show that hot electrons leave R with little deceleration, because a slight counterflow of ambient electrons ensures charge neutrality.

In summary, we have shown that anomalous microwave absorption near ω_p produces dilute hot-electron tails whose properties depend sensitively on density and power. Our data suggest that anomalous microwave absorption is a result of ac parametric instabilities which produce the hot electrons by wave-particle interaction.

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[12]Parametric decay of the microwave pump into electron and ion waves propagating obliquely to B_0 is only possible for $(\omega_p/\omega)^2 \gtrsim 1$.

Magnetically Induced Collisionless Coupling between Counterstreaming Laser-Produced Plasmas*

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A laser plasma, expanding through a photoionized background plasma under collisionless conditions, experiences a significant coupling with the background when an external 700-G field is applied transverse to the flow. A density maximum is formed which decelerates according to the predictions of a conserved-momentum coupling model. The results are consistent with theoretical treatments of magnetized two-stream instabilities.

The mechanisms of momentum transfer between counterstreaming plasmas have been a subject of controversy. Both collisional and collisionless processes can lead to coupling, and the difficulty of establishing any given experimental situation as collision free has made the interpretation of previous studies uncertain. Dean *et al.*[1] at the Naval Research Laboratory (NRL) found an interaction at small radii between a streaming laser plasma and an ionized background, attributed to a collisionless instability induced by spontaneous magnetic fields. It has been suggested that the NRL work may be collisionally dominated,[2] and the inability to suppress a spontaneous field prevents an obvious critical test. The dynamics of an electrically accelerated plasma expanding into a partially ionized background have been modified by an external magnetic field,[3] although collisional mechanisms only indirectly involving the field have been proposed to account for these results[4]; the possibility that the plasma source operated differently in a B field also confuses the interpretation.

Rumsby, Paul, and Beaulieu[5] observed no momentum coupling between a laser-produced and a background plasma under conditions similar to the NRL experiment. Koopman and co-workers, in a series of studies with well-documented electrical diagnostics at radii larger than those examined by Dean, have found momentum coupling between an expanding copper laser plasma and the photoionized component of an unmagnetized hydrogen background under conditions where collisions were important.[6-9]

In this Letter we report evidence of collisionless momentum coupling of a copper plasma to an externally magnetized argon background. Because the degree of photoionization achieved in argon is 2.5 greater than in H_2, an initial background pressure of 1 mTorr Ar ($M_i = 40$) gives the the same background ion mass density as 100 mTorr H_2 ($M_i = 1$). An estimate of the collisional effects in our present work compared to our earlier H_2 studies can be obtained by integrating $dU/dt = -n_k\sigma(j,k)U^2$, to determine the range λ of a particle of species j and initial velocity U_0 in a background of species k and density n_k; $\sigma(j,k)$ is the momentum-transfer cross section. For multi-encounter Coulomb collisions between ions, we use[10]

$$\sigma_C(j,k) = \frac{4\pi z_j^2 z_k^2 e^4 \ln\Lambda}{\mu^2 U^4(1+m_j/m_k)}.$$

For screened nuclear encounters between atoms or ions,[11]

$$\sigma_N(j,k) = \frac{2\pi a_0 s_j s_k e^2}{\mu U^2(s_j^{2/3}+s_k^{2/3})}\left(1+\frac{m_j}{m_k}\right),$$

an approximate form which must be truncated at 2×10^{-16} cm^2 at low velocities to avoid unrealistically large values.[12] In these expressions, μ is the reduced mass, s is the nuclear charge, and z is the ionic charge. In Table I, ranges at which $U = U_0/2$ are given for Cu^{+1} ions and background ions or atoms in 1.0 mTorr of Ar and 100 mTorr of H_2, the dominant cross section being σ_N for the former and σ_C for the latter. Note that small values of λ occur only for the H_2 background; the known presence of multiply charged Cu ions reduces $\lambda(Cu^{+z}, H^+)$ values to even smaller ranges.[7] Recent detailed computer modeling of collisional interactions confirms coupling for the Cu^+-H^+ case and its absence for Cu^+-Ar^+ situations at the stated pressures.[12] Attenuation of Cu^+ by charge exchange is important at 100 mTorr but not at 1 mTorr. Thus we expect the Ar studies to be collisionless.

The apparatus is similar to that described in Refs. 6 and 7, with the addition of a magnetic yoke to provide a uniform magnetic field transverse to the plasma flow. Diagnostic measurements were made with Langmuir probes,[9] and two single-wire microwave interferometers similar to the twin-wire units described elsewhere.[8] The probes were located at $R = 18$ and 28 cm from the source of the copper plasma, and could be operated in either a low-impedance (current) or a high-impedance (floating-potential) mode. The microwave sensors were located at $R = 13$ and 23 cm and calibrated by use of magnetic dispersion relations for 9.6 GHz radiation. References 6 and 7 document that the laser plasma can be described by a quasispherical expansion with a leading-edge velocity of $\sim 10^7$ cm/sec, and an approximately exponential spatial density distribution, while photoionization of argon is complete within ~ 1.5 cm of the focal spot and falls as $1/R^2$ at larger radii.

In Fig. 1, we see Langmuir-probe ion currents in the later regions of the plasma flow, where a front following a momentum-conservation relationship would be expected. Densities as a func-

TABLE I. Collisional range λ (cm) for copper plasma expanding into 1 mTorr Ar and 100 mTorr H_2. Both laser-background and background-background ranges are given for various initial velocities U_0, assuming 100% background ionization for the Coulomb cases.

U_0 (10^7 cm/sec)	λ_N(Cu-Ar)	λ_N(Ar-Ar)	λ_C(Cu^+-H^+)	λ_C(H^+-H^+)
0.2	37.	37.	<0.1	<0.1
0.4	37.	37.	0.6	<0.1
0.6	55.	37.	3.2	<0.1
0.8	130.	55.	10.	<0.1
1.0	184.	100.	24.	0.2

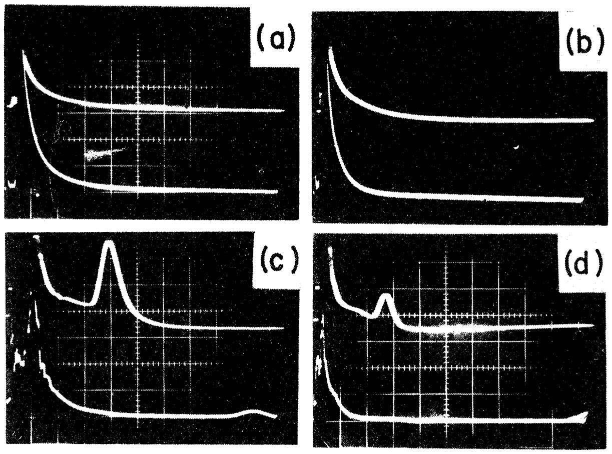

FIG. 1. Ion-current signals from negatively biased Langmuir probes located at $R = 18$ cm (top trace) and 28 cm (lower trace), with (a) $B = 0$, $p = 0.5$ mTorr Ar, 10 μsec/div; (b) $B = 0$, $p = 1.0$ mTorr Ar, 20 μsec/div; (c) $B = 700$ G, 0.5 mTorr Ar, 10 μsec/div; (d) $B = 700$ G, 1.0 mTorr Ar, 20 μsec/div. Vertical scales are identical, at ion flux $= 5 \times 10^{17}$ ions/cm^2 sec per division.

tion of time are shown in Fig. 2. Note that when $B = 0$, the presence of a background plasma has little effect on the expansion of the laser plasma; 1 mTorr of Ar produces only a small attenuation of the early part of the flow. When a 700-G field is present, the data for the early portions of the flow show a high degree of turbulence, characterized by voltage and density fluctuations with periods of $\sim 10^{-7}$ sec. Evidence of the field-induced turbulence can be seen on the lower trace of Figs. 1(c) and 1(d). During this time, the plasma potential rises to ~ 100 V with respect to the grounded chamber, while the electron temperature T_e appears to be 30–70 eV. In later portions of the magnetized flow, the potential and T_e fall by about an order of magnitude; but if a background is present, a second probe-current maximum appears, closely resembling the feature identified as a momentum-conserving interaction shell in our earlier collisional work,[7] but smaller in amplitude because of the lower background number density and higher ion mass used here. As Fig. 1 demonstrates, this second feature arrives at later times as the pressure is increased; it becomes less distinct and finally disappears as the B field is reduced to zero.

Note in Fig. 2 that at $t = 0$, the laser generation of the copper plasma is accompanied by an immediate photoionization of argon at the probe location. The leading edge of the laser plasma arrives at a time consistent with the expected velocity of 1×10^7 cm/sec. The application of the magnetic field produces a second density maximum, demonstrating that the second feature seen on the probes is indeed caused by a shell of increased plasma density passing the diagnostic stations.

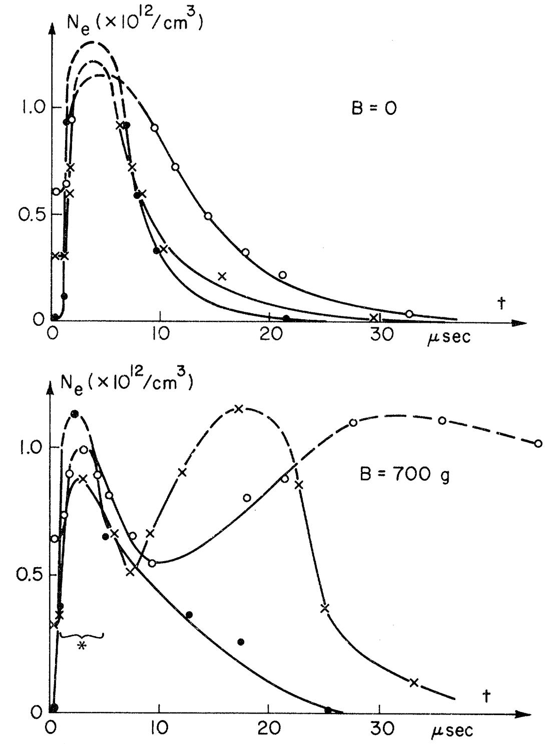

FIG. 2. Electron densities measured by microwave station at $R = 13$ cm. Dashed lines are above microwave cutoff and estimated from probe data. Closed circles, $p = 0$; crosses, $p = 0.5$ mTorr Ar; open circles, $p = 1.0$ mTorr Ar. Region denoted by asterisk for $B = 700$ G is turbulent.

Figure 3 compares the experimentally observed R-t trajectories of the leading edge of the second maxima with the predictions of our momentum-conservation model[7] for the present experimental conditions, assuming that only the ionized fraction of the background is coupled to the laser plasma. The agreement supports the conclusion that a substantial portion of the laser plasma, in the presence of a magnetic field, snowplows the ionized background to form the second maximum we have observed. Coupling to both neutral and ionized background components, as suggested in Ref. 4, would produce different R-t relationships.

Possible mechanisms for coupling in the presence of a magnetic field have been proposed for conditions when the electron cyclotron radius, r_{ce} is small enough to allow the growth of counterstreaming instabilities. The conditions for in-

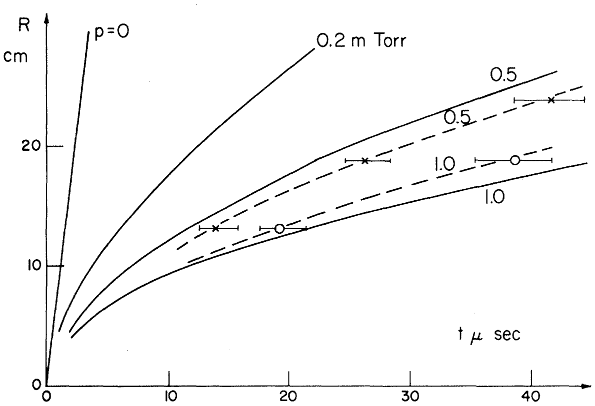

FIG. 3. Comparison of experimental R-t trajectories (dashed lines) of second density edge with computed results (solid lines) from momentum-conservation model, at various pressures.

stability can be written in the approximate forms

$$(kT_i/m_i)^{1/2} < \Delta U < U^*,$$

where

$$U^* = (V_A^2 + 2V_S^2)^{1/2} = V_A(1+\beta_e)^{1/2},$$

and $V_A^2 = B^2/4\pi n m_i$, $V_S^2 = kT_e/m_i$, and $\beta_e = 8\pi nkT_e/B^2$. For a two-stream ion-ion instability, ΔU may be identified as the counterstreaming velocity, U,[13] while for the modified two-stream instability, $(n_B/n_L)U$ is used for ΔU as the relative velocity between ions and displaced thermalized electrons, where n_B and n_L are the background and laser plasma ion densities, assuming that $n_L \gg n_B$.[14]

In our experimental situation, $V_S \approx 10^6$ cm/sec and V_A varies from 2×10^6 cm/sec at radii of a few centimeters to 10^7 cm/sec at larger radii. For the pressure range in which the laser plasma is not completely overwhelmed by the mass of the background ($p < 5$ mTorr) and for radii of ~1 cm or more, the modified two-stream instability condition is satisfied, while the ion-ion instability criterion is met only for radii exceeding ~10 cm. For $\Omega_e \ll \omega_{pe}$, the maximum growth rate of the modified two-stream instability is given by $\gamma = (m_e/m_i)^{1/2}\Omega_e$. A length scale for growth to saturation of the instability viewed in the laboratory frame is estimated to be $L_g = 5U/\gamma$, corresponding to a five e-fold increase of the turbulent electric field. Under the experimental conditions $L_g \simeq 0.5$ to 3 cm. Once the turbulent electric field reaches a large value, wave-particle scattering can couple the plasmas, and reduce the counterstreaming velocity. A length scale for estimating the coupling range is $L_S = U^2/(dU/dt)$, where dU/dt can be computed from the value of the saturation electric field.[14] For the modified two-stream instability, after transforming to laboratory coordinates through momentum-conservation relations, we find $L_S = (M_L n_L/M_B n_B) \times (16U/\Omega_e)(M_L/m_e)^{1/2}$, which yields $L_S \simeq 1-10$ cm. Since both L_g and L_S are comparable with our experimental dimensions, a partial coupling due to magnetic streaming instabilities is expected, and indeed the data for $B = 700$ G in Figs. 1 and 2 resemble the intermediate-pressure data of Figs. 4 and 5 of Ref. 7, where partial coupling through collisional processes occurred.

The dependence of our interaction on the presence of a magnetic field, the collisionless nature of plasma interpenetration in the absence of a field, the similarity of the results with those obtained from momentum transfer induced by collisions, and the agreement of our data with theoretical models for momentum conservation and the onset of counterstreaming instabilities all indicate that a collisionless momentum coupling between interpenetrating plasmas is occurring.

We wish to acknowledge useful discussions with D. A. Tidman and K. Papadopolos.

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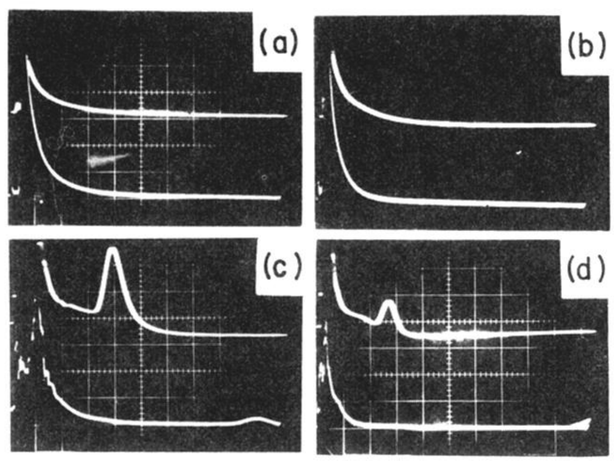

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