a computer fit using a two-Lorentzian program which gave very satisfactory results, while all attempts to fit the experimental data by a single Lorentzian curve were unsuccessful.[5]

For a 10%-acetone mixture and for a scattering vector $K = 2.9\times10^3$ cm^{-1}, we obtain the following parameters for the two Lorentzian curves (at room temperature):

$$\Gamma_c/2\pi = 31\pm2 \text{ sec}^{-1}, \quad I_c(\omega=0) = 1030\pm60;$$

$$\Gamma_d/2\pi = 1590\pm140 \text{ sec}^{-1}, \quad I_d(\omega=0) = 70\pm2;$$

where $I(\omega=0)$ is the rms spectral density at $\omega = 0$ (arbitrary units).

This permits us to calculate

$$D = 2.32\times10^{-5} \text{ cm}^2 \text{ sec}^{-1},$$

$$\Lambda'/\rho'C_p' = 1.2\times10^{-3} \text{ cm}^2 \text{ sec}^{-1}.$$

This last value should be compared with the corresponding value for pure CS_2 given above.

To our knowledge this is the first time that the complete Rayleigh central component of a binary mixture has been observed. This simultaneous observation of the two Lorentzian curves permits us to evaluate directly the ratio of the total integrated intensities of the light scattered by concentration and density fluctuations. We find for a $\simeq10$% concentration of acetone

$$I_c/I_d \sim 2.$$

More sophisticated experiments are now under way with variable concentrations and scattering angles.

[1] R. D. Mountain and J. M. Deutch, J. Chem. Phys. 50, 1103 (1969); L. Blum, J. Chem. Phys. 50, 17 (1969).

[2] P. Calmettes, Thèse 3ème cycle, Paris, 1969 (unpublished).

[3] P. Berge and M. Dubois, to be published.

[4] I. M. Aref'ev et al., Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 5, 438 (1967) [translation: JETP Letters 5, 355 (1967)].

[5] We are greatly indebted to Dr. M. Tournarie for designing the programs and for many stimulating discussions.

REMOTE FEEDBACK STABILIZATION OF COLLISIONAL DRIFT INSTABILITY BY MODULATED MICROWAVE ENERGY SOURCE*

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The collisional drift instability is remotely feedback stabilized by irradiating the plasma with microwaves to heat the electrons locally, by upper-hybrid resonance absorption, at interior plasma locations. The phase and amplitude of the feedback-modulated heating necessary for stabilization agree qualitatively with a linear theory, which includes a feedback-controlled heat source.

Recent work,[1-6] using feedback elements immersed in or in contact with plasmas, has demonstrated feedback stabilization of plasma instabilities and concomitant improvement in plasma confinement. Specifically, the collisional drift instability[7] in the oscillatory regime has been feedback stabilized[6] by immersing electrostatic probes to draw current from the plasma, in agreement with a linear theory which includes feedback-controlled particle sources. The feasibility of feedback control of thermonuclear plasmas, however, depends critically on the availability of remote detection and suppression methods. The present work describes such a remote feedback-suppression method for the collisional drift instability, employing modulated microwaves, and presents a theory which includes a feedback-controlled energy source.

The experiment was performed in the cesium plasma of the Q-1 device ($n_e \simeq 5\times10^{10}$ cm^{-3}, $T = 2800$°K, $B \simeq 4$ kG), with a Langmuir probe as detector and a half-wave dipole antenna (located ~2 cm outside the plasma column, at its midplane) as suppressor. The amplified and phase-shifted ion saturation-current instability signal modulates the microwave source so that its output power is proportional to the instability amplitude. The microwave irradiation heats the electrons,[8,9] by resonance absorption, at interior plasma locations selected by adjusting the microwave frequency to the local upper hybrid frequency $[(f_{ce}^2+f_{pe}^2)^{1/2}\simeq 11$ GHz$]$; correct frequency dependences on both density and magnetic field were measured. Localized heating (determined from floating potential measurements) of a slab ~2 mm thick, and penetration of the evanescent exterior plasma region,[8,10] are achieved by placing a $2\times10\times15$-cm (in r, θ, z directions) iron block, 5 cm off axis, diametrically across from the antenna to introduce a weak magnetic field gradient ($\nabla B/B \approx 0.03$ cm$^{-1} \ll |\nabla n_0/n_0| \approx 1$ cm^{-1}) in the otherwise constant and uniform field. This field gradient produces no observable effects on the general drift-wave behavior. Other plasma conditions are similar to those reported earlier.[7]

For optimum stabilization, the modulated microwave power (~100 μW incident for $\tilde{n}/n_0 = 5\,\%$, where the tilde denotes first-order fluctuation) must be applied to the region of maximum instability amplitude, and approximately 180° out of phase with the local density oscillation. Other measured results—such as feedback destabilization in the stable regime, dependence of instability amplitude and frequency on feedback phase shift and gain, and change of plasma confinement resulting from feedback—are also similar to those obtained with the feedback-modulated electron sink (Ref. 6, Figs. 1-3).

The stability for such feedback-controlled, localized collisional drift modes can be analyzed by including a feedback heat-source term Q in the electron fluid energy equation[11]:

$$\tfrac{3}{2}n_0 dT_e/dt + p_e \nabla\cdot\vec{u}_e = -\nabla\cdot\vec{q}_e + Q\tilde{n}KT_e. \qquad (1)$$

Heat generation due to electron viscous dissipation and ion temperature fluctuations are neglected.[12] Incorporating Eq. (1) into the linearized electron continuity equation,[7] we obtain

$$-i\omega\frac{\tilde{n}}{n_0} + i\omega_e\frac{e\tilde{\varphi}}{KT_e} + \frac{1}{t_\parallel{}'}\left(\frac{\tilde{n}}{n_0} - \frac{e\tilde{\varphi}}{KT_e}\right) = -1.71Q\frac{\tilde{n}}{n_0}\left(-\tfrac{3}{2}i\omega t_\parallel + 4.53\right)^{-1}, \qquad (2)$$

where

$$\frac{1}{t_\parallel} = \frac{k_\parallel{}^2 KT_e}{m_e \nu_{ie}}, \quad \frac{1}{t_\parallel{}'} = \frac{1}{t_\parallel}\,\frac{\omega t_\parallel + 1.08}{\omega t_\parallel + 3.02},$$

$$\omega_e = -k_y\frac{KT_e}{eB}\,\frac{\nabla n_0}{n_0},$$

and the numerical constants contain effects of thermal force and thermal conductivity. Clearly, in the continuity equation the heat source acts effectively as a feedback-controlled particle sink.[6,13] Thus, for optimum stabilization the energy source should lag from ~180° (if $\omega_e t_\parallel \gg 1$) to 270° (if $\omega_e t_\parallel \ll 1$) behind the wave. The dispersion relation of Refs. 7 and 12, modified according to Eq. (2), predicts (for the present experimental plasma parameters) optimum stabilization at a feedback phase delay of 240°. In addition, the feedback power, calculated from linear equations for the measured instability amplitude ($\tilde{n}/n_0 = 0.05$), is 75 μW—also in agreement with the experimental value (~100 μW).

In summary, the significant result of this work is the demonstration of remote feedback stabilization of a plasma instability. Furthermore, a feedback-controlled energy source is shown to stabilize the collisional drift instability. Finally, a linear theory is given which describes qualitatively the measured phase and amplitude of the heating necessary for stabilization, together with the observed instability frequency change.

Additional details will be reported elsewhere.

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[1]V. V. Arsenin, V. A. Zhilkov, and V. A. Chuyanov, 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), Vol. II, p. 515.

[2]V. V. Arsenin, V. Kh. Likhtensktein, and V. A. Chuyanov, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 8, 69 (1968) [translation: JETP Letters 8, 41 (1968)].

[3]V. A. Chuyanov, E. G. Murphy, D. R. Sweetman, and E. Thompson, Bull. Am. Phys. Soc. 14, 1028 (1969).

[4]R. R. Parker and K. I. Thomassen, Phys. Rev. Letters 22, 1171 (1969).

[5]B. E. Keen and R. V. Aldridge, Phys. Rev. Letters 22, 1358 (1969).

[6]T. C. Simonen, T. K. Chu, and H. W. Hendel, Phys. Rev. Letters 23, 568 (1969).

[7]H. W. Hendel, T. K. Chu, and P. A. Politzer, Phys. Fluids 11, 2426 (1968).

[8]T. H. Stix, Phys. Fluids 3, 19 (1960).

[9]A. Y. Wong, Appl. Phys. Letters 6, 147 (1965).

[10]A. Y. Wong and A. F. Kuckes, Phys. Rev. Letters 13, 306 (1964).

[11]S. I. Braginskii, Review of Plasma Physics, edited by M. A. Leontovich (Consultants Bureau, New York,

1965), Vol. I.
[12]S. Tsai, F. W. Perkins, and T. H. Stix, Princeton Plasma Physics Laboratory Report No. MATT-700, 1969 (to be published).
[13]H. P. Furth and P. H. Rutherford, Phys. Fluids 12, 2638 (1969).

MECHANISMS FOR PRODUCTION OF NEUTRON-EMITTING PLASMA BY SUBNANOSECOND LASER-PULSE HEATING*

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One-dimensional numerical calculations have been made of the heating of a thick target of solid-density deuterium by focused subnanosecond pulses of neodymium-glass laser light. The conditions for neutron emission were found to be produced by two different mechanisms. The results are found to be in semiquantitative agreement with recent experimental results.

The production of plasmas at the surface of solid deuterium or lithium deuteride targets by means of a focused laser pulse has recently been investigated experimentally for pulse durations of 10^{-12}-10^{-10} sec.[1-4] In some of these experiments, neutrons have been observed. This is a brief report of some one-dimensional calculations of these experiments.

The numerical calculation code was essentially the one previously used by Kidder[5,6] to calculate heating by nanosecond laser pulses. In these problems the deuterium is fully ionized, but the electrons and ions are at different temperatures, T_e and T_I, respectively. The plasma is treated as a single fluid in the hydrodynamic equations of motion because the Debye length for such dense plasmas is negligible. Changes in electron temperature resulting from heat exchange with ions, specific volume changes, absorption of laser light, free-free bremsstrahlung emission, and electron thermal diffusion are computed for each zone. Similarly, changes in ion temperature are computed from heat exchange with electrons, specific volume changes, shock heating (using the "artificial viscosity" technique),[7] and ion thermal diffusion. The neutron emission due to the reaction $D(d,n)He^3$ is computed from unpublished Maxwell-averaged cross-section calculations.[8]

In the computations, neutron emission was found over a considerable range of conditions. The full width of the trapezoidally shaped laser pulse[5] was varied from 6 to 750 psec while keeping the energy constant. The initial density profile at the target surface was varied to study the effect of absorbent clouds of evaporated target material in front of the solid surface (such clouds might be produced by precursor signals from the picosecond-pulse oscillator and amplifier chain[9]). At the critical density n_c where the plasma frequency equals the frequency ν_L of 1.06-μm neodymium-glass laser light,

$$n_c = (\pi m/e^2)\nu_L = 10^{21}. \qquad (1)$$

The laser-light reflection coefficient was varied in an attempt to model the influence of nonlinear absorption effects.[10] Throughout these various investigations, however, it was found that the most significant variable for neutron production was simply the energy absorbed from the beam, almost independent of the details of the absorption process. Figure 1 shows how the neutron emission varies with absorption energy for both short and long pulses. Variations with density profile and absorption mechanisms appear only as scatter in the points.

The total neutron emission can be compared with the results of the Lebedev experiments for which 20 neutron pulses have been detected in

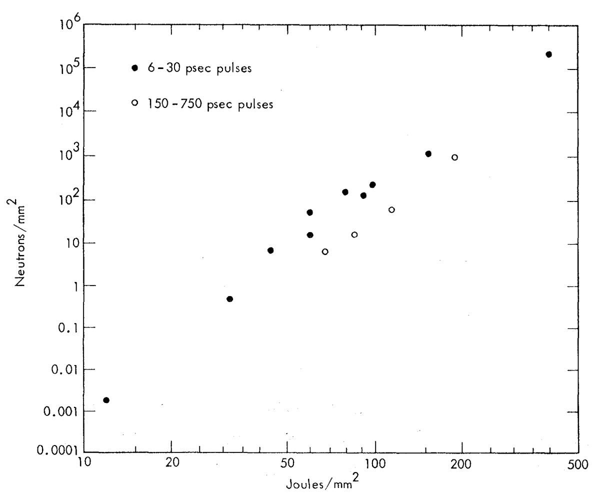

FIG. 1. Neutron emission vs laser energy absorbed.