MERITS OF A SUB-HARMONIC APPROACH TO A SINGLE-PASS, 1.5-Å FEL*

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Abstract

SLAC/SSRL and collaborators elsewhere are studying the physics of a single-pass, FEL amplifier operating in the $1-2$ Å wavelength region based on electron beams from the SLAC linac at ~ 15 GeV energy. Hoping to reduce the total wiggler length needed to reach saturation when starting from shot noise, we have examined the benefits of making the first part of the wiggler resonant at a sub-harmonic wavelength (*e.g.* 4.5 Å) at which the gain length can be significantly shorter. This leads to bunching of the electron beam at both the subharmonic and fundamental wavelengths, thus providing a strong coherent "seed" for exponential growth of radiation at the fundamental in the second part of the wiggler. Using both multi-harmonic and multi-frequency 2D FEL simulation codes, we have examined the predicted performance of such devices and the sensitivity to electron beam parameters such as current, emittance, and instantaneous energy spread.

I. Introduction

Over the past several years, there has been an on-going study of the feasibility of constructing an FEL operating at x-ray wavelengths (*i.e.* 1-5$\AA$) based on 15-GeV energy electron beams produced by the SLAC linac[1]. The device, provisionally named the Linac Coherent Light Source (LCLS), would operate in a single-pass amplifier configuration employing self-amplified spontaneous emission (SASE). Since the effective shot noise seed for SASE in this case is ~ 10 kW and the expected saturation power is $\sim 1-50$ GW, the wiggler must encompass approximately 15 gain lengths. For peak bunch currents of ~ 5 kA and normalized emittances of $1-2\pi$ mm-mrad, gain lengths are typically 2 m or longer. Hence, the required wiggler length lies in the 30-50 m range unless some means is found to shorten the average gain length. One such possibility is making the first part of the wiggler resonant at a sub-harmonic of the ultimate wavelength sought (*e.g.* 4.5Å as compared with 1.5Å). In this portion of the wiggler, the electron bunches at the resonant (subharmonic) wavelength and shorter wavelength harmonics, thus providing a strong, coherent seed for exponential growth at the resonant, fundamental wavelength of the second part of the wiggler.

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This configuration has been suggested previously (see, *e.g.* , [2][3]), although in these cases the input signal was provided by a "master-oscillator" laser. Since SASE's coherence length is relatively short and spectral bandwidth relatively large when compared with those of a master oscillator, the positive results found in [2][3] need to be re-evaluated for the LCLS study. Using the simulation codes GINGER and NUTMEG [4] [5], we have examined the performance of the sub-harmonic approach to a SASE-initiated 1.5Å FEL.

Subharmonic bunching is potentially attractive because of its faster exponential growth rate compared to that of the fundamental. The growth rate scales linearly with the dimensionless FEL parameter [6] ρ where

$$\rho^3 \equiv \frac{\omega_p^2 a_w^2 f_B^2}{16\gamma^3 k_w^2 c^2} \tag{1}$$

Here k_w is the wiggler wavenumber, ω_p is the beam plasma frequency, a_w is the dimensionless RMS wiggler vector potential, f_B denotes the Bessel function coupling term for a linearly-polarized wiggler, and γ is the usual Lorentz factor for the beam electrons. In the LCLS, the dominant focusing will be provided by external quadrupoles (the extremely low beam emittance permits this) so ω_p^2 remains nearly constant in the two wiggler regions. For $a_w \geq 2$, $(\rho_1/\rho_2) \sim [(\lambda_{s,1}/\lambda_{s,2})(\lambda_{w,1}/\lambda_{w,2})]^{1/3}$ where the subscripts 1 and 2 refer to the first and second wigglers respectively. Although the growth rate can be reduced by a number of effects such as instantaneous energy spread, transverse emittance, and diffraction, these play a relatively small role for the adopted LCLS parameters (see Table 1) and we expect the ratio of gain lengths between 4.5Å and 1.5Å to follow closely the ratio in ρ which is about 1.64. Consequently, one might expect to achieve an $\sim 30\%$ reduction in overall wiggler length presuming good "coupling" efficiency in bunching from the first to the second wiggler.

There are a number of phenomena which might reduce the coupling efficiency and performance of the second wiggler, in particular when compared to a single wiggler resonant its entire length with $\lambda_s = 1.5$ Å. First, as realized in ref. [2], the instantaneous energy spread induced by the first wiggler will reduce the gain of the second. To limit this reduction, one must limit bunching in the first wiggler to values well below saturation (*e.g.* $b \equiv |<e^{i\theta}>| \leq 0.1-0.3$). Second, when starting from broad band noise, the output bandwidth $\Delta\omega/\omega$ of the bunching (and light) of the first wiggler can be larger than the "acceptance" of the second wiggler due to its smaller ρ. On the other hand, the coherence length $c\tau_c \propto \lambda_s/\rho$ induced by the

Table 1. Parameters and Simulation Results

Standard parameters: $I_b = 5.0\,\mathrm{kA}$ $\gamma = 2.92\times10^4$				
$\Delta\gamma = 6.0$ $\varepsilon_n(\mathrm{rms}) = 1.0\,\pi$ mm-mrad $\lambda_\beta = 22.4\,\mathrm{m}$				
	Single λ_s Config.		*$3\lambda_s -> \lambda_s$ Config.*	
RUN:	A	B	C	D
λ_s	$4.5\,\mathring{A}$	$1.5\,\mathring{A}$	$4.5\,\mathring{A}$	$1.5\,\mathring{A}$
λ_w	40 mm	30 mm	40 mm	30 mm
a_w	4.27	2.75	4.27	2.75
L_w	23 m	40 m	16 m	20 m
ρ	2.4×10^{-3}	1.5×10^{-3}	2.4×10^{-3}	1.5×10^{-3}
$\Delta\gamma/\gamma\|_\varepsilon$	5.7×10^{-4}	1.3×10^{-3}	5.7×10^{-4}	1.3×10^{-3}
P_{out}	120 GW	30 GW	1.1 GW	22 GW
$\tau_{1/2}$	0.17 fs	0.14 fs	0.10 fs	0.10 fs
$\Delta\omega/\omega_o$	1.6×10^{-3}	6.7×10^{-4}	2.8×10^{-3}	9.4×10^{-4}

first wiggler may be much longer than the value corresponding to saturation of the second wiggler. If so, the effective input signal for the second wiggler is perhaps more similar to a chirped coherent signal than a broad band, shot noise signal. One might then expect that certain temporal regions of the electron beam pulse, whose local bunching wavelength fall within the nominal gain bandpass of the second wiggler, will have strong exponential gain while those regions, whose local bunching wavelength lies outside, will not.

Moreover, since the bunching at the third harmonic (*i.e.* $\lambda = 1.5\,\mathring{A}$) is proportional to the cube of the bunching at the fundamental (*i.e.* $\lambda_s = 4.5\,\mathring{A}$) in the exponential gain regime of the first wiggler, at the same z one would expect a significantly shorter coherence length at the shorter wavelength. All these effects taken together suggest that the number of spikes that will grow in the second wiggler might be similar to that at the output of the first but whose individual temporal duration will be shorter. Ref. [7] gives additional analysis concerning the evolution of "spikes" in the SASE regime.

II. Simulation Results

We performed a number of simulations of the subharmonic seeding configuration for a SASE-initiated, $1.5\,\mathring{A}$ FEL with the 2D, multiple harmonic code NUTMEG and settled on the wiggler parameters listed in Table 1. Although NUTMEG is not a fully time-dependent code, it gives a reasonably accurate answer for the overall growth in SASE power when initiated with a monochromatic input radiation field quantitatively equivalent to shot noise. The NUTMEG results suggest that the first wiggler should be about 20 m in length at whose end there will be about 1 GW of $4.5\,\mathring{A}$ power and a factor of 50 less at $1.5\,\mathring{A}$ for a linearly polarized wiggler. All the runs presented here adopted a helically-polarized wigglers and hence the bunching at the odd harmonics will be due only to the radiation field at the fundamental. According to NUTMEG, a second wiggler of 20 m length will result in about 40 GW of power at $1.5\,\mathring{A}$ which is not significantly different from what a simpler, single wiggler

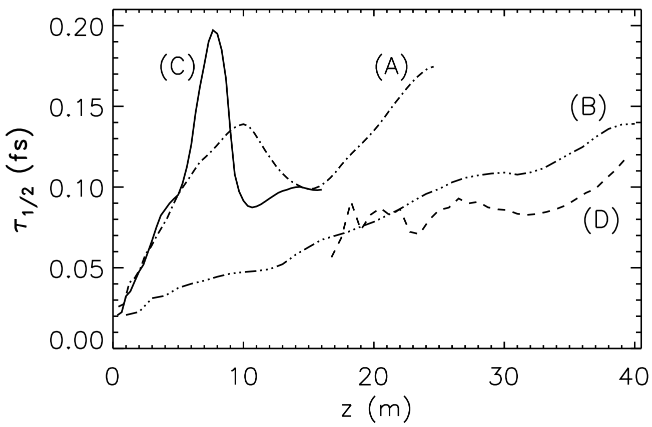

Figure. 1. Autocorrelation time $\tau_{1/2}$ vs. z for different GINGER runs. **(A)** SASE-initiated $\lambda_s = 4.5\,\mathring{A}$, run to saturation at $z = 23$ m **(B)** SASE-initiated $1.5\,\mathring{A}$ run to 40 m, slightly short of saturation **(C)** Same as run A but with only 16 m of wiggler **(D)** $\lambda_s = 1.5\,\mathring{A}$ begun at $z = 16$ m using the bunched output electron beam of run C as a subharmonic "seed".

configuration resonant at $1.5\,\mathring{A}$ would give for a total length of 40 m.

The GINGER simulations listed in Table 1 were done with full temporal and radial resolution of the radiation field and electron beam, and thus include the effects of shot noise, diffraction, optical guiding, and betatron motion of the individual beam particles. We adopted periodic boundary conditions in time with an equivalent "window" of 1.2 fs as compared with the slippage length$/c$ of 0.6 fs in the first wiggler and 0.4 fs in the second. After making a number of trial runs for the subharmonic-seeded configuration (*i.e.* runs C/D), we adopted a first wiggler length of 16 m which is approximately 8 m ($\equiv$ 4 gain lengths in power and 2 in bunching) short of overall saturation at $4.5\mathring{A}$. This wiggler length is shorter than the value of 20 m suggested by the NUTMEG runs. The difference lies in the fact that at a given z, the particle bunching, instantaneous energy spread, and radiation power have temporal "spikes", with peak bunching values at $\lambda = 4.5\,\mathring{A}$ being ≥ 1.6 times greater than the average value of 0.09. Hence, for a given energy spread acceptance of the second wiggler, the allowable output bunching of the first wiggler, when initiated with SASE, will be smaller than that permissible for a monochromatic input field.

At the end of the first wiggler (run C), resonant at $4.5\,\mathring{A}$, the average bunching at the third harmonic $\lambda = 1.5\,\mathring{A}$ (which is the "seed" bunching for the second wiggler $\equiv$ run D) is about 0.01. This is about a factor two higher than is produced at $z = 16$ m in run B which employs a wiggler resonant only at $1.5\,\mathring{A}$. Interestingly, the autocorrelation times of runs B and D, as measured by $\tau_{1/2}$ (the point at which the temporal autocorrelation function $C(\tau)$ falls to a value of 0.5), are nearly the same (see Fig. 1) and about a factor of two less than the $4.5\,\mathring{A}$ runs A and C. Over the next 20 m of wiggler, as the power in run D grows by three orders of magnitude, $\tau_{1/2}$ increases by less than 50%; by comparison, the single wiggler $1.5\,\mathring{A}$ run B has $\tau_{1/2}$ double. Comparisons of the output spectra of these two runs (Fig. 2) shows that the single wiggler configuration has a noticeably narrower spec-

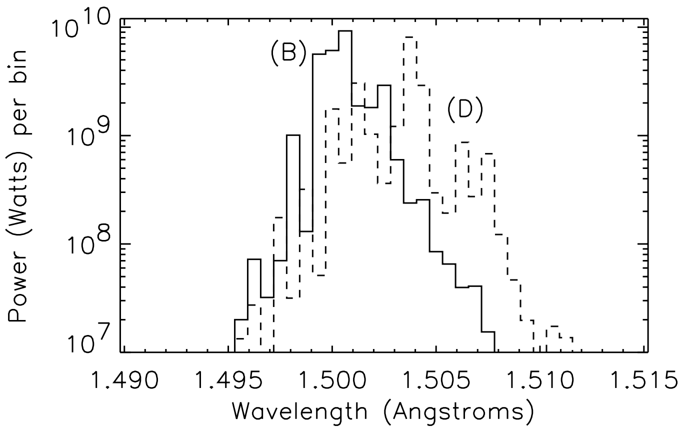

Figure. 2. Output spectra for the $1.5\,\mathring{A}$ runs B and D.

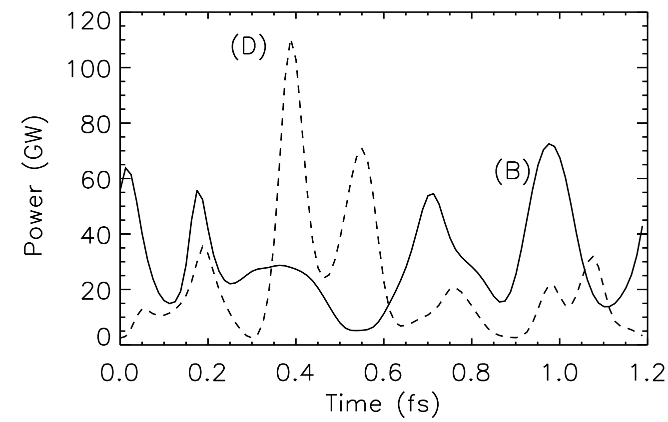

Figure. 3. Output power versus time for runs B and D.

tra than that of the subharmonic seeded configuration as would be expected from the differences in the autocorrelation times. It is not clear if the slight redward shift of run D relative to run B is significant or solely due to chance via random number seeds. (Note: The "bump" in $\tau_{1/2}$ in the 6 to 10 m region of the $4.5\,\mathring{A}$ runs does appear to be "real" as it has appeared in numerous runs with different random number seeds.)

The differences in time-averaged output power of the two $1.5\,\mathring{A}$ runs is significant. The single wiggler configuration (B), if run to saturation, would have exceeded 40 GW, while the subharmonic-seeded run (D) saturated at the lower power of 22 GW. Although the difference is probably not critical for most proposed LCLS applications, it is undoubtedly due to the higher instantaneous energy spread induced by the first wiggler resonant at $4.5\,\mathring{A}$. Time-resolved plots (Fig. 3) of the output power of these two runs shows that while the subharmonic seeded run had less average power, it also has fewer spikes and a greater peak output flux within the spikes. As predicted in refs. [7][8], the relative temporal fluctuation of the output power $\delta P / < P >$ is of order 1 which may have undesirable consequences for some LCLS applications.

We have also studied the sensitivity of the subharmonic-seeded configuration to LCLS beam parameters such as emittance. With as little as a 50% increase of normalized emittance to $1.5\,\pi$ mm-mrad, the $4.5\,\mathring{A}$ power at the output of the first wiggler drops to 0.12 GW and the average bunching to 0.03. The $1.5\,\mathring{A}$ output power at $z = 40$ m from the second wiggler drops to 1.4 GW (as compared with 22 GW in run D), the gain length increases to 2.8 m from 2.4 m, and probably another 7-10 m is needed for saturation. Consequently, a longitudinal variation in transverse emittance as small as 30-50% will be transformed into an extremely large variation in output power for a given wiggler configuration. The same sensitivity applies to beam current. To be fair, note that any configuration requiring ~ 15 exponential gain lengths is likely to be sensitive to parameters such as emittance and current. There is less sensitivity to the instantaneous energy spread because of its relatively small value compared to ρ (see Table 1) although it, together with the effective energy spread due to emittance, does appear large enough to prevent LCLS optical klystron configurations working well at $\lambda_s = 1.5\,\mathring{A}$.

Based upon these results, we do not believe that the subharmonic, double wiggler approach to producing a high power $1.5\mathring{A}$ FEL, given its greater complexity, is particularly attractive relative to the simpler, single wiggler configuration for the presently adopted LCLS parameters.

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