there appears to be a much denser core within the ring, in which the particle density remains at fairly high levels (10^{12}—10^{13}) for longer periods of time. At the present time the mechanism responsible for anomalous diffusion in the Tokomak and Stellarator systems is still not known.

There are several possible theoretical explanations for the effect: higher-mode magnetohydrodynamic instabilities, instabilities characteristic of a plasma with a nonuniform temperature distribution, excitation of ionic sound waves, and so on; the available experimental data are, however, not yet adequate for a unique resolution of this question. The recent startup of the Model C Stellarator, for which we must congratulate the engineers and scientists working at Princeton, will probably yield appreciable information that will be useful in obtaining a definite explanation of the anomalous diffusion found to accompany ohmic heating of a plasma.

There is little hope that ohmic heating in Tokomak or the Stellarator systems will be sufficient, by itself, to heat a plasma to thermonuclear temperatures. However, the possibility is not excluded that this method of producing a hot plasma will be very useful in the initial heating stage, in which the temperature is raised to several hundred electron volts.

Investigations of quasi-stationary discharges in strong magnetic fields are also of great value from the point of view of plasma physics. In these discharges we have for the first time a plasma with a high density of charged particles in a well defined geometry free of the catastrophic deformations which tend, after several microseconds, to change all the parameters in high-power, short-lived discharges.

In recent years intensive effort has gone into the development of a broad class of systems which we may lump together under the common designation of magnetic traps. We refer here to various kinds of mirror machines, magnetic systems with cusp geometries, the Astron device, and systems in which the plasma is contained by high-frequency fields. The Stellarator should actually also be included in this category, since its operation is not really based on the quasi-stationary discharge. In magnetic traps the plasma containment function is performed by an external field and the quantity p can, in principle, be as small as desired compared with $H^2/8\pi$. At small values of $8\pi p/H^2$ the plasma does not have an important effect on the strong external field and this facilitates the stabilization of certain dangerous plasma instabilities.

We first consider the present status of experimental research on mirror machines. Systems in which the plasma is formed by injection and subsequent trapping of fast particles are represented at the present time by Ogra and DCX (I am considering only existing systems). In the last few years studies have been made with Ogra to evaluate a method of forming plasma based on the injection of molecular ions that are dissociated by collisions with the molecules of the residual gas in the chamber. It has been observed that the low density plasma formed in this way is subject to a characteristic instability, which can be regarded as the limiting case of the magnetohydrodynamic flute instability. This instability can be suppressed markedly by means of an electric field. However, even when this stabilization system is used with a high injected-ion current it is not possible to achieve fast ion densities greater than something of the order of 10^7 cm^{-3}. There is also evidence of an instability (variation of the energy spectrum and expansion of the region occupied by the plasma) in the DCX device, in which molecular ions are dissociated on an arc. However, the mechanism responsible for the loss of stability in this case may be of completely different nature than in other magnetic traps because in DCX we are dealing with a peculiar ensemble of particles (a large ion "carousel" in an electron-gas atmosphere).

Workers who are at the present time studying the properties of traps of this kind are concerned not only with methods of suppressing instabilities but also, to a large degree, with the development of new methods of particle injection and capture; this situation has arisen because injection methods based on dissociation of molecular ions are not particularly efficient. In this connection the interesting experiments carried out at Aldermaston may be useful. I refer to the formation of atoms in high excited states by the dissociation of molecular hydrogen ions. Dissociation of a flux of these excited atoms by a magnetic field provides a new technique for capturing charged particles in a trap. However, the conditions that must be satisfied in order for this capture technique to be effective are extremely critical since the ionization probability must be an exponential function of the quantity $\mathbf{v} \times \mathbf{H}$.

An important contribution to the understanding of the important problem of plasma stability in mirror machines has come from the careful investigations of plasma properties that have been carried out for a number of years at the Atomic Energy Institute of the U.S.S.R. Academy of Sciences, on a device called the ion magnetron. A plasma with a fast-ion density of the order of 10^9—10^{10}, which fills the chamber of the ion magnetron, exhibits a characteristic instability that limits the containment time of particles in the magnetic field to something of the order of 100 microseconds. Analysis of the spectrum and the geometric distribution of the radio-frequency plasma oscillations indicates that we are dealing with a typical flute instability. This result is also interesting in another respect—it demonstrates that rough estimates of the decay time for an unstable plasma configuration in which the stabilizing effect of the walls is neglected and in which the deformation rate is determined in the linear approximation can give results which differ by two orders of magnitude from the experimental results. This means that the measurements of plasma containment time must be interpreted with very great care: because of the effect of a number of stabilizing factors the violent instability that would scatter the plasma bunches in a time of the order of fractions of a microsecond can be converted into a slow plasma deterioration that lasts for tenths of a millisecond.

The investigations of magnetic traps with dynamic fields that have been in progress for many years at Livermore are also of great interest. At this laboratory an ingenious plasma-compression technique has been developed in which a plasma bunch is moved, in several steps, from one part of the trap to another, and is gradually compressed and heated in the process. By this means it is apparently possible to produce a plasma with an ion energy of several kilovolts, a particle density of the order of 10^{12}—10^{13} and a duration of several tenths of a microsecond. The stability of the plasma in these experiments, however, is still a matter open to discussion.

In recent years a series of experimental papers have reported investigations of plasma containment in traps in which the so-called cusp geometry is used. The magnetic system in a trap of this kind produces a field in which the lines of force are hyperbolas. The field strength increases in all directions from a central region, at some point of which $H = 0$. The theory predicts that a plasma in such a trap should be magnetohydrodynamically stable.

However, this advantage over conventional mirror machines is obtained at an expensive price. Simple considerations show that the charged particles can escape the trap by approaching sufficiently close to the transverse edge of the region occupied by the plasma (the shape of this region is similar to a child's spinning top).

A calculation of the number of particles that escape from the plasma in this way (through the circular slit) depends very strongly on the assumptions made in the theoretical analysis. Hence the plasma containment time in a cusp system can only be evaluated by direct experiment.

The experimental data on traps with hyperbolic fields available at this time in the U.S.S.R., England, and the U.S.A. are of only preliminary nature. In most cases the trap is filled in the same way. A plasma jet from an injector enters the trap and is partially captured by processes that are as yet not completely clear. In accordance with the predictions of the simple theories it is found that the particles escape from the magnetic system in the radial direction through the circular "slit." The plasma containment time in these devices is of the order of tens of microseconds. Most of these experiments carried out up to this time have been performed with relatively cold plasmas ($T_i \sim 10$ eV) so that Coulomb collisions still play a decisive role in the particle escape mechanism. It should be noted that the behavior of a plasma in the trap must be very sensitive to the nature of the spatial distribution. The particle escape mechanism may be completely different when the plasma is concentrated in the volume from which the field emanates as compared with the case in which the plasma and field displace each other. The experiments carried out at the present time seem to be characterized by the second of these cases.

The first experiments in which a plasma bunch injected into a cusp was rapidly compressed in an increasing magnetic field have not given definite results, but do demonstrate a good experimental technique.

Because mirror machines and traps with opposing fields have (at least theoretically) serious defects and will probably not serve for extended containment of a high temperature plasma, it is a natural step to investigate a magnetic trap with a field configuration that combines the advantages of simple systems and eliminates their shortcomings. A simple example would be a device in which the magnetic mirror field is supplemented by a field produced by currents flowing in metal conductors oriented along the lines of force of the magnetic mirror field (symmetric with respect to the axis). The first experiments with this field configuration carried out at the I. V. Kurchatov Atomic Energy Institute have produced a number of interesting results. It has been found that the fast particle lifetime can be increased by approximately one order of magnitude with this arrangement.

In addition to the increased ion containment time one also observes a sharp reduction in the amplitude of the radio-frequency oscillations in the plasma. If this very preliminary result is verified in the future we will have an effective means of dealing with the form of the magnetohydrodynamic instability that represents the chief danger to magnetic mirror systems.

The most completely developed combined-field trap is the Stellarator. However, this device is so complicated that it is difficult to carry out experimental work with it. Hence it is necessary to seek other means of producing fields that provide stable plasma configurations.

We should say several words about the problem of a "universal anomalous diffusion" which, from time to time, appears on the horizon as a gloomy prediction of impending doom.

We can scarcely agree with the statement that anomalous diffusion is an inevitable property of a plasma confined by a magnetic field. It is much more probable that this behavior is to be associated with characteristics of a given magnetic trap and that it depends on the way in which the plasma is manipulated. For example, the impression is easily gained that it is difficult to avoid anomalous diffusion in ohmic heating. However, if the plasma is not subject to the effect of a current that flows along the lines of force the anomalous diffusion should disappear completely or be markedly suppressed.

Permit me now to make several concluding remarks. In its difficulties the problem of controlled thermonuclear fusion goes far beyond any of the other scientific-technical problems that have arisen in the development of natural science in the twentieth century. These difficulties are especially marked when contrasted with the simplicity of the physical ideas on which actual methods of plasma containment and heating are based.

In evaluating future prospects we can say that the greatest unresolved problem is that of ascertaining the danger associated with various plasma instabilities. However, it is precisely this question which is the present sore spot of the entire problem. Theoretical studies are continually discovering new instabilities. However, they by no means have proved the existence of a universal plasma instability. It should also be kept in mind that the degree of proof of all evaluations of stability is not very high so that in practice stability theory serves to give broad recommendations for caution rather than strict specific rules. Although it cannot be proved one nevertheless has the impression that with the development of presently known methods of heating and thermalizing plasma it will be possible in the future, by using sufficiently strong magnetic fields, to produce a high-temperature plasma of appreciable density which is stable to a first approximation and capable of producing strong thermonuclear reactions. It is probable, however, that the parameter $\beta = 8\pi p/H^2$ will be small. This result can be achieved if the methods being developed at the present time for avoiding the most dangerous magnetohydrodynamic instabilities are successful.

However, this course of events will not mean the achievement of the final practical goal; rather it will mean the overcoming of the first major barrier on the path to this goal. Beyond this barrier there may be other obstacles waiting whose role will become clear as we move forward toward higher and higher temperatures. We may note that if a plasma exhibits electric field fluctuations at a frequency of the order of 1 Mc with an intensity of no more than 10 V/cm this effect alone can be sufficient to limit fast particle lifetimes to several milliseconds.

It is now clear to all that the original predictions that the doors into the promised land of ultrahigh temperature would open without squeaking at the first strong knock of creative energy of physicists was as unjustified as the hope of a sinner to enter the Kingdom of Heaven without first entering purgatory.

All the same, there can hardly be any doubt that the problem of controlled fusion will eventually be solved. The only unknown is the length of our stay in purgatory. We shall not be able to leave purgatory until we have an ideal vacuum technology, completely developed magnetic systems with precisely known geometries, and properly programmed electrical circuits; then we can leave, carrying in our arms a quiet, stable, high-temperature plasma as pure as an idea of a theoretical physicist when it is still uncontaminated by contact with experimental facts.

On behalf of the Soviet delegation I wish to express our deep gratitude to the mayor of the city of Salzburg for his hospitality, and to the Secretariat of the IAEA for the expert organization of this conference.

Translated by H. Lashinsky
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