First Observation of Smith-Purcell Radiation from Relativistic Electrons

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Abstract

A beam of 3.6 MeV electrons has been used to study the generation of radiation in the far infra-red (FIR) by the Smith-Purcell mechanism. The dependence of wavelength on angle of emission, over angles from 56° to 150° and wavelengths from 350μm to 1860μm, 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 could form the basis of a cheap, compact Free Electron Laser (FEL).

1 INTRODUCTION

Smith-Purcell radiation is the name given to electromagnetic radiation generated when an electron beam passes over the surface of a metal grating. It was first observed by Smith and Purcell in 1953 [1] and has since been the subject of a number of theoretical and experimental publications [2]. Previous observations have been made mainly in the visible region, and with beams of energy significantly less than 500 keV.

The electrons interact with the longitudinal component of a slow surface wave of spatial frequencies dominated by harmonics of the grating period. As a means to transfer energy from an electron beam into coherent electromagnetic radiation, it offers another basis for the FEL. The inverse process has been considered as a possible means of electron acceleration to high energy [3].

Kinematics determines the dispersion relation giving the wavelength of the radiation emitted λ_{SP} as:

$$\lambda_{SP} = \lambda_G (1/\beta - \cos\theta) \qquad (1)$$

where λ_G is the grating period, β is the electron velocity in units of c, and θ is the angle of emission of the radiation to the electron beam direction.

The objectives of this experiment were to observe spontaneous Smith-Purcell radiation in the far infra-red generated by a beam of relativistic electrons and measure the output power.

2 THE EXPERIMENT

2.1 Electron Beam

The electrons were accelerated in a modified 10 MV Van de Graaff formerly used for a programme of nuclear structure research at Oxford. Conversion to accelerate electrons had been started in 1989 in preparation for a FEL project which was then not funded. Some of the work necessary to enable efficient electron transmission [4] was completed and an electron gun was kindly lent by the University of Glasgow Department of Physics.

First acceleration of electrons was obtained in October 1990, at up to 3.6 MeV. The grid of the gun was pulsed giving 6μs bursts of electrons at 1Hz. Difficulties were experienced with both the yield and short lifetime of the cathodes; these were not fully overcome since only minimal resources could be applied and operation of the Van de Graaff had to cease for financial reasons by October 1991. Another unsolved problem was a slight positional jitter in the beam and a beam size somewhat larger than expected. The beam size, shape, and transverse position could be controlled using up-stream deflecting magnets and a quadrupole doublet lens.

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 eventually taken in August and October 1991 with a beam size in the grating position of about 3mm (transverse to the grating) by 6mm, and beam currents from 50mA up to a maximum of 200mA; giving current densities in the range 0.35A/cm^2 to 1.7A/cm^2.

2.2 Optics and Detection

The arrangement for the observation of Smith-Purcell radiation is illustrated in Figure 1. In order to detect the radiation emitted at a range of angles a rotatable plane

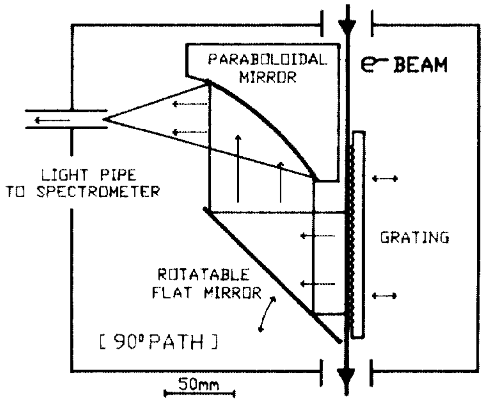

Figure 1: Diagram illustrating the optical arrangement.

mirror was used to reflect light from the grating onto a paraboloidal mirror from which the light collected was focussed at the entrance of a 2m 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 0.5μs and could detect peak powers of less than 10 nW over the wavelength range 400–2500μm.

The light passed through three TPX windows: at the entrance and exit of the separately evacuated copper pipe, and at the entrance to the cryostat. The air path in the spectrometer was about 4m.

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 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 aluminium bars 2cm in width, with a slightly concave surface facing the beam, and with an effective optical length of about 7cm along the beam.

3 RESULTS

A typical Smith-Purcell signal, as recorded on the Lecroy model 9400A digital oscilloscope averaged over 100 pulses, is shown in Figure 2. This was obtained with a 3.6 MeV electron beam passing over a (nominal) 0.030 inch period grating. Fig.3 shows the signal as a function of wavelength using the same grating for an emission angle of 115°. The FWHM is about 88μm, consistent with the range of efficient collection in angle of the optical system, and wider than the spectrometer bandwidth.

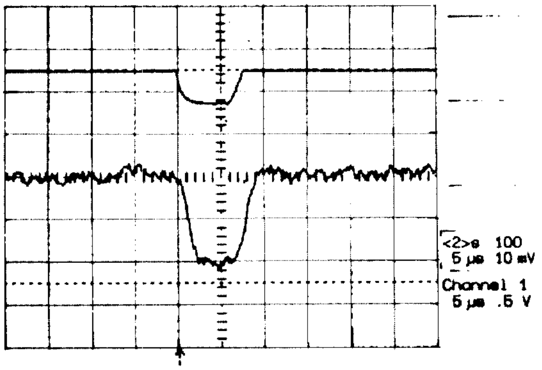

Figure 2: A typical Smith-Purcell signal, averaged over 100 pulses and recorded on a Lecroy 9400A digital oscilloscope; upper trace is the electron beam pulse, used as a trigger.

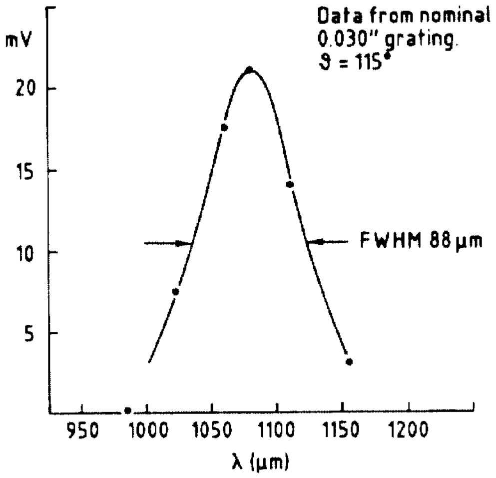

Figure 3: Smith-Purcell signal as a function of wavelength, for emission angle of 115° from (nominal) 0.030 inch period grating.

The results obtained in the two October runs, finishing on 31st, are summarised in Figure 4 showing the relationship between the observed wavelengths, λ_{OBS}, and the values predicted from the dispersion formula (1), λ_{SP}. The agreement is excellent over the whole range[1] of angles explored, from 56° to 150°. There can be no doubt that this is Smith-Purcell radiation.

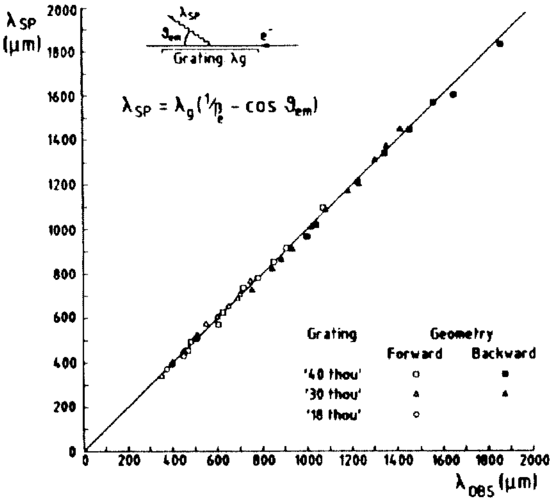

Figure 4: Predicted Smith-Purcell wavelength, λ_{SP}, versus the observed wavelength, λ_{OBS}, for the conditions indicated. The wavelengths covered by one grating (nominal 0.040 inch period) range from 467μm to 1860μm.

Subsequently the grating was replaced by a high pressure mercury vapour lamp with an arc temperature of

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[1] With the gratings used, at angles forward of 56° the wavelength drops below about 350μm where the detector sensitivity is falling rapidly.

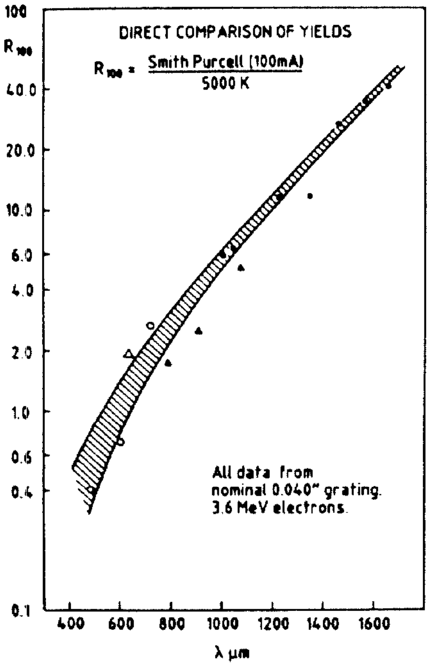

Figure 5: A direct comparison as a function of wavelength of the Smith-Purcell signal levels from a 0.040 inch grating with those obtained from a 5000 K source under closely similar conditions.

5000 K above 400μm [5]. This allowed a direct calibration of the entire system, using the same optical train, spectrometer and detector. Figure 5 shows the yield of spontaneous Smith-Purcell radiation generated by a 0.1A electron beam and entering the detector to be greater than that from the mercury source for wavelengths above 600μm, and more than ten times larger for wavelengths greater than 1200μm. Figure 5 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. Further analysis is underway to obtain figures for the power output as a function of wavelength and angle of emission.

4 CONCLUSIONS

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 350μm to 1860μm.

The first indications from a direct calibration using a mercury vapour source at 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 the basis for an inexpensive, compact, easily tunable IR FEL [6].

5 ACKNOWLEDGEMENTS

The Oxford group wish 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.Walsh wishes to acknowledge support from Vermont Photonics Inc. and from USARO Contract No. DAALO3 91-G-0189.

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