Observation of Coherent Millimeter and Submillimeter Emission from a Microtron-Driven Cherenkov Free-Electron Laser

F. Ciocci, A. Doria, G. P. Gallerano, I. Giabbai, M. F. Kimmitt,[a] G. Messina, and A. Renieri,
Dipartimento Sviluppo Technologie di Punta, Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Centre Ricerche Energia Frascati, C.P. 65-00044 Frascati, Rome, Italy

J. E. Walsh
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755
(Received 19 October 1990)

We report the observation of coherent emission from a Cherenkov free-electron laser driven by a 5-MeV radio-frequency microtron. Power up to 50 W in pulses of 4-μs duration has been generated at the wavelengths of 1.6 and 0.9 mm using two different dielectric-loaded waveguides.

PACS numbers: 42.55.Tb, 41.70.+t

Slow-wave structures, which achieve velocity synchronism between the propagating wave and the interacting electron beam, are considered as potential candidates for the generation of power in the millimeter and submillimeter regions of the spectrum, since they overcome many of the problems related to the excitation of microwave cavities with dimensions of the order of the wavelength.

A number of experiments exploiting the emission of Cherenkov radiation in dielectric-loaded waveguides have been performed in the past,[1] mainly in the millimeter region utilizing electron beams at energy ≤ 1 MeV. In this type of device a beam of relativistic electrons passes at grazing incidence above the surface of a dielectric-loaded waveguide, exciting TM-like surface waves.[2] The longitudinal component of the evanescent electric field causes a bunching of the electrons, which give rise to stimulated emission.[3] In the synchronism condition for a single-slab geometry[2] the radiation is emitted at a wavelength given by

$$\lambda = 2\pi d\gamma(\epsilon - 1)/\epsilon \qquad (1)$$

in the approximation $\gamma \gg 1$, $\lambda \gg d$, where d is the film thickness, ϵ its dielectric constant, and γ the relativistic factor of the electrons.

The coupling efficiency C between a single electron and the TM wave is expressed by an exponential behavior,[2]

$$C = \exp(-2\pi x/\lambda\beta\gamma)\,, \qquad (2)$$

where x is the distance of the electron from the film surface. Operation at high energy is therefore interesting since it can allow either an increase in the coupling efficiency for a given wavelength or reaching a shorter wavelength for a given coupling efficiency.

An experiment utilizing a radio-frequency–driven 5-MeV microtron as the electron-beam source (see Table I) has been designed[4] and performed at the ENEA submillimeter free-electron-laser (FEL) facility in Frascati, in order to test the energy scalability of this type of device. The layout of the experiment is sketched in Fig. 1 and has been described in detail elsewhere.[5] A quasioptical resonator provides feedback and confinement of the radiation (see Fig. 2). Two pairs of permanent magnets, placed symmetrically sideways at the entrance of the resonator, allow the electron beam to be injected above the input mirror and then be displaced so as to travel parallel and close to the surface of the dielectric film. The gap between the magnets can be adjusted in order to optimize the coupling of the electrons to the dielectric film. In the interaction region the electron beam is focused by a triplet of quadrupoles to a small elliptic cross

TABLE I. Microtron parameters.

Radio frequency	3 GHz
e-beam energy	5.3 MeV
e-bunch duration	20 ps
e-bunch spacing	330 ps
Macropulse duration	5 μs
Maximum repetition rate	20 Hz
Macropulse current	200 mA
Peak current	3 A
Vertical emittance	6π mm mrad
Horizontal emittance	18π mm mrad
Energy spread	0.5%

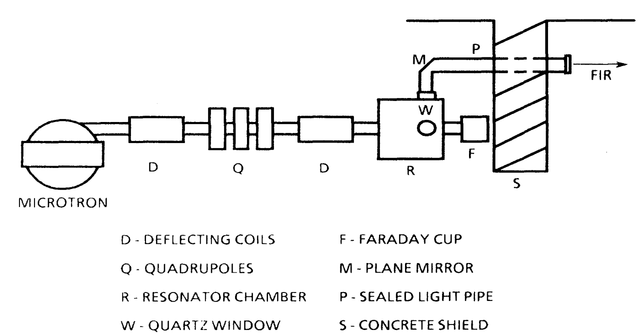

FIG. 1. Layout of the experiment.

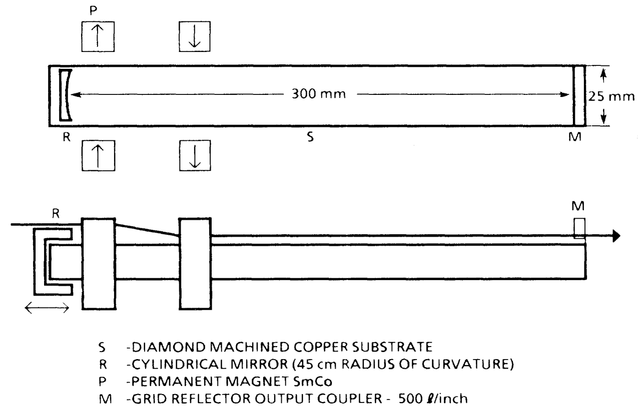

FIG. 2. Quasioptical resonator.

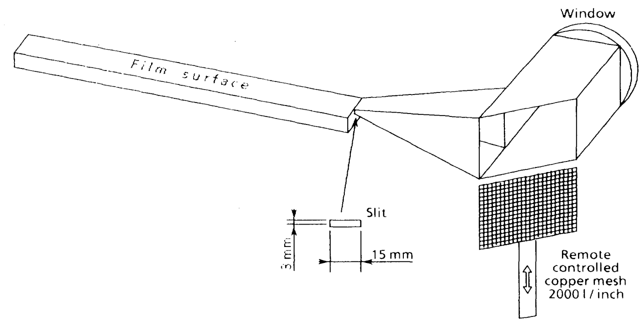

FIG. 3. A view of the dielectric-loaded waveguide and of the copper horn utilized to collect the millimeter and submillimeter radiation.

section (6×3 mm^2).

Particular care has been devoted to the design and realization of an efficient light-collecting system and suitable optical diagnostics. A Ge:Ga extrinsic photoconductor and an InSb electron bolometer, both operating at 4 K, were used as fast detectors to cover the spectral range from 50 μm to several millimeters. Semiconductor detectors are very sensitive to x rays, which are present in a high-energy electron-beam environment. In order to reduce the x-ray noise on the detector, a 2.5-μm-thick mesh (2000 lines/in.) placed into the electron-beam path, reflects the millimeter radiation at 90° out of the resonator chamber. The radiation is then transported through a 3-m-long evacuated light pipe into a shielded diagnostic area (see Fig. 1). Another source of noise is the microwave background associated with the propagation of an rf-modulated electron beam through the metal structure of the transport channel. This background has been removed by inserting, between the resonator output and the z-cut quartz window of the vacuum chamber, a copper horn (see Fig. 3) which collects only the radiation coming out of a narrow slit (15×3 mm^2) at the end of the film surface. The horn also launches the emitted surface wave into the light pipe, avoiding the strong diffraction which would be present with free-space propagation.

In this experimental configuration two different polyethylene films,[6] with thickness of 25 and 50 μm, respectively, have been successfully operated. The wavelength of the emitted radiation is 1660 μm for the 50-μm-thick film and 900 μm for the 25-μm-thick film.

In Fig. 4 a typical signal detected by the InSb bolometer is shown with the electron-beam current pulse. An interesting feature is the signal growth during the macropulse which can be ascribed both to a nonlinear behavior with respect to the variation of the electron current and to feedback in the resonator structure. The analysis of the signal amplitude as a function of the distance of the electron beam from the dielectric film surface gave us a clear indication of a Cherenkov emission process. Maximum signal was obtained not for the maximum transported current, but for the maximum current density above the film surface, which corresponds to a position of the beam centroid approximately on the surface of the dielectric film. A displacement of the beam centroid of 1.5 mm from the film surface caused a decrease of the output signal of a factor of 4, just as one would expect from the coupling coefficient (2) integrated over the electron-beam transverse distribution. A first analysis of the emitted radiation has been performed by measuring the transmission through various n-Ge filters (resistivity 3 Ω cm), with thicknesses ranging between 1 and 6 mm, and through wire polarizers. Tungsten wires of 25 μm diameter wound on a brass frame with spacing in the range 125–2500 μm were used. With the finest available spacing of the polarizers we have measured 80% polarization for the electric field perpendicular to the film surface, in agreement with the excitation of TM-like surface

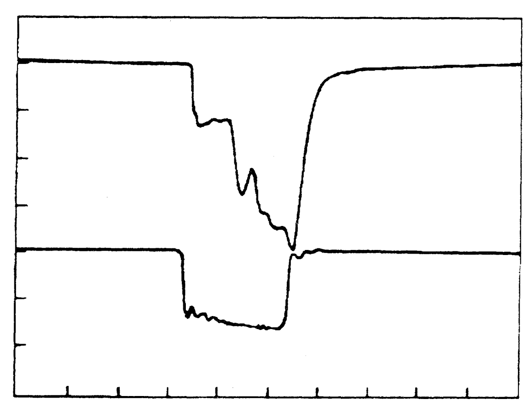

FIG. 4. 50-μm-film operation. Upper trace: InSb-detector signal (200 mV/div). Lower trace: electron-beam current (100 mA/div).

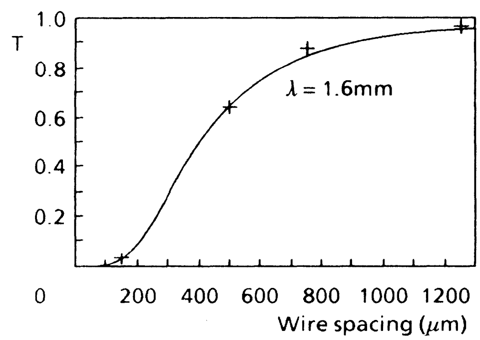

FIG. 5. Transmission through wire polarizers vs wire spacing (wires perpendicular to the film surface). Crosses: experimental points. Solid line: Theoretical curve for $\lambda = 1600$ μm. The measurement was done with the 1.1-mm Ge filter plus a 125-μm-spacing wire polarizer placed in a way to remove the horizontal polarization.

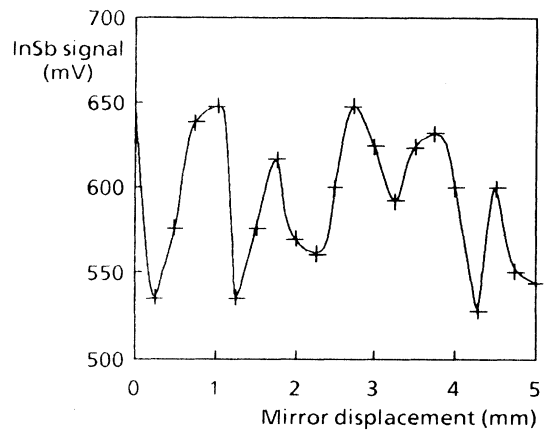

FIG. 6. Amplitude of the detector signal vs resonator-length variation from a starting length $L = 298.5$ mm.

waves. Figure 5 shows the transmission through wire polarizers as a function of the wire spacing for the 50-μm film. The experimental points are fitted well by the theoretical relationship calculated by Ulrich, Bridges, and Pollack[7] for a wavelength $\lambda = 1600$ μm, indicating that emission occurs in a narrow frequency band. Very good agreement has also been obtained with the transmission data available for the n-Ge filters.[8] A 5-mm scan of the resonator length (see Fig. 6) has shown an amplitude modulation with a spatial periodicity of 0.8 mm in agreement with the wire-polarizer measurement. Only a 20% amplitude modulation was observed, indicating a low-efficiency feedback in the resonator. Indeed quite a strong diffraction occurs on the upstream mirror which is only 3 mm in height. A measurement of the resonator Q from the ringdown of the signal was not possible due to the short resonator length (30 cm) which implies a decay time shorter than the detector response time.

Sufficient information has been obtained by the wire-polarizer measurements to allow us to perform a detailed spectral analysis by means of a Fabry-Pérot interferometer (FPI). The FPI utilizes as mirrors the same type of wire polarizers previously described, with grid spacings of 200 and 250 μm, respectively. The mirror distance can be scanned from an effective "zero" gap (mirrors in contact) to several tens of millimeters by a stepper motor with a minimum step of 1 μm. The finesse of the instrument is estimated to be $F \approx 20$ for the 1.6-mm wavelength and $F \approx 10$ for the 0.9-mm wavelength. The FPI was placed at the output of the copper light pipe and a 150-mm focal-length TPX lens was used after the FPI to focus the light onto the detector. A 1.1-mm-thick Ge filter plus a wire polarizer crossed with respect to the FPI mirrors was placed between the light pipe and the FPI in order to remove the residual unwanted polarization which would reduce the amplitude of the FPI modulation. The interferograms relative to a 4-mm scan of the FPI for the 50-μm film and a 2-mm scan for the 25-μm film are shown in Figs. 7(a) and 7(b), respectively. The interferograms clearly indicate an emission band peaked at wavelengths of 1660 μm [Fig. 7(a)] and 900 μm [Fig. 7(b)] in agreement with the relationship (1). The bandwidth of the emitted radiation in both cases is $\Delta\nu/\nu \approx 25\%$ FWHM. The film-thickness uniformity

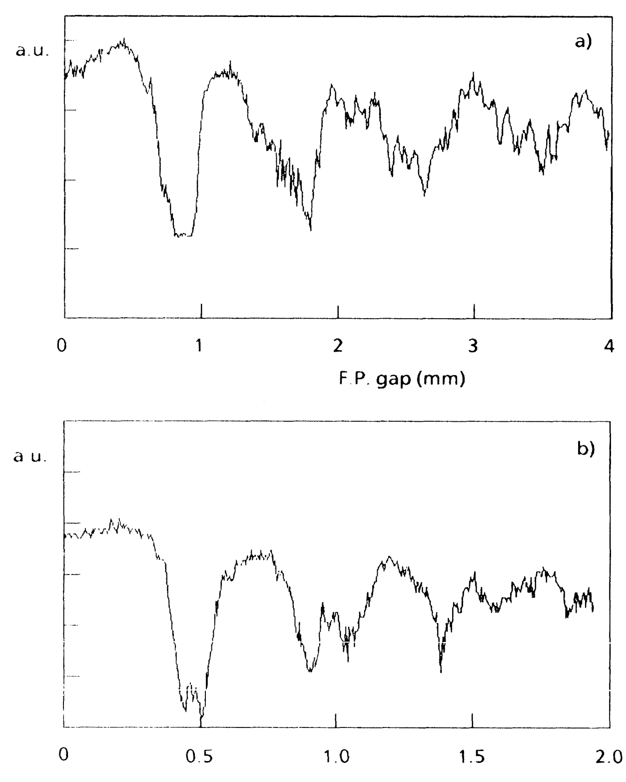

FIG. 7. Fabry-Pérot interferograms for (a) 50-μm film thickness, 4-mm scan (step size 10 μm), and (b) 25-μm film thickness, 2-mm scan (step size 5 μm).

($\pm 5\%$) contributes only in part to this large value of the bandwidth. Orders up to the fourth can be distinguished in the interferograms, revealing a structure with peaks spaced 9 GHz apart.

A measurement of the power emitted with the 50-μm film was performed by means of a Scientech (model 365) 1-in. disk calorimeter with 10-μW resolution placed in front of the vacuum-chamber output window. The power meter was calibrated with a 5-mW impact avalanche transit-time oscillator (IMPATT) source at $\lambda = 2$ mm (150 GHz) (Hughes 47187H) indicating a drop of responsivity of a factor of 2 with respect to the infrared range. By running the accelerator at 10 Hz, 80 μW of average power was measured by the disk calorimeter. Taking into account the coupling losses from the film surface to the chamber window (65%) and a minimum distance of 20 cm from the window to the calorimeter surface, we obtain 30 W of power averaged over the 4-μs macropulse. This number has to be compared with an estimated power of 50 W at the peak of the macropulse derived from the detector voltage responsivity and allowing for the losses of the collecting system. The power emitted with the 25-μm film has only been estimated from the detector responsivity, resulting in about 6 W at the peak of the macropulse. A final test was made by checking for any signal detected with the bare copper plate (no film on it): No signal was detected in the spectral region where the Cherenkov emission was present.

The measurements performed on the output radiation of the Cherenkov FEL relevant to the spectral content, polarization, and sensitivity to the electron-beam steering are in close agreement with the expected characteristics. In spite of the low measured efficiency ($\sim 10^{-4}$), the output power is about 6 orders of magnitude higher than would be expected from spontaneous emission.[2] The observed behavior of the detected signal as a function of the electron current amplitude strongly suggests the occurrence of coherent emission from the current modulation at the resonant frequency, due to the bunched nature of the electron beam. Preliminary calculations, which will be reported in a forthcoming paper, explain the mechanism of gain and saturation in a Cherenkov device with a modulated electron beam.

We would like to thank Dr. G. Dattoli and our colleagues at the Laboratorio Laser di Potenza and Laboratorio Fisica ed Ingegneria degli Acceleratori of the ENEA Frascati research center for many stimulating discussions. We are also grateful to Dr. O. Tudisco for courteously providing the IMPATT source.

[a]Permanent address: Department of Physics, University of Essex, Colchester CO4 3SQ, United Kingdom.

[1]E. P. Garate, S. Moustaizis, J. M. Buzzi, C. Rouille, H. Lamain, J. Walsh, and B. Johnson, Appl. Phys. Lett. **48**, 1326 (1986), and references therein.

[2]F. Ciocci, G. Dattoli, A. Doria, G. Schettini, A. Torre, and J. E. Walsh, Nuovo Cimento **10D**, 1 (1988); F. Ciocci, G. Dattoli, A. Doria, G. P. Gallerano, G. Schettini, and A. Torre, Phys. Rev. A **36**, 207 (1987).

[3]G. Dattoli, A. Doria, G. P. Gallerano, G. Schettini, and A. Torre, Nuovo Cimento **101B**, 79 (1988).

[4]J. E. Walsh, B. Johnson, G. Dattoli, and A. Renieri, Phys. Rev. Lett. **53**, 779 (1984); J. E. Walsh, B. Johnson, C. Shaughnessy, F. Ciocci, G. Dattoli, A. De Angelis, A. Dipace, E. Fiorentino, G. P. Gallerano, T. Letardi, A. Renieri, E. Sabia, I. Giabbai, and G. Giordano, Nucl. Instrum. Methods Phys. Res., Sect. A **250**, 308 (1986).

[5]F. Ciocci, G. Dattoli, A. De Angelis, A. Dipace, A. Doria, G. P. Gallerano, M. F. Kimmitt, A. Renieri, E. Sabia, A. Torre, and J. E. Walsh, in Proceedings of the Eleventh FEL Conference, Naples (U.S.A.), September 1989 (to be published).

[6]50-μm thickness, NOVACEL 4500 low-density PE, $\epsilon = 2.2$. 25-μm thickness, ENICHEM E-141-07 linear PE, $\epsilon = 2.2$.

[7]R. Ulrich, T. J. Bridges, and M. A. Pollack, Appl. Opt. **9**, 2511 (1970). The expression for the reflectivity of the metal meshes with rectangular cross section is reported in the paper. A slight modification has been applied to it to account for the circular cross section of the wires.

[8]J. R. Birch, C. C. Bradley, and M. F. Kimmitt, Infrared Phys. **14**, 189 (1974).