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TITLE: Ka-BAND MICROWAVE GENERATION USING THE SMITH-PURCELL EFFECT

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Ka-BAND MICROWAVE GENERATION USING THE SMITH-PURCELL EFFECT (U)

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ABSTRACT

(U) The CERETRON microwave generator concept relies on the conversion of intense relativistic electron beam (REB) energy into highpower microwave emission through the Smith-Purcell effect. We report initial results from experiments with the production of Ka-band Smith-Purcell radiation generated by a 50-kA, 2.8-MeV beam propagated through a cylindrical transmission grating with $\lambda_0 = 1$ cm. These experiments were performed without a quasi-optical resonator, and the output was limited by breakdown of the grating and by limited access through the 90-kG magnet coil. Nevertheless, the measured power output from these initial experiments was about 7 kW in the Ka band.

1. (U) INTRODUCTION

(U) The CERETRON concept has been motivated by the need for a high-power, monochromatic microwave source for laboratory experiments with microwave-impulse air breakdown at 35 GHz and below. The power requirement suggests the use of a pulse-power REB excited microwave tube. However, for most pulse-power REBs, the beam energy continuously varies during the pulse, and the microwave output frequency would not be monochromatic, but swept, if it were strongly dependent on the beam energy. The CERETRON design is an attempt to circumvent this annoyance while employing an existing pulse-power REB at Los Alamos.

(U) The CERETRON microwave generator converts the energy of an intense relativistic electron beam (REB) into high-power microwave emission using the Smith-Purcell effect,[1,2] which is related to Cerenkov radiation.[3,4] Feedback for efficient beam bunching and high gain is obtained by placing the cylindrical Smith-Purcell transmission grating on the axis of a toroidal quasi-optical resonator. High efficiency results from the use of a thin, cold, annular REB that can be closely coupled to the resonant structure. This geometry provides the desired monochromatic microwave output for the CERETRON.

2. (U) OUTPUT FREQUENCY

(U) Radiation is produced by the Smith-Purcell effect by a charge bunch moving parallel to a periodic conducting grating, in a direction perpendicular to the rulings (Fig. 1).[1,2] The image charge induced on the grating surface produces a force on the moving charge that periodically varies with the charge-surface separation. The result is an oscillating dipole with velocity $\beta = v/c$. Electromagnetic waves are radiated in phase in the θ direction if the time delay between wavelets excited at successive ruling is an integral number of periods. The Huygens construction in Fig. 1 shows the propagation time to be $\delta t = (\lambda_0 \cos \theta)/c$. The transit time for the charge bunch between rulings is $\Delta t = \lambda_0/v$, and the phase matching condition is $\Delta t - \delta t = N/f$. Zero-order radiation (N=0) is described by the familiar expression for Cerenkov radiation, $\cos \theta = 1/\beta$, and first-order radiation (N=0), the Smith-Purcell effect, is described by

$$\lambda = \lambda_0\left(\frac{1}{\beta} - \cos \theta\right) \quad . \tag{1}$$

Many devices for microwave and IR generation have exploited the Smith-Purcell effect radiation from a reflection grating.[5-10]

(U) The same principles can be applied to a charge bunch passing over the transmission grating consisting of alternating conducting and transparent strips shown in Fig. 1,[4,12] and Eq. 1 applies equally well to this geometry.

(U) In the CERETRON, the transmission grating is an azimuthally-slotted cylinder, as shown in Fig. 2. The beam bunching results from interaction of the beam with electric fields reinforced by waves reflected back into the grating from an external quasi-optical resonator.

The dominant modes of the resonator are waves with a transmission angle, $\theta = 90^\circ$. This geometry was selected for the CERETRON in order to achieve the minimum dependence of resonant frequency on beam energy, and because it is ideally suited for coupling to our thin annular REB.[11] From Eq. 1 with $\theta = 90^\circ$ the relation between the wavelength and the grating wavelength is $\lambda = \lambda_0/\beta$. Differentiation of the expression for the wavelength of 90° emission clearly shows the independence of frequency and beam energy for a high-energy REB:

$$\frac{d\lambda}{\lambda} = -\frac{d\beta}{\beta} = -\frac{1}{\gamma^2 - 1}\,\frac{d\gamma}{\gamma} \qquad (2)$$

where $\gamma m_e c^2$ is the total (rest plus kinetic) energy of a beam electron. For example, a CERETRON using a 4.5 MeV beam ($\gamma \sim 10$) would have only ~0.1 percent variation in beam energy. Another example is provided by our REB in P-Division at Los Alamos. This accelerator produces a 2.8-MeV, 50-kA beam with an 85-ns pulsewidth (FWHM) in a magnetically insulated foilless diode.[11] As shown in Fig. 3, the radiation is expected to be monochromatic over most of the pulse, even in the absence of a flat-topped voltage pulse.

3. (U) OUTPUT POWER

(U) The power radiated through a transmission grating by the Smith-Purcell effect has been calculated by Di Francia,[2] and also by Bolotovski and Burtsev.[12] Their results are here used for simple estimates of the CERETRON efficiency. From Di Francia's work, an expression for the apparent radiant emittance of a transmission grating can be arrived at:

$$W = \frac{1}{\epsilon_0}\,\frac{2\pi\nu q^2}{D\lambda_0^2}\,\delta^2\,\frac{\beta^3 \sin\theta}{(1 - \beta\cos\theta)^3} \times \exp\left[-4\pi\frac{d}{\lambda_0}\,\frac{(1 - \beta^2)^{1/2}}{(1 - \beta\cos\theta)}\right] \quad (\mathrm{W/m^2}) \qquad (3)$$

where ν is the rate of passage of bunches with charge q past the grating, which has a transverse dimension D. The distance of the bunch from the grating surface is d. For our cylindrical transmission grating geometry, $D = 2\pi R_g$ and $d = R_g - R_b$, where R_g and R_b are the grating and beam radii. The intensity transmission factor, $\delta = \sin(\pi b/\lambda_0)$, is unity for our grating, which has an open dimension $b = \lambda_0/2$. For a density modulated beam the current is

$$I = I_0\,[1 + \alpha\cos(\omega_0 t - k_0 z)] \qquad (4)$$

where $\omega_0/k_0 = \beta c$. The charge in each "bunch" can be approximated by $q \sim \alpha I_0\lambda_0/\beta c$, and the rate by $\nu \sim \beta c/\lambda_0$. Using these approximations and $\theta = 90^\circ$ in Eq. 3 gives an estimate for the apparent radiant emittance. Multiplying by the emitting surface area ($A = 2\pi R \times Z$) gives the total power radiated from the Smith-Purcell tube:

$$P_m = 60\,(2\pi\,\alpha\,I_0)^2\,\frac{Z}{\lambda_0}\left(1 - \frac{1}{\gamma^2}\right) \times \exp\left[-4\pi\frac{d}{\gamma\lambda_0}\right] \quad (\mathrm{W}) \quad , \qquad (5)$$

(U) The exponential evanescent-field factor in these formulae shows the importance of minimizing the beam-grating separation and using a high-energy ($\gamma \gg 1$) beam for high efficiency.

(U) Close coupling of the beam to the grating is accomplished by using the thin annular REB produced by a 90 kG magnetically insulated diode.[11,13,14] For a thin annular beam, the space-charge limited current from a diode with anode and cathode radii R_a and R_c is

$$I = 17\,\frac{(\gamma_0^{2/3} - 1)^{3/2}}{2\ln(R_a/R_c)} \quad (\mathrm{kA}) \quad , \qquad (6)$$

if $\gamma_0 < \gamma_{cr} = [1 + 4\ln(R_a/R_c)]^{3/2}$,

while if $\gamma_0 > \gamma_{cr}$, then

$$I = 34\left[\frac{\gamma_0^2}{[1 + 4\ln(R_a/R_c)^2]} - 1\right]^{1/2} (\mathrm{kA}) \qquad (7)$$

where γ_0 is related to the diode accelerating potential by $V = 511\,(\gamma_0 - 1)$ keV. Equation 6 or 7 can be used with Eq. 5 to calculate the efficiency, $\eta = P_m/IV$. When this is evaluated, one must use the space-charge depressed beam energy in the cylindrical grating section, which is

$$\gamma_{sc} = \gamma_0^{1/3} \text{ for } \gamma_0 < \gamma_{cr} \text{ , and } \gamma_{sc} = \gamma_0/[1 + 4\ln(R_g/R_b)] \text{ for } \gamma_0 > \gamma_{cr} \quad .$$

The diode voltage, diode power, and expected microwave power are shown in Fig. 3 for our experiment assuming a 1-percent modulation.

4. (U) QUASI-OPTICAL RESONATOR

(U) The dependence of the efficiency on the square of the modulation index, α, emphasizes the necessity for using a resonator to enhance the modulation through feedback. The CERETRON design uses a toroidal quasi-optical resonator.[15] The field in a toroidal, "whispering-gallery" type of resonator can be described by a set of radially propagating modes that have much in common with the axial modes in an open resonator with spherical mirrors, or in a Fabry-Perot etalon. Waves converging on the axis from the mirrors and waves diverging from the axis are described in full generality by Hankel functions of the first and second kind. A useful parameter for describing these modes is the phase factor,

$$\alpha_m(k\rho) = \pi^{-1}\,[J_m(k\rho) + N_m(k\rho)]^{-1},$$

where J and N are Bessel functions of the first and second kind, and m is the azimuthal mode number. The resonant wavelengths of the fundamental radial modes that have an axial electric field for coupling to the grating emission are given by

$$\lambda_{p00} \approx 2\rho_0\left[p - \frac{1}{8} + \frac{1}{8p\pi^2}\right]^{-1} \sim 2\rho_0/p \quad . \qquad (8)$$

For the lowest order azimuthal modes, $\alpha_m(k\rho_0) = k\rho_0/2$ in a resonator with dimensions much greater than a wavelength. The case with the curvature of the toroidal surface, R, related to the ring radius, ρ_0 by $R = 4\,\alpha_m(k\rho_0)/k$ is analogous to the confocal case for two spherical mirrors. Indeed, for $\lambda \ll R, \rho_0$ this simplifies to the confocal condition for spherical mirrors, $R = 2\rho_0$.

(U) The Q for toroidal resonators has been calculated by Goubau and Schwering including diffraction and resistive losses.[15] For copper surface resonators with an axial extent $Z_0 > 2(\lambda\rho_0/\pi)^{1/2}$, the calculated Q is greater than 10^5. This condition on Z_0 also ensures good separation of adjacent modes. Furthermore, in this limit the cavity eigenfunctions can be approximated by Gaussian-Hermite functions, which are more tractable than the more general Hankel functions.

(U) In particular, because Gaussian-Hermite functions also describe the modes of spherical-mirror resonators, many of the standard formulae derived for laser resonators may be taken over for the toroidal quasi-optical resonator. For example, the resonator g parameter, $g = 1 - 2\rho_0/R$, can be used to estimate the waist size of the mode structure, that is, the axial extent at $\rho = 0$;

$$Z_w = \left[\frac{\lambda\rho_0}{\pi}\right]^{1/2} \frac{(1+g)^{1/4}}{(1-g)^{1/4}} \quad . \qquad (9)$$

Likewise, the axial extent of the modes at the toroidal reflector is

$$Z_m = \left[\frac{2\lambda\rho_0}{\pi}\right]^{1/2} \frac{1}{(1-g^2)^{1/4}} \quad . \qquad (10)$$

(U) These formulae are being used to design a toroidal resonator for the CERETRON that simultaneously has adequate mode separation, a waist size large enough to cover the axial extent of the transmission grating ($Z_g < Z_w$), and a reflector dimension large enough to cover the mode size to avoid diffraction losses ($Z_0 > Z_m$). With such a resonator, large values of the beam modulation, α, and high efficiency can be expected.

5. (U) DEMONSTRATION EXPERIMENTS

(U) As the first step in the development of a microwave generator based on the Smith-Purcell effect radiation from a transmission grating, we have performed experiments with the production of radiation from a grating using the Los Alamos P-1 REB. The 2-cm diameter annular REB was produced in a smooth-bore magnetron geometry foilless diode immersed in a 90-kG magnetic field. The 2.8-MeV, 50-kA beam had a 85-ns pulse-width, and was 100-μm or less thick. The beam was very cold: its ~30-mr divergence gives it a brightness of over 10^{12} W/m²/Sr. Two different stainless steel transmission gratings were used during the course of the experiments reported here. The grating parameters for each are listed in Table 1. The grating was surrounded by a 7.6-cm diameter acrylic vacuum chamber with 3.3-mm thick walls. No external quasi-optical resonator was used for these preliminary experiments. Microwave emission was physically limited by the Bitter-plate magnetic field coil, which had only a few small (~1 cm²) apertures for transmission of the 90° Smith-Purcell radiation.

(U) Radiation was collected with a horn located just outside of the magnet, and was transmitted to a remote screen room through 10.7 meters of WR-28 waveguide. Microwave signals were detected in the screen room with a 1N53 crystal in a broadband mount. Highpass filters consisting of sections of smaller waveguides and the dispersion of the long WR-28 waveguide run allowed some crude frequency resolution of the detected signals. Two different horns were used during the experiments. One of these collected all of the power transmitted through three apertures in the coil, and the other collected only the power transmitted through a single 1-cm^2 aperture. Measurements were made with the small horn located at several positions to determine if there was any axial variation in emission. (None was detected.)

6. (U) RESULTS AND CONCLUSIONS

(U) The output power in these initial experiments was very low: only ~7 kW peak power was detected in the 32-40 GHz range. A possible problem with these experiments was breakdown of the grating and vacuum vessel as a result of intense electric fields. Breakdown was observed, and experiments are in progress to attempt to remedy this. If it is assumed that breakdown or other factors did not limit the output power, the measured microwave emission corresponds to a beam modulation $\alpha < 10^{-4}$. This clearly shows the need for a resonator to improve the efficiency.

(U) In conclusion, we have observed ~7 kW of Ka-band Smith-Purcell radiation from a transmission grating driven with an intense REB. However, the efficiency is unacceptably low for use as a high-power microwave generator without incorporating an external resonator for improved beam modulation.

7. (U) ACKNOWLEDGEMENTS

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(U) Table I

Grating No.	R_g (cm)	R_b (cm)	d (mm)	λ_0 (cm)	δ	Z_g (cm)
1	1.18	1.0	1.8	1.0	1	14.5
2	1.33	1.0	3.3	0.95	1	13.5

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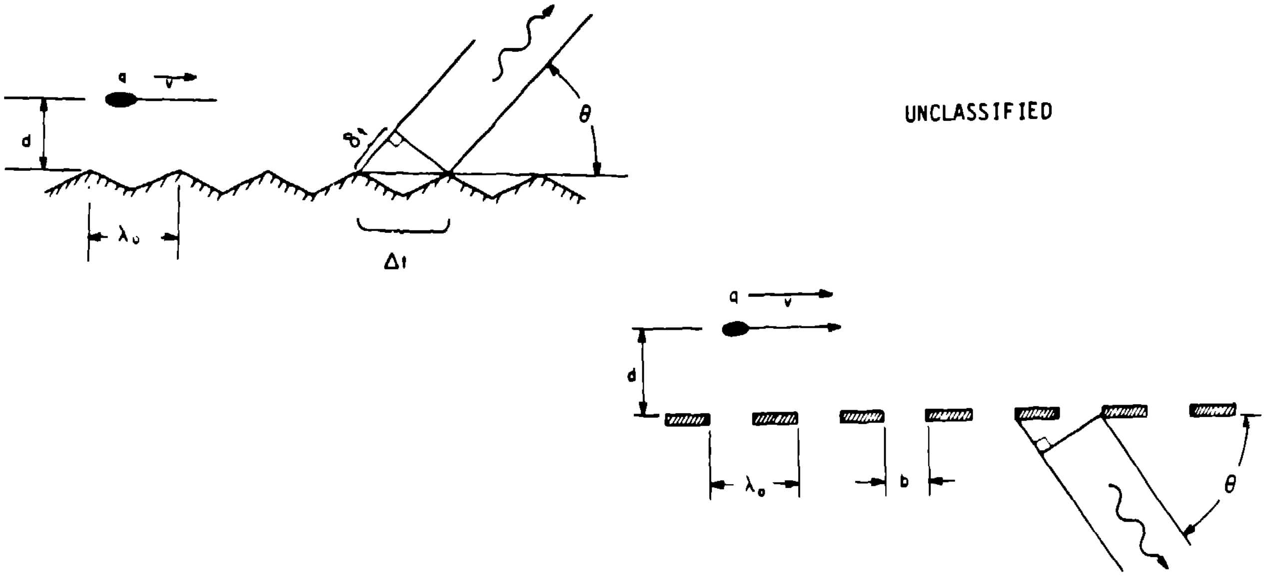

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Fig. 1

(U) Smith-Purcell radiation from a reflection grating (top) and through a transmission grating (bottom).

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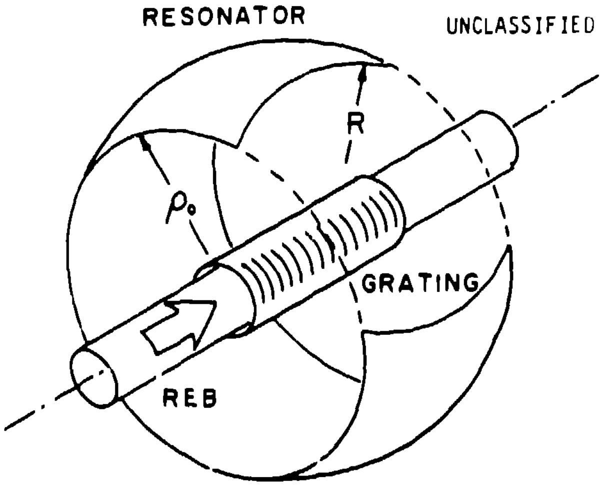
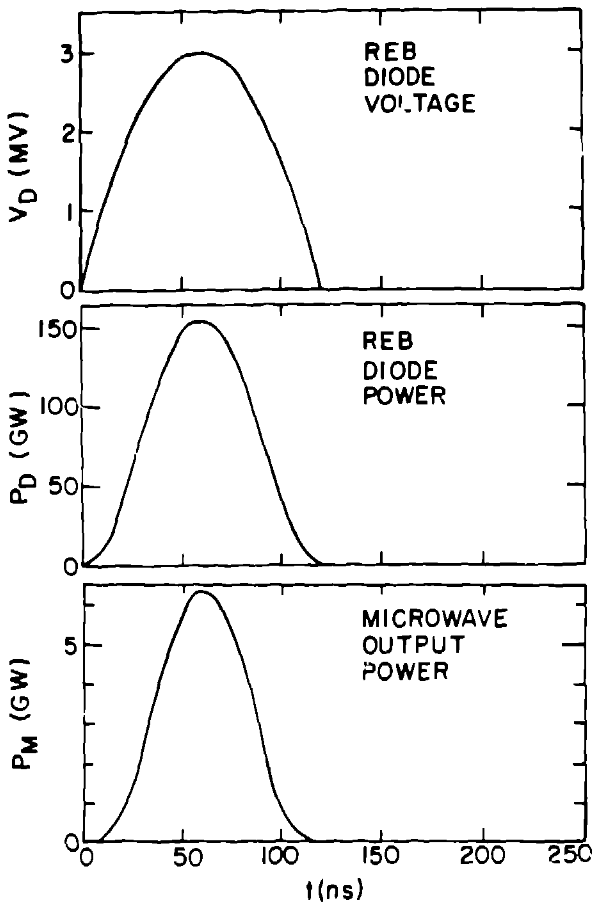


Fig. 2

(U) The CERETRON concept for a high-power microwave generator based on Smith-Purcell radiation from a transmission grating situated in an open, quasi-optical resonator.



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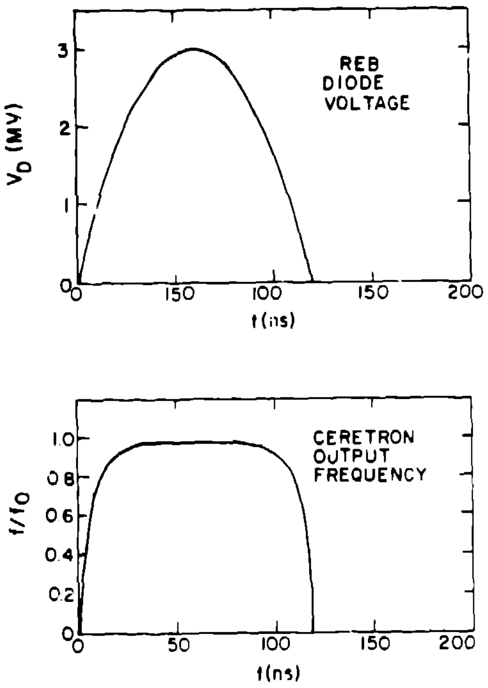

Fig. 3

(U) Voltage and power waveforms for the Los Alamos P-1 REB and the expected frequency and power output at 90° for a Smith-Purcell radiator driven by a closely-coupled, 1 percent modulated beam.

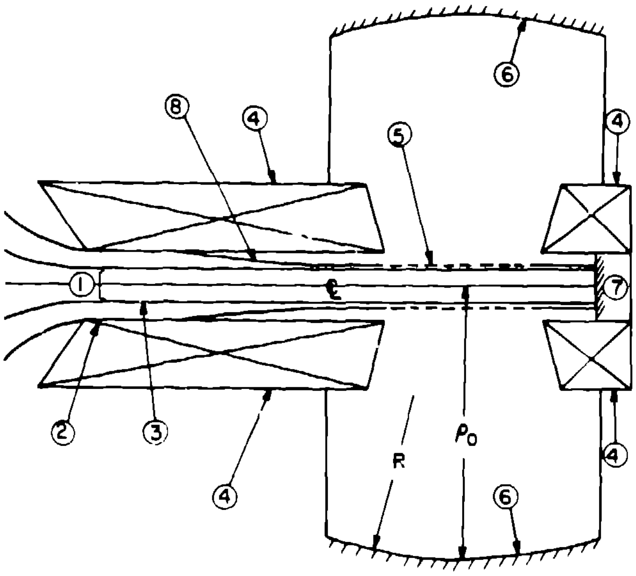

Fig. 4

(U) Diagram showing the necessary elements of a CERETRON microwave generator. 1. Magnetically-insulated diode cathode. 2. Magnetically-insulated diode anode. 3. Thin, annular REB. 4. Axial magnetic-field coils. 5. Cylindrical transmission grating. 6. Toroidal quasi-optical resonator surface. 7. Beam dump. 8. Convergent guide.