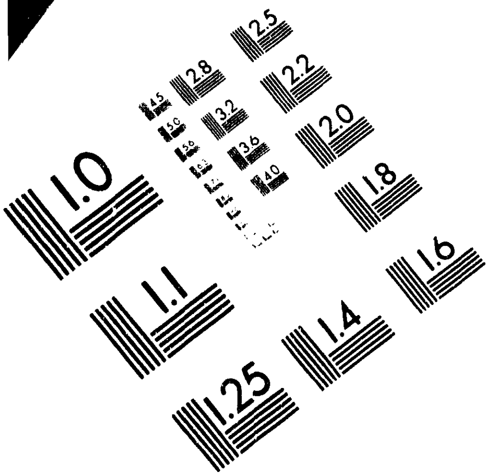

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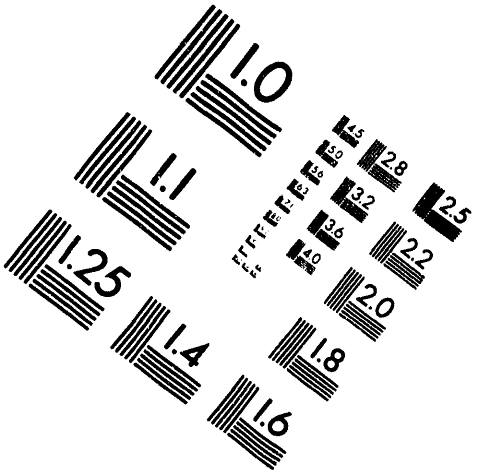

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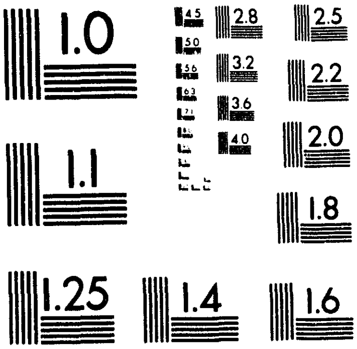
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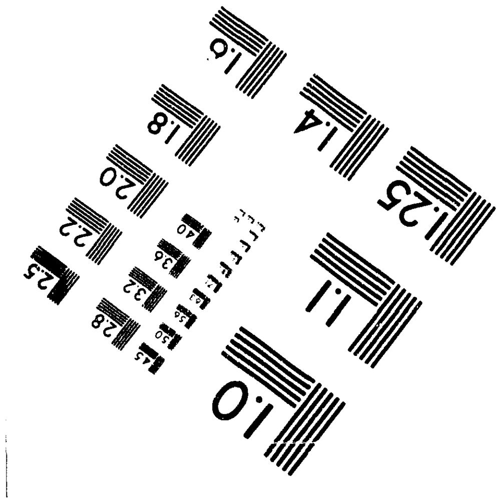

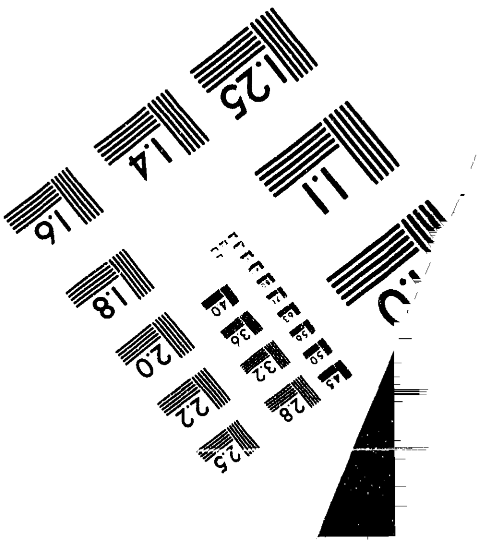

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Coherence and Linewidth Studies of a 4-nm High Power FEL

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Coherence and Linewidth Studies of a 4-nm High Power FEL[*]

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Abstract

Recently the SSRL/SLAC and its collaborators elsewhere have considered[1] the merits of a 2 to 4-nm high power FEL utilizing the SLAC linac electron beam. The FEL would be a single pass amplifier excited by spontaneous emission rather than an oscillator, in order to eliminate the need for a soft X-ray resonant cavity. We have used GINGER, a multifrequency 2D FEL simulation code, to study the expected linewidth and coherence properties of the FEL, in both the exponential and saturated gain regimes. We present results concerning the effective shot noise input power and mode shape, the expected sub-percent output line widths, photon flux, and the field temporal and spatial correlation functions. We also discuss the effects of tapering the wiggler upon the output power and line width.

I. Introduction

The free-electron laser (FEL) has an attractive feature of being tunable over a fairly extensive operating range in wavelength. For the VUV and soft x-ray regions of the spectrum, FEL's may offer brightnesses many orders of magnitude larger than existing lasers and synchrotron light sources, presuming that GeV-energy beams of relatively high currents ($\geq$ 1kA) and low emittance ($\epsilon_n \leq 10$ mm-mrad) are available. Recently workers at SSRL/SLAC and collaborators elsewhere have suggested using the SLAC linac electron beam in a single-pass FEL amplifier excited by spontaneous emission to make an extremely high brightness laser ($\sim$ 10GW peak power, 10^{18}photons/micropulse-mm^2-mrad^2 peak brightness) in the 4-nm wavelength regime. For many applications, the output linewidth and mode shape are primary concerns since the spontaneous emission input "seed" is incoherent both temporally and spatially. In this work, we present results from a multifrequency 2D FEL simulation code that bear on these concerns. First, however, we review theoretical predictions by others for the predicted effective input power, gain lengths, saturated power, and linewidths for a high gain, single pass amplifier relying upon self-amplified, spontaneous emission (SASE).

Many features of an FEL single-pass amplifier depend on the dimensionless FEL parameter[2][3][4] ρ given by

$$\rho^3 \equiv \frac{eZ_o J_o a_w^2 f_B^2}{16\gamma^3 k_w^2 m_e c^2} = \frac{\omega_p^2 a_w^2 f_B^2}{16\gamma^3 k_w^2 c^2} \qquad (1)$$

where k_w is the wiggler wavenumber, a_w is the dimensionless wiggler vector potential, J_o is the current density, $Z_o \approx 377$ ohms, and f_B denotes the Bessel function coupling term for a linearly polarized wiggler. For most FEL's of interest, $\rho \sim 10^{-4} - 10^{-2}$ and is thus a small parameter; the proposed 4-nm SLAC FEL has $\rho \approx 1.5 \times 10^{-3}$. For cases where the diffraction length is much greater than the gain length, the peak growth rate for the power is $\Gamma_{max} \approx 4k_w \rho x_m$ where $x_m = \sqrt{3}/2$ for the limiting case of no energy spread, and approximately $\sqrt{\rho/(\Delta\gamma_{eff}/\gamma)}$ when $\Delta\gamma \geq 2\rho\gamma$. Here $\Delta\gamma_{eff}$ is the total "effective" energy spread (*i.e.* true spread plus the equivalent spread introduced due by non-zero transverse emittance and external focusing effects). Saturation (due to the energy spread exceeding $\rho\gamma$) occurs at a total power[2]

$$P_{sat} \approx \rho P_{beam} \qquad (2)$$

For the particular case of a SASE FEL, Kim[5] predicts that after the necessary 2-3 gain lengths for exponentially growing modes to dominate over decaying and oscillatory modes, the spectral intensity has an rms width

$$\Delta\omega/\omega_o \approx (9\rho/2\pi\sqrt{3}N)^{1/2} \qquad (3)$$

where N is the number of wiggle periods, $k_w z/2\pi$. The effective input power produced by shot noise is

$$P_{in} \approx \rho^2 \gamma m_e c^2 \frac{\omega_o}{2\pi} \qquad (4)$$

Ref. [5] also predicts domination by a single transverse mode with full transverse coherence for most cases of interest and that the spectral bandwidth at saturation is

$$\Delta\omega/\omega_o \approx 1/N_{sat} \approx \rho \qquad (5)$$

Beyond saturation one can extract, in theory at least, additional power by tapering the wiggler (*e.g.* reducing a_w). To the best of our knowledge, there are no quantitative predictions as to the behavior of the spectral bandwidth in a SASE-dominated FEL beyond saturation; *i.e.* in the non-linear regime.

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Table 1. Parameters and Simulation Results

Standard parameters: $\gamma = 1.37 \times 10^4$ $\Delta\gamma = 5.48$ $\varepsilon_n(\mathrm{rms}) = 3.0\,\mathrm{mm\text{-}mrad}$ $a_w = 4.13$ $\lambda_w = 83\,\mathrm{mm}$

Input & Predicted					*Simulation Results*					
I_{beam}	ρ	$1/\rho$	P_{in}	ρP_{beam}	dim.	N_{sat}	P_{in}	P_{sat}	$\tau_{1/2}$	$\Delta\omega/\omega_o$
0.5 kA	9.83×10^{-4}	1015	81 W	3.4 GW	1D	1000	110 W	4.8 GW	3.3 fs	7.6×10^{-4}
0.75 kA	1.13×10^{-3}	885	110 W	5.9 GW	1D	850	140 W	6.2 GW	2.4 fs	1.1×10^{-3}
1.0 kA	1.24×10^{-3}	806	130 W	8.7 GW	1D	745	200 W	8.8 GW	2.5 fs	1.0×10^{-3}
2.5 kA	1.68×10^{-3}	595	240 W	29 GW	1D	565	300 W	32 GW	1.6 fs	1.6×10^{-3}
					2D	865	160 W	17 GW	2.7 fs	9.3×10^{-4}

II. Simulation Code Description

GINGER [6] is a 2D, time-dependent particle simulation code directly descended from the LLNL FEL-simulation code, FRED [6]. Like FRED, it models single-pass amplifiers and follows electron motion in all three dimensions. The electromagnetic field is presumed to be axisymmetric and, as is generally done, to be composed of a "slow" temporal modulation of the "fast" time behavior of the fundamental mode [$\propto \exp(-i\omega_o t)$]. Within GINGER itself, all quantities are followed in the time domain - decomposition into frequency components is done only as a diagnostic by a postprocessor code. Both the electron beam and EM field are divided into longitudinal slices in time (generally 128 in number for this investigation). As the electron-beam slices move through the wiggler, they "slip" behind the optical-field slices due to their slightly lower longitudinal velocity. For these runs, both the beam and field were assumed to be periodic in time, with a period more than twice that of the total slippage time over the full wiggler length of 83 m. Since the expected correlation time is less than one-quarter the slippage time (= 13 fs), we do not believe that the adoption of periodic boundary conditions has led to significant, unphysical effects.

The initial "seed" for the SASE runs presented here was shot noise, which is modeled by adding the appropriate random $\delta\psi$ and δx to the particles's initial uniform longitudinal phase and transverse coordinates respectively.

In order to minimize CPU time, most runs were done in an "1D" mode where both the EM field and beam current are modeled by their on-axis densities. These runs are useful in checking the theoretical results summarized in the Introduction, but neglect effects such as diffraction, emittance, and betatron motion which may play an important role in restricting $\Delta\omega/\omega_o$.

III. Results

We did a series of 1D GINGER simulations, varying the current from 2.5 kA to 0.5 kA keeping all other parameters constant (see Table 1). We adopt, as a "standard case", the parameters of Ref. [1]; namely, $I_b = 2.5\,\mathrm{kA}$ and $\varepsilon_n(\mathrm{rms}) = 3.0\,\mathrm{mm\text{-}mrad}$. The rms beam radius of 66 μm corresponds to that expected from external quadrupole focusing with $\beta = 10\,\mathrm{m}$. Note that this focusing is much greater than the "natural" wiggler focusing. Save for the lowest current density run, saturation occurred well within the chosen wiggler length of 83 m. Plots of the spectral power density show a Gaussian distribution with a width decreasing with increasing z until saturation, as predicted by [5] and others. To measure quantitatively the narrowing of the spectrum, we have computed the temporal autocorrelation function $C(\tau)$. Defining $\tau_{1/2}$ as the point at which $C(\tau)$ falls to a value of 0.5, a Gaussian spectrum distribution of width $\Delta\omega$ will follow

$$\Delta\omega/\omega_o \approx 1.18/\omega_o\tau_{1/2} \tag{6}$$

When the autocorrelation decreases exponentially[7] [*i.e.* $C(\tau) \propto \exp(-\tau/\tau_c)$], the numerical factor increases to ≈ 1.39. Table 1 presents values for $\tau_{1/2}$ and $\Delta\omega/\omega_o$ for the various 1D runs, together with the predicted [*c.f.* Eq.(4)-(5)] and measured values of the effective input power, saturated power and N_{sat}. In general, there is very good agreement between the measured and predicted values, and, furthermore, the growth of $\tau_{1/2}$ with z, as shown in Fig. 1, also confirms the predictions of Eq. (3).

A limited number of 2D GINGER simulations, which include both diffraction and the increased effective energy spread from beam emittance and external focusing, were done for the standard case. The results (see the last row of Table 1) showed larger required distance for saturation, lower saturated power, and reduced spectral bandwidth. The 2D runs shows transverse coherence being established rapidly (*e.g.* within a couple of gain lengths) and excellent optical beam quality at saturation (Strehl ratios of 0.98 or greater). Diffraction (the Rayleigh range is only $\approx 2\,\mathrm{m}$) plays a key role in narrowing the gain curve and thus determining the output spectrum. Fig. 2 shows the spectrum at saturation; since this corresponds to only ≈ 25 fs of a 150-fs micropulse, one should do a mental "ensemble" average of $P(\lambda)$ to obtain a more realistic estimate of the spectral profile. A second 2D run increased the external focusing by a factor of two (*i.e.* $\beta = 5\,\mathrm{m}$), thereby decreasing the electron beam area and Rayleigh range by the same factor. The saturated power increased to 27 GW, nearly the

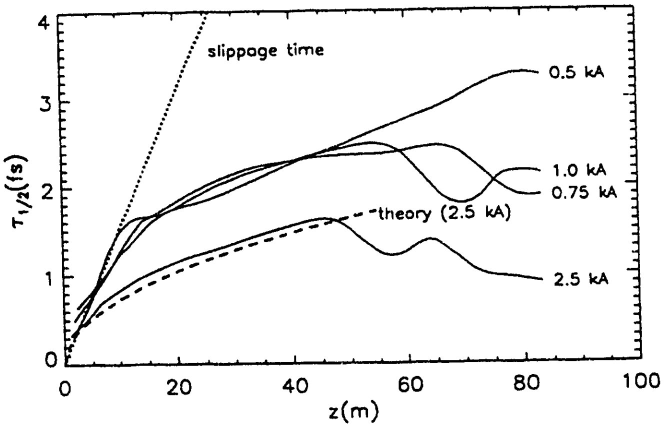

Figure 1: The autocorrelation time $\tau_{1/2}$ versus z for different beam current values; the data are from 1D simulations. The region to the upper left of the dotted line label "slippage time" is forbidden due to causality. The dashed line labeled "theory" corresponds to Eq. (3) and (6).

same as the standard case 1D run, but $\tau_{1/2}$ decreased (to 1.8 fs). Reducing β further to 3 m led to no further power gain but, beginning near the saturation point of $z = 50$ m, the transverse mode quality began to decrease rapidly. As a side note, *monochromatic* 2D runs initiated with 160 W of field power produced saturated powers of 15 GW for the standard case for $\beta = 5$ and 10 m.

We also ran a few 1D simulations with tapered wigglers, in which a_w was appropriately reduced with z to keep a design particle ($\psi_r \equiv 0.35$) at a constant longitudinal phase. Although the output power at $z = 83$ m increased significantly (300 GW for $I_{beam} = 2.5$ kA, 40 GW for 1.0 kA), the output spectral bandwidth increased by 30% or greater compared with the values at power saturation to the untapered wiggler cases. Some of this increase may be due to the peak of the gain curve shifting in wavelength from the nominal value of 4 nm in the untapered regime; this shift might be prevented by a "better" tapering strategy. On the other hand, we have seen no evidence from these 1D simulations that the bandwidth *decreases* from its minimum value at saturation.

IV. Discussion

The results from our simulations confirm the previous theoretical predictions concerning required saturation length, saturated power, and spectral bandwidth for a single-pass FEL amplifier initiated by SASE. Although the predicted power at saturation for a full 2D run is $\approx 40\%$ less than that from 1D theory, this bad news is partially ameliorated by a simultaneous 40% decrease in output spectral bandwidth. If it is desirable for particular applications to reduce ω/ω_o further, it may be necessary to reduce I_b since $\omega/\omega_o \sim \rho \sim I_b^{1/3}$. This would have the consequence of reducing P_{sat} which scales as $I_b^{4/3}$ for an untapered wiggler. Tapering may restore much or all of this lost power while keeping the bandwidth small, but we caution that the output power and electric field is expected to be "spiky" in time (rather than in optical phase which is more common for many chemical lasers). This spikiness might preclude certain applications. Both these changes (lower I_b, tapering) will, of course, require a longer wiggler.

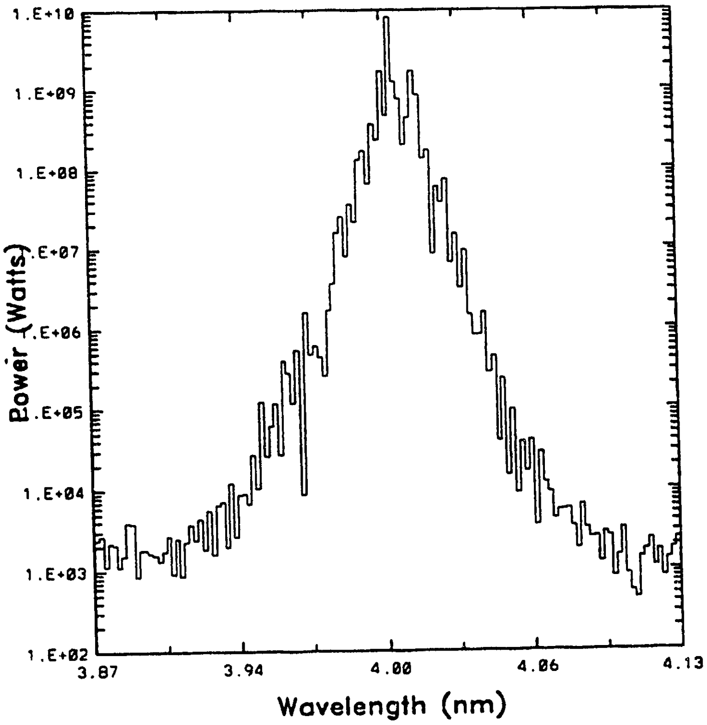

Figure 2: The spectrum at saturation from a 2D GINGER simulation for the "standard case". The power is binned into wavelength intervals of .002 nm.

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