Report from Culham...

1. EXPERIMENTAL PLASMAS

By Lyman Spitzer, Jr.

Seven years after the declassification of the plasma-physics program it is clear that the physics of hot plasmas has become a mature scientific discipline. Plasma theory, which is both extensive and elegant, is in much closer touch with observational research than was possible in the early years of this subject.

Physicists had a chance to hear what is known about some aspects of plasmas in September, when 200 of them from 25 countries gathered at Culham, England, where a Conference on Plasma Physics and Controlled Nuclear Fusion Research was organized by the International Atomic Energy Agency. To summarize adequately the 70 experimental papers presented there would be nearly impossible for one individual. The present review is intended to offer only a rather cursory survey of those particular results which have special interest for me.

Minimum B and stability

The major milestone of this conference, in my opinion, was the experimental work on hydromagnetic stabilization of open-ended systems. The success of minimum-B configurations in stabilizing a plasma marks one more area where theory and experiment in plasma physics have been brought together with gratifying results. It will be instructive, perhaps, to review the gradual confirmation of hydromagnetic stability theory in plasma physics. The self-pinched discharge provided the first observational check of this theory. The kink and sausage instabilities produce such a characteristic and unmistakable distortion of the plasma column that they were easily identified in the early photographs of linear and toroidal pinches some fifteen years ago. In the kink instability a bend in the plasma column grows because the surrounding magnetic field is stronger inside the bend than on the outside; thus the kink gets worse instead of repairing itself. In the sausage instability a constriction in the plasma column becomes accentuated because the surrounding field at a constriction is stronger than elsewhere along the column. Thus the column is pinched tighter at the constriction than elsewhere.

A few years later the predictions of hydromagnetic stability theory as applied to ohmic heating discharges in strong magnetic fields were also verified in both the Soviet Union and in the United States. Results of the instability were somewhat less dramatic in this second case, and the Kruskal-Shafranov limit on current provided the primary contact between theory and observation. Observations clearly indicated that ohmic heating discharges ran into difficulty at currents above this theoretical value although it was not clear how the increasing plasma resistivity and the fluctuating voltages observed above this limit were related to the occurrence of the instability. It need not surprise us if a linearized theory, based on *infinitesimal displacements*, gives relatively meager information on how a system actually behaves when large displacements develop because of some instability.

If the confining magnetic field decreases outwards, an instability of interchange or flute type should be present as pointed out by theorists some

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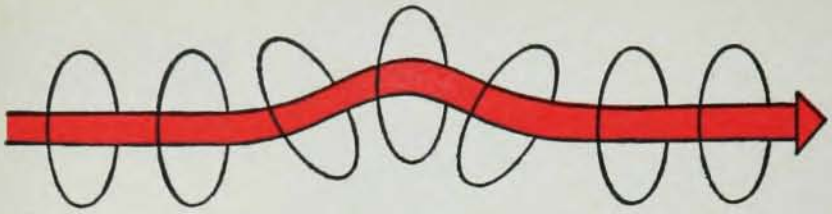
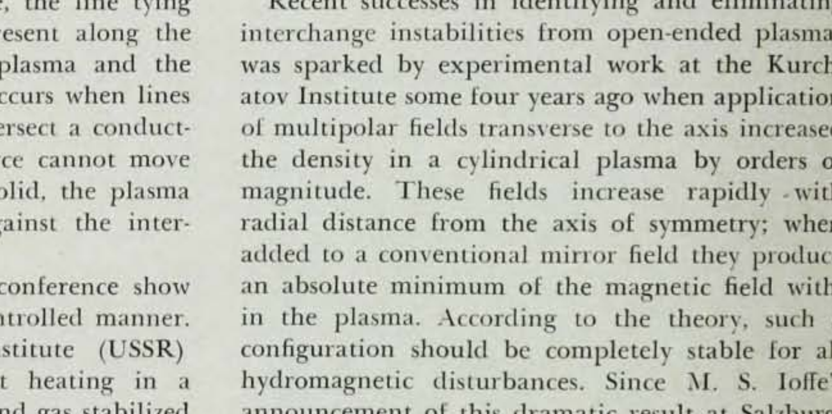


ten years ago. When this instability occurs, a filament of plasma at the edge of the column, where the plasma density is low, exchanges places with a filament deeper in the plasma, where the density is high. Lines of magnetic force are not bent in this instability but are simply interchanged with a resultant net motion of plasma toward the wall.

Ten years ago it was not clear whether any of the difficulties observed in various plasmas could be ascribed to this cause. Quite apart from the many technical difficulties experienced, stability in magnetic-mirror devices was apparently achieved at that time by another influence, the line tying achieved when cold plasma is present along the lines of force between the hot plasma and the wall. Line tying is an effect that occurs when lines of magnetic force in a plasma intersect a conducting wall. Because the lines of force cannot move rapidly through the conducting solid, the plasma can be stabilized in this way against the interchange instability.

Two papers presented at this conference show this line-tying effect in a more controlled manner. A paper from the Kurchatov Institute (USSR) dealing primarily with turbulent heating in a mirror device shows that background gas stabilized the plasma in a simple mirror, with energetic electrons confined for 160 msec, and reduction of the background pressure decreased this confinement time to about 0.4 msec. Similarly, in a mirror-confined plasma at General Atomic (USA) the hydromagnetic flute instability was much reduced by either the use of conducting end plates or injection of substantial amounts of relatively cold plasma; if sufficient plasma is present, apparently even a dielectric plate will carry current in a surface layer and provide this line tying. As a result of these effects the interchange instability in early mirror devices was sometimes suppressed. During the last two years a substantial improvement of the background pressure required to reduce charge-exchange losses brought the interchange instability out of hiding.

Recent successes in identifying and eliminating interchange instabilities from open-ended plasmas was sparked by experimental work at the Kurchatov Institute some four years ago when application of multipolar fields transverse to the axis increased the density in a cylindrical plasma by orders of magnitude. These fields increase rapidly with radial distance from the axis of symmetry; when added to a conventional mirror field they produce an absolute minimum of the magnetic field within the plasma. According to the theory, such a configuration should be completely stable for all hydromagnetic disturbances. Since M. S. Ioffe's announcement of this dramatic result at Salzburg, a number of groups have carried out investigations in this field, and at Culham six papers dealt at least in large part with this important topic; several others provided additional related information. All six papers deal with magnetic-mirror con-



finement of a relatively hot plasma with a radius substantially larger than the radius of gyration. In all cases either the density of the trapped particles or their mean confinement time increases significantly when the multipolar fields are turned on, the average increase amounting to a factor of about five.

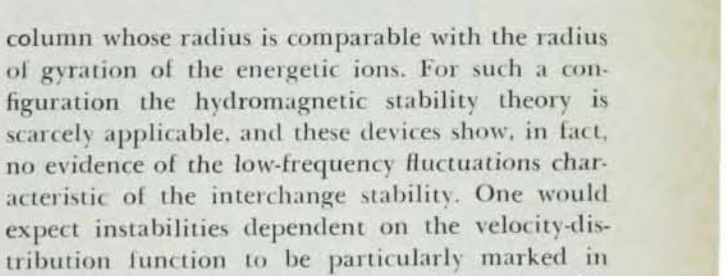
These experimental devices are quite different from one another, with the plasma produced in different ways. One device at the Kurchatov Institute is heated with an rf magnetron, devices at Culham (England) and Fontenay (France) use plasma injected from a gun, and three devices—Alice at Livermore (USA), Ogra at the Kurchatov Institute, and Phoenix at Culham—rely on injection of energetic neutral atoms. The qualitative agreement among these six different devices gives important assurance that the general result is correct.

More detailed diagnostic studies tend to confirm this general picture, though some discrepancies remain. Particularly in Alice and Phoenix detailed probe measures in the simple mirror configuration show the low-frequency oscillations characteristic of the rotating flutes that appear to be associated with the interchange instability. When a field minimum is produced within the plasma these oscillations disappear. On the other hand, in Ogra these oscillations do not disappear when the hexapole coils are energized although they do become more irregular. An unexpected benefit from minimum-B fields is that they appear to diminish sharply the plasma activity associated with emission of radiation at about the ion cyclotron frequency. This result, which is shown by Ogra as well as Alice and Phoenix, is not understood theoretically. The possibility cannot be entirely excluded that much of the plasma loss is produced by this activity rather than by the interchange instability and that the unexpected stabilization of this high-frequency activity accounts for the improved confinement with minimum-B systems. As is often true in an active scientific area, more work is needed before a really conclusive picture is available.

When hydromagnetic instability is eliminated, as we may assume it has been in these devices, the plasma confinement will necessarily be determined by some other physical factor. In three of the six devices referred to, charge exchange or even collisional diffusion into the loss cone are believed to become limiting. (If the particle velocity makes too small an angle with the magnetic field —that is, if the velocity is in the loss cone—the particle will escape through the mirror.) In the other three devices there are definite indications that some type of microinstability associated with non-Maxwellian velocity distribution is responsible for plasma losses. Bursts of radiation at the ion cyclotron frequency are sometimes observed, together with an escape of some plasma. A somewhat similar instability in a hot electron plasma in a mirror device has been studied at Livermore. Theoretical study of a two-stream instability associated with the loss cone predicts that several versions of this loss-cone instability should be very serious problems in mirror devices, which are particularly vulnerable to any factor that increases end loss. The theory is undoubtedly approximate, however, and such instabilities may not yet have been observed. Perhaps within the next few years these nonhydromagnetic sources of plasma loss can also be understood and brought under control. Identification and control of one major source of instability every three years or so would be a not unreasonable rate of progress in this difficult field.

Other injection studies with open-ended systems

For filling a magnetic mirror with plasma, injection of molecular ions is used in three devices, one at Fontenay and two at Oak Ridge (USA). Breakup of molecular ions tends to form a plasma



column whose radius is comparable with the radius of gyration of the energetic ions. For such a configuration the hydromagnetic stability theory is scarcely applicable, and these devices show, in fact, no evidence of the low-frequency fluctuations characteristic of the interchange stability. One would expect instabilities dependent on the velocity-distribution function to be particularly marked in such devices, and there is some evidence that this is true. In DCX-1 at Oak Ridge the instabilities associated with plasma emission at the cyclotron frequency and its harmonics alter proton orbits markedly and produce a loss of ions ten times as great as the charge-exchange rate. In the Fontenay device, on the other hand, there is no evidence of any rf emission from the trapped ions or plasma, and the loss of the energetic ions appears to occur primarily by charge exchange. There are many differences between these two devices, and further work is required to indicate which of them is responsible for the difference in results. Possibly the stability of the Fontenay device is one more indication of the stabilizing effect of cold plasma since the background pressure is considerably greater than in DCX-1. In DCX-2 the situation is not yet fully analyzed. Plasma activity is undoubtedly present, increasing the mean energy to many times the injected energy, but its effect on the ion loss rate is not clear. More precise measures are needed to yield an understanding of the complex processes occurring in this device.

In Astron at Livermore confinement is achieved by a trapped layer of relativistic electrons injected into a magnetic mirror. This large device has gone into operation during the last year, and the number of trapped electrons in the layer has been increased to about one percent of its desired value. At this level of operation no outstanding problems with plasma instabilities have been encountered, a result that appears most encouraging.

In addition to the work with these major mirror machines, extensive progress was reported at Culham on injecton into a variety of open-ended devices. Several papers have dealt with injection into a cusp, a magnetic field of the type produced by two Helmholtz coils with currents flowing in opposite directions. At Culham and Osaka (Japan) plasma guns have been used, while at Jutphaas (Netherlands) energetic ions have been injected. A cusp configuration is a minimum-B device and should confine a plasma with the same hydromagnetic stability as a magnetic mirror with quadrupoles. Moreover a large cusp can be operated at $\beta = 1$ (plasma pressure equal to applied magnetic pressure), and its end losses, according to a simplified theory, should be substantially less than from a large mirror device. A cusp configuration is undoubtedly a more complicated experimental tool than a mirror, but research is clearly desirable to indicate whether or not the predicted low loss rate can be achieved. Getting the plasma into the cusp at all is a nontrivial problem, and these experiments seem to indicate that in fact a cusp can be filled with energetic plasma. Analysis of the loss processes is only beginning.

Linear pinches

Early papers on controlled fusion placed very great emphasis on linear pinched discharges. This interest still continues, with fourteen papers on the subject at the Culham conference. Although it is unlikely that a linear pinch can be used for producing useful thermonuclear power, research with these devices is certainly an important phase of plasma-physics research and may help to elucidate plasma behavior in general.

The evolution of research with the theta pinch (plasma compressed by a rapidly rising solenoidal magnetic field) is an important indication of how a large part of the controlled-fusion program is developing. Initial work in this field naturally placed primary emphasis on the temperatures reached and production of neutrons. Now the theta pinch is used as a research tool for a wide variety of investigations including such topics as Rayleigh-Taylor instability (Jülich, West Germany) and the sharpness of shock fronts (Frascati, Italy). On the central problem of plasma confinement one of the most important steps has been improving the magnetic field to eliminate inhomogeneities and transverse fields that were responsible for slow plasma drifts. With increasing plasma length the flute instability observed in a shorter, more sharply curved system was observed to disappear (Los Alamos, USA). Confinement times of about 10 microseconds have been observed for these kilovolt plasmas (US Naval Research Laboratory) when reverse fields are trapped in the plasma to reduce end losses. As longer confinement times are achieved, these compressed plasmas may yield further information on plasma confinement.

Toroidal plasmas and minimum Average B

Toroidal plasmas are considerably more complicated experimentally than open-ended configurations, and for this reason have not been investigated so intensively. However, as charge-exchange losses and hydromagnetic-interchange losses are decreased in magnetic mirrors, end losses become limiting, and the intrinsic advantage of toroidal systems in this respect is increasing the interest in these devices.

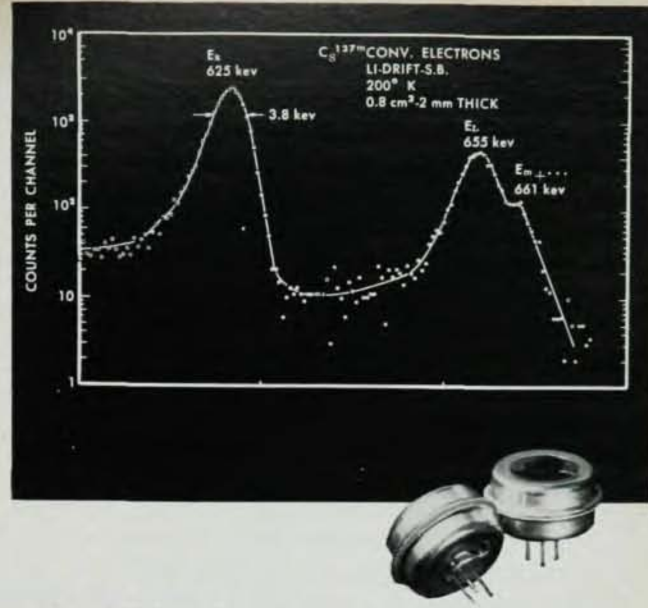
The chief problem of toroidal devices is anomalous loss of particles across the magnetic field, sometimes called "pumpout." The evidence presented at Culham on the subject of these losses does not add up to a consistent picture. On the one hand, most of the groups working with toroidal plasmas have found that anomalous particle loss is a rather general characteristic. Measurements of plasma density as a function of time are sometimes not a very reliable indication of plasma loss because the escaping plasma can become neutralized at the wall and return to the plasma, becoming ionized again. The Tokamak (Kurchatov Institute) group has corrected for this recycling by measurements of the neutral gas, with both a fast ion gauge and measurements on the flux of the charge-exchange neutrals resulting when this cold gas enters the hot plasma. In the C stellarator (Princeton, USA) this recycling has been measured at high temperatures in helium with spectroscopic observations of light intensity from the cold gas streaming back into the discharge; measurements have also been made at temperatures of about 1 eV, at which no new ionization can be produced. These studies all indicate that the diffusion rate agrees in general order of magnitude with the simple diffusion formula given many years ago by Bohm. In the largest Tokamak device the losses reported are less than this theoretical value by about an order of magnitude; in the C stellarator, loss rate about equals the Bohn value, and in smaller stellarators it was about three times the Bohm value.

More important, perhaps, than the precise value of this loss rate is that its presence seems independent of any particular heating mechanism. The C stellarator measurements with ion cyclotron heating, with electron cyclotron heating, or even with no heating at all, agree with the Bohm diffusion rate obtained with ohmic heating over wide ranges in magnetic field, electron temperature, and plasma density. In the Levitron (Livermore), where electron cyclotron heating has also been employed, the plasma activity seems to be about the same as with ohmic heating. Thus early hopes that a toroidal plasma would become quiescent in the absence of any electric current along the magnetic field have been dispelled.

A discrepant and more hopeful set of results has been obtained at Munich-Garching (West Germany) where the measured density of a toroidal cesium plasma, together with the known input rate of cesium, appears to require an equilibrium loss rate about equal to the collisional diffusion value—and about a tenth the anomalous value predicted from the Bohm formula. Obviously it is of great interest to explore in detail the conditions under which a toroidal plasma is confined with no anomalous particle losses.

The theoretical explanation of pumpout is still a mystery. One possibility is that hydromagnetic instabilities are involved; since the losses are apparently not much affected by shear, an instability of resistive type must be assumed. Some entirely different process may well be responsible, however. If the theorists uncover new instabilities during the next three years at the same rate as during the past three years, we shall have an even wider variety of possible mechanisms to choose from at the next conference.

Partly because of the successful stabilization of interchange instabilities in mirror systems by min-



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imum-B fields, much interest has developed in a related technique for toroidal systems. A true minimum in magnetic field is apparently not possible in toroidal geometry, but one can devise a configuration that is stable on the average, which we may call a minimum <B> system. If hydromagnetic resistive instabilities are responsible for pumpout, a minimum <B> system should provide at least partial stabilization. The extensive theoretical work in this field will not be summarized here, but mention is made of the preliminary work on an octupole system (General Atomic). In this toroidal device four circular rods within the plasma chamber, all carrying current in the same direction and all concentric with the toroidal axis of symmetry, produce an octupole field that surrounds the rods and provides a minimum <B> configuration. Plasma is injected into this system from a gun and confinement of energetic ions analyzed. Most of the experiments carried out to date are affected by a large influx of neutral gas, but tentative measurements at low density suggest that confinement time of the energetic ions is down at the limiting value set by the support rods that cross the plasma. Quiescent, stable confinement of plasma at appreciable densities in a device of this type would undoubtedly be a major milestone of the controlled-fusion program.

Plasma-heating techniques

Important progress was reported at Culham on various methods for heating plasma. The Kharkov (USSR) group has reported that ion cyclotron heating increases the positive ion temperature to about 2000 eV within 10 microseconds, and no further increase follows. Similar positive-ion temperatures in short mirror sections of the C stellarator have been reported by the Princeton scientists, who suggest a theoretical explanation for the leveling off of the ion temperature. Direct heating of plasma electrons was also observed by the Princeton group; this effect, which had not been anticipated, can apparently be attributed to the inverse of Landau damping.

A new field of plasma research has developed in beam-plasma interactions and turbulent heating in general. In this interesting technique, developed at the Kurchatov Institute, the Massachusetts Institute of Technology (USA), Oak Ridge (USA), and Sukhumi (USSR), passage of an intense electric current or an initially monoenergetic electron beam through a gas can heat electrons rather rapidly to relatively high energies. Positive ions are also heated, though to a lesser extent. This heating method uses a number of plasma instabilities to randomize the available energy in the electron drift current or beam. Certainly the philosophy, "If you can't lick 'em, join 'em," is frequently useful. Experimental results reported at Culham indicate that in some cases average energy of heated plasma is much less than the maximum energy reached by a few very energetic particles. But there is no question that this is a rapid and effective method for heating plasma in open-ended systems. From a physics standpoint, detailed understanding of complex processes occurring in turbulent heating offers a substantial challenge.

Another related method of plasma heating, which also relies on plasma instabilities to randomize directed kinetic energies, is the use of strong shocks. It has been believed for several years that behind a collisionless shock instabilities would provide the randomization of velocities that collisions provide in normal shocks. A paper from the Novosibirsk (USSR) group discusses this effect, and shows experimentally that temperatures of 10 keV can be achieved for both ions and electrons. This technique is not easy but offers certain advantages in rapid heating of a plasma.

Electron cyclotron waves for plasma heating—a technique pioneered in large part at Oak Ridge—provides a new and useful tool that is getting more attention. The important part played by this technique in research with toroidal plasmas has already been discussed. At the Culham conference, papers from the Kurchatov Institute and from Saclay (France) discussed specifically the application to plasmas of ultrahigh frequencies in the neighborhood of the electron cyclotron frequency. Possibly the end losses from open-ended systems might be suppressed by this technique.

Another separate field of research is the use of intense rf magnetic fields for heating and confining plasma. Most of this work has been done in the USSR, and four papers on this subject were presented at Culham. Apparently strong rf fields can indeed be helpful in plasma stabilization. Streak photographs obtained at the Kurchatov Institute show that instabilities in a linear plasma can be effectively suppressed by 15 kA of rf current in hexapole rods. Research at Sukhumi indicates that a similar technique is effective in toroidal systems and can provide equilibrium as well as stability.

Basic research and controlled fusion

Finally, mention should be made of many Culham papers dealing with basic problems of plasma physics not necessarily related to specific devices with potentialities for controlled fusion. In this

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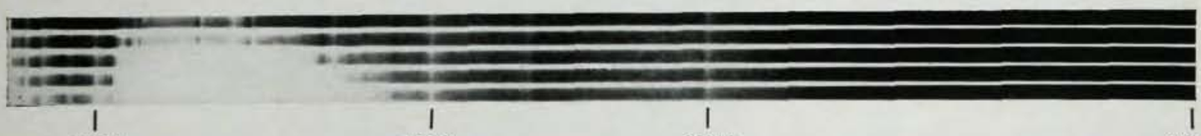

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category are included the research at Stockholm (Sweden) on rotating plasmas, which shows such gratifying agreement with theory, the elegant experimental demonstration of Landau damping at General Atomic, and the work at Culham and Leningrad (USSR) on propagation of electromagnetic waves through turbulent plasmas. The research on plasma production by laser evaporation of small droplets at Frascati and at United Aircraft (USA) is of interest in that it may mark the beginning of an active research field.

In general the experimental papers presented at the conference showed a high degree of scientific quality. As regards controlled fusion as a practical goal, more knowledge is needed to indicate whether this objective can or cannot be attained. Although both theory and experiment indicate a complexity of instabilities that is somewhat bewildering from a practical standpoint, stabilization of some of these modes appears possible, and adequate plasma confinement for a controlled fusion reactor may well prove feasible.

2. PLASMA THEORY

By Edward A. Frieman

As an appendix to Professor Spitzer's survey of the experimental papers presented at the Culham meeting, we here give a short survey of the theoretical papers with the intent of illustrating the present thinking rather than very explicit or detailed results.

Some time ago Rosenbluth and Post showed that the nonscalar pressure which necessarily results in mirror or open-ended containment devices leads to an electrostatic instability. At the conference, Galeev (USSR) presented a calculation which indicated that the nonlinear effects of this instability lead to an anomalously high diffusion in velocity space into the loss cone of the system. At the present time the only method proposed for curing this loss involves building a very short, fat device. As a consequence of these results, more attention has recently been focused on closed or toroidal containment systems.

The closed devices such as Tokamak (USSR), Zeta (UK), Levitron (USA), and stellarators (USA, USSR, Fed. Repub. of Germany) have had a checkered career at the hands of the theorists. It was demonstrated many years ago that sheared fields were necessary to avoid hydromagnetic instabilities induced by the curvature of the magnetic field in these devices. It was later found that even in the presence of shear, dissipative effects arising from electron-ion collisions lead to unstable behavior. In order to avoid these resistive modes it was then proposed that the sign of the curvature be changed; or in other words, that a minimum-B system be built which is stable against resistive modes. Unfortunately, Maxwell's equations will not cooperate in this endeavor to make a minimum-B toroidal system and the best that can be done is to create a minimum-average-B device. At the present time there is therefore a high degree of interest in fields possessing this happy property. Contributions from the USA, UK, and USSR contingents on new systems of this type and calculations of their properties were presented and discussed.

At the same time stability calculations continue to supply employment for a large number of plasma theorists. There were contributions again from the USA, UK, and USSR on the stability of sheared devices both with and without the minimum-average-B property.

Two papers, (USA), indicated that at sufficiently high ion temperatures, the resistive modes discussed above are, in fact, stabilized by viscous effects. Thus, in principle, the new minimum-average-B systems are not needed. However, some preliminary work (USA) does indicate that the new systems will probably be better numerically, i.e., they will be easier to stabilize than the systems with shear and poor curvature.

Surveys (USSR, USA) of all low-frequency modes which are likely to occur in these systems, indicate that with high enough ion temperatures and large enough shear they are all either stable or else will grow to a small amplitude and be limited by nonlinear effects. Estimates of the anomalous diffusion resulting in this situation indicate that it should be quite small indeed. Thus, the theoretical predictions made at the meeting were optimistic. Perhaps by the time of the next meeting of this kind some experimental evidence will have accumulated to check these predictions.