# EXPERIMENTAL OBSERVATION OF THE EVANESCENT WAVE IN A SMITH-PURCELL FREE-ELECTRON LASER

H. L. Andrews*, C. A. Brau and J. D. Jarvis
Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
C. F. Guertin, A. O'Donnell, B. Durant, T. H. Lowell and M. R. Mross
Vermont Photonics, Bellows Falls, VT, 05101, USA

### *Abstract*

We present the first experimental observations of the evanescent wave in a Smith-Purcell free-electron laser (FEL). This wave, predicted by both theory and simulations, has a wavelength longer than the Smith-Purcell radiation, has a group veloctiy anti-parallel to the electron beam, and for sufficiently high current, provides feedback to bunch the electron beam. This feedback is the basis of oscillator operation of the Smith-Purcell FEL. The wavelengths observed agree with theoretical predictions, and strong radiation from the upstream end of the grating confirms the negative group velocity. Radiation observed at the second harmonic indicates electron bunching by the evanescent wave.

## INTRODUCTION

Given the historic paucity of narrowband tunable sources in the far-infrared, or terahertz (THz), region, there has been a long-standing interest in developing such a source for applications in fields such as biology, chemistry and materials science [1, 2]. One particular approach has been to develop a table-top sized free-electron laser (FEL) based on either the Smith-Purcell or Cherenkov interaction. In recent years the theory of operation of a Smith-Purcell FEL (SPFEL) has developed to a point where theories from separate institutions agree well with each other and with simulations performed with particle-in-cell (PIC) codes such as MAGIC [3, 4, 5, 6, 7]. All of these theories predict that an evanescent wave, a non-radiating wave bound to the grating, is responsible for exchanging energy with the electron beam, and acting as the lasing mechanism. When the evanescent wave travels in the opposite direction as the electron beam, the system provides its own feedback so that oscillation is possible. Recently, full three-dimensional theories have been introduced, with and without side walls on the grating, and they agree well with PIC code simulations [8, 9, 10]. However, there has been no experimental corroboration of the calculations.

## THEORETICAL PREDICTIONS

In the SPFEL, an electron beam travels close to the surface of a conducting metallic grating, so that the fields of the electrons interact with the grating. There are two types of radiation given off by this interaction. The first is spontaneous Smith-Purcell radiation [11], whose wavelength depends on grating period $L$, normalized electron beam energy $\beta = v/c$, order number of the radiation $n$ and angle of observation, $\theta$ measured from the electron beam, according to the Smith-Purcell relation

$$\lambda = \frac{L}{|n|}\left(\frac{1}{\beta} - \cos\theta\right). \tag{1}$$

The second type is an evanescent wave, whose wavelength is longer than that of the lowest Smith-Purcell band so it is non-radiative and only scatters off the ends of the grating. The evanescent wave has a phase velocity that matches the electron beam velocity, but its group velocity is either parallel or anti-parallel to the electron beam depending on the grating parameters. For the case of negative group velocity, operation is very much like a backward-wave oscillator. The wave grows as it travels upstream, so each new electron entering the grating encounters a more intense field and interacts more strongly. In this manner, the evanescent wave bunches the electron beam and provides its own feedback. For sufficiently high electron beam current, the growth rate of the field overcomes losses at the ends of the grating and the field grows exponentially. In a BWO, the evanescent wave is collected as the output, but for an SPFEL, the evanescent wave bunches the electron beam strongly enough to excite higher harmonics whose wavelengths fall in the allowed Smith-Purcell bands. This way various wavelengths can be produced in the same device. The evanescent wave has been predicted for years, but only observed in recent experiments.

## EXPERIMENT DETAILS

Experiments were conducted at Vermont Photonics. The apparatus used in these experiments is based on a scanning electron microscope (SEM) design [12]. The path of the electron beam is shown in Figure 1. The electron beam originates at a lanthanum hexaboride ($LaB_6$) thermionic cathode. The emission current level is controlled by a cathode heater and a wehnelt (or extractor) potential bias. The beam is accelerated by an anode, and passes through two focusing lenses to adjust the Rayleigh range and depth of focus. The position of the beam over the grating in the plane perpendicular to the direction of travel is controlled by two steering coils (not shown). In typical experiments,

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* heather.l.andrews@vanderbilt.edu

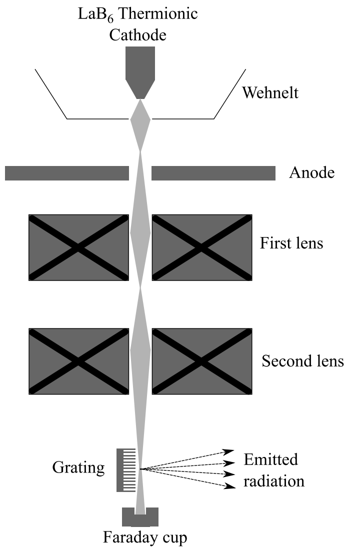

Figure 1: Electron beam path. The electron beam originates at a LaB$_6$ thermionic cathode. The current can be controlled either by heater current, or by wehnelt bias voltage. Possible beam energies for the system range from 26 - 38 kV, and beam currents range from 0.3-17 mA. The beam is focused by two sets of magnetic lenses and is directed perpendicular to the direction of travel by two sets of coils not shown.

a voltage and current are selected, then the steering coils and lenses are adjusted to position the beam over the grating to maximize output radiation. The collection optical path for output radiation is shown in Figure 2. Radiation is collected and collimated by an off-axis paraboloidal mirror and directed through the output window of the vacuum chamber. The location of the mirror can be adjusted so that radiation from different parts of the grating, upstream, middle or downstream with respect to the electron beam, can be collected. The collimated output radiation is directed into a Michelson fourier-transform infrared (FTIR) interferometer. The output is finally directed into a composite silicon bolometer. The typical voltage range of experiments ran from 26-34 kV. The apparatus can produce 0.3 - 17 mA beam current, but all measurements presented here were taken at 5-6 mA.

The evanescent wave was observed with two gratings, both of which were equipped with smooth vertical side walls extending at least 500 $\mu$m above the grating surface [13]. Both gratings have a rectangular profile, and are fabricated out of copper. The first, denoted W-048, was a design frequently used at Vermont Photonics before this collaboration. The grating denoted VBLT-001 was designed to maximize the evanescent wave output using the three-dimensional theory including grating sidewalls developed at Vanderbilt [8]. Grating parameters are shown in Table 1.

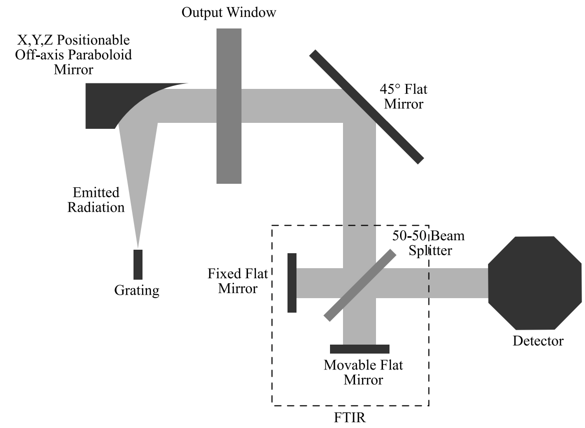

Figure 2: Path of emitted radiation. Radiation produced by the grating is collected by an off-axis paraboloidal mirror, directed out of the vacuum chamber, through a Michelson FTIR interferometer and into a composite silicon bolometer. In this diagram the electron beam runs into the page above the grating.

Table 1: Grating parameters.

| Grating | W-048 | VBLT-001 |
|---|---|---|
| Period | 157 $\mu$m | 157 $\mu$m |
| Slot width | 25 $\mu$m | 48 $\mu$m |
| Slot depth | 122 $\mu$m | 228 $\mu$m |
| Length | 40 periods | 40 periods |
| Width | 610 $\mu$m | 500 $\mu$m |

Though the total range of possible Smith-Purcell emission wavelengths range from 295 - 605 $\mu$m for both W-048 and VBLT-001, only a small fraction of this wavelength range, corresponding to the angle of observation, is detected. The relatively narrow width of the detected Smith-Purcell band reflects the limited angular acceptance of the collection optics.

## RESULTS AND DISCUSSION

Spectra taken with the W-048 grating at a variety of beam energies are shown in Figure 3. Each trace plotted is the point wise average of at least 3 separate spectra. The height of each curve has been scaled to the maximum power through the interferometer. The scaled curves give a better comparison of the relative intensity of the spectra. The Smith-Purcell band around 90 degrees appears between 460-580 $\mu$m, and the evanescent wave is clearly visible between 630 - 700 $\mu$m for the different beam energies. The wavelengths observed agree well with those predicted by the theory, as summarized in Table 2. Both the peak of the spontaneous radiation and the evanescent wavelength shift to shorter wavelength for higher voltages, as expected.

A plot of the dispersion relation for grating VBLT-001 predicted by the two-dimensional theory [3] and the

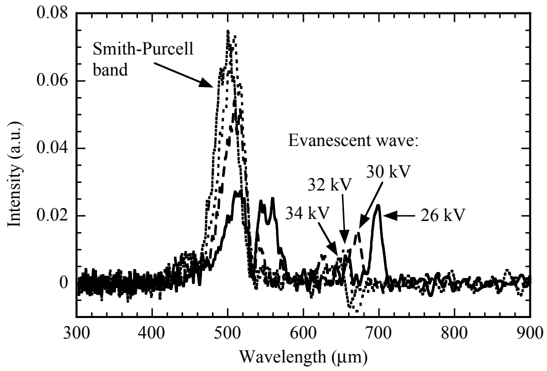

Figure 3: Spectrum showing Smith-Purcell radiation between 460-580 $\mu$m and evanescent wave between 630-700 $\mu$m for four voltages of grating W-048.

three-dimensional theory for gratings with sidewalls [8], is shown in Figure 4. The intersection point of the dispersion curve and beam line indicates the wavelength of the evanescent wave. The group velocity of the wave is given by the slope of the dispersion curve at the intersection. For this grating the 2D theory predicts a wave with wavelength around 900 $\mu$m and positive group velcity, meaning it travels parallel to the electron beam. The 3D theory predicts a wavelength of about 790 $\mu$m and a negative group velocity, meaning the wave travels opposite to the electron beam, a remarkable difference from the 2D theory.

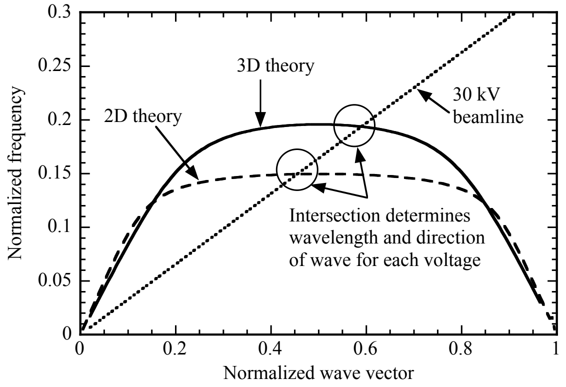

Figure 4: Theoretical predictions for the dispersion relations for grating VBLT-001 by the 2D theory and 3D theory with walls. The intersection of the beam line and dispersion relation predict the wavelength and group velocity of the evanescent wave. The 2D theory predicts a longer wavelength and opposite group velocity compared to the 3D theory.

Spectra collected from VBLT-001 at 30 kV at different ends of the grating are shown in Figure 5. The Smith-Purcell band appears between 400-580 $\mu$m, and the evanescent wave appears around 770 $\mu$m. The solid line is the spectrum taken with collection optics positioned at the upstream end of the grating, and the dotted line is the spectrum taken from the downstream end of the grating. As expected, the evanescent wave is much stronger at the upstream end of the grating, indicating it is traveling opposite to the electron beam and scattering off the upstream end of the grating. The observed wavelength also agrees well with the 3D theory.

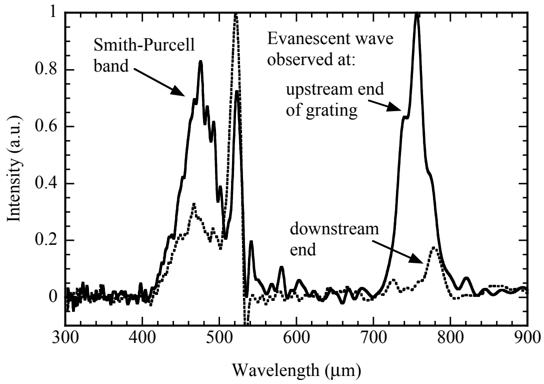

Figure 5: Spectra taken at 30 kV for two different positions of the collection optics. The solid line was taken with the optics tuned to collect radiation from the upstream end of the grating, while the dotted line was taken at the downstream end of the grating. As predicted by the 3D theory in Figure 4, the evanescent wave is much stronger at the upstream end of the grating, and appears at a wavelength near 790 $\mu$m.

Figure 6 shows spectra collected from VBLT-001 at 26, 30 and 34 kV with collection optics positioned at the downstream end of the grating. The Smith-Purcell peak occurs between 420-580 $\mu$m, and the evanescent wave is visible between 770-810 $\mu$m. For 34 kV, there is also a peak at 375 $\mu$m, which corresponds to the second harmonic of the evanescent wave. This peak occurs only when the evanescent wave is particularly strong, and at a wavelength which

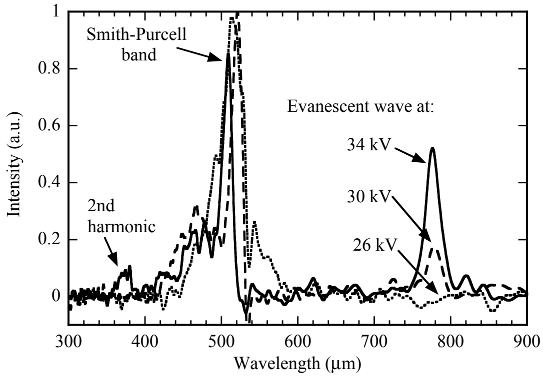

Figure 6: Spectra taken at three beam voltages for grating VBLT-001. The Smith-Purcell band appears between 420-580 $\mu$m and evanescent wave between 770-820 $\mu$m. In the 34 kV spectrum there is another peak near 375 $\mu$m, the second harmonic of the evanescent wave. This peak indicates bunching of the electron beam by the evanescent wave.

corresponds to an angle outside the range of the collection optics. The presence of this peak suggests that there is strong bunching of the electron beam by the evanescent wave, and that the second harmonic has been excited and is radiating enough to be detected.

A comparison of predicted and observed wavelengths of the evanescent wave for two gratings over a range of electron beam energies is shown in Table 2. The predictions were made using the three-dimensional model including grating walls [8].

Table 2: Comparison of predictions and observations for gratings W-048 and VBLT-001 at four different operating voltages.

| Voltage | W-048 | | VBLT-001 | |
|---|---|---|---|---|
| | theory | obs. | theory | obs. |
| 26 kV | 688 $\mu$m | 697 $\mu$m | 805 $\mu$m | 809 $\mu$m |
| 30 kV | 659 $\mu$m | 668 $\mu$m | 797 $\mu$m | 778 $\mu$m |
| 32 kV | 654 $\mu$m | 647 $\mu$m | 795 $\mu$m | NA |
| 34 kV | 640 $\mu$m | 637 $\mu$m | 792 $\mu$m | 776 $\mu$m |

## CONCLUSIONS AND FURTHER WORK

We present the first experimental observation of the evanescent wave in a SP-FEL. This wave is predicted by both analytic theories and particle-in-cell code simulations. The wavelengths observed agree well with those expected from the most recent three-dimensional theory for a grating with flat, vertical sidewalls. The next step in this project will be to confirm these measurements and optimize the collection optics to detect radiation emitted at 62 degrees, the angle at which the observed second harmonic is emitted according to the Smith-Purcell relation. It will also be desirable to design a grating with high gain for which the second harmonic is emitted nearer to 90 degrees.

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