SUPERLINEAR CURRENT DEPENDENCE IN A GRATING-BASED TUNABLE THz SOURCE

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Abstract

Recent experiments have demonstrated a strongly superlinear dependence of Smith-Purcell radiation on electron-beam current, similar to previous observations. This results in an increase of output power of up to 100 times that expected from a linear current dependence, which makes the device a useful source of THz radiation. This behavior strongly suggests superradiant effects caused by bunching of the electron beam on length scales on the order of the optical wavelength. However, the observed spectrum of emitted radiation remains unchanged over the entire current range. For this to be consistent with a superradiant mechanism, the bunching frequency must be smaller than the spectrometer resolution, which is on the order of 10 GHz. The magnitude of such bunching would increase with increasing current to account for the large power increase. The modulation might be caused by virtual-cathode oscillations or other electron-beam instabilities. To test this mechanism, we can look for peaks in the output radiation spectrum with a higher-resolution spectrometer or measure the GHz modulation on the electron beam directly.

INTRODUCTION

For many years grating based free-electron lasers (FELs) have gained attention as a potential compact, tunable source of far-infrared or terahertz (THz) radiation for use in fields such as biology, chemistry and materials science [1, 2]. The discovery by the Walsh group at Dartmouth College a decade ago, that output from a grating based FEL increased non-linearly with current, spurred this research [3, 4], but remains unexplained. Since the Dartmouth discovery, the theory of operation of a so called Smith-Purcell FEL (SP-FEL) has developed [5, 6, 7, 8] and at least one unsuccessful attempt was made to reproduce the Dartmouth results [9]. Recent experiments, conducted at Vermont Photonics, reproduce the Dartmouth results, and have produced the first observation of the predicted evanescent wave and possible evidence for electron bunching due to that wave [10]. While the theory agrees very well with the observed evanescent wave, it does not describe the superlinear current dependence.

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SUMMARY OF THEORY

The SP-FEL is composed of an electron beam passing close to a metal grating. The first type of radiation produced by this interaction 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 θ measured from the direction of the electron beam according to the 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, 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 time. In this regime, the evanescent wave bunches the electron beam strongly enough to excite higher harmonics whose wavelengths fall in the allowed Smith-Purcell bands.

Theory also predicts that for an unbunched beam traveling over a grating, output power should depend linearly on the beam current. If the beam is bunched to a length shorter than the output wavelength, the power will depend on the square of the current, and for a train of bunches, the spectrum will shift so it is peaked at harmonics of the bunching frequency [12]. If the bunching frequency is high, as for the evanescent wave, the harmonics are widely spaced and only a few harmonics appear in the Smith-Purcell band. If the bunching frequency is low, the harmonics are closely spaced and may not be distinguishable at low spectral resolution.

EXPERIMENTAL SET UP

Experiments were conducted at Vermont Photonics using a design based on an electron microscope column [13]. As shown in Figure 1, the beam is emitted from a LaB_6

thermionic cathode, where the current level is controlled both by the cathode heater and by the Wehnelt or extractor voltage. The beam is accelerated by an anode, and passes through two focusing lenses to adjust the focal point 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). After passing over the grating, the beam is dumped into a Faraday cup. 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 output radiation. The typical range of useful experimental parameters is shown in Table 1.

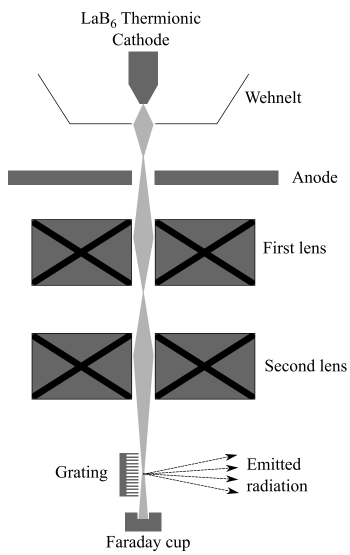

Figure 1: The electron beam originates at a LaB_6 thermionic cathode. The current can be controlled either by heater current, or by wehnelt bias voltage. Possible beam energies for the system range from 26 - 38 kV, and beam currents range from 0.3-17 mA. The beam is focused by two sets of magnetic lenses and is directed perpendicular to the direction of travel by two sets of coils not shown.

Table 1: Typical parameters used in experiments at Vermont Photonics.

Beam energy	26 - 38 kV
Beam current	0.3 - 15 mA
Beam waist	44 μm
Grating length	40 or 55 periods
Grating width	600 or 500 μm
Grating period	157 or 114 μm
Slot width	25 μm
Slot depth	120 or 76 μm

Gratings used in these experiments have a rectangular profile and are machined out of copper. They are also all bounded on the sides by smooth vertical metallic walls, similar to geometries used at Dartmouth [14]. Radiation emitted from the grating is collected and collimated by an off-axis paraboloidal mirror, and directed through viewport of the vacuum chamber. From there it is either directed through at Michelson fourier-transform infrared interferometer and into a composite silicon bolometer, or focused directly into the bolometer. The optical beam path including the interferometer is shown in Figure 2.

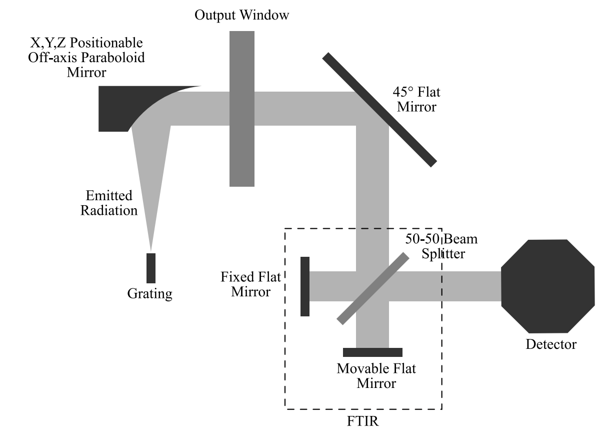

Figure 2: Optical beam path including interferometer. Radiation produced by the grating is collected by an off-axis paraboloidal mirror, directed out of the vacuum chamber, through a Michelson FTIR interferometer and into a composite silicon bolometer. In this diagram the electron beam runs into the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

OBSERVATIONS

While the Vermont Photonics experiments do include observations of the evanescent wave, the data presented here were all taken in absence of the evanescent wave. Perhaps more importantly, this behavior persisted regardless of whether the evanescent wave was strong enough to observe or not.

A typical curve of output power as a function of current is shown in Figure 3. We observe that power depends on current linearly below about 1.2 mA, then depends of current cubed until about 8 mA, then rolls off to almost linear, and begins to drop at very high current. At high currents a roll off or power saturation was typical. However, beyond that results varied and we disregard the high current drop in this discussion. The transition from linear to superlinear dependence always occurs between 0.3-1.5 mA. In the superlinear region, dependence on current ranges from current cubed to current to the ninth power. The exact exponent varies from day to day, but is generally repeatable from one measurement to the next, and qualitatively this behavior is very reproducible.

Qualitatively similar behavior was observed regardless of whether the current was adjusted by changing the cathode heater current or the wehnelt (or extractor) bias volt-

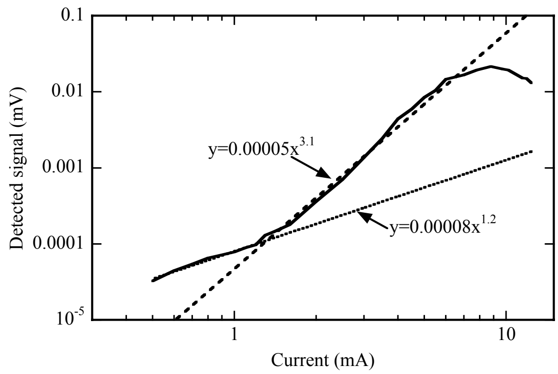

Figure 3: Typical curve of detected signal as a function of current. This plot shows a small linear region below 1.2 mA, then a steep region up to 8 mA, then the signal increase rolls off. Both the linear (dotted line) and super linear (dashed line) regions have been fit as shown.

age. In Figure 4 there are two curves of power versus current. The solid lines were obtained by fixing the wehnelt potential and changing only the heater current. The dash-dotted lines were obtained by fixing the heater current and changing only the wehnelt potential. Fits to both curves for both the linear (dotted lines) and superlinear (dashed lines) regions are marked. Notice that power increases to around 100 times more than the extrapolated linear fits indicate.

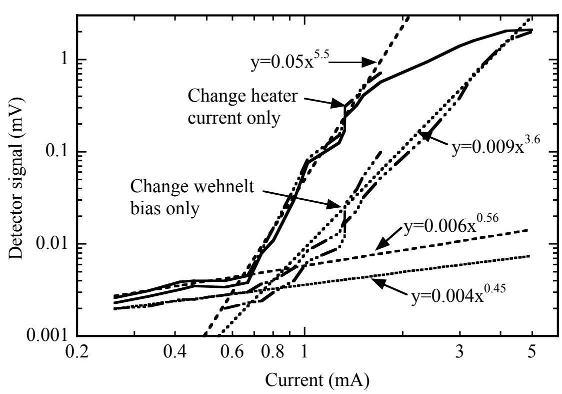

Figure 4: The solid curve shows the emitted power as a function of current when only the heater current is adjusted. The dot-dashed curve shows emitted power as a function of current when only the wehnelt bias voltage is adjusted. Both curves exhibit a linear region at low current and a region of superlinear current dependence at higher current. Curve fits to both these regions are marked. At 5 mA the emitted power is a factor of 100 above the extrapolated linear current fit.

The most striking thing about all these observations is that the spectrum remains constant over the range of current. Even at the highest currents, the spectrum agrees exactly with spontaneous Smith-Purcell radiation, and has the expected dependencies on grating period, electron beam energy and angle of observation. This nonlinear behavior is observed regardless of whether the evanescent wave is present or not. The current at which this nonlinear increase begins is always between 0.3 - 1.5 mA. The fact that it is never orders of magnitude away from this current range, no matter what grating is used, suggests that this behavior is due to an electron beam phenomenon rather than an interaction with the grating.

DISCUSSION

The results suggest that the nonlinear current dependence could be caused by a superradiance effect due to bunching in the beam. If the bunching frequency is close to the frequency of the emitted radiation, one would expect to see power growth only for wavelengths near the bunching frequency. For bunching at a frequency less than the emitted radiation, one would expect to see enhancement at a series of wavelengths corresponding to harmonics of the bunching frequency. The spectrum is observed to be smooth to within the resolution of the spectrometer (6 GHz), so any beam bunching must occur at a frequency lower than this. If bunching occurs at 6 GHz, and frequencies of around 0.5 THz are enhanced, the bunching is affecting the 100th harmonic. One way to test for bunching of this sort would be to examine the spectrum with a very high resolution spectrometer, similar to experiments performed at MIT [15].

The observation of a smooth spectrum rules out the possibility that bunching is caused by the evanescent wave or orotron feedback on the Smith-Purcell radiation itself. Evanescent wave bunching would cause widely spaced harmonics, and we calculate that gain on orotron modes in the vacuum chamber would be extremely low. Another possible cause of bunching could be some variety of cathode oscillation, such as the virtual cathode oscillations observed at the UMER cathode [16]. Generally these oscillations are $<$ 10 GHz, as required by our observations. The variation of the enhancement with current could be explained by increasing oscillations at higher current. Similarly at the highest currents, the power roll off could indicate that maximum bunching has been reached.

Possible ways to test for bunching of the beam over the grating include transition radiation and loop antennas. We calculate that transition radiation would be too weak to detect. The apparatus is also limited in that the electron beam melts any intercepting diagnostics. The best measurement techniques left are a loop antenna or a Rogowski coil.

CONCLUSIONS

We have observed that Smith-Purcell radiation from a grating can have a superlinear dependence on electron beam current. The existing SP-FEL theory [7] describes a distinctly different behavior, and cannot account for this phenomena. We propose that the cause is an electron beam instability that leads to a density modulation over the grating. The authors welcome other possible explanations or suggestions for experiments.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge helpful discussions with J. H. Brownell and I. Haber.

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