Enhanced Radiation from a Theta-Pinch Plasma*

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Radiation exceeding thermal bremsstrahlung by more than three orders of magnitude has been observed from a theta-pinch plasma. The spectrum consists of two broad and partially overlapping bands centered approximately at the electron plasma frequency and its first harmonic.

Electromagnetic radiation originating from the scattering of longitudinal plasma waves on each other may be a significant source of emission from nonthermal plasmas. Such mechanisms have been proposed theoretically[1,2] in order to interpret the phenomena of types II and III radio bursts associated with solar flares. We report here the observation of strongly enhanced radiation from a laboratory plasma at far-infrared wavelengths, where one normally expects that the only significant source of radiation is bremsstrahlung from free-free transitions of more or less uncorrelated electrons. We believe the observed enchanced emissions to be manifestations of "anomalous bremsstrahlung" from plasma waves.

The plasma was generated in a theta pinch with a 16-cm-i.d. quartz tube in two 20-cm-long coils spaced $\frac{1}{2}$ in. apart for side-on observations. The tube was filled to 18 mTorr with helium, and the initial plasma was generated with a spark discharge followed by the discharge of a "preheater" capacitor (0.5 μF, 25 kV). About 85 μsec after the preheater discharge, the driving field (~+3.5 kG in 0.8 μsec) was switched on at the peak of a reverse-bias field (~ −600 G in 40 μsec). The far-infrared radiation was observed side-on with a grating spectrometer and a liquid-helium cooled (1.9°K) InSb photoconductive detector in the 7-kG field of a superconducting magnet. Simultaneous side-on and end-on observations of visible spectral lines were made to determine the plasma (electron) density, temperature, and the average fluctuating electric fields. As usual, all data were recorded as photographs of oscilloscope traces.

Figure 1 shows a typical oscilloscope trace of the far-infrared detector monitoring the total or "white-light" emission of the plasma as a function of time from the initial switching on of the driving magnetic field. Strong far-infrared emission is evident within the first $1\frac{1}{2}$ μsec and, in fact, peaks in about 0.8 μsec, approximately the time it takes the driving field to reach its maximum. Figures 2 and 3 show the far-infrared spectrum at various moments during the first implosion. The data points are the averages of three separate spectral scans; during each scan, at least six exposures were made per wavelength setting. A two-banded spectrum is evident. The emission at the longer wavelengths is present at all times and reaches a peak intensity in about 0.7 μsec; at shorter wavelengths, the emission tends to grow with time both in intensity and in bandwidth, reaching a peak intensity at about 0.9 μsec.

These distinct differences in behavior suggest that different mechanisms are responsible for the emissions in the two bands. Were we instead to attribute the total emission to radiation at the electron plasma frequency, this would imply a

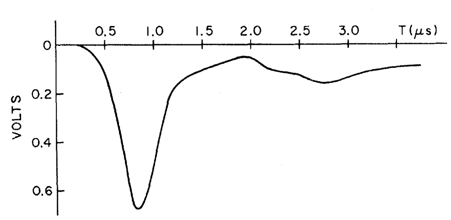

FIG. 1. Output signal of InSb detector, monitoring total (far-infrared) emission.

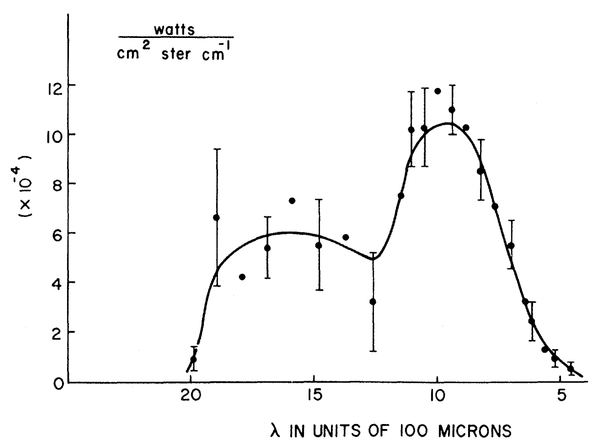

FIG. 2. (Far-infrared) emission spectrum at $T = 800$ nsec.

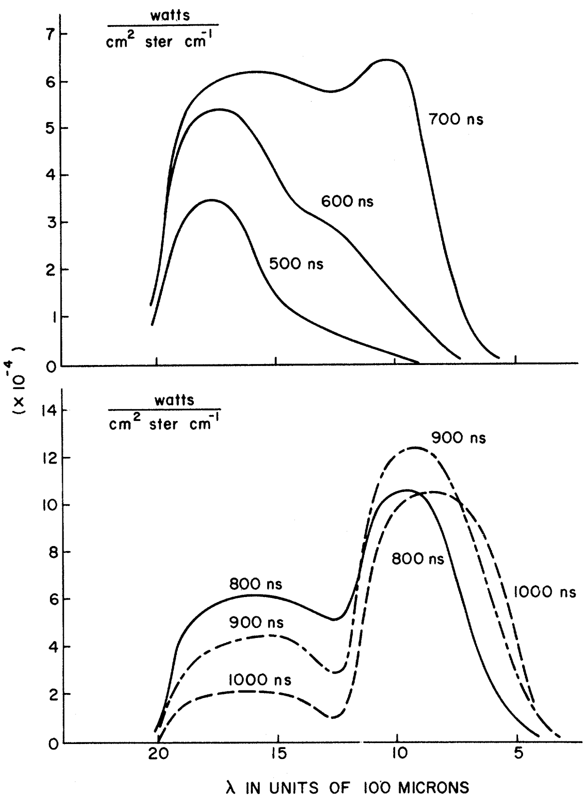

FIG. 3. The time development of (far-infrared) emission spectrum.

density range from 3×10^{14} cm^{-3} to about 7×10^{15} cm^{-3} within the plasma. Such a large density range is very unlikely and would be inconsistent with the results of a magnetic-probe analysis. The latter reveals fast diffusion of the magnetic field into the plasma during the initial implosion, rather than compression. An estimate of the actual electron density was obtained from the Stark width of the He I 4026-Å (2^3P-5^3D) line,[3] with resulting time- and space-averaged values of (1.1 and 1.2)$\times10^{14}$ cm^{-3}, from side-on and end-on observations, respectively. Measured line profiles were uniformly narrow (~0.3 Å) over a time period beginning well before the onset of the "strong" turbulence. While the above densities are probably characteristic of the early phases before the onset of the strong turbulence, these measured densities should correspond to the cooler and more tenuous plasma regions outside the "turbulent zone" at later times. Considering the diffusive character of the piston, a spatial distribution with peak densities of, say, $\sim4\times10^{14}$ cm^{-3} thus seems very reasonable. Identification of the first band (2000 to ~1200 μm) with radiation at the electron-plasma frequency would require densities from 3 $\times10^{14}$ to about 8×10^{14} cm^{-3}. If we remember that even a thermal plasma has a spectrum of plasma waves in the approximate frequency range $\omega_p \leq \omega \lesssim 1.4\omega_p$, then the required density range [($\approx$1.5-4)$\times10^{14}$ cm^{-3}] would come even closer to the measured density. When fully developed, the radiation bands are roughly in harmonic ratio. The implication of radiation at the electron-plasma frequency and its first harmonic is obvious.

The fact that the radiation is indeed nonthermal is evidenced (besides by its spectrum) by the unusually high levels of intensity attained in both bands. The theoretical intensity or surface brightness of an infinite slab of thermal helium plasma 5 cm thick, with $n_e = n_i = 5\times10^{14}$ cm^{-3} and $T_e = 50$ eV, calculated in the usual way, with collective effects neglected, is less than 10^{-6} W cm^{-2} sr^{-1}/cm^{-1}. Our measured peak intensities are about three orders of magnitude larger. (They were obtained from the calibration of the far-infrared system with a mercury arc lamp, an almost universal source in this wavelength region.[4])

Attempts to measure the spectrum of the fluctuating electric fields in the plasma by means of the plasma satellites of forbidden helium lines have so far been inconclusive. However, the average fluctuating electric field and the ion temperature, as determined from the widths of ionized helium lines,[5] attain values as high[6] as 15 kV/cm and 100 eV, respectively. The corresponding electron temperature is estimated to be about 50 eV from the appearance of impurity (C III and C IV) lines.

Judging from the magnetic-probe data, no well-defined shock appears to develop in the plasma. Thus, turbulence in a shock front should be ruled out as the source of the enhanced radiation. The turbulent fields are probably generated in the high current streams of the diffuse "piston". Indeed, the persistence of the far-infrared emission over the first $1\frac{1}{2}$ μsec, and the close correlation of the total intensity with the rising magnetic field, seem to bear this out.

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[6]Such field fluctuations exceed thermal fluctuations (calculated at the particle temperatures) by four or more orders of magnitude.

Apparent Universal Behavior of Fluctuation-Induced Diamagnetism in Superconductors*

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The dependence on temperature and magnetic field of the diamagnetism due to fluctuations above T_c, while showing marked deviations from the behavior expected on the basis of the Ginzburg-Landau theory, appears to follow a universal behavior if one introduces a new characteristic field H_s, which may be expressed in terms of other known material-dependent parameters.

We have previously reported[1] observation of a temperature-dependent diamagnetism above the critical temperature T_c due to thermal fluctuations of the superconducting order parameter Ψ. We have since extended these measurements to other materials (including type-II superconductors) and to much higher fields and temperatures; these results will be reported in detail elsewhere.[2] The purpose of this note is to show that these data are well described by an apparently universal function of appropriately scaled field and temperature variables. This empirically derived function deviates markedly from the behavior predicted[3,4] on the basis of the simple Ginzburg-Landau (GL) theory, especially for $T \gtrsim 2T_c$ and for fields comparable with $H_{c2}(0)$. These deviations demonstrate the expected breakdown of the GL theory in these regimes where short-wavelength fluctuations dominate, and where consequently the slow-variation approximations of the GL theory break down.[5] The apparent generality of our results suggests that there may exist a reasonably simple extension of the GL theory to deal with situations in which Ψ varies rapidly on the scale of $\xi(0)$, the zero-temperature GL coherence length. The attempt of Patton, Ambegaokar, and Wilkins[6] (PAW) to deal with the problem by means of an ad hoc cutoff energy is shown to have qualitative, but not quantitative, success.

Prange's calculation[4] of M', the magnetization due to thermal fluctuations, is exact within the framework of the GL theory. It is found that M' diverges at the temperature $T_{c2}(H)$, defined by the condition $H = H_{c2}(T_{c2})$, where the energy cost of a small fluctuation toward the superconducting state vanishes. Above T_{c2}, $M'(T)$ is predicted to fall off roughly as $(T-T_{c2})^{-1/2}$. In the temperature range near T_c where $H_{c2}(T)$ is linear in T, it is predicted that a field- and material-independent curve should be obtained if $M'/H^{1/2}T$ is plotted versus the dimensionless scaled temperature difference $(dH_{c2}/dT)(T-T_c)/H$. In particular, at the zero-field critical temperature T_c, it is predicted that

$$M'/H^{1/2}T_c = -0.323\Phi_0^{-3/2}k_B \qquad (1)$$

is a universal constant for all superconductors. Here Φ_0 is the flux quantum $hc/2e$. While our data show some of the qualitative features of Prange's result, they do not agree quantitatively nor do they scale so simply, except perhaps near T_{c2}.

The PAW theory attempts to correct for the overestimate in GL theory of short-wavelength fluctuations by introducing an unknown energy-cutoff parameter E into the fluctuation spectrum. As a result, they find that the magnetization is strongly depressed below the Prange value if $H > H^* \equiv mcE/\hbar e$ or if $T - T_c > T^* \equiv 4m\xi^2(0)T_cE/\hbar^2$, where $2m$ is the electronic pair mass. The expectation that the GL theory should break down when the characteristic wavelength over which the order parameter varies is smaller than $\xi(0)$ suggests that $E \approx \hbar^2/4m\xi^2(0)$, which corresponds to $H^* \approx H_{c2}(0)$ and $T^* \approx T_c$. Wavelengths as short as $\xi(0)$ occur for even the least energetic modes