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MEASUREMENT OF LINAC
BUNCH PARAMETERS USING THE
CERENKOV EFFECT

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MEASUREMENT OF LINAC BUNCH PARAMETERS USING THE CERENKOV EFFECT

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ABSTRACT

High energy electrons above about 25 MeV may produce microwave radiation in air by the Cerenkov mechanism. Electrons accelerated by a travelling wave accelerator are emitted in bunches. The radiation produced by such a beam in air should consist of the basic accelerator frequency and many harmonics. Here it is explored how the microwave harmonics may be used to determine the spatial structure of the bunches.

INTRODUCTION

In a previous publication, an investigation was made of radiation produced by electrons moving at a velocity v faster than c, the radiation velocity in a medium (Cerenkov radiation). In particular, the electrons were considered to be emitted in *periodic* bunches, as would be found in a linac beam. At microwave frequencies, the electrons in the bunch radiate coherently, but as the wave length decreases relative to the bunch size, the intensity decreases relative to what would be expected for a small bunch having the same charge. References 1 and 2 contain the basic equations which are developed further here.

Equations (33) and A17 from the earlier paper describe the energy loss per unit path length per bunch, $\frac{dE}{dx}$. For periodic bunches:

$$\frac{dE(\omega)}{dx} = \frac{\mu}{4\pi} \omega\omega_o \sin^2\Theta_c q^2 F^2(\vec{k}) \tag{1}$$

Here, ω_o is the linac angular frequency, the radiation is emitted at a harmonic ω of ω_o, Θ_c is the Cerenkov angle, where $\cos\Theta_c = \frac{c}{v}$, q is the total charge in the bunch, and $F(\vec{k})$ is the form factor of the charge distribution $\rho_o'(\vec{r})$ for a bunch.

$$F(\vec{k}) = \frac{1}{q}\iiint e^{i\vec{k}\cdot\vec{r}} \rho_o(r) d^3r \tag{2}$$

The vector $\vec{k}$ is the propagation vector for the emitted wave. In the case of a single bunch, the frequency distribution is continuous and we have for the radiation emitted in a range $d\omega$

$$\frac{dE}{dx} = \frac{\mu}{4\pi} \omega \, d\omega \sin^2\Theta_c q^2 F^2(\vec{k}) \tag{3}$$

It was also noted in the earlier paper that if the emission region is of finite length, the radiation is emitted in a range of angle about the Cerenkov angle Θ_c, but in the following considerations, those effects are neglected.

We consider here a more detailed investigation of the form factor $F(\vec{k})$ and how radiation intensity may be used to infer properties of the bunch.

The electrons in the accelerator have slightly different energies, depending on the phase angle ψ of the electron relative to the wave traveling down the accelerator. Fig. (1) shows the energy of representative electrons, and a magnetic deflection and slit system at the end of the accelerator passes a limited range of energies ΔE, so that the phase is limited to $\pm\ \Delta\psi$ about $\psi = 0$. See Appendix A for details. If the electrons were uniformly distributed in phase, the output pulse charge density would be a series of square pulses, separated by a distance $x = v\ 2\pi/\omega_o$ and of length $x' = x 2\ \Delta\psi/2\pi$, as shown in Fig. (2a). Fig. (2b) shows possible gaussian bunches.

CALCULATIONS FOR SPECIFIC BUNCH DISTRIBUTION

The theory, namely Equations (1) and (2), make it tempting to attempt measurements to determine the charge distribution function by means of experimental measurements. In the ideal situation, sufficient measurements of power at many frequencies would determine the fourier transform of the charge bunch, which could be inverted to give the spatial charge density $\rho(\vec{r})$.

Calculations of $P(\omega)$, the power radiated (proportional to dE/dx from Equation (1)) were performed for various assumed charge distributions. $P(\omega)$ is plotted for a uniform bunch (Figure 3), a cosine bunch (Figure 4), a Gaussian bunch (Figure 5) and a rather artificial hollow spherical shell (Figure 6). All of the $P(\omega)$ curves show slight differences; in particular the Gaussian has no nulls as expected, and the hollow shell has many nulls and very strong high frequencies. However, the possibility to distinguish between charge distributions is very limited. All of the distributions have a parameter determining the spatial range, the parameter b in the Gaussian $\exp(-r^2b^2)$, and k in the cosine function cos kr. The values of such parameters can be suitably chosen so that the lowest power peak in Figures 3 to 6 are very similar.

We conclude that experimentally, it would be hard to distinguish between different functions, but that it would be possible to determine a range parameter rather accurately.

REFERENCES

1. F. R. Buskirk and J. R. Neighbours, Phys. Rev. A 28, 1531 (1983).

2. J. R. Neighbours and F. R. Buskirk (To be published in Phys. Rev. A 29, June (1984).

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Appendix A

TEMPORAL STRUCTURE OF THE ELECTRON PULSE FROM A TRAVELING WAVE ACCELERATOR.

Assume that the energy of a single electron emerging from a linac with phase relative to the traveling wave field is

$$E = E_o \cos \psi \tag{A1}$$

This relation is shown on Fig. 3, along with some dots representing electrons near the maximum energy E_o, with phases clustered about $\psi = o$ and $\psi = 2\pi$. Two bunches, separated by a phase difference of 2π, are separated by a time $T_1 = 1/f_o$ where f_o is the accelerator frequency, which is $f_o = 2.85 \times 10^9$ Hz for a typical S-band accelerator of the Stanford type.

If a deflection system with energy resolution slit passes only energies E from E_o to E_o-E the corresponding range of phase $\Delta\psi$ is

$$\Delta E = E - E_o = E_o\ (1 - \cos\Delta\psi) \tag{A2}$$

For $\Delta\psi$ small, this reduces to

$$\frac{\Delta E}{E_o} = \frac{(\Delta\psi)^2}{2} \tag{A3}$$

The temporal pulse length T_2 is

$$T_2 = 2\Delta\psi \, T_1/2\pi \tag{A4}$$

or

$$T_2 = T_1 \cdot 2\Delta\psi/2\pi$$

If C3 is used to evaluate $\Delta\psi$ in terms of the fractional energy resolution $\Delta E/E_o$,

$$T_2 = T_1 \left(\frac{2\Delta E}{E_o}\right)^{1/2} \frac{1}{\pi} \tag{A5}$$

For 1% energy resolution, T_2/T_1 is about 1/20. The electrons thus emerge in short bunches, and the charge and current, when expressed in a fourier expansion, should have very strong harmonic content up to and above the 20th harmonic.

Appendix B

FORM FACTORS

This section provides details and examples of form factors for various charge distributions. From the main text, F differs only from ρ', the fourier transform of ρ, by the total charge q of the bunch, so that for $\vec{k} = o$, F reduces to unity. Thus we define

$$F(\vec{k}) = \frac{1}{q} \iiint d^3r \, \rho(\vec{r}) e^{i\vec{k}\cdot\vec{r}} \qquad \text{(B1)}$$

For spherically symmetric charge distributions, let $\vec{k}\cdot\vec{r} = kru$ where u is the cosine of the angle between $\vec{k}$ and $\vec{r}$. In spherical coordinates, $d^3r = d\phi du r^2 dr$. Then we find,

$$F(\vec{k}) = \frac{1}{q} \frac{4\pi}{k} \int_0^\infty dr \, r \, \rho(r) \sin kr \qquad \text{(B2)}$$

For k very small, sin x may be replaced by $x - x^3/6$ and we have

$$F(k) = \frac{1}{q} \frac{4\pi}{k} \int_0^\infty dr \, r \, \rho(r)[kr - k^3r^3/6] \qquad \text{(B3)}$$

Then the two terms in the square bracket lead to separate integrals, the first term being unity and the second is similar to the integral used to calculate the mean square radius, $\langle r^2 \rangle$, except for a factor $k^2/6$. Thus we have

$$F(k) = 1 - k^2 \langle r^2 \rangle / 6 \qquad \text{(B4)}$$

For a uniform spherical charge distribution of radius R well as a spherical shell of radius k, the integral of (B2) performed easily

$$F(k) = \frac{3}{(kR)^3} (\sin kR - kR \cos kR) \quad \text{(Solid sphere)} \quad ($$

$$F(k) = \frac{1}{kR} \sin(kR) \quad \text{(Spherical shell)} \quad ($$

For a line charge concentrated on the z axis, we may re (B1) and let $\rho(r) = \delta(x)\, \delta(y)\, \rho''(z)$, so that

$$F(k) = \frac{1}{q} \int dz\, \rho''(z)\, e^{ikz} \quad \text{(Line charge)} \quad ($$

$$F(k) = \frac{2}{kZ} \sin\left(\frac{kZ}{2}\right) \quad \text{(Uniform line charge of length Z)} \quad ($$

Distorted spherical symmetry may be said to occur if th transformation $z' = pz$ serves to make ρ spherically symmetri prime system. Let F_s be the form factor calculated by (B2) prime frame. It is simple to show that

$$F(k_x, k_y, k_z) = F_s(k_x^o, k_y^o, k_z^o/p) \quad ($$

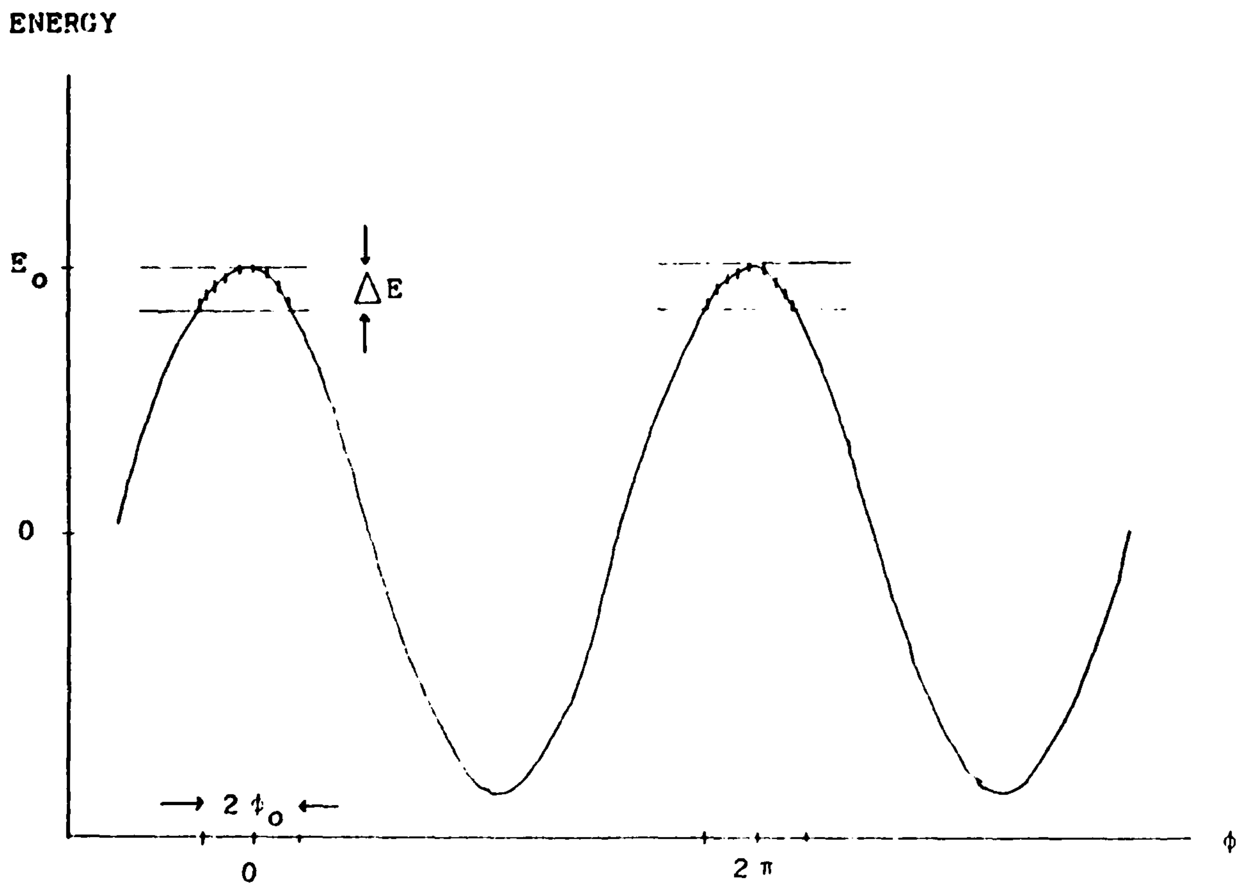


FIGURE 1 STRUCTURE OF CHARGE PULSE FROM A TRAVELING WAVE ACCELERATOR. ϕ is the phase angle of an electron relative to the peak of the wave. Electrons in the range $\pm\phi_o$ are passed by a magnetic deflection system.

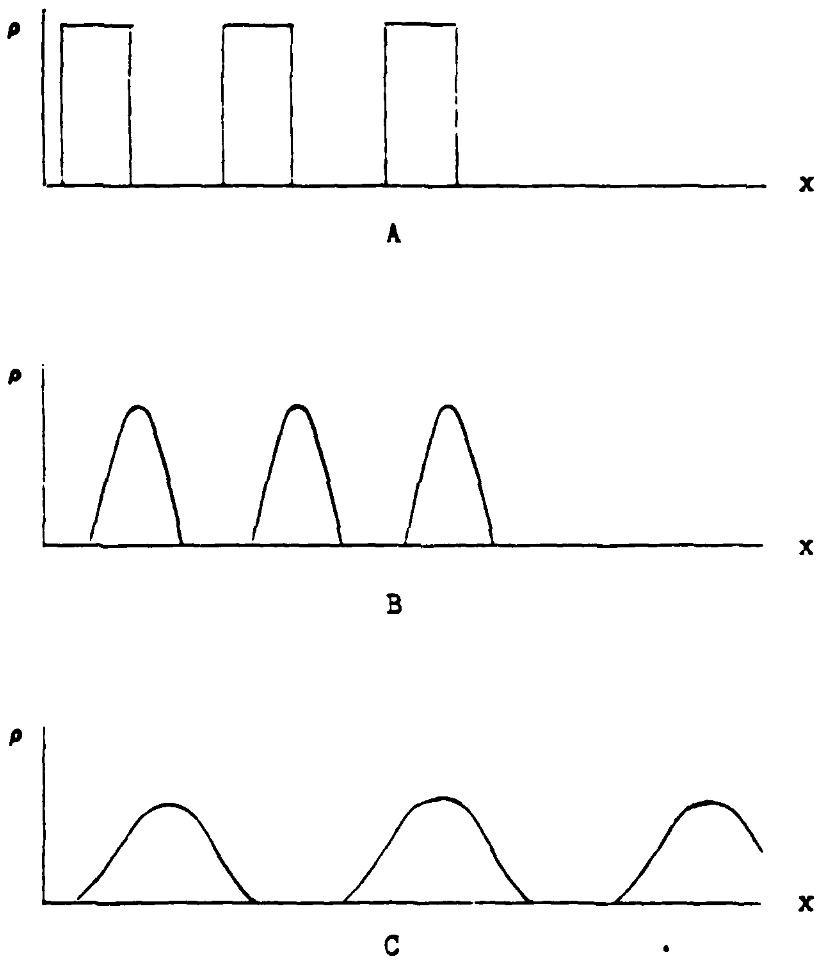
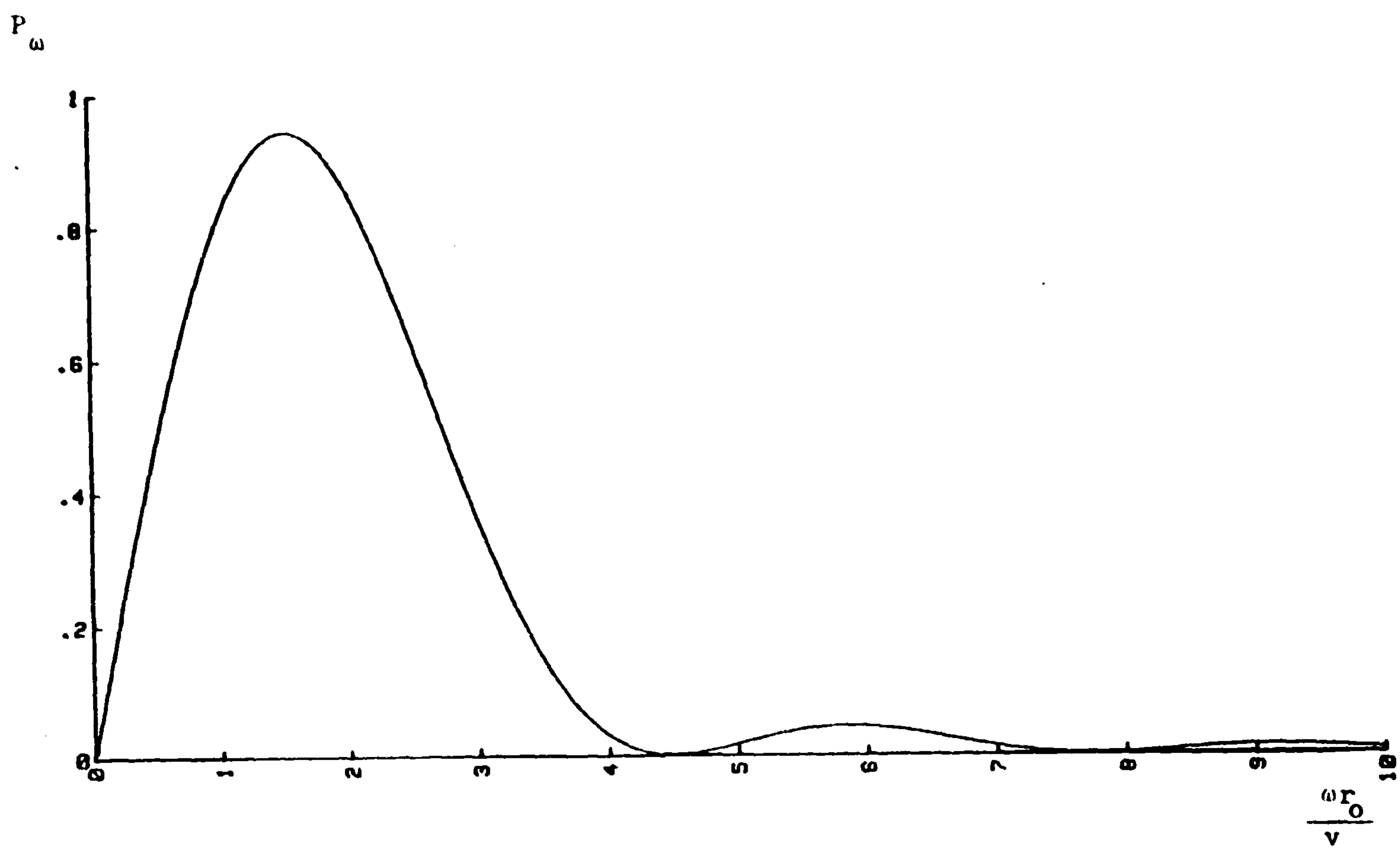
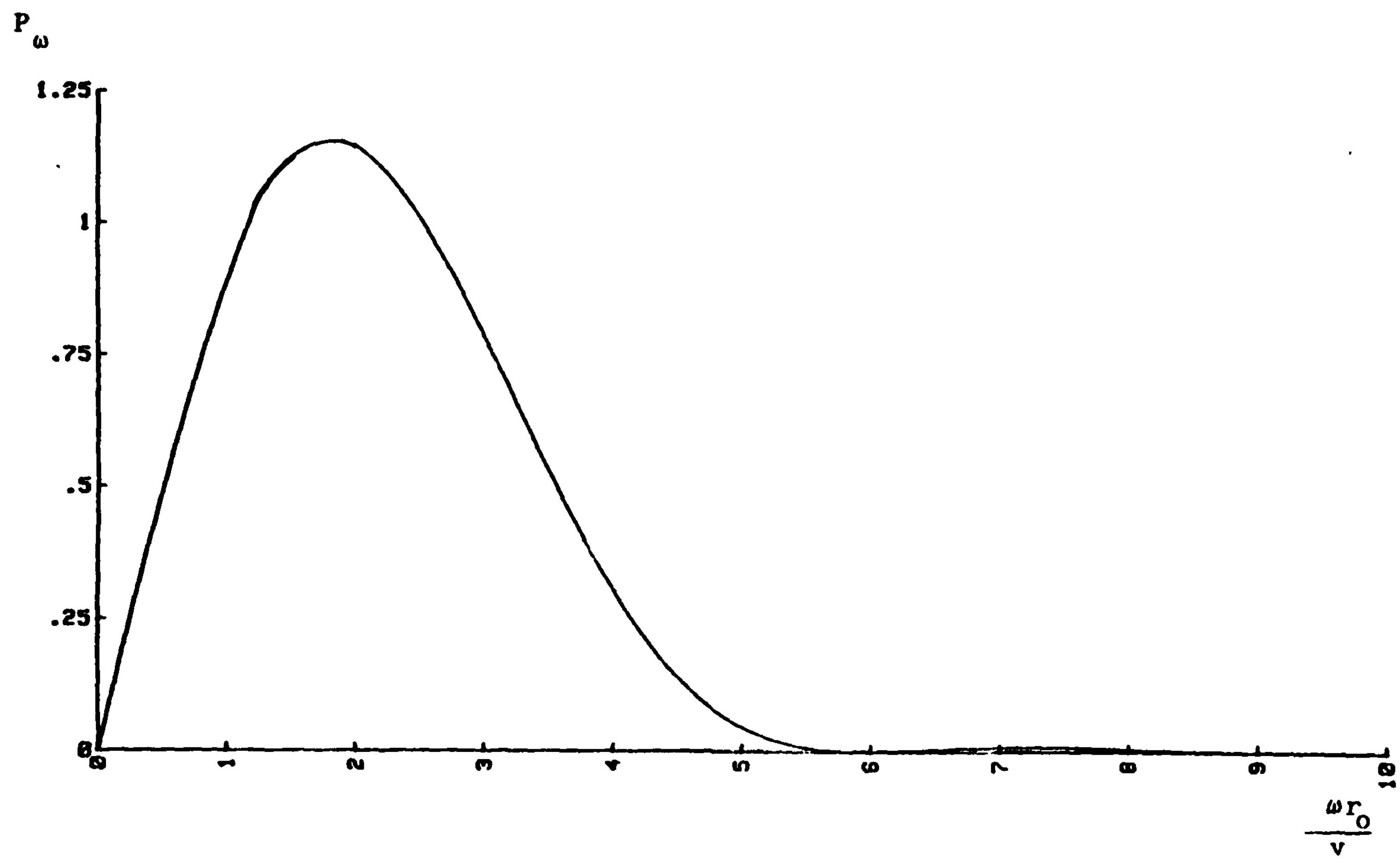


FIGURE 2 . POSSIBLE ELECTRON BUNCH STRUCTURES.
A. Uniform
B. Cosine
C. Gaussian



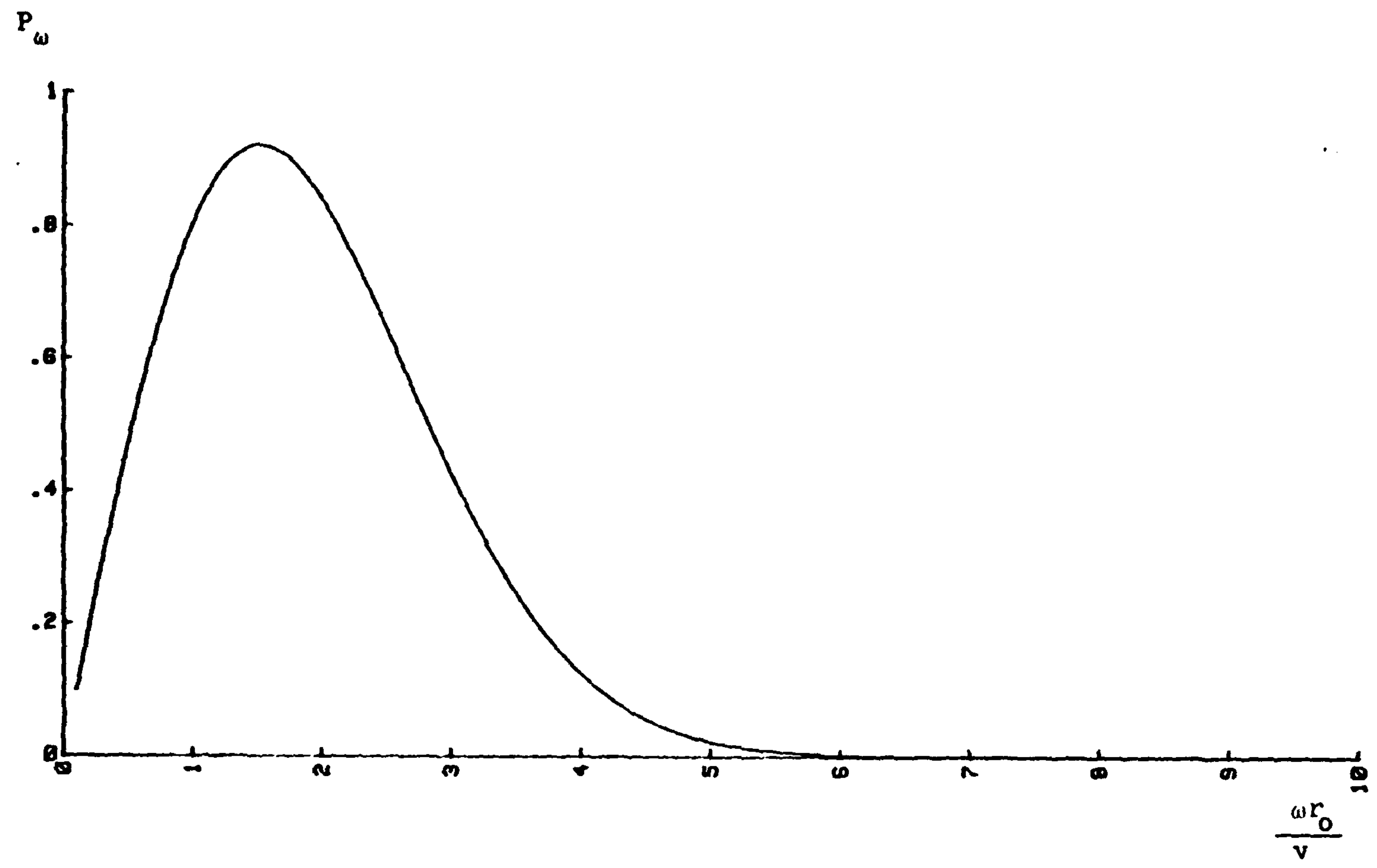
UNIFORM BUNCH RADIATED POWER

FIGURE 3



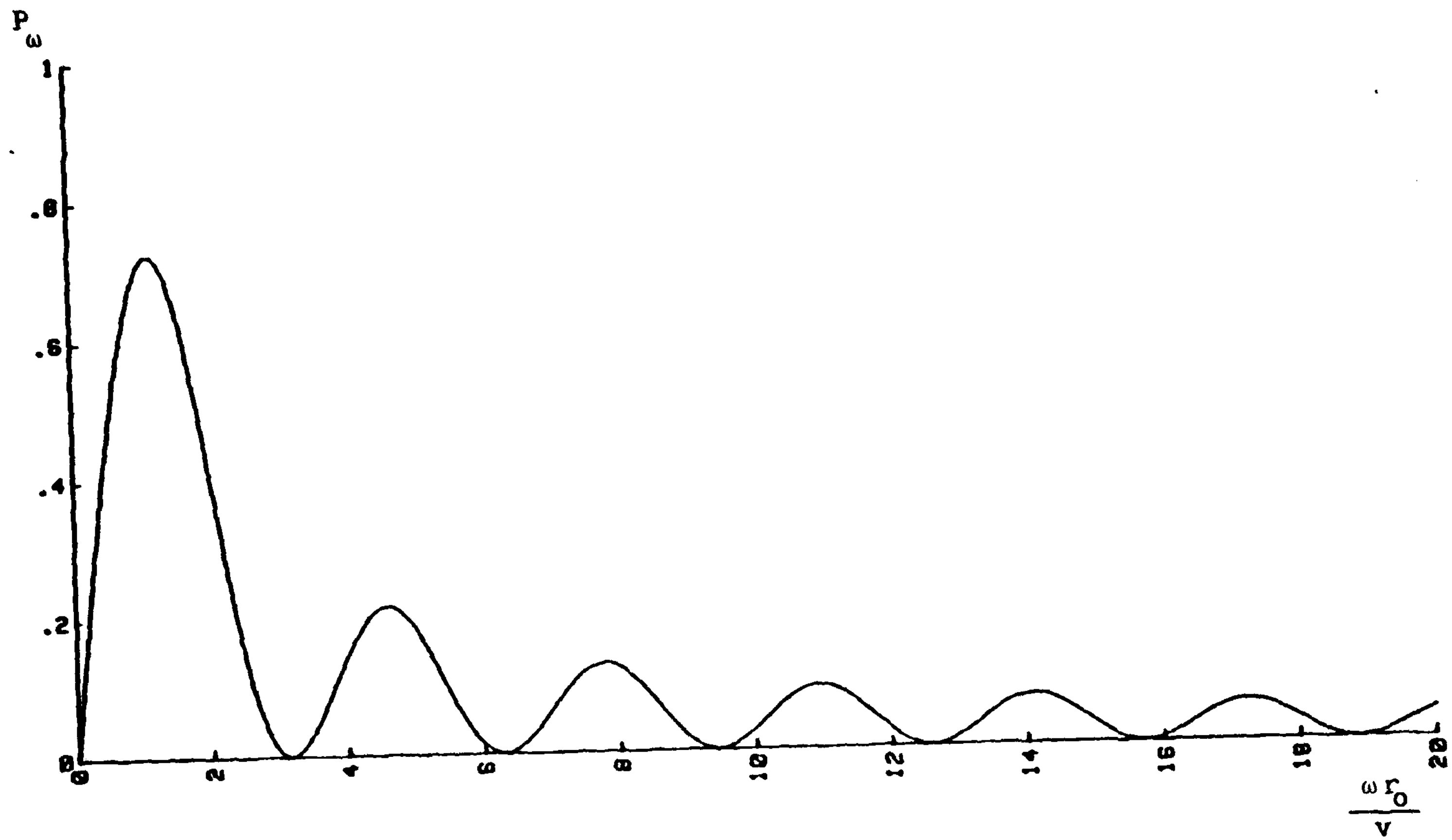
COSINE BUNCH RADIATED POWER

FIGURE 4



GAUSSIAN BUNCH RADIATED POWER

FIGURE 5



SPHERICAL SHELL BUNCH RADIATED POWER

FIGURE 6

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