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VELOCITY-SPACE PLASMA INSTABILITIES OBSERVED IN A MIRROR MACHINE*

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We have previously reported[1,2] our first observations of a deliberately induced velocity-space instability of magnetically compressed plasma, adiabatically confined in a mirror machine. Search for this instability was prompted by theoretical calculations, to our knowledge first performed by Rosenbluth,[3] predicting that hydromagnetic instabilities could arise in magnetically confined plasmas, the particle distributions of which are anisotropic in velocity space. The observations reported in this Letter show that plasma instability can be induced in an otherwise stable plasma, under the conditions predicted by theory. The instability is detected by observing the greatly enhanced rate of transport of particles (across the flux lines of the confining magnetic field) which it causes, as compared to a stable case.

Aside from its relevance to plasma research, the instability we have observed may be of more general interest because it can be made to appear at very low plasma densities. Thus it might arise in situations (such as in some high-current accelerators) where cooperative effects are normally considered unimportant.

The instability in question is the so-called "mirror instability," predicted to occur in plasmas where $p_\perp > p_\parallel$ (the pressure tensor component perpendicular to the lines is greater than that parallel to the lines), whenever the local value of $\beta = (p_\perp)/[(B^2/8\pi) + p_\perp]$ exceeds a local critical value β_c. In these regions where $\beta > \beta_c$, theory predicts that random perturbations in the magnetic field should rapidly develop exponentially (until some nonlinear limit is reached). As suggested by its name, one can understand this instability by noting that within the plasma any local perturbation, depending on whether it increases or decreases the field, must create either a local "magnetic mirror," or else a trapping region between two mirrors. If the plasma velocity distribution is anisotropic, this in turn must lead either to the turning back or to the trapping of some particles by the perturbation. The diamagnetic effects associated with these excluded or trapped particles will in either case then act to amplify the initial perturbation, the effects becoming regenerative if $\beta > \beta_c$. One therefore expects that in unstable regions turbulent "rippling" of the magnetic field would develop, destroying the adiabaticity of the particle motions, and thus leading to enhanced transport effects.

Clearly, the more anisotropic the distribution, the smaller will be the value of β_c. Conversely, in the mirror machine, confined plasmas which have reached diffusion equilibrium with the end losses are normally only slightly anisotropic and will therefore be characterized by large β_c values, typically 0.5 or greater.[4] To observe the mirror instability at smaller values of β, the anisotropy must therefore be made anomalously large.

Theoretical expressions from which β_c can be calculated for an "infinite" plasma in a uniform magnetic field have been reported.[3,5-7] To calculate β_c for a finite plasma in pressure equilibrium in a nonuniform magnetic field (as in the mirror machine), a condition derivable from the work of Newcomb[8] will be used. The condition is

$$\beta < \beta_c = [\tfrac{1}{2} |(\nabla p_\perp / p_\perp)/(\nabla B/B)| + 1]^{-1} \text{ stable}, \quad (1)$$

the gradients being taken in the direction of the magnetic field. This condition is to be applied at any point in the plasma. In deriving this expression, individual particle motions have been assumed to be governed by the usual adiabatic invariants, i.e., the magnetic field varies slowly in time, and particle orbit diameters are small.[9]

In these experiments the confined anisotropic plasma is produced by the adiabatic magnetic compression of an injected "blob" of low-energy plasma. As previously discussed[10,11] this process can be used in a mirror machine to generate a stably confined plasma of very high electron temperature (~25 kev); we induce the instability in these experiments by manipulation of the electron component of the plasma, the ions playing an unimportant role. Because magnetic compression acts primarily to increase the "temperature" of only one component of particle motion, that perpendicular to the lines of force, anisotropy results. It is appropriate therefore to describe the final particle distribution by two "temperature" parameters, $T_\perp$ and $T_\parallel$, and to take the midplane distribution function to be a "two-temperature Maxwellian,"

$$f = \exp\{-\tfrac{1}{2}m[(v_\perp^2/T_\perp) + (v_\parallel^2/T_\parallel)]\}, \qquad (2)$$

within the allowed values of $v_\perp/v_\parallel$. Calculating $p_\perp$ from (2), (1) can be evaluated for various values of the mirror ratio, $R = B_{\max}/B_0$, as a function of position between the midplane (B_0) and the mirrors ($B_{\max}$). For values of $t = T_\parallel/T_\perp \ll 1$, it is found that the minimum β_c occurs at the midplane. Figure 1 shows $\beta_c(\min)$ as a function of t, for various values of R. Since in our experiment $R \approx 2$, Fig. 1 shows $\beta_c(\min) = t$, to close approximation. Parenthetically, it can be shown that the curves of Fig. 1 also represent $\beta_c(\min)$ for a midplane distribution function which is any differentiable function of the variable $(v_\perp^2/T_\perp + v_\parallel^2/T_\parallel)$, not merely the special exponential form assumed above.

To observe the instability at small values of β, the anisotropy must be large; this requires a large magnetic compression ratio. But since collisions tend to destroy anisotropy, it is also necessary that the initial plasma density be low enough that collision effects are unimportant during the compression, but not so low that β lies below its critical value. Therefore, in order to produce the instability, it was necessary to reduce the initial density about a factor 10 below that normally used.[11] Magnetic compression ratios $B_f/B_i = 10^3$ or more were used, so that $t = \beta_c \approx 10^{-3}$. The peak magnetic field, B_f, was 10 kilogauss.

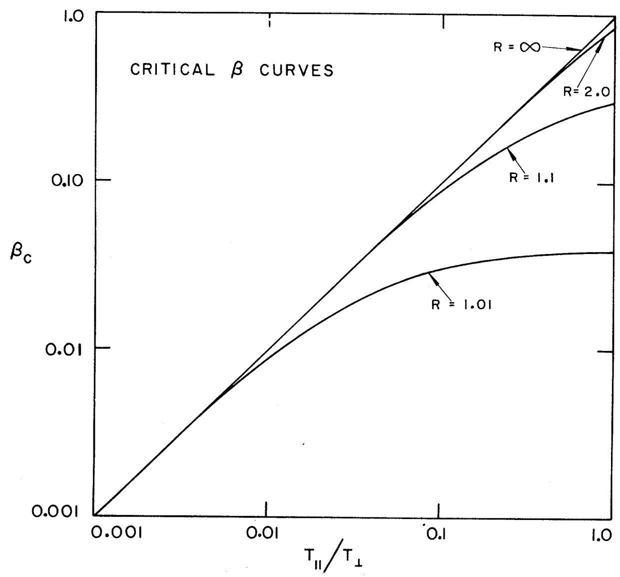

FIG. 1. Critical β curves for the midplane for several values of the mirror ratio R.

Figure 2 shows the experimental arrangement used. Scintillation probes were used to detect the fluxes of radially and axially escaping electrons. The plasma conditions, which determined whether or not instability occurred, were varied by changing (a) the initial magnetic field, (b) the intensity and the timing (relative to the pulsed magnetic field) of the injected plasma burst, and (c) the residual gas pressure.

Most of the observations consisted of correlating the intensity of signals received at the radial scintillation probe (see Fig. 2), with changes in the plasma or compression parameters. The most striking feature of the signals received by this probe was the extreme variation in intensity between stable and unstable cases. Whereas strong signals, several orders of magnitude above multiplier noise, were detectable in the unstable cases, signal levels dropped below detectability when the plasma was rendered stable. Figure 3 illustrates the effect of changing plasma density (by varying the plasma-source-pulse-capacitor charging voltage). Although the signal received by the end scintillation probe increases monotonically until detector saturation occurs, the time-integrated radial probe signal increases only up to a critical density and then falls rapidly to zero with further increase in density. At this density we believe that collisional randomization becomes important and suppresses the instability. This interpretation is apparently borne out by

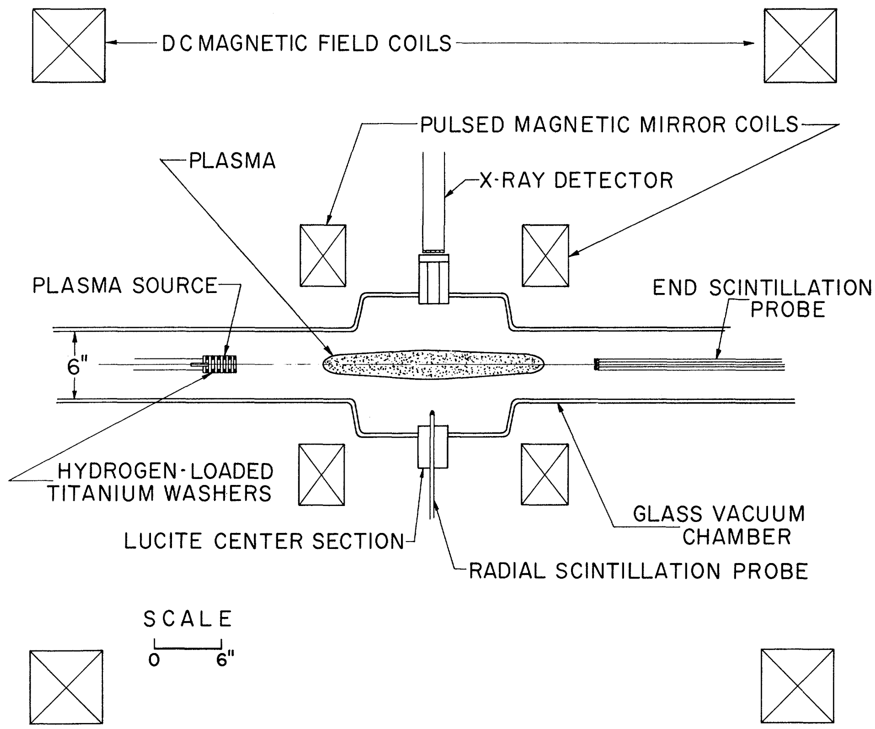

FIG. 2. Experimental arrangement.

experiments in which a neutral "scattering gas" (helium) was admitted to the chamber. As the helium density was raised above about 3×10^{12} cm^{-3}, the ratio of radial-to-axial signal dropped rapidly to zero. From scattering theory one can calculate that, for electrons of mean energy of 20 kev, this density of helium scattering centers would smooth out all anisotropies in about 300 microseconds, i.e., in a time comparable to the compression time of 500 microseconds.

The velocity of plasma transport (across the magnetic field lines) caused by the instability was estimated by three methods: (1) Calculation from the rate of collapse of flux tubes during compression; the plasma collected during compression must possess at least enough velocity to "paddle upstream" to the detectors. (2) Time correlation between signals received by scintillation probes at two different radial positions. (3) Observation of the effect of a movable obstacle which projects into the chamber at a point diametrically opposite the radial probe. By inserting this probe into the chamber to a radius less than that of the radial scintillator probe we decreased its signals; from these data and from the known mean precession time of electrons around the chamber (about 8 microseconds), the radial transport velocity can be calculated. The mean velocities deduced by the above three methods ranged between 2×10^4 and 2×10^5 cm/sec. These velocities are more than 10^7 times the "classical" diffusion velocities appropriate to the plasma density and temperature, and are at least 10^4 times the upper limits experimentally deduced[11,12] for the stable, higher density, plasmas studied earlier in the same apparatus.

Associated with the presence or absence of the instability one expects substantial changes in the radial density distribution of the compressed plasma. By using a movable scintillator probe located just outside one of the mirrors, the radial distribution of the escaping electrons was measured; from such measurements radial density distributions can be inferred. Figure 4 shows these data for two cases: (1) plasma density in the range where instabilities are observed; (2) "low" plasma density, i.e., $\beta<\beta_c$. The differences are striking. Similar constricting effects were found upon increasing the initial field (lowering B_f/B_i, therefore reducing anisotropy), even though the theoretical radial compression itself was thereby reduced.

Approximate quantitative agreement between the theoretical β_c and experimental β values was obtained from the following considerations: The theoretically predicted axial variation of plasma density [calculated by using Eq. (2)] was compared with the experimental data (obtained by axial move-

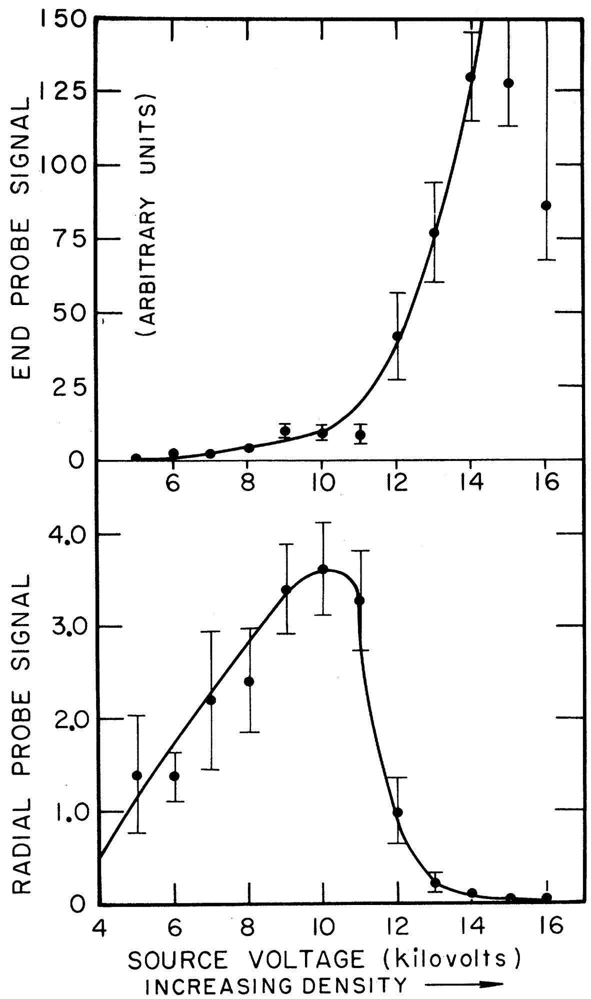

FIG. 3. Probe signals as a function of plasma-source pulse-capacitor charging voltage.

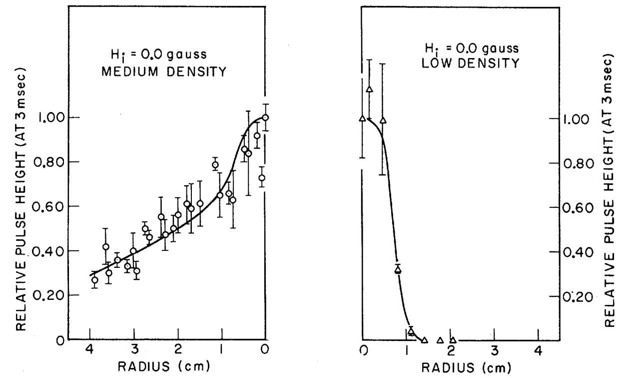

FIG. 4. End escaping flux as a function of radius for an initial magnetic field of 0.0 gauss for medium and low densities.

ment of a scintillator probe about the midplane) to determine the anisotropy. In the cases analyzed $t \approx 10^{-3}$, so that, from Fig. 1, $\beta_c \approx 10^{-3}$. From calorimetric measurements[13] of the energy flux carried radially by the escaping plasma, and from the measured plasma volume, experimental values of β could be deduced. For a plasma that had diffused out to the scintillator, these ranged between 1×10^{-3} and 4×10^{-3}, i.e., between about 1 and 4 times the "theoretical" value of β_c. (The corresponding plasma density was therefore of order 10^{11} cm^{-3}.) However, the value of β prior to expansion of the plasma out to the detector should be larger than its value after expansion. This means that we believe that whenever the pressure of the compressed plasma was initially only slightly above the critical value, only the most anisotropic components were able to diffuse out to the radial probe, the pressure of the rest of the plasma dropping below β_c (so that the plasma became "frozen" to the field lines) before it could reach the detector. We have obtained experimental evidence for this interesting selective transport effect by method (3), above, used to measure radial transport velocity. These measurements showed a clear separation of the radial probe signals into two groups: (1) a "fast" group, appearing within about 500 μsec of the initiation of compression; (2) a "slow" group, appearing several milliseconds after peak field, i.e., not until inner field lines of the collapsing field had expanded out to the detector. For the "slow" group a relative motion of the obstacle and detector of only 0.005 inch was sufficient to extinguish most of the detected signal. The "late" plasma particles appeared therefore to be frozen to the expanding field lines. In support of this interpretation, it was found from the axial variation of the radial flux about the midplane that only the "fast" group was characterized by a very large ratio of $p_\perp/p_\parallel$. These measurements also apparently resolve an old mystery; we had earlier discovered[10] that under certain conditions the outermost energetic electrons of an otherwise stable compressed plasma core could apparently diffuse rapidly to the chamber walls, producing x rays. Their rate of radial transport was much greater than that predicted by classical theory. We now believe that this effect was early evidence of the "mirror" instability here discussed, but occurring only in the outer, low-density, portion of the plasma core.

In summary, we believe that we have established the existence and some of the manifestations of a hydromagnetic velocity-space instability of the "mirror" type. In our experiments, using high-energy electrons, it has been observed to cause an enhanced rate of transport of particles across field lines. It may also cause other effects, such as more rapid thermalization of the plasma, or the emission of plasma radiation. These effects, or those which might arise when the instability is associated with anisotropies in the ionic component of the plasma rather than the electronic component, we have not investigated. Although it is possible to avoid the instability by controlling the plasma parameters, we have shown that it may occur in plasma compression experiments. It also seems likely that any method of creating a hot plasma which results in anomalously large anisotropies (such as the method of injecting highly directed high-energy particles), may stimulate this instability during buildup, even if the final plasma state aimed for is stable. Finally, since this instability feeds on perturbation in energy density, and is not of electrostatic origin, it should persist in the limit of very low particle densities, provided the anisotropy becomes correspondingly large. For this reason, it (or related instabilities) might occur in some astrophysical situations or in particle accelerators, even though the conditions are such that cooperative effects would normally be considered unimportant.

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SUPERCONDUCTIVITY IN Nb_3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

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We have observed superconductivity in Nb_3Sn at average current densities exceeding 100 000 amperes/cm^2 in magnetic fields as large as 88 kgauss. The nature of the variation of the critical current (the maximum current at a given field for which there is no energy dissipation) with magnetic field shows that superconductivity extends to still higher fields. Existing theory does not account for these observations. In addition to some remarkable implications concerning superconductivity, these observations suggest the feasibility of constructing superconducting solenoid magnets capable of fields approaching 100 kgauss, such as are desired as laboratory facilities and for containing plasmas for nuclear fusion reactions.[1,2]

The highest values of critical magnetic fields previously reported for high current densities