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Waves and Turbulence in a Tokamak Fusion Plasma

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Summary. The tokamak is a prototype fusion device in which a toroidal magnetic field is used to confine a hot plasma. Coherent waves, excited near the plasma edge, can be used to transport energy into the plasma in order to heat it to the temperatures required for thermonuclear fusion. In addition, tokamak plasmas are known to exhibit high levels of turbulent density fluctuations, which can transport particles and energy out of the plasma. Recently, experiments have been conducted to elucidate the nature of both the coherent waves and the turbulence. The experiments provide insight into a broad range of interesting linear and nonlinear plasma phenomena and into many of the processes that determine such practical things as plasma heating and confinement.

The behavior of systems of many particles can often be dominated by collective effects. For example, consider the nearly coherent waves generated on the surface of a liquid by vibrating its container. An example of a more turbulent state is the surface of a lake excited by a strong wind, so that the many waves which are excited interact to produce a state of nearly random fluctuations. In a plasma, which is a collection of charged particles such as positive ions and electrons, collective phenomena are crucial to a complete description of the system. This article will treat both coherent waves and turbulence in the hot, dense plasmas that are relevant to the goal of thermonuclear fusion.

Study of the waves and turbulence in plasmas is of interest from two different points of view. First, many interesting linear and nonlinear wave phenomena are conveniently studied in plasmas. Second, from a technological point of view, magnetic confinement of a hot plasma is a promising approach to controlled thermonuclear fusion (*1–3*). To achieve thermonuclear fusion requires that the plasma temperature be greater than approximately 100 million degrees and that the product of plasma density and energy containment time be greater than 1×10^{14} cm^{-3} sec (*1–3*). Consequently, heating such a plasma with coherent waves and understanding the mechanisms by which energy can be transported out of the plasma by naturally occurring turbulence are both important to this goal (*1–3*).

The tokamak is a prototype fusion device in which a toroidal magnetic field configuration is used to contain a hot plasma. This is shown schematically in Fig. 1 (*1*). Plasma containment is provided by the magnetic field since, if collisions and turbulence are neglected, the charged particles make only small excursions transverse to the field lines. In a tokamak, the magnetic field lines are twisted by a current induced in the plasma. This twisting of the field lines prevents separation of the positive ions and the electrons and is essential to the plasma equilibrium.

Phenomena involving waves and turbulence are likely to be relevant to virtually all approaches to controlled thermonuclear fusion (*3*). However, we will limit our discussion of waves and turbulence to tokamaks, since they provide a relatively long-lived plasma (one with a lifetime greater than 1 second) in which to study wave phenomena. In addition, the data set and the level of understanding of waves and fluctuation phenomena are probably greater for tokamaks than for any other prototype fusion device. We will discuss only fluctuations in plasma density, although fluctuations in other quantities (such as magnetic field and temperature) are also important to a complete description of the plasma (*1, 2*).

Turbulence in Tokamak Plasmas

Containment of a hot, dense plasma leads immediately to a profound consequence: the resulting state of the plasma is not static but is intrinsically time-dependent (*4–13*). This is because one has necessarily introduced gradients in both temperature and density, and therefore there is a free energy of expansion available to drive fluctuations and instabilities. Indeed, in magnetically confined plasmas, the parameters of the plasma such as density, electrical potential, and magnetic field are not invariant in time but fluctuate on one or more time scales characteristic of the collective modes of oscillation of the plasma (*4–13*). The most violent of these fluctuations can result in abrupt termination of a discharge. Fortunately, research has uncovered relatively large operating regimes where such violent "disruptions" of the plasma can be avoided (*1–3*). There remains, however, a plasma turbulence that is reasonably insensitive to the specific operating conditions. This turbulence may have a considerable effect on transport in tokamak plasmas and will be discussed in some detail.

Tokamak plasmas exhibit anomalously high levels of particle and energy transport. In other words, the fluxes of energy and particles across the magnetic field are large compared to those expect-

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ed from "classical" coulomb collisions of the charged plasma particles (*1, 2*). This enhanced transport of energy out of the plasma is deleterious, since it reduces the energy containment time. Thus, understanding and controlling this transport are very important to the goal of achieving controlled nuclear fusion.

Crude estimates indicate that the turbulent density fluctuations observed in tokamak plasmas are sufficient to produce the observed transport (*1, 2*); however, the direct connection of this turbulence with the energy transport has not been established. Consequently, understanding the nature of the turbulence and its contribution to the transport is still a major goal in this field of research.

Nature of the turbulence. It is typical of tokamak plasmas that density fluctuations are present throughout the life of the plasma (*5–13*). The spatial scale (that is, the typical wavelength) of these fluctuations has been determined in numerous experiments with both microwave and laser scattering and metal probes that can be inserted near the plasma edge to measure density and electrical potential (*5–13*). In the scattering experiments, the wavelength of the fluctuations is measured directly by the angle of scattering relative to the direction of the incident electromagnetic radiation. Such a scattering process is called Bragg scattering, a term that originally referred to the scattering of x-rays from the electron distribution in a crystal. As in the crystalline case, scattering experiments in plasmas measure the spatial distribution of the electrons. From this kind of experiment in tokamak plasmas, the mean wavelength, $\bar{\lambda}_{\text{fluct}}$, of the density fluctuations in the direction perpendicular to the magnetic field is found to be of the order of 1 cm (*5–10, 13*). In terms of the parameters that characterize the plasma, it is found that

$$\bar{\lambda}_{\text{fluct}} \gtrsim 2\pi\rho_i \tag{1}$$

where ρ_i, the characteristic radius of gyration of the plasma ions in the magnetic field, is typically a few millimeters.

The wavelength $\bar{\lambda}_{\text{fluct}}$ is small compared to the minor diameter of the plasma, which is typically several tens of centimeters. Consequently, these fluctuations are frequently described as a microturbulence (*5*) to distinguish them from macroscopic magnetohydrodynamic (MHD) oscillations, which have wavelengths comparable to the plasma size (*14*).

The tokamak plasma is a very anisotropic system with a strong toroidal magnetic field and gradients in plasma density and temperature perpendicular to the magnetic field (Fig. 1). Laser and microwave scattering experiments have shown that the wavelengths associated with the fluctuations are very similar in both directions perpendicular to the magnetic field (*5–9*). With CO_2 laser scattering experiments, it has also been shown that the wavelengths of the fluctuations parallel to the toroidal magnetic field are long compared to the wavelengths of the fluctuations perpendicular to the field (*6, 9, 11*). Thus a qualitative picture is that of a relatively isotropic, two-dimensional turbulence in the plane perpendicular to the toroidal magnetic field, with the characteristic scale size of the turbulence being small compared to the minor diameter of the plasma (Fig. 1).

By use of scattering and probe techniques, the characteristic frequency of the fluctuations has been found to be in the range of a few kilohertz to a few hundred kilohertz. The mean frequency, $\bar{f}$, of the fluctuations is lower than the characteristic frequency of gyration of the plasma ions in the magnetic field, f_{ci}. The experiments are (very roughly) consistent with (*4–13*)

$$\bar{f} \sim (\rho_i/L_n)f_{ci} \tag{2}$$

where L_n is the length associated with the gradient in plasma density [$L_n = n/(dn/dr)$, where n is the plasma density and r is the minor radius of the plasma]. Since the frequency f_{ci} is typically tens of megahertz and ρ_i/L_n is of order 1/100, $\bar{f}$ is in the range of hundreds of kilohertz.

It is plausible that the natural spatial dimension of the turbulence in the direction perpendicular to the magnetic field is of the order of the ion gyroradius ρ_i (Eq. 1), since, at the characteristic frequencies of the turbulence, fluctuations with these wavelengths are typically the least stable (*2, 15, 16*). Also, the frequency described by Eq. 2 is qualitatively consistent with the spatial scale of the fluctuations and the fact that, in an inhomogeneous plasma such as that in a tokamak, there is an associated drift velocity, v_d, of waves traveling in the direction perpendicular to both the magnetic field and the density gradient. Thus, one can imagine a disturbance of wavelength $2\pi\rho_i$ propagating at a velocity v_d which results in a mean frequency $\bar{f}$ (in the laboratory frame) equal to $v_d/2\pi\rho_i$. This expression for the frequency turns out to be identical to the right-hand side of Eq. 2.

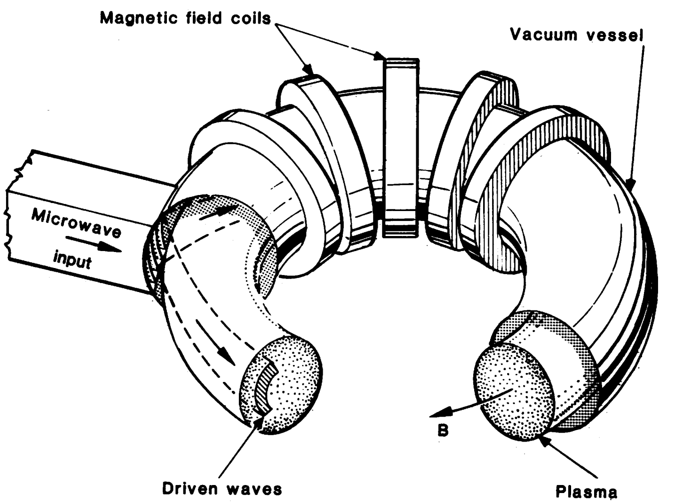


Fig. 1. A tokamak plasma. External coils generate the principal confining magnetic field *B*, and a current induced in the plasma produces a twist to the magnetic field lines (not shown). Turbulence in the plasma is illustrated by dots in the minor cross sections. Waves, used to heat the plasma and drive currrents, can be excited by antennas at the plasma edge.

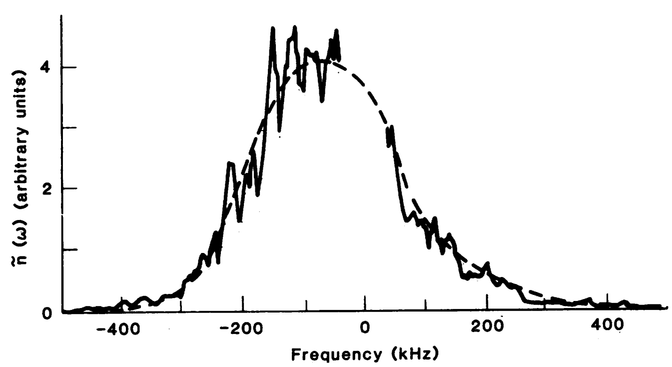


Fig. 2. Frequency spectrum of density fluctuations in a plasma in the Princeton Large Torus (PLT) tokamak, shown from a well-defined region and for a single wavelength of 0.9 cm [adapted from (*13*)]. The dashed curve is a guide to the eye and would be typical of an average over several plasmas. The spectrum is much broader than the range of frequencies of 100 to 130 kHz which would be expected for "linear" drift waves. This spectrum illustrates the turbulent nature of the density fluctuations in tokamaks.

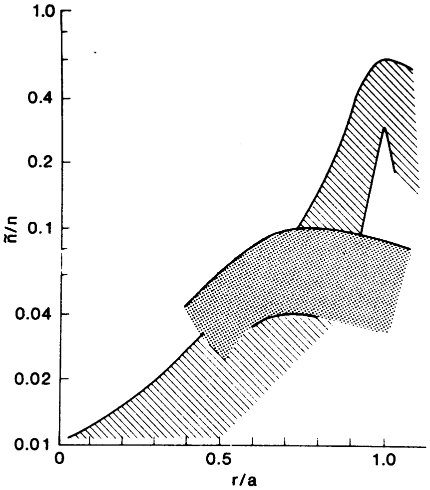


Fig. 3. Relative amplitude of density fluctuations $\tilde{n}/n$ as a function of the normalized minor radius r/a (a is the radius of the plasma limiter) for two plasmas in the Alcator A tokamak [adapted from (*12*)]. The hatched region corresponds to the limits allowed by the data for high-density plasmas ($\bar{n} = 3 \times 10^{14}$ cm^{-3}) and the dotted region to plasmas with densities a factor of 10 lower. Note the very high level of fluctuations near the plasma edge for the case of the higher plasma density.

A general and important feature of the fluctuations observed in a large number of experiments is that the frequency width, Δf, asociated with a single wavelength is very large ($\Delta f \approx f$) (*5–13*). This broad frequency spectrum was recently reexamined by Mazzucato (*13*). In order to eliminate the possibility that different frequencies were actually occurring at different spatial locations within the volume of plasma being observed, he used a microwave scattering apparatus specifically designed for good spatial resolution. Figure 2 shows his data for the frequency spectrum of the fluctuations at a well-defined wavelength and a well-localized position in the plasma (*13*). The observed wide range of frequencies at a given wave number supports the conclusion that the naturally occurring waves in tokamak plasmas are qualitatively described as a turbulence, in contrast to the case of a superposition of "linear" modes, each having a specific wavelength and having associated with it a well-defined frequency. As discussed below, such a conclusion has important consequences with regard to a physical picture of these fluctuations.

An important feature of the turbulence is the amplitude, $\tilde{n}$, of the density fluctuations relative to the local plasma density n. A number of experiments have established that the normalized fluctuation amplitude, $\tilde{n}/n$, can vary by more than an order of magnitude between different spatial locations in plasma. It has been shown by use of both CO_2 laser scattering and metal probe techniques that $\tilde{n}/n$ near the plasma edge can be very large and, in some cases, can vary significantly with mean plasma density (*10–12*). Figure 3 shows profiles of $\tilde{n}/n$ as a function of radius for two different plasma densities (*11, 12*). The fluctuation amplitude near the plasma edge at high plasma densities is the maximum possible value for random fluctuations, $\tilde{n}/n = 0.5$.

Figure 4 shows a photograph of the edge turbulence of a tokamak plasma. This picture was taken with an exposure time of approximately 1/3000 second, so that fluctuations with frequencies less than about 2 kHz are resolved (*17*). The filamentary structure that appears in this picture is predominantly the long-wavelength, low-frequency part of the density fluctuation spectrum, which is localized near the plasma edge. The long coherence length of the fluctuations along the magnetic field can be seen as the horizontal lines that curve toward the inner wall. The relatively short coherence length across the field is indicated by the alternating intensity of these lines.

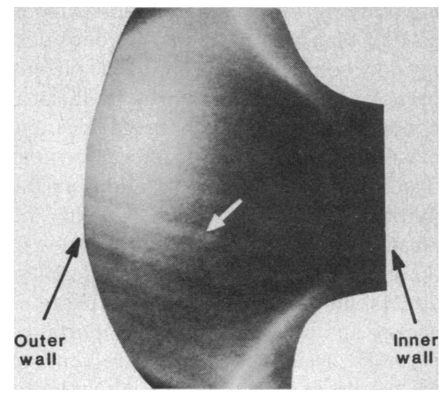


Fig. 4. Photograph of a plasma in the ASDEX tokamak at Garching, West Germany. The exposure time is 1/3000 second; thus fluctuations with frequencies less than 2 kHz are most prominent. The outline roughly corresponds to the profile of the minor cross section viewed in the direction tangential to the torus. The inner edge of the plasma is seen as the bright region curving along the inner wall. The filamentary structure in the photograph along the field lines (arrow) is due to the high level of turbulence near the plasma edge. [Photograph courtesy of D. H. J. Goodall (*17*)]

We have discussed in some detail the normalized amplitude of the turbulence $\tilde{n}/n$. In order to understand the nature of the turbulence, it is important to identify the dependence of $\tilde{n}/n$ on the other quantities that characterize the state of the plasma. Figure 5 shows $\tilde{n}/n$ as a function of $1/\bar{K}L_n$ for data from a number of different tokamak devices. Here, $\bar{K}$ is the mean wave number of the turbulence ($\bar{K} = 2\pi/\bar{\lambda}_\perp$, where $\bar{\lambda}_\perp$ is the mean wavelength of the turbulence in the direction perpendicular to the magnetic field) and L_n is the gradient length of the density defined in connection with Eq. 2. The existing data for $\tilde{n}/n$, both in the plasma interior and near the edge, can be crudely summarized by the expression

$$\tilde{n}/n \sim 1/\bar{K}L_n \quad (3)$$

Qualitatively, the normalized fluctuation amplitude, $\tilde{n}/n$, described by Eq. 3 might be thought of as a balance between the free energy of expansion of the fluctuations with mean spatial scale $(\bar{K})^{-1}$ and the free energy available from the gradient in plasma density with a spatial scale L_n. However, it has proved difficult to derive this result in any rigorous way (*15, 16, 18–21*).

Present state of the theory. If the fluctuations in tokamaks were a set of weakly interacting, linear modes, the present theories of waves in plasmas could describe the situation reasonably well (*15, 16*). However, this is not the case. Thus, the experimental data (for instance, Fig. 2) indicating a broadband turbulent state pose a significant challenge to the theory. Recently, much theoretical progress has been made. It is now generally accepted that, for fluctuations with wavelengths of the order of the ion gyroradius (Eq. 1), there are nonlinearities that will necessarily broaden the frequency spectrum of a set of linear modes (*18–20*). In addition, computer simulations (*21*) have shown that the fluctuations excited at wave numbers, K, of the order of ρ_i^{-1} can interact nonlinearly to produce fluctuations with much smaller wave numbers. What is now required is a theory with a self-consistent set of assumptions valid over the many different regions of temperature and density appropriate to tokamak plasmas (for instance, a hot plasma in the center or a cool plasma near the edge). A complete theory of the turbulence should even include the region where $\tilde{n}/n$ is as large as it can possibly be ($\tilde{n}/n = 0.5$).

In focusing attention on the problem of microturbulent fluctuations in tokamak plasmas, we are pushing on a forefront in classical physics—an accurate and nonlinear kinetic description of plasma turbulence.

Turbulent transport of particles and energy. The most significant practical goal of the research on turbulence in fusion plasmas is understanding the relation between the turbulence and the transport of particles and energy in the plasma (*1*). It has been established quite generally that the electron thermal conductivity is larger (by a factor of as much as 100) than that predicted by considering only coulomb collisions of the plasma particles. This factor of 100 in thermal conductivity degrades the achievable plasma containment for thermonuclear fusion in a serious way. In addition, the particle diffusion coefficient near the plasma edge is very large compared with the classical value (*1, 2*). Consequently, understanding the turbulent diffusion of energy and particles is quite important.

As discussed above, measurements of the spectrum and amplitude of the density fluctuations now exist. However, these measurements are not sufficient to determine the transport, since it involves not just fluctuations in one quantity such as density but a correlation between different quantities such as density and electric field or magnetic field and current. If a complete and unambiguous theory of the turbulence existed, it could be used to relate the present measurements to the transport. However, at present, no such theory is available.

One strategy for establishing the connection between the turbulence and plasma transport is to measure directly the combination of fluctuating quantities that give rise to the transport. For example, consider the particle diffusion caused by the presence of turbulent density fluctuations $\tilde{n}$. These fluctuations have associated with them electric field fluctuations, $\tilde{E}$. The combination of $\tilde{E}$ and the toroidal magnetic field acts to produce a fluctuating drift velocity, $\tilde{v}$, of the plasma across the field. The time-averaged value of $\tilde{n}\tilde{v}$ is the particle flux. Thus, the diffusion coefficient, $D_{\tilde{n}}$, of the particles across the magnetic field lines due to the density fluctuations is directly related to the correlation between $\tilde{n}$ and $\tilde{E}$.

The first experiment to measure the correlation between $\tilde{n}$ and $\tilde{E}$ in a tokamak was recently carried out in the edge plasma by Zweben *et al.* (*22*), using metal probe techniques. In this experiment, both the magnitude and the sign of $D_{\tilde{n}}$ were found to agree with the estimated particle flux, at least in the equatorial plane near the outside edge of the plasma. It is conceivable that a similar experiment could be accomplished to measure $D_{\tilde{n}}$ in the plasma interior by ion beam (*2*) technques (that is, measuring the modulation and deflection of an energetic ion beam by the turbulent fluctuations). While very difficult, such an experiment could provide valuable insight into the relation between the turbulence and plasma transport.

It has been shown that small local fluctuations in the direction of the magnetic field in a tokamak can produce significant energy transport (*23*). Consequently, measurement of these magnetic fluctuations (and the relevant correlation between electron current and magnetic field perturbations) in hot tokamak plasmas is of considerable interest. At present, there are not experimental techniques available with the required sensitivity to carry out such measurements in a hot tokamak plasma.

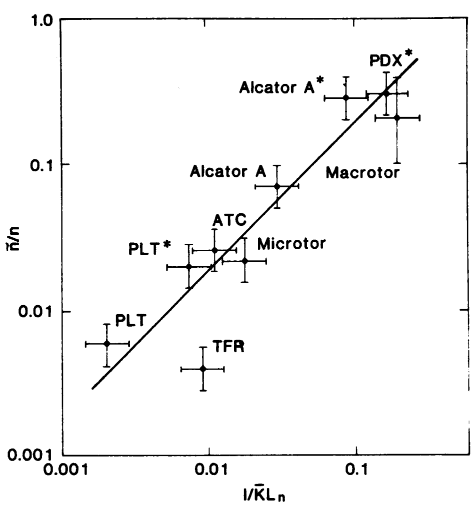
Coherent Waves in Tokamak Plasmas

We will now consider situations where relatively coherent waves are excited in the plasma by means of antenna or microwave structures located at the plasma edge (for instance, see Fig. 1). These coherent waves in the plasma can couple to the particles to produce plasma heating (*1, 2*). For example, waves whose phase velocity closely matches the velocity of the plasma particles can transfer wave energy to the particles by a process known as Landau damping (*2*).

The simplest way to heat the plasma is ohmic heating, where an induced electron current heats the plasma by coulomb collisions between the electrons and ions. However, as the plasma temperature increases, its resistivity decreases and this heating method is no longer efficient. Thus an alternative method is required to heat the plasma from the temperatures of about 20 million degrees obtained with ohmic heating to the temperatures of the order of 100 million degrees required for fusion. One of the major motivations for understanding coherent wave phenomena is to develop relatively simple and efficient ways (*24*) to heat the plasma. We will describe two examples of coherent wave experiments in tokamaks, chosen not for the absolute heating efficiency obtained, but for the insight they provide into the nature of these waves and their propagation and damping in tokamak plasmas.

Lower hybrid waves. The lower hybrid (LH) wave is a mode of the plasma that propagates with frequencies between the electron and the ion plasma frequency (that is, between the characteristic frequencies of oscillation of a collection of electrons and ions). This wave propagates at an angle to the toroidal magnetic field, with the wavelength perpendicular to the field becoming shorter as the wave penetrates to the higher density regions near the plasma center. The parallel and perpendicular wavelengths (and hence phase velocities) of the waves can be adjusted to heat the plasma ions and electrons near the center of the plasma.

In addition to plasma heating, LH waves can drive significant electrical currents in the plasma (*25*). As noted above, the current in a tokamak and the concomitant twisting of the magnetic field lines are essential to the equilibrium of the plasma. In the past, these currents



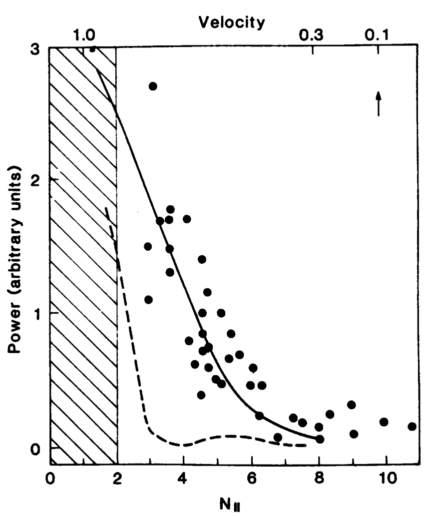


Fig. 5 (left). Amplitude, $\tilde{n}/n$, of the turbulent density fluctuations in various tokamaks as a function of $1/\bar{K}L_n$, the reciprocal of the product of the mean wave number, $\bar{K}$, and the scale length, L_n, of the density gradient (*5–13*). The dependence $\tilde{n}/n = 2/\bar{K}L_n$ is indicated by the solid line. Each data point is labeled by the acronym for the tokamak (*PDX*, Poloidal Diverter Experiment; *ATC*, Adiabatic Toroidal Compressor; *PLT*, Princeton Large Torus; *TFR*, Tokamak Fontenay-aux-Roses). Asterisks indicate measurements nearer the plasma edge. Fig. 6 (right). Relative power of lower hybrid waves in plasmas in the Alcator A tokamak as a function of the index of refraction, $N_{\|}$, of the waves parallel to the magnetic field [adapted from (*27*)]. The upper scale indicates the wave phase velocity in units of the speed of light. The arrow corresponds to a phase velocity three times the electron thermal velocity. The solid and dashed curves are the power distributions predicted from the simplest theory for the wave guides out of phase and in phase, respectively. (The solid curve is fit to the data at one point.) Contrary to these predictions, the data are independent of wave guide phase.

have been provided by inductive coupling to the plasma, which is necessarily pulsed in time. Use of radio-frequency waves to drive current in the plasma could help to eliminate the requirement that the plasma current be pulsed and allow the possibility of a more nearly steady-state reactor.

The LH waves are typically launched near the plasma edge by a phased array of microwave wave guides, as shown in Fig. 1. These phased wave guides fix the wavelength of the waves parallel to the magnetic field. The waves can be detected by scattering experiments. The first study to observe the LH waves in a hot tokamak plasma was conducted at the Plasma Fusion Center at Massachusetts Institute of Technology, using CO_2 laser scattering (*26, 27*). In this experiment, the spectrum of wavelengths of the LH waves was directly measured in the plasma. Figure 6 shows the power spectrum of the waves as a function of their "index of refraction" $N_{\parallel}$ (defined as the ratio of the wavelength of an electromagnetic wave at the excitation frequency to the wavelength of the LH wave along the magnetic field). It is this distribution in $N_{\parallel}$ that determines the coupling of the waves to the plasma ions and electrons. For example, electron heating results from those portions of the spectrum for which the parallel, LH phase velocity (Fig. 6, upper scale) is comparable to the velocity of the electrons. In the MIT experiment it was possible to study the dependence of the observed plasma heating (*28, 29*) on the wave amplitude and the $N_{\parallel}$ spectrum of the waves as well as the variation of these dependences with plasma parameters such as density.

A remarkable feature of the data in Fig. 6 is that, in contrast to the existing models of LH wave propagation when the experiment was conducted, the data are not dependent on wave guide phase. These models also predicted that the LH waves propagate in well-defined trajectories in a tokamak plasma. One such trajectory is shown schematically in Fig. 1. In the experiment, no such spatially localized trajectories were observed. Instead, the waves were observed over wide ranges of spatial locations and plasma parameters. A clue to this puzzle is the observation that the waves in the plasma had an appreciable frequency spread ($\Delta f \leqslant 6$ MHz) about the exciting frequency of 2450 MHz, indicating that the lower hybrid waves were interacting with a low-frequency disturbance (*26, 27*).

This behavior of the LH waves can be explained by considering the nonlinear interaction of the waves with the large-amplitude, turbulent density fluctuations present near the plasma edge which were discussed in the first part of this article. The turbulence interacts strongly with the LH waves, scattering the waves and simultaneously producing the observed frequency spread (*26, 27, 30, 31*). The lack of dependence of the power spectrum shown in Fig. 6 on wave guide phase can also be explained by considering the scattering of the LH waves from the turbulent density fluctuations. When this is taken into account, there is a mechanism by which the $N_{\parallel}$ spectrum at low $N_{\parallel}$ can be appreciably upshifted. Present theories that include these scattering effects can achieve semiquantitative agreement (*30, 31*) with the data shown in Fig. 6 (*32*).

More recent LH experiments indicate that there are, in fact, other circumstances in which changes in wave guide phase can affect the LH power spectrum in the plasma. These phenomena are now being studied (*33*).

Waves near the ion cyclotron frequency. In a magnetic field, the charged particles gyrate about the magnetic fluid lines with a characteristic frequency (the cyclotron frequency) independent of the velocity of the particles. For ions in a tokamak plasma, this frequency is typically several tens of megahertz. Waves in the plasma in this frequency range can be excited by loop antennas located near the plasma edge. These waves can be used to heat the plasma ions efficiently.

Recently, experiments using both laser and microwave scattering techniques have been conducted to study the nature of these ion cyclotron waves in tokamak plasmas (*34–36*). Loop antennas located near the plasma edge can generate a long-wavelength wave (with a wavelength comparable to the plasma size) that is sometimes referred to as a fast wave since its phase velocity is close to the speed of light. While this fast wave transports energy, it does not have associated with it a significant electron density perturbation, and consequently it is not directly observable with laser or microwave scattering techniques. However, by cleverly exploiting the nonlinear coupling of the electric field of the fast wave to the turbulence described above, a group at Fontenay-aux-Roses in France recently discovered a method for measuring the fast-wave amplitude with scattering techniques (*35*). Therefore one can study directly the conversion of electromagnetic energy to wave energy in the plasma.

In plasmas that contain a mixture of ion species (such as deuterium and tritium), the fast wave can convert in the hot plasma interior to one with a shorter wavelength, referred to as an ion Bernstein wave. This wave can also be used to heat the plasma particles efficiently. The ion Bernstein wave has an appreciable electron density associated with it, and it can be observed directly with scattering techniques (*34–36*). The process of conversion of the fast wave to the ion Bernstein wave has been studied by a group at the University of California at Los Angeles (*34*) and by the group in France (*35*). The UCLA group has directly verified the mode conversion process by measuring the characteristic dependence of the wavelength of the ion Bernstein wave on the exciting frequency of the fast wave (*34*). They have also been able to monitor the position in the plasma at which this mode conversion takes place and the dependence of this position on the ratio of the concentrations of the different ion species. Measurement of the wavelengths of ion Bernstein waves in the hot plasma can also provide a useful measure of the ion temperature (*34, 37*). Such a measurement is difficult to make by other methods.

These experiments have placed on a much firmer ground our understanding of the mechanism by which waves in the ion cyclotron range of frequencies interact with tokamak plasmas. As with the LH wave studies discussed above, they also provide new insights into the processes by which collective phenomena can be used to heat tokamak plasmas.

Conclusions and a Look to the Future

Experiments conducted in the past few years have provided a quantitative picture of the small-scale, turbulent density fluctuations present in tokamak plasmas. While there is qualitative agreement between the predictions of current theories and these experimental results, a detailed verification of any specific theoretical picture has yet to be achieved. Another challenge for both theory and experiment is to establish in a definitive way the possible connection between the observed small-scale turbulence and the rapid transport of energy out of tokamak plasmas.

Several other issues involving naturally occurring turbulence in tokamaks are also of interest. In many cases, the energy containment time in tokamaks is observed to decrease when the plasma temperature is increased by methods other than ohmic heating. The possible role of plasma turbulence in this process has been addressed only briefly by either theory or experiment. As tokamak research moves toward larger and hotter plasmas, it is also possible that instabilities at other frequencies will be important. For example, one of the by-products of the fusion of deuterium and tritium ions is energetic alpha particles. It is conceivable that these particles can provide a source of free energy to drive a higher frequency turbulence of Alfvén waves (*16*). Finally, the actual "contact" of the tokamak plasma with the outside world is through the relatively cool edge plasma. The high level of turbulence in this region probably determines the transport of the plasma particles and impurity ions into and out of the device. The scaling of this transport with both the plasma size and parameters such as plasma density and temperature is not understood at present and is an important topic for future research.

Coherent waves in several different frequency ranges have been used successfully to heat tokamak plasmas and to drive electrical currents. Much of the understanding of the phenomena involved in the generation and propagation of the waves as well as the mechanisms by which these coherent waves can heat plasmas has been derived from the recent experiments discussed in this article. It is likely that this kind of progress will continue in the next generation of these experiments, which are now being conducted (*38*). In addition, similar experiments are in progress to study the generation and mode conversion of Alfvén waves (excited at frequencies below the ion cyclotron frequency) (*39*). These waves can also be used to heat tokamak plasmas (*40, 41*).

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