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Resonator amplification of microwave emission from a relativistic beam-plasma system

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Electromagnetic emission produced by a propagating electron beam in a cylindrical drift chamber can be amplified by axially reflecting screens. Radiation appears at the first and second plasma harmonics with linewidths $\sim 0.1 \nu_p$. Amplification scales with ν_p^2 and lags electron-beam voltage by several hundred nanoseconds, implying that electrostatic waves moving at the electron thermal speed must traverse the resonator before amplification begins. Rotating the reflectors beyond 30° lessens amplification, suggesting a broad reflection property.

I. INTRODUCTION

While beam-plasma systems electromagnetically radiate at ν_p, the plasma frequency, and $2\nu_p$, there are several models for the detailed processes which produce this.[1-10] We have studied this phenomenon before, considering wave-wave mixing and soliton radiation as potential explanations. Here we detail experiments which explore how emission can be increased by trapping plasma electrostatic waves in the propagation chamber. These methods can have practical use in plasma diagnostics, and in ionizing gas by increasing the ionizing wave strength.

II. EXPERIMENT

In our experiments[3] we fired a 1-μs, 15-kA, 400-keV relativistic electron beam (REB) from a vacuum diode connected directly to a 27-stage, 10-kJ Marx generator. We used either a 5-cm-diam annular graphite cathode and a stainless-steel screen anode at 4-cm anode-cathode distance, or else a foilless configuration. In vacuum, the voltage peaks in 150 ns and decays in 1.5 μs from diode impedance collapse.

The beam propagates into a 20-cm-diam, 1.5-m-long drift tube which is filled with plasma produced by two or four small TiH$_2$ plasma guns. We fired the beam within 50 μs of the plasma gun discharge to avoid diode shorting from the plasma and neutrals from recombination. We selected delay times to study varying values of beam current I_b, which yield different beam-plasma growth rates. The plasma density was measured at two different points along the drift tube by a symmetric system of two-microwave interferometers using one source, a 40-GHz Gunn oscillator.[2] The two interferometer traces were recorded on a double-beam oscilloscope for measuring axial gradients in plasma density. A homogeneous axial magnetic field of a few kilogauss, provided by four 3-ft-diam coils, confined the plasma and the beam.

The microwave receiving system is composed of five horns for the bands X, Ku, K, Ka, V. The 8–40-GHz range was divided in seven channels recorded in parallel by a 100-MHz, nine-channel fast waveform analyzer, LeCroy 3500. The remaining two channels of the analyzer recorded beam voltage and current. For high-frequency detection we used a V- and N-band detector, connected to the V-band horn, using a directional coupler and a $V \rightarrow N$ transition. The signals from these two detectors were recorded on fast oscilloscopes and cameras.

Our software provides after each shot (a) the voltage signals from the detectors, (b) the absolute calibrated power and energy for each channel, together with (c) the power and energy spectrum of the shot at different times or (d) the spectrum of the peak power of each channel.

We used a 5-kV voltage on the two plasma guns connected in parallel through 4-Ω resistors, mounted at the far end of the drift tube from the REB diode, and a 2-kG axial magnetic field. It takes 15–20 μs for the plasma to fill the drift tube and ~ 50 μs to short the diode. The magnetic field improves the axial homogeneity in plasma density, but we still had an axial plasma frequency gradient $\Delta\nu_p \sim 6$ GHz in the clear tube, as measured by the two interferometers. We scan for different plasma frequencies by changing the delay time t_d between the beam and the plasma discharge with 15 μs $< t_d <$ 50 μs.

To turn our propagation tube into a resonant chamber, we first installed two parallel metal screens fixed normal to the beam (Fig. 1). These allow plasma and beam to flow through, but reflect microwaves from the several-millimeter-sized screen openings. The screens had a diameter $D = 21$ cm and separation $L = 66$ cm. Separation was adjusted by turning long screws. We also covered the tube walls with microwave absorber material to avoid complicating reflections, leaving windows for receiving and interferometer horns.

III. OBSERVATIONS

We found that waiting until beam-plasma collisions had completed ionization led to a stationary plasma density. This appeared as a sharp plasma line after about 400-ns delay time. Figure 2 displays a typical emission at 20 GHz. Emission at 40 GHz was 10^{-3} times smaller. There was also emission below ν_p in the first quarter of the beam pulse. We found this had an exponential spectrum, consistent with reflexing, as we observed before.[10] As beam propagation improved, this vanished.

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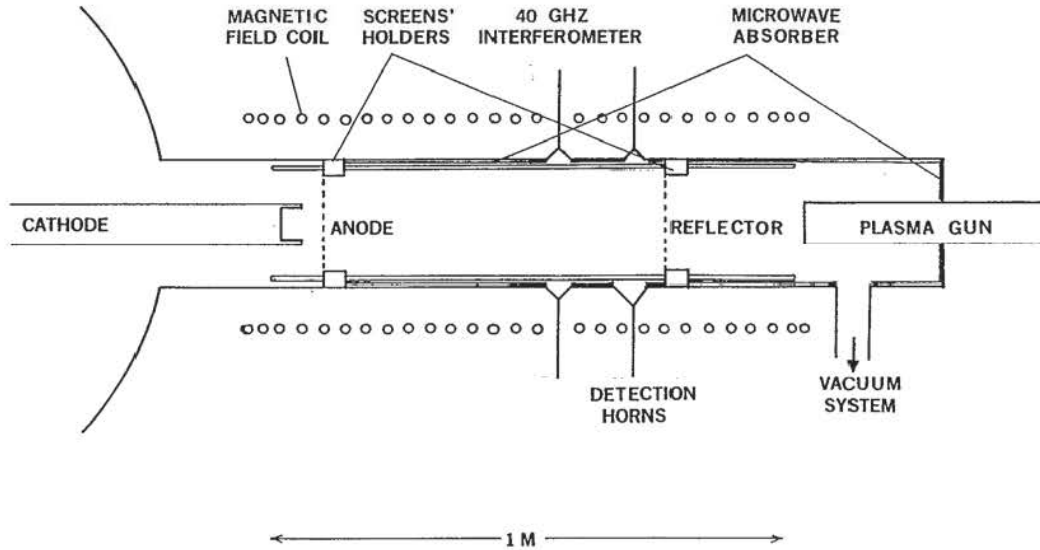V = 450 KV

I = 16 KA

$B_Z = 1$ KGAUSS

FIG. 1. Experiment configuration.

We found that addition of the reflecting screens generally enhanced emission, despite some loss of beam current. Figure 3 displays (top) amplification A varying roughly as v_p^2 up to our measurement limit, 40 GHz. The lower part shows a typical series of shots with fixed plasma frequency, with amplification by about a factor of 3 at the peak. One of the complications of such measurements appears in Fig. 4. The plasma density rises more quickly with reflectors, presumably because the increased electrostatic wave intensity in the cavity increases the ionization rate. The beam terminates at a microsecond and density slowly falls. However, without the reflector, density remains higher longer. This complicates a clean observation of the emitted plasma line.

We could slant the screens individually with respect to the axial line. We found no significant decrease in amplification with this slant angle, θ, until $\theta > 30°$.

We found a systematic delay in amplification, i.e., power rose in a curve echoing the beam current with a delay time

$$T = 50 \text{ ns} + 75 \text{ ns} \left[(v/10 \text{ GHz}) - I \right]. \quad (1)$$

Similarly, amplification lagged the fall in beam current.

Because the reflector separation is 66 cm, much larger than the resonant beam-plasma wavelength $\lambda_0 \simeq v_b / v_p \sim$ cm, we can regard the linearly unstable electrostatic waves as essentially propagating in an infinite medium, and so use a plane-wave picture, as usual. If these waves decay into shorter wavelengths, this picture would alter.

The important point is that we cannot measure either the electrostatic or electromagnetic wave properties in the chamber, because the relativistic electron beam noise swamps all probes inserted, and indeed electron impact often destroys them. Probably the electromagnetic waves have wavelength

$$\lambda \simeq 2\pi c (\omega^2 - \omega_p^2)^{-1/2} \simeq \frac{2\pi c}{\Delta \omega}$$

with linewidth $\Delta \omega$. For our observed linewidths ~ 5 GHz, this yields about 60 cm for the electromagnetic waters, which means they are roughly of the chamber size. Thus the entire wave picture is probably complex and not easily analyzed. Since we cannot measure such aspects, we concentrate on the phenomena of amplification, in the spirit of an exploratory experiment.

IV. MODELING

An obvious agent for amplification is the enhanced assistance of electrostatic waves in the cavity, built up by reflections along the chamber (Fig. 5). These waves can act like a hot reservoir of energy for electromagnetic waves passing quickly outward, enhancing the original emission mechanism. Also, colliding electrostatic waves could increase emission at $2v_p$.

An electromagnetic wave of power P reflecting from one end of a one-dimensional box with efficiency e can then reflect from the second (emitting) surface with efficiency h. Allowing for no side losses, the power P^* in the cavity is then

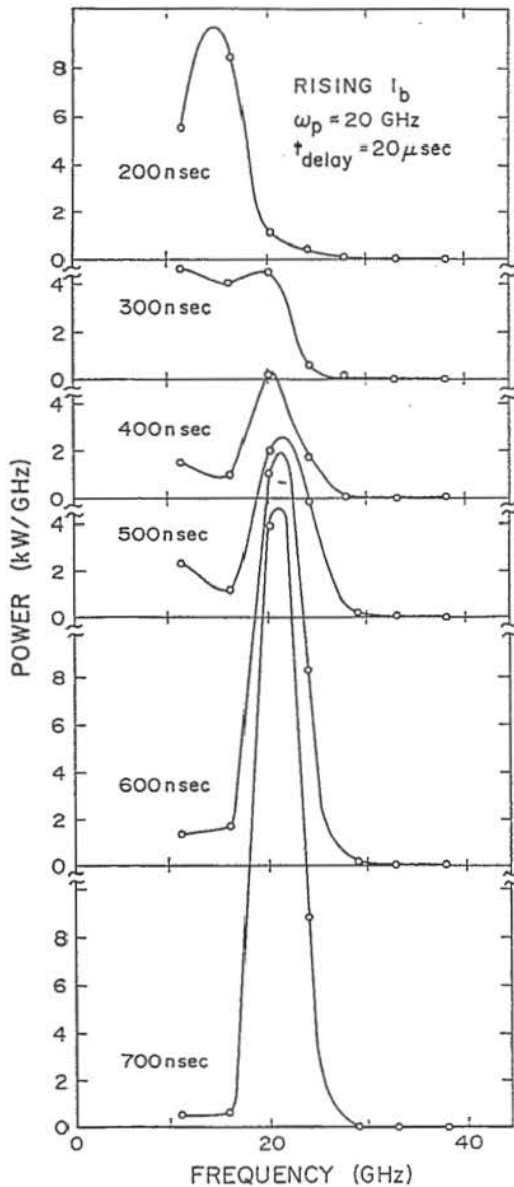$$P^* = P \frac{1 + \epsilon}{1 - \eta \epsilon}. \quad (2)$$

FIG. 2. Typical electromagnetic power as beam current rises slowly, completing ionization. Later times in the pulse yield clear plasma fundamental lines.

FIG. 3. (Top) Amplification of emitted power vs frequency of the plasma line. (Bottom) A typical series of shots with and without reflectors.

If $\eta = \epsilon = 0.9$, then $P^*/P = 10$, the largest amplification we saw. This is a plausible result, considering that our cavity necessarily had side losses from the microwave absorber, and that observed reflection efficiencies[11] are quite high, ~98%.

Generally the efficiency of a perfectly reflecting surface which suffers side losses because the reflected radiation cone has an opening angle ϕ is

$$\epsilon^* = (1 + 4L \sin \phi/D)^{-1}. \quad (3)$$

For our experiment, $L/D = 3.13$, and Eq. (2) yields a drop of 94% for a 30° tilt of the screens. While we see a fall of about 50% for a 30° slant of a single screen, this suggests that side losses are not as important as simple theory implies.
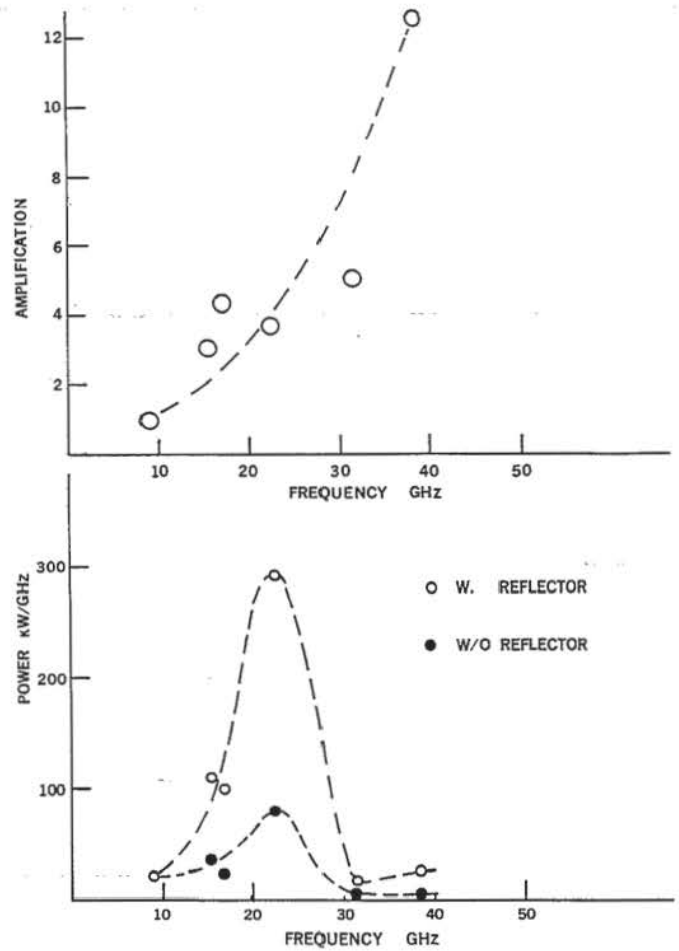
The observed time delay, Eq. (1) may arise from the cavity's need to establish a standing electrostatic wave, so the system builds up wave intensity. Electromagnetic reflections would do this within a few nanoseconds, and we expect it does occur. Electrostatic transport across the length by Langmuir waves at their phase velocity takes a time

$$t_p = L(k\lambda_D)/v_e = 500 \text{ ns}(k\lambda_D)(T/10 \text{ eV})^{-1/2}, \quad (4)$$

where we choose the plasma temperature T as about 10 eV, based on numerical solution of the heating equations.[12] For $(k\lambda_D) \approx 0.3$ this could describe Eq. (1). Transport at the group velocity takes

$$t_g = 210 \text{ ns}(k\lambda_D)^{-1}(T/10 \text{ eV})^{-1/2}. \quad (5)$$

Unless $(k\lambda_D) \sim 1$, this is a longer time than Eq. (1) demands. However, the time scale does suggest that electrostatic reflection plays the dominant role in amplification.

We now turn to models of ν_p emission. Much work devoted to plasma harmonic emission[4–10] begins with a strong turbulence picture, in which a linear wave packet compresses into a planar soliton ("caviton"), emitting primarily at ν_p. During a second stage when transverse instabilities lead to collapse and dissipation ("burnout"), both
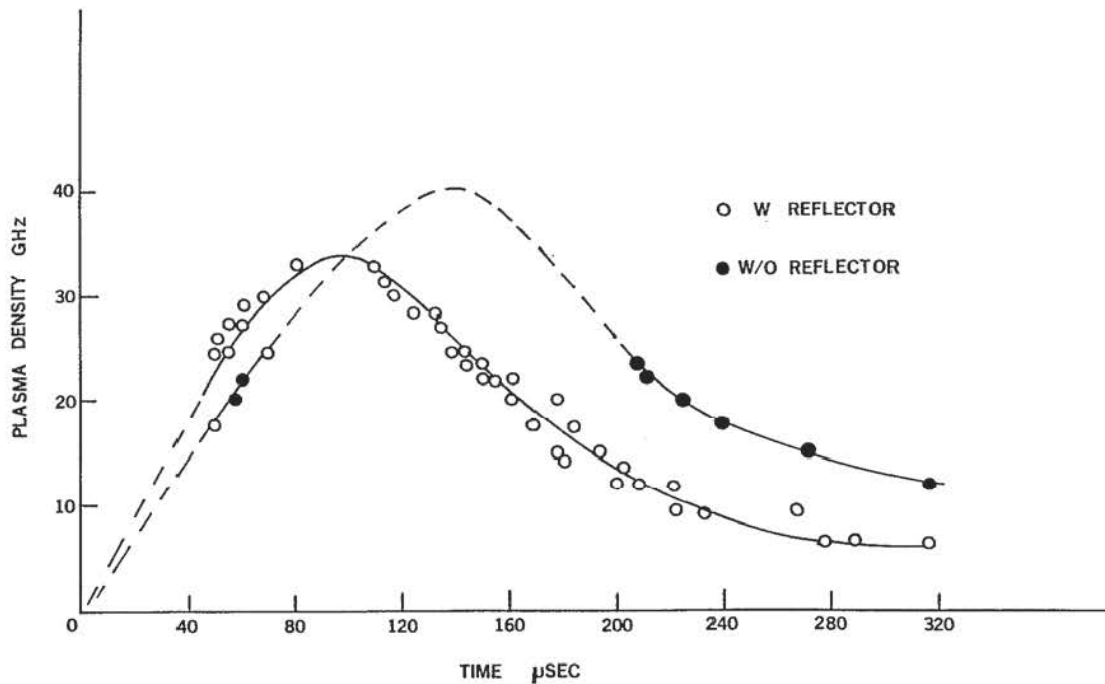
FIG. 4. Plasma density as revealed in the plasma lines (in GHz) as the delay time between the plasma gun and the beam onset increases. The reflectors initially increase plasma density, then at long times lead to a lower density than the reflection-free case.

ν_p and $2\nu_p$ emission occur, often of comparable intensity. Akimoto *et al.*[8] found that $P(\nu_p) \sim P(2\nu_p)$ in this advanced stage. This fails decidedly to describe our results, with or without amplification, for we consistently see $P(\nu_p) \gtrsim 1000\,P(2\nu_p)$.
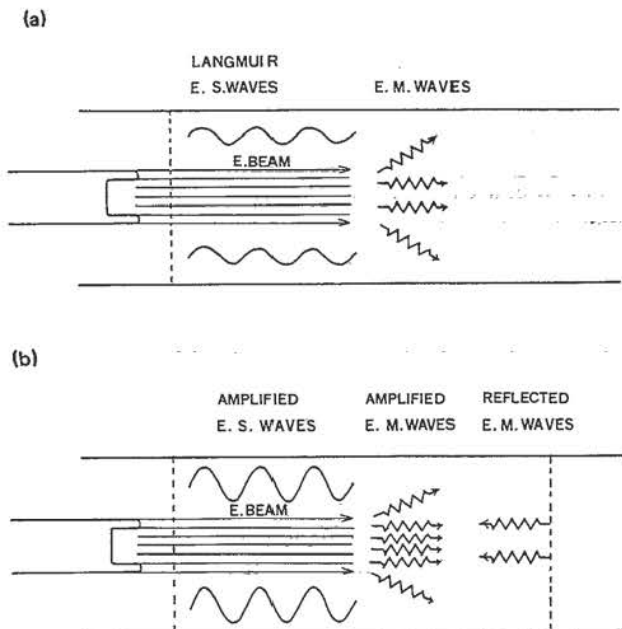

FIG. 5. (a) Beam propagation without reflectors. Walls are lined with a microwave absorber. (b) With absorbers in the curved walls, reflectors enhance both electromagnetic and electrostatic waves back into the cavity.

An earlier treatment[1] found second harmonic emission compatible with our measurements. Theory for the fundamental yielded an emitted power

$$P(\nu_p) = 5 \times 10^6 \ \text{W}[(k\lambda_D)^2_{-2} V_4 W n^2_{13} (T/\text{eV})^3 e^{\mu L}], \qquad (6)$$

where $W = \langle E^2 \rangle / 4\pi nkT$ and V is the experimental volume in cm^{-3}, with all subscripts indicating orders of magnitude in cgs units. The parameters can fit our experiment and yield the observed order of magnitude of power. The important factor is the $\exp(\mu L)$, which represents the plasma-wave scattering from the polarization cloud of an ion, transforming into an electromagnetic wave. Plasma-wave intensity W amplifies the emission. The amplification factor

$$\mu = 3W\lambda_D^{-1}(v_e/v_b) \qquad (7)$$

depends on the typical wave number in the plasma spectrum. Here v_e is the electron thermal velocity and v_b the beam speed, $v_b \sim 1000\,v_e$. Benford and Smith[1] argued for a feedback stabilization of turbulence with radiation playing an important role. Using Eq. (7), we find

$$\mu \cong 0.4 \ \text{cm}^{-1} W_{-2} \qquad (8)$$

of our conditions. This implies enormous growth due to the high effective temperature of the plasma-wave spectrum. This is not compatible with $P(\nu_p)$, which requires $\exp(\mu L) \sim 1$. Neither does it agree with the comparatively modest amplification we find (~ 10), or with the ν_p^2 scaling of the amplification. Thus we conclude that simple wave scattering can account for our observed emission, without spatial geometric reflection calculation of Eq. (2) it suffices to explain the amplification, because the increase of elec-

trostatic wave intensity will be ~ 10 and this enters linearly in Eq. (7) in E^2 through W.

V. CONCLUSION

We find amplification by $\leqslant 10$ in emitted power in the plasma line when simple reflecting screens fixed at the ends of the propagation tube for a relativistic electron-plasma system. Without attempting to maximize amplification by making the cylindrical wall reflect also, we found that tilting the reflectors by $\sim 30°$ significantly decreased amplification. Resorting to standard emission theory showed that while second harmonic emission was insignificant for a process in which plasma waves scatter from ions, this same model also predicted a bulk emissivity which was compatible with observed power, but it also suggested a spatial amplification which we do *not* observe. We believe our results come from a simple adding of electrostatic wave intensity in the cavity. This may prove useful in applications in which gas ionization can be augmented by wave-induced electron jitter.

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