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Observation of microwave Cerenkov radiation as a diffraction pattern

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Measurement of microwave Cerenkov radiation in air exhibits the diffraction pattern predicted in earlier work. The radiation appears only at harmonics of the frequency of periodic electron bunches. Angular distribution power measurements are presented for frequencies of 2.86, 5.71, 8.57, and 11.42 GHz corresponding to the fundamental and the first three harmonics of an *S*-band rf linac.

INTRODUCTION

When the interaction region of a charged particle going faster than the speed of light in a dielectric medium has a finite length[1–4] the Cerenkov radiation is spread over a range of emission angles. This condition is readily realized by passing a relativistic electron beam through a gas such as air. In a previous work,[1] Cerenkov radiation from periodic electron bunches was considered and the radiation pattern was calculated. A subsequent paper[2] reported the measurement of *X*- and *K*-band Cerenkov radiation from a finite length path in a gas. We report here further measurements of microwave Cerenkov radiation emphasizing the observation of diffraction patterns at harmonics of the frequency of the periodic electron bunches in agreement with calculations previously presented.

Electrons from a 100-MeV linac exceed the velocity of light in air and Cerenkov radiation is expected to be emitted at an angle of 1.29°–1.36°, depending upon the wavelength. In the microwave region it is possible to define the interaction region so that the ratio of the emission length to the observed radiation wavelength L/λ is finite. In this case the power emitted per unit solid angle $dP/d\Omega$ is

$$\frac{dP}{d\Omega} = \sum^{\infty} W(\nu,\hat{n}), \tag{1}$$

where $W(\nu,\hat{n})$ is the power per unit solid angle radiated at frequency $\nu = ck/2\pi$, c is the speed of light in the medium, $k = 2\pi/\lambda$ is the wave number of the emitted radiation, and $\hat{n}$ is the unit vector in the emission direction. The sum is over the allowed frequencies:

$$W(\nu,\hat{n}) = \frac{\mu c \nu_0^2}{8\pi} q^2 |F(\mathbf{k})|^2 [(kL)\sin\theta I(u)]^2. \tag{2}$$

The parameters describing the radiation are

$$u = (kL/2)(\cos\theta_c - \cos\theta),$$
$$I(u) = \sin u/u,$$
$$\mathbf{k} = (\omega/c)\hat{n}, \tag{3}$$
$$\tilde{\rho}'(\mathbf{k}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dx'dy'dz' \times \exp(-i\mathbf{k}\cdot\mathbf{r}')\rho_0(r'),$$
$$= qF(\mathbf{k}),$$

where L is the length of the interaction region. The observation angle θ is defined by $\cos\theta = \hat{n}\cdot\hat{z}$, where $\hat{z}$ defines the direction of the electron beam. θ_c is the classical Cerenkov angle with $\cos\theta_c = c/v$. The total charge of one bunch is q, corresponding to a charge distribution $\rho_0(\mathbf{r})$ with Fourier transform $\tilde{\rho}_0(\mathbf{k})$ and $F(\mathbf{k})$ is defined as a dimensionless form factor. The bunch frequency ν_0 is equal to the electron velocity divided by the electron bunch spacing, i.e., the fundamental operating frequency of the linac. Radiation is emitted only at frequencies ν which are integer multiples of ν_0.

A fuller discussion of Eqs. (1)–(3) is presented in Refs. 1 and 2.

EXPERIMENT

The experimental configuration of this experiment is similar to that reported earlier.[2] The source of relativistic electrons was the Naval Postgraduate School 100-MeV electron linac operating at the *S*-band frequency of 2856 MHz. In addition to the mirror configuration of Ref. 2, direct measurements were made with the arrangement illustrated schematically in Fig. 1.

The antenna-detector arrangement is illustrated in Fig. 2. The output of the antenna was fed through a TWT (traveling-wave tube) amplifier to a YIG (yttrium-iron-garnet) filter which was tunable from 1 to 18 GHz. The frequency filtered signal was then fed to a crystal detector whose output was observed on an oscilloscope or voltage recorder. The antenna assembly was mounted on tracks to be able to sweep

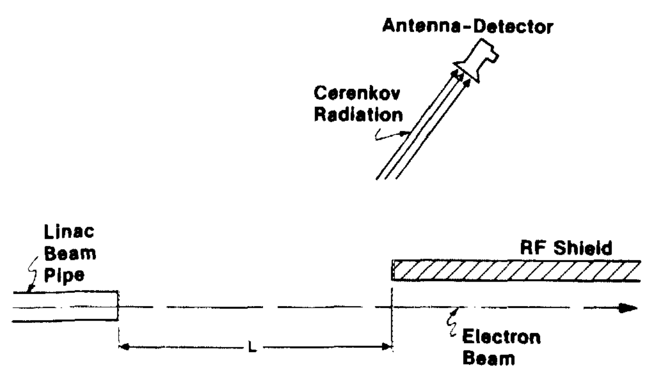

FIG. 1. Schematic experimental arrangement for direct measurements. Electrons pass from the accelerator into air and generate Cerenkov radiation which is measured by an antenna-detector assembly which can be translated on a track (not shown). The emission length L is defined between the exit window of the linac and an rf shield.

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FIG. 2. Block diagram of the microwave antenna-detector apparatus. Horn antennas were used to observe frequencies above 8 GHz and a pyramidal antenna was used to observe below 8 GHz. Crystal detectors and TWT amplifiers were matched to the frquency sensitivity of the antennas. The YIG filter was tunable from 1–18 GHz. A frequency resolution of ± 20 MHz was attained in these measurements.

the emission angle range from 0° to 60° in the reflection geometry. The direct measurements were restricted to angles greater than 20° because at small angles the antenna assembly begins to intercept the electron beam.

OBSERVATIONS

Radiation was observed only at the discrete frequencies of 2.86, 5.71, 8.57, and 11.42 GHz. These frequencies correspond to the fundamental and the three higher harmonics of the operating frequency of the S-band rf linac. In this experiment we did not attempt to measure the K-band radiation reported in Ref. 2. These observations confirm the prediction that radiation appears for $\nu = j\nu_0$, where j is an integer. In the previous work the frequency resolution was broad, but in this measurement, we are able to identify separately the mode numbers $j = 1, 2, 3$, and 4.

Another improvement of the present measurement over the previous measurement is the possibility to decrease the emission length L to 14 cm, so that all measurements were done in the far field.[5] The experimental room was too small to increase the distance from the source to the antenna. The decrease in L had the consequence of making more pronounced the diffraction effect and shifted the observed peak radiation angle from the classical Cerenkov angle of 1.29° to angles from 20° to 45°.

A first series of measurements are presented in Fig. 3 for the frequencies corresponding to $j = 1, 2, 3$, and 4. In the analysis of these measurements the angular distribution was shifted arbitrarily (approximately 12°) so that the calculated pattern enveloped the observed radiation pattern. This empirical shift in angle was necessitated by the lack of definition of the electron beam direction and mirror orientation due to the short lever arms available in a small experimental space. Furthermore, the data exhibited fine structure, inconsistent with predictions, since the charge distribution within a single bunch is unlikely to have structure large enough for the form factor of Eq. (2) to influence the radiation pattern. Instead, the observed fine structure is thought to be due to interference of the primary radiation with reflections from physical structures in the experimental area, which include reflections from metal cable trays, a large magnetic spectrometer and its mount, and plumbing fixtures.

A direct measurement was made after some improvement in shielding and the results are presented in Fig. 4. At all frequencies, the radiation pattern was observed to lie within the envelope defined by the calculated prediction without angular shift. In particular, for $j = 3$ and 4, the observed peak value and the null between the first and second peak are consistent with theory. The inconclusive results for $j = 1$ and 2 are thought to arise from the use of a pyramidal antenna whose angular resolution was broad and susceptible to radiation reflected from structures which were not in the emission region. In addition, the emission length is only a few wavelengths long and edge effects with their subsequent interference are more pronounced. The fine structure is still evident.

In order to show that the fine structure was due to interference from reflected signals, the area near the emission region was carefully shielded with airmat, an rf absorbing material. In addition, a copper screen wall was erected between the experimental area and the klystron gallery of the rf linac. Our efforts were concentrated on measuring Cerenkov radiation at the frequency $\nu = 3\nu_0$. A mirror configuration was used in order to be able to measure the full

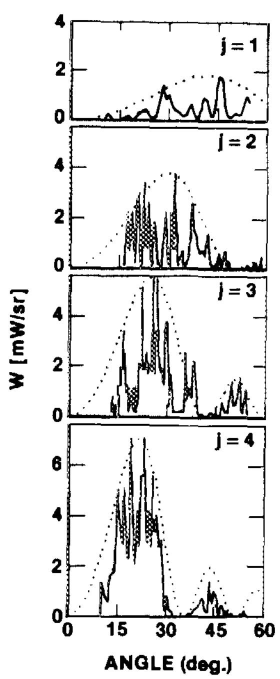

FIG. 3. The observed angular distribution of microwave Cerenkov radiation with a mirror geometry (preliminary results). The solid curve is the measurements and the dotted curve is calculated. The fine structure is believed to be the result of interference from reflected radiation from physical structure in the experimental area. The observed angle has been increased approximately 12° (see text). The emission length L is 14 cm. The data have been normalized to the calculated power per unit solid angle assuming $q = 1.5 \times 10^{12}$ C.

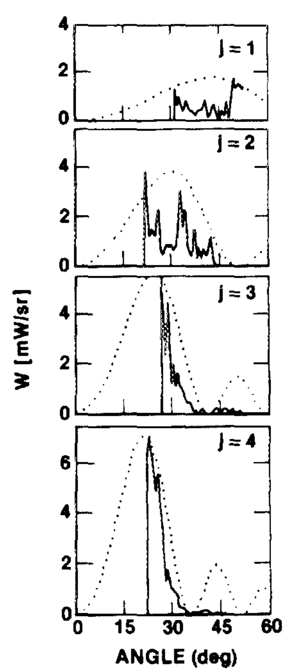

FIG. 4. Direct measurement of microwave Cerenkov radiation. The solid curve is the measurement and the dotted curve is calculated. At angles less than 20°, the antenna assembly begins to intercept the electron beam and therefore radiation at small angles was not measurable. The emission length $L = 14$ cm. The data have been normalized to the calculated power per unit solid angle assuming $q = 1.5 \times 10^{-12}$ C.

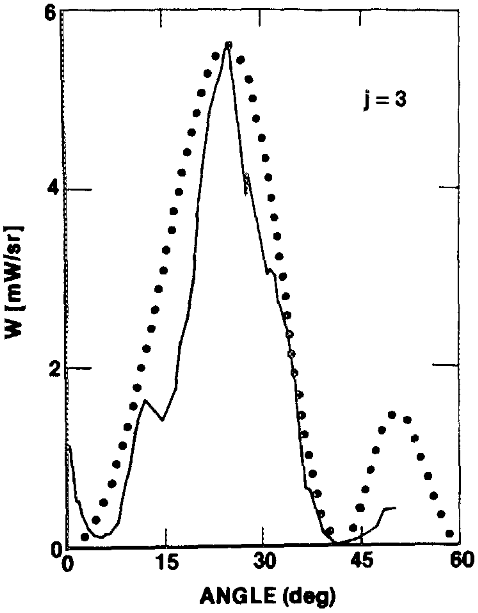

FIG. 5. Microwave Cerenkov radiation at $\nu = 3\nu_0$ after shielding to eliminate interference effects. The solid curve represents the measured data and the dotted curve is calculated. The emission length $L = 14$ cm. The data have been normalized to the calculated power per unit solid angle assuming $q = 1.5\times10^{-12}$ C.

angular range of the first lobe. The result is presented in Fig. 5.

In these measurements, no rigorous attempt was made to measure the absolute power and the observations have been normalized to the calculated values. An incompletely calibrated measurement of the observed peak power per unit solid angle for $j = 3$ and 4 gave results consistent to 20% with the predicted power levels. In Figs. 3–5 each bunch of electrons is assumed to contain 1.5×10^{-12} C. This value corresponds to an average linac current of 0.25 μA with a pulse repetition rate of 60 Hz and macropulse length of 1 μs.

CONCLUSIONS

Refinements of the experimental configuration beyond that of Ref. 2 have led to agreement with the theoretical calculations. Although some fine structure remains in Fig. 5 we ascribe this to interference of reflected waves rather than a fundamental mechanism. The measurements demonstrate the diffraction nature of Cerenkov radiation when the path of the beam in a medium is of finite length and that periodic bunches will produce Cerenkov radiation only at harmonics of the bunch frequency.

Improvements in the measurement environment and apparatus are being contemplated to test other features of the predictions of the previous works as manifested in Eqs. (1)–(3); in particular, to test the predicted quadratic dependence on the radiated power to the total bunch charge q, and more refined measurements of mode numbers other than $j = 3$. Form-factor effects will be realizable only at much higher frequencies or for physically larger bunches. A short discussion of form-factor effects and their consequences for induction linacs appears in another work.[6]

ACKNOWLEDGMENTS

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