First Observation of Smith-Purcell Radiation from Relativistic Electrons

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A beam of 3.6-MeV electrons has been used to study the generation of radiation in the far infrared (FIR) by the Smith-Purcell mechanism. The dependence of wavelength on angle of emission, over angles from 56° to 150° and wavelengths from 350 to 1860 μm, is in excellent agreement with the Smith-Purcell dispersion relation. Comparison of the yield with that from a 5000-K source suggests that the spontaneous Smith-Purcell effect offers an easily tunable alternative to the synchrotron as a coherent FIR source, and that it could also form the basis of an inexpensive, compact free-electron laser.

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We report the first observations of Smith-Purcell (SP) radiation in the submillimeter–far-infrared region of the spectrum. Unlike both early [1] and more recent work [2], which relied on low-energy electron beams and concentrated on emission in the visible, here a relativistic electron beam was employed and the emphasis is on a spectral region where the population of sources is sparse.

Comparison of the measured value of the emitted wavelength (λ_{SP}) and the emission angle (θ) for a series of gratings confirms in detail that the process obeys the celebrated SP formula:

$$\lambda_{SP} = \lambda_G [1/\beta - \cos\theta] . \quad (1)$$

The parameter λ_G is the grating period and β is the relative velocity of a beam electron. In the spectral region where the radiation was observed, the level is comparable to that produced by an infrared beam line on a synchrotron. The emission from compact, linear-accelerator-driven gratings would be much greater. Thus, the process provides a means whereby Fourier-transform spectroscopic techniques can be extended into the technologically important long-wavelength spectral region. The grating is also a much simpler structure than a magnetic undulator and with adequate feedback it offers another basis for the free-electron laser (FEL) [3].

The inverse SP process has also been considered as a possible means of accelerating electrons to high energy [4]. Although in the present work acceleration was not the object, coupling of near speed of light electrons and gratings has been demonstrated.

The electrons were accelerated in a modified 10-MV Van de Graaff accelerator formerly used for a program of nuclear structure research at Oxford. Conversion to accelerate electrons had been started in preparation for a FEL project which was then not funded. Work necessary to enable efficient electron transmission [5] was completed and an electron gun was kindly lent by the Department of Physics, University of Glasgow.

First, acceleration of the electrons was obtained at an energy of 3.6 MeV. The grid of the gun was pulsed, giving 6-μs bursts of electrons at 1 Hz. Considerable difficulties were experienced with both the yield and short lifetime of the cathodes; these were not fully overcome. Another pair of unsolved problems were a slight positional jitter in the beam and a beam size slightly larger than expected. The beam size, shape, and transverse position could be controlled using the up-stream deflecting magnets and quadrupole (Fig. 1).

The electron beam current was measured at the gun exit and by measuring the charge collected on the grating and the beam dump; the latter signal also served as a trigger for recording the Smith-Purcell optical signal. The data were taken with a beam size which was 3 mm (normal to the grating) by 6 mm (transverse), and beam currents varied from 50 mA up to a maximum of 200 mA, giving current densities in the range of 0.35 to 1.7 A/cm^2.

The arrangement for the observation of Smith-Purcell

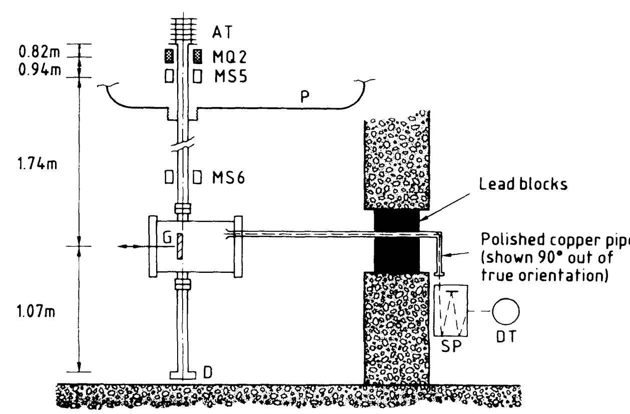

FIG. 1. Schematic of the experiment layout showing beam control elements, grating and optical chamber, light pipe, x-ray shielding, spectrometer, and detector.

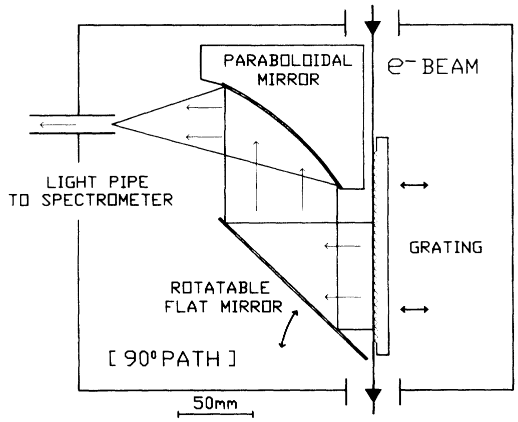

FIG. 2. Diagram illustrating the optical arrangement. Rotation of the flat mirror allows observation of radiation emitted from the grating at angles from 25° to 94° to the forward beam direction. By turning the optical platform through 180°, emission angles of 85° to 155° could be studied.

radiation is illustrated in Figs. 1 and 2. In order to detect the radiation emitted over a range of angles, a rotatable plane mirror from which the light collected was focused at the entrance of a 2-m-long internally polished copper tube. This took the light to the entrance of a Czerny-Turner spectrometer behind a lead-brick wall.

A helium-cooled InSb electron bolometer was placed at the exit slit of the monochromator. This had a response time of ~ 0.5 μs and could detect peak powers of less than 10 nW over the wavelength range 400–2500 μm.

The light pipe was evacuated separately from the accelerator and beam transport, with TPX windows at both ends and a third at the cryostat entrance. The air path in the spectrometer was about 4 m.

Movement of the plane mirror enabled observations at emission angles of 25° up to 94° from the forward direction of the beam. The relationship between mirror angle and emission angle was directly calibrated externally using a helium neon laser. Angles in the backward direction could be reached by dismounting the plate carrying the grating and mirrors, rotating it through 180°, and introducing a short periscope to convey the light to the light pipe entrance. It was subsequently discovered that a slight misalignment occurred in the periscope and a 2° correction was applied to this set of data. The positions of the plane mirror and the grating were under independent remote control, as was the angle of the spectrometer grating.

The gratings were ruled with a 30° blaze on aluminum bars 2 cm in width, with a slightly concave surface facing the beam, and with an effective optical length of about 7 cm along the beam.

A typical Smith-Purcell signal, as recorded on the Lecroy model 9400A digital oscilloscope averaged over 100 pulses, is shown in Fig. 3. This was obtained with a 3.6-MeV electron beam passing over a (nominal) 0.030-

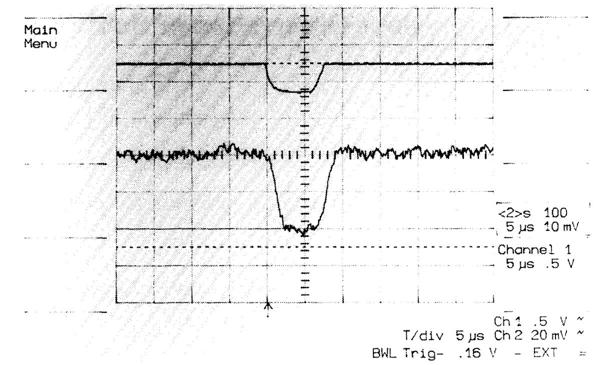

FIG. 3. A typical Smith-Purcell signal, averaged over 100 pulses and recorded on a Lecroy 9400A digital oscilloscope; upper trace is the electron beam pulse, used as a trigger.

in. period grating; the emission angle was 136° and the wavelength 1300 μm. Figure 4 shows the signal as a function of wavelength in another case using the same grating at an emission angle of 115°. The FWHM is about 88 μm, consistent with the range of efficient collection in angle of the optical system and wider than the spectrometer bandwidth.

The results obtained in two runs are summarized in the plot (Fig. 5) of observed wavelengths, λ_{obs}, against the values predicted from the dispersion formula (1), λ_{SP}. The agreement is excellent over the whole range [6] of angles explored, from 56° to 150°. There can be no doubt that this is Smith-Purcell radiation.

Subsequently the grating was replaced by a high-pressure mercury vapor lamp with an arc temperature of ~ 5000 K above 400 μm [7]. This allowed a direct calibration of the entire system, using the same optical train, spectrometer, and detector. The preliminary analysis of the results, Fig. 6, shows the yield of Smith-Purcell radiation generated by a 0.1-A electron beam and entering the detector to be greater than that from the mercury source for wavelengths above 600 μm, and more than 10 times

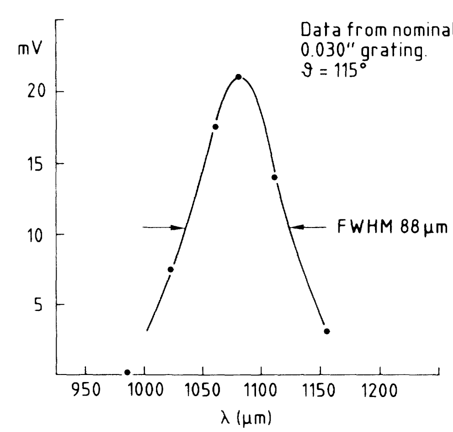

FIG. 4. Smith-Purcell signal as a function of wavelength, for emission angle of 115° from nominal 0.030-in. period grating.

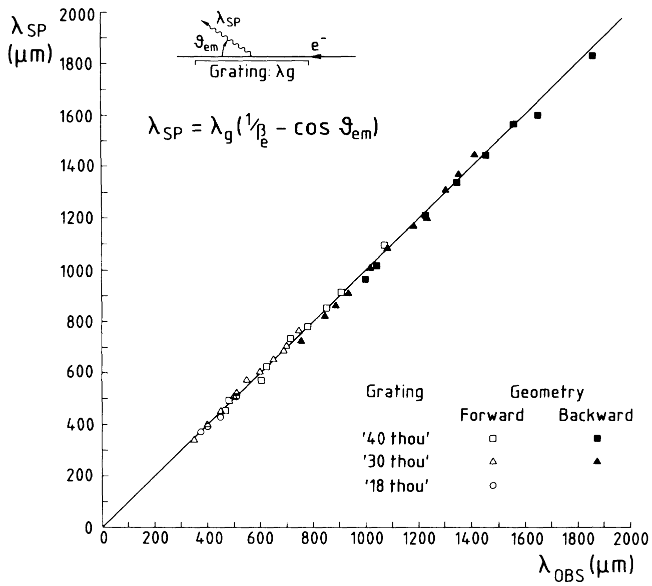

FIG. 5. Predicted Smith-Purcell wavelength, λ_{SP}, vs the observed wavelength, λ_{obs}, for the conditions indicated. The wavelengths covered by one grating (nominal 0.40-in. period) range from 467 to 1860 μm.

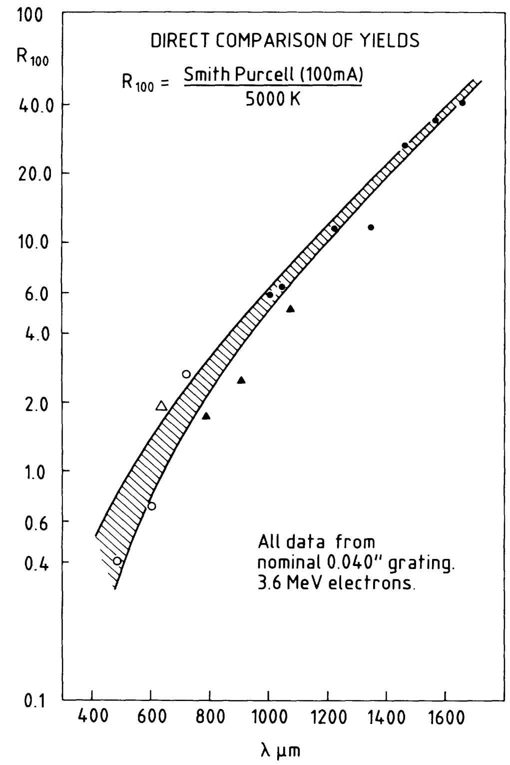

FIG. 6. A direct comparison as a function of wavelength of the Smith-Purcell signal levels form a 0.040-in. grating with those obtained from a 5000-K source under closely similar conditions.

larger for wavelengths greater than 1200 μm. Figure 6 uses data from four different runs and the systematic shifts in position are consistent with being due to difficulties in reproducing identical operating conditions for the beam; however, the overall conclusion is not affected.

It is also instructive to compare the power levels observed with the performance of an infrared beam line on a synchrotron [8]. Following Ref. [8] we observe that the National Synchrotron Light Source beam produces approximately 10^{16} photons/sec sr in a 0.1% bandwidth at a wavelength of 1 mm for a current of 1 A. The present SP source produces approximately 10^{15} photons/sec sr in the same fractional bandwidth when the current is 100 mA. Thus, these sources are comparable at this wavelength.

Detailed theoretical models of the emission process have not yet been subjected to any critical experimental test; however, assuming that the SP process falls in the general category of wake field phenomena [3], emission should scale as

$$\frac{dP}{dz} \sim A_b e^{-\lambda_0/\lambda} \frac{d\lambda}{\lambda^3}, \tag{2}$$

where A_b is of the order of the beam area and the exponential term results from the coupling to the space harmonic component whose phase velocity is synchronous with the beam velocity. The characteristic cutoff wave number λ_0 will scale [3] with $\bar{\sigma}/\beta\gamma$ where $\bar{\sigma}$ is the beam thickness and γ is the relative energy. In the present experiment $\bar{\sigma}$ was approximately 2 mm and the estimated beam emittance was very high ($>20\pi$ mm mrad, normalized). A low-emittance, low-energy, compact linear accelerator will, on the other hand, have a typical emittance in the $4-5\pi$ mm mrad range in the energy range of these experiments. Thus, $\bar{\sigma}$ in the 0.2–0.4-mm range are easily obtained. The linac will also have much higher (peak) current. In the best case a micropulse may contain 1–2 nC of charge and hence $I_b \sim 100$ A is available. The radiation produced by a grating driven by such a beam would exceed the level produced by a synchrotron (and a blackbody) by many orders of magnitude.

Smith-Purcell radiation has been observed in the far infrared generated by relativistic electrons of energy 3.6 MeV, over a continuous range of emission angles from 56° to 150°, and wavelengths from 350 to 1860 μm.

The first indications from a direct calibration using a mercury vapor source at $\sim$5000 K are that even with an electron beam clearly very inferior to state of the art, the yield can be significantly greater in this region of the spectrum and, given optimal beam conditions, suggest that a device based on the spontaneous Smith-Purcell mechanism could rival the synchrotron as a coherent FIR source.

Moreover, these results give encouragement to proposals to use the Smith-Purcell effect as a basis for an inexpensive, compact, easily tunable ir FEL [3].

The Oxford group wishes to thank their colleagues in the Particle and Nuclear Physics Laboratory for their support of this experiment, especially in times of great pressure on resources. We also thank Professor Bob Owens of Glasgow University for the loan of an electron gun. The successful conversion and operation of the Van de Graaff for this last experiment was made possible by the enthusiasm and efforts of Tony Henwood, Colin Graham, George Hammett, and Bill Linford who also designed and made the grating and optics mounting; finally we thank Brian Hawes and Graham Salmon for their help and advice on the cryogenics. EC European Network Contract [SC1-0471-C (A)] provided funds for certain travel expenses, and for the purchase of the InSb crystal lent by Professor Carl Pidgeon of Heriot Watt University. J.W. wishes to acknowledge support from Vermont Photonics, Inc., from U.S. ARO Contract No. DAAL03-91-G-0189, and from NSF Contract No. INT-8815235.

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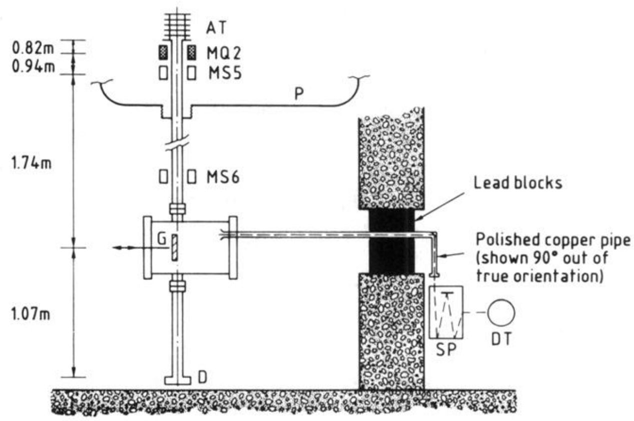

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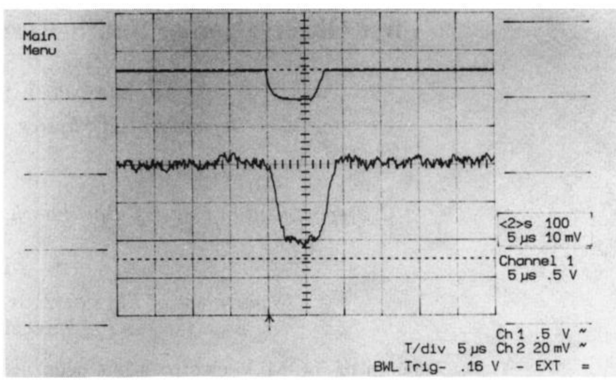

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