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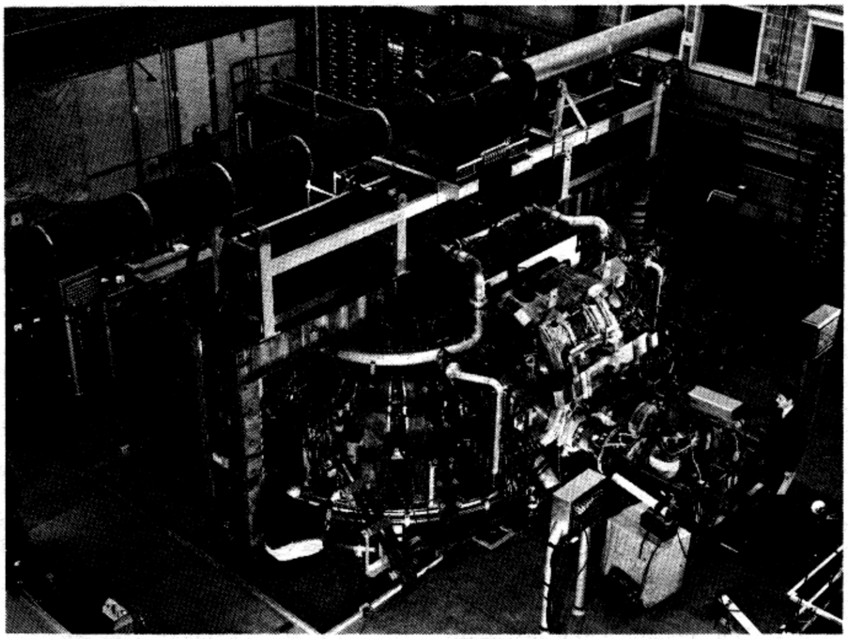
PHYSICS TODAY VOL 20 NO 10

Fusioneers Look for Leaks, Escapes and Irregularities

What is the connection between theoretically predicted instabilities and the anomalously fast escape of plasma across magnetic fields that has plagued thermonuclear fusion research? This was the central question in the International Symposium on Fluctuations and Diffusion in Plasmas held last June at Princeton University. Not surprisingly, of the 38 experimental papers that I report here, those which bore on this question came mostly from Q (for quiescent) machines (cesium or potassium plasmas produced by thermal ionization) and from multipoles (magnetic wells produced by conductors inside the plasma). In these types of devices the low-frequency oscillations, which can most efficiently transport ions across the magnetic field, can be turned on or off by slight changes in operating parameters.



MODEL C STELLARATOR in the Plasma Physics Laboratory at Princeton.

Mode identification. Near threshold, instabilities can be identified by the propagation velocity of the density or potential perturbations and by the conditions for the onset of the instability. Particularly interesting are universal instabilities, which are driven only by the plasma pressure gradient. Identification of a universal instability, or drift wave, has been made in several Q machines that are relatively free from energy sources that can drive other instabilities. Hans W. Hendel, Tsu-kai Chu and Peter A. Politzer (Princeton) reported on extensive measurements of coherent drift waves in a potassium plasma. As predicted, the waves propagated azimuthally in the direction of the electron diamagnetic drift, and the wave velocity and onset conditions agreed well with a theory that includes ion viscosity. Philip F. Little (Culham) found similar waves at very low densities ($n \approx 5 \times 10^8$ cm^{-3}); this may be the first identification of a collisionless, rather than resistive, universal instability. Francis F. Chen, Claude Etievant and David Mosher (Princeton) measured wave velocities in a turbulent potassium plasma by correlation techniques and identified drift instabilities with a continuous spectrum of frequencies. Charles W. Hartman (Livermore) found that he could reverse the direction of the wave by changing the temperature gradient. In all these experiments subtraction of the Doppler shift due to the weak radial electric field had to be performed carefully because the frequencies were so low (of the order of 1 kHz).

In multipoles, in which the magnetic field B varies greatly along the field lines, identification of oscillations is a little more difficult than in Q machines with a uniform field. Tihiro Ohkawa reported on new results from the General Atomic toroidal octopole when a toroidal field B_t is added to the octopole field, thus destroying the closure of lines of force and adding shear. The previously identified drift-cyclotron instability is suppressed by a small B_t of only 10 gauss or so, but then another instability appears. This mode, which disappears at low ion temperature, appears to be a universal instability modified by the ∇B drift. A third mode, found even at $B_t = 0$, appears at low ion temperature and low density and appears to be a flute perturbation propagating in the direction of the ion diamagnetic drift. Dale Meade and Shoichi Yoshikawa (Princeton) reported on oscillations in a linear quadrupole device called "LM-1." A high-frequency (about 200 kHz) oscillation localized to regions of unfavorable magnetic curvature was identified as the kinetic ballooning instability. This disappeared with the addition of a small amount of axial magnetic field (corresponding to B_t in toroidal devices), but a so far unidentified low-frequency flute-like mode remained. All of the remarks above apply to the region inside ψ_{crit}, the flux surface that, in multipoles, separates the region of minimum average B from the region of unfavorable average curvature. Outside ψ_{crit}, one expects ordinary flute interchange instabilities; indeed, they have been found in LM-1. In the next section I will discuss extensive measurements, made with the Wisconsin octopole, on this mode and on an unidentified mode inside ψ_{crit}.

In magnetic mirror devices slowly growing drift instabilities are masked by stronger velocity-space instabilities driven by anisotropy in particle distribution functions. Fred Coensgen (Livermore) showed measurements of the rf signal from the 2X device, a large mirror machine with Ioffe bars that provide a minimum-*B* field. In good agreement with theory, the frequencies were slightly higher than the ion cyclotron frequency and at harmonics thereof.

Fluctuations and anomalous losses. Table 1 summarizes experimental results pertaining to this question. The last column, labeled $\langle n_{\text{ac}}E_{\text{ac}}\rangle$, requires some explanation. The simultaneous appearance of oscillations and of enhanced losses does not, of course, prove that the former cause the latter. A definitive relation can, however, be established by measuring the time-averaged particle flux $j_r = \langle (n_0 + n_{ac})(v_0 + v_{\text{ac}})_r \rangle$. Assuming that v_r is given by $E\theta/B$, we have $j_r = [n_0E\theta + \langle n_{\text{ac}}E\theta_{\text{ac}}\rangle]/B$, in which the first term is the loss due to radial dc drifts and the second term is the correlated loss due to the fluctuations. Four methods for measuring $\langle n_{\text{ac}}E_{\text{ac}}\rangle$ have been used. In the work of Hendel and colleagues (Princeton), the oscillations were pure sine waves, and one had to measure only the phase shift between the density and plasma potential signals. In other experiments, either an electronic correlator was used or the signals were digitized and the correlation function computed numerically. Preliminary results on a novel method by Michael Rusbridge (Culham), involving the asymmetry of signals from a double probe, were reported by Edward Meservey (Princeton).

The clearest demonstration of drift-wave-induced transport was provided by Chu, Hendel and Politzer. By a slight change in *B*, a coherent oscillation could be turned on and off, and the concomitant jump in density and value of $\langle n_{\text{ac}}E_{\text{ac}}\rangle$ could be measured accurately. A similar result was obtained by Chen, Etievant and Mosher, working at low densities, where the fluctuations were more random. In this case, the oscillations were turned off by applying a small shear field; the $\langle n_{\text{ac}}E_{\text{ac}}\rangle$ correlation, however, was very small. With large shear fields, they found an improvement in confinement that was not related to the suppression of oscillations. Thus diffusion by oscillations does not appear to be the whole story. The same conclusion was reached by Robert Motley and Schweikhard von Goeler (Princeton) who measured diffusion by the spreading of a thin cesium beam.

Joseph Schmidt (Wisconsin), who used a computer to calculate the correlation functions, gave the most detailed measurements of $\langle n_{\text{ac}}E_{\text{ac}}\rangle$. The computed diffusion coefficient was of the order of the Bohm coefficient D_B outside ψ_{crit} and was 100 times smaller inside ψ_{crit}, as would be expected in this case.

Fred L. Ribe and Max Daehler (Los Alamos) described the most elegant method for measuring fluctuations. The plasma was so dense and hot that the usual Langmuir probes could not be used (they would burn

Fluctuations and Anomalous Losses

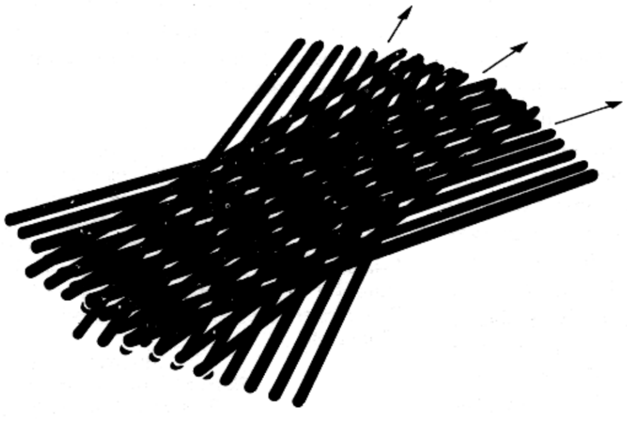
Author(s)	*Device*	*Regime*	*Fluctuations*	*Anomalous loss*	$\langle N_{\text{ac}}E_{\text{ac}}\rangle$
Double-ended Q machines					
Chu, Hendel, Politzer	Q-1	High density	Coherent	Yes	Large ($D \approx 0.1D_B$)
Chen, Etievant, Mosher	L-2Q Q machine with hard core	Low shear	Hashy	Yes ($D \gtrsim D_B$)	≈ 0
		High shear	None	Yes ($D \lesssim D_B$)	≈ 0
Motley von Goeler	Q-3 Narrow column	Low density	None	Yes	—
		High density	None	No	—
Single-ended Q machines					
Decker	Q machine with minimum-B	Uniform B	Yes	Yes ($D > D_B$)	—
		Minimum-B	No	Yes	—
Eastlund	Cs plasma with pulsed K tracer	Grounded collector	Yes	Yes	—
		Positive collector	No	No	—
Multipoles					
Ohkawa	Toroidal octopole	$B_t = 0$	Yes	No	—
		$B_t \neq 0$	Yes	No	—
Schmidt	Toroidal octopole	Outside ψ_{crit}	Yes	Yes	Large ($D = D_B$)
		Inside ψ_{crit}	Yes	No	Small ($D = 0.01D_B$)
Meade, Yoshikawa	LM-1 Linear quadrupole	Outside ψ_{crit}	Yes	Yes	Yes
		Inside ψ_{crit}	Yes	Yes	No
Stellarators					
Young, Ornstein	Model C	High current	Yes	Yes	Yes
		Low current	Yes	Yes	No
Ellis, Bol	Etude	μ wave heating	Yes	Yes	No
Haberstich, Hsi, Meservey	Model C	High current	Yes	Yes	Yes
Mirror Machines					
Coensgen	2X		Yes	Yes	—
Ribe, Daehler	Θ-pinch		Small $\approx .05\%$	No	—
Ronald Blanken, W. Ard	ECR, cyclotron resonance heating		Yes	Yes	—

up); instead, they used the scattering of a focused laser beam. The method separated a low level of nonthermal fluctuations from the thermal noise. Unfortunately they measured at the center of the plasma, where the density gradient was zero and where one would not have expected any interesting oscillation to occur.

Convective cells? Although it is too early to draw any conclusions, several experiments listed in table 1 suggest that a large part of what was thought to be "Bohm diffusion" is actually caused by quasi-dc electric fields in the plasma. Even a small electric field, if it has a theta component, can cause rapid convection of plasma toward the walls. In the linear quadrupole of Meade and Yoshikawa, the plasma escaped radially at a rate quite independent of the amplitude of oscillations. In the Q-machine experiments by Chen and colleagues, John A. Decker (Sperry-Rand), and Motley and von Goeler, anomalous losses were found in the absence of low-frequency oscillations. In Q machines small temperature nonuniformities of the hot end plates could give rise to dc electric fields in the plasma. In Decker's experiment the entire anomalous loss rate was attributed to this effect, but the temperature gradient in the experiments by Chen and coworkers appeared to be too small to account for all the losses. Direct measurement of the dc electric field by Chen and colleagues showed a very large azimuthal component at the edge of the plasma column. Although the existence of quasi-dc drifts may somehow be peculiar to the linear devices discussed here, it is clear that this phenomenon deserves more attention in the future, even in toroidal devices.

Shear stabilization. Perhaps the most exciting news from the symposium was that the effectiveness of magnetic shear has finally been demonstrated on the Princeton stellarators. Robert A. Ellis and Harold P. Eubank (Princeton) reported a factor of 10 improvement in confinement time in the Etude and B-3 stellarators with a simultaneous increase in shear and rotational transform. They obtained this result by plasma-gun injection, and it is not yet clear whether the difference from previous experiments is primarily due to an increase in ion temperature, ion mass or plasma conductivity. From the Model C stellarator, Don Grove, Meservey and Kenneth Young (Princeton) reported a fivefold increase in confinement time with application of shear. They achieved the increase by doubling the number of helical windings over what was previously available and by working with heavy ions (Xenon) so that viscous damping would suppress the resistive-g instabilities. It is too early to tell, however, whether this improvement is connected with the suppression of oscillations. In an off-center levitron with very large shear, Oscar Anderson, Dale H. Birdsall and Charles W. Hartman (Livermore) obtained indications of confinement 100 times better than what Bohm diffusion would give.

Arc plasmas. The first observations of anomalous transport were made in partially ionized arc and glow discharges, and the number of papers on small devices proved that interest in this field is still strong. Klaus Geissler (ESSA, Boulder) studied the Simon short-circuit effect in a very weakly ionized plasma and found that diffusion was nearly classical when the end walls were allowed to float but that diffusion perpendicular to the magnetic field increased to 3.8 times the Bohm rate when the end walls were grounded. Geissler attributed the difference to a change in fast electron population. Working with a hollow-cathode arc, David J. Rose and Kunmo Chung (MIT) may have been the first to identify a universal instability in something other than a Q machine. In a similar discharge Frans Boeschoten (Aerojet General) measured plasma rotation and found a discrepancy between calculated and measured rotation velocities. Using the duoplasmatron-produced plasma that he perfected through the years, Fred Schwirzke (General Atomic) showed that the enhanced diffusion was connected with oscillations excited by the radial electric field which, in turn, was caused by the radial temperature gradient. By heating the end wall to emission, he could replace the hot electrons with cold ones, thus reducing the temperature gradient. The diffusion coefficient was reduced to $0.1D_B$. Georges Briffod (Saclay) also reported the existence of a relatively quiescent plasma with $D \approx 0.1D_B$, produced by differentially pumping the plasma streaming out of a plasma source. Correlation measurements on the oscillations are now in progress. Edward J. Powers (Texas) described the onset of instability in an rf discharge as the magnetic field is increased. The conditions for onset agree with a criterion given by A. V. Timofeev for the universal instability in weakly ionized gases. Manfred Raether and Heinz Böhmer (Illinois) showed detailed measurements of enhanced diffusion caused by an intense electron beam shot into a plasma. The losses did not appear to be correlated with the high-frequency noise generated; however, no low-frequency measurements were made. Harry Robertson (Miami)



SHEAR FIELDS. Reprinted by permission from A. S. Bishop, *Project Sherwood—The U.S. Program in Controlled Fusion*, 1958, Addison-Wesley, Reading, Mass. (Courtesy of the US AEC.)

showed theoretically that stochastic motion of filamentary structures in arcs can give rise to observed anomalous loss rates. T. Tsukishima (Nagoya), C. Keith McLane, and G. S. Mills (ESSA, Boulder) described an advanced measurement of classical diffusion in a quiescent brush-cathode discharge in zero magnetic field. The method involves taking the cross correlation of thermal density fluctuations at two points in the plasma.

Nonlinear effects. In contrast to the theoretical program, where most new results concerned nonlinear rather than linear effects, there were few experimental results on nonlinear phenomena. A notable exception is the Q-machine experiment of Alfred Y. Wong, F. Hai and Richard Rowberg (UCLA), in which a drift wave of frequency ω was excited parametrically by an applied signal at 2ω. Also, a signal applied at 4ω would generate subharmonics at 3ω and ω, or at 2ω. The increase in damping rate with amplitude was also measured. A detailed experimental and theoretical study by Larry M. Lidsky (MIT) of the interaction of particles with whistler waves also falls in this category. He discovered that perturbation theory was inadequate and had to use exact orbit theory.

Space and solid-state plasmas. Two short sessions were devoted to fluctuation measurements in space plasmas and plasmas in solids. Francis Perkins (Princeton) gave a particularly impressive review of radar-scattering experiments off the ionosphere. Despite the great distances separating the apparatus from the plasma, correlation techniques yielded reasonable data on velocity distributions, ion wave fluctuations and diffusion in the ionosphere. William M. Hooke (Princeton) reviewed experiments by Mark Gurnee (Princeton) on diffusion and recombination of photo-produced plasma in indium antimonide, and by George Goldsmith (Princeton) on local plasma density measurements in germanium by means of infrared absorption. Betsy Ancker-Johnson (Boeing) described a systematic study of plasma decay in indium antimonide that was measured by the two-pulse technique. A small magnetic field slows down the decay rate, but too large a field is detrimental.

Summary. What conclusion can be drawn from the seemingly contradictory results reported on the connection between oscillations and anomalous losses? It appears to me that almost all the results can be reconciled by the following heuristic generalizations.

- When a large source of free energy is available to drive instabilities, oscillations are responsible for almost all of the anomalous losses. This is the case in mirror machines and in stellarators with large ohmic-heating currents.
- When the only source of free energy is in the plasma pressure gradient and the average magnetic curvature is not unfavorable, only universal-type instabilities can occur; these can lead to a diffusion coefficient no larger than 0.1 D_B. This is the case in toroidal multipoles and in certain arc experiments. If $D > 0.1D_B$ is measured, the main losses are not connected with oscillations but are probably due to dc drifts. This is the case in linear devices, particularly with Q machines.
- When no large source of free energy exists but the average magnetic curvature is unfavorable, the stability criterion against gravitational-type instabilities determines whether the first or second generalization applies. Thus the first point applies to stellarators with weak shear and light atoms and to the region outside ψ_{crit} in multipoles, while the second point applies to stellarators with heavy atoms and to devices with large shear, such as levitrons.

Theoreticians from the USSR were sorely missed; for experiments are reaching a stage where the extensive Russian work on nonlinear estimates of diffusion from specific instabilities could be checked.

This symposium was organized by a committee headed by Thomas H. Stix and was sponsored by the Princeton Plasma Physics Laboratory, headed by Melvin B. Gottlieb. The author has benefited from review papers given by Harold P. Furth (Princeton), Richard F. Post (Livermore) and Shoichi Yoshikawa (Princeton).

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