[11] B. A. Marinin and W. N. Tsvetkov, Acta Physicochim. URSS 11, 837 (1939). See also W. Helfrich, J. Chem. Phys. 50, 100 (1969).

[12] A. Saupe, Z. Naturforsch. 15a, 815 (1960).

[13] The Bloch equation gives a Lorentzian line shape for uniform modes whose lifetime is not infinite and whose shape is actually more complex. We stress that the theory presented here is linearized and hydrodynamic. Extensions of the theory to include nonlinear and nonhydrodynamic effects, when simplified to manageable form, would have other points of contact with the continuum mechanics approach of Ericksen and Leslie.

UNDERSTANDING TURBULENT ION HEATING IN THE OAK RIDGE MIRROR MACHINE, "BURNOUT V"*

I. Alexeff, K. Estabrook,† A. Hirose, W. D. Jones, R. V. Neidigh, J. N. Olsen,‡ F. R. Scott,§
W. L. Stirling, M. M. Widner, and W. R. Wing∥
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 3 August 1970)

For several years, we have been empirically producing steady-state, mirror-confined hot-ion plasmas with $T_i \approx$ a few keV and $n_i \approx 10^{13}/\mathrm{cm}^3$. We describe here the ion-heating mechanism, which is an instability having a fine-grained azimuthal structure covering a broad band of frequencies around ω_{pi}, having a rapid growth rate on the order of ω_{pi}, and being driven by an intense radial dc electric field. It does not require that $T_e > T_i$.

By "turbulent heating" we mean that the appropriate direct-current power is converted by the plasma itself to radio-frequency oscillations that result in intense heating of the plasma. Such turbulent heating experiments have been extremely successful in the past.[1,2] However, in heating ions, the general assumptions are that the electrons must be heated first by the turbulent discharge, then ions are heated by some secondary process that depends on the presence of hot electrons. In this Letter, we demonstrate a contrasting case in which, in our apparatus, ions are heated intensely, although the electrons remain relatively cold.

Our present ion-heating device is a magnetic-mirror system with an intense, dc magnetic field[2] (50-25-50 kG). As shown in Fig. 1, an intense electron beam (typically 15 kV at 5 to 10 A) is injected axially into the center of the device, where plasma is generated from deuterium gas. An important feature of the device is that the injected electrons must flow radially across the strong magnetic field to reach magnetic field lines that flow to the grounded hollow anodes. Investigation of the x-ray photon spectrum from a 10-kV electron beam inside the plasma showed that the electron beam was both spread in energy (expected from a conventional axial beam-plasma interaction), and reduced in energy to about 5 keV. This reduction of the electron-beam energy suggested that the center of the plasma was about 5 kV negative with respect to the wall. Hence, we suspected that a radial dc electric field of about 10 kV/cm (5 kV across $\frac{1}{2}$ cm) was present and could be responsible for the ion-heating mechanism.

Additional important information was obtained with our high-speed auto- and cross-correlators,[3] which now have an upper frequency limit of 2×10^{10} Hz. Using specially designed electrostatic probes, we observed that the plasma showed intense radio-frequency activity (kilovolts per centimeter) at about ν_{pi} (10^9 Hz), that the rf electric field was directed primarily perpendicular to the dc magnetic field, and that the azimuthal wavelength was $\lesssim 1$ mm. In addition, we could detect bulk azimuthal plasma rotation which also suggested a radial dc electric field of about 10

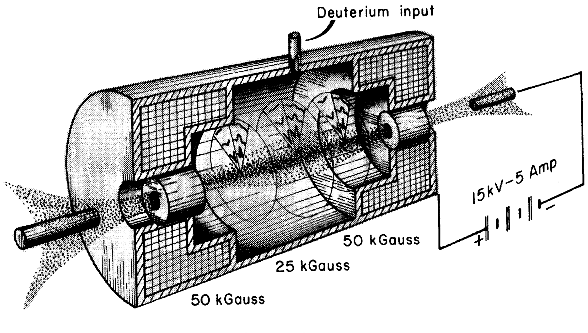

FIG. 1. Schematic of ion-heating apparatus. The length between mirrors is about 50 cm. The azimuthal sectors schematically illustrate the results of rf correlation measurements near ω_{pi} that show (1) excellent axial cross-correlations, (2) poor azimuthal cross-correlations, and (3) rapid decrease in amplitude with increasing radius.

kV/cm.

That both the applied dc and the ion-heating ac electric fields must be primarily perpendicular to the axial dc magnetic field appears reasonable, since we infer from x-ray, Langmuir probe, and helium singlet-triplet spectroscopic data that the bulk of the plasma electrons are relatively cold ($T_e \lesssim 100$ eV), and hence cannot sustain intense low-frequency electric fields parallel to the magnetic field. Additional evidence that dc and low-frequency ac ($\ll \omega_{pe}, \omega_{ce}$) electric fields are radial (i.e., $\perp \vec{B}_0$) was obtained by observing the polarization of electric-field-induced spectral emission from helium[4] added to the system. These fields give rise to satellite spectra of the helium 2^3P-$4^3D, {}^3F$ triplet (4471 Å), and the 2^1P-$4^1D, {}^1F$ singlet (4922 Å) emission lines. Electric field strengths increasing from near zero on the magnetic axis to about 7 kV cm^{-1} at 1 cm, and then decreasing to less than 2 kV cm^{-1} at 2 cm radial distance, are found. An Abel inversion giving intensity of the satellite lines as a function of plasma radius, together with the displacement and intensity of π and σ components in the Zeeman structure of the satellites, gives the electric field strength and implies that the direction of the electric field is perpendicular to the magnetic axis.

We have mathematically analyzed the instability in the following way. We assume that an intense, dc radial electric field induces rapid $\vec{E}_0 \times \vec{B}_0$ azimuthal rotation in the plasma. At these high azimuthal rates of rotation, mass-dependent centrifugal-force effects become appreciable, and the ions rotate at a slower velocity than do the electrons. Also, we note that in the frequency range of interest, $\omega_{ce} > \omega_{pe} > \omega \approx \omega_{pi} > \omega_{ci}$, the ions can be considered moving freely as in an azimuthal beam, while the electrons can be considered "magnetized." Thus one expects an entire family of azimuthal beam-plasma-like instabilities to occur. Those instabilities investigated so far, along with the basic assumptions for each and their resulting characteristics, are tabulated in Table I. All these instabilities have the basic features of oscillating near ω_{pi}, having enormous growth rates (10^7-10^9 e-folds/sec), and heating ions without necessarily heating electrons. The table is valid only for our operating conditions, in which the heating occurs in a shell having an effective radius of 1 cm, and a radial dc field $\vec{E}_0$ of about 10 kV/cm. One of these instabilities (No. 1 in Table I) gives the highest growth rate and is probably our basic heating mechanism. It requires a strong radial density gradient. This instability has been briefly discussed previously,[5] although apparently not correlated with experiment. A comparison of a computed graph of growth rate versus frequency for this particular instability with an experimentally observed frequency spectrum (Fig. 2) shows good agreement. We here assume that the saturated amplitude of the instability is proportional to its growth rate.

An additional interesting feature of these instabilities is that they heat ions without requiring hot electrons to be present first. Also, they heat ions so as to increase the velocity perpendicular to $\vec{B}_0$, and so may tend to heat ions out of the loss cone in mirror machines. For example, the time required to heat an ion to 1 keV corresponds to about one "bounce" time between the mirrors in our machine. Any intense quasi-dc radial elec-

Table I. Theoretically predicted instabilities evaluated for the conditions of our mirror machine.

Instability	Conditions required	Growth time (max)	Azimuthal wave number for maximum temporal growth[a]
1.	Radial density gradient[b]	10^{-9} sec	$k \approx \omega_{pi}/\Delta\mu$
2.	Electrons move axially, ions azimuthally[b]	10^{-7} sec[c]	...[d]
3.	Radial density gradient caused by applied $\vec{E}$ field	10^{-7} sec	$k \approx \omega_{pi}/\Delta\mu$
4.	Collisions between electrons and ions	10^{-8} sec	$k \approx \omega_{pi}/\Delta\mu$
5.	Velocity shear in rotating ion cloud	10^{-7} sec[e]	$k \approx \omega_{pi}/\mu_i$
6.	Mixture of 50% D$^+$ and 50% T$^+$ [f]	10^{-9} sec	$k \approx \omega_{pi}/\Delta\mu$

[a] $\Delta\mu$ is relative drift of ions and electrons; μ_i is the ion drift velocity.

[b] See Ref. 5.

[c] Computer solution for one case.

[d] Not studied, as it is damped by ion-electron collisions.

[e] This is the growth time predicted by perturbation theory; numerical analysis predicts growth times ~100 times shorter.

[f] No radial density gradient required.

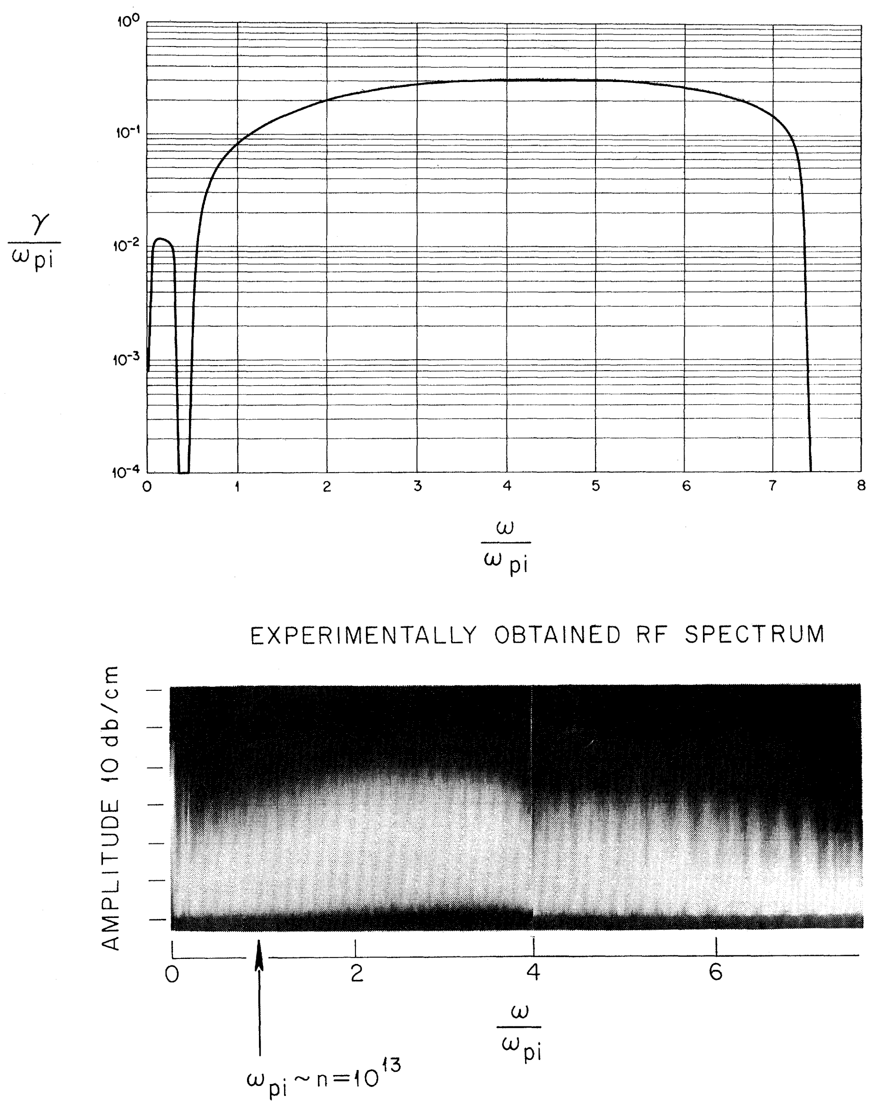

FIG. 2. Comparison of rf spectrum extracted from an electrostatic probe immersed deep in the plasma with a typical computer solution for γ (growth rate) vs ω_{real} (frequency), both normalized to ω_{pi} for instability No. 1 in Table I. The break in the experimental spectrum at $\omega/\omega_{pi} = 4$ is due to a change of scale in the spectrum analyzer.

tric field perpendicular to a strong magnetic field produces these instabilities; hence they may possibly be produced in any convenient (open and perhaps closed) magnetic geometry. Finally, since the fluctuations are both experimentally and theoretically fine-grained ($\lambda \lesssim 1$ mm in our case), and are confined to a small, cylindrical heating zone, they can heat ions without necessarily causing rapid, convective plasma loss across the magnetic field.

A final point is that for ion heating, it is necessary that $\omega_{ce} > \omega_{pe}$. Computations verify past experimental results and demonstrate that as ω_{pe} is increased above ω_{ce}, the growth rates for ion-heating modes in general decrease rapidly. In their place, electron-heating modes abruptly appear. Such behavior is expected, since in the limit as $\omega_{ce} \to 0$, the electrons are unmagnetized, and one expects to recover the electron-heating modes of the standard beam-plasma interactions. Since, to heat ions, ω_{ce} must be larger than ω_{pe}, we require high magnetic fields to heat ions at high plasma densities (25 kG and 10^{13} cm^{-3} in our case).

We appreciate the fine operating help from V. J. Meece, theoretical discussions held with Dr. Owen Eldridge, Dr. Gareth Guest, and Dr. J. R. McNally, and the support of Dr. A. H. Snell and Dr. Herman Postma.

---

*Research sponsored by the U. S. Atomic Energy

Commission under contract with the Union Carbide Corporation.

†Oak Ridge Associated Universities Fellow from the University of Tennessee, Knoxville, Tenn.

‡Oak Ridge Associated Universities Fellow from the Ohio State University, Columbus, Ohio.

§Consultant, University of Tennessee, Knoxville, Tenn.

‖ Student Guest from The University of Iowa, Iowa City, Ia.

[1] T. H. Jenson and F. R. Scott, Phys. Fluids 11, 1809 (1968); S. D. Fanchenko, B. A. Demidov, N. I. Elagin, and N. F. Perepelkin, Phys. Rev. Lett. 21, 789 (1968); S. M. Hamberger, A. Malein, J. H. Adlam, and M. Friedman, Phys. Rev. Lett. 19, 350 (1967); F. Kawabe and H. Eubank, private communication; M. V. Babykin, P. P. Gavrin, E. K. Zavoiskii, S. L. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 52, 643 (1967) [Sov. Phys. JETP 25, 421 (1967)]; M. S. Ioffe, R. I. Sobolev, V. G. Tel'kovskii, and E. E. Yushmanov, Zh. Eksp. Teor. Fiz. 39, 1062 (1960) [Sov. Phys. JETP 12, 1117 (1961)]; M. V. Nezlin, in *Proceedings of a Conference on Plasma Physics and Controlled Nuclear Fusion Research, Novosibirsk, U. S. S. R., 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 257; E. K. Zavoisky, S. L. Nedoseev, L. I. Rudakov, V. D. Rusanov, V. A. Skoryupin, and S. D. Franchenko, *ibid.*, p. 235; M. Fumelli, R. Dei-Cas, J. P. Girard, and F. P. G. Valckx, Association EURATOM—Commissariat à l'Energie Atomique Report No. EUR-CEA-FC-503, 1969 (unpublished); C. B. Wharton, D. S. Prono, and F. Sandel, in *Proceedings of the Ninth International Conference on Phenomena in Ionized Gasses, Bucharest, Rumania, 1969,* edited by G. Musa, A. Popescu, and L. Nastose (Institute of Physics, Bucharest, Rumania, 1969), p. 649.

[2] R. V. Neidigh, I. Alexeff, G. E. Guest, W. D. Jones, D. C. Montgomery, D. J. Rose, and W. L. Stirling, in *Proceedings of the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. 2, p. 693; I. Alexeff, W. D. Jones, and R. V. Neidigh, Phys. Rev. Lett. 18, 1109 (1967).

[3] I. Alexeff, R. V. Neidigh, and W. R. Wing, Int. J. Eng. Sci. 7, 531 (1969). (Note: Our present correlators are greatly improved over that discussed in the above reference.)

[4] F. R. Scott, R. V. Neidigh, J. R. McNally, Jr., and W. S. Cooper, III, to be published. See also M. Baranger and B. Mozer, Phys. Rev. 123, 25 (1961); W. S. Cooper, III, and H. Ringler, Phys. Rev. 179, 226 (1969); H. J. Kunze and H. R. Griem, Phys. Rev. Lett. 21, 1048 (1968).

[5] A. B. Mikhailovskii and V. S. Tsypin, Zh. Eksp. Teor. Fiz.—Pis'ma Redakt. 3, 247 (1966) [JETP Lett. 3, 158 (1966)].

LINEAR MECHANISM FOR THERMAL ENERGY TRANSPORT IN CURRENT-CARRYING PLASMAS*

B. Coppi†
International Centre for Theoretical Physics, Miramare, Trieste, Italy

(Received 6 July 1970)

Collisionless modes extracting electron thermal energy and convecting it radially are considered as a possible explanation of the electron thermal energy radial transport, larger than the one predicted by the proper collisional theory, in confined high-temperature plasmas carrying a current along the magnetic field.

Recent experiments on plasma confined in toroidal magnetic configurations in which electrons are resistively heated by a current flowing along the magnetic field have indicated that the electron thermal-energy transport across the field is much larger than that obtained by the proper collisional transport theory.[1-4] In other words, while it appears that the resistivity as predicted by previous experimental and theoretical work is anomalous[5] (that is, enhanced by a finite factor over its collisional value), the evidence seems to be that the resulting increased electron heating is accompanied by enhanced electron thermal-energy loss.

We propose for this a mechanism which relies on the excitation of current-driven drift modes of the same type as those which have been invoked to explain the observation of anomalous resistivity.[5] These modes have frequency proportional to the radial gradient of the electron pressure $p_{e\parallel}$ parallel to the magnetic field and tend to grow at the expense of longitudinal electron thermal energy. The existence of drift modes is consistent with the observation of a relatively flat electron pressure profile[2] in the plasma column of the T-3 Tokamak in the sense that their excitation is expected to reduce the electron pressure gradient.

We consider for simplicity a one-dimensional plane model of a confined plasma with density gradient in the x direction and the main magnetic field in the z direction. In the neighborhood of a point $x=x_0$ the magnetic field can be represented by $\vec{B}\approx B_0[\vec{e}_z+\vec{e}_y(x-x_0)]/L_s$, the latter term indicat-

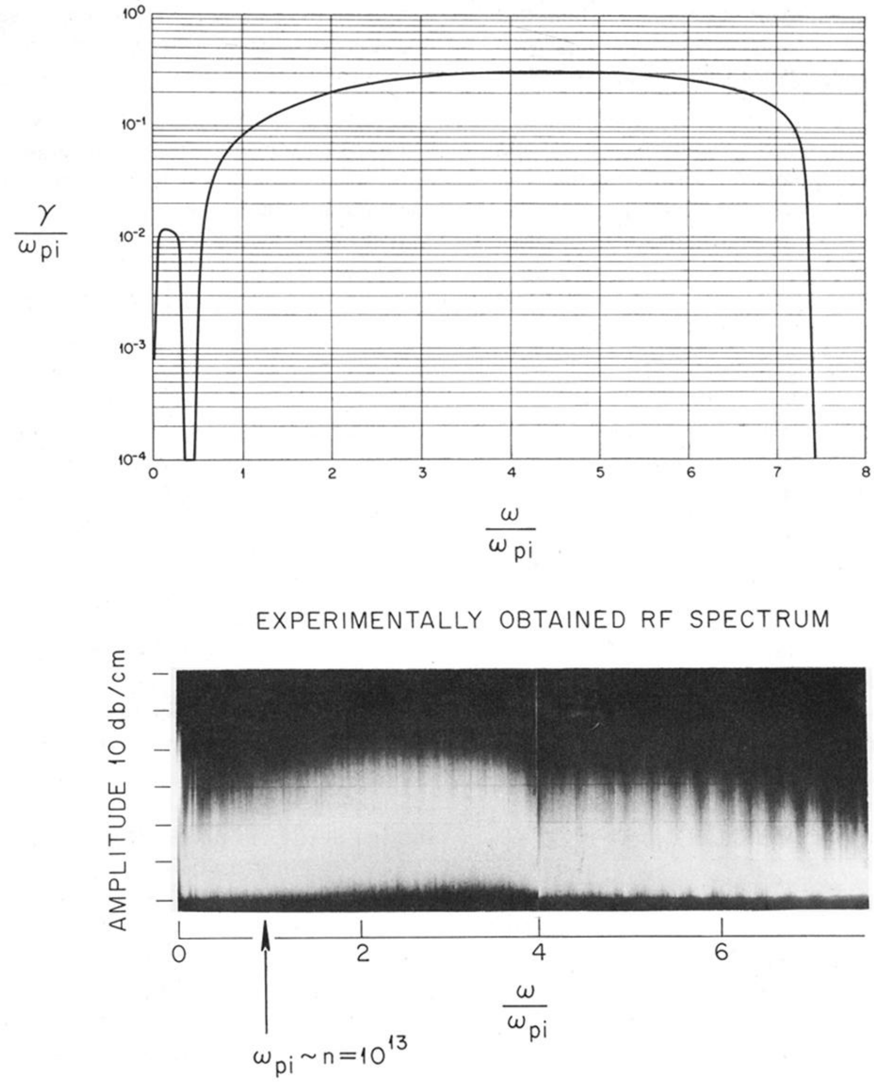

FIG. 2. Comparison of rf spectrum extracted from an electrostatic probe immersed deep in the plasma with a typical computer solution for γ (growth rate) vs ω_{real} (frequency), both normalized to ω_{pi} for instability No. 1 in Table I. The break in the experimental spectrum at $\omega/\omega_{pi} = 4$ is due to a change of scale in the spectrum analyzer.