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Infrared (IR) vs. X-Ray Power Generation in the SLAC Linac Coherent Light Source (LCLS)*

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Abstract

The LCLS, a Free-Electron Laser (FEL) designed for operation at a first harmonic energy of 300 eV ($\lambda \approx 40\text{\AA}$) in the Self-Amplified Spontaneous Emission (SASE) regime, will utilize electron bunches compressed down to durations of $<0.5\text{ps}$, or lengths of $<150\text{ }\mu$. It is natural to inquire whether coherent radiation of this (and longer) wavelength will constitute a significant component of the total coherent output of the FEL. In this paper a determination of a simple upper bound on the IR that can be generated by the compressed bunches is outlined. Under the assumed operating parameters of the LCLS undulator, it is shown that the IR component of the coherent output should be strongly dominated by the x-ray component.

I. INTRODUCTION

We are interested in estimating upper bounds on the coherent IR emission generated by the LCLS bunches as they pass through the LCLS undulator [1]. In preface, attempting to associate copious quantities of coherent radiation at wavelengths equal to or exceeding the bunch length might appear, *prima facie*, warranted. After all, there is a naive tendency to infer that if the emitted wavelength is longer than the entire bunch, the emission should be enhanced in proportion to the square of the number of particles in the bunch. In fact, as will be shown, for short-to-medium period insertion devices this inference can be justified only for suitably low values of the particle bunch energy; at ultrarelativistic energies relativistic effects serve to suppress the necessary coherent superposition to relatively small or even negligible values.

In addressing this problem we will employ: 1) the result that the total number of photons emitted by a physical system is a relativistic invariant, and 2) the relativistic Doppler shift relations, expressed in reference to Fig. 1 as

$$f = f' \gamma (1 + \beta \cos \theta') \quad (1)$$

and

$$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'} \quad (2)$$

where $\beta \cdot c$ ($\beta \approx 1 - \{1 + K^2/2\}/2\gamma^2$), with K the undulator deflection parameter) represents the average speed of the electron bunch in the forward direction.

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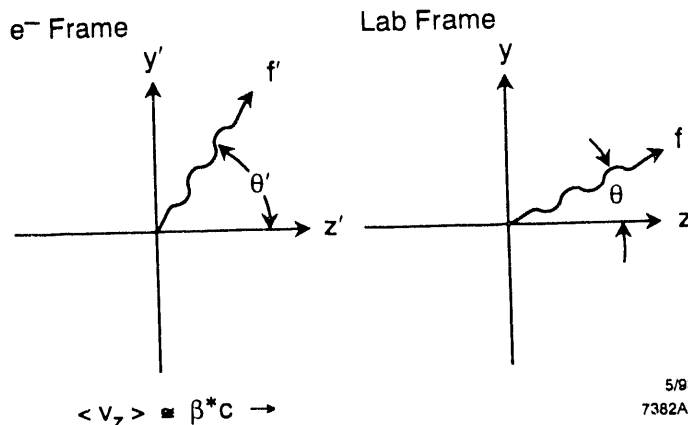


Figure 1. Monochromatic emission observed in electron and lab frames.

In Table 1, we list the physical parameters of the LCLS required for our analysis.

Table 1
Basic LCLS parameters for 40Å operation.

$(2\pi)^{0.5} \sigma_B$ (bunch length)	150 μ
N_C (total number of particles in bunch)	10^{10}
B (undulator field amplitude)	0.8T
λ_u (undulator period)	8cm
$K (=0.934B \lambda_u)$	6
L_u (undulator length)	60m
N_u (number of undulator periods)	750
E (electron energy)	7GeV
N_{SP} (total number of spontaneously emitted photons in 40Å equivalents per pulse)	3×10^{13}
N_{COH} (number of coherent x-ray photons per pulse)	10^{14}

II. ANALYSIS

Our basic approach to the problem will be to analyze the emission in question in the average rest frame (e-frame) of the electron bunch [2]. For low-to-moderate values of K , the dominant radiation component in the e-frame is a dipole pattern, as depicted in Fig. 2. We note that at the tabulated value of K the periodic electron motion in the e-frame will be relativistic. As a consequence, in addition to higher discrete multipole components stemming from K , there will also be a set of continuous spectral components arising from synchrotron radiation (SR) emitted by the circulatory motion of the electron in the e-frame [3]. However, the lowest spectral component will be the fundamental determined by the period of the undulator as observed in the e-frame, and it is this component that will dominate contributions to the IR

emissions in the lab frame.

Dipole Radiation Pattern ($K \ll 1$) vs Isotropic Intensity Distribution

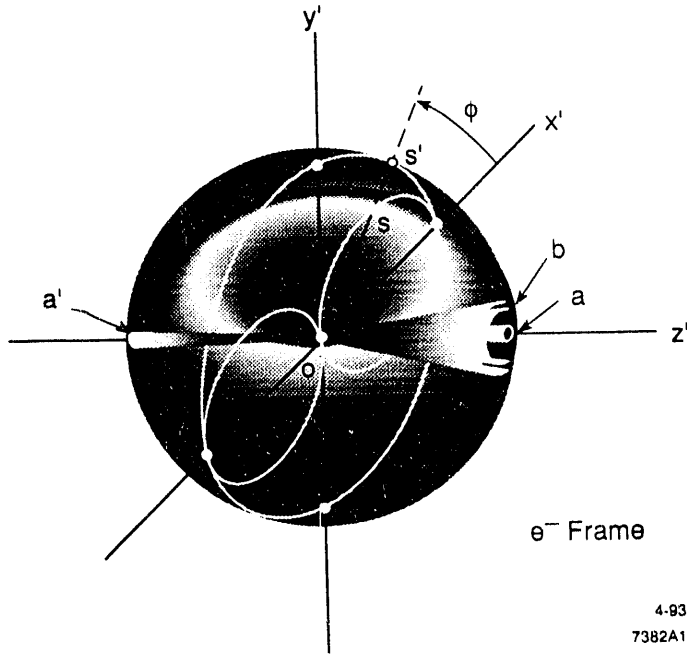


Figure 2. Dipole radiation pattern in the electron frame.

In the electron frame the undulator appears contracted by the factor $E/m_e c^2 (= \gamma)$, while the bunch is dilated by the same factor (see Fig. 3). The frequency of the fundamental in

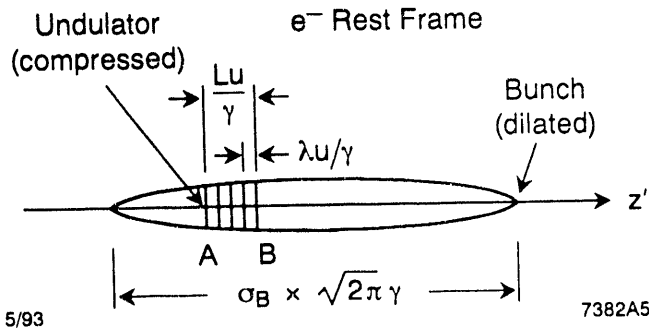


Figure 3. Relativistic scaling in the e'lectron frame.

the e-frame is consequently given by $f = c\gamma / \lambda_u$. Assuming an approximately isotropic distribution in this frame, we use the Doppler relation (1) to identify the angle θ' at which f' gets converted into the desired IR component in the lab frame. Specifically, we have

$$\frac{c}{\sqrt{2\pi}\sigma_B} = \left(\frac{c\gamma}{\lambda_u} \right) \gamma (1 + \beta \cos \theta'). \quad (3)$$

This transformation is depicted in Fig. 4. Using the parameter

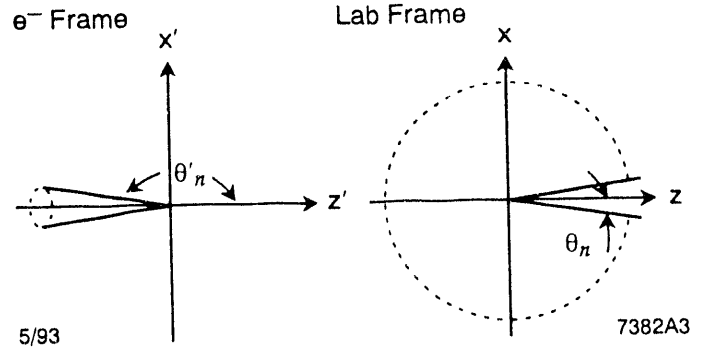


Figure 4. Transformation of the backward fundamental emission angle ($\pi - \theta'_n$) in the e-frame into the IR emission angle ($\pi - \theta_n$) in the lab frame. Radiation cones are defined by the dotted contours

values in Table 1, we find $\pi - \theta'_n = 2.34 \text{ mr}$ and, using eq. (2), $\theta_n = 0.264 \text{ r}$. As anticipated, the radiation that appears as IR of the desired frequency in the lab frame originates from a very small solid angle in the e-frame.

We next define the total number of spontaneously emitted photons per electron per each period of the undulator in the lab frame by the quantity $(N_{sp}/N_u N_C)$. Clearly, this number will be the same for each electron in the e-frame. Referring to Fig. 3 and assuming, for simplicity, a uniform density vs. z' , the total number of spontaneously emitted photons by the electron group traversed by one undulator period can be approximated by

$$f_1 = (N_C/f_2)(N_{sp}/N_u N_C), \quad (4)$$

with

$$f_2 = (2\pi)^{0.5} \sigma_B \gamma^2 / \lambda_u. \quad (5)$$

Next, the same group of electrons will emit the same number of photons N_u times, for a total number of $N_u f_1$ photons. Clearly, there are f_2 such groups in the entire bunch, and we consequently have $N_u f_1 f_2 = N_{sp}$, as expected.

Next, we define the fraction f_3 of these photons that are converted into the desired IR photons in the lab frame by referring to Figs. 2 and 4. Taking into account the geometry of the dipole pattern, we obtain

$$f_3 = (\pi - \theta'_n)^2 / 2. \quad (5)$$

We can now consider the effects of the FEL bunching process in enhancing the number of radiated photons in the e-frame. In Fig. 5 we depict the relative bunching (or phase coherence) of the electrons within each period of the undulator. Although it is evident that any group of electrons of the order of size of an undulator period doesn't attain full bunching until almost the entire undulator has passed over it, for our purpose of estimating upper bounds, we will assume that each such group is actually fully bunched, but that the radiation from the N_u individual groups is uncorrelated. This leads to the enhancement of the number of photons emitted by each group

by the factor N_C/f_2 , i.e., the number of photons becomes proportional to the square of the number of electrons in each group. Denoting the number of IR photons in the lab frame by

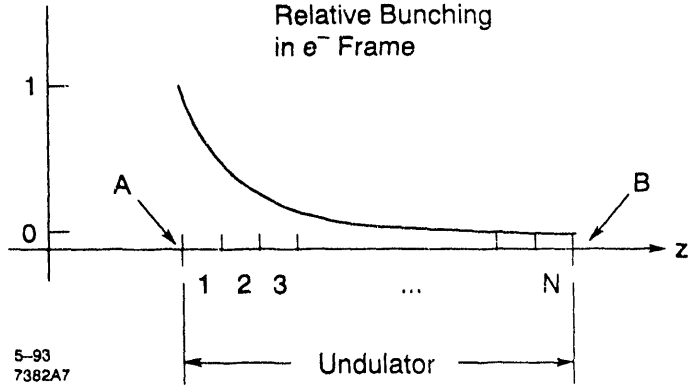


Figure 5. FEL bunching along undulator in electron frame.

N_{IR} , the resulting upper bound may be expressed as

$$\frac{N_{IR}}{N_{COH}} < \frac{N_C f_3}{f_2} \left\{ \frac{N_{SP}}{N_{COH}} \right\} = \frac{N_C (\pi - \theta'_n)^2 \lambda_u}{2\sqrt{2}\pi\sigma_B \gamma^2} \left\{ \frac{N_{SP}}{N_{COH}} \right\}. \quad (6)$$

Inserting the previously derived numbers for θ'_n and the values from Table 1 yields $(N_{IR}/N_{COH}) < 0.022$.

III. DISCUSSION

We have derived an upper bound on IR emission from the LCLS for lab frame wavelengths equal to or greater than $(2\pi)^{0.5} \sigma_B (=150 \mu)$. This can be considered a weak upper bound, viable in the present case due to the strong suppression (by the relativistic f_3 (or $(\pi - \theta'_n)^2/2$) factor) of the greatly overestimated coherent emission in the e-frame. While it is noteworthy that this upper limit is inversely proportional to σ_B , which indicates that IR emissions from the LCLS should remain perturbative on the coherent x-ray emission even for bunches down to 30μ long, we point out that for significantly smaller energies and/or bunches more than 10 times shorter our upper bound estimate should start being replaced with more comprehensive analytical calculations of the spontaneous and coherent radiation distributions.

It is of interest to inquire whether significant IR emission of the wavelength in question could in fact be induced by the LCLS, and under what conditions. The general criterion is straightforward, namely that the standard resonance condition, viz.,

$$\frac{\lambda_u}{2\gamma^2} \left(1 + K^2/2 \right) = \lambda \geq (2\pi)^{0.5} \sigma_B \Rightarrow \lambda_u \geq \frac{2(2\pi)^{0.5} \gamma^2 \sigma_B}{1 + (K^2/2)}, \quad (7)$$

be fulfilled. We can examine this criterion quantitatively by contrasting λ_u at the LCLS beam energy of 7GeV with bunch and energy parameters appropriate to a 40MeV short-bunch generation experiment planned at SSRL [4]. Table 2 shows

the relevant parameters.

Table 2

Undulator periods required for resonant IR emission @ $K=6$.

40MeV	7GeV
$(2\pi)^{0.5} \sigma_B = 12 \mu$	$(2\pi)^{0.5} \sigma_B = 150 \mu$
$\gamma = 80$	$\gamma = 13700$
$\gamma^2 = 6400$	$\gamma^2 = 1.9 \times 10^8$
$\lambda_u \geq 8 \text{ mm}$	$\lambda_u \geq 1185 \text{ m}$

This comparison dramatically illustrates the extent to which ultrarelativistic energies tend to suppress IR emission. At 7GeV, the LCLS undulator field structure, with its 8cm period, would need to contain significantly strong Fourier components of $>1\text{km}$ period to resonantly induce IR emission from the 150μ bunch (see Fig. 6). With reasonably careful design and alignment, such aberrations (represented in the figure by an impulsive offset associated with a non-zero 1st field integral) should not be overly difficult to suppress.

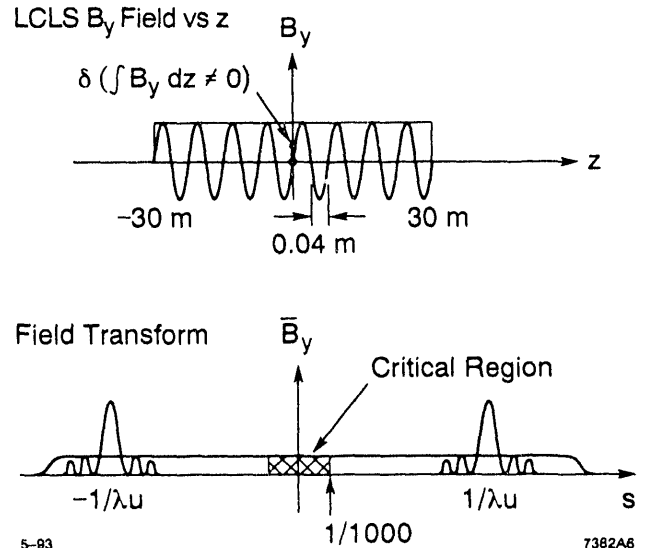


Figure 6. Fourier decomposition of undulator field along z .

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