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Mr. John Greenewald Jr.
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Dear Mr. Greenewald:

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FINAL REPORT

for

Contract No. N00014-67-A-0112-0033

METHODS FOR OBTAINING LASER ACTION AT WAVELENGTHS SHORTER THAN 3000 Å

for the period

1 January 1969 - 28 February 1972

for

Navy Office of Naval Research

M. L. Report No. 2066

June 1972

Microwave Laboratory
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Stanford University
Stanford, California

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13. ABSTRACT The objective of this work is to obtain an ultraviolet source using Cerenkov radiation. Both the spontaneous and stimulated Cerenkov effects are studied theoretically and experimentally, to determine their feasibility as uv sources.

From a classical analysis of the spontaneous Cerenkov effect a brightness formula is derived for a relativistic electron beam moving through a dielectric of finite thickness and suffering no collisions. The brightness is shown to vary as $1/\lambda^5$, thus making this effect an excellent prospect for uv generation. For a 6 mm quartz target a brightness of 161 watts/Å-ster-cm^2 (at 125 cm distance for an 0.83 amp relativistic beam) is predicted at 3500 Å. The analysis is extended to include the effects of coulomb scattering from electron-atom collisions. Experimentally such a beam produces a brightness of 39 watts/Å-ster-cm^2 showing that scattering is not an important factor.

The stimulated Cerenkov effect is analyzed classically from the Boltzmann and wave equations. The calculation follows the TWT (Traveling Wave Tube) analysis. The gain per unit length is found to vary as $1/\lambda^{1/3}$, again lending itself to uv generation. From the analysis an experimental device was designed using a quartz Fabry-Perot resonator. A small increase in power over the spontaneously produced radiation was noted (3 dB increase). However, this gain can be attributed to experimental error. To obtain an increase in gain it is necessary to increase the interaction volume common to the beam and dielectric. It may be possible to achieve this by designing a resonator with a large light beam waist.

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Traveling Wave Tube Analysis						
Brightness measurement						

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METHODS FOR OBTAINING LASER ACTION

AT WAVELENGTHS SHORTER THAN 3000 Å

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Page	
15	First line below Eq. (9), change "Alvagadros" to "Avogadro's".
20	First line of text, change "coloring" to "color".
22	Fourth line from bottom, change "convering" to "covering".

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ABSTRACT

The objective of this work is to obtain an ultraviolet source using Cerenkov radiation. Both the spontaneous and stimulated Cerenkov effects are studied theoretically and experimentally, to determine their feasibility as uv sources.

From a classical analysis of the spontaneous Cerenkov effect a brightness formula is derived for a relativistic electron beam moving through a dielectric of finite thickness and suffering no collisions. The brightness is shown to vary as $1/\lambda^5$, thus making this effect an excellent prospect for uv generation. For a 6 mm quartz target a brightness of 161 watts/Å-ster-cm^2 (at 125 cm distance for an 0.83 amp relativistic beam) is predicted at 3500 Å. The analysis is extended to include the effects of coulomb scattering from electron-atom collisions using results by Dedrick[9], who has theoretically derived the resultant angular distribution of light intensity. For a 400 MeV electron beam with the same beam current and distance from the target as the previous example, a brightness of 13.6 mW/Å-ster-cm^2 is predicted at 3500 Å. However, experimentally such a beam produces a brightness of 39 watts/Å-ster-cm^2 showing that scattering is not an important factor.

A comparison between the spontaneous Cerenkov effect and other uv sources shows it to be an extremely high-brightness source of uv radiation. For example, in the nonscattered case, a 1 cm quartz crystal pumped by a 40 amp relativistic (> 1 GeV) electron beam produces a 2000 Å beam of

brightness 1.9×10^8 watts/Å-ster-cm^2 at a distance of 10 cm from the quartz. A 1000 watt uv mercury lamp produces an average power of 8 watts/Å-ster-cm^2 in the 2000 to 3000 Å range (the GE A-H6 water cooled quartz uv lamp).

The stimulated Cerenkov effect is analyzed classically from the Boltzmann and wave equations. The calculation follows the TWT (Traveling Wave Tube) analysis. Effects of electron velocity-spread, phase error, and electron-atom collisions are included in the analysis. The gain per unit length is found to vary as $1/\lambda^{1/3}$, again lending itself to uv generation. A 3000 Å plane wave interacting with a 400 MeV 0.83 amp electron beam in 3 cm of quartz will increase 3 dB in power. From the analysis an experimental device was designed using a quartz Fabry-Perot resonator. A small increase in power over the spontaneously produced radiation was noted (3 dB increase). However, this gain can be attributed to experimental error. To obtain an increase in gain it is necessary to increase the interaction volume common to the beam and dielectric. It may be possible to achieve this by designing a resonator with a large light beam waist.

I. INTRODUCTION

A. SPONTANEOUS CERENKOV EFFECT

When a high energy charged particle passes through a material at a velocity exceeding the velocity of light in the material ($v > c/n$), a broad spectrum of electromagnetic radiation is produced by the Cerenkov effect[1,2] (v is the velocity of electron; c, the speed of light, and n, the index of refraction). This radiation is emitted into a thin annular cone about the forward direction at an angle relative to the electron beam given by $\cos \theta_c = 1/n\beta$, where $\beta = v/c$. (See Fig. 1) The Cerenkov angle is simply the angle at which wavelets emerging from different points on the electron track interfere constructively and thus produce a macroscopic propagating wave.

The relation, $\cos \theta_c = \frac{1}{\beta n}$, is known as the Cerenkov condition. A few important facts can be obtained from this simple relation: a) If the angle, θ_c, is to be real, then the condition $\cos \theta_c \leq 1$ must hold. Hence, there is a minimum threshold velocity, $\beta_{th} = \frac{1}{n}$, below which no radiation will take place. This condition in turn establishes the minimum threshold energy of the electron beam for Cerenkov radiation to occur (Fig. 2). The higher the index, the lower the accelerating energy required. b) For $v \cong c$, a maximum angle will be given by $\cos \theta_{max} = \frac{1}{n}$. d) For real angles, the condition $n(\omega) > 1/\beta$ must hold. Since all real media are dispersive, and contain absorptive regions throughout the electromagnetic spectrum, the index of refraction is found to vary with frequency. A dispersion curve of a typical

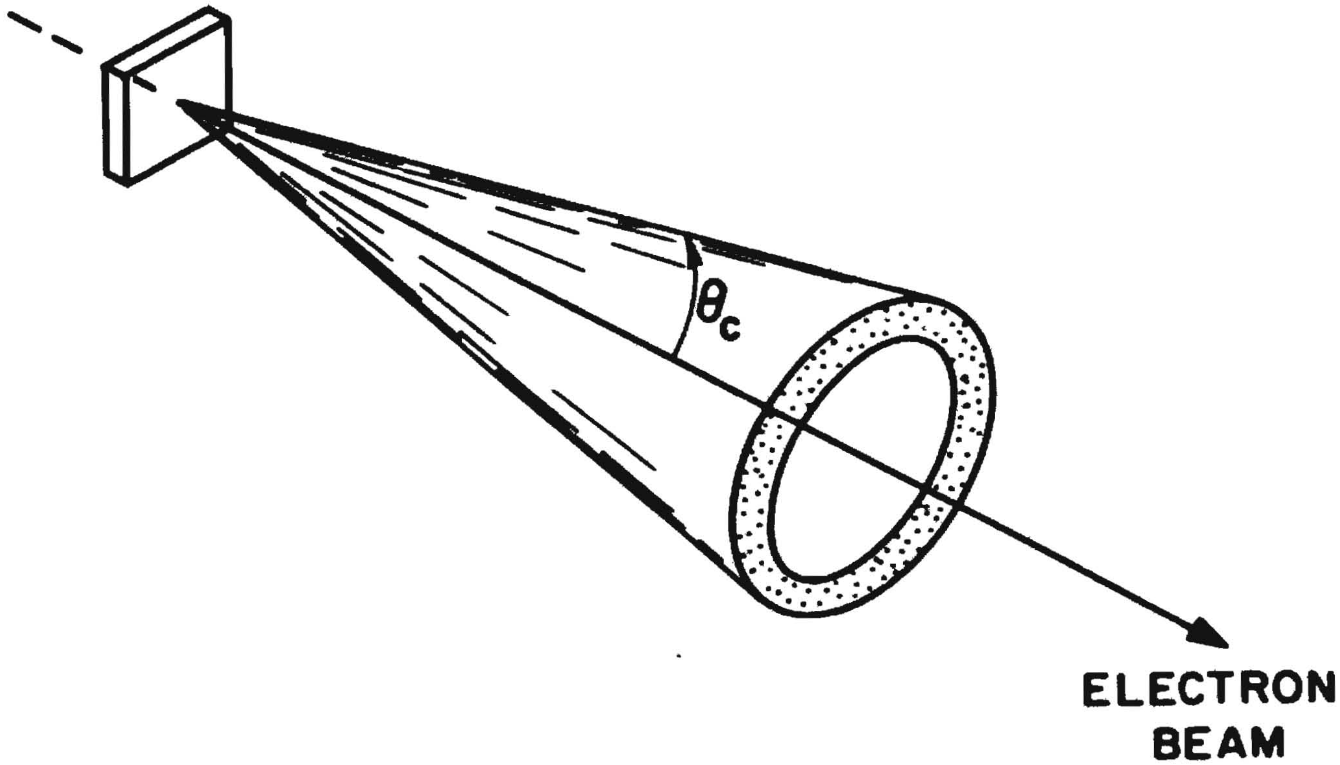


FIG. 1--Generation of Cerenkov light cone at angle θ_c .

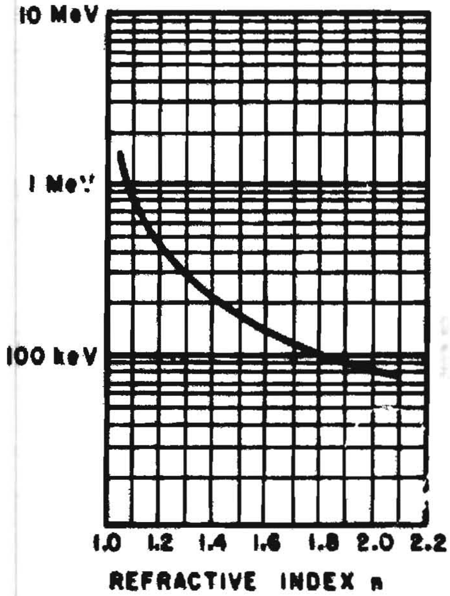


Fig. 2--Minimum threshold electron energy for Cerenkov Radiation to occur.

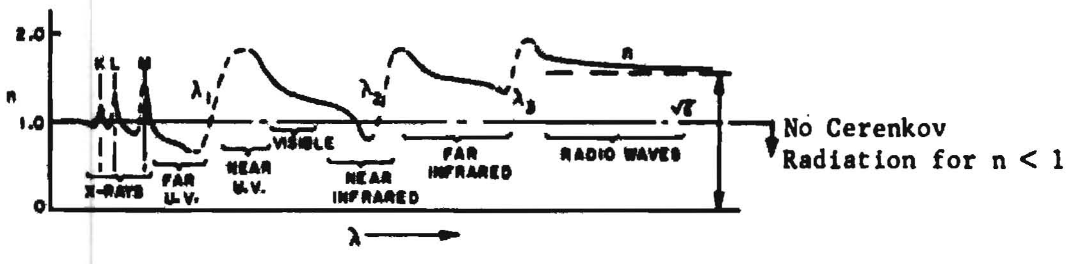


Fig. ´--The dispersion curve of a typical transparent medium over the whole electromagnetic spectrum. (After Jenkins and White, 1937).

transparent medium is shown in Fig. 3. Since $\beta \leq 1$, in regions where $n(\omega) < 1$ radiation is forbidden.

B. STIMULATED CERENKOV EFFECT

The outstanding success of laser research in infrared and optical portions of the spectrum is well known. Unfortunately, at ultraviolet frequencies laser action by the standard process of population inversion becomes difficult. With a given laser pump power density, the gain at the laser wavelength decreases rapidly with increasing frequency. This is due to the fact that the decay time from various metastable states in excited atoms is extremely short at ultraviolet frequencies. Other methods of stimulated emission are needed.

There are many reasons why it is desirable to develop broadly-tunable lasers in the ultraviolet and x-ray regions of the spectrum. There is, of course, the general requirement for a broadly tunable ultraviolet source for spectroscopic applications. There is a specific requirement for a tunable ultraviolet source for photoemission studies reaching toward the soft x-ray region. For this application complex and expensive systems are presently under consideration, e.g., synchroton radiation from an electron storage ring in a high energy accelerator system. In holographic applications the magnification ratio obtainable goes as the ratio of the coherent source frequencies used for the construction and viewing; thus, holography could benefit from the availability of a short-wavelength coherent source. As we approach the x-ray region of the spectrum, there are requirements in high energy physics scattering experiments for polarized photons of variable energies. In medical applications, the availability of a coherent x-ray source would allow higher resolution in x-ray photography, thus making possible the observation of minute cellular and tissue structure. As a final example, for long distance communication applications (e.g., interplanetary), the beam width decreases with increasing frequency, leading to increased transmission efficiency as the x-ray region of the spectrum is approached.

The stimulated Cerenkov process lends itself to short wavelength generation. Theoretical calculations given in section II show the gain per cm to be proportional to $\lambda^{-1/3}$. Unlike ordinary laser action, the Cerenkov gain increases as the wavelength decreases making it an excellent prospect for uv generation.

In this paper we present a gain calculation which indicates the feasibility of constructing a Cerenkov laser, i.e., a device based on the stimulated Cerenkov effect. One dimensional analyses have been presented by plasma workers in the 1960's . For example, Ginzburg and Zheleznyakov have worked out what they termed "negative Cerenkov absorption" in plasmas.[3]

Their analysis is divided into two parts: a low density, $N_s \ll N_0$, and a high density, $N_s \gtrsim N_0$, electron beam (where N_s is the electron density and N_0 is the plasma density). The first problem is solved quantum mechanically. However, at the relatively high current densities required for the second problem, a classical analysis is more tractable. Here simple perturbation theory can no longer be easily applied since we are now dealing with large exponential gains. The Ginzburg analysis in fact shows the stimulated Cerenkov process to be identical with the traveling wave tube (TWT) theory.[3] Perturbation theory is unable to describe the exponential growth of electromagnetic waves in the TWT; hence, nothing would be gained by attempting to use perturbation theory on the stimulated Cerenkov effect.

Another way to calculate the gain constant for stimulated emission is to take the spontaneous cross section, and from this determine the stimulated cross section per mode by applying the mode density formula and replacing a factor of unity by N in accordance with the usual N + 1 factor for stimulated plus spontaneous emission.[4] This, however, would not include the effect of electron bunching, a strong factor in the classical gain calculation.

A simpler calculation is to employ a classical TWT analysis. The analysis differs from the usual TWT analysis in the following respects: 1) The analysis must be carried out relativistically. 2) In place of a slow-wave structure, such as a helix, we consider simply a plane wave propagating off-axis with respect to the electron beam, and at a velocity slower than the beam ($v_{el.} \approx c$, $v_{rad.}$ · c/n). 3) The deterioration of gain due to the scattering of electrons by atoms of the propagating medium, and the nonphase matching conditions due to both electron velocity spread and Cerenkov angle error are included in the analysis.

The relativistic TWT analysis leads to a cubic equation for the gain. The three solutions represent three waves, one growing, one decaying, and one neutral, noninteracting wave. A minimum value for the gain is shown to be needed for the positive wave to rise above the other waves.

From these experimental calculations a Cerenkov laser was proposed and tested using a quartz Fabry-Perot resonator. The device consists of a special radiation resistant quartz disc with two axially aligned polished mirrors. These mirrors are coated with standard laser dielectric surfaces which have maximum reflectivity at uv and visible frequencies depending upon the desired range of operation. This mirror quartz structure forms a resonant cavity. A relativistic electron beam was fired through this cavity at an angle relative to the axis of the mirror which corresponded to the Cerenkov angle (Fig.8). Some of the Cerenkov radiation generated in the quartz cavity lies along the resonant axis of the cavity causing the radiation to be reflected back onto the electron beam. This radiation in turn modulates the beam in a feedback process which results in more radiation and, hence, gain.

Experimental results are shown in section III. The device was undamaged by the intense electron bombardment after many hours of use. Small amounts of gain (3 dB) over the spontaneous radiation were observed over the bandwidth of the Fabry-Perot resonator. Unfortunately this is within experimental error. The failure of operation is due to the finite size of the light beam waist. The theoretical calculation of the gain is for the case of a plane wave with an infinite beam waist. A finite waist reduces the electron — light beam interaction area, thus reducing gain. However, by increasing the interaction length sufficient gain may be achieved for self-sustained oscillations. This will be discussed in the theoretical section.

II. THEORETICAL CALCULATIONS

A. SPONTANEOUS CERENKOV EFFECT

Even in the absence of stimulated emission, spontaneous Cerenkov radiation is useful as a source of uv radiation because of its directionality and high brightness. For this reason it can be used in some spectroscopic applications where uv radiation is required and with a brightness almost comparable with that of lasers. To investigate these claims we will calculate the brightness from previous analyses of Cerenkov radiation. The problem is solved in the texts of Jackson,[2] or Panofsky and Phillips.[5] These analyses include the diffraction of the light cone due to a finite electron path length. The energy radiated per unit solid angle per unit radian frequency interval by an electron passing through a dielectric slab of thickness L in a time $T = L/v = L/\beta^2c^2$ is calculated by Jackson to be:

$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2n\beta^2\sin^2\theta}{c}\left|\frac{\omega T}{2\pi}\frac{\sin\left[\frac{\omega T}{2}(1 - n\beta\cos\theta)\right]}{\left[\frac{\omega T}{2}(1 - n\beta\cos\theta)\right]}\right|^2 \qquad (1)$$

where Ω is the solid angle, ω is the frequency, and θ is the angle between the electron path and the radiation path.

Examination of the angular dependence of Eq. (1) reveals that the angular width of the radiation cone inside the material to be $\Delta\theta = \lambda/nL\sin\theta_c$, where λ is the free space wavelength. Thus the radiation is emitted into a solid angle $\Delta\Omega = \sin\theta\,\Delta\theta\Delta\varphi = 2\pi(\lambda/n)/L$. Outside the material θ and $\Delta\Omega$ are increased by a factor n, the index of refraction of the dielectric. The radiation flux is confined to an annular area $\Delta A = 2\pi R\sin\theta R\Delta\epsilon = 2\pi R^2\lambda/L$, where R is the distance from the slab. Converting Eq. (1) from a single electron to a current I and dividing by ΔA and $\Delta\Omega$ leads to the following brightness formula:

$$\frac{d^3P}{d\lambda d\Omega dA} = 15\,\frac{L^3(\text{cm})\ I(\text{amps})\sin^2\theta_c}{\lambda^5(\text{thous of Å})R^2\ (\text{cm})}\ \frac{\text{gigawatts}}{\text{Å-ster-cm}^2} \qquad (2)$$

This formula neglects the effects of electron beam velocity spread, and electron scattering by atoms of the medium.

The power per unit wavelength is obtained by integration over area and solid angle with the result

$$\frac{dP}{d\lambda} = 60\ \frac{L(\text{cm})\ I(\text{amps})\sin^2\theta_c}{\lambda^3(\text{thous of Å})}\ \frac{\text{watts}}{\text{Å}} \qquad (3)$$

At first glance, Eq. (2) seems to indicate extremely high brightness of tunable uv radiation at reasonable electron beam power levels. For example a 1 cm fused quartz slab pumped by a 40 amp source produces a 2000 Å cone of brightness 1.9×10^8 watts/Å-ster-cm^2 at a distance of 10 cm from the quartz. Compare this with a typical organic dye laser brightness of 10^9 watts/Å-ster-cm^2 and a xenon flashlamp brightness of 20 watts/Å-ster-cm^2.

Unfortunately, during their passage through the medium the electrons undergo multiple coulomb scattering in the vicinity of the dielectric's atomic nuclei. Since the individual electrons each have their paths altered as they traverse the medium, their individually generated light cones will emerge in different directions. This causes spreading of the Cerenkov light cone and, consequently, a deterioration of the brightness even though the power per unit bandwidth remains constant.

Because coulomb scattering arises from multiple and random collision events, the problem of finding how the electron paths are altered must be done statistically. This has been done and a mean square angle of scatter, $\langle\theta^2\rangle$, has been calculated by Rossi:[6]

$$\langle\theta^2\rangle^{1/2} = \frac{21}{E}\sqrt{\frac{L}{X_0}} \qquad (4)$$

where E is the energy of the electron beam in MeV, L the thickness of the scatterer, and X_0, a constant, dependent upon the medium and known as the radiation length.[7] Values of X_0 for some materials are given in the following table.

Material	Radiation Length X_0(cm)
Aluminium	9.69
Argon	0.12×10^5
Air	0.33×10^5
Copper	1.47
Lead	0.517
Carbon	22.14
Water	43.0
Fused Quartz	13.7

For example, at 500 MeV a 6 mm quartz slab will produce an rms scattering angle of 8.8 milliradians or 0.5 degrees. At 2 MeV 0.6 mm quartz produces 40 degrees of scatter. This last example is beyond the accuracy of Eq. (4), which is good only for small angles. However, such large angles of scatter raise doubts as to the accuracy of the brightness formula.[2]

The effect of colomb scattering on the brightness cannot be calculated in an elementary way. An approximate solution to the problem can be made if the angular width of the Cerenkov cone is known. This has been calculated by Dedrick[9] who solved the problem in the following manner: using the established theory of multiple scattering, he considers the path of the electron to be a series of straight line segments, each path radiating classical Cerenkov cones. An ensemble average was taken over all possible paths, and the width of the light cone established.

To find a good approximation for a brightness figure we would like an estimate of the width of the Cerenkov cone. From the Dedrick analysis for relativistic electron beams and small angles we can estimate the 3 dB intensity width to be $\Delta\theta \simeq \langle\theta^2\rangle^{1/2}/\sqrt{2}$ where $\langle\theta^2\rangle^{1/2}$ is the rms scattering angle given by Eq. (4). The radiation of this cone is emitted into a solid angle $\Delta\Omega = \sin\theta\, \Delta\theta\Delta\varphi = (2\pi/\sqrt{2}) \sin\theta\, \langle\theta^2\rangle^{1/2}$, and, thus, is confined to an annular area $\Delta A = R^2\Delta\Omega = R^2(2\pi/\sqrt{2}) \sin\theta\langle\theta^2\rangle^{1/2}$, where R is the distance from the medium. Dividing the power per unit bandwidth (Eq. 3) by ΔA and $\Delta\Omega$ we obtain the brightness

$$\frac{d^3P}{d\lambda d\Omega dA} = 30 \frac{L(\mathrm{cm})\ I(\mathrm{amps})}{\lambda^3(\mathrm{thous\ of\ \mathring{A}})R^2(\mathrm{cm})\langle\theta^2\rangle} \frac{\mathrm{watts}}{\mathrm{\mathring{A}\text{-}ster\text{-}cm^2}}$$

or substituting Eq. (4) for $\langle\theta^2\rangle$ we find

$$\frac{d^3P}{d\lambda d\Omega dA} = 30 \frac{I(\mathrm{amps})\ X_0(\mathrm{cm})}{\lambda^3(\mathrm{thous\ of\ \mathring{A}})R^2(\mathrm{cm})} \cdot \left(\frac{E(\mathrm{MeV})}{21}\right)^2 \frac{\mathrm{watts}}{\mathrm{\mathring{A}\text{-}ster\text{-}cm^2}} \tag{5}$$

This equation is plotted in Fig. 4 for quartz. Note, L has canceled out of the equation and the brightness is now independent of the slab thickness. It appears, within the order of the approximation made, that increasing the electron path length will not increase the brightness. This is because most of the Cerenkov light comes from the initial part of the electron path before scattering dominates. The minimum path length where Eq. (5) is still valid can be calculated from the Dedrick

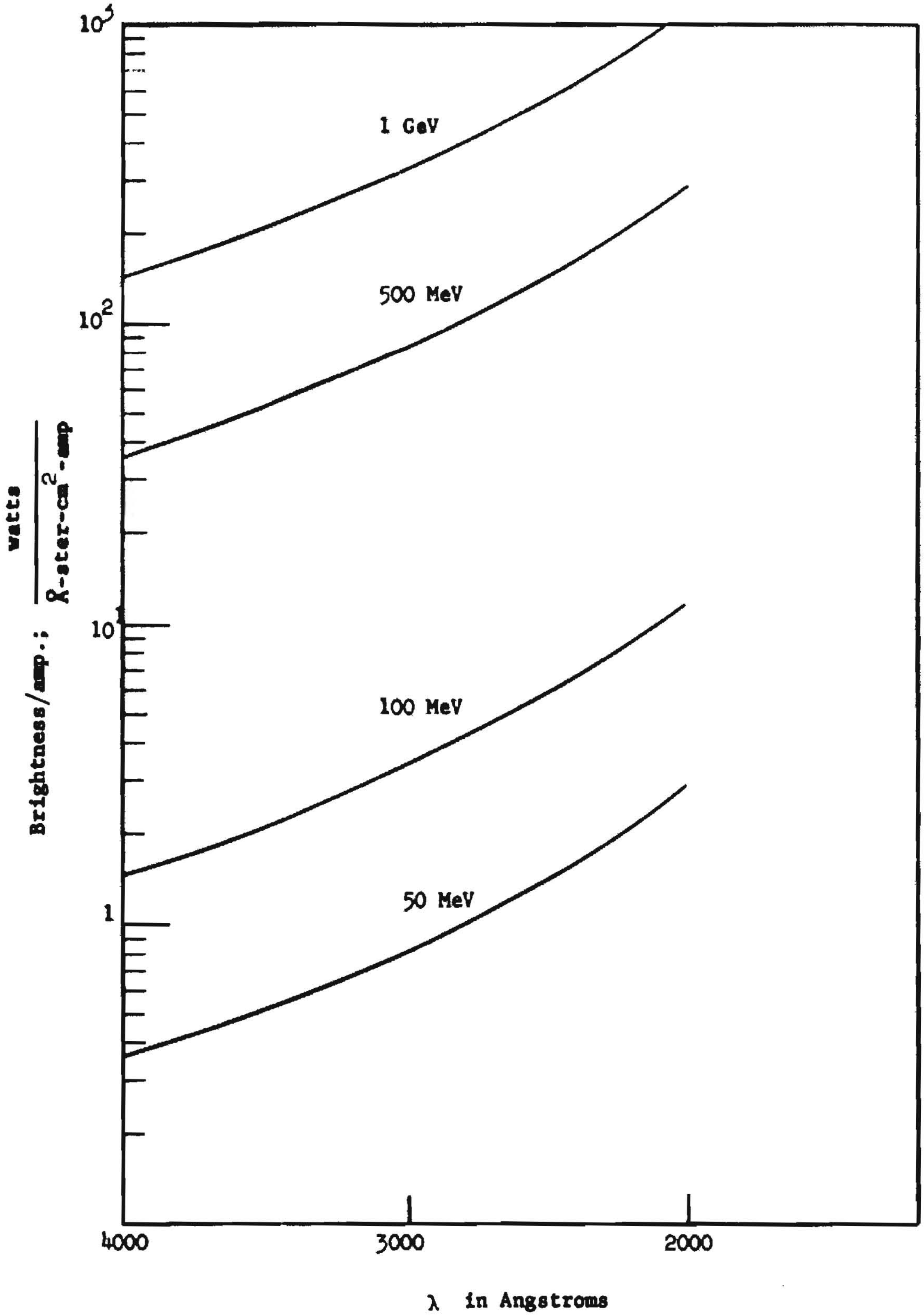


Fig. 4--Brightness per ampere vs wavelength from quartz at various electron beam energies for path lengths, $L \gg L_{min}$ where

$$L_{min} = \left(\frac{\lambda(\mathrm{cm})\ X_0^{1/2}(\mathrm{cm})\ E(\mathrm{MeV})}{10\ n\ \sin\theta_c} \right)^{2/3} .$$

analysis to be

$$L \geq L_{min} = 0.215 \left(\frac{\lambda(\text{cm})\ X_0^{1/2}(\text{cm})\ E(\text{MeV})}{n\ \sin\theta_c} \right)^{2/3}_{\text{cm}} \qquad (6)$$

Path lengths substantially larger than this do not contribute to the brightness. This is, of course, not true for the total number of photons which will continue to be produced as the electron path increases. Even for relatively large electron energies, the minimum path length can be small. For a 500 MeV, 40 amp, electron beam in quartz, a path length of 0.06 mm will generate most of the brightness. Hence, for any $L \gg L_{min} = 0.06$ mm Eq. (5) gives a brightness of 1.2×10^4 watts/Å-ster-cm^2. This is a considerably lower brightness than the previous calculated value of 1.9×10^8 watts/Å-ster-cm^2 from Eq. (2). However, it is still three to four orders of magnitude brighter than the General Electric A-H6, a water cooled quartz uv lamp with an average brightness of 8 watts/Å-ster-cm^2 (measured at 10 cm distance, ~ 2000 Å to 3000 Å). This 1000 watt lamp is one of the most powerful available sources in the ultraviolet.[10]

For longer minimum path lengths gases give larger brightnesses. For example, the electron beam of the previous example with a path length of $L > 70$ cm gives a brightness of 2.8×10^7 watts/Å-ster-cm^2 in air at 760 mm mercury pressure. Thus, even with scattering, the Cerenkov effect in gases produces brightness comparable to that of dye lasers.

Experimentally, we will find in section 3 that the measured brightness for the case of a 320 MeV 0.83 amp beam in 6 mm of quartz is much closer to the nonscattered case than the scattered. Hence for energies greater than 100 MeV, Eq. (2) may be used as a best estimate. Thus the spontaneous Cerenkov effect produces good uv powers with relativistic electron beams.

B. STIMULATED CERENKOV EFFECT

In this section gain calculations are presented which indicate the feasibility of constructing a Cerenkov laser, i.e., a device based on stimulated Cerenkov radiation.

As stated in the introduction, at the relatively high current densities required for large gains, it is appropriate to analyze the stimulated Cerenkov effect along the lines of a TWT (traveling wave tube) analysis.[11] The analysis is different in that it is three dimensional, relativistic, and includes terms which indicate deterioration of gain due to electron-atom collisions, electron velocity spread and nonphase matching of the radiation wave and electron beam ($\theta \neq \theta_c$). In place of a slow wave circuit such as a helix or loaded waveguide, we simply consider plane wave propagation off axis with respect to the electron beam ($V_{electron} \approx C$, $V_{radiation} \simeq C/n$).

The relativistic TWT analysis leads to a standard cubic equation for the gain, modified to include relativistic effects

$$j\delta[(\delta - d + jb)^2 + f^2] = \beta_e^3 C^3 \qquad (7)$$

where

$$C = \frac{4.9 \times 10^{-5}}{2\pi n}\left[\frac{n^2-1}{n}\tan^2\theta_c \frac{J(\text{amps/cm}^2)}{E(\text{MeV})\lambda(\text{thous of Å})}\right]^{1/3} \qquad (8)$$

J is the current density, E is the beam energy, β_e the propagation constant of the dielectric. b represents the nonphase matched error: $b = \alpha \frac{\tan\theta_c}{C}$ where $\alpha = \theta_c - \theta$; f represents the electron velocity spread: $f = \frac{\Delta u}{u} \frac{1}{C}$, where Δu is the spread in electron velocity; and d represents attenuation due to electron-atom scattering:[12]

$$d = \frac{2N}{\lambda} \frac{Z^2}{A} r_e^2 \left(\frac{E_e}{E}\right) \frac{\rho}{\theta^2 + \theta_1^2} \tag{9}$$

where N is Alvagadros number; Z , the atomic number; A, the atomic weight; ρ , the density of the medium; r_e , the classical radius of the electron; E_e, the electron rest energy; E , the total electron beam energy; and θ , the far angle spread of resonator beam waist.

For the simple case where there is phase matching (b=0), no electron-atom collisions (d=0), and no electron velocity spread (f=0), the roots of the cubic equation are:[13]

$$\delta_1 = (0.866 - j\,0.5)\beta_e C$$

$$\delta_2 = (-\,0.866 - j\,0.5)\beta_e C$$

$$\delta_3 = j\beta_e C \quad .$$

These three roots delineate three possible waves traveling at the Cerenkov angle. δ_1 represents a wave which increases as exp $(+\,0.866\,\beta_e C\xi)$; δ_2 , one that decreases as exp $(-\,0.866\,\beta_e C\xi)$; and δ_3 , one that is of constant amplitude with phase variation $\exp[-(1 - C)\beta_e\,\xi]$ (ξ is the distance measured along the Cerenkov angle). As the waves travel through the medium, the first wave begins to predominate over the other two. The total wave goes as

$$E = \frac{E_i}{3} e^{-j\beta_e(1-C)\xi} \left(1 + 2\cosh((\sqrt{3}/2)\beta_e C\xi) \cdot e^{-j(3/2)\beta_e C\xi}\right)$$

where E_i is the input wave.

Squaring this expression and expressing the gain in dB as 10 $\log_{10}$ $\left(\frac{E}{E_i}\right)^2$, we may plot gain versus CN where N is the number of cycles into the medium ($N = n\xi/\lambda$). In Fig. 5 we find that E_μ does not begin to change until it is well within the medium. At $CN > 0.2$ the increasing wave begins to predominate. This establishes a minimum path length needed to achieve gain ($N \geq 0.2/C$).

To see how the gain varies with wavelength, we note that CN is proportional to $\lambda^{-1/3}$. Hence, as we proceed into the uv the gain should increase.

To find out if gain is possible in quartz we plot C versus the current density J for various beam energies. This is shown in Fig. 6 for the case of $\lambda = 3000$ Å. A 500 MeV, 40 amps/cm^2 beam gives a C of 4×10^{-6}. For a 1 cm path length in quartz CN = 0.2. For a 2 MeV, 500 amp beam and at 1 mm path length, CN = 0.27. A resonator can be designed in which the power is fed back onto the electron beam leading to self sustained oscillations.

The effects of scattering, phase error and electron beam spread on the gain can be calculated from Eq. 7. This is done in Pierce.[14] From these calculations one may determine the limits of d, b, and f for gain to occur. Nominally these conditions are

$$\alpha \leq C$$
$$d \leq C$$
$$\frac{\Delta u}{u} \leq C$$

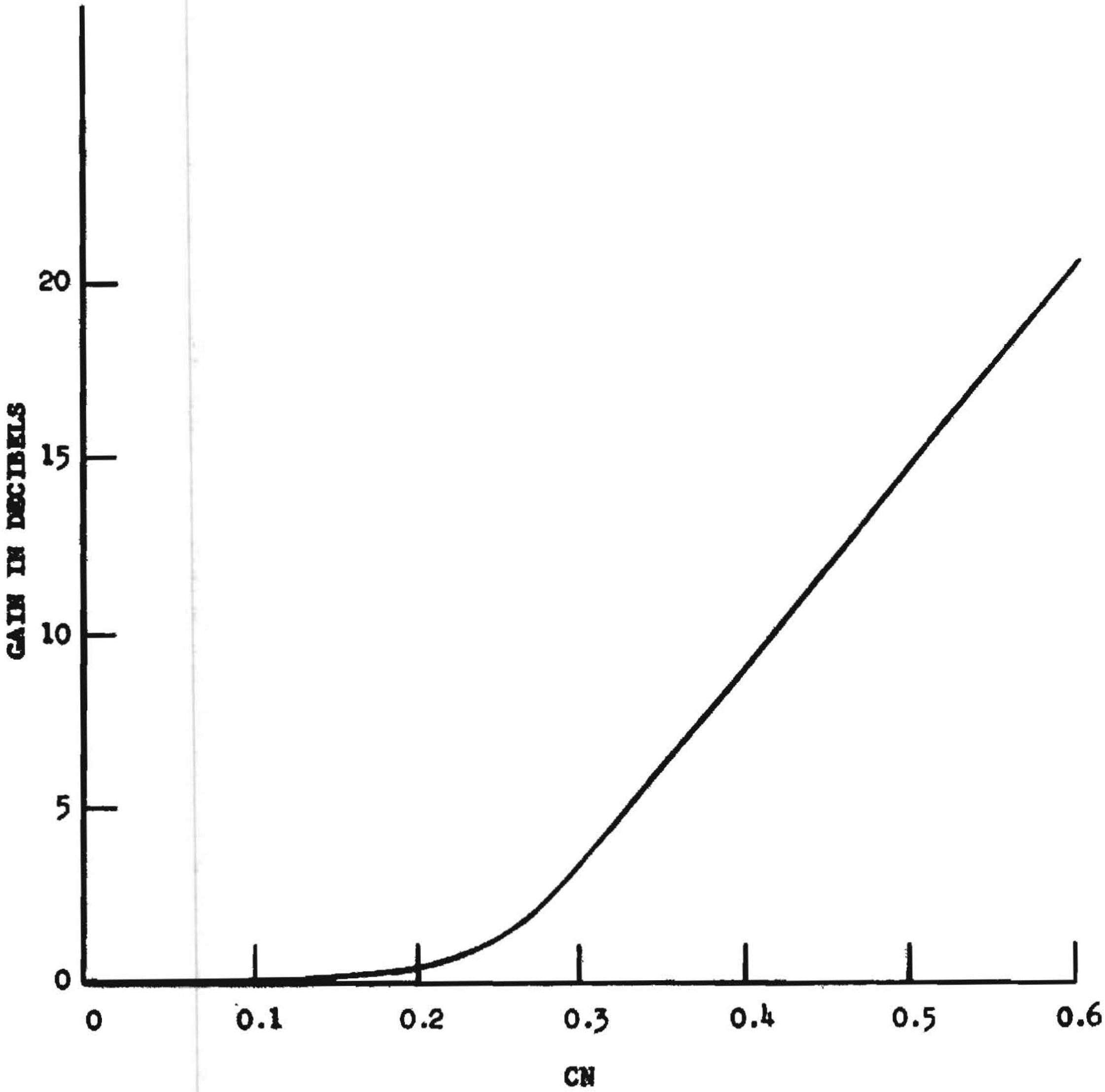


Fig. 5--Gain vs CN where N is the number of wavelengths into the medium $\beta_e \ell / 2\pi$, and

$$C = \frac{4.9 \times 10^{-5} \lambda}{2\pi \ n} \left[\frac{n^2 - 1}{n} \tan^2 \theta_c \ \frac{J(\text{amps/cm}^2)}{E(\text{MeV}) \ \lambda(\text{thous of Å})} \right]^{1/3} .$$

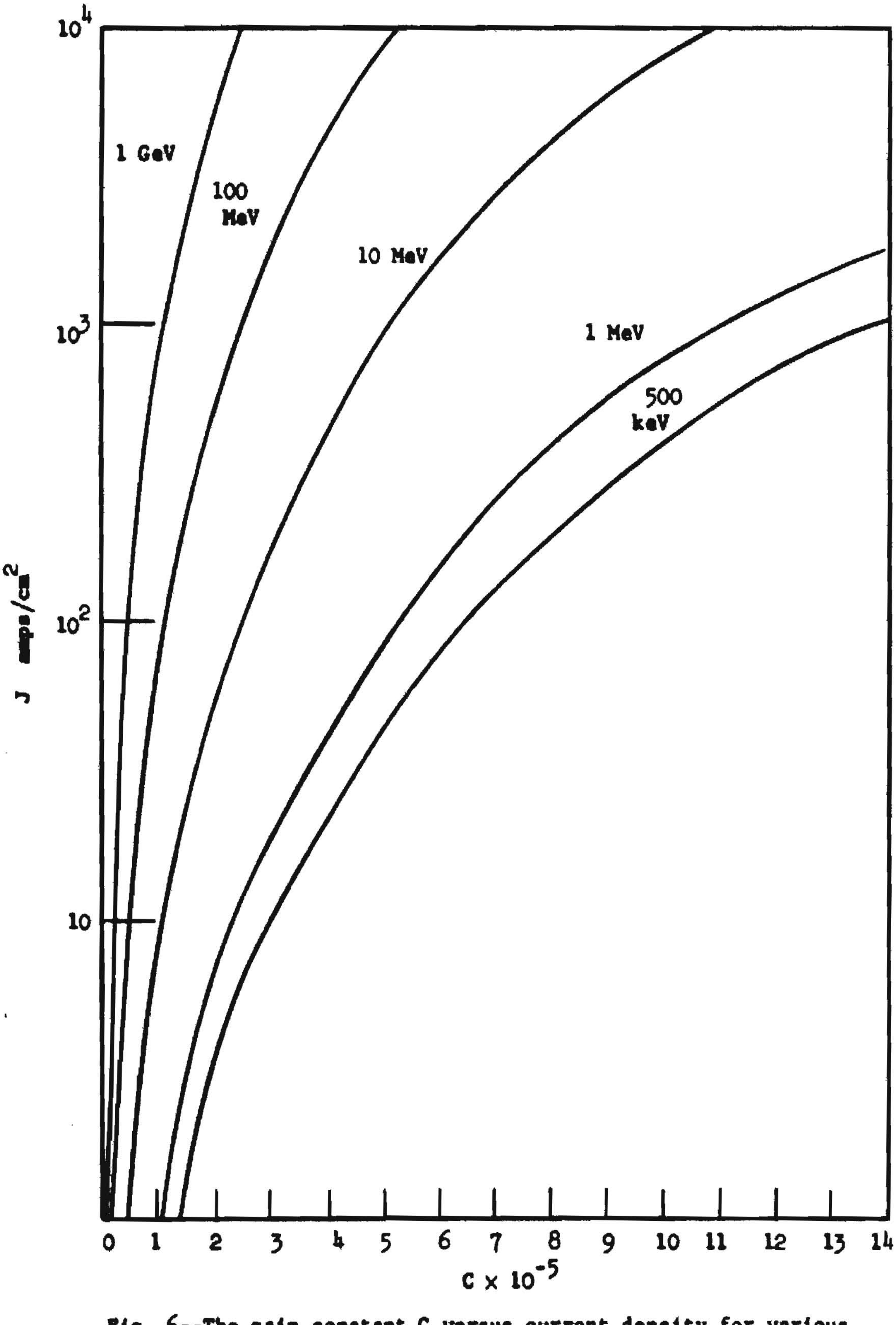


Fig. 6--The gain constant C versus current density for various electron beam energies (λ = 3000 Å).

where C is given by Eq. (8). The conditions, $\alpha \leq C$, $\Delta u/u \leq C$ are easily met for relativistic electron beams ($E \geq 2$ MeV) from conventional sources. However, for quartz, a higher energy electron beam is needed to meet the scattering condition of $d \leq C$. Beams of $E \geq 100$ MeV are sufficient to meet this condition with properly designed resonator cavities. Thus with conventional relativistic electron sources of 100 MeV or greater and a quartz Fabry-Perot resonator with sufficient interaction length, stimulated Cerenkov radiation will occur.

III. EXPERIMENTAL WORK

A. MATERIAL TESTING

Initial experiments were done at Stanford's High Energy Physics Laboratory (HEPL) using the 1 GeV linear accelator. The machine is capable of a 100 MeV to 1.1 GeV electron beam with a 2.5 amps peak current.

The first experiments were concerned with the search for a material that would produce the Cerenkov effect without radiation damage. It is well known that most transparent materials damage under intense particle bombardment. The damage manifests itself in darkening or, in some cases, heating and melting of the material.

The first experiment consisted simply of placing 1/4 inch samples directly in the electron beam at an energy of 500 MeV and at peak current. Ordinary quartz was found to darken with only a few minutes of bombardment. The darkening manifested itself as a bluish blackening, causing the quartz to be almost opaque. Both glass and plexiglass were tried. The former darkened easily while the latter melted.

The darkening is known to be caused by coloring centers in the quartz. Fortunately high quality pure quartz has been produced lately for high radiation environments. This quartz goes under the trade name of Suprasil quartz. The manufacturer, Englehard Industries, promises "low fluorescence" and "low bubble content" with a 0.175 to 2.2 micron optimum transmission range. The quartz was found not to darken or damage after many hours of irradiation with intense electron beams. The Cerenkov target and its mount are shown in Fig. 7.

In order to make a suitable cavity for the stimulated Cerenkov effect, dielectric mirrors were also needed to withstand the electron beam. Ordinary laser dielectric mirrors were deposited on the suprasil quartz targets. This was done with a standard commercial process available at Spectra Physics. Four targets were tried at various stages of the experiment. Three of the mirrors had their bandwidths centered at 5000 Å and one at 3250 Å. These targets were bombarded with the 500 MeV, 0.42 amp (peak current) beam at HEPL and later with the 2 MeV, 500 amp, 200 nanosecond beam at Physics International. None of the mirror surfaces were found to be damaged or changed after many hours of use. The reflectivity of these mirrors was checked after bombardment using a Cary spectrometer. The absorption curve showed no change from the initial curves made at Spectra Physics.

B. EXPERIMENTAL FINDINGS, SPONTANEOUS CERENKOV EFFECT.

1. Early Work

The spontaneous Cerenkov effect was studied using the Stanford HEPL 1 GeV accelerator. Early experiments were concerned with devising photographic and experimental techniques to observe the Cerenkov light.

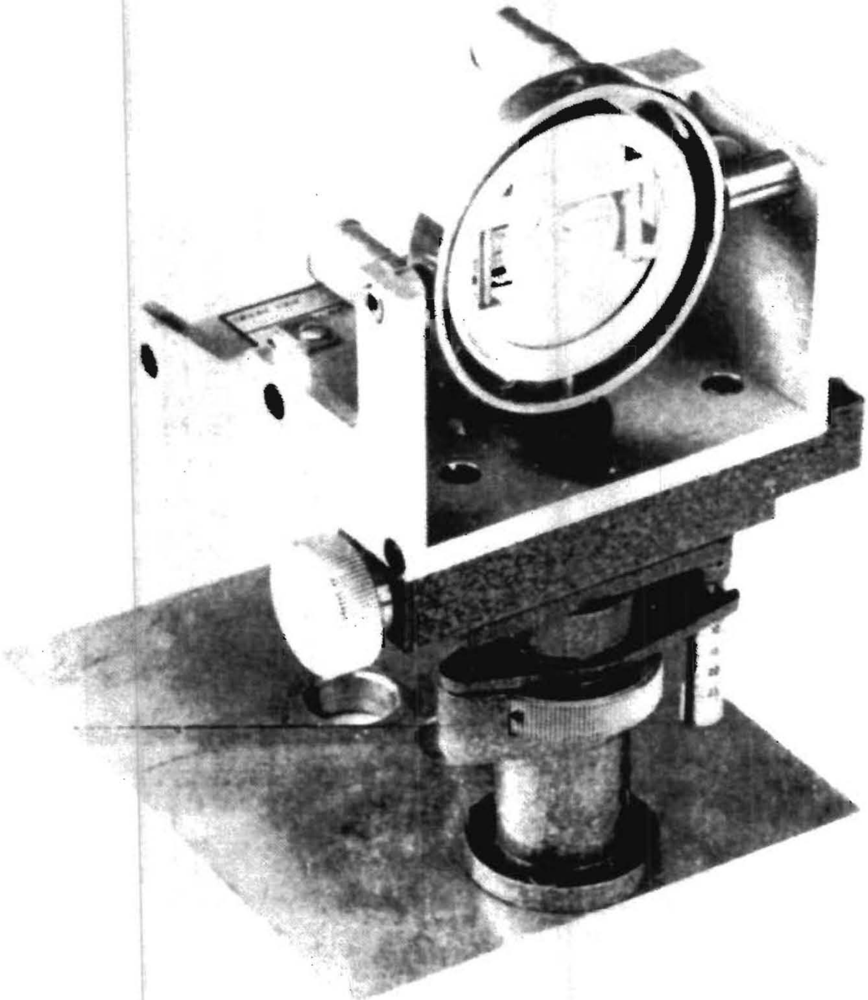


Fig. 7--Cerenkov target (suprasil quartz).

The experiment itself could not be viewed directly because of the intense radiation generated by the electron beam.

In the first experiment a 1/4" suprasil slab was bombarded with a 500 MeV, 0.5 amp peak current, electron beam using the experimental setup shown in Fig. 8. (The lens cavity is replaced with the quartz slab in the figure.)

A 500 MeV electron beam will produce a Cerenkov angle of approximately 47^{o}. Placing the perpendicular to the surface of the quartz at 47^{o} relative to the electron beam allows part of the Cerenkov cone to emerge without refraction. When viewing from this angle, one is looking along the edge of the cone.

Because of dispersion the Cerenkov angle changes with frequency. The entire visible spectrum is dispersed over a 46^{o} to 47^{o} angle. A stationary observer viewing the target at the Cerenkov angle would see the entire color spectrum as the quartz slab is rotated in the beam.

This dispersive effect was observed at a distance of 100 feet from the target using a series of mirrors to conduct the light over a concrete radiation barrier to a telescope. Tne quartz was rotated through the Cerenkov angle while the observer remained fixed with respect to the electron beam. Rotation was accomplished by remote control using a variable speed, reversible electric motor.

Brilliant tunable light was observed convering the entire spectrum. Each individual color was seen as the slab was rotated. (The light produced at this angle seemed comparable to a 60 watt incandescent lamp.) Color photographs of the light were also obtained.

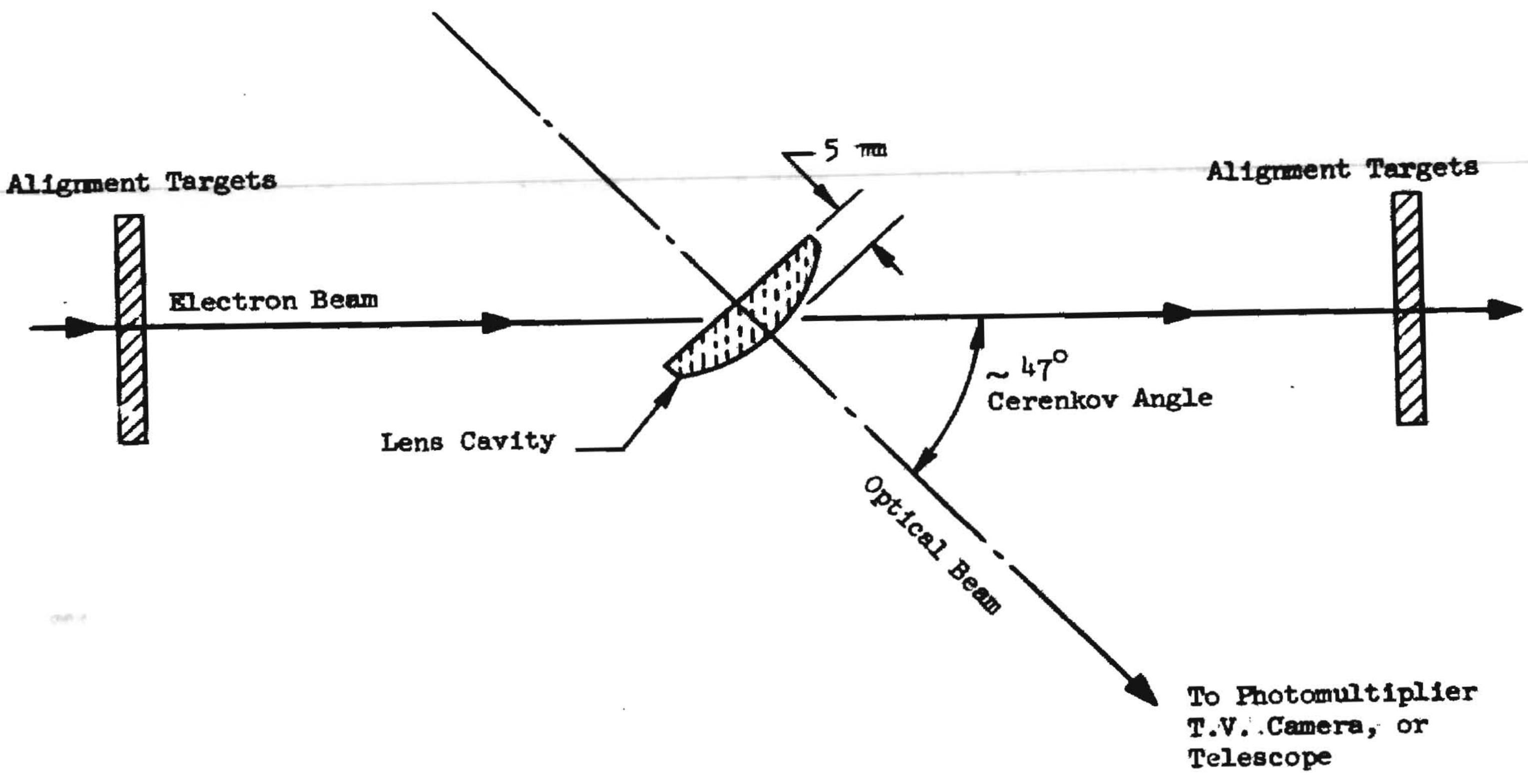


FIG. 8--Preliminary experimental setup.

2. Brightness Measurement, Spontaneous Cerenkov Effect.

A more recent experiment was concerned with the measurement of the spectral brightness of the Cerenkov radiation in the near uv and visible bands. The experimental setup is shown in Figs. 9 and 10. It consisted principally of alignment targets, quartz slab (replacing the lens cavity in Fig. 6), monochrometer, and photomultiplier. A system of mirrors functioned to keep the Cerenkov arc on the 150 micron spectrometer slit while the quartz target was rotated. This allowed various frequency selections for the monochrometer. Both the monochrometer and the rotation of the target were controlled by small electric motors and were monitored by a potentiometer and digital readout system. This permitted both instantaneous readout of the Cerenkov angle and the particular frequency setting of the monochrometer. The photomultiplier voltage was viewed on an HP-555 oscilloscope along with a monitor pulse from the electron beam current. For alignment purposes, two TV cameras monitored the electron beam on phosphorous alignment targets. This setup was also used to measure the stimulated Cerenkov brightness.

Peak brightness measurements for this experiment are shown in Fig. 11 for a 6 mm suprasil target measured with the photomultiplier 1.25 meters away. The accelerator characteristics for the experiment were 320 MeV at 0.42 amp peak current. The quartz target was set at three different angles and the monochrometer was scanned. Various phototube response voltages were read from the oscilloscope at 50 Å intervals. The brightness was then calculated from the known photomultiplier response.

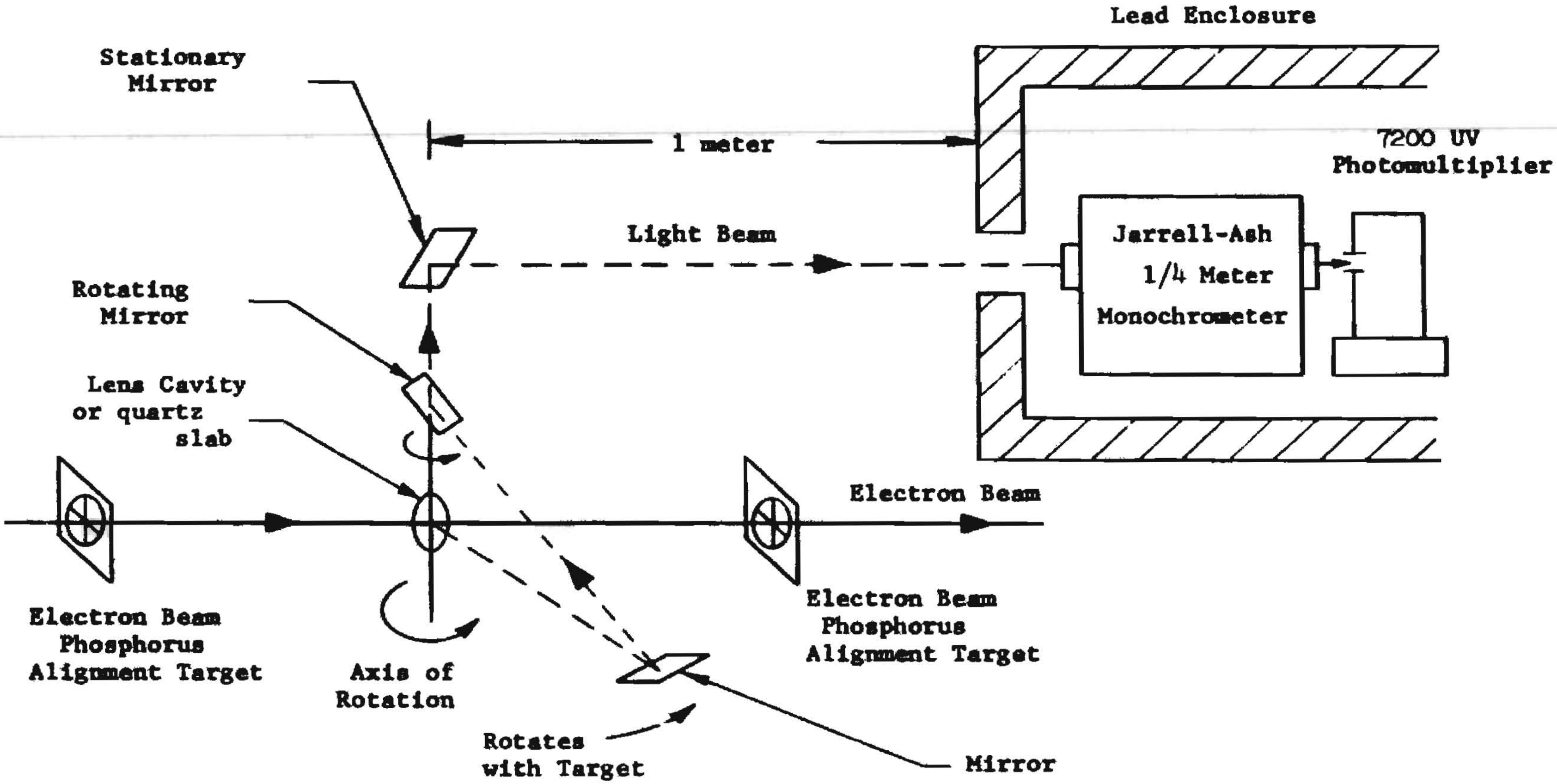


Fig. 9--Experimental setup for the brightness measurement of the spontaneous and stimulated Cerenkov effects.

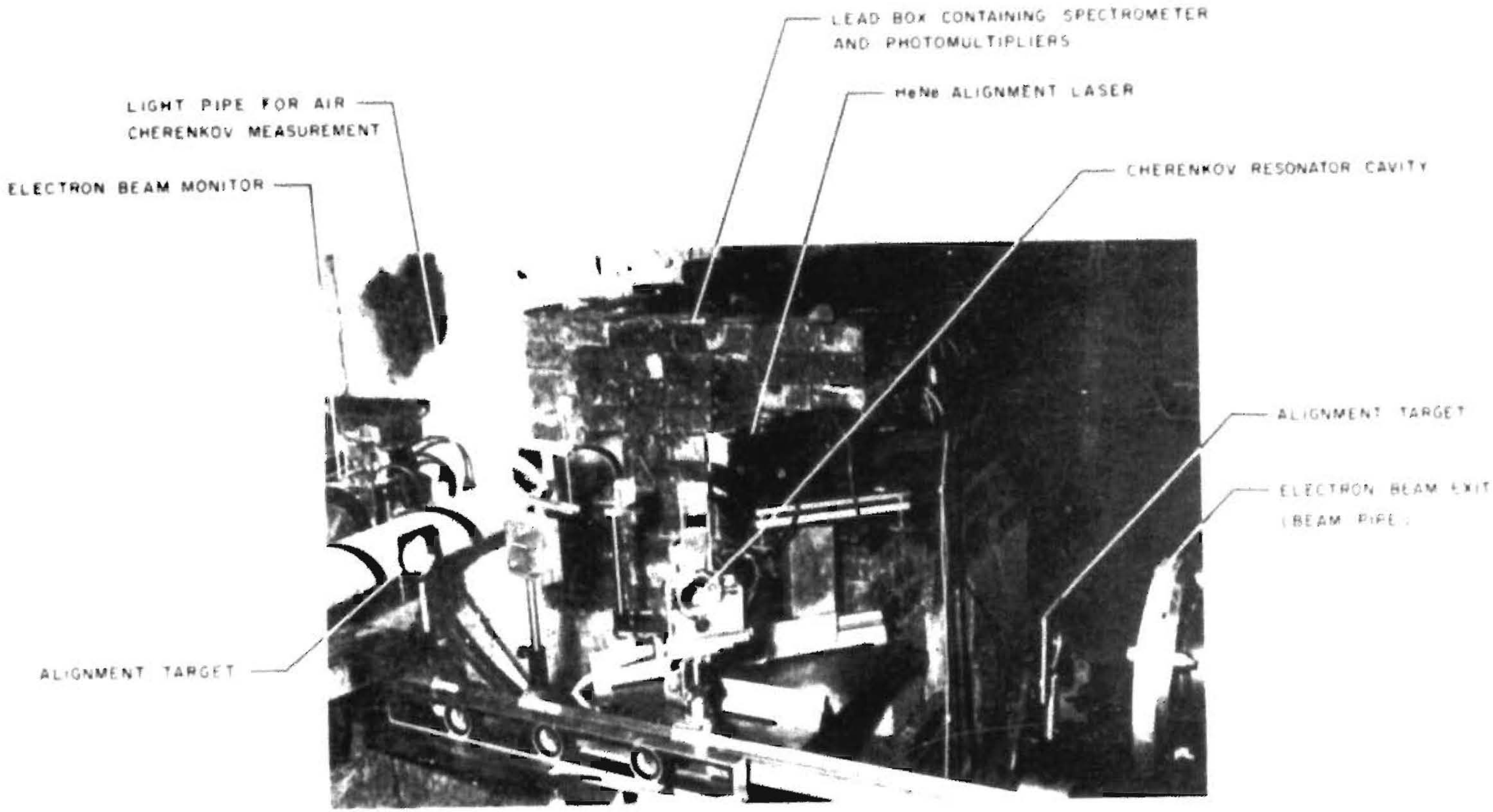


Fig. 1 -Close up of Cerenkov cavity and alignment targets

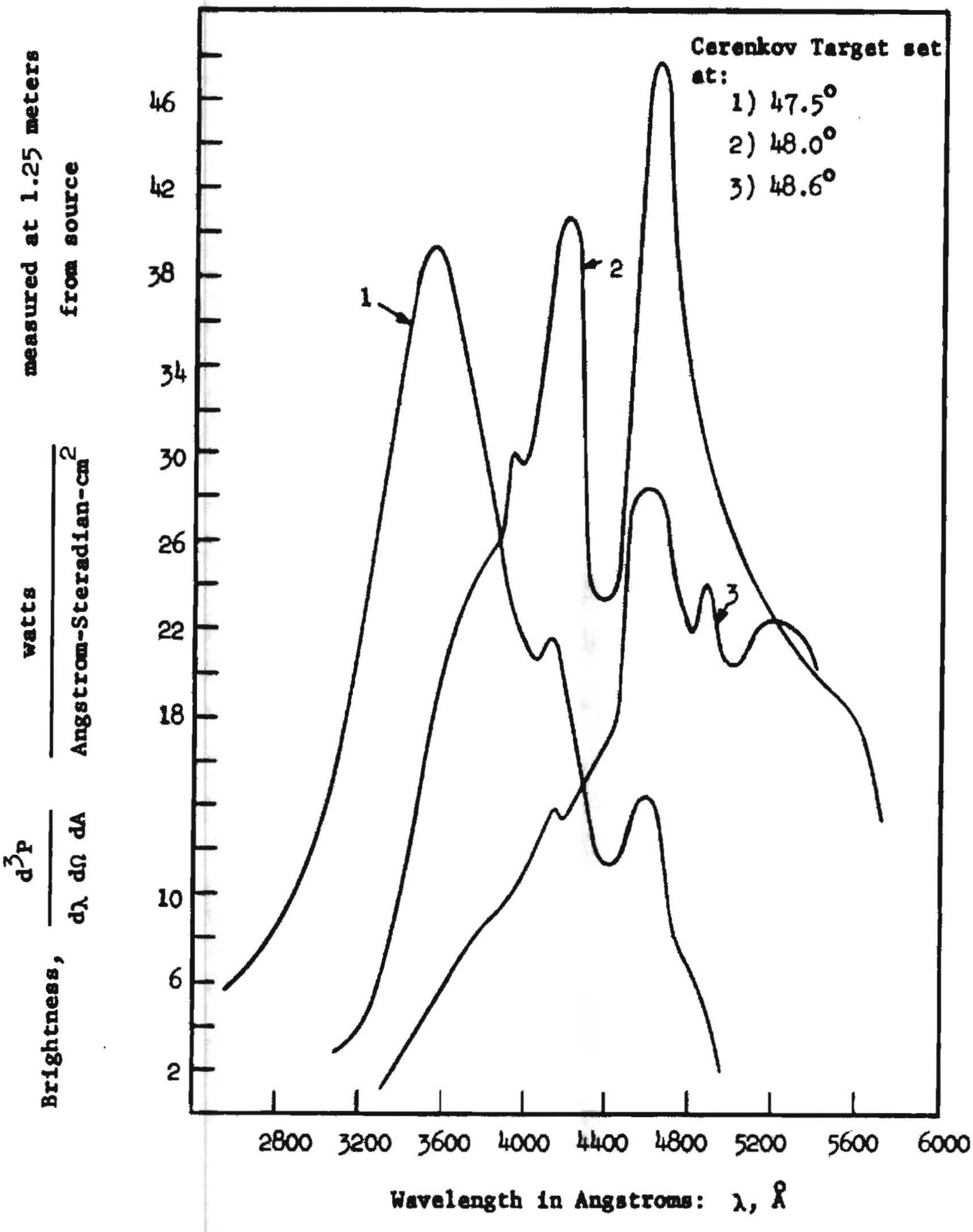


Fig. 11--Spontaneous Cerenkov brightness for different target angles.

These measurements gave a large value of brightness. Since the electron beam was of low enough energy, electron scattering determined the cone width and, hence, the brightness is determined by Eq. (5). A calculation from this formula shows that the theoretical brightness is 40 mW/Å-ster-cm at 4000 Å, a factor of 10^3 less than the value measured experimentally. If we consider the cone width to be caused entirely by dispersion due to finite crystal length, we find that Eq. (2) gives a brightness factor of 15 higher than the experimentally determined values. Thus the experimental value lies between the two extremes of possible brightness represented by Eqs. (2) and (5). In fact the values lie much closer to the nonscattering formula, indicating that scattering is not too important at this electron energy. Since we used the same energy for the stimulated experiments the possibility exists that scattering does not affect the stimulated gain as much as the theoretical calculations in section 2 seem to indicate.

C. EXPERIMENTAL FINDINGS, STIMULATED CERENKOV EFFECT

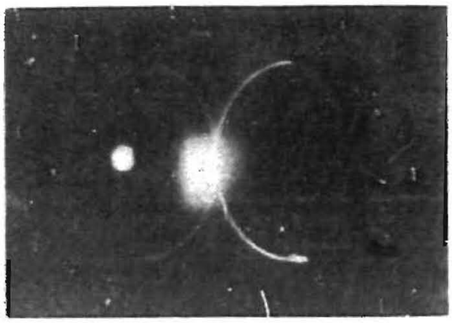
1. Cavity Design and Initial Experiments.

The stimulated Cerenkov experiments were centered around the irradiation of a polished suprasil lens cavity with dielectric mirrors. The cavity consisted of a plano-convex suprasil lens coated with standard laser mirrors. The curved side of the lens was coated with a highly reflecting mirror (99.6%) while on the flat side, a small percent - 0.04% to 0.6% transmission of light was allowed. The lens-mirror system formed a Fabry-Perot optical resonator along the axis of the mirror. By placing this axis at the Cerenkov angle the light generated by the Cerenkov effect is fed back onto the electron beam thus creating the conditions for a gain process to occur. Since, due to dispersion, the Cerenkov angle changes with frequency, particular resonances within the bandwidth of the mirrors can be selected by rotating the lens in the beam, thus making a tunable laser.

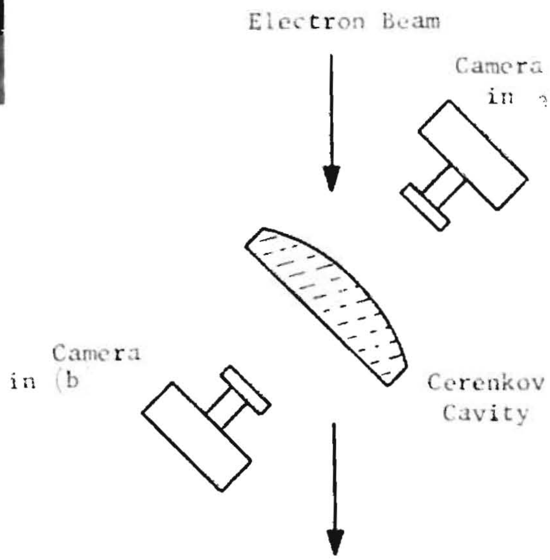
Four cavities were constructed. Three were made from standard one inch diameter, 50 mm focal length, 6 mm thick lenses purchased from Oriel Optics Corporation. All of these were coated with mirrors centered at 5000 Å. The fourth mirror, also purchased from Oriel, was a 2 inch diameter 2000 mm focal length, 6.4 mm thick lens. The surfaces were coated to provide mirrors centered at 3250 Å with a 300 Å bandwidth.

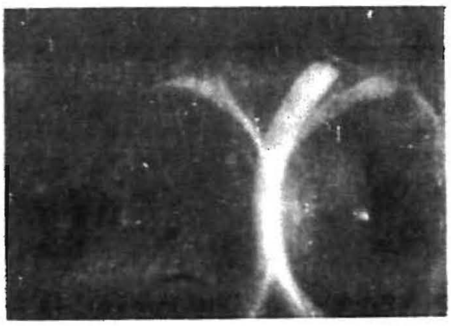
Preliminary experiments were done in the visible band for experimental simplicity of visual observation and photography. These experiments consisted of photographing, visual observing, and obtaining spectrographic analysis of the device in operation. The same experimental setup shown in Fig. 8 was used. The lens cavity was rotated by remote control as was the quartz slab for the spontaneous measurement.

Color photographs were taken directly along the axis of the device. Views of both the flat side (0.4% transmittance mirror) and the curved side (high reflectance mirror) were obtained as shown in Fig. 12. The Cerenkov arc appears to be brighter at the axis of the mirror as would be expected if some sort of gain process were occurring. A photograph through a diffuser also shows this to be true (Fig. 13). No collimated



a. High Reflectance Mirror





b. Transmission (0.[illegible]% Mirror

Fig. 12--Photographs of Cerenkov cavity in operation.

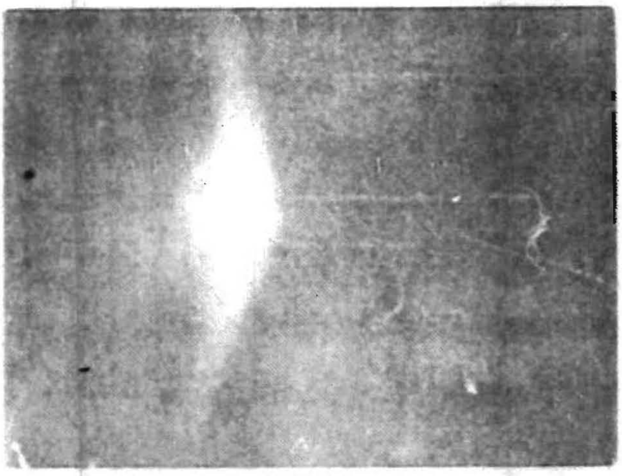


FIG. 13--Light produced by Cerenkov cavity seen through diffuser.

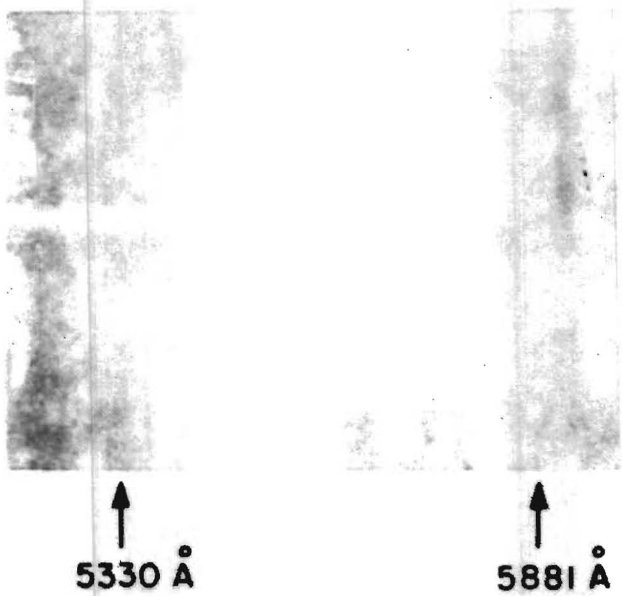


FIG. 14--Spectrographic recording from 1 meter spectrometer of light produced from Cerenkov cavity. Mirrors centered at 5000 Å, ~ 1700 Å bandwidth.

light beam was expected from the device since the cavity design utilized an extremely small beam waist. Hence, a large beam spread was expected outside the cavity.

The light was also spectrographically analyzed as shown in Fig. 14. The light from the device was focused through a lens-mirror system onto a one meter spectrometer. The cavity was rotated through the Cerenkov angle. The photograph shows that light was being produced in the band of maximum mirror reflectivity, again indicating stimulated gain. However, this was not conclusive evidence. New quantitative experiments were needed to show that the stimulated light was indeed brighter than the spontaneous. Quantitative measurements of the device's brightness were proposed. Two such measurements were made and are detailed in the following sections.

2. An Experiment Using a Low Energy, High Current Accelerator.

Recent advances have been made in high current low energy accelerators. Currents of 10^4 amps at 10 MeV have been achieved. The devices usually consist of a Marx generator, pulse forming network, and a field emission diode, and all operate on a single pulse basis in the 10 to 200 nanosecond range. Since the gain varies as $J^{1/3}$, an increase in current would greatly improve the chance of operating successfully.

A 2 MeV, 6000 amp machine was used at Physics International in the fall of 1970 for two days. The experimental setup is shown in Fig. 15. Since accelerator use time was limited, several different experiments were attempted at the same time. Photographic, and spectrographic measurements were performed and visual observations were made.

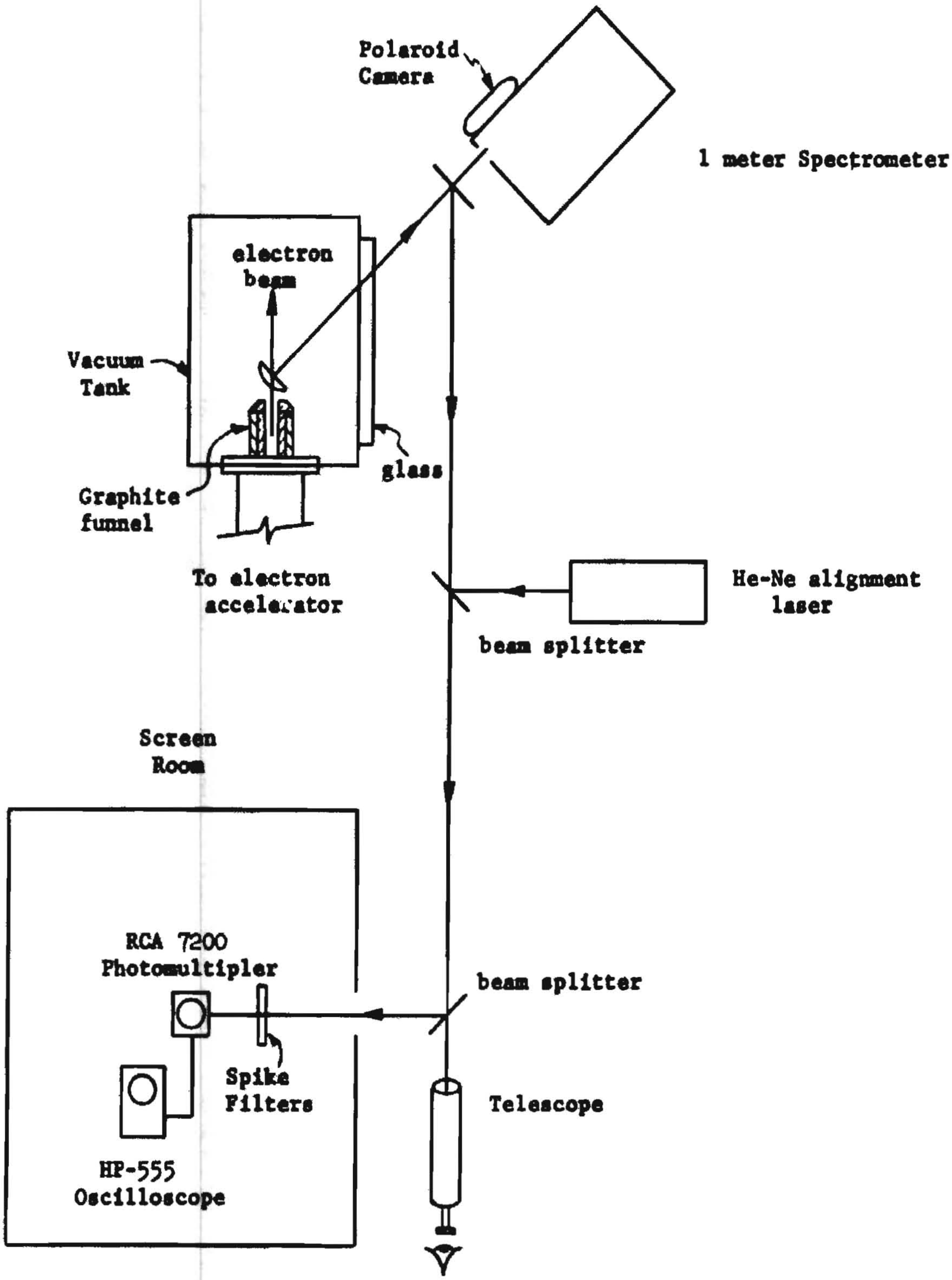


Fig. 15--Experimental setup using low energy, high current electron accelerator at Physics International, San Leandro, California.

A one meter spectrometer, used to analyze the light, failed to operate because the single pulse operation did not produce an adequate amount of light for the exposure of the spectrometer film. However, a measure of the relative spectral power over the optical band was made using spike filters and a photomultiplier (Fig. 16).

The electron beam was collimated by using a graphite funnel. The funnel consisted of a 3 inch long graphite tube with interchangeable funnel orifices (1/4 inch to 1/2 inch inside diameter). The tube fitted onto the output port of the accelerator. When the electron beam was fired, the graphite nozzle stripped off any electrons that were not moving down the axis of the funnel. The lens cavity was placed at the exit port of the nozzle.

Collimation was also improved by varying the gas pressure at the exit port. The electron beam was fired into a vacuum chamber where this was easily accomplished. Since the electron beam was of such high density, the electrons tended to rapidly diverge because of coulomb repulsion. However, if positive ions were introduced by varying the gas pressure, a relatively stable beam was achieved. A stable 500 amp, 200 nanosec., 1/4 inch diameter beam was attained using this method.

Since we were dealing with such a large electron beam density, electrical noise became a considerable problem. This was solved by placing all the electronics in a copper screen room, thus locating the photomultiplier 40 feet away from the target. Fortunately there was more than enough light generated to register a signal on the oscilloscope. Polaroid photographs were taken of the oscilloscope's response since the pulses were far too short to be visually observed.

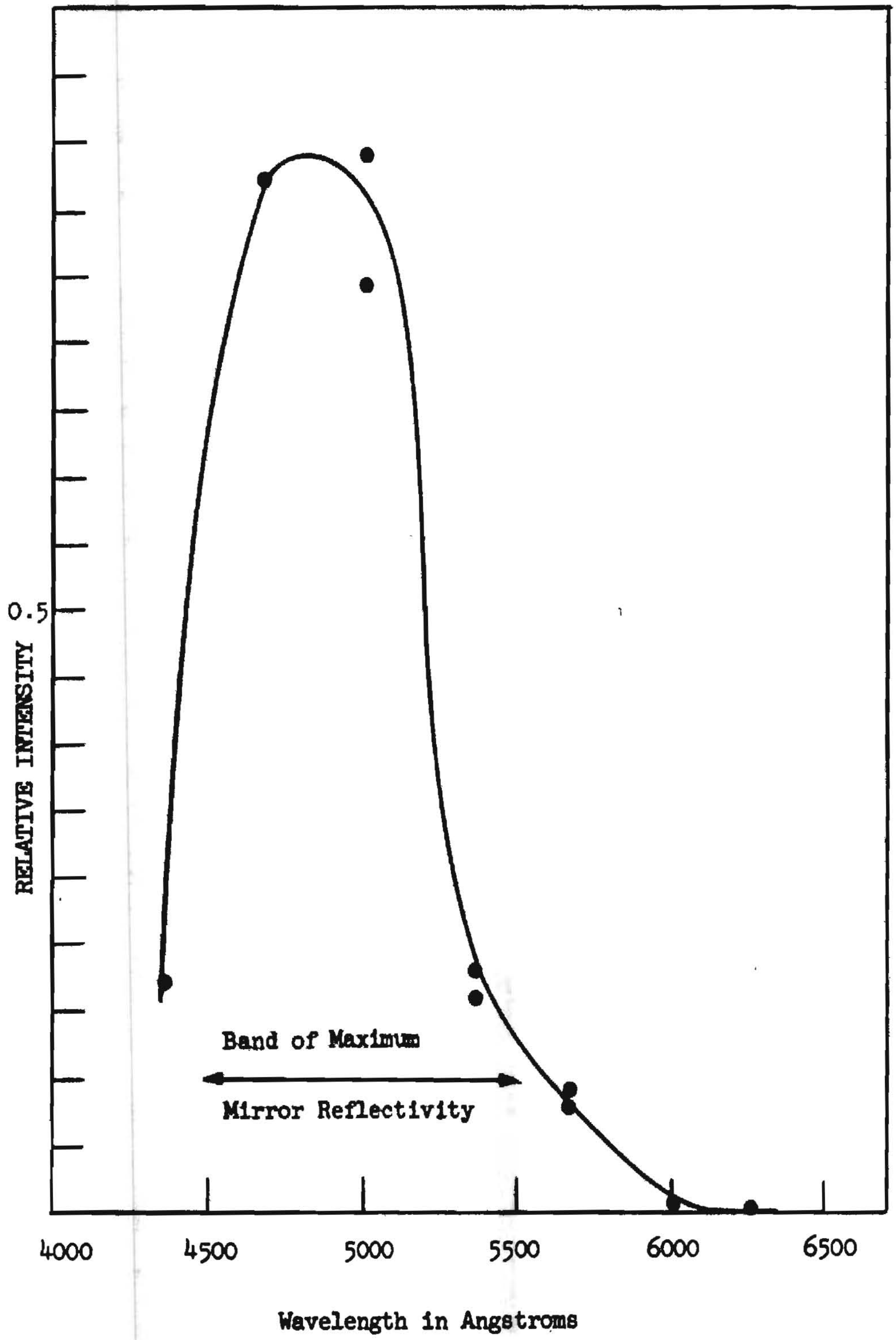


FIG. 16--Spectral distribution of Cerenkov light from quartz coated with dielectric mirrors.

From these measurements relative spectral power was calculated, taking into account attenuation due to mirrors and beam splitters, and the fact that the photomultiplier's response varied with frequency. Frequency selection was accomplished using Oriel spike filters. There was no apparent increase in power over the bandwidth of the cavity; however, using the transmission curves of the dielectric mirrors, the power inside the cavity was calculated from the externally determined value. This showed an increase in the spectral power, thus indicating a gain process was occurring (Fig. 16). Unfortunately this small increase may be within experimental error.

Visual observation of the device in operation was done at a distance of 30 feet from the source using a 10 X refractor telescope (Fig. 15). The device exhibited bright white light when observed along the Cerenkov angle. None of the characteristic arcs were seen as in the case of the experiment in section C-1. Nor were there any separate spectral colors. This seems to indicate that no coherence process was occurring.

The experiment was performed before the exact effect of electron-atom collisions on the gain was theoretically calculated. As noted in section 2, an electron beam energy of $E \geq 100$ MeV is needed to keep scattering from destroying the coherency of the stimulated Cerenkov effect. Hence, this experiment was done at a beam energy far below the required one. Originally it was theorized that because the current density was so high enough electrons would be unscattered and still cause gain. The later analysis shows this to be incorrect. Fortunately higher energy machines do exist, but without the tremendous currents of these lower energy machines.

3. Brightness Measurement, the Stimulated Cerenkov Effect

A brightness measurement of stimulated Cerenkov effect was made using the same experimental setup described in section A-2 and shown in Figs. 11 and 12. In the new experiment the lens-cavity replaces the quartz slab used in the spontaneous measurement. Both these experiments were done concurrently. It was hoped that the stimulated effect would show a marked increase in power over the spontaneous emission.

The experiment was set up on the central beam port of the HEPL accelerator where the beam current was a factor of four greater than the previously used "nine foot side" port. A beam of 1 to 2.5 amps was achieved depending upon the condition of the machine and the operator's ability to "fine tune" the accelerator klystrons.

The system of mirrors shown in Fig. 9 functioned to keep the Cerenkov arc on the 150 micron spectrometer slit while the lens cavity was rotated. A digital readout system in the control room read the angle of the cavity and the frequency setting of the monochrometer. An HP 555 oscilloscope monitored the electron beam pulse and the 7200 photomultiplier.

A new lens cavity was constructed using a 2000 mm focal length, 2 inch diameter, plano-convex lens with uv mirrors centered at 3250 Å. This cavity, because of its small curvature mirror, gave a larger beam waist and, hence, a smaller beam divergence than did the 75 mm focal length cavities.

The brightness measurement showed no increase in power outside the cavity; however, as in the case of relative power measurement made on the 2 MeV 500 amp machine, the brightness inside the cavity showed a 3 dB increase over the spontaneous value (Fig. 17). The spontaneous power was estimated by selecting a "gap" in the reflectivity of the dielectric mirrors, i.e., a range of frequencies where the lens-cavity was transparent. The spontaneous power at this point was then measured experimentally and plotted on the graph. The other points on the curve were extrapolated from this value using the fact that the spontaneous brightness should vary as λ^{-5} (Eq. 2). This is the best possible case: the electron path length determines the cone width and scattering is neglected.

Again, as in the spontaneous brightness measurement of section B-2 the brightness is larger than one would expect if only a spontaneous process were occurring. If scattering was dominating and accelerator was operating at peak efficiency, Eq. (5) gives a brightness of 0.6 watts/Å-ster-cm^2 at 3000 Å for a 2.5 amp, 320 MeV beam. However, if scattering is neglected, then (2) holds and one would expect a brightness of 10^4 watts/Å-ster-cm^2 at these beam values. Again, as in the case of the spontaneous measurement the experimental value lies between these two extremes.

The observed 3 dB gain is within experimental error. Small gain results from having a small interaction volume for the electron and light beams. In the original theoretical analysis an infinite plane electro-magnetic wave interacts with an electron beam of infinite width. Experimentally the Fabry-Perot resonator supports a light beam of finite width ($\omega \simeq 0.033$ to 0.07 mm). Thus, the interaction volume of the electron and light beams is severely limited. In the

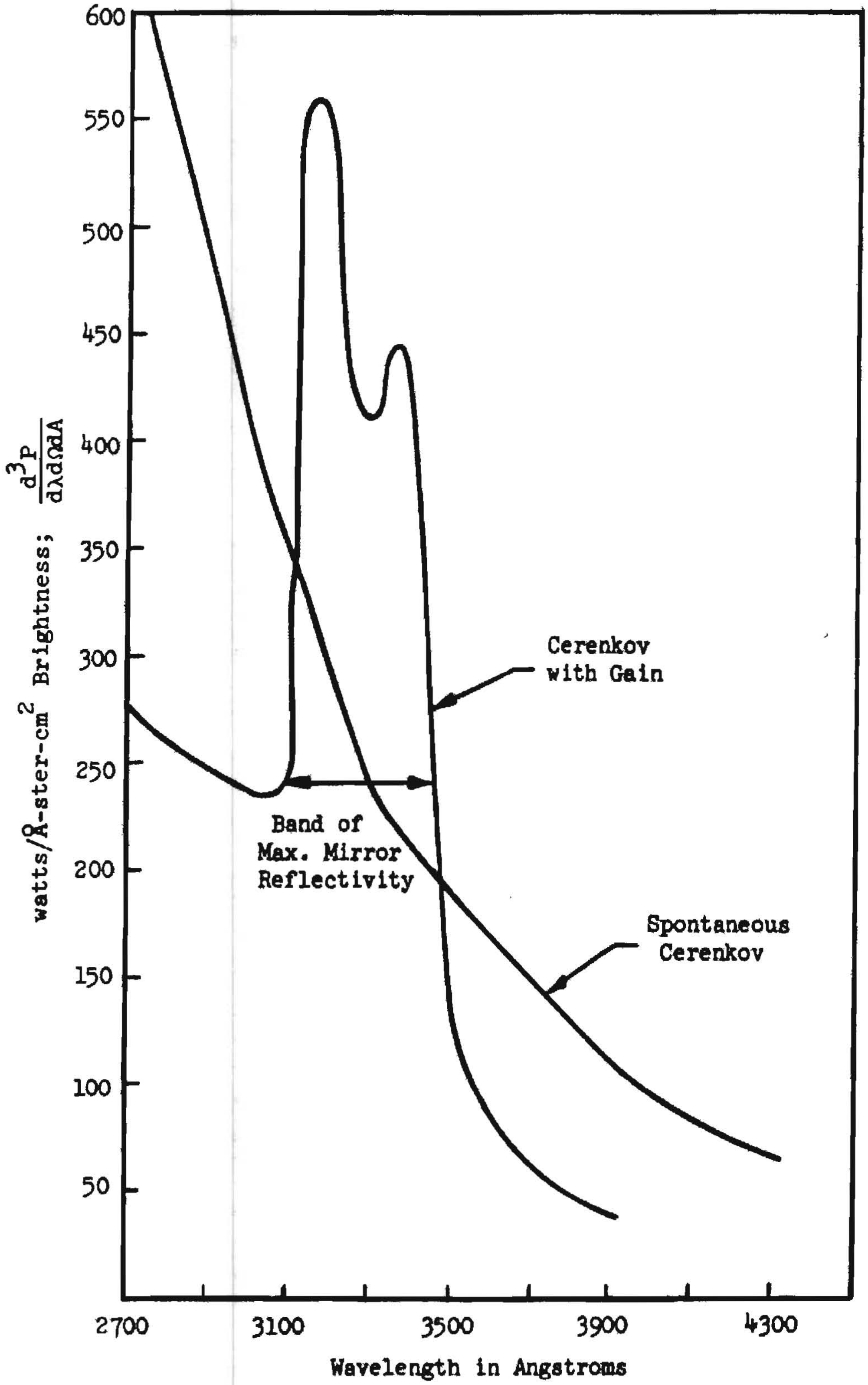


FIG. 17--Spectral distribution of Cerenkov light from quartz coated with dielectric mirrors whose band of maximum reflectivity is at 3250 Å .

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