MICROWAVE INTERACTIONS IN CRYOGENIC AFTERGLOW PLASMAS

P. D. Goldan, J. A. Berlande, and L. Goldstein
University of Illinois, Urbana, Illinois
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In the course of a series of investigations into the nature of electron collisional processes in cryogenically cooled helium afterglow plasmas (to be reported on at a later date) several effects have been observed which differ considerably from observations made under similar conditions at higher gas temperatures.

It has been previously demonstrated[1] that the application of a relatively low-level (~10^{-2} watt) pulsed microwave signal to an isothermal afterglow plasma results in an increase in the electron gas temperature, T_e, with a consequent alteration in the rates of all processes which are dependent upon T_e. Specifically, the rate of the electron-positive ion volume recombination process, which gives rise to the observed afterglow, is altered resulting in a detectable "quenching" of the afterglow luminosity. Also the electron effective collision frequency for momentum transfer may change, resulting in an alteration of the electrical conductivity and hence the microwave propagation characteristics of the plasma. If a second microwave signal, of power sufficiently low that no detectable effects result from its presence ($\ll$1 mW), is simultaneously propagated through the plasma, this alteration of the microwave propagation characteristics of the plasma medium manifests itself as an interaction with or cross-modulation upon the low-level "sensing" signal. Upon removal of the perturbing or "heating" signal, the afterglow light intensity has previously been observed to relax back to its unperturbed level with little or no overshoot.[1,2] The relaxation of the electron collision frequency in the wake of the "heating" wave, as detected by the "sensing" signal, has been related to electron-collisional processes within the plasma and in the case of helium at 300°K has been demonstrated to have an exponential behavior for sufficiently small electron energy deviations.[3] The purpose of this note is to briefly report significant deviations from the previously reported behavior of both the "quenching" of the afterglow light intensity and the microwave cross modulation in the case of helium under circumstances where the parent gas is maintained at 4.2°K and 77°K and in the case of neon maintained at 77°K.

The experimental setup consists essentially of a 24-cm-long, rectangular, glass discharge tube located in a section of standard X-band waveguide which was situated in a double Dewar system suitable for the containment of both liquid nitrogen and liquid helium. The discharge plasma was initiated by high-voltage dc pulses of 1 or 2 microseconds duration. The dc power input to the plasma was controlled to prevent significant heating of the parent gas. A microwave signal at 9800 Mc/sec, whose power level was adjustable up to 50 milliwatts, was pulse modulated and served as the "heating" wave. A lower level ($\ll$1 milliwatt) microwave signal at 8600 Mc/sec served as the "sensing" signal. A crystal detector in conjunction with a rejection filter, turned to eliminate the "heating" wave, served to detect the "sensing" waveform. The afterglow light intensity was monitored, through 5-ft flexible quartz-fiber light pipes, by means of a photomultiplier tube.

Figure 1 shows an oscilloscopic display of a

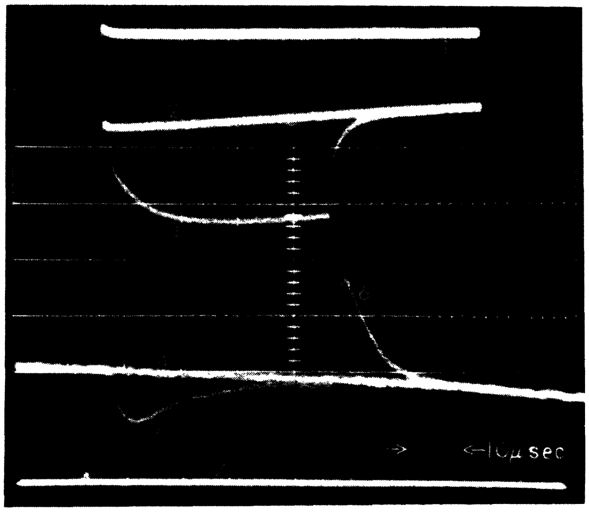

FIG. 1. Microwave cross-modulation and light "quenching" in helium 0.81 mm Hg at 4.2°K. 25-milliwatt "heating" pulse introduced 900 μsec after dc breakdown. Traces 1 through 3 are detected "sensing" signal with (1) no plasma, (2) plasma but no perturbation, and (3) plasma and "heating" wave present. Trace 4 is the unperturbed afterglow light, (5) "quenched" light signal (6) light "afterpulse," and (7) zero light level. Increasing light intensity and transmitted microwave power upward. Duration of square "heating" pulse indicated by vertical dashed lines.

portion of the amplified photocurrent resulting from the visible afterglow in a decaying helium plasma together with the concurrently measured microwave cross modulation. It is seen that the perturbed light signal consists essentially of three parts: an initial quenching whose initial slope is measurably smaller than that of the cross-modulated signal, a slower recovery to a new steady-state value followed, upon removal of the "heating" wave, by an increase in the afterglow light intensity or "afterpulse" considerably exceeding that preceding the application of the perturbation. Spectral measurements indicate that this increase is not the result of a significant change in the emitted spectrum. The relatively low power levels of all of the microwave signals involved seem to preclude the possibility of producing any excitation of atomic or molecular electronic states. Measurement of the electron radiation temperature during the afterglow indicate the electron temperature to be well below 300°K and decreasing smoothly at times several hundred microseconds after cessation of active discharge.[4] Similar wave forms are observed at 77°K both in helium and in neon.

As can be seen from Fig. 2, the amplitude of the light "afterpulse" is dependent upon the heating pulse length as well as its amplitude, disappearing at constant heating power level for sufficiently short heating pulse lengths and approaching a saturation for sufficiently long heating pulses.

Figure 3 shows the microwave cross-modulation envelope during and in the wake of the "heating" pulse in helium at 77°K. Two quite separate rates of increase of microwave absorption caused by the application of the "heating" pulse (trace portions 2 and 3) and rates of relaxation in its wake (trace portions 4 and 5) are clearly visible belying any simple interpretation solely in terms of electron energy relaxation. Similar data are obtained in helium at 4.2°K with the difference between the two growth and two relaxation rates being not so striking. The amplitude of the more slowly relaxing tail of the wave form (trace portion 5) diminishes with decreasing "heating" pulse length in a manner similar to the decrease of the light "afterpulse" illustrated in Fig. 2.

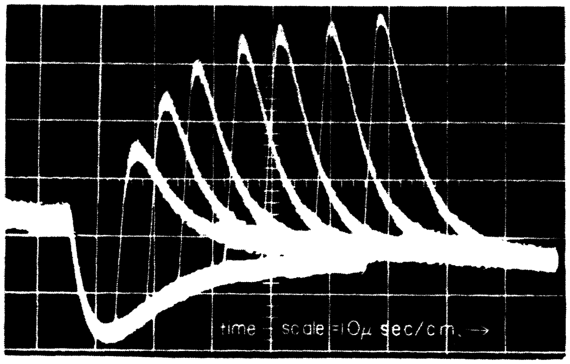

FIG. 2. Afterglow light "quenching" and afterpulse as a function of "heating" pulse length; helium 0.81 mm Hg at 4.2°K. "Afterpulse" for heating pulse lengths of 8, 14, 19, 27, 34, 43, and 50 μsec. Increasing light intensity upward.

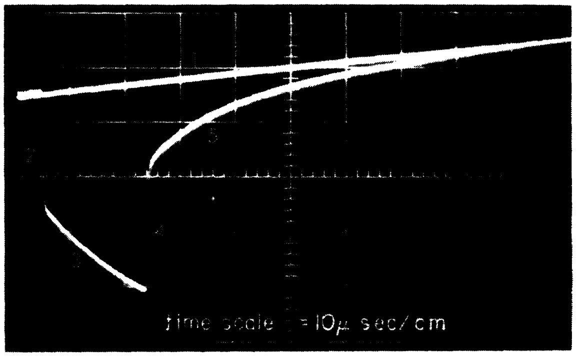

FIG. 3. Microwave cross-modulation in helium; 10 mm Hg at 77°K. 50-milliwatt "heating" pulse introduced 2 milliseconds after 2-μsec dc excitation. (1) Unperturbed "sensing" signal; (2,3) perturbed "sensing" signal during microwave heating; (4,5) perturbed "sensing" signal in the wake of "heating" pulse. Increasing microwave power upward.

Interpretation of this slower relaxation rate in terms of an electron collision frequency, ν, for neutral gas pressures in the range 0.1 to 5 mm Hg at 4.2°K have been made according to an analysis similar to that of Bailey and Martyn[5] as indicated in reference 3. Such determination differs from ν measured using a microwave propagation technique[6] by as much as an order of magnitude whereas good agreement has been noted between the two techniques at higher temperatures.[3]

The behavior described above undoubtedly has its basis in a mechanism considerably more complicated than that usually ascribed to such light "quenching" and cross-modulation measurements.[1-3] Spatially resolved afterglow light measurements have revealed that gross charge-density redistribution of the plasma as a result of the spatially nonuniform "heating" field cannot account for the observed phenomena. One possible mechanism that suggests itself in the case of helium involves the balance between the production of helium molecular ions during the afterglow and their disappearance through recombination. It should be noted in passing that under the conditions of these experiments, charged particle diffusion is expected to be negligible with respect to volume recombination.

It is generally accepted that the predominant electron volume loss mechanism in a decaying helium plasma of low charge density is recombination with helium molecular ions, the He_2^+ being formed during the afterglow. At reduced ion and electron temperatures, the associated recombination coefficient, α, is expected to increase[2] whereas the molecular-ion production rate may be decreased. Thus by cryogenically cooling the plasma, the possibility exists of obtaining, in helium, a situation in which the electron loss rate is predominantly controlled by the production of its voracious recombination partner. Temporary heating of the electron gas, with its subsequent decrease in α, would then allow a new higher steady-state concentration of He_2^+ to be approached at a rate dependent upon the neutral-atom and electron number densities. Removal of the source of heat with the attendant relaxation of T_e would, in such a situation, result in a relatively large temporary increase in the afterglow luminosity.

Such temporal variations in the relative ion concentrations could also affect the microwave absorption properties of the plasma through electron collisional excitation of low-lying rotational states of the He_2^+ molecule. Stabler[7] has indicated that the cross section for such excitation is large. Such considerations account qualitatively for the observed waveforms and their behavior as a function of "heating" pulse length. Attempts at experimental verification of the various hypotheses are in progress.

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COLLISIONLESS DAMPING OF ELECTROSTATIC PLASMA WAVES*

J. H. Malmberg and C. B. Wharton
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation, San Diego, California

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It has been predicted by Landau[1] that electrostatic electron waves in a plasma of finite temperature will be damped, even in the absence of collisions. Landau's theory has been challenged on various grounds[2] and a number of experiments designed to detect the effect for electrostatic electron waves or ion acoustic waves have been reported.[3] The existence of the damping is of interest not only for its own sake, but because the method of calculation has been widely used for related problems. We report here preliminary results of an experiment designed to measure the Landau damping of electrostatic electron waves. We observe heavy damping which exhibits the expected dependence on phase velocity.

The machine which produces the plasma has been described in detail elsewhere.[4] The plasma is produced in a duoplasmatron-type hydrogen arc source and drifts from it into a long uniform magnetic field of a few hundred gauss. The entire machine is steady state. The resulting plasma has, in a typical case, a radius of 7 mm, a length of 230 cm, a density of 5×10^8 electrons/cm^3, and a temperature of 12 ± 3 eV as measured by Langmuir probes. The background pressure is 1.7×10^{-5} Torr (mostly H_2). Hence, the Debye length is about 1 mm, the electron mean free path for electron-ion collisions is of the order of 1000 meters and for electron-neutral collisions is about 40 meters. The plasma is surrounded by a stainless steel tube 3.8 cm in radius which acts as a waveguide beyond cutoff to reduce electromagnetic coupling between probes. The plasma density depends somewhat on distance from the source.

Two probes, each consisting of a 0.2-mm di-

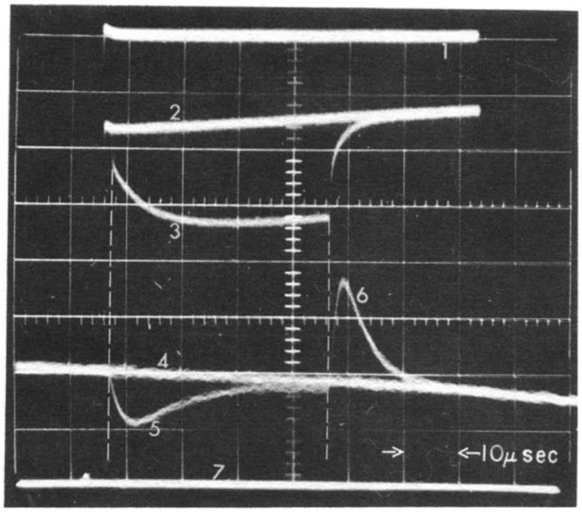

FIG. 1. Microwave cross-modulation and light "quenching" in helium 0.81 mm Hg at 4.2°K. 25-milliwatt "heating" pulse introduced 900 μsec after dc breakdown. Traces 1 through 3 are detected "sensing" signal with (1) no plasma, (2) plasma but no perturbation, and (3) plasma and "heating" wave present. Trace 4 is the unperturbed afterglow light, (5) "quenched" light signal (6) light "afterpulse," and (7) zero light level. Increasing light intensity and transmitted microwave power upward. Duration of square "heating" pulse indicated by vertical dashed lines.

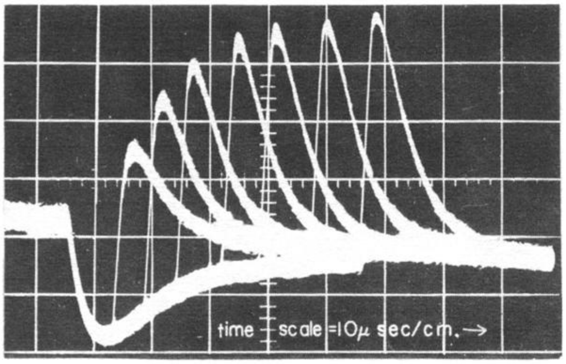

FIG. 2. Afterglow light "quenching" and afterpulse as a function of "heating" pulse length; helium 0.81 mm Hg at 4.2°K. "Afterpulse" for heating pulse lengths of 8, 14, 19, 27, 34, 43, and 50 μsec. Increasing light intensity upward.

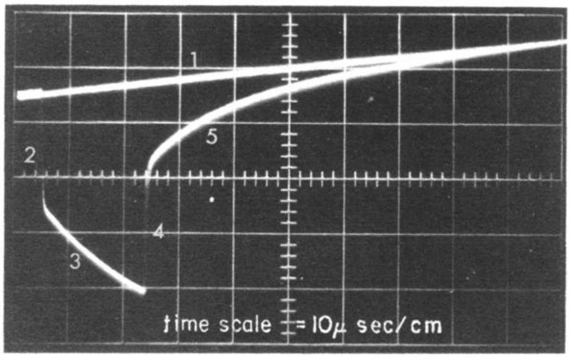

FIG. 3. Microwave cross-modulation in helium; 10 mm Hg at 77°K. 50-milliwatt "heating" pulse introduced 2 milliseconds after 2-μsec dc excitation. (1) Unperturbed "sensing" signal; (2, 3) perturbed "sensing" signal during microwave heating; (4, 5) perturbed "sensing" signal in the wake of "heating" pulse. Increasing microwave power upward.