# STUDIES OF LCLS FEL DIVERGENCE*

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*Abstract*

Simulations show various impacts on x-ray divergence. With the motivation to maximize intensity at the focus, these LCLS beam studies were designed to study parameter space and beam qualities impacting divergence, and therefore aperture related clipping and diffraction. With multiple simultaneous users, beam constraints increase, requiring an improving knowledge of the mechanism of impact of changing parameters. These studies have that goal in order to improve beam control.

## MOTIVATION

Intensity lost at the focus is a strong function of capture by the mirror systems given the impact of diffraction, see Figure 1.

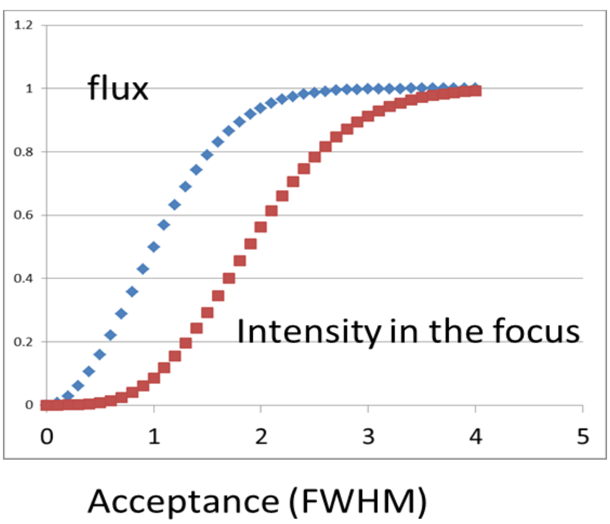


Figure 1: Vertical axis is relative intensity, horizontal axis acceptance of mirror systems cutting in both planes. Blue line is the intensity cut off by mirrors. Red line is the intensity at a downstream focus. Diffraction effects are taken into account.

## STUDY APPROACH

We have made many measurements in the Front End Enclosure (FEE) where the distance is relatively close, 87 meters from the end of the undulator. Since increasing the FEL intensity via longitudinal collimation [1] (see Y. Ding's WEP024), we run into the dilemma of either saturating our diagnostic (YAGs) or attenuating the fundamental to the point where third harmonic will begin to impact the measurement. So we extend our measurements to a diagnostic near the Far Hall (FEH) 335 meters from the end of the undulator (Figure 2).

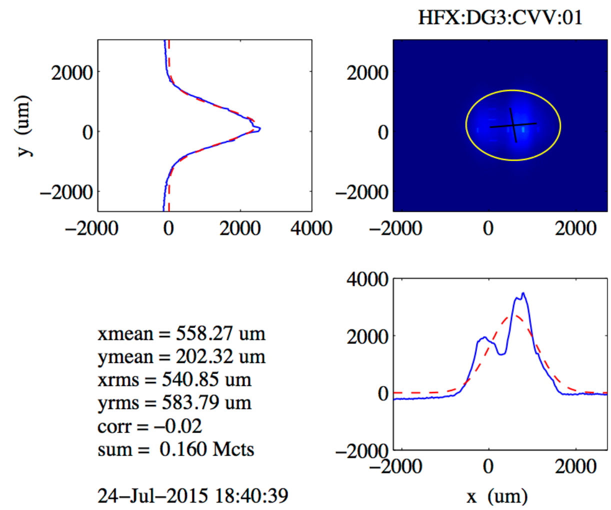


Figure 2: Beam size measured at the Far Hall 335 meters from the end of the undulator. Energy is 8.2 keV. Note the horizontal distortion is due to mirror figure error and diffraction effects [2].

### *Divergence Model*

We applied Z. Huang and K. J. Kim approximation [3], derived in the linear regime, to calculate the photon source size (eq. 2) and the divergence (eq. 3). 1D gain length $L_{1D}$, in the equation 1, was generated using the Ming Xie parameterization [4]

$$\sigma_D = \sqrt{\lambda L_{1D} / 4\pi} \tag{1}$$

$$\sigma_{ph} \approx \sqrt{\sigma_D \sigma_{el}} \tag{2}$$

$$\sigma_\vartheta = \lambda / 4\pi\sigma_{ph} \tag{3}$$

Figure 3 shows confidence in the Z. Huang and K.J. Kim model (HK model) by corroboration with start to end simulation, which were performed using the GENESIS code [5]. The simulation produces a curved wave front at the end of the undulator, which is then back propagated to the source point, and forward propagated to imager points (see Figure 5).

Figure 4 shows that simulation at 300eV indicates the HK model, derived in the linear regime, should also be good in the non-linear regime.

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-AC02-76SF00515.

ISBN 978-3-95450-134-2

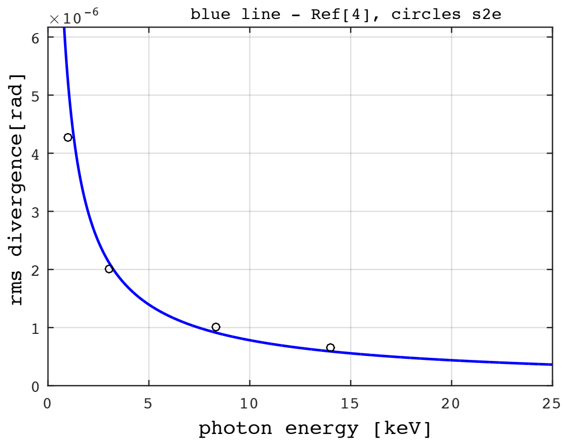


Figure 3: HK Divergence Model (blue line) compared to start-to-end simulations and forward propagation (circles).

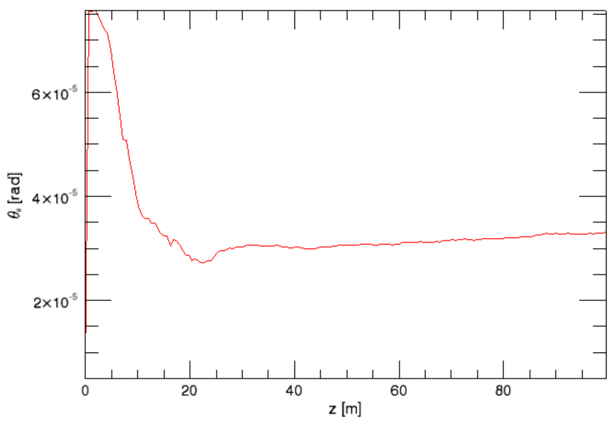


Figure 4: Simulation indicates that at 300 eV there is very small divergence change in the non-linear growth regime. This indicates the HK model should also predict divergence in the non-linear regime.

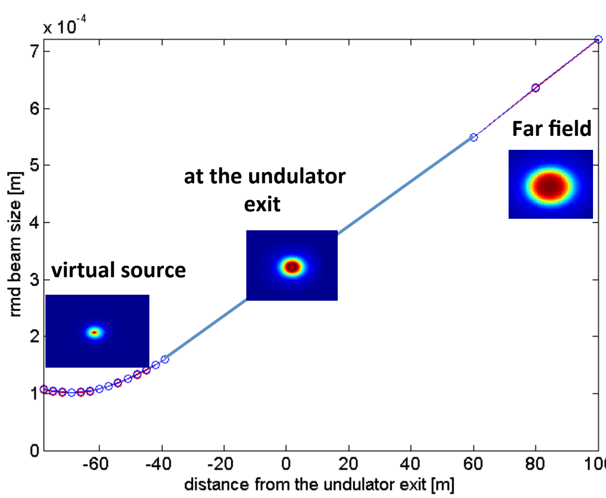


Figure 5: Simulation gives wave front at the exit of the undulator, then it is propagated backward and forward giving the waist (source) and the far field.

## *Measurements*

X-ray beam profile and from that divergence measurements were made both at the 87 meter point and the 335 meter point at various energies near 9 keV. Profiles are fit with a Gaussian and rms values are recorded. Figure 6 shows simulation and model from Figure 3 with measurement results of various operating conditions landing within the rectangle drawn on the plot. This discrepancy of 1.5-2 μrad instead of near 1.0 μrad is the object of study.

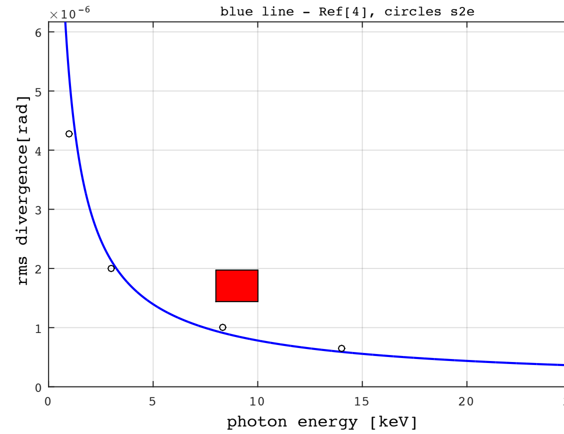


Figure 6: Recent hard x-ray divergence measurements over the past year are represented by the red rectangle.

At 8.2 keV studies were done to understand the difference between measurement and model. Electron beam beta-match in the undulator and undulator alignment were studied.

Beta match in the undulator required expert measurements of electron beam beta-match in the undulator using “beam finder wires” which were originally installed for alignment purposes. Measurement and matching using wire scanners upstream of the undulator leads to very good match in the undulator implying a good model of optics from the wires through the undulator. See Figure 7.

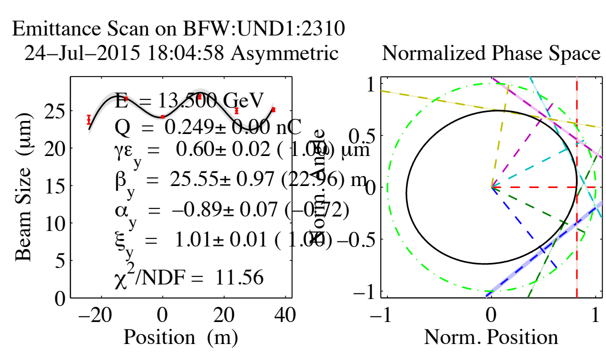


Figure 7: Vertical beta measurement in the undulator using 6 “beam finder wires”. Beta match parameter is 1.01 +/- 0.01 with perfect being 1.0.



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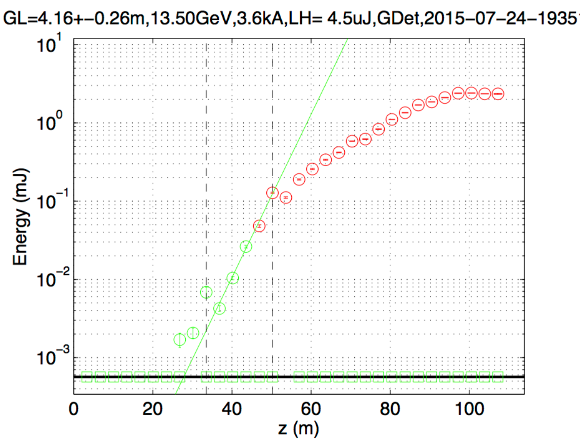


Figure 8: The gain length is measured by a system of gas detector PMTs (photomultiplier tubes) at different high voltage settings to achieve a large dynamic range.

Gain length was measured to insure input to our model was accurate see Figure 8 above.

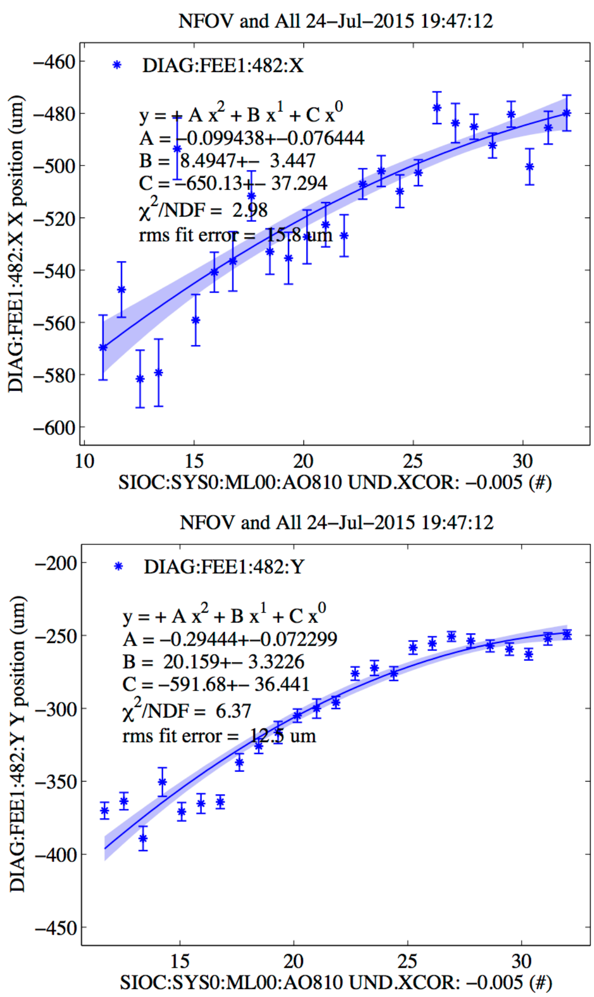


Figure 9: Electron beam is kicked at different points to suppress lasing beyond each point. X-ray position is measured at the imager 87 meters after the undulator.

Curvature of the electron orbit in the undulator was measured in the matched, 4 meter gainlength, 8.2 keV condition shown in Figure 9. Horizontal motion is the top plot, and vertical the bottom.

The electron beta match was varied using a single defocussing quadrupole. The out of plane match change was measured to be very small.

BMAG shown in the bottom plot of Figure 10 is an effective size magnification factor indicating how well the electron beta function is matched [6]. The matched condition was with the quadrupole at -91.4 kG.

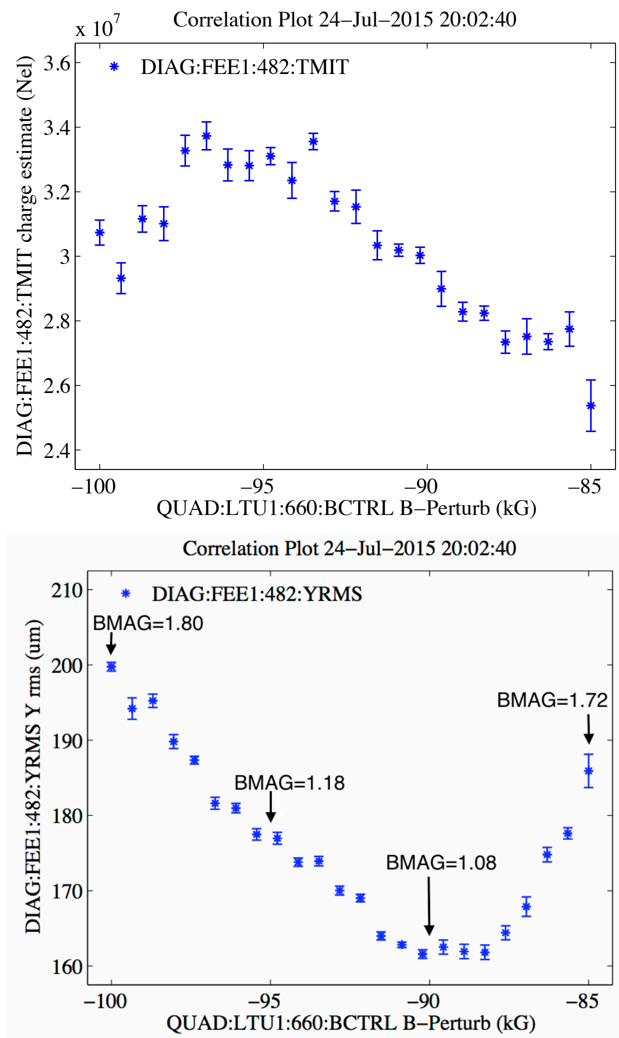


Figure 10: Top plot: x-ray intensity varies with quadrupole scan. Bottom plot: beam divergence changes with match change in the undulator.

## SUMMARY

The hard x-ray divergence in LCLS still has an unknown factor of about 1.5 to 2.0 with respect to theory. Studies and improvements in theory and measurement toward understanding are on-going.

Orbit curvature doesn't appear large enough to cause this divergence discrepancy.

Study of matching vertical beta function into the undulator shows minimum divergence in the matched

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condition as simulated by S. Reiche [7]. The intensity upstream of any x-ray focussing is not greatest at that matched condition however.

For normal operation, measurements of electron beam beta-match and x-ray divergence become very important when experiments are working in the focus.

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