Expression of Interest -- Generating Coherent Smith-Purcell Radiation from a Flat Electron Beam via Self-Amplified Spontaneous Emission

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Statement of the Problem

One generates Smith-Purcell radiation (SPR) by passing an electron close to a metallic grating, as illustrated in Figure 1. The electron responds self-consistently to the electric field of its own image charge. As the electron passes along the grating, that field is time-dependent, and the electron therefore experiences a time-dependent, fully electromagnetic field. The field accelerates the electron, inducing it to radiate.

Smith and Purcell demonstrated the phenomenon in a 1953 experiment that produced incoherent light at visible wavelengths from an electron beam [1]. The phenomenon is therefore "old". It was motivated in the general context of exploring possible light sources, but due to the invention of the laser in 1960, it was not explored in great depth. However, due to recent advances in both scanning-electron-microscope and injector technology for the production of high-brightness electron beams, SPR has received renewed interest as an avenue toward generating tunable far-infrared light [2].

The observation of gain in recent SPR experiments has heightened interest in the phenomenon [3]. Whether the gain is exponential remains to be established. K.-J. Kim and S.B. Song theoretically explored the possibility that self-amplified spontaneous emission (SASE) is responsible for the amplification [4]. In this process the fundamental mode generated by, and having the same phase velocity as, the electron beam is evanescent, not propagating. Scattering of the fundamental mode at the grating surface results in propagating modes. Consequently SASE SPR proceeds differently from a conventional free-electron laser (FEL) interaction wherein the beam couples to a comoving propagating mode.

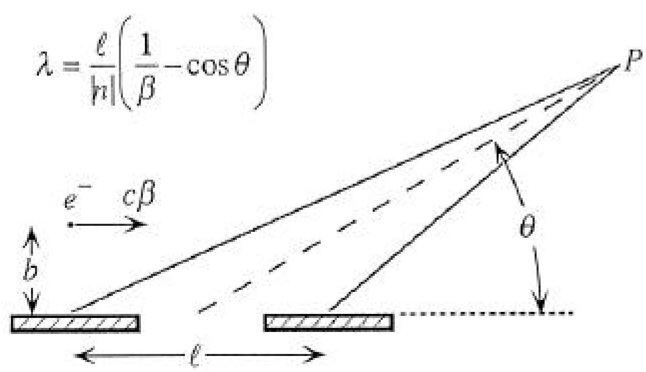

Figure 1. Generation of Smith-Purcell radiation. The wavelength of the light depends on the viewing angle. The light is therefore "tunable" via, e.g., use of a moveable, rotating mirror to sweep through a wide range of viewing angles.

Kim and Song model the electron beam as a sheet and then calculate the gain length of SASE SPR in terms of beam and grating parameters. In this Expression of Interest (EOI), we calculate the gain length associated with high-brightness flat beams that may plausibly be generated with the Fermilab/NICADD Photoinjector Laboratory (FNPL) injector given successful completion of FNPL flat-beam and bunch-compression studies. We show the potential for using FNPL beam to generate coherent, ps-pulse (and therefore high-peak-power) mid-to-far infrared (IR) light.

The wavelength of SPR depends on viewing angle *?*, beam velocity *ß* or energy *?*, grating length *l* and order number *n* in the manner

$$l = \frac{\ell}{|n|}\left(\frac{1}{b} - \cos q\right) \cong \frac{\ell}{|n|}\left[\frac{1}{2g^{2}} + 2\sin^{2}(q/2)\right].$$

In the forward (*?* = 0) direction the wavelength comprises the product of a Lorentz transform and Doppler shift, just as for a conventional FEL, implying the possibility of short-wavelength production with a high-energy beam. However, the SPR intensity in the forward direction is relatively very low, as indicated in Fig. 2 [5]. Consequently, tunability of SPR comes not so much from adjusting the beam energy, but much more so by adjusting the viewing angle using, e.g., a moveable, rotating mirror to sweep through a range of viewing angles.

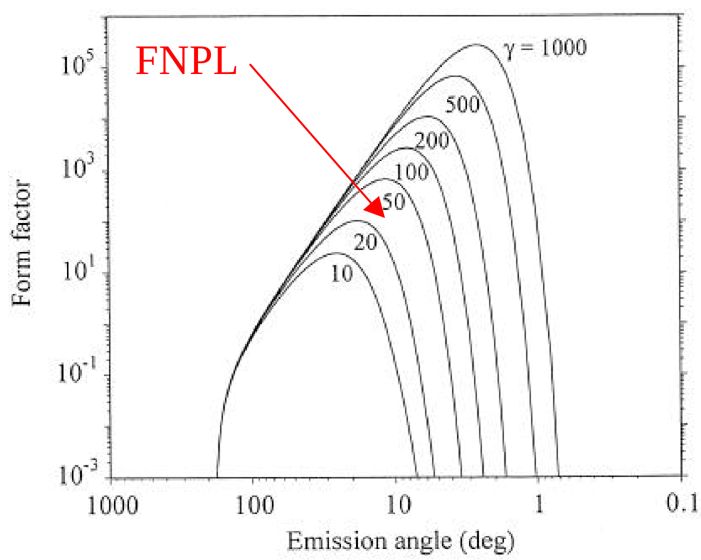

Figure 2. Angular form factor for strip-grating SPR vs. beam energy. For FNPL, ?~34.

Analysis

The maximum grating length for SPR experiments depends on the beam emittance, as is conceptually illustrated in Fig. 3, and is chosen to avoid spurious radiation and damage from beam impinging on the grating. The maximum grating length *L* in terms of the impact parameter *b* and beam parameters at the center of the grating (rms normalized emittance e_x, lattice beta function $ß_0$, and full beam half-width *X*) is [6]

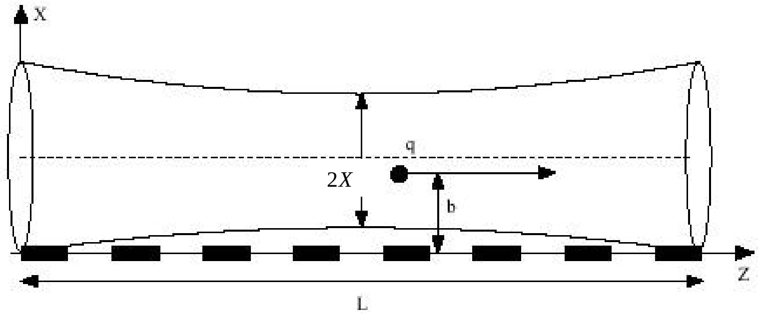

Figure 3. Strip-grating geometry showing the relationship between the maximum grating length L and the beam parameters.

$$L \cong \frac{g\, b^2}{e_x} \cong 5 b_0 \quad \text{for} \quad b = \sqrt{2}X .$$

Using this expression for the grating length, one can compare it to the gain length g by using the theory of Kim and Song to calculate L/g. For high-brightness beams with large charge per bunch, space charge can become significant. To avoid Debye screening of the electromagnetic field from the grating so that all of the electrons are, in principle, able to contribute to SPR, one would like to see the ratio of the Debye length to the full beam width be larger than unity:

$$\frac{\bar{l}_D}{2X} \cong \left[\frac{5\sqrt{5}}{24}\frac{I_A}{c}\left(\frac{g^2 s_z e_N \sqrt{R}}{q b_0}\right)\right]^{1/2}.$$

This expression is obtained by using the properties of a beam bunch corresponding to its "equivalent uniform ellipsoid" [7,8]; I_A denotes the Alfvén current (17 kA), c the speed of light, s_z the rms bunch length, $e_N = (e_x e_y)^{1/2}$ the geometric rms normalized emittance (with y denoting the long transverse axis of the beam), and $R = e_y/e_x = 1$ constitutes the measure of beam "flatness". Again using the equivalent uniform ellipsoid as a model of the bunch to estimate the gain length (the estimate is insensitive, within about ±15%, to the choice of model bunch structure, e.g., uniform vs. gaussian), the ratio of grating length to gain length is

$$\frac{L}{g} \cong \left[\frac{75p^2}{\sqrt{50}}\left(\frac{c e_{00}}{I_A l}\right)\left(\frac{q b_0^{3/2}}{g^{7/2} s_z \sqrt{e_N} R^{1/4}}\right)\exp\left(-\frac{4p\sqrt{5}}{l}\frac{\sqrt{b_0 e_N}}{g^{3/2}R^{1/4}}\right) - \left(\frac{5p b_0 \Delta_E}{g^2 l}\right)^2\right]^{1/2};$$

in which e_{00} is the grating's reflectivity of the fundamental mode, and $?_E$ is the full beam-energy spread. Of course, the ideal situation for achieving full coherence (saturation) is that this quantity be large compared to unity.

The FNPL photoinjector produces beam with ?~10 (from the gun) through ?~34 (maximum energy) [9]. A reasonable projection is that successful completion of the flat-beam and bunch-compression studies could yield a prescription for generating beam bunches with the following parameters: $q = 2$ nC, $e_N = 3$ µm, $s_z = 0.6$ mm, and $?_E = 0.01$. The grating should be inserted at a location where the beam waist can be made small; a reasonable expectation is that $ß_0 = 0.2$ m [10]. Taking the grating length to be $L = 1$ m and grating reflectivity $e_{00} = 0.95$ for the fundamental mode results in a plausibly achievable family of relationships between *L/g* vs. wavelength, with the flatness *R* parameterizing the family.

Figure 4 illustrates how the beam flatness *R* influences the importance of space charge as quantified by the ratio of Debye length to full beam width; increasing the flatness works to suppress space charge. Figure 5 illustrates how the ratio of grating length to gain length depends on wavelength (which in turn depends on grating geometry and viewing angle) and on *R*. A plausibly achievable beam flatness is *R* ~ 50-100, and the figures show that it is likewise conceivable to generate ~2-3 gain lengths along the grating with only modest influence from space charge. Consequently SASE-induced coherence appears to be achievable over the difficult-to-access wavelength range of ~20-200+ µm.

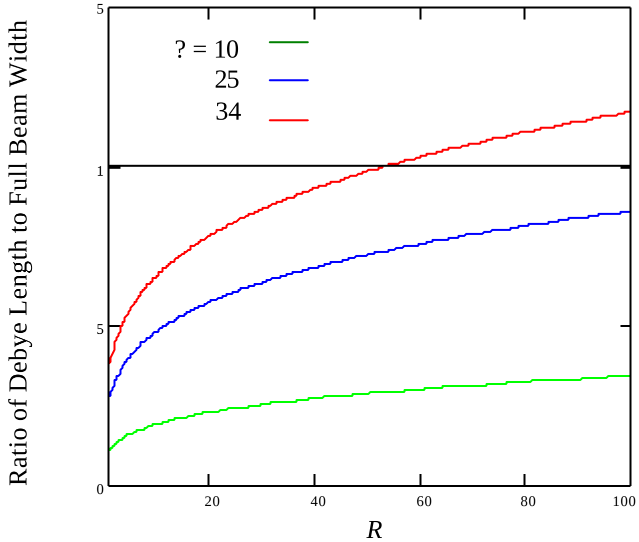

Figure 4. Importance of space charge decreases as beam flatness increases.

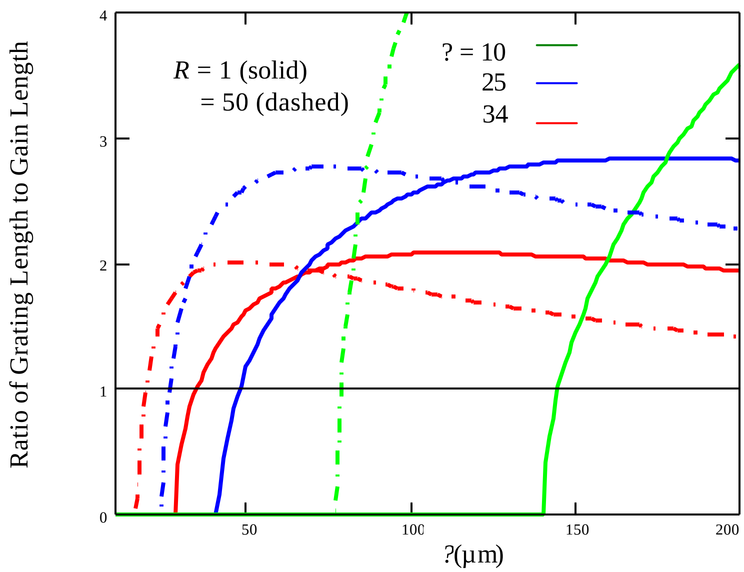

Figure 5. Number of gain lengths vs. wavelength for a 1-m-long grating and *R* = 1, 50.

The foregoing analysis suggests that, once the generation of high-quality, flat, compressed bunches has been perfected at FNPL, one can do an interesting SASE SPR experiments that take advantage of, and are ideally suited to, the flat-beam geometry. Such experiments would incorporate a metallic grating ~1 m in length which would support typically 2-3 gain lengths over a wavelength range of ~20-200+ µm. A rough estimate of the grating period ?$_g$ optimized for incoherent SPR is [6]

$$l_g \sim 2p\sqrt{\frac{5b_0 e_N}{g\sqrt{R}}}\ ,$$

which corresponds to a radiated wavelength of ?$_r$ ~ ?$_g$/? in the fundamental (n = -1) mode at the corresponding optimal viewing angle

$$q\,(\mathrm{deg}) \sim \frac{180}{p}\arccos\left(\sqrt{\frac{g-1}{g+1}}\right).$$

Given ?= 34, R = 50, and the cited beam parameters, these quantities are ?$_g$ ~ 0.7 mm, ?$_r$ ~ 21 µm, and ? ~ 14°. Of course, other wavelengths remain accessible at other viewing angles. Moreover, SASE would amplify essentially all of the wavelength range. A schematic, "cartoon" representation of intensity versus viewing angle appears in Figure 6, indicating even the longest IR wavelengths propagating orthogonally from the grid may be considerably amplified [5].

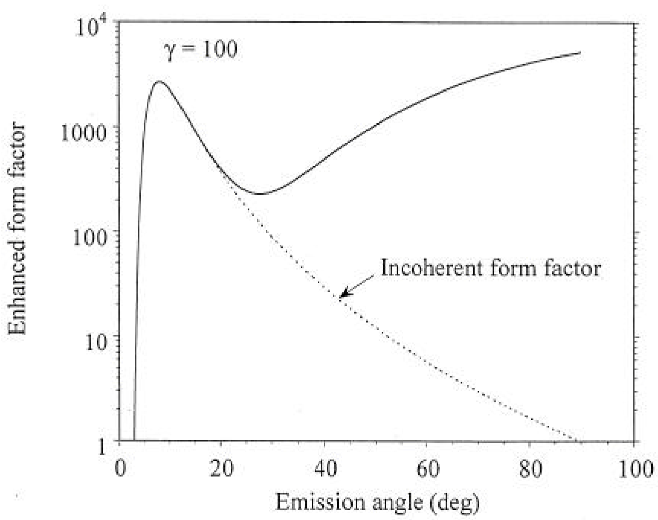

Figure 6. Schematic of coherent amplification of SPR versus viewing angle.

For wavelengths that are comparable to or larger than the rms bunch length (0.6 mm in our hypothetical example, which corresponds to viewing angles near 90º if the grating period is 0.7 mm), another mechanism for coherent amplification will surface, namely coherent synchrotron radiation (CSR). This mechanism provides the means to extend coherence to the far IR. Consequently, a light-source experiment like the one described herein can permit access to a wealth of beam-radiation-coupling physics as well as a broad band of tunable wavelengths corresponding to coherent, high-peak-power mid-to-far IR light.

Notional Requirements for Experiment

We believe the prospects for generating coherent Smith-Purcell radiation via SASE, and possibly also CSR, using high-quality flat beams from FNPL merit an experiment. Though the preceding analysis scopes the experiment and its capability, its design remains to be done. At minimum, the required hardware will encompass: (1) a metallic grating of length ~1 m and period ~1 mm with a mount that enables remote precision adjustment of the grating's position and tilt with respect to the beam, (2) an optical transport system consisting of precision-mounted, remotely moveable and tiltable mirrors, (3) a vacuum chamber to encompass both of these systems, and (4) a suitable array of mid-to-far IR detectors. The vacuum chamber will require ~1.5 m of space in the beamline at a location that corresponds to a low beta function.

The entire experiment is predicated on the availability of suitable beam from the FNPL injector, beam that is presently unavailable. Hence, the experiment must be viewed as a possible beneficiary that would use the results of a successful program of flat-beam and bunch-compression studies. It also requires a well-characterized beam for proper interpretation of the results. Detailed design of the experiment can take place in parallel with the flat-beam and bunch-compression studies. Once it is installed, we estimate that it will take ~200 hours of beam time to obtain a set of conclusive results. Detailed parametric studies may involve closer to ~1000 total hours of beam time, depending on progress and interest.

References

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