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STIMULATED CERENKOV RADIATION PRODUCED BY 100 MEV ELECTRONS.(U)
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Monterey, California

THESIS

STIMULATED CERENKOV RADIATION PRODUCED BY
100 MeV ELECTRONS

by

Leslie John Brown

December 1981

Thesis Advisor: Fred R. Buskirk

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Stimulated Cerenkov Radiation Produced by 100 MeV Electrons

by

Leslie John Brown
Lieutenant, United States Navy
B.S., Kansas University, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1981

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ABSTRACT

It is proposed that electromagnetic radiation of a specified frequency can be produced by stimulated Cerenkov radiation in a dielectric resonator excited by a relativistic electron beam. The frequency generated depends upon the energy of the electrons and the refractive index and dimensions of the dielectric. This work describes the continuation of an experiment designed to verify the proposed radiation using 100 MeV electrons and a polyethylene slab. Problems encountered during the experiment are discussed and suggestions for continuing work are provided. Radiation is produced at several discrete frequencies, which are harmonics of the electron bunch frequency as produced by the LINAC. The absence of modes at the resonant frequency of the dielectric is understandable, considering the short length of the resonator. When the limitations imposed by the physical dimensions of the dielectric slab are considered, the results support the prediction.

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I. INTRODUCTION

Cerenkov radiation is that radiation produced by a charged particle moving at greater than light speed in a particular medium. It has been used occasionally as a detector of high speed charged particles. Other than this it has been considered primarily as a curiosity, and the phenomenon is usually thought to be a source of only broadband radiation.

Recently, Professor John E. Walsh theorized that radiation of a particular frequency could be generated using relativistic electrons and a dielectric by properly choosing the dimensions and refractive index of the dielectric and electron energy [Ref. 1]. He has conducted a series of experiments which support this prediction [Ref. 2].

In an attempt to verify and extend Walsh's work, David E. McLaughlin conducted an experiment parallel to Walsh's using a different dielectric geometry. This experiment was reported in McLaughlin's masters thesis [Ref. 3]. The present experiment is a continuation and a refinement of McLaughlin's.

Walsh's experiments involved the interaction of 300 KeV electrons with a dielectric in the shape of a cylindrical annulus. The present experiment is an investigation of the interaction of 30 to 100 MeV electrons with a dielectric slab, resulting in microwave radiation in the X and K bands (8--12 GHz and 12--40 GHz respectively).

II. THEORY

A. BACKGROUND

McLaughlin calculated the frequency expected to be generated by his experimental apparatus. His derivation is outlined below. For the complete derivation, refer to his thesis.

Consider a dielectric slab of finite thickness, but extending to infinity in both of its other dimensions. One of its faces borders the vacuum and the other is bonded to a perfect conductor. It is reasonable to expect that electromagnetic radiation should be able to propagate through the dielectric. But because one of the faces borders the vacuum, there will be an evanescent wave in the vacuum which must satisfy boundary conditions along with the wave in the dielectric. By considering Maxwell's equations and the boundary conditions, the speed of the wave can be derived as a function of the refractive index and thickness of the dielectric slab and frequency of the wave. The modes associated with this structure have some features similar to the usual modes in a hollow metal waveguide. Namely, both TE and TM modes exist, and the modes exhibit a strong frequency dispersion.

Now consider a beam of relativistic electrons moving in the vacuum along a line parallel to and very close to the face of the dielectric, so that the electrons are in the evanescent wave and travelling in the same direction as the wave. There will be a component of the wave's electric field in the direction of travel, since a TM mode is present. It should then be possible for the electrons to either give energy to the wave or take energy from it. The attractive feature of the dielectric waveguide is the fact that the phase velocity of the mode is between the velocity of light in the dielectric and the velocity of light in vacuum. Then, proper choice of dielectric thickness will allow the phase velocity of the mode to be matched to the electron velocity. Therefore, for a given dielectric material and thickness there should be a one to one correspondence between electron energy and propagating wave frequency. This relation is

$$f = \frac{1}{2\pi l\left(\mu_0\varepsilon - \frac{1}{\beta^2 c^2}\right)} \left\{ m\pi + \tan^{-1} n^2 \frac{\left(\frac{1}{\beta^2 c^2} - \mu_0\varepsilon_0\right)^{\frac{1}{2}}}{\left(\mu_0\varepsilon - \frac{1}{\beta^2 c^2}\right)^{\frac{1}{2}}} \right\} \tag{1}$$

where the wave mode $m = 0, 1, 2, \ldots$ and l = the thickness of the slab. For the parameters eventually chosen, $m = 1$ most nearly matches the available electron energy.)

Much of McLaughlin's effort was directed toward detecting the frequency corresponding to a given electron energy. It is shown below, however, that due to the differences between the apparatus used in the experiment and the simplified model used in the calculations, the correspondence of frequency to electron energy is only a general one and not nearly so significant as earlier assumed.

B. EFFECT OF FINITE SLAB LENGTH

It is the infinite slab assumption that makes the previous calculations not completely applicable to the experimental apparatus. If the slab were infinite and if velocities were exactly matched, then work done on an electron would be proportional to $\sin(\phi)$ where ϕ is the phase angle between the electron and the peak amplitude of the EM wave. Then to get any net work out of the electron beam, the beam would have to be so structured as to have small bunches of electrons near the peak amplitude of the wave. But if velocities are not exactly matched, any electron would receive just as much energy from the wave as it gives to the wave as it continuously changes phase with the wave. But, because the slab is finite (approximately 20 cm in length in this case), any given electron can interact with the travelling wave for only a small number of cycles of the wave. During this interaction time, if the phase shift is different from an integer number of whole cycles, then net energy will be exchanged. As will be seen in the next chapter, the frequencies of interest to this experiment are in the range of about 8 GHz to about 30 GHz and the electron energies are of the order of 100 MeV, i.e $\beta = .999987$. Table I lists several frequencies within the range of interest, β of the EM waves in the dielectric, their wavelengths, the distance travelled by a given wavefront in 2/3 of a nanosecond (since the electrons require 2/3 of a nanosecond to travel the 20 cm slab-length), and the amount of phase (in cycles) that a 100 MeV electron would shift during its trip along the 20 cm slab. (Note that even though the frequencies chosen look quite suspicious, they were not chosen arbitrarily, and the reason for their selection will become clear later.)

TABLE I

Freq(GHz)	β	Wavelength	Distance	Δφ (cycles)
8.57	(complex)	3.50 cm	20 cm	0.00
11.12	.999987	2.70	20	0.00
11.42	.99895	2.62	19.98	0.01
14.28	.9395	1.97	18.79	0.61
17.14	.8664	1.52	17.3	1.75
19.99	.8149	1.18	16.3	3.11
22.85	.7832	1.028	15.7	4.21
25.70	.7614	0.889	15.2	5.40
28.56	.7461	0.784	14.9	6.46

The right-most column of Table I is the important result. Since β of the electron beam does not equal β of the wave except at one frequency, a given electron shifts in phase with respect to the EM wave. For frequencies close to the 11.12 GHz "tuned" frequency, this phase shift is only a small fraction of a cycle, during the electron's trip along the dielectric, and is therefore of little significance. For the higher frequencies, however, the phase shift is large; that is, a large fraction of a cycle or even more than a whole cycle. If the total phase shift of any electron with respect to the wave were exactly a whole number of cycles, there would be no net energy transfer from the electron to the wave, or vice versa, because the longitudinal component of the wave's electric field would average to zero. But any phase shift that is a fractional number of cycles represents a net gain or loss of energy by the EM wave.

C. LINEAR ACCELERATOR

The linear accelerator at the Naval Postgraduate School is the source of the electron beam for this experiment. It produces a bunched rather than continuous beam, which has a most significant influence upon the nature of the resulting radiation. Hence a somewhat detailed look at the structure of the beam is in order.

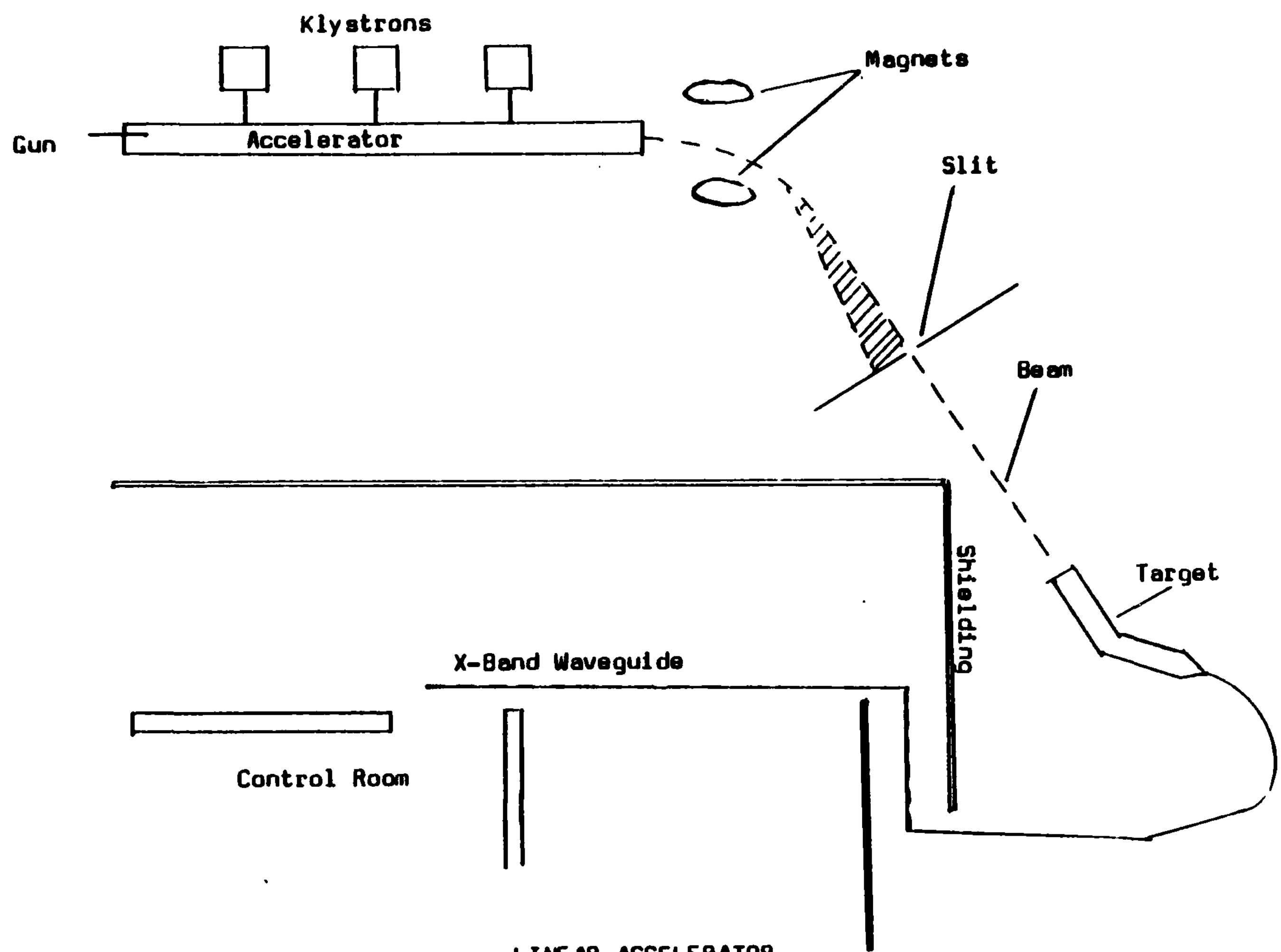
The LINAC consists of a 30 ft long section of circular waveguide into which the output of three klystron tubes is coupled in such a way as to cause the RF energy to travel along the guide in a TM mode. An electron gun at one end of the waveguide injects electrons at about $\beta = .5$. Because the RF energy is in a TM mode there is a longitudinal component of electric field which accelerates the electrons.

But the magnitude of the acceleration of any single electron is dependent upon where it happens to be in the phase of the RF accelerating wave. (Actually, after travelling only a few centimeters, the electrons, for most purposes, can be considered to be moving at speed c, and are merely gaining energy from the wave rather than accelerating.) Consequently a wide spread of electron energies is produced. In order to narrow the energy spread of the beam, only the most energetic are selected by an arrangement of magnets and a slit. Figure 1 is a schematic view looking down on the arrangement. The magnets bend the beam horizontally. But since the radius of curvature of the path of any single electron depends upon its energy, the electrons arrive at the plane of the slit already sorted out along a horizontal line according to their energies. Picking off the most energetic electrons is then a matter of proper horizontal positioning of the vertical slit.

A byproduct of this mechanism is that the beam is formed of bunches. The most energetic electrons are those which have ridden along on the RF wave where its longitudinal E-field is strongest, i.e. near the peak of the sinusoidal travelling wave. as shown in Figure 2.

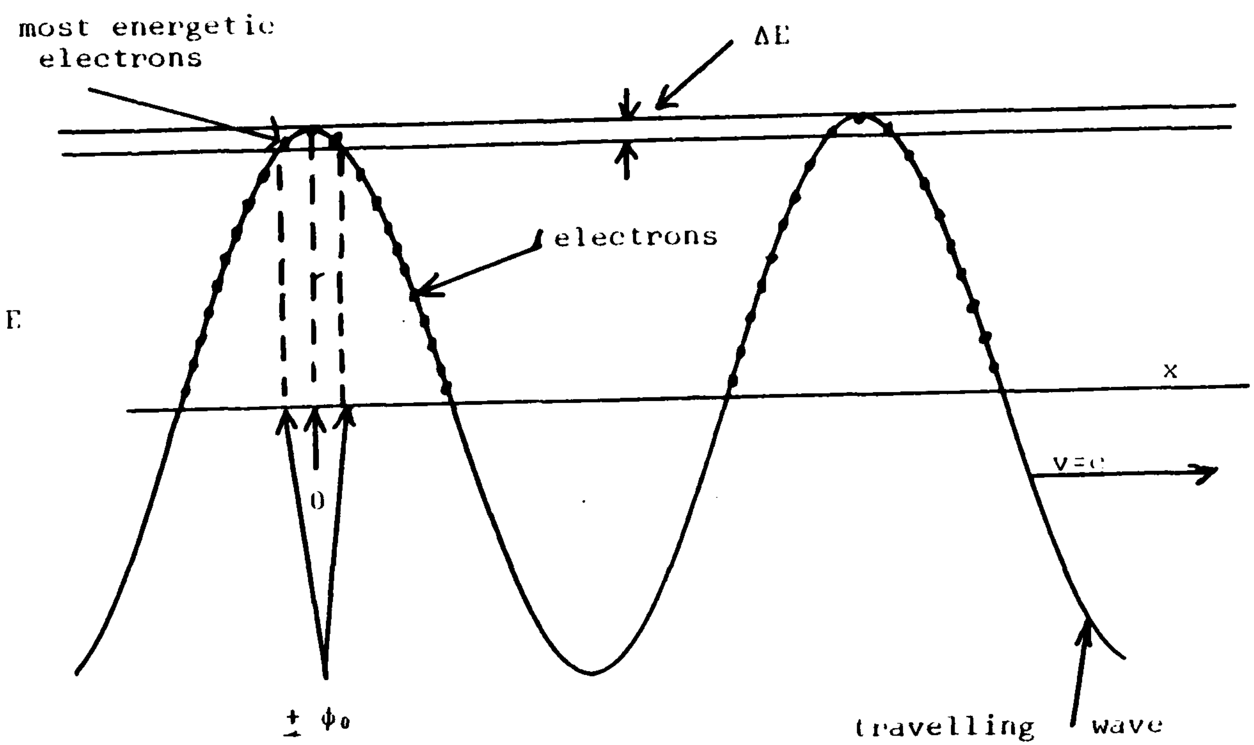
If ϕ is the phase angle relative to the peak energy, then the energy of any electron is

$$E = E_0 \cos(\phi) \qquad (2)$$



LINEAR ACCELERATOR

FIGURE 1.



ELECTRONS IN LONGITUDINAL E-FIELD

FIGURE 2.

where E_0 is the maximum energy. The magnet--slit structure accepts any electron with energy between E_0 and $E_0 - \Delta E$. ΔE must correspond to a particular phase angle ϕ_0. That is, electrons of interest must be riding on the wave within the phase angle range between $-\phi_0$ and ϕ_0. The least energetic electrons accepted have energy

$$E_0 - \Delta E = E_0 \cos(\phi_0) \qquad (3)$$

$$1 - \frac{\Delta E}{E_0} = \cos(\phi_0)$$

$$= 1 - \frac{\phi_0^2}{2} \quad , \text{ for small } \phi_0$$

$$\frac{\phi_0^2}{2} = \frac{\Delta E}{E_0} \qquad (4)$$

For the magnet--slit structure in question

$$\frac{\Delta E}{E} \approx .01 \qquad (5)$$

$$\phi_0^2 = .02 \qquad (6)$$

$$\phi_0 = .14 \text{ radians}$$

$$2\phi_0 = .28 \text{ radians}$$

$$\frac{2\phi_0}{2\pi} \approx .05 \qquad (7)$$

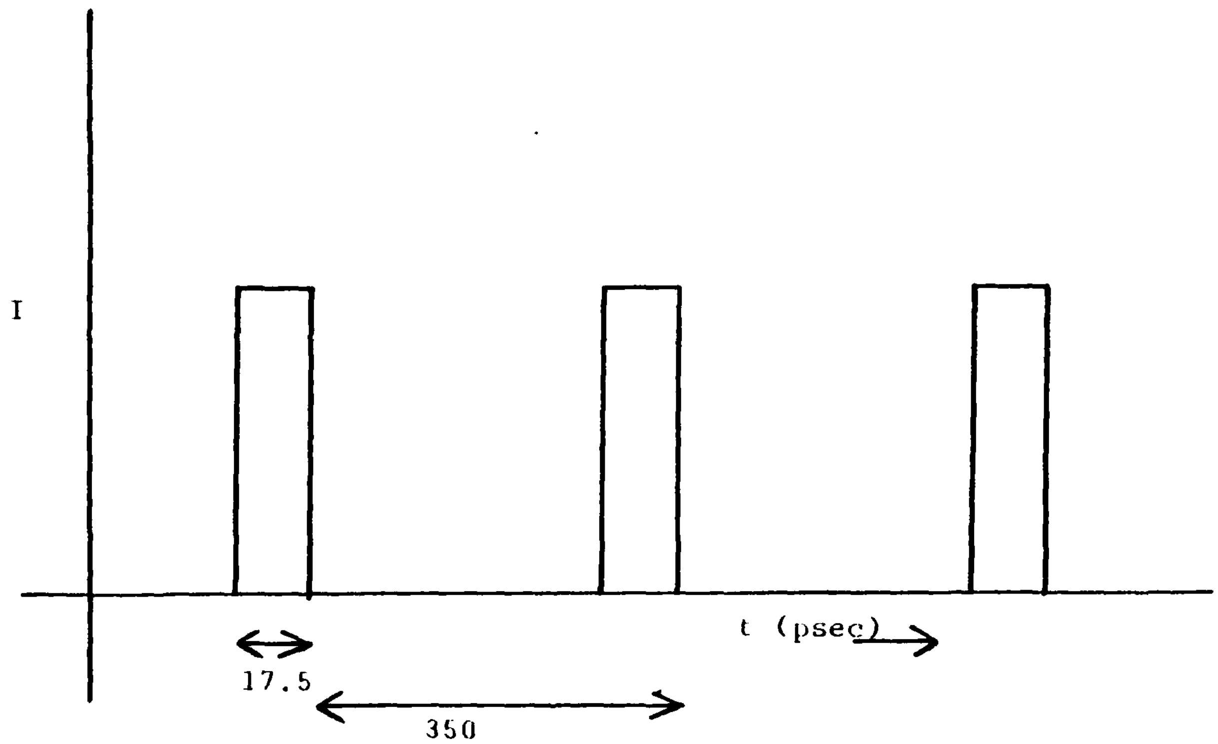
Equation (7) means that electrons are accepted for about 5% of each cycle. Our LINAC klystrons operate at 2.856 GHz.

$$.05/2.856 \text{ GHz} = 17.5 \text{ psec} \tag{8}$$

Therefore, the LINAC produces pulses that are 17.5 picoseconds long. Incidentally, it does so in one microsecond bursts at the rate of 60 bursts per second.

Figure 3 is a sketch of the beam current. For simplicity it is assumed that the current is constant over its 17.5 psec on-time, rather than having some more complicated shape. Figure 4 is a sketch of the Fourier transform of the current [Ref. 4]. The frequency spacing, 2.856 GHz, is the pulse repetition rate, i.e. the klystron frequency, and the amplitude envelope is the transform of the pulse duration.

Since the slab is short and its "tuning" is rather broad, as demonstrated in Table I, it can be driven at frequencies which fall within its "broad-tuning" envelope. Energy is being delivered to our apparatus not continuously, but at intervals corresponding to the harmonics of the fundamental frequency of the accelerator's klystrons. It is therefore reasonable to expect that any emissions from our sample dielectric will be at harmonic frequencies of the accelerator. As will be seen in the next chapter, our measureing method does not respond to the fundamental



BEAM CURRENT AS A FUNCTION OF TIME

FIGURE 3.

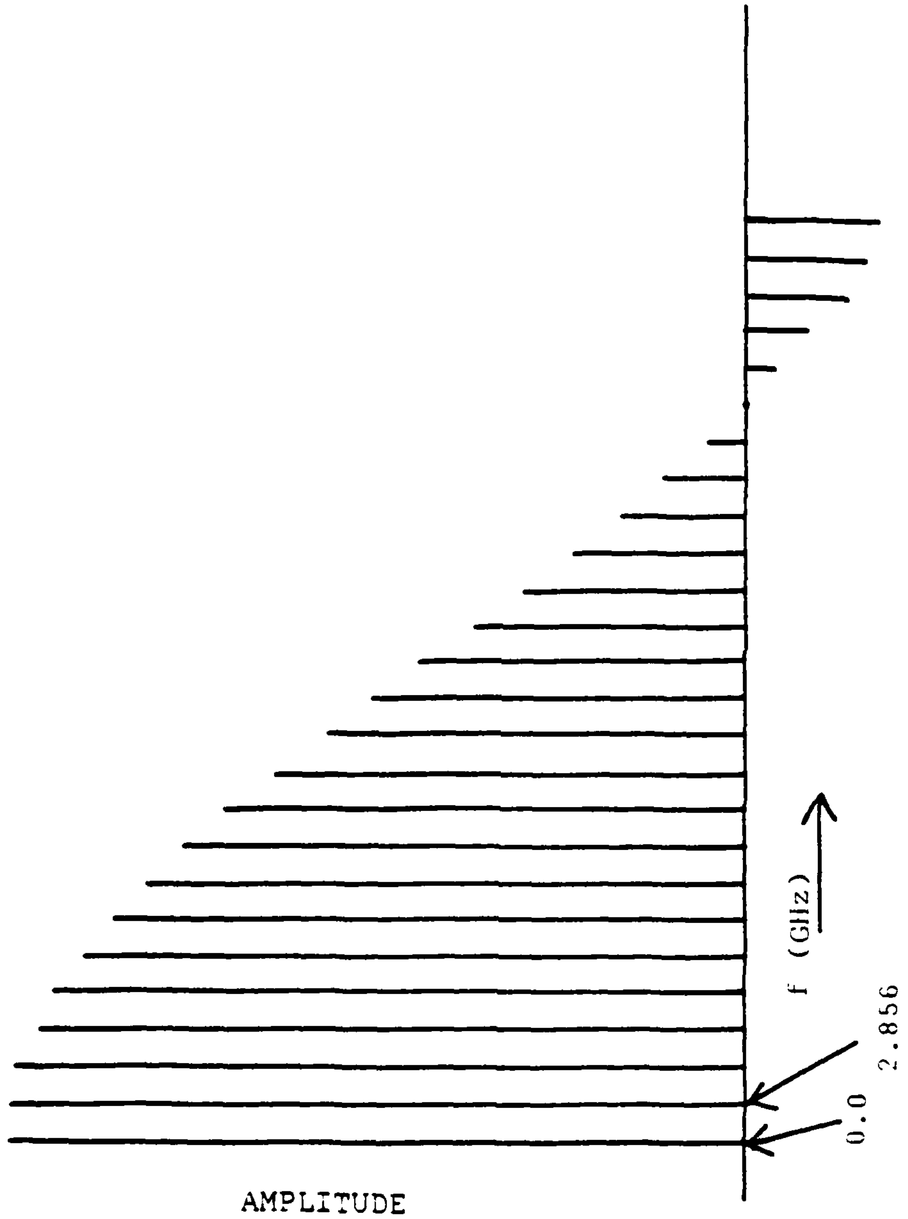


FIGURE 4.

FOURIER TRANSFORM OF BEAM CURRENT

and second harmonic. It is these harmonics (third through tenth), along with the theoretical 11.12 GHz "tuned" frequency, that are listed in Table I.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURE

A. BACKGROUND

McLaughlin calculated that the speed of the expected Stimulated Cerenkov Radiation (SCR) wave in the dielectric slab waveguide is greater than c/n for the dielectric material used and less than c. (Actually, it is less than the speed of light of whatever is in contact with the exposed face of the slab--air, for instance.) It was desired to select the material and slab thickness such that the wave speed would match the speed of electrons available from the LINAC. The LINAC provides electrons most conveniently at three selectable energies. These are 30, 60, and 100 MeV. These correspond to β's of .99985, .999964, and .999987 respectively.

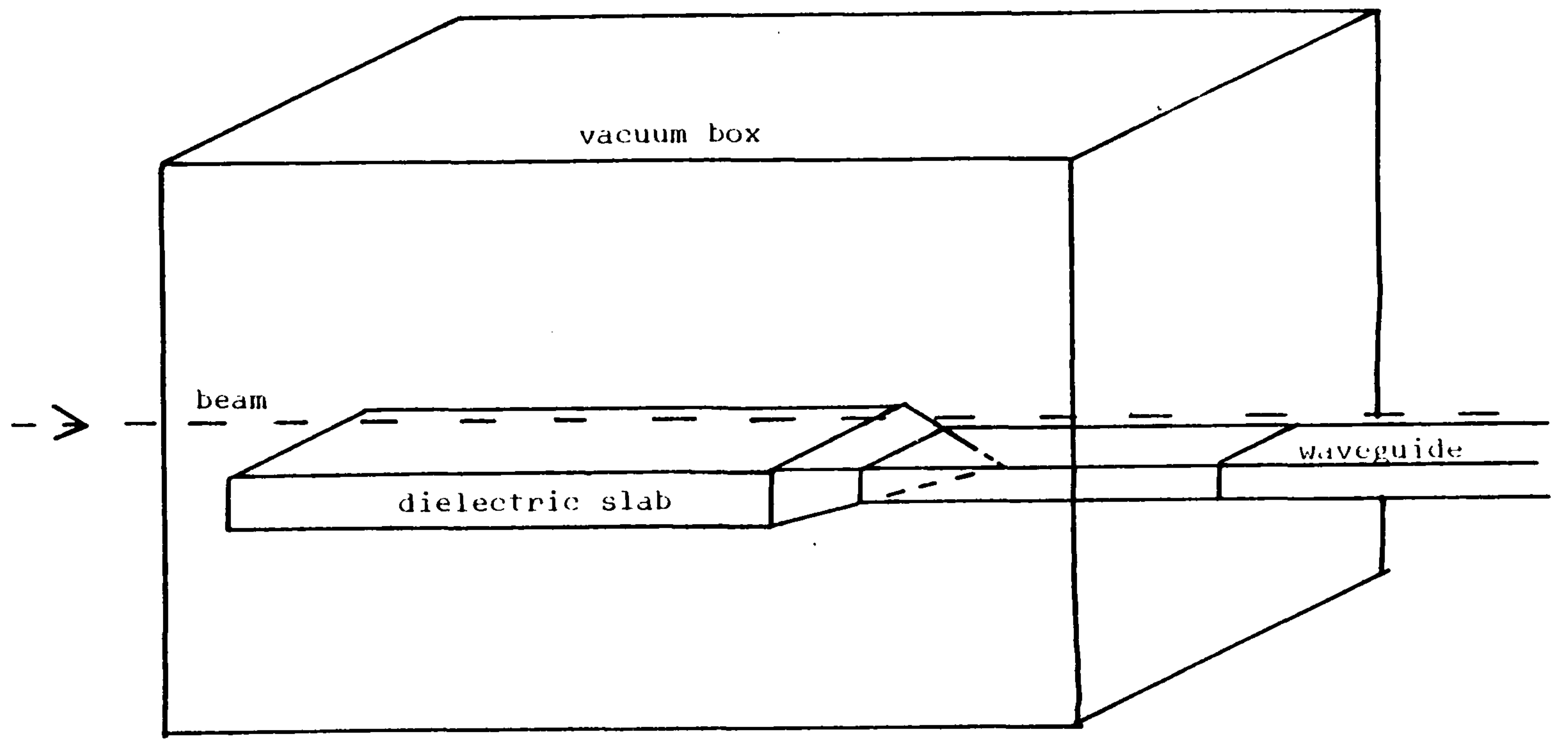
If the experiment were conducted in air, for which n = 1.0003 [Ref. 5], electrons exceeding 21 MeV would be moving faster than the speed of light in air. Since the lowest energy electrons available from the LINAC are about 30 MeV, it was concluded that the experiment could not be conducted in air, since the SCR wave speed could not match the electron speed. So it was decided to construct a vacuum box for the slab through which the electrons could pass. A section of X-band rectangular waveguide was coupled to one end of the slab and led through the box wall to an observation station for measurement. (For a more detailed explanation of the arrangement, the reader is once again referred to McLaughlin's thesis.) See Figure 5 for a sketch of the apparatus. The dielectric material selected was polyethylene, which has an index of refraction of 1.461 [Ref. 6]. The test slab was 1/2 inch (1.27 cm) thick, giving an expected SCR wave frequency of 11.12 GHz, 5 cm wide and 20 cm long.

It was expected that the device should act an an amplifier of an 11 GHz signal already propagating along the slab. But the first time the electron beam was passed over the slab, without providing an 11 GHz signal by some other means, a signal was detected. From this point onward McLaughlin's efforts were to analyze the signal obtained.

B. PRIOR CONCLUSIONS

About 75 ft of X-band waveguide was used to convey EM signals from the slab to the control room area. This waveguide has a low frequency cutoff of 6.56 GHz. (This is the reason the first and second harmonics of the LINAC klystrons cannot be measured.) At the observation station the waveguide was terminated into either a diode detector for measurement of the magnitude of the electric field of the wave on an oscilloscope or a quarter-wave adaptor to provide a signal to a Tektronix 491 spectrum analyzer (491-S/A).

McLaughlin observed that the SCR emission was composed of several discrete frequency components. Most of these



PREVIOUS CONFIGURATION

FIGURE 5.

were harmonics of the LINAC klystrons. He considered these to be parasitic signals entering the measurement equipments' transmission lines by some unexplained mechanism. There were two other frequencies upon which he focused his attention. These were a moderately strong signal supposedly at 10.21 GHz and a very weak signal at 10.92 GHz. Since these were near his predicted frequency of 11.12 GHz, he held some hope for their representing the desired emission.

C. REFINEMENT OF PREVIOUS EXPERIMENT

Upon attempting to repeat McLaughlin's measurements there were several difficulties encountered which ultimately led to reconfiguring the experimental setup. These included ambiguities in the 491-S/A display, possible antenna characteristics of the X-band waveguide, and uncertainties concerning the resonance modes of the metallic vacuum container.

1. Tektronix Spectrum Analyzer Display

The 491-S/A has a CRT display which plots signal amplitude versus frequency. As a small hand crank is turned, the center frequency of the display shifts one way or the other. When an interesting signal is centered on the CRT by turning the crank, the corresponding frequency is read off a scale that is mechanically linked to the crank. But two scales, not one, are linked to the crank, and the S/A responds to a signal at either of the indicated frequencies. This is a consequence of the manner in which the S/A mixes the incoming signal with a local oscillator. Even though this trait is a design feature of the instrument, it does cause its user to be uncertain about which frequency is actually present.

As stated above, one of the observed signals was reported to be at 10.21 GHz. As it happens, the 491-S/A scale alignment is such that 10.21 GHz on one scale is opposite 17.14 GHz on the other scale. Note from Table I that the sixth harmonic of the LINAC klystrons is 17.136 GHz.

It has since been verified that this signal is indeed at the higher of the two possible frequencies. This was done by coupling the X-band waveguide to a foot-long section of K-band waveguide to act as a high-pass filter. With the aid of a continuously variable microwave RF generator it was experimentally demonstrated that this filter provides a very sharp cutoff at 14.06 GHz. With this filter in place the signal in question was still present, indicating that it must be at the higher of the two frequencies--also a LINAC harmonic.

2. <u>Antenna Characteristics</u>

A section of rectangular waveguide which is not properly terminated, but simply left open to free space at one end will act as an antenna. If such an antenna radiates a signal and a stream of electrons passes through that signal, the electrons' motion will be disturbed. By imposing reciprocity, it is expected that electrons passing through the near field of a non-radiating waveguide/ antenna should induce a signal into the waveguide.

The initial experimental setup had the electron beam only the order of one wavelength away from the mouth of the guide. Indeed, with the dielectric slab removed, a signal was still detected when the beam was turned on. In fact, it was difficult to see any difference in the signal whether the slab was in place or not, indicating that the slab may not have been responsible for the emission.

3. Vacuum Box

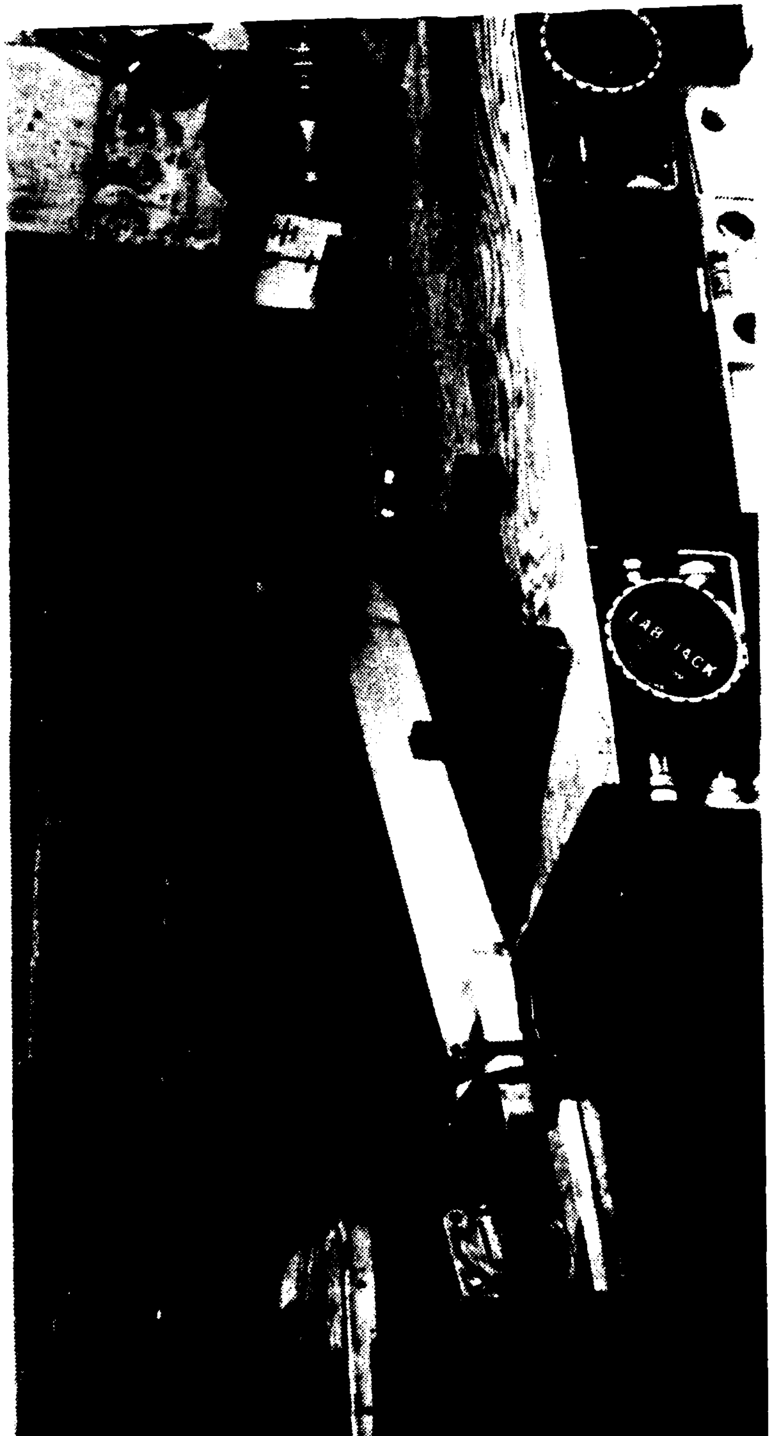
Recall that the apparatus was enclosed in a vessel to permit the evacuation of air. This vessel was an aluminum rectangular box. Rectangular boxes have resonances. The transverse dimensions of the box were of the order of one to a few wavelengths of the desired signal. This possible cause of confusion, the fact that (as was shown in the previous chapter) a vacuum is not really necessary considering the dimensions of our test slab, plus the fact that the confinement imposed by the size of the box prevented an arrangement where the X-band waveguide mouth could be removed from the immediate vicinity of the electron beam led to the decision to reconfigure the experiment, eliminating the box altogether.

D. NEW CONFIGURATION

Since the closeness of the mouth of the X-band waveguide to the electron beam had been the apparent cause of an unwanted signal, it seemed imperative that it be moved several cm away from the beam. But this means that there would have to be some way of getting the desired signal from the test slab to the metal guide. That is, some other form of waveguide was needed to interface the test slab with the X-band guide; and, of course, the junction of the slab with this new intermediate waveguide might then become an antenna for an unwanted signal. So it was decided to extend the length of the test slab and put a bend in its middle, so that downstream of the bend it would diverge from the beam, where it could then couple into the X-band guide. Due to the stiffness of the 1/2 inch thick polyethylene, actually bending the slab proved impossible, so two sections were bonded together at a 20 degree angle. Figure 6 is a photograph of the final configuration of the test slab.

E. INITIAL MEASUREMENTS

Upon starting up the beam after arranging the slab as outlined above, a signal was detected both on the 491-S/A and on the oscilloscope through the diode detector. Then the polyethylene was removed, but the X-band waveguide left unmoved to verify that it was sufficiently distant from the beam--and indeed, no signal could be detected. We then believed that we were seeing the hoped for SCR. The next task was to eliminate all other possible causes of the observed signal.



FINAL CONFIGURATION

Figure 6

The other possible causes include: ordinary Cerenkov radiation at microwave frequencies caused by the electron beam in the air, and some sort of radiation caused by a portion of the beam striking the dielectric.

1. Ordinary Cerenkov Radiation

Since this experiment is conducted in air, which has a refractive index of 1.0003, electrons travelling at more than c/1.0003 will produce ordinary Cerenkov radiation. It is conceivable that this radiation is entering the dielectric and then becomes trapped in the slab. The most straightforward way to rule out this possibility might seem to remove the air. But the vacuum box used proviously caused the aforementioned problems, and constructing one free of those problems might conceivably be too lengthy a task for the available time. An alternative method was devised to demonstrate that ordinary Cerenkov was not the source of radiation.

In an earlier experiment at the Naval Postgraduate School LINAC, William M. Decker and Joseph Mackin [Ref. 7] examined the Cerenkov radiation patterns caused by the electron beam at the three available energies as it passed through various materials. They also measured the spreading of the beam caused by those materials.

Since helium at atmospheric pressure has a refractive index of 1.000033 [Ref 5] and since the condition for Cerenkov radiation is that βn be greater than 1, helium should not cause Cerenkov radiation if β of the electrons remains below .999967, which corresponds to an electron energy of 63 MeV. Recall that the LINAC can produce electrons with as low as 30 MeV, which is below the Cerenkov threshold for helium, but still above the 21 MeV threshold for standard air. (The measurements of Decker and Mackin tended to support this prediction, although there was some question about the purity of the helium used in their experiment.) If the observed radiation were due to ordinary Cerenkov radiation, it would be expected that a 30 MeV beam should still cause the radiation in air, but not in helium.

Segre predictsthat air should cause considerably more angular spreading of the beam than helium, and that the spreading becomes greater as the beam energy is reduced [Ref. 8]. The relationship is given by

$$\theta^2 = (E_s/PV)^2(L/L_{rad}) \tag{9}$$

E_s is a constant equal to 21.2 MeV, PV is approximately the energy of the extremely relativistic particle, L_{rad} is the radiation length in g/cm^2, and L is the scattering length which is equal to the thickness of the scatterer times the density. Decker and Mackin experimentally confirmed these predictions. Table II is a list of pertinent parameters, where the scattering length is chosen to be

25 cm for gases, since this is the distance travelled by our beam from where it first emerges into atmospheric pressure to the end of the test slab, and .03 cm for aluminum since this is the approximate thickness of the luminous screen used to visually locate the beam.

TABLE II

Material	L_{rad} (g/cm^2)	Density (mg/cm^3)	PV (MeV)	θ
Helium	85.0	0.179	100	.0015
Helium	85.0	0.179	60	.0025
Helium	85.0	0.179	30	.0051
Air	36.5	1.30	100	.0063
Air	36.5	1.30	60	.010
Air	36.5	1.30	30	.021
Aluminum	23.9	2700.	100	.0069
Aluminum	23.9	2700.	60	.011
Aluminum	23.9	2700.	30	.023

The significance of Table II is that to assure that there is no ordinary Cerenkov radiation given off in helium, 30 MeV electrons must be used. Then a comparison must be made between the radiation in air and in helium at this energy. But at this energy the spread due to air is considerably more than the spreading due to helium. Over their 25 cm of travel, a 30 MeV electron beam spreads to about 1.1 cm diameter due to the combined effect of the luminous screen and air, compared to about .7 cm diameter due to the screen and helium. As will be seen later, the radiation amplitude is quite sensitive to proximity to the slab and horizontal position over the slab.

The test apparatus was enclosed in a large plastic bag, vented near its lowest point, and helium was continuously piped in to purge air from the bag. The radiation amplitude (measured on the oscilloscope through the diode detector) was about 1 mV with a 33 MeV beam of 8×10^{-9} amperes in helium, and about .5 mV with a similar beam in air. (Incidentally, .5 mV is at the sensitivity limit of our oscilliscope.) This then supports our expectations that the radiation is not due to ordinary Cerenkov, since the signal did not disappear when helium was used. Indeed, the signal was stronger in helium, which can be explained by the difference in beam spreading. More will be said on this point later.

2. <u>Electron Collisions</u>

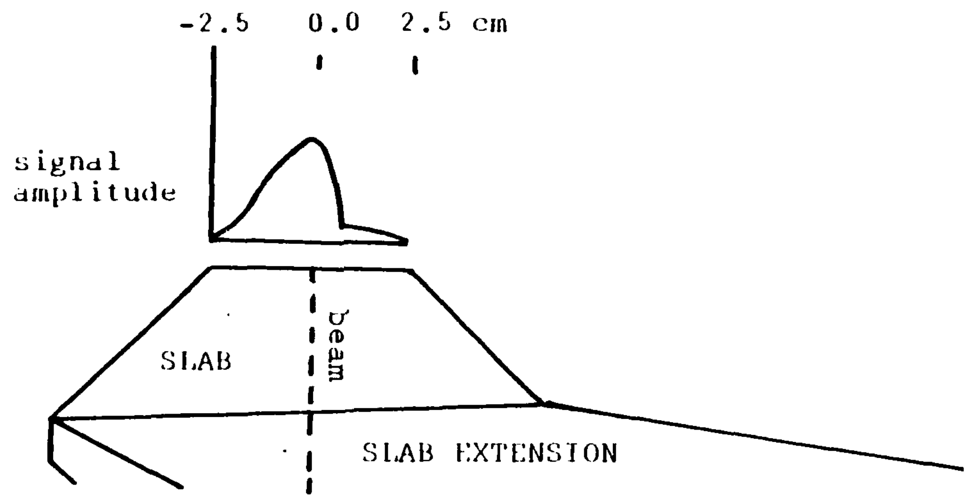
The theory says that as the electron beam approaches the dielectric, without coming so close as to strike it, the Stimulated Cerenkov Radiation amplitude should increase. However, the LINAC's beam is not infinitesimally small. It has some finite cross section or radial distribution. From Table II the diameter of the beam in air at 100 MeV grows to at least 1/3 cm by the time it reaches the far end of the slab, and in practice is usually somewhat larger. (This is due to the manner in which the beam is steered from the control room. If the beam is very sharply focused, there is no remote steering control available. So in practice, the beam is usually intentionally defocused slightly to allow for some control over the beam's position.) As the beam is steered to attain the strongest signal, there will almost certainly be some electrons striking the dielectric, because of the width of the beam. Then perhaps the observed signal is due to some sort of collision interaction of electrons with the polyethylene.

It is believed that the major part of the observed signal is not caused by direct electron collisions in the dielectric. The position of the beam is monitored by observing the bright spots on luminous screens, one near each end of the slab, as the beam passes through them. A closed circuit TV system is used to view the spots. The light from the spots is intense enough to saturate the TV system, so no accurate picture of the beam's radial distribution is available. The spot size serves only as a rough measure of the beam size. Nevertheless, the observed microwave radiation is apparently due to the electrons very near the dielectric slab, rather than those striking it. As the beam is steered vertically, the radiation amplitude varies. The amplitude is greatest when the centers of the luminous spots are 2 mm or so above the slab. With the beam in this position some electrons are obviously striking the slab; the polyethylene is seen to luminesce on the TV monitor. As the beam is lowered from this position, however, the signal amplitude quickly decreases as more of the beam is driven into the slab. On the other hand, as the beam is raised the signal decreases somewhat more slowly: to about 1/3 its greatest amplitude in 1/2 cm.

F. FURTHER MEASUREMENTS

In attempting to verify that the measured signal was SCR, the signal strength as a function of beam height above the slab was determined. However, McLaughlin's calculations assumed that the slab was infinitely long and wide. Since the test sample is certainly not infinite, it remained to be measured how signal strength varies as a function of the beam's horizontal position.

To accomplish this, the LINAC was adjusted to attain as well focused a beam as possible. This localizes the position of the beam quite well but does not allow for any remote beam steering. So the procedure was to physically position the slab and note its position, next to turn on the beam and record the corresponding signal strength, then to turn off the beam and physically move the slab horizontally, etc. The results are recorded in Table III and plotted in figure 7. Recall that the slab is 5 cm wide. The + or - in Table III refers to horizontal displacement of the beam relative to the slab's centerline, + being to the right looking back into the beam. Amplitudes are to the nearest 0.5 mV.



SIGNAL AMPLITUDE AS A FUNCTION OF POSITION

FIGURE 7.

TABLE III

Horizontal Displacement (cm)	Signal Amplitude (mV)
-2.0	0.0
-1.5	0.5
-1.0	3.5
-0.5	5.0
0.0	1.5
+0.5	0.0
+1.0	0.0
+1.5	0.5
+2.0	0.5

Note that the slab responds better to the beam if it is somewhat left of centerline. Possible causes of this asymmetry are discussed in the next chapter.

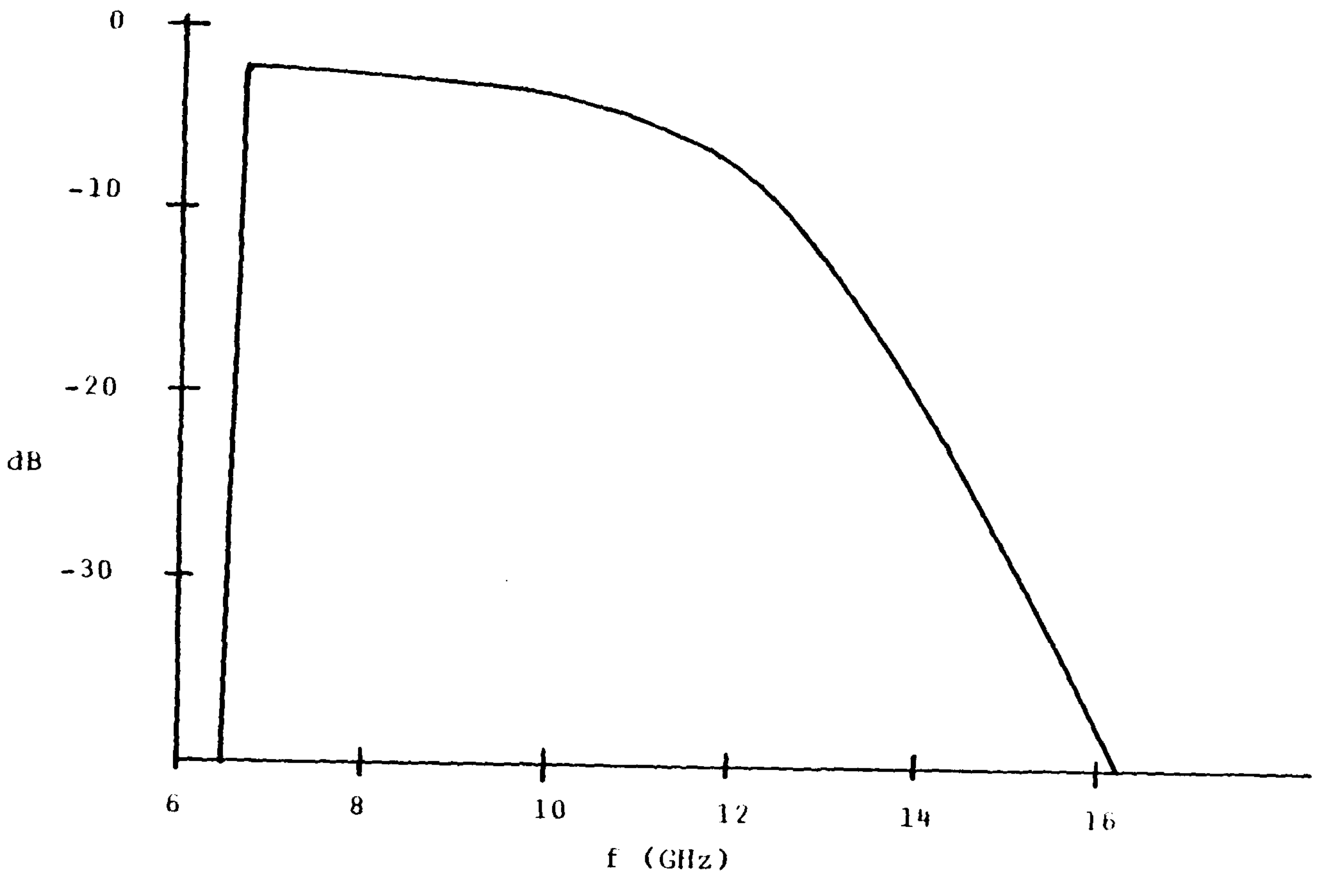
G. FREQUENCY STRUCTURE

As discussed in Chapter II, a particular frequency structure was anticipated in the SCR signal. This was measured by connecting the 491-S/A either to a quarter-wave adaptor (HP model X281A) on the end of the X-band guide or, for the higher frequencies, to a quarter-wave adaptor (Tektronix model UF-595/U) on the end of a section of K-band guide which was coupled to the X-band guide through a rectangular copper funnel. Knowing the frequency response of these adaptors enables some quantitative evaluation of the SCR signal. The K-band adaptor was used to measure signals only within (or very nearly within) its specified frequency range; so its response is assumed to be constant within a few dB. The X-band adaptor was used to measure signals outside of its specified frequency range of 8.2 to 12.4 GHz [Ref. 9]; so its response was measured using a tuneable microwave source and a Hewlett-Packard HP 8566A spectrum analyzer, and is plotted in Figure 8. Table IV is a list of the observed frequency components and their power (in dBm) into a 50 ohm termination, corrected for the frequency response of the X-band adaptor where appropriate, but not for whatever losses exist due to the 75 ft long X-band waveguide run.

TABLE IV

Freq (GHz)	Harmonic #	Power (dBm) (uncorrected)	Power (dBm) (corrected)
8.57	3	-63	-60
11.42	4	-81	-77
14.28	5	-96	-74
17.14	6	-74	-71
19.53	?	-81	-78
21.45	?	-88	-85
23.95	?	-84	-81
24.52	?	-84	-81
26.65	?	-83	-80

Data were taken on several different days to verify that they were repeatable. The third through sixth harmonic could be counted on any day, but the higher frequencies were sometimes present and sometimes not. Note also that



FREQUENCY RESPONSE OF X-BAND ADAPTOR

FIGURE 8.

the higher frequencies are not harmonics of the LINAC's RF frequency.

Anyone familiar with the use of spectrum analyzers knows that, when pushed to their sensitivity limits--which the 491-S/A was, their inherent non-linearities give rise to image signals, which are generated in mixers and not really present at the analyzers' inputs. With the real signals and their images nearly buried in the background noise, the display becomes very confusing and it is difficult to distinguish among true signals, images, and noise. The Hewlett-Packard S/A which had been used to measure the frequency response of the waveguide adaptor, was substituted for the 491-S/A in an attempt to resolve these uncertainties. The HP S/A did not indicate any of the higher signals listed in table IV, but neither did it indicate the fifth and sixth harmonic signals, as the HP 8566A had a noise floor that was some 15 dB higher than that of the Tektronix 491 and all these higher frequencies were thus buried in the noise if present.

The uncorrected power is also listed in Table IV. This is to give some indication of the validity of the measurement. The noise floor of the 491-S/A was about -105 to -90 dBm depending upon frequency (higher floor at higher frequencies). Note, for instance, that the fifth harmonic uncorrected power is very low. This is because it is considerably outside the normal operating range of the X-band adaptor (see Figure 8). It would probably not have been noticed had it not been specifically searched for.

IV. DISCUSSION

A. EFFECT OF DIELECTRIC GEOMETRY

Calculations performed subsequent to the experiment indicate that a significant improvement in the performance of the apparatus might be accomplished by a change in geometry of the slab.

From calculations by McLaughlin the electric field component in the direction of propagation (horizontal) of the evanescent wave is proportional to $\exp(-az)$, where z is the height of the beam above the slab, and a is some characteristic inverse distance. When McLaughlin first planned the experiment his intention was to choose the pertinent parameters such that the resulting SCR would be mm wave radiation. He wanted the parameter a to be 1/(a few centimeters). If the SCR were mm waves, the 20 cm length and 5 cm width of the slab would have made a reasonable approximation to an infinite slab. However, as the practical arrangements were carried out prior to the experiment, he found that no measuring equipment for mm waves was available to him, but equipment to measure cm waves was available. He therefore decided to change the thickness of the slab so that it would prefer the 11 GHz (i.e. 2.7 cm) signal referred to earlier. But doing so changed the parameter a to an unrealistic value, which was not recognized.

McLaughlin showed that

$$a^2 = k^2 - \omega^2/c^2 \tag{10}$$

where k is the wave number of the SCR, and that

$$k = \omega/\beta c \tag{11}$$

Therefore,

$$a^2 = (\omega^2/c^2)(1/\beta^2 - 1)$$

$$= (\omega^2/c^2)((1-\beta^2)/\beta^2)$$

$$a \simeq \omega/\gamma c \tag{12}$$

That is, the characteristic distance of the evanescent wave above the dielectric is

$$z_0 = 1/a = \gamma c/\omega \tag{13}$$

$$z_0 \simeq 80 \text{ cm}$$

for the 11.12 GHz signal sought.

Recall from the previous chapter that the amplitude of the observed signal fell to 1/3 its maximum when raised only 1/2 cm, which is very different from the calculated 80 cm. But the slab is only 20 cm long. This is another indication that the infinite slab assumption is not appropriate. To make the slab approximate an infinite one its length would have to be at least a few times as great as the wave's characteristic vertical distance. Of course, doing so would make the slab's tuning much sharper than it is presently, which may exclude many of the LINAC harmonics from propagating. It would also make beam spreading in the air a much greater problem, so a vacuum container might be considered again.

An alternative would be to use a different dielectric material and/or slab thickness to obtain radiation of such a wavelength that would allow the slab to remain a more manageable size--if proper measuring equipment could be found. A complicating factor is that if very short wavelengths are desired, when the SCR wavelength becomes the order of 5 mm it is then of the same order of magnitude as the spatial length of the LINAC's electron bunches, which would tend to negate any energy transfer from the beam to the wave.

Another geometric feature to be considered is the 20 degree bend between the slab and its extension. As noted earlier the response of the slab to the horizontal position of the beam is asymmetric. Figure 7 illustrates that the "preferred" portion of the slab is the side opposite the direction to which the extension bends. This suggests that the EM wave has some trouble turning corners. An improvement might be to lessen or change the curvature in some manner. However, care must be taken in how this curve is made. At one point the possibility of making the slab extension to angle downward rather than to the side was considered. This was ruled out, however, because it would cause the evanescent wave to become superluminal as it rounded the bend, thus causing some portion of the signal to be lost.

B. FREQUENCY CONTENT

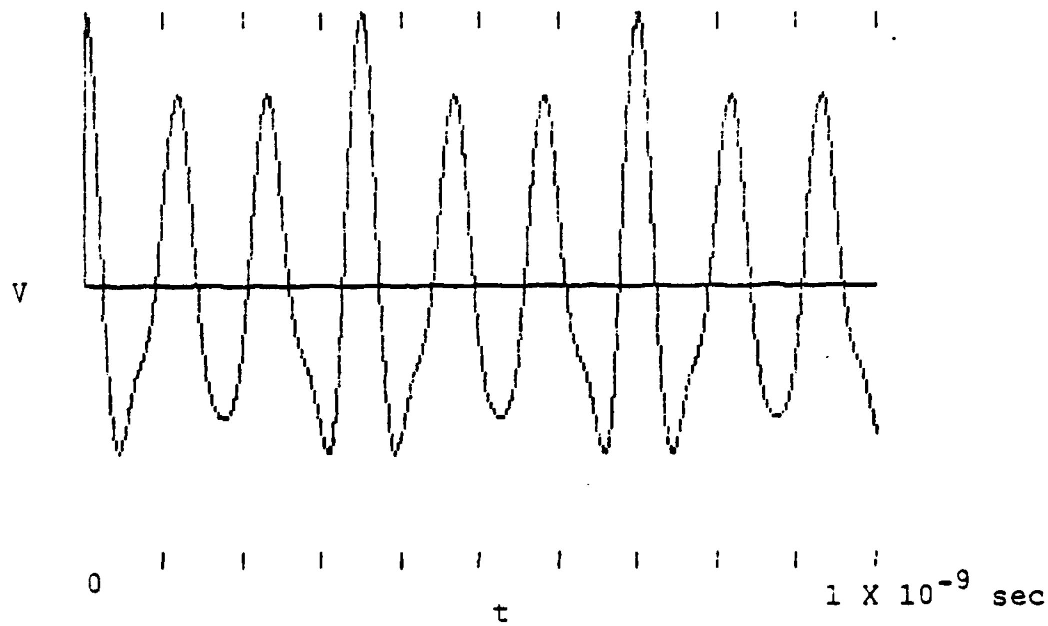
In an attempt to make some sense of the frequency content of the observed signal, a simple Fourier series summation program was written on a microcomputer. The listing for this program is to be found in the appendix.

Figure 9 is the Fourier sum of the first four terms listed in Table IV, which are those frequencies that are clearly harmonics of the LINAC. Figure 10 is the Fourier sum of all the terms in Table IV.

If the plots shown in Figures 9 and 10 are imagined to be the displays of some very responsive oscilloscope, one must admit that almost assuredly the observer would conclude that Figure 10 is just Figure 9 with some noise added to it. Although this is certainly not conclusive proof that the non-harmonic components of the observed signal are parasitic, it does give credence to such a deduction.

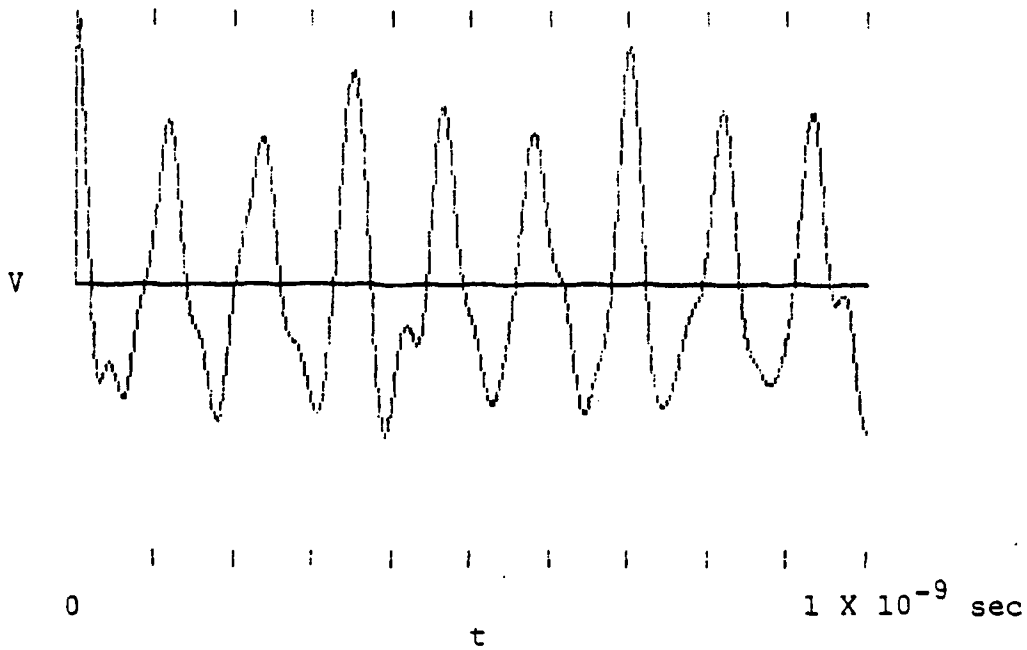
C. CONCLUSION

The suggestion that Stimulated Cerenkov Radiation can be produced by the interaction of relativistic electrons with a dielectric slab seems to be supported by this experiment. All evidence seen here qualitatively supports the



TIME DOMAIN AMPLITUDE OF OBSERVED SIGNAL
USING ONLY HARMONIC COMPONENTS

FIGURE 9.



TIME DOMAIN AMPLITUDE OF OBSERVED SIGNAL
USING ALL FREQUENCY COMPONENTS

FIGURE 10.

prediction. Nevertheless, many refinements remain to be done. Some specific suggestions are given below.

1. Length of Resonator

Since the length of the slab at present is inappropriate to the frequency of radiation observed, either a longer slab or a higher frequency should be used. The decision as to which should be changed must be made carefully, since each has its potential complications.

2. Symmetry

The cause of the asymmetry of the slab response to the beam's horizontal position is only conjecture. Various geometric configurations should be tested to find the cause.

3. Coupling of Resonator to Detector

The radiation induced in the slab is believed to be a TM mode. The X-band transmission waveguide to which the slab is coupled most readily propagates a TE mode. McLaughlin did some work to assure that the slab and waveguide were properly coupled, but the fact that some components of the observed signal are at the sensitivity limits of the measurement equipment suggests that anything that can be done to strengthen the signal can only help. Therefore, some detailed analysis of and experimentation with various coupling schemes are in order.

4. Electron Beam Monitor

As the experiment progressed and the impact of the electron beam structure became evident, it was realized that some of the details of the beam structure could be deduced from the observed signal. As it is now the slab is only very broadly tuned, and several of the beam's frequency components are consequently represented in the observed signal. If some scheme could be developed so that the first two harmonics of the beam structure could also be measured, a fairly complete picture of the electron beam bunches might be generated. This could be a useful instrument in the LINAC's control room, since no such beam monitor is currently employed.

APPENDIX

Fourier Sum Program Listing

The following is a program listing of a Fourier series summation of the frequencies and their amplitudes measured in the signal observed in the experiment. It is written in "Extended Color BASIC", which is a version of Microsoft BASIC, written under copyright of Microsoft for the Radio Shack TRS 80 Color Computer, which is a Motorola MC6809 based machine.

The Color Computer is a CRT graphics oriented machine. Consequently, some of the BASIC statements are screen oriented and unique to the Color Computer. The CRT screen resolution is 256 (horizontal) by 192, and hence the frequent use of the numbers 255 and 191.

Keeping these remarks in mind, a translation from Extended Color BASIC to another dielect of BASIC should not prove too great a task.

Radio Shack's machine language program "Screen Print Program", catalogue number 26-3021 ($4.95), permits the CRT display to be dumped directly onto an 80 column printer. The variable N6 in line 100 changes the time scale of the display. The program makes the assumption that all frequency components are cosine functions which are in phase at time $t = 0$.

```
10 REM ****FSUM***(FOURIER SUM)*****
20 PCLEAR 4 : REM THESE STATEMENTS
30 PMODE 4  : REM RESERVE MEMORY FOR
40 PCLS:CLS: REM CRT GRAPHICS
50 TERMS = 9
60 DATA  1,.14,.2,.28,.13,.06,.09,.09,.10 : REM AMPLITUDES
70 DATA 8.57, 11.42,.14.28,27.14,19.53,21.45,23.95,24.52,
     25.65 : REM FREQUENCIES
80 DIM AMP(TERMS),F7(TERMS)
90 DIV = 0
100 N6 = .5
120 FOR T7 = 1 TO TERMS
130 READ AMP(T7)
140 DIV = DIV+ABS(AMP(T7))
150 NEXT T7
160 FOR T7 = 1 TO TERMS
170 READ F7(T7)
180 F7(T7) = F7(T7)
190 NEXT
200 PISCALE = 3.14159265/255*2.856/N6
210 SCREEN 1,1
260 LINE (255,95)-(0,95),PSET
270 FOR I = 0 TO 255
280 CSSM = 0
290 FOR J = 1 TO TERMS
300 CSSM = CSSM + COS(F7(J)/2.856*I*PISCALE)*AMP(J)
310 NEXT J
320 NEXT I
```

LIST OF REFERENCES

1. Walsh, J. E., "Stimulated Cerenkov Radiation," Physics of Quantum Electronics, Vol. 5, Ed. S. F. Jacobs et al, Addison Wesley Publishing Company, Inc., 1978.

2. Walsh, J. E., Cerenkov Laser Experiment, Dartmouth College, June 25, 1980

3. McLaughlin, D. E., Cerenkov Radiation Produced by 100 MeV Electrons, Masters Thesis, Naval Postgraduate School, Monterey, 1981

4. Brigham, E. O., The Fast Fourier Transform, p. 24-27, Prentice-Hall, 1974

5. Hodgman, C. D., Handbook of Chemistry and Physics, 38th Edition, Chemical Rubber Publishing Co., 1956

6. Simonis, G. J., "Near mm Wave Materials," Harry Diamond Labs.

7. Decker, W. M. and Mackin, J. P., Measurement of Pumped Superluminal Electromagnetic Radiation, Masters Thesis, Naval Postgraduate School, Monterey, 1980

8. Segre, E., Nuclei and Particles, W. A. Benjamin, Inc., New York, 1964.

9. Engineering Staff of the Microwave Division of Hewlett-Packard, Microwave Theory and Measurements, Prentice-Hall, 1962

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