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Alignment and Magnet Error Tolerances for the LCLS X-Ray FEL*

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Abstract

We have examined the influence of misalignments and magnet errors on the predicted performance of the Linac Coherent Light Source (LCLS). Due to the extremely large number of wiggler periods ($> 10^3$) and the small optical mode size ($20\ \mu$m), alignment and magnet tolerances will be quite demanding. These demands may increase if the wiggler is split into separate sections by the possible inclusion of diagnostic stations, dispersive sections, *etc.* We have attempted to quantify such tolerances using the numerical simulation code FRED-3D.

1 INTRODUCTION

The LCLS is a multi-institutional proposal for a single-pass x-ray FEL operating in the 1-2 Å wavelength region, using electron beams from the SLAC linac at $\sim$ 15 GeV energy [1]. The effect of field and steering errors on the performance of an X-Ray FEL operating at an optical wavelength of 4 nm based on a 7 GeV electron beam from the SLAC linac has been studied before by Kim et. al. [2]. Since then the proposed target wavelength for the LCLS project has been reduced. This change was based on the results of the workshop on Scientific Applications of Coherent X-Rays [3] held at SLAC in 1994. The change in wavelength required a reduction in electron beam emittance by more than an order of magnitude to stay at the diffraction limit given by $\lambda/2\pi$. This could be achieved by an increase in electron energy and by making use of further progress in the development of low emittance guns, reducing the projected value for the normalized emittance from 3 down to 1 mm mrad. The resulting emittance is still larger than $\lambda/2\pi$ but, as fig. 1 shows, the decrease in FEL performance is expected to be moderate. With the optimum β-function basically unchanged, the transverse beam size is reduced by a factor of about 2.5. The tolerances for field and steering errors should scale approximately by this factor. The present paper presents the results of 3-D simulations for the new LCLS design, also comparing the two wiggler models that are presently discussed.

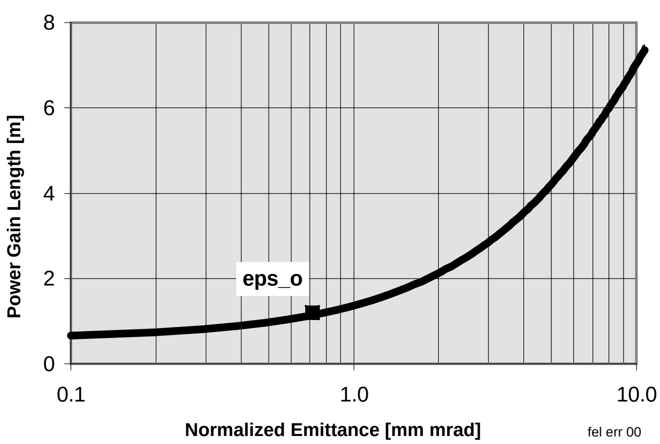

Figure 1: Power Gain Length vs. Normalized Emittance as a result of FRED-3D simulations for the helical wiggler."**eps_o**" marks the diffraction limited emittance at the optical wavelength of 1.5 Å.

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2 WIGGLER MODELS

Table 1: LCLS wiggler and FEL parameters

	SC	Hybrid
Type	Helical	Planar
Period Length	2.0 cm	3.0 cm
Optical Wavelength	1.5 Å	1.5 Å
K	3.4	3.7
Peak Field	1.8 T	1.3 T
Gap	0.6 mm	0.6 mm
Number of Periods	1500	1667
Wiggler Length	30 m	55 m
Focussing β	4.9 m/rad	10 m/rad
RMS Beam Radius	19 μm	13 μm
Pierce Parameter ρ	7.4×10^{-4}	7.4×10^{-4}
Gain Length	1.5 m	3.1 m

The wiggler models that are presently considered include a Superconducting Helical Wiggler [4] and a Planar Neodymium-Iron Hybrid Wiggler. The optimized parameters [5] are listed in table 1. The electron beam parameters are listed in table 2.

Table 2: LCLS electron beam parameters

RMS Bunch Length	30 μm
R¡S Bunch Length	100 fs
Normalized RMS Emittance	1.5 mm mrad
Uncorrelated RMS Energy Spread	2×10^{-4}
Electron Energy	15 GeV

3 WIGGLER ERRORS

Error fields can arise from (1) iron pole, Electromagnetic coil, and/or Permanent Magnet (PM) positioning/orientation errors, (2) PM strength and global/local easy-axis misorientation errors, and (3) iron nonuniformities, including saturation effects. Symmetric field errors $\Delta B_y(z)$ are perpendicular to the midplane in the midplane and lead to both a horizontal displacement and steering of the beam. Antisymmetric field errors are parallel to the midplane in the midplane. Those errors $\Delta B_z(z)$ that are also parallel to the electron trajectory have no detrimental effects. Those errors $\Delta B_x(z)$ parallel to the midplane, but perpendicular to the electron trajectory, cause vertical beam steering and displacement. In the ironless helical superconducting wiggler, field errors are dominated by positioning errors of the superconducting coil, which can arise either during the manufacturing process or from magnetic forces during training. There is no iron surface present to channel magnetic flux and thereby govern the field distribution as in the case of the planar hybrid design. Magnetic material placed near the coils can also alter the field on-axis. Mispositioning of the magnetic structure itself or variation of the period length give rise to systematic phase errors. If the electron beam is misoriented with respect to the wiggler magnetic structure or if wiggler sections are not coaxial then steering errors can arise.

4 FRED-3D SIMULATION CODE

The simulations in this paper have been done with the FRED-3D [6] simulation code on the NERSC computer systems at LLNL. FRED-3D simulates the interaction between the electron beam and optical field in the wiggler of an FEL amplifier. The effects of random pole-to-pole errors in the wiggler magnetic field on the centroid motion of the electron beam and on relative electron-to-radiation phase are included: in each half-period, a transverse momentum increment corresponding to the magnetic field error at that magnetic pole is added to the motion of each particle. The field errors are chosen from a truncated Gaussian distribution. The RMS fractional field error and truncation level are specified as input parameters; for this paper, truncation at three standard deviations is used. The transverse random walk of the electron beam generated by these errors reduces the overlap between the electron and photon beams and causes dephasing of the electrons with respect to the FEL ponderomotive potential wells.

The random walk can be partially corrected in FRED-3D by introducing "steering stations", at which the position of the electron beam is measured and a transverse momentum kick is applied to steer the electron beam onto the axis at the next steering station. The position measurement is assumed to be imperfect, with specifiable errors in the accuracy with which the beam position monitors are aligned and the accuracy with which they can measure the beam position. In addition, an overall displacement and tilt of an average beam position monitor axis from the wiggler axis can be specified. The positions of steering stations along the wiggler axis and the magnitude of the steering errors are inputs to the code.

FRED-3D does not explicitly include the phase effects of random fluctuations in the wiggler period, because the cumulative effect of these fluctuations over many periods should be identical to a slight change in wiggler period, which can be simulated by permitting the period to change between wiggler sections.

5 ERROR ANALYSIS

5.1 *Wiggler Magnetization Errors (Field Errors)*

The sensitivity of wiggler output power on wiggler magnetization errors has been studied.

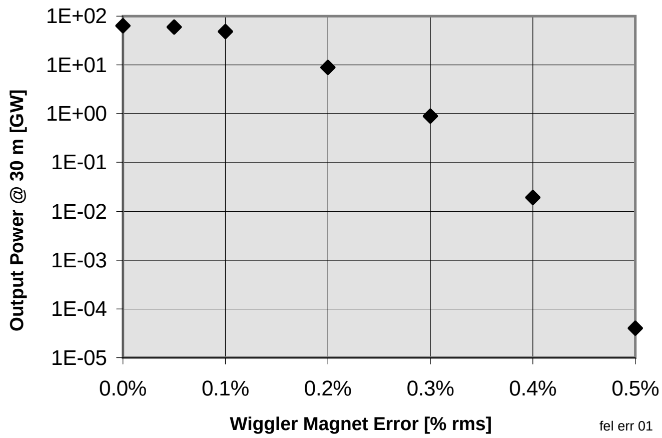

Figure 2: Output Power vs. Magnet Errors for Helical Wiggler

Figs 2 and 3 show the effect of random fluctuations of the on-axis peak magnetic field on the FEL power when using error-free steering stations separated by 2.5 m. Error bars, which are significant for large values of the rms wiggler error, are not shown. The peak power levels[1] are shown for wiggler lengths at which the error free device would saturate, i.e. at 30 m for the helical and at 55 m for the planar wiggler, *resp.* The output power levels drop by a factor of two for RMS error levels of about 0.15 %.

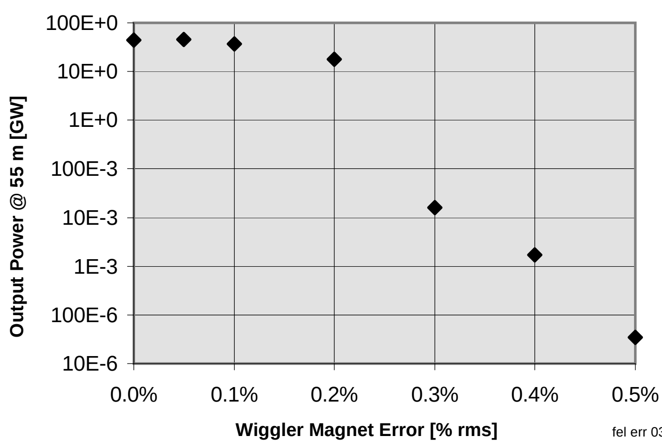

Figure 3: Output Power vs. Magnet Errors for Planar Wiggler

A detailed analysis of topics such as a comparison of global and local error tolerances and the relative contribution of dephasing of the electrons and reduction in beam overlap has not been done yet. Work by Yu et. al. [7] indicate that the performance reduction due to dephasing should be significantly less than the results that we get for the combined effect.

[1] 1 kW of input power has been used in the simulations since FRED-3D does not simulate startup from noise

The natural focussing of the wiggler is not strong enough at the operational energy. Strong external focussing is required to achieve the optimum beta functions as listed in table 1. While the simulations used a constant focussing gradient along the wiggler axis, in practice it is more likely that a lattice of separate quadrupole magnets (FODO) will be used. Required integrated quadrupole strengths are 10 T for the helical and 5 T for the planar wiggler. If the electron beam passes off-axis through the quadrupole magnets it will experience additional transverse kicks. To keep these kicks at the same level as those produced by wiggler errors (0.15 %), transverse alignment tolerances for the quadrupoles of a few micro-meter are necessary.

5.2 Steering Errors

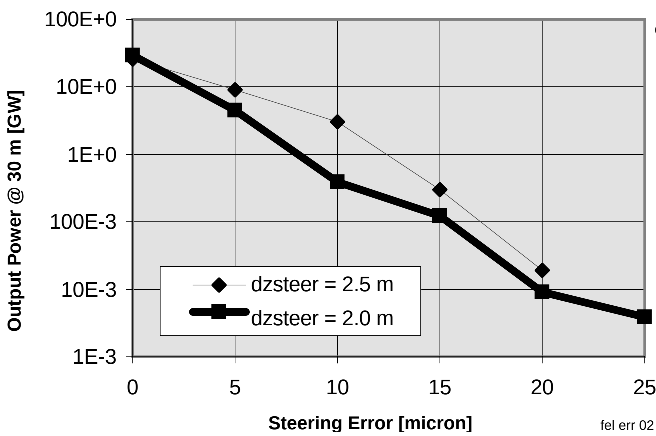

Figure 4: Output Power vs. Steering Errors for Helical Wiggler

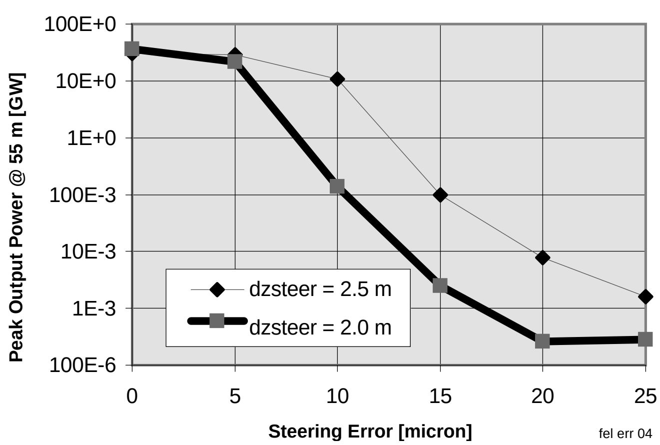

Figure 5: Output Power vs. Steering Errors for Planar Wiggler

Figs 4 and 5 show the effect of steering errors for the helical and planar wiggler models as result of the simulations. Field amplitude fluctuations of 0.15 % were used in both cases. Each figure shows the result for two different separations of the steering stations: 2.0 and 2.5 m. With steering errors present, FEL performance decreases when steering stations are spaced too closely. The optimum spacing of the steering stations for the planar wiggler is between 2.5 and 5 m (for an RMS steering error of 10 μm).

Fig. 6 shows the effect of separating 5 m long wiggler sections by short drift spaces to simplify modular assembly and to provide space for diagnostics, vacuum pumps *etc.* The simulations used an rms magnetization error of 0.15 %, a separation of steering stations of 5 m and a steering error of 10 μm. The performance

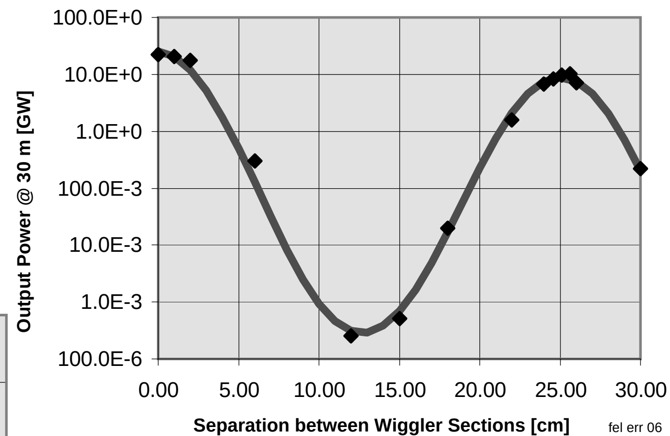

Figure 6: Output Power vs. Section Separation for Helical Wiggler

drops significantly due to phase slippage for separations $\mathbf{L_{sep}}$ shorter than about 25 cm, at which point the slippage distance $(1-\beta)\mathbf{L_{sep}}$ is equal to one optical wavelength $\lambda_\mathbf{r}$. Using $(1-\beta)\approx 1/2\gamma^2$ and the FEL resonance condition one gets for the first matching separation $\mathbf{L_{sep}^{match}} \approx 2\gamma^2\lambda_\mathbf{r} = \lambda_\mathbf{w}(1+\mathbf{K}^2)$=25.12 cm for the helical wiggler, which for high energies is independent of both the energy and the radiation wavelength. This has been shown by Kim et. al. [8]. Thus, wiggler section separations need not affect FEL tunability, if tuning is done with γ. Tuning cannot be done by using K.

6 REFERENCES

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