Dissipation in HIGH-TEMPERATURE PLASMAS

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By ***H. E. Petschek***

UNDER high temperature plasma conditions, both in the laboratory and in interplanetary space, there is considerable experimental evidence for the existence of turbulence. In both cases, large-scale fluctuations in the magnetic field have been observed. In the laboratory, fluctuations in other measured quantities are also observed, and, furthermore, the containment times are much shorter than one would expect from considerations based on diffusion across the magnetic field by particle collisions. In order to understand the basic interactions occurring, we must acquire some understanding of plasma turbulence.

Some insight into the problem can be gained from our experience with aerodynamic turbulence. We must, however, be careful not to take the analogy too far. This is particularly true since our present state of knowledge in aerodynamic turbulence is principally a large body of empirical correlations rather than a basic understanding of the phenomenon.

In view of our experience in aerodynamics, the fact that turbulence should arise in high-temperature plasmas is not particularly surprising. In ordinary aerodynamic flow, turbulence becomes important when the viscous dissipation process becomes very slow, i.e., when the Reynolds number, which is essentially the ratio of dynamic forces to viscous forces, becomes large. Thus, when the viscous dissipation mechanism is slow, the fluid finds a faster mechanism of dissipation by developing turbulence. In the case of the plasma at high temperatures, collisional dissipation also becomes slow because of the strong temperature dependence of the Coulomb cross section, and thus we might expect the plasma to find a more effective means of dissipating.

The basic characteristics of what might be described as turbulence in a plasma are that more or less random fluctuations exist and that these fluctuations have sufficiently large amplitudes so that nonlinear interactions are important. At this point, we might comment on a basic difference which one may expect between turbulence in plasmas and in ordinary fluids. In the latter case, the basic elements of turbulence are vortices which, since there is no restoring force, do not propagate relative to the fluid. In a plasma, almost any motion (except a vortex precisely aligned with the magnetic field) distorts the magnetic field and thus has a restoring force. The fluctuations will therefore propagate through the fluid rather than remaining attached to the same fluid particles. Aside from the basic difference that waves will transport energy and momentum across the fluid more readily, this suggests a possible simplification which is not justified in ordinary turbulence. Since the different waves comprising the turbulence move relative to one another, the nonlinear interactions will tend to be between waves which have not previously interacted. It may therefore be justified to assume that the interacting waves have random phases.

When should nonlinear interactions be considered?

In order to get some quantitative feeling for conditions under which turbulence may be of importance, let us compare the rate at which nonlinear interactions affect a propagating wave with the rate associated with various linear processes. To estimate the nonlinear effects, we consider a plasma in which a random group of waves of fairly small amplitude already exists. Since these waves give rise to changes in the magnetic field and in the density, the index of refraction of the plasma is nonuniform. A wave propagating through this medium is then scattered much as a light wave would be scattered in propagating through a piece of glass with small-scale variations in its optical properties. If we assume that the disturbing waves and the wave we are considering have comparable wave lengths, then the angle of scattering of the wave in moving a reciprocal wave number $(1/k)$ is of the order of the fractional change in index of refraction, $\Delta n/n$. If the disturbing field is assumed to be random, then the angle through which the wave is scattered will proceed by random-walk process, such that each time the wave moves a reciprocal wave number, it is scattered through an angle whose magnitude is $\Delta n/n$ and whose direction is ran-

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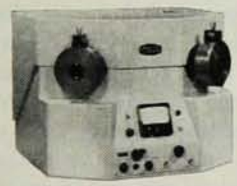

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dom. The distance the wave moves before the rms angle through which it has been scattered is more than one radian, therefore, becomes $1/k(\Delta n/n)^2$. This length may then be viewed as the distance which the wave goes before its interactions with other waves present become significant. A corresponding time for the nonlinear interactions to occur is $1/\omega(\Delta n/n)^2$ where we have assumed that the group and phase velocities of the wave are comparable. Roughly speaking, if we consider waves in which the magnetic field is disturbed, the change in index of refraction will be proportional to the change in magnetic field, $\Delta n/n = \Delta B/B$. The relationship $(\Delta B/B)^2$ may be taken as the ratio of the wave-energy density to the energy density in the average magnetic field. By analogy with the conventional use of β to describe the ratio of particle pressure (roughly energy density) to magnetic pressure, we may define the quantity above as β_w. The time it takes for nonlinear interactions to become important is then $1/\omega\beta_w$.

To compare this time with the time for linear processes to affect the amplitude of a wave, let us consider a plasma at a temperature of 300 eV, a density of 10^{16} particles per cubic centimeter, and a magnetic field strength of 2×10^4 gauss. If we assume rather arbitrarily a wave frequency which is the geometric mean between the electron ion cyclotron frequencies, the time for nonlinear interactions to become important becomes $10^{-10}/\beta_w$ sec. The time for linear damping associated with particle collisions must be greater than the mean free time for electron scattering and is therefore 10^{-7} sec or longer. Another linear-loss mechanism for waves is that they may leave the system. Because of the large change of index of refraction at the plasma boundary, one would expect the wave to be reflected fairly efficiently. The time for loss from the system is thus greater than the time which it takes a wave to move across the plasma. If 10 cm is the plasma dimension, and if the velocity equals the Alfvén speed, this time is then longer than 2×10^{-7} sec. A further linear damping or growth mechanism is caused by resonant particles (the generalization of the Landau mechanism to other wave modes). The magnitude of this effect is quite sensitive to the distribution of particle velocities and to the wave mode and wave number which are being considered. There are large regions of the wave spectrum in which the number of particles moving at an appropriate speed to be resonant with the wave becomes insignificant. In those regions of the spectrum, the resonant damping therefore becomes extremely slow.

Comparing these times, we see that in certain regions of the wave spectrum, the nonlinear interactions can become dominant even if β_w is as low as 10^{-3}. If we bear in mind that, in most laboratory experiments, plasmas are produced by rather violent processes and that, in the interplanetary plasma, there is certainly abundant evidence for violent disturbances of the plasma, it is rather difficult to imagine that one would obtain a plasma which is so quiescent that the ratio of wave energy to magnetic energy is this small.

Nonlinear wave growth

The preceding arguments suggest that nonlinear interactions of waves can in many cases be important in determining the history of a particular wave. This, in itself, places some limits on the conditions under which linear calculations, such as stability analyses, are valid, but it does not yet show that the existence of waves in the plasma will result in significant effects relating to the over-all behavior of the plasma. If, however, one can demonstrate that the presence of waves in the plasma can lead to a process by which the organized energy of the plasma can be converted to wave energy, then the possibility arises that, starting from a small but finite amount of wave energy, the wave energy will build up to sufficient amplitude to cause appreciable changes in the gross behavior of the plasma.

The conditions under which waves can grow may be much more general when nonlinear interactions are important than they are in the linear case. A linearly unstable wave maintains a constant frequency. Therefore, as the energy increases, the action (or, in quantum-mechanical terms, the number of quanta) must also increase. In order to achieve a growth of action, the process must be nonadiabatic. Linear instabilities are therefore restricted to those cases in which a nonadiabatic energy source exists. The typical cases encountered are ones where the instability is caused by particles which move in resonance with the wave or cases in which a resonance between two wave modes exists.

For nonlinear wave growth, it becomes possible to separate the process of adding energy to the waves and the process of increasing their action. This means that more general energy sources may lead to wave growth. For example, an adiabatic process leads to a change in wave energy which is proportional to the change in frequency. This, by itself, would not be of particular interest since, in order to achieve a large change in energy, a large change in frequency is required. This would probably move the wave to a region of the spectrum where damping becomes important. The wave would then damp and the process would be over. Nonlinear interactions, however, give rise to nonadiabatic effects and, therefore, can either increase or decrease the total action in the wave. If the wave spectrum is such that the action increases at constant energy, this is equivalent to reducing the mean frequency of the waves. The growth of the waves may therefore proceed by an adiabatic process which increases the wave energy and frequency and by a nonlinear process which reduces the mean frequency, the two processes being balanced so that a continuous growth of energy is achieved at a more or less constant mean frequency.

Adiabatic energy changes can occur in a plasma whenever nonuniform flow velocities exist. For example, if a wave is moving in a compressive flow field, the compression does work against the pressure associated with the wave, giving rise to an adiabatic increase of energy. Similarly, a shear flow can do work on a wave. In both of these cases, the order of magnitude of the

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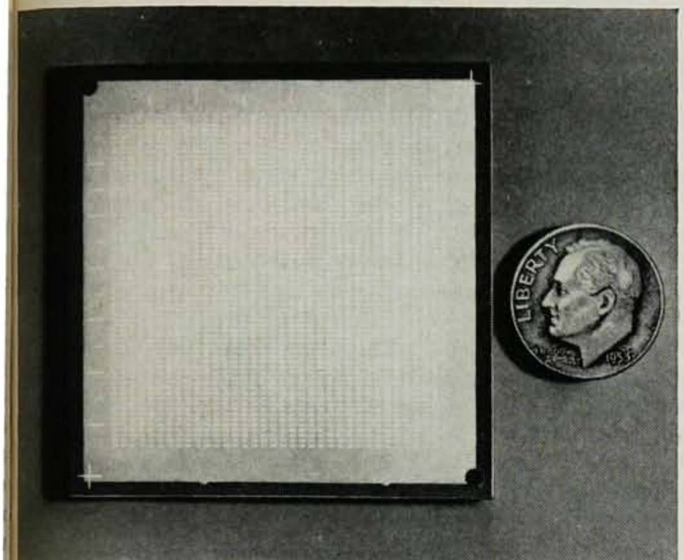

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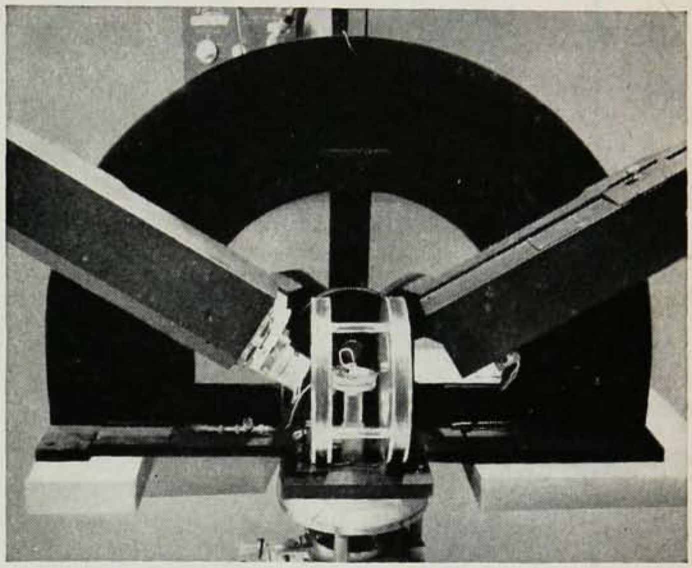

The switching speed of this experimental thin-film device (center) is being measured by timing a polarized light beam which rotates each time direction of magnetization changes.

Computing speed is accelerating constantly. But before computers can process data, they must pass it through main storage. Unless ways are found to transfer more information in less time from main storage to central processing units, the time required to obtain stored data will limit the speed of the computer.

To shorten access time, IBM is developing advanced memories. Recently, IBM scientists fabricated a magnetic thin-film memory which completes a full read-write cycle in 100 nanoseconds. They also have put to use a technique for measuring switching times in the nanosecond range with polarized light. Experiments with this technique revealed that a multi-layer-bit thin-film "sandwich" switched ten times faster than an equivalent single-layer-bit device.

More immediate gains in access time can be attained through new developments in ferrite core technology. By reducing the core size from 50 thousandths of an inch to 30 thousandths of an inch in outside diameter, IBM engineers have created a 1.2 million bit magnetic core memory with a cycle time of only 2 microseconds. A device which contributed greatly to this development, a load-sharing matrix switch, was also instrumental in the creation of a 74,000 bit "scratch pad" ferrite core memory capable of a read-write cycle time of less than 700 nanoseconds. This matrix switch makes it possible for the switching-power load to be shared by several drivers at once, thus reducing the total power requirements.

The efficiency of computing systems can be increased by improving the design of their memory structures as well as through the development of new components. IBM engineers are developing nondestructive read-out techniques which can reduce the number of machine operations required in thin-film and ferrite core memories. They have formulated addressing systems in which machine-word lengths vary according to the natural lengths of the bits of information being stored. They have devised associative memory techniques which retrieve information on the basis of related data rather than specified addresses. Out of several developments like these, which reduce machine references to memory and simplify programming, may come the memory systems of the future.

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factor by which the energy is increased is the ratio of the change in flow velocity through which the wave moves to the phase velocity of the wave. Furthermore, since there are waves which are associated principally with the electrons rather than the ions, these waves would be affected by nonuniform electron motions, i.e., by nonuniform currents. Adiabatic mechanisms for increasing wave energy thus exist in any plasma which is not completely uniform.

The requirement that the nonlinear interactions produce rather than decrease action is not particularly restrictive. In lowest order in the nonlinear interactions, three waves take part. If the two higher-frequency waves have larger amplitudes, the interaction will tend to populate the lower-frequency wave, thus reducing the mean frequency. At the same time, the requirements of conservation of momentum and energy will not allow two arbitrary waves to interact to produce a third wave. Therefore, the two high-frequency waves cannot, in general, also interact to produce a still-higher-frequency wave. Thus, nonlinear interactions could lead to an increase in action if the wave spectrum consists of a group of waves at high frequency which can interact to produce lower frequency waves but do not occupy so large a region of wave number space that the production of higher-frequency waves is important.

Thus, the combination of the adiabatic mechanism for increasing the energy of individual waves with the nonlinear interactions which reduce the frequency and allow the process to repeat itself gives rise to a possible mechanism for the continuous growth of wave energy in any plasma in which a gradient of flow velocity or of current exists.

At the present time, these arguments are very qualitative and no complete self-consistent picture has been formulated to tell us when these effects will in fact be important. However, the earlier argument that nonlinear effects can become important for extremely low values of the ratio of wave energy to magnetic field energy suggests that one should be aware of this possibility even in cases where the plasma has been treated very gently. Indeed one may ask whether it is reasonable to hope that one can achieve a fusion reactor design in which the plasma is treated so carefully that turbulent phenomena will not be of importance.

Some of these arguments have been presented in more detail in earlier papers.[1,2] The general picture of plasma turbulence and its probable importance has resulted from discussions with A. R. Kantrowitz and M. M. Litvak. Work in this area has been largely supported by the Fluid Dynamics Branch of the Office of Naval Research under Contract Nonr-2524(00).

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