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GENERATION OF A HOT, DENSE PLASMA BY A COLLECTIVE BEAM-PLASMA INTERACTION*

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We wish to report some experiments on the production of a plasma by a pulsed electron beam. The plasma is generated primarily by the energetic plasma electrons; and these, in turn, obtain their energy from the strong oscillations resulting from the interactions between the electron beam and the plasma. These strong oscillations appear to be a very effective means of using some of the beam's dc kinetic energy to produce and heat a plasma. The energy-transfer phenomena reported here are apparently related to those observed by Kharchenko et al.[1]

A pulsed, 10-keV, 1-A electron beam of 0.080-in. diameter is projected from a Pierce type of electron gun into a drift region where it is confined by an axial magnetic field of 200 to 1000 gauss. The gun is shielded from the magnetic field and differentially pumped so that the gun chamber pressure is maintained at approximately 10^{-5} mm Hg, while a pressure of 10^{-4}-10^{-3} mm Hg of argon or hydrogen is maintained in the drift region.

Figure 1 indicates the various quantities that are observed: the instantaneous currents to the wall, anode, and collector; the response of a photomultiplier pointed at the path of the beam; the video output of a tunable microwave receiver; and x radiation.

Under the conditions of the experiment, the mean free path for elastic scattering of the 10-keV beam electrons is approximately 100 times the length of the drift region. The rate of production of ion-electron pairs is such that the beam can neutralize itself in a time T_n of 0.25-0.5 μsec, and thereafter, if no other mechanism comes into play, the plasma electron density increases at a rate given for argon by

$$N_{pe} = 3.2\, p N_b (t - T_n), \tag{1}$$

where N_b is the beam electron density (approximately $7\times10^9/\text{cm}^3$, in our case), t is in μsec, and p is the pressure in μ Hg.

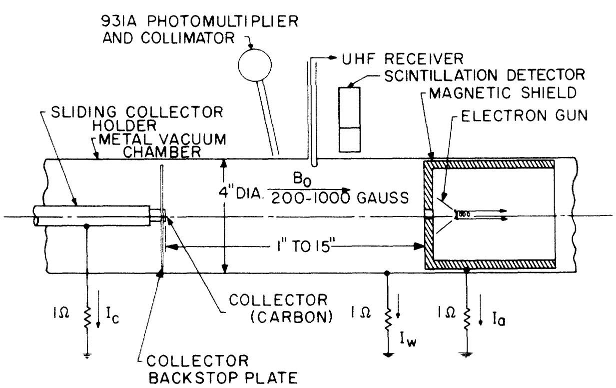

FIG. 1. Schematic drawing of the beam-plasma interaction region.

Figure 2 shows a group of oscillograms taken during the first 3.5 μsec of a typical experiment with short beam pulse lengths. The collector current I_c reaches its full value and remains constant for about 1.5 μsec, when it suddenly decreases sharply. This "missing" current appears at the walls (I_w) in spite of the fact that the radius of

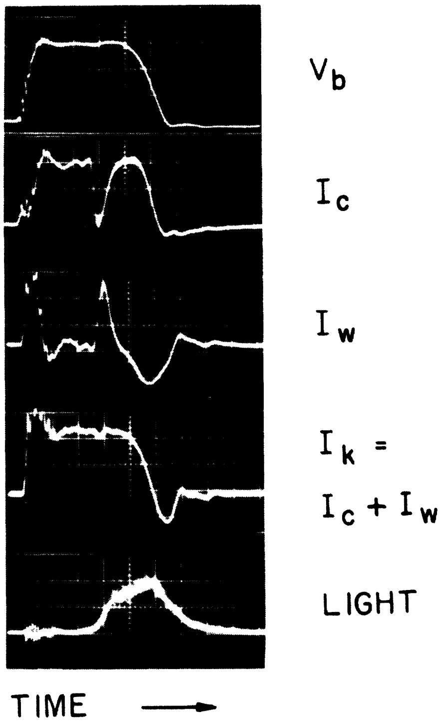

FIG. 2. Oscillograms showing a typical beam breakup. The conditions are: V_b, 2000 volts per large division; I_c, I_w, and I_k, 250 mA per large division; sweep rate, approximately 0.7 μsec per large division; pressure, 0.6 μ Hg of argon; and minimum magnetic induction 500 gauss. Positive deflection indicates electron current. The leading and trailing pulses in I_w indicate displacement current.

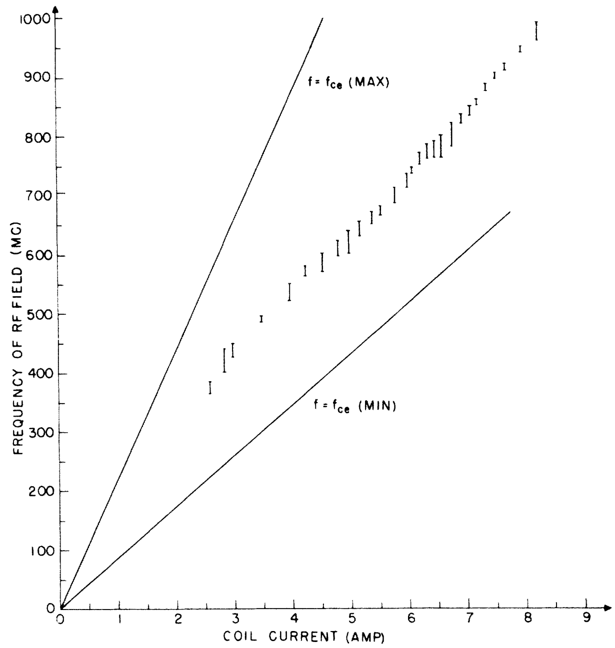

FIG. 3. Magnetic-field dependence of the initial oscillation frequency. The conditions are: V_b (peak) = 6000 volts; I_c (peak) = 750 mA; pressure, 0.2 μ Hg of argon; gun shield-to-collector spacing 12 in.

gyration of a 10-keV electron in a 500-gauss field is 0.7 cm, and our apparatus has a radius of 5 cm. For the beam to reach the wall, we require either a very strong dc radial potential gradient, or (more likely) a strong oscillating, transverse electric field.

Approximately 0.5 μsec before the break in collector current, we observe a strong rf field in the drift region. Although the oscillation frequency of this field increases rapidly with time, it always starts at a value that is proportional to the axial magnetic flux density, as shown in Fig. 3. Because the flux density varies along the beam axis, lines are drawn in Fig. 3 to show the upper and lower limits of f_{ce} (the electron cyclotron frequency) as a function of the coil current. The frequency of the rf field starts at a value slightly above f_{ce} (min). In the time interval between the appearance of cyclotron oscillations and the break in the collector current, the oscillation frequency increases steadily with time.

Coincident with the appearance of the rf oscillations is a burst of light whose intensity starts to increase slowly at the time of the initial cyclotron oscillations and increases more rapidly when the drop in the collector current occurs. The peak intensity reached by the light is 50 to 100 times greater than the level just before the onset of rf oscillations. The visible spectrum of the burst of light shows only argon I and II lines plus a few faint oxygen lines. The light observed before oscillations start is presumably due to direct excitation by the 10-keV beam electrons. To account for the 100-fold light increase we must assume that an additional electron population is taking part in the excitation process. Preliminary scintillation measurements with Willemite-coated probes indicate the existence of a large group of electrons with almost randomly directed energies of at least 100 eV, 2 to 3 μsec after the start of the pulse. These energetic electrons were detected everywhere along the beam length and in a column approximately 2 inches in diameter.

A simplified analysis of the beam-plasma system[2-4] indicates that a strong "backwave-wave" interaction occurs between the slow cyclotron wave on the beam $[\beta = (\omega + \omega_{ce})/v_0]$ and the negative dispersion wave that the plasma column can sustain when $\omega_{ce} < \omega < (\omega_{ce}^2 + \omega_p^2)^{1/2}$, for $\omega_p < \omega_{ce}$. Self-excited oscillations would be expected at the frequency for which these two waves are synchronous. The dependence of this frequency on magnetic field agrees with the experimental curve shown in Fig. 3. Similar interactions, at nearly the same frequency, are predicted for higher order angular dependencies of the oscillating fields ($n = 1, 2, \cdots$, etc.). Thus far, we have not determined which of these modes is predominant in our experiment, but we suspect that it is in the $n = 1$ mode. If we use the same theoretical model, but assume that $\omega_p > \omega_{ce}$, then the frequency of strongest interaction is expected to be approximately equal to ω_p (the plasma resonance frequency). (This is the interaction reported by Boyd et al.[5])

Sometime after the break in collector current, we detected strong oscillations which extended over a wide range of frequencies, but with a highest value of about 5000 Mc/sec. Using the above theoretical model, we conclude that the observed frequency of 5000 Mc/sec corresponds to a density of roughly $3 \times 10^{11}/\text{cm}^3$. This value of plasma electron density (about 40 times greater than the beam electron density) is consistent with the density required to produce the observed increase in light intensity if the electron energies are in the neighborhood or greater than 100 eV. If the electron energies are lower, a greater density is required to produce the observed light.

Figure 4 illustrates preliminary results with pulse lengths of approximately 100 μsec. The general behavior of the collector and wall currents for the first few μsec of the pulse resembles that described for short pulses. By adjusting the magnetic field strength and shape, we can obtain a beam breakup similar to that shown in Fig. 2 with either argon or hydrogen. However, the currents differed considerably at later times, with details which depended on the type of gas used. With argon, the heavier ion, ion currents of 1 ampere were observed at the walls, and a corresponding increase in net electron current to the collector was observed. Since our beam current is only 1 ampere, the effective rate of ionizing collisions is approximately 300 times greater than the rate due to the beam alone, as given by Eq. (1).

With hydrogen, the wall currents were much smaller although the rf interaction appeared to be as strong. Measurements of the rf spectrum showed strong oscillations in broad patches up to 15 000 Mc/sec, with the highest frequency observed near the end of the pulse. Interpreted as above, we tentatively conclude that this represents a density of about 2×10^{12} electrons/cm^3.

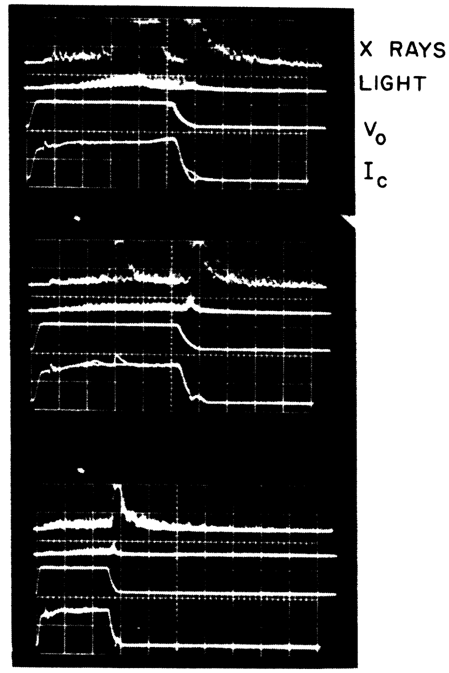

FIG. 4. The interaction obtained with a 50-μsec pulse. The magnetic field forms a weak mirror with approximately 1.6 to 1 ratio. $B_{\min}$ is 670, 820, and 1000 gauss, in the oscillographs from top to bottom. Pressure is 0.6 μ Hg of H_2. $V_0 = 10$ kV, $I_c = 1$ A (in vacuum).

Figure 4 also shows the output of a photomultiplier illuminated by a polyvinyl scintillator. The detector was mounted outside the vacuum, and was wrapped in aluminum foil. X rays were detected through a $\frac{3}{4}$-in. Plexiglas window, were strongly attenuated by a Pyrex glass window, and did not penetrate the $\frac{1}{8}$-in. bronze wall of the chamber. Note that the x rays continue for about 100 μsec after the beam current has gone to zero, clearly indicating that the x rays are not produced solely by the primary beam electrons. By pointing the scintillator, it was possible to show that the x rays were generated primarily at the side walls. (Similar measurements of x rays have not yet been made for other gases.)

We can use the small-signal theory of the beam-plasma interaction to help interpret these results. The initial cyclotron-frequency oscillations excite the plasma electrons sufficiently so that they begin to ionize the gas, and the plasma density grows exponentially with time. Thus, by the end of the first or second beam breakup, ω_p exceeds ω_{ce}, and the oscillations become essentially longitudinal and have their highest frequency at about ω_p. The plasma electrons, driven by the beam through the longitudinal oscillation mode, continue to make ionizing and exciting collisions, and the limiting plasma density is presumably governed by the rate of leakage out of the system.

It is anticipated that the use of longer pulses, higher power beams, and better and stronger mirror fields will result in the production of denser and hotter plasmas. Such experiments are now being prepared.

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MICROWAVE EMISSION AND ABSORPTION AT CYCLOTRON HARMONICS OF A WARM PLASMA

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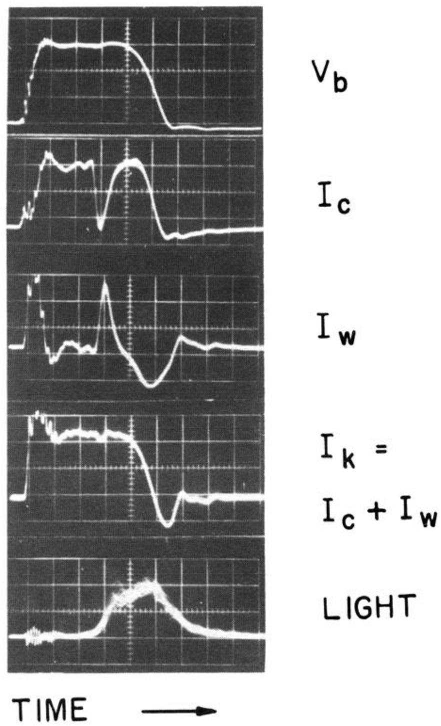
We present results of measurements on the microwave emission from and absorption by a plasma column in a magnetic field. In the experiments the plasma frequency ω_p was of the order of, or greater than, the microwave radian frequency ω, and the electron collision frequencies were much less than ω ($10^{-4} \leq \nu/\omega \leq 10^{-1}$). Under such conditions, the measured magnitudes and spectra of the emitted and absorbed radiation are found to differ greatly from those predicted theoretically on the basis of models of an infinite, uniform plasma near thermal equilibrium. The magnitudes of the emission and absorption lines of the electron cyclotron harmonics are several orders of magnitude greater than those calculated for a warm plasma with a Maxwellian distribution of electron velocities. Furthermore, the observed line shapes are usually not Lorentzian.

Calculations[1] show that the power absorption coefficient $\alpha = 2\,\mathrm{Im}k$ of a monochromatic plane wave, with a propagation vector $\vec{k}$ in a uniform warm plasma with a Maxwellian velocity distribution at a temperature T, exhibits a series of maxima at the harmonics of the electron cyclotron frequency $\omega_b = eB/m$, where B is the applied magnetic field. A condition for the appearance of these harmonics is that $\vec{k}$ be not exactly parallel to $\vec{B}$. The relative magnitude of the successive harmonics decreases approximately as $(\mathrm{Re}n)KT/mc^2$, where n is the complex refractive index of the plasma $\vec{n} = c\vec{k}/\omega$. In our experiments the refractive index $\mathrm{Re}n$ of the plasma was determined to be close to unity, and the mean electron energy lay between 1 and 10 eV; thus, contrary to observation, no significant variation in α should occur at harmonics higher than the second.

Since, in a plasma whose electrons have a Maxwellian distribution, the absorption and the incoherent emission are related by Kirchhoff's law, the emission spectrum should be similar to the predicted absorption spectrum. Therefore, successive harmonics in emission should decrease as $(\mathrm{Re}n)KT/mc^2$, and, as in the case of absorption, no emission peaks beyond the second should be observed.

In Fig. 1 are shown plots of the absorption of a microwave signal at a fixed frequency of 5000 Mc/sec as a function of the magnetic field B, for three different electron densities. In this experiment the positive column (diameter = 1 cm) of a weakly



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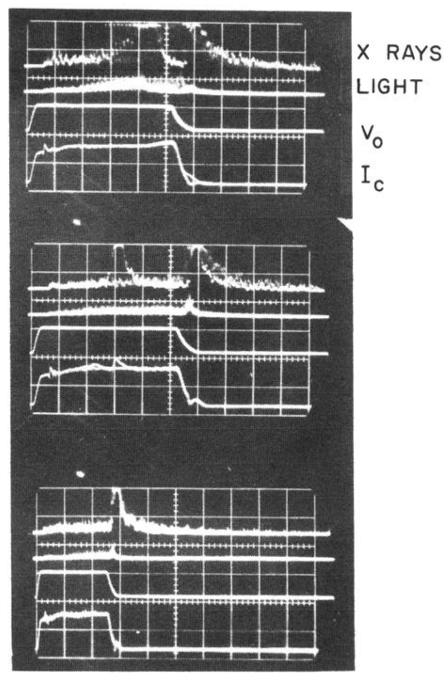

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