FURTHER OBSERVATIONS OF EVANESCENT WAVES IN A SMITH-PURCELL FREE-ELECTRON LASER

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Abstract

We present further experimental observations of evanescent waves in a Smith-Purcell free-electron laser (FEL) with vertical conducting walls bounding the sides of the grating. Evanescent waves are the basis of oscillator operation of the Smith-Purcell FEL. They have group veloctiy anti-parallel to the electron beam and for sufficiently high current, provide feedback to bunch the electron beam.A grating with side walls supports multiple transverse modes; we have observed emission from the two lowest such modes. The observed wavelengths and wavelength shift with changing operating voltage agree with theoretical predictions.

INTRODUCTION

There is a long-standing interest in developing narrow-band tunable sources in the far-infrared, or terahertz (THz), region of the spectrum 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 two-dimensional theory of operation of a Smith-Purcell FEL (SPFEL) has developed to a point where theories [3, 4, 5] from separate institutions agree well with each other, with simulations performed with particle-in-cell (PIC) codes such as MAGIC [6, 7], and with experiments using a sheet beam [8, 9]. 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 [10, 11]. These agree well with PIC code simulations [12, 13, 14] and experiments [15]. In this paper we present further observations of evanescent waves from an SPFEL and show preliminary data on the effect of transverse position of the electron beam.

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THEORETICAL PREDICTIONS

In the SPFEL, an electron beam travels close to the surface of a conducting metallic grating, exciting two types of radiation. The first is spontaneous Smith-Purcell radiation [16], whose wavelength depends on grating period L, normalized electron beam energy $\beta = v/c$, order number of the radiation n and angle of observation, θ 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 but can be collected when it scatters at the ends of the grating. The phase velocity of the evanescent wave matches the electron beam velocity, but its group velocity can be 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, called the start 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.

The 2-D theory for the SPFEL has been well developed and confirmed both by PIC code simulations and experiments. The 3-D theory including grating sidewalls has also demonstrated excellent agreement with experiments. The 3-D theory with an infinitely wide open grating shows that when a narrow electron beam is used, diffraction effects make the device much less efficient than in the other two cases. The presence of sidewalls confines the optical mode, effectively increasing the interaction with a narrow electron beam, and practically, improves the collection efficiency of the spontaneous Smith-Purcell radiation.

Figure 1 shows the dispersion plane for the grating used in these experiments. Dispersion curves for the 2-D theory and the first four transverse modes, denoted r=0,1,2,3, predicted by the 3-D theory including sidewalls are shown along with the 34 kV beam line. Notice that the 2-D theory predicts a forward wave and a much longer wavelength than the 3-D theory. The 3-D theory predicts only backward evanescent waves, with a distinct wavelength difference between the r=0 and higher transverse modes.

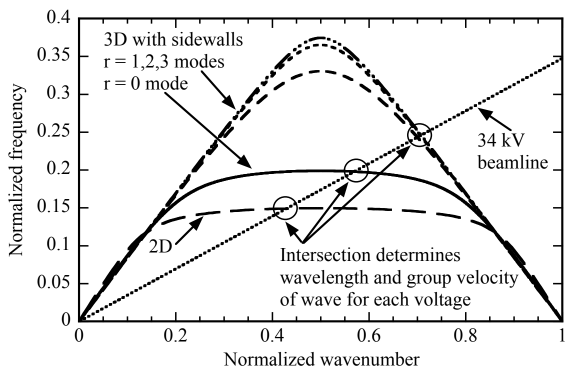

Figure 1: Dispersion curves predicted by 2-D theory and lowest four transverse modes from 3-D theory including sidewalls are shown with 34 kV beam line. The 2-D theory predicts a long wavelength forward wave while the 3-D theory predicts shorter wavelength backward waves.

We have also predicted the start current for the r=0 mode, shown in Figure 2. This value is close to actual operating parameters, but does not include losses. The start current for the r=1 mode is around 350 mA at 34 kV. Despite this very large value, the mode should be present because the evanescent modes are always excited by the electron beam. Observation of the mode well below start current is a matter of collection efficiency. However, only above the start current do modes grow exponentially and bunch the electron beam.

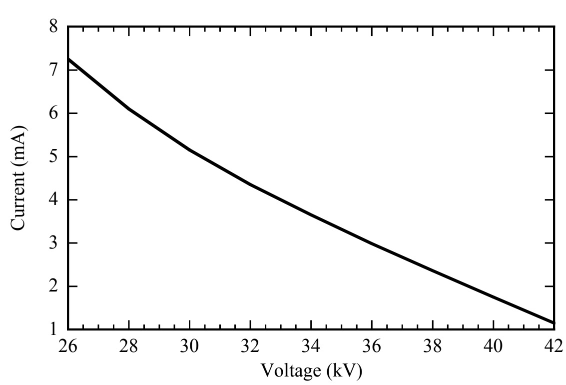

Figure 2: Start current for the r=0 mode predicted by the 3-D theory with side walls without losses as a function of beam voltage. Experiments discussed here operated in this current range.

EXPERIMENT DETAILS

Experiments were conducted at Vermont Photonics. The apparatus used in these experiments is based on a scanning electron microscope (SEM) design [17] as shown in Figure 3. The electron beam originates at a lanthanum hexaboride

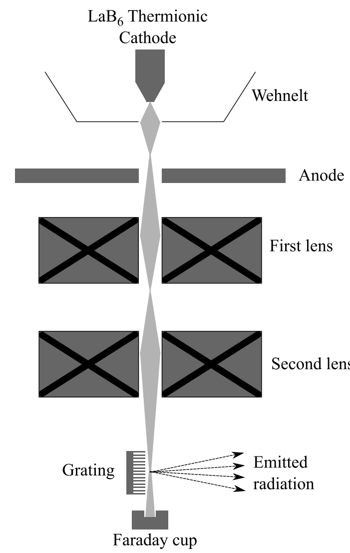

Figure 3: Electron beam path. The electron beam originates at a LaB_6 thermionic cathode. The current can be controlled either by heater current, or by wehnelt bias voltage. Possible beam energies for the system range from 26-38 kV, and beam currents range from 0.3-17 mA. The beam is focused by two sets of magnetic lenses and is directed perpendicular to the direction of travel by steering coils (not shown).

(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 longitudinal position 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). The typical voltage range of experiments is 26-34 kV. The apparatus can produce 0.3-17 mA beam current, but all measurements presented here were taken at 5-10 mA. The beam radius is estimated from aperture measurements and simulations to be about 25 μm, implying an emittance of about 0.4 mm-mrad. In typical experiments, a voltage and current are selected, then the steering coils and lenses are adjusted to position the beam over the grating to maximize total output radiation. From damage patterns in the grating observed after runs, we infer that for most cases the beam skims the grating.

Radiation emitted by the grating is collected and collimated by an off-axis paraboloidal mirror and directed through the output window of the vacuum chamber. The center of the mirror can be moved along the length of the grating by an external motor 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 with a 200 μm long-pass filter. Collected interferograms were transformed using the Mertz method fast Fourier-transform technique [18]. They are normalized to the area under the spectrum, so that spectra taken under different conditions can be accurately compared. All presented data are the average of two or three spectra taken under identical conditions.

The gratings used in these experiments have a rectangular profile, are fabricated out of copper and were equipped with smooth vertical copper side walls extending at least 500 μm above the grating surface [19]. The grating figure (period 157 μm, slot width 48 μm, slot depth 228 μm, length 50 periods, width 500 μm) was designed to maximize the evanescent wave output using the 3-D theory including grating sidewalls [10]. Three instances of this grating design were used. Unfortunately due to fabrication issues, the actual parameters varied along a given grating and from one to another by about ± 10 μm.

The first order Smith-Purcell wavelengths emitted from this grating into the full 180° range are 295-605 μm. Only a small fraction of this wavelength range, corresponding to the $\pm 20°$ acceptance angle of the collection optics, is observed. All spectra presented were taken at the upstream end of the grating.

RESULTS AND DISCUSSION

The most unexpected observation during these experiments was that of the r=1 transverse mode, shown with the r=0 mode and Smith-Purcell peak in Figure 4. It was originally thought that because of the large group velocity on the r=1 mode that it would have little interaction with the electron beam and be to weak to observe. It may be the case that the large group velocity instead acts to transport more power from this mode to the end of the grating where it is collected.

As expected, the wavelength of the r=1 mode shifts to shorter wavelength for higher operating voltages as shown in Figure 5. Also note that the strength of the wave does not change over the range of voltages shown. This is likely the case because the group velocity is nearly constant over this voltage range, so there should not be any change in interaction with the beam.

Figure 6 illustrates the remarkable agreement of the observed and predicted wavelengths for the VBLT-001 grating. Data points with error bars indicate the complete range of observed wavelengths at each voltage and the dotted lines above and below the curves denote the range of wavelengths predicted for the range of actual grating parameters used.

We began to explore the effect of changing the transverse

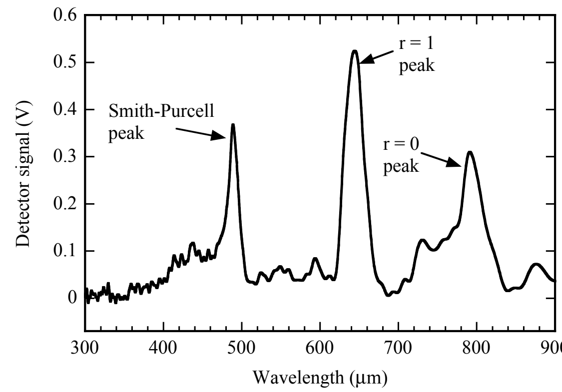

Figure 4: Both the r=0 (645 μm) and r=1 (790 μm) transverse evanescent modes are observed here, along with the Smith-Purcell peak (420-500 μm). The spectra were taken at 34 kV.

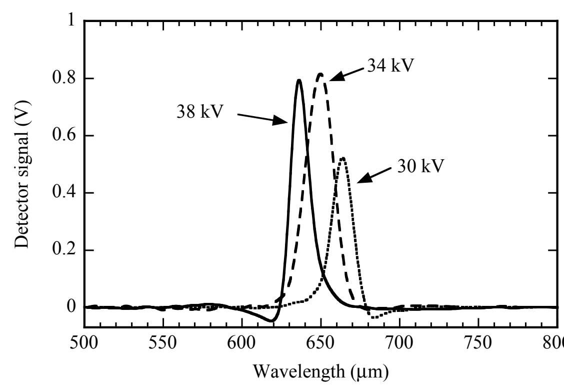

Figure 5: Observed wavelengths for the r=1 mode shift to shorter wavelength with increasing voltage as expected. The intensity is nearly constant across the voltage range.

location of the electron beam above the grating. As seen in Figure 7, the spectra for two beam locations are distinct. This behavior of changing spectral components with shift in beam location was reproducible, but it was nearly impossible to quantify the absolute location of the electron beam for any given spectrum. Evidently we are exciting different modes preferentially by moving the electron beam because the modes have different transverse structure. Further work is needed to explore this behavior.

CONCLUSIONS AND FURTHER WORK

Though we have observed both the r=0 and r=1 transverse modes, shown excellent agreement between predicted and observed wavelengths, and begun to explore the implications of beam location over the grating, we have not observed oscillation of an SPFEL. In the future we plan to use gratings with a more consistent figure and explore designing a grating with the second harmonic emitted closer to 90 degrees to further this effort.

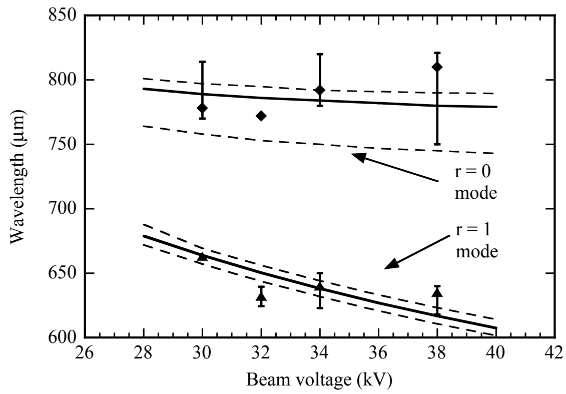

Figure 6: The observed wavelengths for both the r=0 and r=1 modes agree well with predictions from the 3-D theory with sidewalls. Error bars on the data points indicate the entire range of observed wavelengths. Dotted lines above and below the solid lines indicate the range of predicted wavelengths based on the variation of actual grating parameters used.

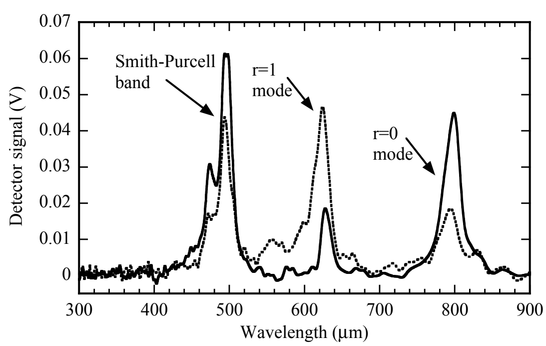

Figure 7: Changing the transverse position of the electron beam with respect to the grating side walls results in changes the observed spectrum. Initial observations hint that beam position might be used to selectively drive different transverse evanescent modes.

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