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DISPERSION CHARACTERISTICS OF A BEAM-DRIVEN CYLINDRICAL WAVEGUIDE--ETC(U)

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Dispersion Characteristics of a Beam-Driven Cylindrical Waveguide with Dielectric Liner

By G. Daniel Dockery

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**U.S. Army Electronics Research
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Harry Diamond Laboratories
Adelphi, MD 20783**

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20. ABSTRACT (Cont'd)

varied to illustrate their effects on the dispersion curve. Higher TM_{0n} modes (through TM_{06}) are calculated to show how it is possible to couple to higher modes by using appropriate dielectric thicknesses.

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1. INTRODUCTION

An investigation is being conducted at the Harry Diamond Laboratories (HDL) to develop a Cerenkov device as a relatively intense source of near-millimeter radiation. Sources (both pulsed and continuous) that produce high power are desired for many of the projected applications of near-millimeter waves. The experiment initiated at HDL represents one approach to designing such a radiation source.

The foundation for this experiment has been laid by Felch et al at Dartmouth College.^{1,2} Very simply, that experiment consists of passing an intense, relativistic electron beam through a cylindrical waveguide with a thin dielectric liner. The beam current is pulsed, having a peak value of 1 to 10 A, and the electrons are accelerated to relativistic speeds through the dielectric-lined resonator, where the actual production of radiation takes place.

As a result of the considerable success of the Dartmouth device, HDL has undertaken a similar experiment. Dartmouth's pulsed device has generated powers on the order of hundreds of watts and at fairly widely spaced frequencies.¹ However, the detailed characterization of the output has proven difficult partially because of effects introduced by the pulsing process. To overcome these difficulties, a continuous wave (cw) device is being investigated at HDL. The system will have a 200-kV electron beam with a maximum continuous current of about 250 mA. In most other respects, the two systems will be similar.

This report deals with the design of the resonating structure. The basic principles for the design of a Cerenkov power source have been worked out to a considerable degree at Dartmouth College.^{2,3} Since the theories underlying the HDL and Dartmouth experiments are fundamentally the same, the Dartmouth results are used as a basis for the design.

Radiation in the Cerenkov device is generated by an interaction between the electron beam and the partially filled waveguide. Deriving the dispersion relation for a relativistic electron beam in a partially filled waveguide reveals that the phase velocities of modes that can propagate in the guide are all superluminal, that is, greater than the

¹K. L. Felch, K. O. Busby, R. W. Layman, and J. E. Walsh, *Cerenkov and Cerenkov-Raman Masers: Experiments, Physics of Quantum Electronics*, 7 (1980), 255-300 and 301-322.

²K. L. Felch, *Cerenkov Radiation in Dielectric-Loaded Waveguides*, Doctoral Dissertation, Dartmouth College, Dartmouth, NH (1980).

³M. Johnson, *Cerenkov Interaction in a Waveguide Partially Filled with Dielectric*, Master's Thesis, Dartmouth College, Dartmouth, NH (1978).

speed of light in the dielectric. By using a beam with a particle velocity that also is superluminal, it is possible to couple the beam to a given waveguide mode, thus driving an instability with a sizable growth rate.

The problem discussed here is the use of these theoretical considerations, approximate though they are, in the design of a resonating structure for the proposed power source. The basic parameters are beam current, beam velocity (voltage), dielectric constant of the liner, radius of the waveguide, and thickness of the liner. Since this is intended as a near-millimeter wave source, an output frequency of 120 GHz will be assumed.

The remainder of this report begins with a brief section on the theoretical foundation. This is followed by an analysis that first uses the no-beam dispersion relation derived by Felch² to calculate modes for parameters relevant to our experiment. Next, our analysis continues by using a program that we have written to solve for higher order modes in the resonator to consider the possibility of coupling the beam to higher modes. Finally, there is a summary of what can be concluded from the analysis.

2. THEORY

The derivation outlined here parallels the work of Felch.² The dispersion relation for this system is obtained by using a linear perturbation method and by making the following assumptions: (1) the dielectric-lined waveguide is infinitely long, (2) the metal portions of the guide are perfectly conducting, and (3) the magnetic waveguide field is sufficiently strong to make the transverse velocity of the electrons in our beam negligible. The frequency and the magnetic field proposed for this experiment justify assumptions (2) and (3).

The geometry being considered is shown in figure 1, in which the center region is evacuated and entirely filled by the electron beam.

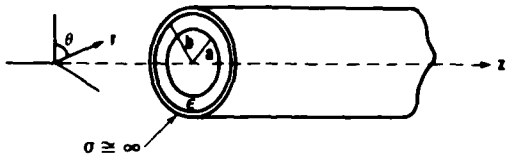


Figure 1. Geometry of beam-driven cylindrical waveguide with dielectric liner.

²K. L. Felch, *Cerenkov Radiation in Dielectric-Loaded Waveguides*, Doctoral Dissertation, Dartmouth College, Dartmouth, NH (1980).

The following form of Maxwell's equations is used:

$$\vec{\nabla} \cdot \vec{D} = 4\pi\rho = -4\pi ne \quad , \quad (1)$$

$$\vec{\nabla} \cdot \vec{B} = 0 \quad , \quad (2)$$

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c} \vec{j} + \frac{1}{c} \frac{\partial \vec{D}}{\partial t} \quad , \quad (3)$$

$$\vec{\nabla} \times \vec{E} = - \frac{1}{c} \frac{\partial \vec{B}}{\partial t} \quad . \quad (4)$$

Also, the Lorentz force and continuity equations are used:

$$\frac{m d(\gamma \vec{v})}{dt} = -e\vec{E} - \frac{e}{c} \vec{v} \times \vec{B} \quad , \quad (5)$$

$$\frac{\partial n}{\partial t} + \vec{\nabla} \cdot (n\vec{v}) = 0 \quad , \quad (6)$$

where

$$\vec{D} = \begin{cases} \epsilon \vec{E}, & a < r < b, \\ \vec{E}, & 0 < r < a, \end{cases}$$

ϵ = dielectric constant of liner,

\vec{E} = electric field strength,

n = electron density in beam,

$-e$ = electronic charge,

\vec{B} = magnetic induction,

c = velocity of light in vacuum,

\vec{j} = current density = $-en\vec{v}$,

\vec{v} = velocity of electrons in beam,

m = electronic mass,

$\gamma = 1/(1 - v^2/c^2)^{1/2}$.

In the general case of a partially filled waveguide, transverse magnetic (TM), transverse electric (TE), and hybrid modes can propagate in the waveguide.^{4,5} The discussion is restricted to TM modes since a complete analysis reveals that the beam will couple to the z-component of the electric field. Further, because of the cylindrical symmetry of the guide, only TM_{0n} modes need be considered.

The field components of the TM_{0n} mode are

$$\vec{E} = E_r(r)e^{ikz-i\omega t}\hat{e}_r + E_z(r)e^{ikz-i\omega t}\hat{e}_z, \quad (7)$$

$$\vec{B} = B_\theta(r)e^{ikz-i\omega t}\hat{e}_\theta + B_0\hat{e}_z, \quad (8)$$

where

k = guide wave number,
 ω = angular frequency,
 E_r = component of E in r direction,
 E_z = component of E in z direction,
 B_θ = component of B in θ direction,
 B_0 = external magnetic field.

In general, these fields will perturb n and \vec{v} with plane-wave components. The result is

$$n = n_0 + n_1(r)e^{ikz-i\omega t}, \quad (9)$$

$$\vec{v} = v_0\hat{e}_z + v_1(r)e^{ikz-i\omega t}\hat{e}_z. \quad (10)$$

In equations (9) and (10) and subsequent equations, the "0" subscript on n , v , and j refers to a zero-order quantity and the "1" subscript on n , v , and j refers to a first-order approximation.

If one assumes that the fields and, correspondingly, $n_1(r)$ and $v_1(r)$ are small, then only first-order terms need be kept and

⁴M. Miyagi and S. Nishida, *Transmission Characteristics of Dielectric Tube Leaky Waveguide*, *IEEE Trans. Microwave Theory Tech.*, MTT-28 (June 1980), 536-541.

⁵L. Pincherle, *Electromagnetic Waves in Metal Tubes Filled Longitudinally with Two Dielectrics*, *Phys. Rev.*, 66 (September 1944), 118-130.

$$\begin{aligned}
\vec{j} &= ne\vec{v} \\
&= \left[-n_0ev_0 - n_1(r)ev_0e^{ikz-i\omega t} - n_0ev_1(r)e^{ikz-i\omega t} \right] \hat{e}_z \quad (11) \\
&= \vec{j}_0 + \vec{j}_1(r) .
\end{aligned}$$

Now, using equations (5) and (6), one may find expressions for $n_1(r)$ and $v_1(r)$, which when substituted into equation (11) lead to

$$\vec{j}_1(r) = \frac{\omega_p^2 \omega}{4\pi\gamma^3(\omega^2 - kv_0)^2} E_z(r) \hat{e}_z \quad , \quad (12)$$

where $\omega_p^2 = 4\pi n_0 e^2/m$ is the plasma frequency of the electron beam.

Manipulation of Maxwell's equations readily yields

$$\vec{\nabla} \cdot \left(\frac{-4\pi n_1 e}{\epsilon} \right) - \nabla^2 \vec{E} = \frac{4\pi i \omega}{c^2} \vec{j}_1 + \frac{\omega^2 \epsilon}{c^2} \vec{E} \quad , \quad (13)$$

the z-component of which is

$$\frac{1}{r} \frac{\delta}{\delta r} \frac{r \partial E_z(r)}{\partial r} + q^2 S^2 E_z(r) = 0 \quad , \quad (14)$$

where

$$q^2 \equiv \frac{\omega^2 \epsilon}{c^2} - k^2 \quad , \quad (15)$$

$$S^2 \equiv 1 - \frac{\omega_p^2}{\epsilon \gamma^3 (\omega - kv_0)^2} \quad , \quad (16)$$

and equation (12) is used for \vec{j}_1 .

Equation (14) is Bessel's equation and has the general solution

$$E_z(r) = AJ_0(qSr) + BY_0(qSr) \quad , \quad (17)$$

where J_0 and Y_0 are zero-order Bessel functions of the first and second kinds, respectively.

In the same way, examination of the r-component of equation (13) yields

$$E_r = \frac{ik}{q^2} \frac{\partial E_z}{\partial r} \quad (18)$$

Consider the two regions in the waveguide with the conditions

$$\left. \begin{array}{l} \epsilon = \epsilon \\ \omega_p^2 = 0 \end{array} \right\} , \quad a < r < b \quad (19)$$

and

$$\left. \begin{array}{l} \epsilon = 1 \\ \omega_p^2 \neq 0 \end{array} \right\} , \quad r < a \quad (20)$$

Then

$$\left. \begin{array}{l} E_r(r) = -\frac{ik}{q} [AJ_1(qr) + BY_1(qr)] \\ E_z(r) = AJ_0(qr) + BY_0(qr) \end{array} \right\} , \quad a < r < b \quad (21)$$

$$\left. \begin{array}{l} E_r(r) = -\frac{ikT}{ip} [A'J_1(ipTr) + B'Y_0(ipTr)] \\ E_z(r) = A'J_0(ipTr) + B'Y_0(ipTr) \end{array} \right\} , \quad r < a \quad (22)$$

where J_1 and Y_1 are first-order Bessel functions of the first and second kinds, respectively,

$$T^2 \equiv 1 - \frac{\omega_p^2}{\gamma^3(\omega - kv_0)^2} \quad (23)$$

$$p^2 \equiv k^2 - \frac{\omega^2}{c^2} \quad (24)$$

and A , B , A' , and B' are constants. The constants are evaluated by applying the usual boundary conditions:

- $E = 0$ at $r = b$.
- E is finite at $r = 0$.
- The tangential component of E is continuous at $r = a$.
- The normal component of ϵE is continuous at $r = a$.

Applying these boundary conditions results in the following transcendental relation:

$$\begin{aligned} \frac{iT}{p} J_1(ipTa) [J_0(qb)Y_0(qa) - Y_0(qb)J_0(qa)] \\ + \frac{\epsilon}{q} J_0(ipTa) [J_0(qb)Y_1(qa) - Y_0(qb)J_1(qa)] = 0 \end{aligned} \quad (25)$$

which is the dispersion relation from TM_{0n} modes for this system.

In the next section, we consider this dispersion relation in the context of our experiment.

3. ANALYSIS

3.1 System Parameters

The calculations to be described have been made for parameters similar to those that we expect to have with our experiment. The goal of producing 120-GHz (wavelength of 2.5 mm) radiation encourages the use of as small a waveguide as is practical. On the other hand, beam powers of many kilowatts and the problems of fabrication force us to use a larger waveguide than would otherwise be necessary for 120-GHz operation.

We deal with beam velocities no greater than $0.7c$ (200 kV), so a relatively large dielectric constant is desirable to assure that the particle velocity is well into the superluminal region. One possibility is fused quartz with $\epsilon = 3.78$. The following are then a reasonable set of initial values for our analysis:

- Output frequency = 120 GHz.
- Relative beam velocity, $\beta = v/c = 0.7$.
- Inner waveguide radius, $a = 0.45$ cm.
- Dielectric constant, $\epsilon = 3.78$.

3.2 Dispersion Curves

If we choose a fixed value for ω , then there are many values of k that satisfy equation (25). Each one of these roots corresponds to the wave number of a mode that will propagate in the waveguide at frequency ω . The values of k corresponding to the fundamental mode, TM_{01} , for varying ω have been found by Johnson.³ However, solving equation (25) in this way is fairly difficult since k is generally complex. Fortunately, as demonstrated by Johnson, even for beam currents much higher than those that we intend to produce, the no-beam approximation is very close to the exact solution. This is the approximation used by Felch² as well.

The no-beam approximation results from setting $\omega_p = 0$ in equation (25). Thus, it reduces to

$$\begin{aligned} \frac{i}{p} J_1(ipa) [J_0(qb)Y_0(qa) - Y_0(qb)J_0(qa)] \\ + \frac{\epsilon}{q} J_0(ipa) [J_0(qb)Y_1(qa) - Y_0(qb)J_1(qa)] = 0 \end{aligned} \quad (26)$$

A convenient way of examining this relation is to plot ω/c as a function of k while varying the different parameters. In figure 2, these are plotted for different dielectric thicknesses for the TM_{01} mode. Since the beam-to-dielectric distance is critical, we have fixed the inner radius at $a = 0.45$ cm and varied b . For $b/a = 1.0$, the dispersion curve asymptotically approaches that for a plane wave in a vacuum. This is the expected result for any empty waveguide. As we consider dielectric liners of increasing thicknesses, the phase velocity of the modes approaches the speed of light in the dielectric.

The curve $\omega/ck = \beta = 0.7$ represents the "beam curve," that is, the dispersion curve of the electron beam. We note where the different waveguide curves cross the beam curve. At this frequency, called the synchronous frequency, the maximum transfer of energy from the beam to the waveguide mode should occur.³ Clearly, as the dielectric gets thinner, the synchronous frequency becomes higher. It is easy to see from figure 2 that we may vary the synchronous frequency also by varying the beam velocity.

²K. L. Felch, *Cerenkov Radiation in Dielectric-Loaded Waveguides*, Doctoral Dissertation, Dartmouth College, Dartmouth, NH (1980).

³M. Johnson, *Cerenkov Interaction in a Waveguide Partially Filled with Dielectric*, Master's Thesis, Dartmouth College, Dartmouth, NH (1978).

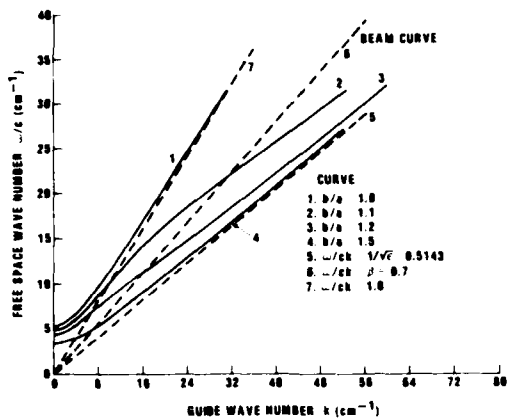


Figure 2. Behavior of waveguide dispersion relation for different dielectric liner thicknesses, TM_{01} mode: $\beta = 0.7$, $\epsilon = 3.78$, and $a = 0.45$ cm.

Figure 3 shows the case where the beam couples to the waveguide at 120 GHz. This coupling requires a thickness of $b/a = 1.085$, which corresponds to a wall thickness of 0.3825 mm (0.015 in.).

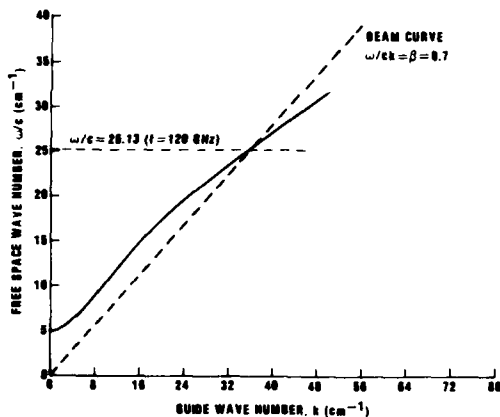


Figure 3. Behavior of waveguide dispersion relation for $b/a = 1.085$, TM_{01} mode: $\beta = 0.7$, $\epsilon = 3.78$, and $a = 0.45$ cm.

These curves were all generated by using $\epsilon = 3.78$; however, as shown in figure 4, we may use the dielectric constant to choose a coupling frequency if various dielectrics are available to us. Comparison of figures 2 and 4 indicates that the dispersion curves are more sensitive to the dielectric thickness than to the dielectric constant.

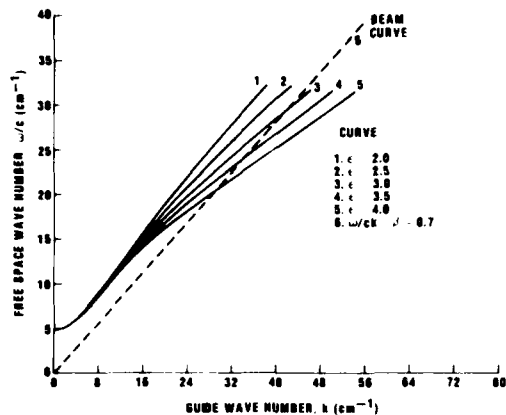


Figure 4. Behavior of waveguide dispersion relation for different dielectric constants, TM_{01} mode: $\beta = 0.7$, $a = 0.45$ cm, and $b/a = 1.1$.

A fourth way to change the characteristics of the waveguide is to vary the inner radius, a , of the guide. Figure 5 illustrates this variance for several values of a from 0.35 to 0.55 cm. Again, the curves are less sensitive to the inner radius than to the liner thickness. Clearly, there are numerous ways to select a preferred frequency for coupling. To a large extent, the method we use depends on the detailed mechanical design of the system.

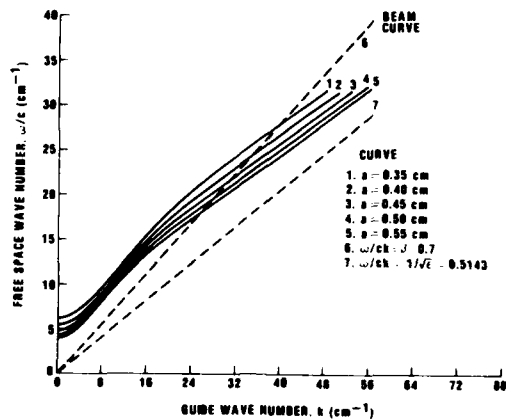


Figure 5. Behavior of waveguide dispersion relation for different inner radii, TM_{01} mode: $\beta = 0.7$, $\epsilon = 3.78$, and $b/a = 1.1$.

3.3 Higher Order Modes

The program that generated figures 2 to 5 was an adaptation of the one written by Felch² and calculates only the fundamental (TM_{01}) mode. It is conceivable that we may wish to couple to a higher order

²K. L. Felch, *Cerenkov Radiation in Dielectric-Loaded Waveguides*, Doctoral Dissertation, Dartmouth College, Dartmouth, NH (1980).

mode. For example, the situation represented in figure 3 requires a dielectric wall of 0.3825 mm, whereas coupling to a higher mode would allow a larger thickness, which would be easier to fabricate. We are interested also in the separation of the different modes; therefore, it was instructive to write a program to calculate the dispersion relations for the higher order TM_{0n} modes. In this calculation, we assume that the previous no-beam approximation remains valid for the higher modes.

Figure 6 shows the higher modes for $b/a = 1.085$ and $\epsilon = 3.78$. As in figure 3, the synchronous frequency for TM_{01} is about 120 GHz ($\omega/c = 25.13$). In figure 7, $b/a = 1.3$ and the TM_{02} mode couples to the beam at the desired frequency. Similarly, figure 8 shows this condition for TM_{03} with $b/a = 1.5$. Thus, we can couple to higher modes by using thicker liners. Choosing higher modes is feasible also by varying the beam velocity or the dielectric constant as we have demonstrated for the fundamental mode.

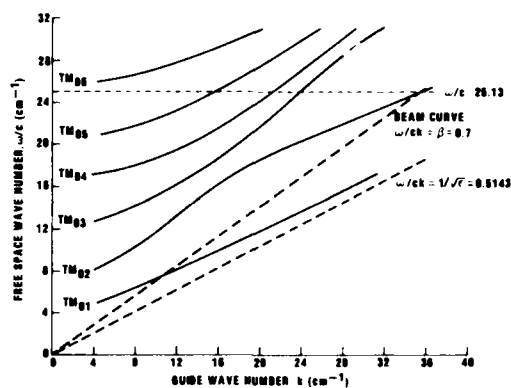
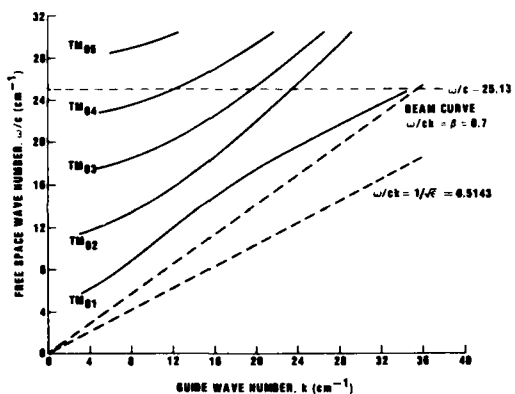


Figure 6. Dispersion relations for higher order TM_{0n} modes: $\beta = 0.7$, $\epsilon = 3.78$, $a = 0.45$ cm, and $b/a = 1.085$.

Figure 7. Dispersion relations for higher order TM_{0n} modes: $\beta = 0.7$, $\epsilon = 3.78$, $a = 0.45$ cm, and $b/a = 1.3$.

When coupling to higher modes, one has to consider the possibility of mode competition from lower modes as well as from modes that are higher still. One can see from figure 7 that, while coupling to TM_{02} at 120 GHz, we couple also to TM_{01} at 38 GHz. Similarly, figure 8 demonstrates that coupling to TM_{03} at our desired frequency results in coupling also to TM_{01} at 23 GHz and to TM_{02} at 71 GHz. Although the figures presented here do not illustrate coupling to higher modes (TM_{04} , TM_{05} , etc.), this coupling can occur and should be considered. Therefore, one needs to examine the competition between these different modes to determine the practicality of coupling to a higher order mode.

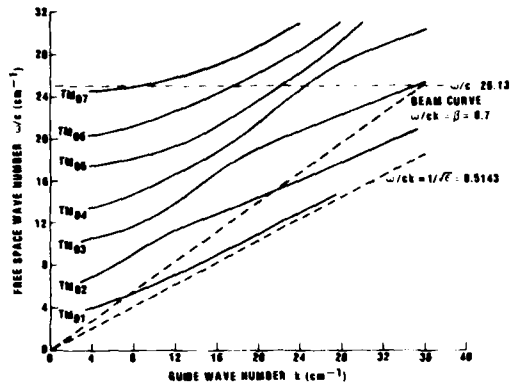


Figure 8. Dispersion relations for higher order TM_{0n} modes: $\beta = 0.7$, $\epsilon = 3.78$, $a = 0.45$ cm, and $b/a = 1.5$.

4. CONCLUSIONS

Presented here is an approach to designing the resonator for the Cerenkov device based on the theoretical dispersion relation and some physical restrictions of the system. It has been demonstrated that by using the proper dimensions, dielectric, and beam velocity, we can reasonably expect to couple the beam to low order TM modes at the desired frequency.

When solving the exact dispersion relation, Johnson³ suggests that the imaginary roots contain information about the growth rates of the instability being driven by the beam. Fortunately, his results indicate that the parameters given in section 3.1 should produce relatively high growth rates, provided that the beam energy is sufficient. Further analysis of the growth rates should yield useful information regarding mode competition when coupling to higher order modes as well as helping to maximize the coupling for the fundamental mode.

This model of our resonating structure is not exact. Numerous approximations were made, including a very narrow velocity distribution in the electron beam and an infinitely strong and straight magnetic field for the beam. But perhaps the most unrealistic approximation was the assumption of an infinitely long resonator. For these calculations to be representative of the experimental arrangement, one would probably need to do some impedance matching at both ends of the dielectric liner to minimize reflection of the radiation at these areas. Nevertheless, this analysis suggests the parameters to use in the initial fabrication of the resonator.

³M. Johnson, *Cerenkov Interaction in a Waveguide Partially Filled with Dielectric*, Master's Thesis, Dartmouth College, Dartmouth, NH (1978).

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- (2) K. L. Felch, Cerenkov Radiation in Dielectric-Loaded Waveguides, Doctoral Dissertation, Dartmouth College, Dartmouth, NH (1980).
- (3) M. Johnson, Cerenkov Interaction in a Waveguide Partially Filled with Dielectric, Master's Thesis, Dartmouth College, Dartmouth, NH (1978).
- (4) M. Miyagi and S. Nishida, Transmission Characteristics of Dielectric Tube Leaky Waveguide, IEEE Trans. Microwave Theory Tech., MTT-28 (June 1980), 536-541.
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