Detailed Spectra of High-Power Broadband Microwave Emission from Intense Electron-Beam–Plasma Interactions

Keith G. Kato, Gregory Benford, and David Tzach
Department of Physics, University of California, Irvine, California 92717
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For a relativistic electron beam penetrating an unmagnetized plasma, a change is seen in the emission spectrum from $\omega \sim \omega_p, 2\omega_p$ line emission to continuous $\omega \gg \omega_p$ emission, as $n_b/n_p \to 1$. High-power (of order megawatts per gigahertz) broadband radiation up to ~100 GHz suggests collective Compton-boosting mechanisms in a new regime of *superstrong* turbulence. Highly directional emission and magnetic field dependence agree with this interpretation.

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There is much recent interest in mechanisms whereby unstable electrostatic waves of a beam-plasma system convert into electromagnetic radiation. This basic problem applies to such diverse phenomena as auroral kilometric emission,[1,2] type-III solar bursts,[3-5] and plasma ω_p radiation in tokamaks.[6]

Two classes of theory dominate the discussion: weak turbulence (Thompson-type scattering of plasma waves of ion inhomogeneities to produce ω_p radiation[7,8]) and strong turbulence (nonlinear electric-field terms driving, via the ponderomotive force, the formation of low-density solitons which emit ω_p and $2\omega_p$ radiation as they collapse[4]).

Both theory and experiment have concentrated on weakly perturbing beams ($n_b/n_p \ll 1$) which are at best mildly relativistic.[9,10] Here we report detailed spectra from experiments with relativistic electrons ($\gamma \approx 3$) and $0.01 < n_b/n_p < 1$, with n_b (n_p) the beam (plasma) density. Because the emission is wholly unanticipated by either theory we call this the *superstrong* regime of beam-plasma turbulence.

In these experiments we fire an intense, annular, pulsed, relativistic electron beam along the axis of a plasma column and observe the radiation through radial side ports of the drift tube.[11] The electron accelerator is a standard Marx generator/pulse-forming transmission-line system. Typical operating values are $I = 128$ kA, $V = 893$ kV ($\gamma = 2.75$), 50 ns full width at half maximum, and 80 ns total pulse. The accelerator diode has an annular graphite cathode ($r \simeq 3$ cm; $\Delta r \simeq 1$ cm) with both foil and foilless operation. The drift-tube chamber is 20 cm diam × 200 cm long, with suitable field coils to produce uniform axial magnetic fields B. The plasma source is a hydrated-Ti stack-washer gun, and plasma density is monitored by a 140-GHz microwave interferometer. The spectrum is analyzed by a fifteen-channel spectrometer using two waveguide systems and two grating systems. This gives unequivocal determination of radiation frequency, simultaneous broadband frequency coverage from 5.85 to 40 GHz in 2.3-GHz bin widths, and absolute power measurements.[12] Values of n_b vary in the chamber because of thermal spreading. We give n_b at the anode; values in the region immediately near the microwave horns are lower by a factor of ~0.1.

Figure 1 shows, for $B = 0$, a sample of our spectra as $f_p \equiv \omega_p/2\pi$ changes. Figure 1(a) has $f_p = 5.8$ GHz and shows a broadband plateau starting at about 20 GHz. The plateau shows little sign of rolloff as high as the sixth harmonic. Cylindrical modes have frequencies $\lesssim 1$ GHz and cannot affect our results. Unfortunately, the f_p bin of the spectrometer was not active for these tests, and so we could not detect f_p emission. Figure 1(b) has $f_p = 24.7$ GHz, and the broadband plateau remains. Any ostensive f_p emission

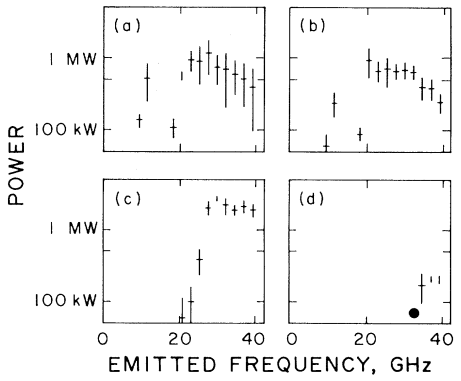

FIG. 1. Power spectrum for plasma frequency f_p of (a) 5.8 GHz; (b) 24.7 GHz; (c) 74.2 GHz; (d) 167 GHz. Power is given in 1/2.2 W/GHz. As f_p rises the broadband emission moves to higher frequencies.

would be within the broadband region, but no prominent feature appears above the broadband power level. Figure 1(c) has $f_p = 74.2$ GHz, and the broadband plateau is beginning to show some weak f_p dependence by moving upward in frequency and out of our observational window. Figure 1(d) has $f_p = 167$ GHz and little radiation.

The presence of radiation below f_p is not surprising, because the plasma has a spatial dependence $\sim\cos^2(\pi r/2R)$ and the beam can interact with plasma densities lower than the nominal value cited. Radiation far above $2f_p$ is unexpected, and we hypothesize the following mechanism.

A plasma wave $(\omega, \vec{k})$ and beam electron $(\vec{p} = \gamma m\vec{v})$ collide at angle θ, and an EM wave $(\omega', \vec{k}')$ and beam electron $(\vec{p}' = \gamma' m\vec{v}')$ emerge at angle θ'. If we write the invariant four-momenta and use the approximation $|\vec{v}'| \simeq |\vec{v}|$ and the electromagnetic dispersion relation $\omega'^2 = \omega_p^2 + k'^2c^2$, then[13]

$$\omega[1 - (kv/\omega)\cos\theta] = \omega'[1 - (k'v'/\omega')\cos\theta']. \quad (1)$$

If $\omega' \simeq k'c \gg \omega_p$ and $\theta' \ll 1$, then

$$\omega' \simeq \frac{2\gamma^2\omega_p[1 - (kv'/\omega)\cos\theta]}{1 + \gamma^2\theta'^2 + (\gamma\omega_p/\omega)^2}. \quad (2)$$

This yields a maximum possible frequency

$$\omega_{max}' \simeq 2\gamma^2\omega_p(1 - \cos\theta). \quad (3)$$

Since for our experiments $\gamma = 2.75$, the frequency increase can be large if the angular factor is ~ 1. The appearance of a γ^2 factor comes from the Compton effect ("Compton boosting").

Single-particle kinematics can thus explain high frequencies, but the high emitted power implies a collective process. Beam-plasma instability generates strong Langmuir turbulence[4] and beam bunching.[11] We hypothesize a "collision" between bunched beam electrons and large-amplitude electrostatic waves generated by instability. We shall publish separately a two-step theory: bunching, followed by Compton boosting of electrostatic waves into electromagnetic emission. (This differs from a one-step electromagnetic instability, which can be suppressed by beam velocity spread.[13]) The required beam bunching, $\delta n_b/n_b \leq 0.1$, seems plausible.

The beam opening angle θ_b fixes a lower bound on the angle θ between electrons and plasma waves since we deal with beam-generated waves. The intrinsic angular spread of the waves, φ, will enter into θ roughly as $\theta \geq \theta_b + \varphi$. Thus a complex angular average will enter into any observed spectrum. This, plus the range of available outgoing angles θ', means that emission must be broadband, not a set of lines.

This is distinctly different from earlier nonrelativistic work,[14] which observed some broadband electro*static* emission for $\omega \lesssim 3\omega_p$ at power levels $\sim 10^{-10}$ of ours.

In free-electron–laser language, we use an electrostatic wiggler, and beam bunching forces coherent emission. Our wiggler does not have a sharp k like free-electron lasers, because the unstable electrostatic spectrum has an unavoidable width. In free-electron lasers using magnetic wigglers,[15] the highest available k is ~ 6 cm^{-1}, whereas ours is ~ 20 cm^{-1}. Mechanical wigglers have as strength parameter $\epsilon \equiv \Omega_w/kc \sim 1$, with Ω_w the cyclotron frequency of the wiggler's magnetic field. For our work, with use of beam electron trapping in the electrostatic waves to determine the wave strength, $\epsilon \sim 1$ as well, and use of free-electron–laser growth rates[15] gives short amplification time of order nanoseconds. Thus there is an underlying analogy, though in our work the wiggler is spontaneously produced.

A convincing test of (3) would be a cutoff in the spectrum at $\omega \sim \gamma^2\theta^2\omega_p$. We used our grating in second- and third-order operation, ~ 120 GHz, and found significant power at frequencies up to the limit. While this indicates broad emission, for most values of ω_p the cutoff lies above 120 GHz. The 5.8-GHz case may be complicated by production of low–phase-velocity plasma waves, which (2) shows can yield very high frequencies. Future work in the ~ 200-GHz range may provide information on the kinematic cutoff condition, (3).

Figure 2 shows, for $B = 0$ and $f_p = 18$ GHz, how the spectrum changes as n_b/n_p falls. Figure 2(a) has $n_b/n_p \leq 0.70$ and is the baseline spectrum. These experiments were performed with extremely careful control over f_p. Figure 2(a) shows a prominent rise in power of the bin near 20 GHz relative to its neighbors, and a pronounced roll-off in power in the higher frequencies of the broadband region. Figure 2(b) has $n_b/n_p \leq 0.17$, and shows prominent f_p, $2f_p$ emission with $P(f_p)/P(2f_p) \simeq 5$. Figure 2(c) has $n_b/n_p \leq 0.01$, and shows only a prominent f_p emission above a general power level in all other channels.

From these and other data we extract several salient features: (a) Total emitted power scales roughly as n_b^2 and is $\sim 10^6$ times that of a single-particle (incoherent) process. This was found as well in earlier experiments with the same setup.[11,16] (b) Total power is not strongly dependent

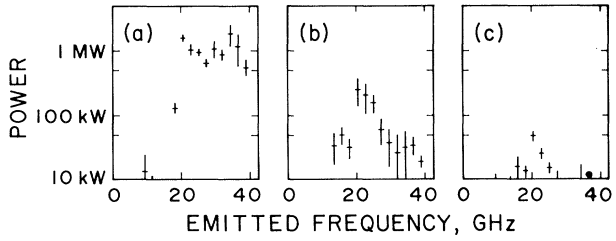

FIG. 2. Dependence of power on n_b with $f_p = 18$ GHz. (a) $n_b = n_0 = 10^{12}/\mathrm{cm}^3$; (b) $n_b = n_0/4$; (c) $n_b = n_0/50$. As n_b falls, lines at $\sim f_p$ and $\sim 2f_p$ become more prominent.

on either beam energy or n_p. (c) The broadband radiation is highly directional, with maximum power received at a pickup angle corresponding to the opening half-angle (15°) of the beam (as measured by damage rods), and power lying within about a 60° range. We instrumented two ports of the drift tube with 26.5–40.0-GHz waveguide systems; one waveguide pickup pointed directly radially inward, as before, and the other (located farther down the drift tube to see approximately the same volume) at a fixed angle. We measured the ratio of power fluxes for these stations as a function of pickup angle.

We expect that electron momentum dominates the kinematics; hence the maximum. The ~60° range of radiation is consistent with the $1/\gamma$ half-angle expected from the radiation of relativistic particles.

Application of a weak magnetic field B_z demonstrates that f_p emission has a different mechanism from broadband emission. These experiments were performed with a Ti foil anode to ensure consistent diode behavior. As B_z increases from 0 to 800 G, the f_p line disappears while the broadband emission remains. Figure 3(a) shows, for $f_p = 18$ GHz and a Ti foil anode, the case $B = 0$; Fig. 3(b) shows the case $B = 800$ G where it is clear that the f_p line is gone. Figure 3(c) plots the power ratio of the f_p bin to the interpolated value of the f_p bin (using adjacent bins) as a function of B. The f_p line disappears at about 400 G, which is understandable as a change in the linear-wave dispersion relation. For a Langmuir wave traveling at angle θ with respect to an external magnetic field, the dispersion relation is

$$\omega^2 = \omega_p^2\left(1 + \frac{3k^2}{\omega_p^2}\frac{k_B T_e}{m_e} + \frac{\omega_{ce}^2}{\omega_p^2}\sin^2\theta\right). \quad (4)$$

For our experiment, $k \simeq \omega_p/v_b \simeq \omega_p/c$, $T_e \sim 5$ eV

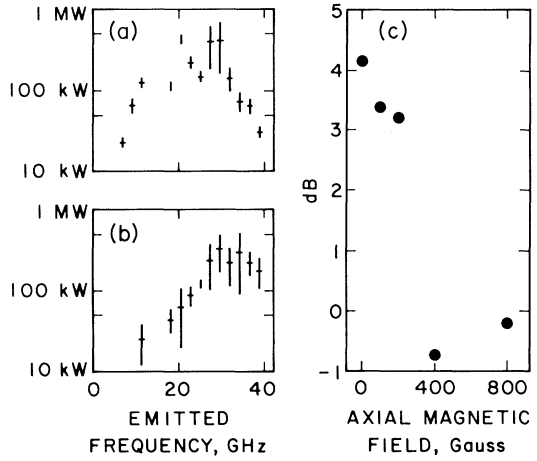

FIG. 3. Dependence of $\sim f_p$ line on axial field B_z. (a) $B_z = 0$, a prominent f_p line; (b) $B_z = 800$ G, f_p line gone. (c) Dependence of $f \sim f_p$ emission as B_z increases.

from Thompson scattering experiments on similar plasmas, and $\theta \simeq 15°$ by both our damage-rod measurements and directivity measurements. The thermal and magnetic parts of the dispersion relation become equal at 135 G, and at 400 G the magnetic term is nine times the size of the thermal term. This apparently affects the line emission but not the Compton-boosted broadband radiation.

Further experiments and theory will be published later.

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