Contemporary problems of plasma theory (from Materials of International Conference Held at Kiev, 28 October–1 November 1974)

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Usp. Fiz. Nauk 117, 368–373 (October 1975)

PACS numbers: 01.10.Fv, 52.90.+z

Plasma physics is a vitally important division of modern physics with a direct bearing on such important scientific-technical problems as the conduct of controlled thermonuclear fusion, the development of magnetohydrodynamic process for the conversion of thermal to electrical energy, the design of a new type of space engine, etc. Elaboration of the fundamental problems of plasma physics is a most important prerequisite to successful practical realization of plasma-physics research and its future development. Here there is no doubt that theory must take the leading role, or that significant progress will be impossible without extensive collaboration among specialists working not only in plasma physics, but also in the contiguous fields of physics and mathematics. The Second International Conference on Plasma Theory, which was held from October 28 through November 1, 1974 at Kiev, was devoted to discussion of general theoretical problems in plasma physics and also in statistical physics. The conference was organized by the Ukrainian Academy of Sciences Institute of Theoretical Physics and the P. N. Lebedev Physics Institute of the USSR Academy of Sciences with support from the International Union of Pure and Applied Physics.

More than 250 theoretical physicists from various physics centers of the Soviet Union (Moscow, Kiev, Leningrad, Khar'kov, Tbilisi, Novosibirsk, Gor'kii, and others) and about 50 prominent foreign scientists representing 16 countries (the USA, France, East Germany, West Germany, Poland, Belgium, Bulgaria, and others) took part in the work of the conference. The conference program was drawn up on the basis of the papers submitted and was approved by the International Program Committee (Chairman B. B. Kadomtsev; M. S. Rabinovich, A. G. Sitenko, I. P. Yakimenko (USSR), R. Balescu (Belgium), H. Wallis (GDR), N. Weinstock and F. Perkins (USA), and R. Klima (Czechoslovakia). Thirteen review papers reflecting the contemporary state of practically all trends in plasma theory were heard at the nine plenary sessions. The overwhelming majority of the original papers (191) were submitted by specially chosen reporters—specialists in the corresponding divisions of plasma theory. A limited number (33) of the most interesting original communications were presented by their own authors. A series of seminars that became forums for lively discussion were also held.

The conference considered and discussed the following problems in detail: general problems of the statistical theory; equilibrium, stability, and transport processes in plasma; study of vibrations and waves in plasma; nonlinear processes in plasma; interaction of charged-particle beams with plasma; plasma turbulence; mathematical simulation and computer methods in plasma theory, interaction of radiation with plasma, and various other urgent problems of plasma physics.

The physics of processes in equilibrium or nonequilibrium but quiescent plasmas has now been quite thoroughly studied. The electromagnetic properties of such plasmas are described by linear electrodynamics, while the dynamics of the plasma is described quite well by the hydrodynamic or kinetic theory. The traditional methods of confining and heating the plasma (open and closed magnetic traps, electrostatic systems, pinch systems, etc.) are based on the assumption that it is possible to eliminate all anomalies in the behavior of the plasma (including suppression of all instabilities) and to create stable plasma systems with controllable properties in which thermonuclear fusion reactions can take place. Substantial progress has been made in this direction, and work is now being done on long-term projects whose ultimate purpose is the development of economically advantageous thermonuclear energy sources.

We understand little of the properties of plasmas under anomalous conditions (ultrahigh temperatures, ultrastrong magnetic fields, ultrahigh densities, ultrastrong radiation intensities, high charged-particle beam densities, etc). The same can also be said concerning the dynamics of the processes that unfold in the plasma under such conditions. It must be remembered that we encounter manifestations of anomalous plasma properties not only in the study of processes that take place at cosmic distances in astrophysical objects and in explosive thermonuclear process, but also in a number of experimental situations that prevail in the realizations of various new technical projects that have been proposed with the object of practical realization of controlled thermonuclear fusion, an essential feature of which is colossal concentration of energy in the space-time scales. As examples, we note methods of heating and compressing matter with a powerful laser beam, compressing and heating plasmas to thermonuclear temperatures with a focused beam of relativistic electrons, compressing plasma with an imploded metallic shell, etc. A characteristic distinctive property of the processes that occur in such plasmas is their nonlinearity, which renders many of our accustomed conceptions unworkable. The collective properties of the plasma, which determine its specific behavior in substantial measure, play an important role here. New conceptions of strong turbulence in plasma have recently been under intensive development, necessitating the introduction of a whole series of new concepts and the use of new computer methods of investigation. We might cite as examples new conceptions as to the energy fluxes in phase space in the turbulent plasma, space-time granulation of excitation energy, the occurrence of collapse (as a result of concentration of plasma oscillations in regions of lower density) in turbulent plasmas, etc.

Let us dwell in greater detail on some of the problems that were discussed at the conference.

GENERAL PROBLEMS OF THE STATISTICAL THEORY

Contemporary plasma theory is based on extensive use of the methods of statistical physics. There are different approaches to the description of the properties of the statistical systems. For example, detailed description of the statistical and electrodynamic properties of plasma is possible on the basis of fluctuation analysis (paper by A. G. Sitenko). In linear electrodynamics, the fluctuation-dissipation relationship links the fluctuations of the various quantities to the electrodynamic properties of the medium. Thus, knowing the spectrum of the fluctuations in the plasma, we can invert the fluctuation-dissipation relation to determine the electrical susceptibility of the plasma. Generalization of the fluctuation-dissipation relation to the nonlinear case makes it possible in similar fashion to describe the nonlinear electrodynamic properties of the plasma. Allowance for nonlinear wave interaction explains the saturation of the fluctuation level in the nonequilibrium plasma under critical conditions. Here the level corresponding to the stationary turbulent state of the plasma may exceed the thermal level considerably. In the kinetic equation for the waves it is essential to take account of their interaction with the fluctuation field. Neglect of this interaction (which is resorted to in many papers) is illegitimate in the case of a nonequilibrium plasma. In the stationary case, the solution of the kinetic equation determines the spectral distribution of the fluctuations for the turbulent state of the plasma. The approach developed is extremely promising for study of the scattering and transformation of waves in plasma.

The transfer of methods based on the mathematical formalism of field theory, and especially the method of equal-time Green's functions, to statistical physics has played an important role in the study of collective effects in plasma. Application of the Green's-function approach to model systems of statistical physics has led to rigorous proof of the possibility of finding exact solutions for them in the thermodynamic limit (paper by N. N. Bogolyubov, Jr.). A kinetic theory that takes account of large-scale fluctuations can be constructed on the basis of microscopic equations if the condition of complete suppression of the initial correlations (the Bogolyubov condition) is replaced by suppression of small-scale correlations. Taking account of large-scale fluctuations means that we abandon the hypothesis of a continuous process of successive collisions, which determines the collision integrals; here the kinetic equation is regarded as a Langevin equation with the corresponding random source (paper by Yu. L. Klimontovich). A new approach to description of stochastic processes on the basis of the Vlasov equation was proposed by R. Balescu. The asymptotic equation for the averaged distribution function was reduced to Markov form, making it possible to clarify the role of turbulent collisions and ballistic effects associated with evolution of the initial fluctuations. The conversion to the quasilinear approximation is discussed, and the validity of the asymptotic approximation used is investigated by separation of dynamics.

STABILITY, OSCILLATIONS, AND WAVES IN PLASMA

Study of oscillations, emission, and various instabilities in plasma and especially in bounded plasma systems occupies an important position in the theory. A statistical theory of the electromagnetic processes based on inversion of the fluctuation-dissipation relation and use of the transition probability in a system of uncorrelated particles can also be constructed for a bounded plasma (paper by I. P. Yakimenko). The spectral distributions of the fluctuations and the linear-response functions for bounded nonequilibrium plasma systems are determined both by the nature of the departure from equilibrium, which results from the presence of charged-particle fluxes, external force fields, or a temperature anisotropy, and by the nature of the boundary conditions that develop on the collective effects.

The microscopic theory of fields in plasma was considered in the paper by G. Ecker. The spectral functions of microfields in plasma were determined on the basis of the dynamic screening principle. The influence of collective effects on the distribution of the microfields was investigated. It was shown that collective effects strongly modify the spectral distribution of the field in the case of ion-acoustic turbulence. O. de Barbieri discussed solution of the problem of reabsorption of cyclotron radiation in a high-temperature electron plasma. The question as to the stability of the plasma doughnut with noncircular cross section was considered by J. Soule, who showed that a kink instability can develop even in the absence of a pressure gradient.

Thermonuclear instabilities may develop in a high-temperature plasma that contains a small admixture of thermonuclear-reaction products. Analysis of the nonlinear stage in the development of low-frequency instabilities showed that the particle-wave interaction gives rise to directional motion of deuterium and tritium ions toward the center of the plasma column, while the fluxes of electrons and thermonuclear-reaction products are directed outward. Sequential analysis of both the linear and the nonlinear stages in the development of the thermonuclear instabilities makes it possible to obtain criteria for the existence of thermonuclear instabilities in a stationary thermonuclear reactor (paper by V. N. Oraevskiĭ).

NONLINEAR PROCESSES IN PLASMA

To a significant degree, the dynamics of a plasma is determined by the nonlinear nature of the wave interaction. It has been possible to obtain interesting results for analysis of nonlinear problems by use of the inverse-problem method of scattering theory (paper by V. E. Zakharov). In the case of a nonlinear equation, solution of the initial problem reduces to solution of the direct and inverse spectral problems for a certain linear operator, yielding asymptotically exact solutions. For example, the system of nonlinear equations describing the resonant interaction of three one-dimensional wave packets can be solved exactly by the inverse-problem method, with rigorous proof of the conservations laws and indication of the complete integrability of the equations. In the case of decaying resonant interaction of the wave packets, the physical picture depends on the relation between the velocities of the pump and secondary waves: if the pump velocity is intermediate between the velocities of the secondary waves, a long pump packet decays practically completely on collision with arbitrary small packets of secondary waves; but if the pump velocity is one of the extremes, destruction of the pump wave is possible only on collision with sufficiently intense, secondary-wave packets. Exact solutions describing the appearance of local features in bounded wave packets were found for the case of explosive instability.

The propagation of waves in an inhomogeneous plasma is accompanied by absorption and transformation of the waves. For example, harmonics may be generated in propagation of Trivelpiece-Gould waves in an axially inhomogeneous plasma. Analysis of the equations of a cold plasma in the second order of perturbation theory has shown that the nonlinear terms that appear in the equation for the potential of the second harmonic are larger than the usual nonlinear terms for an axially homogeneous column. This made it possible to explain the experimentally observed effect in which higher harmonics appear when an external electromagnetic wave is incident on a plasma (paper by J. Hirschfeld).

INTERACTION OF CHARGED-PARTICLE BEAMS WITH PLASMA

According to contemporary conceptions, one of the basic methods of heating plasma is based on the use of the interaction of charged-particle beams with the plasma. Here the most promising systems use relativistic electron beams. The dynamics of the plasma-beam system is determined to a substantial degree by the relaxation of the beam. The most important and most complex part of the problem of the relaxation of a relativistic electron beam in a plasma consists in finding the spectrum of the turbulent oscillations excited by the beam. The greatest progress toward finding the turbulence spectrum has been made for systems with small beam-to-plasma density ratios. The principal nonlinear processes that limit the energy of the oscillations have been established in such systems, and the steady-state energy of the oscillations has been estimated. Stationary solutions have been found in certain cases, but it is not yet clear whether the spectrum necessarily relaxes toward one of them or whether quasistationary pulsating solutions can exist. The theory of weak turbulence is inapplicable to beams of rather high density, and it is necessary to consider a number of added effects, such as spontaneous formation of inhomogeneities, which weakens the interaction of the oscillations with the beam (paper by D. D. Ryutov).

An extremely interesting communication from J. Freeman pointed to the possibility of heating a small spherical target with a specially focused electron beam in a system of the hollow-cathode-diode type. An advantage of the electron beam over the laser consists in the possibility of obtaining higher energy concentrations (up to 10^6 J) and much higher efficiency (about 30—50%). The results of numerical calculations for cathodes with diameters with 13 to 46 cm were submitted, and indicate the possibility of obtaining satisfactory focusing.

A paper by A. A. Kolomenskiĭ set forth the results of a theoretical investigation of the self-acceleration effect in the interaction of a heavy-current relativistic electron beam with a moderating structure of the diaphragmed-waveguide type. In the self-acceleration process, energy is transferred from one part of the beam through an electromagnetic field excited in the medium or in the structure by the beam itself to another part of the beam, whose energy may be increased to several times its initial value. A series of numerical simulating experiments was performed in addition to approximate analytic calculations. The basic stages in the development of the process were investigated: a linear stage with exponential increase of the amplitude of the excited wave, a nonlinear stage of saturation with capture of particles by the wave, and a stage of nonlinear decay of the wave with stochastization of the phase-plane distribution of the particles. The effectiveness of self-acceleration can be increased considerably by cutting off the low-energy part of the beam spectrum.

TURBULENCE IN PLASMA

The most efficient mechanism of energy transfer to plasma by intense electron beams and light fluxes is associated with the formation of a strongly turbulent state in the plasma. The appearance of this state can be explained on the basis of a soliton model of turbulence (paper by L. I. Rudakov). Solitons are formed as a result of modulation instability of the turbulent state, and take the form of sets of waves that are captured by regions of low plasma density, which, in turn, appear under the pressure of a high-frequency field. The formation of solitons is energywise favored because it lowers the frequency of Langmuir quanta and the energy released in this process helps to form regions of lowered density. Solitons may decay or merge as a result of collisions. If the distances between solitons exceed their dimensions, binary collisions play the principal role. Electrons can acquire energy as a result of multiple collisions with solitons, and this results in a change in the distribution function. This picture is confirmed for the one-dimensional case by numerical integration of the nonlinear equations of Langmuir turbulence. Merging of solitons may result in the phenomenon of collapse, i.e., in dynamic accumulation of energy in certain regions of the space. Under special assumptions, the existence of this process is confirmed by the numerical calculations. Interaction of the particles with the collapsing formations results in heating of the particles in the medium.

A model of the Langmuir condensate based on the hypothetical existence of an average stationary state of strongly interacting modulation perturbations in the plasma makes it possible to construct a three-dimensional theory of the turbulence (paper by V. N. Tsytovich). The specific properties of the strongly turbulent plasma state are reflected in a number of effects, some of which are: a destabilizing effect of high-frequency turbulence on low-frequency oscillations (paper by M. Nambu); development of parametric and explosive stabilities in the presence of inhomogeneities in the plasma; turbulent generation of Alfven waves in the solar wind near the earth; generation of a magnetic field by ion-acoustic turbulence; temperature turbulence in the conductive gas (paper by V. I. Petviashvili).

MATHEMATICAL SIMULATION AND COMPUTER METHODS IN PLASMA THEORY

The computer experiment is of exceptional importance in the development of work in plasma physics and on the problem of controlled thermonuclear fusion. Mathematical simulation makes possible detailed study of complex physical processes in plasmas under conditions that offer fusion possibilities. Examples of computer experiments of this kind are computations made with the object of studying the feasibility of thermonuclear fusion induced by laser radiation. Not only do these calculations investigate the physical peculiarities of thermonuclear-reaction initiation as a result of heating and compression of a plasma by a powerful laser pulse; they also analyze methods of utilizing the released energy and even consider problems in the design of possible reactors (paper by A. A. Samarskiĭ). Two types of models are now in extensive use: the continuous-medium model and the kinetic model of the collisionless plasma. In the former, the plasma is described by hydrodynamic or magnetohydrodynamic equations with consideration of radiation-transfer processes. Mention can be made of a number of recently solved problems in magnetic radiation hydrodynamics: compression of a drop of deuterated plasma (the calculations indicated that the external wave is formed as a result of heating of air by radiation from the heated target, and is an ionization wave; the internal wave is a shock wave formed by the pressure of the disintegrated target), the emission of heavy-current discharges, magnetic cumulation (compression of the field by an imploded metal shell), and dynamic problems in tokamaks (hydrodynamic equilibrium and stability; modeling of the energy and particle balance). It is helpful to use self-similar analytic and stationary solutions to understand the nonlinear phenomena in the plasma and to test the accuracy of the numerical method. A number of self-similar and analytic solutions have been found in connection with the radiation-matter interaction problem, e.g., it has been possible to find the compression regime of a spherical drop without a shock wave. Study of this type of self-similar solution has made it possible to detect the existence of nonmonotonic temperature profiles in the compressed plasma—curious structures brought into being by the development of dissipative instability. The development and successful application of the discrete-modeling method continue for the collisionless plasma. To illustrate the problems that have been solved, we might point to that of anomalous heating of plasma by a high-frequency field, the two-dimensional problem of anomalous plasma diffusion in an external magnetic field, and the theory of the moving probe. Use of the Vlasov equation is inconvenient in a number of strongly nonlinear problems, especially if the main nonlinearities are associated with the motion of ions. In this case it is necessary to average the motion of the electrons over a fast time connected to their oscillations. A series of models that have been used for analytic and numerical solution of problems bearing on soliton dynamics and Langmuir collapse in plasma has been constructed in this way.

One of the most important aspects of the thermonuclear fusion problem is heating of plasma confined in magnetic systems. Study of the propagation and absorption of ion-cyclotron and magnetoacoustic waves in tokamaks has shown that collisionless damping of magnetoacoustic waves is sufficient to heat the plasma even at low wave intensities; here the ion-cyclotron waves heat the periphery of the plasma preferentially (paper by F. Perkins). The results of numerical modeling of the quasilinear evolution of the ion distribution function agree satisfactorily with experimental results obtained with a tokamak.

INTERACTION OF RADIATION WITH PLASMA

A distinctive feature of the interaction of high-power radiation with plasma is the fact that the parameters characterizing the plasma change under the action of the strong electromagnetic field. As in the case of nonclosed mechanical oscillatory systems, this change makes possible parametric resonance manifested in the appearance of an internal fluctuation field that increases with time. The development of parametric stability brings the plasma into a turbulent state. Since the spectrum of the growing fluctuation field lies in a range of frequencies smaller than or comparable to the frequency of the pump wave, the appearance of the turbulent state is accompanied by rapid transfer of energy of the radiation to the plasma. This is attended by a particle-velocity redistribution. This picture of the parametric effect of high-power radiation on plasma is shown by theoretical and experimental studies of recent years (paper by V. P. Silin) to be applicable both to the plasma in the absence of the magnetic field and to a magnetized plasma acted upon by radio-frequency waves or laser radiation. For the development of parametric instability to be possible, the transformed energy of the pump field must exceed the energy loss of the plasma waves due to dissipation. This means that the effects of the parametric action of radiation on the plasma are threshold effects. The threshold value is determined essentially by the nature of the dissipation and by the nonuniformity in the spatial distribution of the plasma. One of the possible mechanisms of parametric-instability stabilization is spectral transfer of Langmuir oscillations from the range of wave vectors in which the oscillations build up to the range in which they are damped.

Experimental study of the anomalous interaction of strong laser radiation with a dense plasma has recently brought out the following effects: almost total absorption of strong light beams by the laser plasma; time oscillations of the intensity of the weak signal reflected by the plasma at the laser frequency; specular reflection (scattering) of the unabsorbed light; generation of harmonics of the laser radiation frequency by the plasma; a nonoscillatory monotonic change in the intensity of the second harmonic in time; anisotropy of x-ray emission from the laser plasma (paper by A. S. Shikanov). The observed phenomena can be interpreted fully within the framework of parametric-resonance theory with the aid of conceptions of turbulence and quasilinear relaxation in the plasma.

The conference was closed by B. B. Kadomtsev, who observed that its subject matter had been concentrated around general theoretical problems in plasma physics. Problems with a direct bearing on controlled thermonuclear fusion and other applied problems were discussed at considerably lesser length. This was because the Kiev conference was to be followed immediately by the International Conference on Controlled Thermonuclear Fusion at Tokyo, where these problems would be dealt with specifically. The Kiev conference, which brought together many leading theoreticians working in the field of plasma physics and related areas, made it possible to discuss the most fundamental priority problems of modern plasma theory and to mark out basic trends for its further development as the foundation for a number of extremely important scientific and engineering trends. The conference gave its participants an excellent opportunity to acquaint each other with the work being done in plasma theory at the various scientific centers.

The matter of the next conference was discussed at a session of the International Program Committee. It was agreed that the best course would be to accept the proposal of A. Salam, the director of the International Center for Theoretical Physics, that the next, Third International Conference on Plasma Theory be convened at Trieste, Italy in 1976.

Translated by R. W. Bowers