

OBSERVATION OF COHERENT SMITH-PURCELL RADIATION USING AN INITIALLY CONTINUOUS FLAT BEAM

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Abstract

A few years ago, a new theory for producing coherent Smith-Purcell (SP) radiation from an initially continuous electron beam was proposed. It was two-dimensional (2-D), and it has been supported by 2-D particle-in-code simulations. We report here the results of an experiment using an intense continuous flat beam that confirms the theory. A maximum voltage of 100 kV was supplied by a single-shot pulsed-power source. The beam was typically 10 cm wide and a few mm thick, with a peak current of 150 A. The lamellar grating had twenty 2-cm periods, and radiation was observed at the predicted fundamental grating mode frequency near 4.5 GHz. The second and third harmonics were also observed at the angles predicted by the SP formula. Direct evidence for beam bunching was obtained using both a current monitor and a pick-up loop placed at the end of a groove. In general, good agreement between this experiment and theory is found.

INTRODUCTION

The origin of the work reported here was the FEL 2004 Conference in Trieste. At that meeting, a scientific dispute arose concerning the nature of coherent Smith-Purcell radiation [1]. On one side Andrews and Brau [2] (henceforth AB) had presented a model in which the gain was ultimately proportional to the cube root of the current I , while earlier work by Kim and Song [3] suggested a square-root dependence. Since both of the underlying theories were two-dimensional, it occurred to an author (JTD) that it should be possible to use a Particle-in-Cell electromagnetic code to distinguish between them. Another author (JG) had access to and experience with the commercially available Finite-Difference Time Dependent code MAGIC [4]. Since most of that experience had occurred in the microwave frequency range, and the AB theory can be expressed in terms of dimensionless variables, it was decided to simulate an S-P experiment at microwave frequencies. The results of the simulation [5] offered strong support to the AB model. In particular, the AB dispersion relation, the Floquet nature of the evanescent wave, and the operation as a backward wave operator were confirmed, as was the $I^{1/3}$ law for gain far above a threshold current. The evanescent wave has a frequency less than the lowest allowed S-P frequency. We remind the reader of the standard S-P relation

$$\lambda = \frac{L}{|n|} (1/\beta - \cos \theta)$$

that relates the wavelength λ , the relative electron velocity β , the grating period L , the angle between the beam and radiation θ , and the order of diffraction. The interaction between the beam and the evanescent wave causes the beam to bunch at the frequency of the wave, but of itself this can't generate SP radiation. However, if the bunching is strong enough, higher harmonics will occur in the current, and these may correspond to allowed S-P frequencies. When this occurs, coherent interbunch radiation is emitted at multiples of the evanescent frequency and only at certain well-defined angles. MAGIC simulations were also performed by Dazhi Li and collaborators [6] which corroborated the validity of the AB paradigm. Subsequently Kumar and Kim [7] presented an analysis which, although differing in detail, yielded results similar to those of AB. Theoretical work on a two-sided SP free electron laser was performed by Freund and Abu-Elfadi [8]. It thus appeared that a consensus among theories and simulations had arrived at a consistent picture of coherent S-P radiation.

Meanwhile, on the experimental side, a group at MIT had observed interbunch coherent S-P radiation at many harmonics using a pre-bunched 15 MeV beam [9]. Quite recently intrabunch coherent S-P radiation was measured for a beam of 28 GeV electrons, as a tool to determine bunch lengths [10].

Despite the consensus concerning the generation of coherent SP radiation from an initially unbunched beam, no experimental confirmation was available, except for an article by Skrynnik and collaborators [11]. This paper anticipates to some extent the work of AB, but it was performed at such low beam energies (5-7 keV) that only very high harmonics of the evanescent wave were SP allowed frequencies. Excluding it, no other confirmation of the AB picture was available until quite recently. At the FEL 2008 conference in Gyeongju, the Vanderbilt University – Vermont Photonics collaboration reported the first observation of the evanescent wave and its first harmonic [12].

Although the 3-D equivalent of the AB theory has not yet reached its final form, both theoretical and simulations have been reported. In particular the effect of putting sidewalks on the ends of the grooves has been studied theoretically by Andrews, Brau, and Jarvis [13], while Dazhi Li and collaborators have performed a 3-D simulation of such a set-up [14].

Among reasons as to why previous experiments had failed to observe coherent S-P radiation, two are evident. The theory and the simulations are 2-D, while most

experiments had used narrow round beams. Indeed, Kim and Kumar have argued that a flat or sheet beam is essential to good operation [15]. Secondly most experiments have used low current sources, which may have been too weak to reach the threshold current needed for gain. The estimation of this start current is difficult, since it depends on the rate of escape of the evanescent wave at the grating ends. This, in turn, is sensitive to the details of the grating geometry, at least in the simulations. The experiment reported here was designed to overcome these difficulties, by brute force if necessary. A fairly complete description of the experiment we proposed (prior to its execution) has appeared [16], and we refer the interested reader to it for more details.

DESCRIPTION OF THE EXPERIMENT

Although most of the interest in coherent SP radiation concerns the Terahertz frequency range, a demonstration experiment of the AB paradigm may be performed at any frequency. In our case, material for detecting radiation in the range of 5-20 GHz was available at the CESTA facility of the CEA. In addition, a pulsed power source with the capacity to generate high current existed. Under these circumstances, we chose to use a grating with the parameters listed in Table 1, which are essentially those used in our first 2-D MAGIC simulation.

Table 1: Experimental Parameters

Peak beam energy	85 keV
Peak current	150 A
Pulse duration	300 ns
Beam thickness	$\delta = 3\text{mm}$
Beam-grating distance	$e = 2\text{ mm}$
Beam width	10 cm
Grating period	$L = 2\text{ cm}$
Grating groove depth	$H = 1\text{ cm}$
Grating groove width	$A = 1\text{ cm}$
Grating width	10 cm
Number of periods	$N = 20$
External magnetic field	$B_z = 0.3\text{-}0.6\text{ T}$

Magnetic Field and Solenoid

The theories of AB and Of Kim and Kumar include only the interaction of the beam with the evanescent wave, whereas the simulations take into account all the electric and magnetic fields generated by the electron beam. If high currents are involved, quite large quasi-static fields will be generated. The fields in turn may drive the beam onto the grating causing considerable

beam loss. To avoid this, in the 2-D simulations a uniform axial field of 2 T was used to constrain the electrons to essentially 1-D motion. However, the MAGIC 2-D algorithm calculates the motion of the electrons in 3-D, and this in turn gives rise to small parasitic magnetic fields which do not occur in the purely 2-D TM modes used in the theory. In this experiment, a pulsed solenoid enclosing the grating and the cathode was used to provide a fairly uniform field. The intensity could be varied, and while below 0.3 T beam propagation was problematic, for fields between 0.3 and 0.6 T beam it was satisfactory. While the solenoid is an essential feature of our set-up, it prevents direct observation of the S-P radiation except at very small angles with respect to the beam. To observe the radiation a movable mirror was placed above the grating. It could be oriented so as to cause radiation emitted at an arbitrary angle to emerge in the forward direction. It could also be moved to any position along the grating.

Power Supply and Cathode

The power supply, built at CESTA, can furnish 1 kA at maximum voltage of 200 kV, for duration of 300 ns, within 10%. It is composed of a transformer with four 40 Ω coaxial cables, a 50 kV Blumlein system in the primary circuit, and a peaking spark gap in the secondary to reduce the rise-time. The particular arrangement of these cables increases their coupling and reduces losses in the common mode. In the primary circuit each of the two discrete-element Blumlein systems, arranged in parallel, has a trigatron that is fired by its own triggering circuit. Synchronization to within 5 ns of these two spark gaps permits a repetition rate up to 100 Hz. All operation was in single shot mode. A thin copper sheet placed on a dielectric substrate formed the cathode. Its width could be varied but most shots were made with the full 10-cm width.

Measurements of Current, Fields and Radiation

Several measuring devices were used to observe both the beam bunching and the radiation emitted, along with the voltage and current as a function of time throughout the pulse. A pick-up loop measured the transverse magnetic field at the end of a groove. The radiation emerging in the forward direction through a vacuum window was measured using a X-band horn for the second and third harmonic, and a S-band horn for the evanescent wave. A Rogowski coil on the return stalk measured the current.

In Figure 1, the cathode, grating and movable mirror are shown, along with the B-dot pick-up loop.

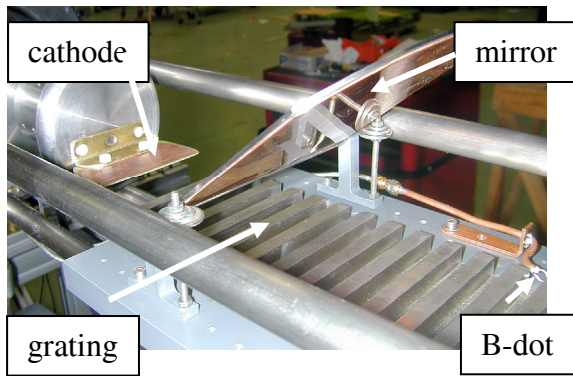


Figure 1: Photograph of cathode, grating, movable mirror and B-dot loop at end of groove.

The voltage and current forms for a typical shot are shown in Figure 2. Although the voltage could be easily varied, we were unable to vary the current appreciably.

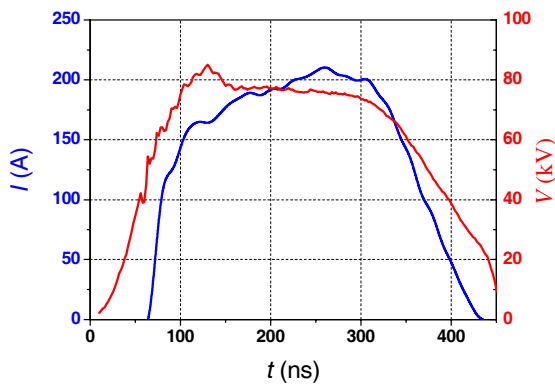


Figure 2: Current (blue) and voltage (red) wave forms for a typical shot.

PREDICTIONS OF THE AB THEORY

From our previous simulations, we show here the predictions of the 2-D AB theory for a nominal energy of 100 keV. In Figure 3 the dispersion relation is shown in red, as calculated and as determined empirically with MAGIC by installing a current source in a groove and driving it at a given frequency. A spatial Fourier transform gives two values for the axial wave number, whose sum is $K = L/2\pi$. The beam line $k = 2\pi \nu f$ is shown in blue, where ν denotes the beam velocity. The intersection occurs on the descending part of the dispersion relation, indicating a negative group velocity, i.e., a backward wave. Then using the S-P relation between wavelength and angle, we show in Figure 4 where we expect to see the second, third, and fourth harmonics of the evanescent wave.

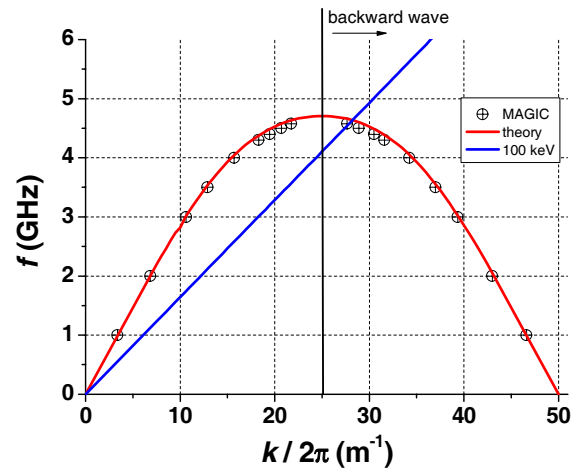


Figure 3: The 2-D dispersion relation for our grating according to the AB theory, along with the beam line.

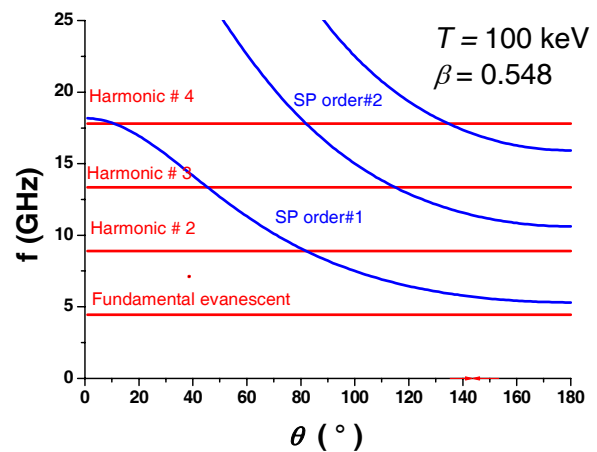


Figure 4: Angles at which coherent S-P radiation is expected to occur.

From Figure 4, we see that coherent radiation of the second harmonic at approximately 80° is expected, while the third harmonic should occur near 40° . If the mirror is oriented at 40° the second harmonic will be deflected into the forward direction.

EXPERIMENTAL RESULTS

The principal experimental results are displayed in Figure 5. The wave forms and their Fast Fourier Transforms are shown for the X-band horn (red), the S-band horn, (green) and the B-dot pick-up loop (blue) placed at the end of a groove. The waveforms are from a 12 GHz oscilloscope.

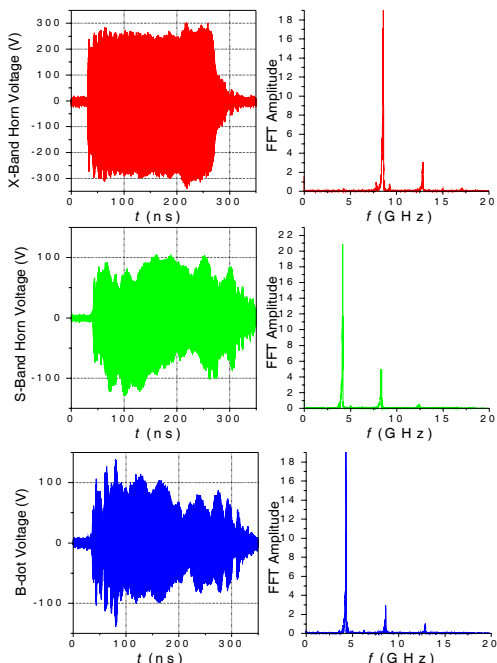


Figure 5: Waveforms and FFTs of the output from the X-band horn, the S-band horn, and the B-dot loop.

These measurements are consistent, and provide strong evidence in favor of the AB paradigm. Note that the second and third harmonics seen by the loop are seen also by the X band horn, while the S band horn sees mainly the fundamental and some second harmonic.

Finally we show in Figure 6 evidence for the evanescent nature of the grating wave. By moving the cathode vertically, we could vary the distance dak_y

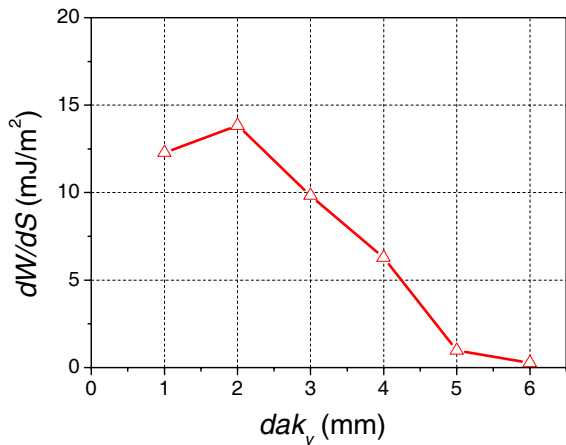


Figure 6: Variation of X-band horn energy signal as a function of height above grating top.

between the top of the grating and the cathode. The results are shown in Figure 6, where it is seen that the signal diminishes strongly when the beam is raised too far above the grating.

CONCLUSIONS

The results shown here confirm the validity of the 2-D AB theory provided a flat wide beam is used.

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