MULTIPLE SCATTERING-INDUCED MITIGATION OF COTR EMISSION FROM MICROBUNCHED ELECTRON BEAMS

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Abstract

The recently observed spontaneous microbunching formation in high brightness beams atoptical frequencies degrades the utility of optical transition radiation (OTR) beam profile monitors, and as such introduces a challenge to the diagnostics community. Here it is proposed to use an emittance spoiler foil, which would substantially reduce a parasitic background from the backscattered coherent optical transition radiation (COTR) in the OTRbeam profilemeasurement systems.

INTRODUCTION

The unexpected observation of coherent optical transition radiation (COTR) in many high brightness beam and free-electron laser laboratories around the world has provoked considerable interest [1-3]. This interest arises from two sources: an unknown mechanism for the self-organization of the beam on the optical length scale, and the fact that the introduction of coherence in the transition radiation dramatically limits the utility of the profile monitors needed to measure beam trajectories and properties. As other methods of profilometry based on scintillation have also shown collective effects that severely limit their use in high brightness and high intensity beams [4], the loss of OTR as a diagnostic tool presents serious challenges to the workings of next generation free-electron lasers and related machines.

There is considerable ongoing research directed towards understanding the optical microbunching [5], which is a challenging enterprise, as one must have models with predictive power at the level of the mean interparticle distance. To this point, estimates obtained in theoretical models thus far hold hope for the possible mitigation of the optical microbunching through use of the laser heater [6], and a significant progress has been demonstrated by recent LCLS results [7]. Nevertheless, a considerable uncertainty remains and thus there is a strong motivation to look at schemes that can directly mitigate the effects of optical microbunching in transition radiation (TR)-based diagnostics.

In this note, therefore, we examine the effects of multiple-scattering on coherence in the TR emission from the downstream side of a metallic foil. When the scattering angle of an electron in the foil becomes notably larger than the angular spreadin the single-particle TR emission spectrum (~ γ^{-1}, the inverse of the beam electron's Lorentz factor), the near field constructive interference between the individual electrons in a microbunch decreases, resulting in attenuation of coherent emission. At the moderate energies associated with the onset of COTR observation, one may easily induce a level of rms multiple scattering in the beam that greatly exceeds γ^{-1}, without introducing a significant changes to the electron beam transverse profile at the spoiler foil exit.

A similar effect has indeed been observed before at longer wavelengths, in the initial microbunching CTR experiments performed on FEL [8] and inverse FEL [9] systems, particularly in the experiments described in Ref. 9, where a very thick foil was employed, and a notable diminishing of the signal was expected. It has also been observed indirectly at the LCLS, where the COTR signal was degraded by a factor of 12 when an upstream foil (1 micron Al) was inserted [3], giving a larger downstream emittance.

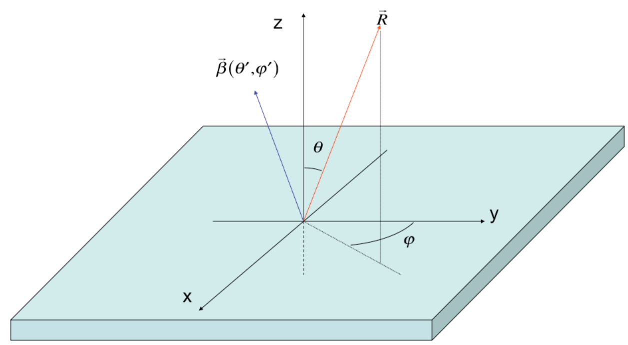

Figure 1: Geometry for specifying electron state leaving planar conducting surface, and observation angle for transition radiation.

In this paper we examine the theory of transition radiation due to a multiply scattered beam exiting a metallic foil. We derive general aspects of the theory, and apply these results to high brightness beams typical of those encountered in modern FEL facilities. Conditions, in terms of specified foil thickness in radiation lengths, for mitigation of the COTR phenomenon are given.

CTR FORM FACTOR CALCULATION

We begin our discussion by reviewing a transition radiations by electron beam as it exits the surface of an ideal conductor (the basic geometry is introduced in Fig. 1).Following fairly closely the treatment of Shibata [10], a spectral angular radiated power by an electron beam of N electrons is given by,

$$\frac{d^2U}{dkd\Omega} = N^2\chi(\theta)F(k,\theta)\frac{d^2U_0}{dkd\Omega}, \tag{1}$$

where $F(k,\theta)$is a 3D form factor, $\chi(\theta)$ is a momentum space form factor due to angular divergence, and a single electron emission is given by,

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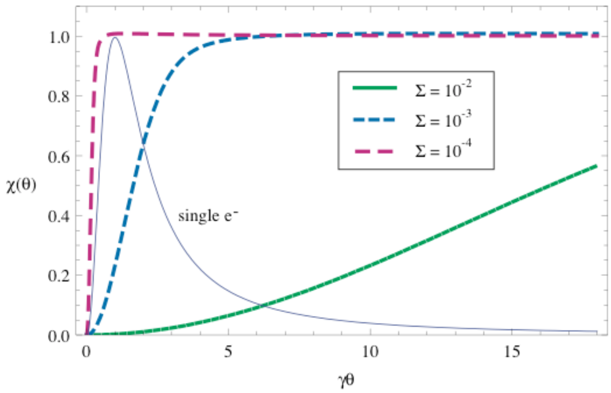

Figure 2: The angular distribution attenuation factor for various values of beam divergence.

$$\frac{d^2U_0}{dkd\Omega}=\frac{e^2}{4\pi^3\varepsilon_0}\frac{\sin^2\theta}{\left(1-\beta^2\cos^2\theta\right)^2}. \quad (2)$$

In the case of expected azimuthally symmetric phase space distributionthe angular divergence factor was derived in [10] in the context of "macro"-CTR, which is typically in mm and sub-mm spectral range:

$$\chi(\theta)=\left\{\frac{2\theta^2}{\pi\Sigma^2}\int_0^1\mu\begin{bmatrix}(1-\mu)K(\nu)+\\(1+\mu)E(\nu)\end{bmatrix}\exp\left[-\frac{\mu^2\theta^2}{\Sigma^2}\right]d\mu\right\}^2, \quad (3)$$

where $\nu=2\mu^{1/2}/(1+\mu)$, $K(\nu)$ and $E(\nu)$ are complete elliptical integrals, and $\Sigma=\sqrt{2}\sigma'_x$ is a measure of beam divergence. Fig. 2 compares a single particle angular emission profile, with the attenuation factor due to the angular divergence in Eq. 3.

Physically, a stronger divergence implies poor far field overlap of the fields of individual electrons. Overall, however the dependence on the rms beam angle is not as strong as one might have hoped, because the field overlap integral samples the single particle TR angular spectrum. As shown in Fig. 2, this spectrum has a slow angular dependence, and so even very large angles allow for a significant field overlap to develop. Nevertheless, at a shorter microbunching wavelengths, such as is the case with COTR a combination of attenuation effect shown in Fig. 2 with a small coherent angle associated with the large source size to wavelength ratioleads to COTR suppression by orders of magnitude. To demonstrate this we solve the Eq. 1 for a specific case of microbunching at optical frequencies.

ANGULAR SPREAD EFFECT ON COTR

For what follows, we assume that a microbunched (bunching factor b_1) distribution gives rise to the coherence at a given frequency $\omega=k_1c$, and so the signal lies in a narrow band about this frequency, and we have,

$$\frac{\partial U_1}{\partial k}\sim b_1^2\exp\left[-(k-k_1)^2\sigma_z^2\right], \quad (4)$$

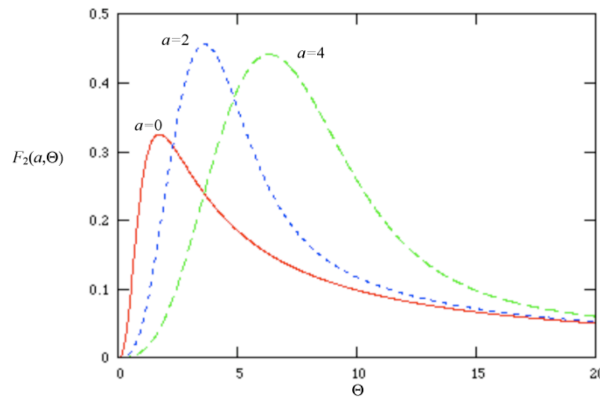

Figure 3: A COTR angular distribution, for various values of beam divergence in a narrow beam limit.

assuming a Gaussian macro bunch distribution. This factor only serves to identify the frequency of interest in the following analysis. For a Gaussian transverse distribution, the 3D form factor in Eq.1 is straightforward [11], and integrating the expression around the microbunching frequency and azimuthal angle yields the following result:

$$\frac{dU_1(a)}{d\Theta}\approx\frac{N^2e^2b_1^2}{2\pi^2\varepsilon_0c}F_1(k_1,\Theta)F_2(a,\Theta), \quad (5)$$

where $a=\Sigma\gamma/\sqrt{2}$ and $\Theta=\theta\gamma$ are energy normalized beam divergence and angle, respectively; $F_1(k_1,\Theta)$ is a spatial coherence form factor, given by

$$F_1(k_1,\Theta)\approx\exp\left[-k_1^2\sigma_x^2\Theta^2/\gamma^2\right]. \quad (6)$$

The physical meaning of a spatial coherence form factor in Eq. 6 is in a so-called "antenna effect", namely the larger is the area of a radiating beam, the more forward directional is the coherent radiation cone. This term become unity in a *narrow beam limit*,

$$\sigma_{x,y}k_1<<\gamma. \quad (7)$$

The second term in Eq. 5, is a COTR angular distribution which is simply a superposition of the far field patterns of individual electrons in the beam with a finite divergence,

$$F_2(a,\Theta)=\left|\frac{\Theta^{3/2}}{a^2}\int\frac{e^{-\frac{\Theta^2}{2a^2}}\Psi d\Psi}{\sqrt{\left(1+(\Theta+\Psi)^2\right)\left(1+(\Theta-\Psi)^2\right)}}\right|^2. \quad (8)$$

Here it is important to note, that in a limit of a non-divergent beam, the expression in Eq. 8 is reduced to a single particle behavior at a normal incidence (Eq. 2),

$$\lim_{a\to0}\left[F_2(a,\Theta)\right]=\frac{\Theta^3}{\left(1+\Theta^2\right)^2}. \quad (9)$$

In a more general case, the numerical solution of Eq. 8 is shown in Fig. 3 for a=0,2,4, and it indicates that in a narrow beam limit, while the peak intensity shifts towards larger angles, an integratedCOTR emission intensity has a very weak dependence on the beam angular divergence.

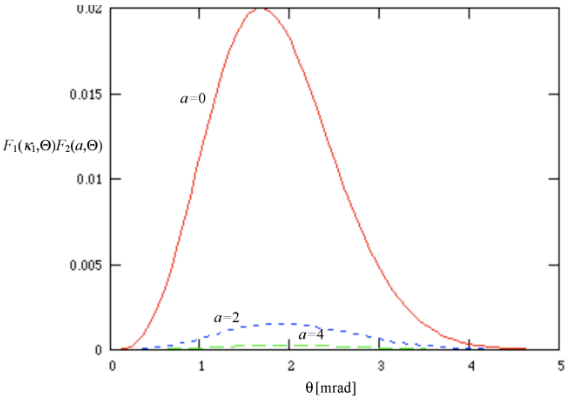

Figure 4: A COTR angular distribution for various values of *a*, using LCLS beam parameters at 135 MeV.

On the other hand, when the narrow beam limit condition in Eq. 7 is not met, a spatial coherence form factor is strongly biased towards forward direction, and in combination with the peak intensity shift towards larger angles results in a strong attenuation of COTR emission.

For example, in the case of LCLS post-injectionline (135 MeV, 50 µm rms spot size), a location where a strong COTR background was observed [3], the narrow beam limit in Eq. 8 is clearly violated and numerical integration of Eq. 5 shows dramatic dependence of COTR intensity on a beam divergence (Fig. 4).In that case the spoiler foil approach would be very effective in removing a COTR background from the OTR measurements. Specifically, in the LCLS example in Fig. 4, the *a*=4 case corresponds to a 140 µm thick copper spoiler foil.

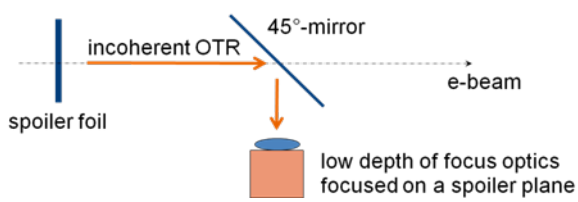

Figure 5: A schematics of COTR suppression for backscattered OTR beam profile measurements.

A suggested schematics for an OTR beam profile monitor in such case is shown in Fig. 5. A spoiler foil introduces a large divergence, into the beam distribution via multiple scattering, which attenuates COTR emission, while the incoherent OTR more representative of the actual beam density profile is emitted from the back surface of the spoiler and collected with a low depth of focus optical system via a 45°-mirror.

At a significantly higher energy, the effect becomes less pronounced as the beam parameters approach a narrow beam limit behavior shown in Fig. 3. For example, in the case of FLASH, where COTRwas observed at 1.4 µm, but at the energy of 900 MeV, the COTR intensity fall-off is less pronounced, unless the beam size is very large (Fig. 6). Hence, in this example, in order to apply the method of COTR background reduction in Fig. 4, a thicker spoiler is required, so that a normalized beam divergence at the spoiler output is on the order of $a \geq 10$.

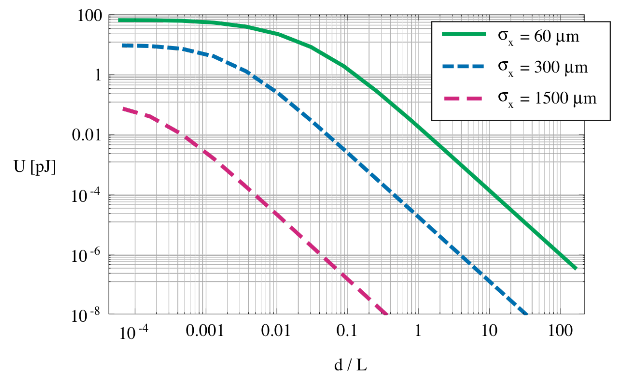

Figure 6: Total emitted coherent CTR energy for various values of the beam transverse rms size, using FLASH beam parameters(Q=800 pC,b_l=0.01).

CONCLUSIONS

We proposed to use a spoiler foil as a method to mitigate the COTR background to improve the OTR beam profile measurements reliability. This approach is the most efficient, at moderate beam energies and larger spot sizes. At higher energies, or when the narrow beam limit,in Eq. 8 is otherwise satisfied, the proposed approach lacks efficacy, and other COTR mitigation methods could be appropriate, such as spectral or angular sampling approaches [12,13] or a combination. Experimental verification of the method proposed herein would further enhance diagnostic capabilities of high brightness, FEL-quality electron beam delivery systems; and provide valuable results for improved understanding of COTR formation, the recently discovered phenomenon of electron beams self-modulation at the optical frequencies.

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