posed on the electron distribution produced by resonant absorption and/or parametric instabilities near critical density. On the other hand, at maximum densities near $\frac{1}{10}n_c$, the hot-electron emission is neither peaked along the two 45° directions, nor is it sensitive to the plane of polarization of the incident 10.6-μm radiation. The details of electron emission below the quarter-critical density will be published elsewhere. However, the hot electron emission observed near $\frac{1}{10}n_c$ and $\frac{1}{4}n_c$ with S-polarized incident light is tentatively attributed to stimulated Raman scattering. The effective Maxwellian temperature of this distribution $kT_e \sim 10-15$ keV.

For efficient acceleration of electrons, the phase velocity must be of the order of the thermal velocity. If we assume that the "temperature" of the hot electrons measured here is roughly $\frac{1}{2}M_e V_p^2$, where V_p is the phase velocity of the electron plasma wave, then $V_p \sim 10^{10}$ cm/s. This is about two orders of magnitude higher than the phase velocity of the decay waves in the strong-damping limit ($k\lambda_D \sim 1$, where λ_D is the Debye length) where energy coupling into electrons would be most effective. Thus after trapping and subsequent acceleration by the plasmons, collisional damping, and not Landau damping, produces the electrons in the tail of the background distribution. Finally, we note that the maximum hot-electron energies and the effective Maxwellian distributions observed in these experiments are in good agreement with those predicted in simulations of the two-plasmon decay instability.[5]

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[(a)]Present address: Mason Laboratory, Yale University, New Haven, Conn. 06520.

[(b)]Present address: Department of Electrical Sciences and Engineering, University of California, Los Angeles, Cal.

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Collective Microwave Emission from Intense Elecron-Beam Interactions: Theory and Experiment

Gregory Benford, David Tzach, and Keith Kato
Physics Department, University of California at Irvine, Irvine, California 92717

and

Dean F. Smith
Department of Astrogeophysics, University of Colorado, Boulder, Colorado 80309

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High-power microwaves are observed in two clear frequency bands when an intense relativistic electron beam passes through an unmagnetized plasma. The high-frequency band has frequency which scales with ω_p and resembles radiation from processes in type-III solar bursts. Theory indicates beam-plasma stabilization may arise from radiative losses. The lower-frequency band, with frequency independent of ω_p, may represent conversion of electrostatic waves near the plasma boundary in inhomogeneities of size ~0.3 cm. Experiments in a magnetic field qualitatively agree with our models.

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Though the problem of collective emission from beam-plasma instabilities is old,[1-6] there is surprisingly little laboratory work.[7-9] Most theory has focused on type-III solar radiation bursts.[1-4] There are both weak-turbulence and strong-turbulence models for emission at the first plasma harmonic and above.[10-12] Though there is some laboratory work on collective emission by intense beams in a strong magnetic field,[7,8] there are no definitive observations without a field,

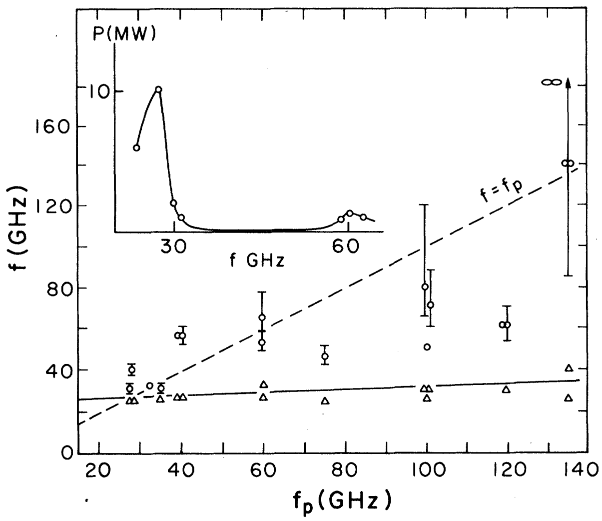

FIG. 1. Observed frequencies of two emission bands vs f_p, plasma frequency of density along tube axis. Dashed line is $f = f_p$. Typical spectrum appears in inset (power in magawatts, frequency in gigahertz).

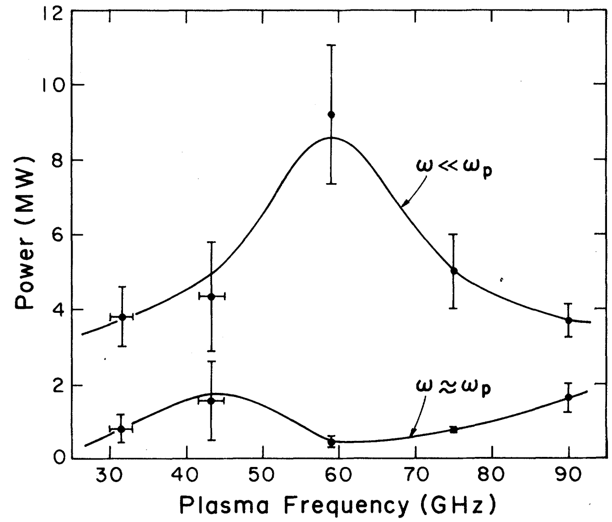

FIG. 2. Observed power in two bands vs plasma frequency of the axial density peak.

even though this is more typical of the type-III regime. This Letter reports experiments designed to explore the collective emission from strong beams penetrating a meter-long plasma cylinder, and compare with current theoretical ideas.[13-16]

We have observed radiation from an intense ($I \sim 50$ kA), relativistic ($\gamma = 3$), hollow ($r = 3$ cm) electron beam fired into a cylindrical, unmagnetized hydrogen plasma of density n_p. The central region filled rapidly as the beam moved downstream, propagating with high efficiency and achieving $>95\%$ current neutralization. The microwave horn was located 30 cm from the diode in a 1-m drift tube and was radially oriented. Emission fell into two well-defined bands: a low-frequency band with frequency f independent of n_p and a high-frequency band which scales with $n_p^{1/2}$ (Fig. 1). The lower band carried most of the power (Fig. 2). A *Ka*-band horn coupled the emission into a 30-m dispersive delay line used to measure f. Frequencies up to ~ 80 GHz were measured with reasonable accuracy and some emission appeared above 100 GHz. Further experimental details may be found in Refs. 7 and 8. Values of plasma frequency ω_p and n_p are given for the *peak* of the $n_p(r)$ profile, which was nearly Gaussian. Very little emission appeared between the two bands, implying two different, spatially separated processes (Fig. 1, inset). Each point in our data represents between two and seven shots at the relevant n_p. We observed isotropic radiation. The steel of the drift tube jacket ($R = 10$ cm) scatters radiation well, and so we observe no details of the emission isotropy. Power was calculated from observed flux at the horn.

To explain the $\omega \approx \omega_p$ emission (high-frequency band) we employ the traditional formalism devised to explain type-III solar radiation.[1-6] Weak-turbulence theory can apply if the beam is stabilized by modulational instability.[5] In the usual picture this instability produces solitons, which in turn scatter the resonant modes at a frequency ν^*, which at steady state equals the linear growth rate,[1]

$$\gamma_b = \tfrac{1}{2}\pi\omega_p (n_b/n_p)[\gamma(\Delta\theta)^2]^{-1}. \tag{1}$$

Energy moves from resonant modes E_0 to the large-k region; again, the steady-state rate is set by $\nu^* = \gamma_M$, where the modulational rate is[5]

$$\gamma_M = \omega_p (m_e/3m_i)^{1/2}(W_p/n_p T_e)^{1/2}. \tag{2}$$

Subscript e (i) refers to the plasma electrons (ions). However, damping of plasma waves at a rate ν can prevent soliton collapse if $\gamma_M < \nu$, while allowing growth if $\gamma_b > \nu$. In our experiments the collective radiative loss itself is large enough to fit these requirements, leading to a picture differing from the type-III case: There is no significant transfer of waves to high k, and $W_p \equiv \langle E^2\rangle/4\pi$ is comparable to the resonant field energy density, $E_0^2/4\pi$. Details of these calculations will appear elsewhere.[16]

Emission at $\sim\omega_p$ can occur when a plasma wave scatters from the polarization cloud of an ion and becomes electromagnetic. The background plasma can amplify this process as slow plasma waves pumped by the beam-plasma instability deliver energy to the radiation passing through. This yields a power[1]

$$P(\omega_p) = VJ_1(\omega_p)e^{\mu L}, \tag{3}$$

where $J_1(\omega_p)$ is the volume emissivity, μ the amplification factor, L a mean distance over which amplification occurs, and V the emitting plasma volume, about 3000 cm^3. The spectral width of the high-frequency band ($\delta\omega/\omega \approx \delta\omega_p/\omega_p$) sets a spatial limit on the distance an electromagnetic wave can travel and still be amplified at $\sim\omega_p(r)$ by the background electrostatic waves at $r+\delta r$. This leads to $L \lesssim 6$ cm. To satisfy $\gamma_b > \nu > \gamma_m$, set $\gamma_M = \epsilon\gamma_b$, $\epsilon < 1$. Using this in Eqs. (1) and (2) we find W_p. From type-III–burst theory,[1]

$$\mu = \pi\omega_p^2 W_p / 24\sqrt{3}\, n_p m v_e^3 k_p c, \tag{4}$$

where k_p is a typical wave number for the spectrum (typically $k_p \sim \omega_p/c$). Writing the plasma electron temperature T in electronvolts, peak plasma density as $n_{13} = n_p/(10^{13}\ \mathrm{cm}^3)$, and $n_* = n_b/(4\times 10^{10}\ \mathrm{cm}^3)$, we find $\mu = 110\, n^2\epsilon^2 n_{13}^{-3/2} T^{-1/2}$. In our experiments $T \approx 5$, so that $\mu^{-1} = 0.18$ cm. Here we chose $\epsilon = \frac{1}{3}$, a value which satisfies $\gamma_b > \nu > \gamma_M$. If the emitting plasma volume is $V_4 = V/(10^4\ \mathrm{cm}^3)$, then $\nu = 10^9 P/(T n_{13} V_4)\ \mathrm{sec}^{-1}$, with P the observed power in megawatts ($P \sim 1$). Then $\gamma_b > \nu$ means $1.5\, n_* T n_{13}^{1/2}\, V_4 > P$, which is satisfied, and choosing $\epsilon = \frac{1}{3}$ means $W_p/n_p T = 0.39(\epsilon n_*/n_{13})^2$, and so $\epsilon < 1$ keeps us within the weak-turbulence regime, $W_p \ll n_p T$. With use of Eq. (3), $P \sim 5\times 10^{-8} \times e^{\mu L} W$, and so our estimate $\mu^{-1} = 0.18$ cm means that an amplification length $L \approx 5.5$ cm will yield the required $P \sim$ MW. This agrees with the estimate above that a beam electron moving with a typical angle $\Delta\theta \approx 30°$ will excite electrostatic waves over a distance ~ 6 cm in the peak plasma region of radius ~ 3 cm. However, the power is not a sensitive check of the theory, since L is not well known and cannot be directly observed. A further prediction, however, is borne out: Radiation follows the beam voltage to within the ~ 5-ns resolution of the experiment. This follows because the plasma wave-group velocity, $v_g = 3v_e^2 k/\omega_p \sim 10^6$ cm/sec, is slow, and thus longitudinal waves are exhausted in amplifying the last of the escaping radiation. They do not survive to radiate after the beam is gone.

The low-frequency band emission has two distinct features: (1) The power appears at frequencies typical of the local plasma frequencies $\omega_p(r)$ within the outer 2 cm of the chamber; (2) power peaks at ≈ 60 GHz, a peak not seen in the high-frequency band. A cavity mode with these features is unlikely. We have developed a theory based on conversion of longitudinal, beam-driven waves as they strike density gradients near the plasma boundary. Consider random, spherical inhomogeneities of dimensionless magnitude ξ, volume V, and scale length d,

$$\delta n_p(r) = n_p(r)(\xi V/d^2)\exp(-x^2/d^2)$$

with spherical radius x. Using a fully electromagnetic Valsov equation, we can calculate the power emitted from N such fluctuations[14,15]

$$P' = \frac{NV^2\xi^2 E^2 v_e \omega_p^2(r)}{18\pi v_b c^3}\exp[-2(kd)^2]. \tag{5}$$

We take $k \approx v_b/\omega_p(r)$, v_b the beam velocity, and v_e the electron thermal velocity. The electrostatic energy density E^2 we set as $qn_p T_e$ and estimate that $q \approx 0.1$. The exponential in (5) implies that radiation is most efficient for wavelengths exceeding d, i.e., sharp gradients are most effective. If we scale the combination $E^2\omega_p^4 \propto n_p^{\,y}$, Eq. (5) has a peak at a density which varies as $y^{1/2}$. Using the observed peak at f_p^* in Fig. 2, we can estimate $d = [(14.2\ \mathrm{GHz})/f_p^*]y^{1/2}$ cm. With $f_p^* = 60$ GHz, $d \approx 0.24\, y^{1/2}$. Plausible values of y lie between 1 and 3, suggesting $d \sim 0.3$ cm. This agrees with our Langmuir-probe measurements, which find significant variations on this scale for $r > 8$ cm. Equation (5) then yields a peak power

$$P' = (NV^2)_4 \xi_{-1}^2\, q T_1^{3/2}(3\times 10^6)\ \mathrm{W},$$

where all subscripts indicate $\xi_{-1} = 10\,\xi$, etc., and T_1 is plasma temperature in units of 10 eV. The observed ~ 10 MW peak power is consistent with modest values of ξ_{-1} and q. The low-frequency band spectrum is nearly independent of n_p, the axis density, indicating that emission occurs near the steep plasma boundary. To check this idea we measured emission in an external magnetic field large enough (>150 G) to make the electron Larmor radius smaller than the drift-tube radius. Power dropped a factor of 10^{-2} with $B > 200$ G, implying that removal of beam electrons from the outer zone substantially inhibits emission, probably by reducing the beam-plasma instability growth rate, which is proportional to n_b.

These deductions are consistent also with the absence of emission at $\omega \approx \omega_p(r)$ typical of regions 3 cm $< r <$ 8 cm. The beam expands as it propagates, so a fall in n_b enters into Eq. (3) exponentially through μ. Thus no radiation emerges until the beam reaches the region of significant density inhomogeneities, $r \geq 8$ cm, because electrostatic wave amplitudes are small. The large density gradients for $r > 8$ cm, however, make possible significant collective emission.

These experiments appear to make contact for the first time with the phenomena of type-III-burst theory, and with earlier work on emission from inhomogeneities.[14] The nonlinear theory employed points to a regime in which the radiation itself plays an important dynamical role in the beam-plasma instability. These results are particularly interesting because they have been discovered with use of intense electron beams, which themselves have many applications. Radiation may be an important diagnostic of beam conditions and propagation, and the nonlinear states of the turbulence.

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Fluctuations in the Ion-Cyclotron-Frequency Range: Possible Measurement of T_e/T_i in Tokamaks

J. P. M. Schmitt and T. Lehner
Laboratoire de Physique des Milieux Ionisés, Groupe de Recherche du Centre National de la Recherche Scientifique, Ecole Polytechnique, F-91128 Palaiseau, France
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The thermal density fluctuations in a typical tokamak plasma, for a wave vector perpendicular to the magnetic field and for a wavelength of the order of the ion gyroradius, are shown to be maximum at the frequency of the zero-group-velocity ion cyclotron waves. This frequency is sensitive to the ion- to electron-temperature ratio and the spectrum remains peaked despite a poor scattering-vector definition and destabilizing effects such as presence of a current. Possible applications to tokamak diagnosis are emphasized.

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Diagnosis by charge exchange is currently used for ion temperature measurement in magnetically confined fusion plasma but it will become unsuitable for the forthcoming large machines. Infrared-light scattering[1] will hopefully be an alternative way of measuring T_i. However, the only way considered so far was to scatter from ion acoustic fluctuations[2] and, even for the most advanced source, a CO_2 laser,[3] this technique suffers from the low scattering level and difficulty