Numerical Study of the 3-D Effect on FEL Performance and Its Application to the APS LEUTL FEL *

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I. Introduction

A Low-Energy Undulator Test Line (LEUTL) is under construction at the Advanced Photon Source (APS) [1]. In LEUTL periodic focusing is provided by external quadrupoles. This results in an elliptical beam with its betatron oscillation envelope varying along the undulators. The free-electron laser (FEL) interaction with such a beam will exhibit truly 3-D effects. Thus the investigation of 3-D effects is important in optimizing the FEL performance. The programs GINGER [2] and TDA3D [3], coupled with theoretically known facts, have been used for this purpose. Both programs are fully 3-D in moving the particle, but model the interaction between particles and axially symmetric electromagnetic waves. Even though TDA3D can include a few azimuthal modes in the interaction, it is still not a fully 3-D FEL code. However, we show that these 2-D programs can still be used for an elliptical beam whose aspect ratio is within certain limits.

We present numerical results of FEL performance for the circular beam, the elliptical beam, and finally for the beam in the realistic LEUTL lattice.

II. Matched, Circular Beam

In this section we assume a long planar undulator with symmetric x-y focusing whose strength is half of the natural undulator focusing. We also assume that the electron beam is matched, namely the envelope of betatron oscillation is constant along the undulator. With these assumptions we present in Table 1 a set of parameters of the LEUTL FEL that can be considered as nominal values for this study.

Table 1
Nominal Parameters for LEUTL FEL

Energy	E	220.0	MeV
Energy Spread	dE	0.1	%
Norm. Emittance (rms)	ϵ_n	5.0	mm-mrad
Undulator Period	λ_w	3.3	cm
Undulator Parameter (Peak)	K	3.1	
Matched β	β_0	1.46	m
Wavelength	λ_r	516.75	nm

We used the parameterization developed by M. Xie [4] in order to estimate the FEL performance and compare with the result from the GINGER simulation operated in SASE mode. The agreements in the saturation power and length are excellent, as shown in Figure 1. Also shown are the results from TDA3D and GINGER operating in single-frequency FRED mode. The gain lengths from the simulations and theory are similar to within two percent.

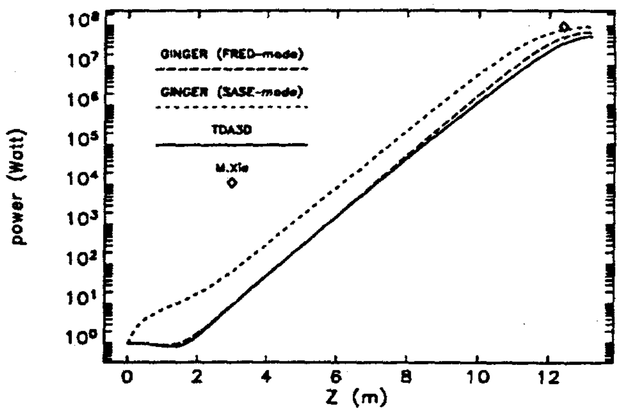

Figure 1
Comparison of results from GINGER (SASE and FRED) and TDA3D and M. Xie's formula.

III. Matched, Elliptical Beam

For design optimization we considered betatron focusing, which is asymmetric in the x and y directions. The matched beam will have elliptical cross section. We used a three-dimensional FEL theory generalized to this case [5]. There it was shown that the growth rate of the fundamental guided mode can be expressed by using six dimensionless scaling parameters

$$\frac{Re(q)}{k_w D} = F\left(2k_1\epsilon_x, 2k_1\epsilon_y, \frac{\sigma_\gamma}{D}, \frac{k_{\beta x}}{k_w D}, \frac{k_{\beta y}}{k_w D}, \frac{k-k_1}{k_1 D}\right), \quad (1)$$

where $Re(q)$ is the growth rate in the exponential growth regime. The growth rate is related to the power gain length L_g as $Re(q) = 1/2L_g$.

We solved the dispersion relation, specifically Eq. (39) in Ref. [5], to obtain the growth rate $Re(q)$ for a Gaussian beam. One of the results is shown in Figure 2, where we varied the aspect ratio σ_x/σ_y while keeping the cross-sectional area the same as the circular beam considered in the previous section. The growth rate is normalized by the circular beam results.

Based on the above results, we can make the aspect ratio of the beam in the LEUTL FEL less than 2 and only suffer a reduction in the growth rate of less than 5% compared with the matched, circular beam case.

Also presented in the figure are the results from TDA3D. These results were generated using only circular optical mode, whereas the results from theory are generated using the correctly matched elliptical optical mode. From these results we see that the growth rates of the two fundamental

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guide mode types, circular or elliptical, are very close to one another up to an aspect ratio of 3. This has practical implication in that the beam aspect ratio along the LEUTL lattice will be less than 2. We see that we still can use the 2-D program in estimating the performance of the LEUTL FEL.

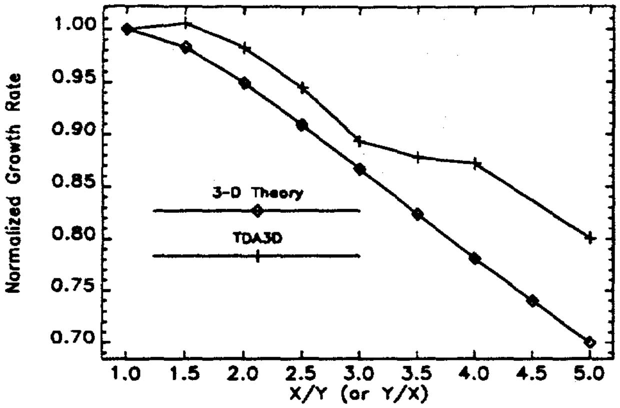

Figure 2
Growth rate as functions of beam aspect ratios.

IV. Beam in LEUTL Lattice

The undulators in LEUTL are separated by a drift where a horizontally focusing quadrupole is located. Each planar undulator provides the necessary vertical focusing to the beam. The lattice then is FOFO in the horizontal plane and FODO in the vertical plane. The horizontal/vertical phase advance per sector is $110^0/120^0$, respectively. The maximum β-function beat occurs in the middle of the undulator where $\beta_y/\beta_x \sim 2.0$. The periodicity of the electron beam envelope, an output generated by the TDA3D simulation, is shown in Figure 3. Also shown is the radiation beam size along the LEUTL. This clearly shows the gain-guiding in the undulators and the diffraction in the drift spaces.

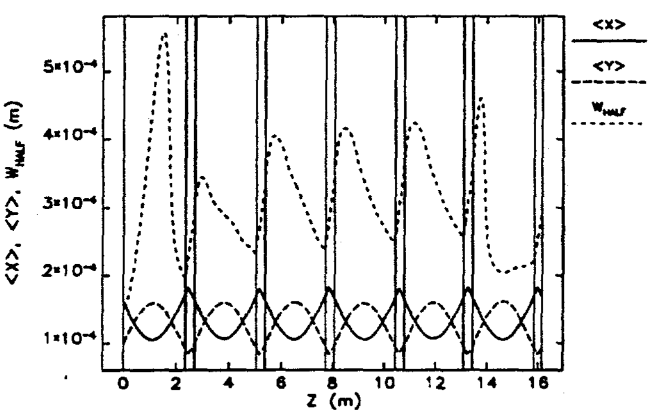

Figure 3
Electron and radiation beam size variation along LEUTL FEL.

Using TDA3D simulation, the exponential gain in the LEUTL FEL is shown in Figure 4.

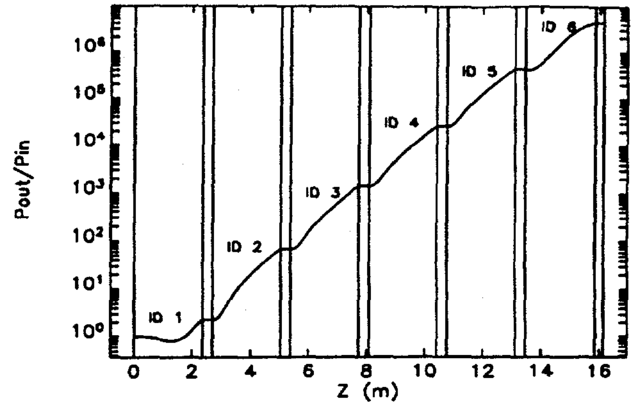

Figure 4
Gain along the LEUTL FEL.

Finally, we show a result for the undulators with an error in K. We consider three undulators of which the middle one has an error ΔK. Figure 5 shows the results from TDA3D for $\Delta K/K = 0$, $\pm 0.5\%$. For $\Delta K > 0$ the gain is considerably reduced, but the growth rate becomes larger than ΔK=0 in the third undulator and consequently ends with better performance. This shows the effect of tapering and an optimization on the saturation length is underway.

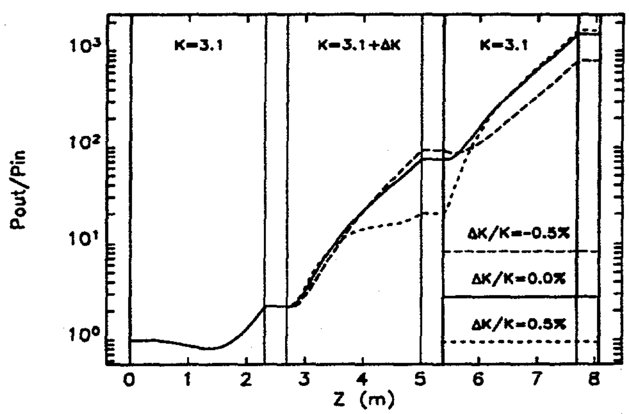

Figure 5
Effects of gap variation (tapering).

V. Acknowledgments

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VI. References

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