AN EXPERIMENTAL STUDY OF THE BEAM-STEERING EFFECT ON THE FEL GAIN AT LEUTL'S SEGMENTED UNDULATORS*

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Abstract

The electron trajectories at the low-energy undulator test line (LEUTL), a self-amplified spontaneous emission (SASE) free-electron laser (FEL) facility at Argonne, were routinely corrected during the user run in order to deliver maximum radiation power to the user. Even though we knew from experience that SASE gain at the segmented undulators was dependent on the trajectory, the quantitative understanding of steering effects associated with the specific trajectory was lacking. Recently Tanaka et al. [1] proposed an analytical model for the single-kick error (SKE) effect. Since the LEUTL has eight segmented undulators, we performed the first measurement of SKE on the FEL gain. In the experiments we varied the corrector strength up to the critical angle, and the gain over the undulator was measured for each corrector setting. The results were compared with the analytical model and GENESIS simulations. We also measured the e-beam positions and SASE intensities over the undulators. The experimental data were analyzed and their results were reproduced by GENESIS simulation. The simulation condition, including the measured not-so-ideal trajectory, was used to predict performance enhancements that could be achieved by upgrading e-beam current, e-beam emittance, or trajectory control.

EXPERIMENTAL SETUP

The low-energy undulator test line (LEUTL) is the Advanced Photon Source's self-amplified spontaneous emission (SASE) free-electron laser (FEL) facility, which has shown high gain and saturation near 530 nm and 385 nm, as reported elsewhere [2]. The schematic of the facility is shown in Fig. 1, which includes a photocathode rf-gun, a 650-MeV linac, 3-screen emittance measurement area, and undulators with diagnostic stations between them.

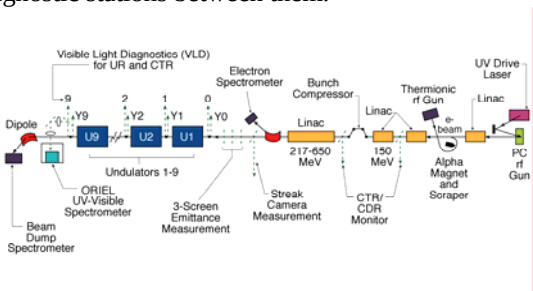

Figure 1: Schematic of APS SASE FEL experiment.

The experiments were performed around the fifth undulator ID-5, which also includes a horizontally focusing quadrupole, a steering coil, and a reflecting mirror that transports the radiation to VUV cameras, as shown in Fig. 2.

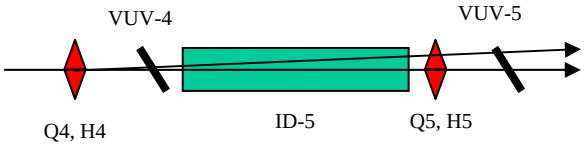

Figure 2: Schematic of a segmented undulator used for single-kick-error (SKE) measurement; shown are quadrupoles Q4 and Q5 with steering coils H4 and H5, mirror and cameras VUV-4 and VUV-5, and the fifth undulator ID-5 over which we measure the gain of SASE radiation.

During experiment we steered the orbit by using the H4 corrector. For a given H4 strength we record the radiation images by using cameras VUV-4 and VUV-5 before and after undulator ID-5. The undulator radiation by SASE was used to measure the gain over the undulator. The coherent transition radiation (CTR) was used not only to measure the electron beam's microbunching but also to measure the beam's position in order to estimate the steering angle. The CTR is generated by interaction of a 6-μm-thick Al foil and the beam, as describe in Ref. [3]. The angle estimate is based on the fact that in the horizontal plane the undulator is a drift space where the e-beam's trajectory is straight. For each radiation type, SASE or CTR, we took near-field and far-field imaging. Because of the statistical nature of the SASE process, we took 100 images of each type of radiation for a given steering angle.

At the beginning of the experiment we established a reference orbit that should provide exponential gain over ID-5 but should not be saturated there. The experimental conditions were radiation wavelength λ=130 nm, beam energy E=439 MeV, charge Q=250 pC, FWHM pulse length σ_t=250 fs, energy spread σ_E=0.15%, and normalized emittance $\varepsilon_x/\varepsilon_y$=4.5/3.5 π mm-mrad, respectively. The measured SASE intensity along the undulators is shown in Fig. 3, where two results from processing near-field and far-field images are presented. The horizontal axis refers to the location after the nth-undulator.

Radiation power or intensity shown in Fig. 3 was estimated by integrating the intensities of image as follows: 1) project 100 images into the horizontal or vertical axis in order to obtain the profile in either

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plane, 2) take the average of 100 profiles to make a single profile representing the average state of the measurement condition, 3) set the baseline of the profile to zero as a background removal, and 4) integrate the profile in order to obtain the total intensity. Thus this total intensity represents the averaged power of 100 radiation pulses resulting from a given experimental condition. Since the background of the profile is different in the horizontal and vertical planes, the resultant intensities I_x and I_y are not necessarily the same. In order to have a unique quantity, we take the average of the two quantities $I=(I_x+I_y)/2$. The unit of intensity obtained this way is arbitrary, but the real radiation power is proportional to this quantity so that we can estimate the gain.

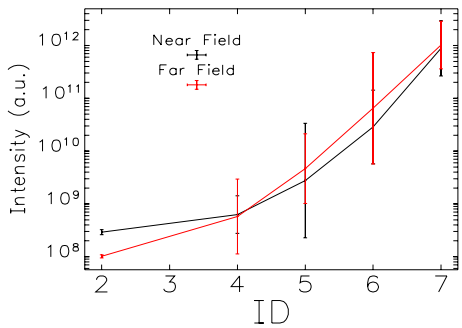

Figure 3: The z-dependent SASE power measurements at ID-2,4,5,6,7; both far-field and near-field results are included for comparison.

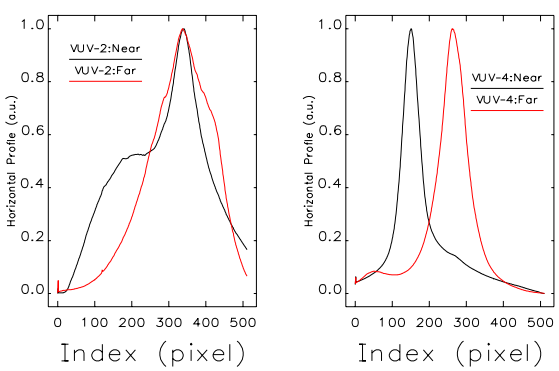

Figure 4: Horizontal profiles of undulator radiation images at two different locations at ID-2 and ID-4. The images from ID-2 in small-gain are displayed on the left and the ones from ID-4 in exponential gain are compared on the right. The far-field images in red provide better-defined profiles than the near-field images in black which have broader shoulders.

Far-field and near-field images were examined in order to explain the discrepancies shown in Fig. 3. We found that radiation profiles from near-field images have a broader shoulder than the far-field images shown in Fig. 4, which were taken at VUV-2 and VUV-4. Whether this shoulder resulted from the variation in trajectory or from the reflection in the light tube due to the limited acceptance is yet to be determined. We observed that the far-field images in general provide better-defined profiles with higher intensities. Thus we decided to use far-field images in measuring the intensity of the SASE pulse in the SKE experiment where we vary the steering angle.

SINGLE-KICK ERROR (SKE) EXPERIMENT

According to Tanaka's model [1] the gain will be degraded by the SKE due to two effects: 1) the mismatch between incoherent radiation with angle of incidence and coherent radiation with its wave-front normal in the z-direction and 2) the smearing of micro-bunching. Since the analysis of microbunching is incomplete when providing the results in bounded form, we only refer to the first case where we compare the experiment and the theory. The model predicts that the gain will be degraded according to

$$L_g' = \frac{L_g}{1-x^2}, \qquad (1)$$

where $x = \theta/\theta_c$. The critical angle is defined as $\theta_c = \sqrt{\lambda / L_g}$, where λ is the radiation wavelength and L_g is the gain length of ideal trajectory, and θ is the steering angle.

After we established the reference trajectory described in the previous section we adjusted the angle of trajectory by varying the corrector H4. A calibration was performed on H4 and found that it can steer 0.34 mrad/A. Since the critical angle of this experiment was estimated to be 0.4 mrad we decided to vary H4 by ±1 A with the respect to the currently set -0.7 A. For each H4 setting we measured the intensities at VUV-4 and VUV-5. Even though VUV-4 measurements shouldn't depend on the H4s, the repeated measurements were necessary in order to make sure that we could detect drift of beam condition while we were taking data for five hours.

The intensities as a function of H4 are shown at the top of Fig. 5. The black curve represents the intensity at VUV-4 showing we maintained steady beam operation, and the red curve gives the results at VUV-5 showing the significant variation on average power over the H4s. We also note large fluctuations at VUV-5, a characteristic of exponential gain regime. The ratio of average power between VUV-4 and VUV-5 is the gain to be compared with the SKE model of Eq. (1). At the same time we also acquired CTR images. The centroids of images representing the e-beam positions are also shown in Fig. 5 as a function of H4.

Data shown in Fig. 5 were processed in terms of gain and steering angle. The result is fitted by Eq. (1) with two parameters, the offset angle θ_0 in slightly generalized $x=(\theta_0-\theta)/\theta_c$ and the gain length L_g. We found θ_0 close to zero and L_g equal to 1.6 m. The comparison between the experiment and theory is

shown in Fig. 6. Since the critical angle with λ=130 nm and L_g=1.6 m is 0.28 mrad, two data points whose steering angles are greater than 0.3 mrad are out of range but still had small gain. One data point near 0.1 mrad, whose gain is far smaller than theory predicts, corresponds to the corrector setting H4=-0.2 A where the beam position didn't respond to the setting, as was revealed in Fig. 5. Thus we are suspicious about this data point, and we may disregard its validity in its gain. Other than that we have good agreement between the measurement and the model prediction.

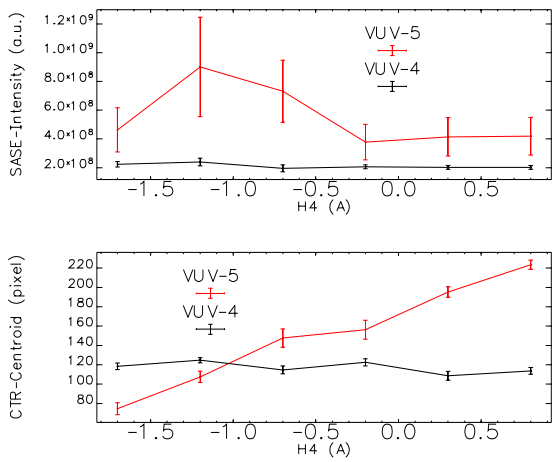

Figure 5: SASE radiation intensities measured by cameras VUV-4 and VUV-5 as a function of H4 (top) and electron beam position estimated by CTR images as a function of H4 (bottom)

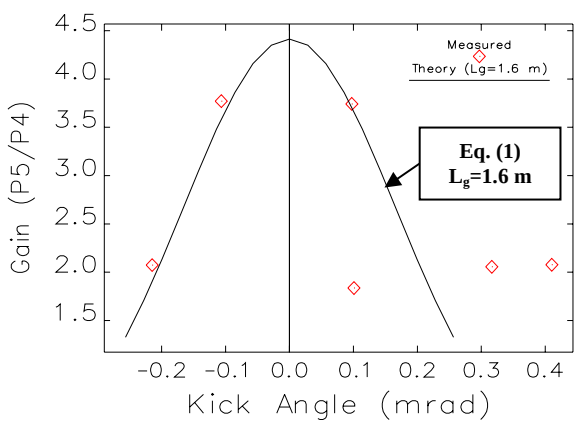

Figure 6: Measured gains as a function of steering angle compared with theory (Eq. (1)).

COMPARISON WITH SIMULATION

We used the GENESIS program [4] in order to compare the experimental results with simulation. The simulation conditions were the same as the experimental condition specified in the previous section. In the simulation we needed to vary the beam current in order to find the condition resulting in the gain length equal to 1.6 m. In the steady-state simulation we found the solution at 380 A, and in the SASE simulation the solution was 550 A for a given 250-fs pulse length.

Once we settled on the beam parameters, we varied the corrector in the GENESIS simulations in a segmented undulator configuration; both steady-state and SASE simulations were performed. All results, including experiment, theory, and simulations, are included in Fig. 7 and show good agreement with each other. We note that the theory and steady-state simulations have better agreement because the analytical model assumed DC beam. The results by pulsed beam, which represents a more realistic situation, indicates that the ideal gain length should be slightly shorter than 1.6 m in order to have a better fit.

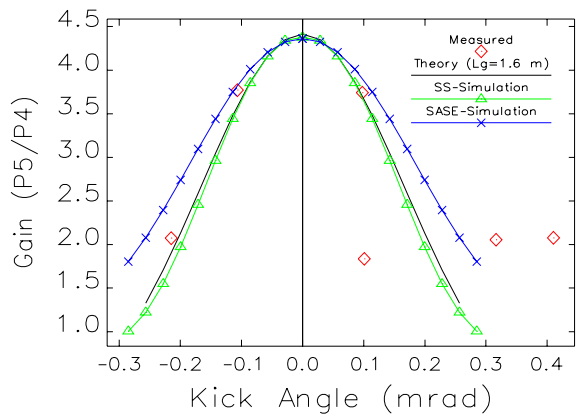

Figure 7: Gain vs. steering angle: experiment (diamond symbol), theory (black line), steady-state (SS) simulation (green line with symbol), time-dependent (SASE) simulation (blue line with symbol).

TRAJECTORY ANALYSIS

As we verified the steering effect quantitatively, we gained a better understanding of the importance of trajectory control in the segmented undulators. However, we questioned how much we could improve the FEL performance by correcting the trajectory. With this as motivation, we tried to reproduce by simulations the measured trajectory and z-dependent gains. Then, the simulation conditions found this way could be used to benchmark the effectiveness of trajectory control vs. upgrading other beam parameters such as beam current and beam emittances.

The first requirement for trajectory analysis is to determine the trajectory. Instead of relying on beam position monitors (BPMs) installed in the LEUTL tunnel, we used CTR images for determining e-beam positions. As usual, 100 shots of images were taken at the camera stationed between the undulators.

The trajectory responsible for the gain shown in Fig. 3 has been determined experimentally, and its results are depicted in Fig. 8, which includes the centroid coordinates of the e-beam and the alignment laser on the viewing screen. The difference between the two will be the beam position with respect to the alignment

laser; this trajectory is shown at the bottom of Fig. 8. Since not all stations have VUV or diagnostic cameras, we could only measure positions at VUV-2,4,5,6,7. Even though we measured both horizontal and vertical positions, we only took the horizontal trajectory into account in our simulation.

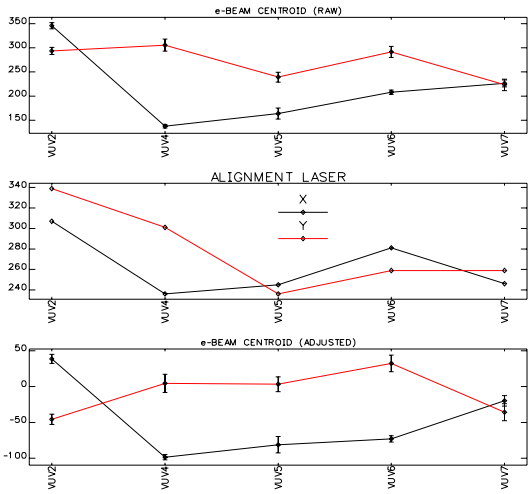

Figure 8: Trajectory measurement along the undulators by using CTR images: (top) electron beam centroid, (middle) alignment laser beam, (bottom) electron beam positions with respect to the alignment laser at VUV-2,4,5,6,7.

Since our measured trajectories were limited, we tried several simulated trajectories with right betatron oscillations. The most successful "guesstimate" is depicted in Fig. 9 together with measured beam positions. With these simulated trajectories we could reproduce the z-dependent gain quite accurately, as shown in Fig. 10. Because of this good agreement in gain measurement, we use this simulated trajectory testing in several performance upgrading scenarios.

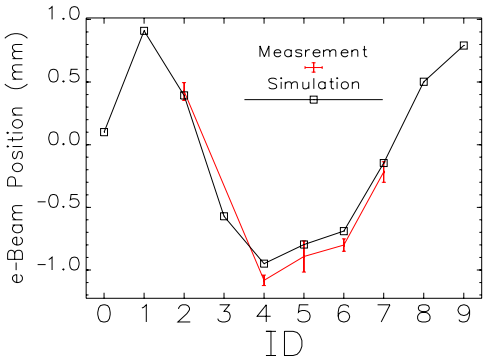

Figure 9: Measured beam positions and their simulated trajectories used in the GENESIS simulation.

For definite comparison we put three upgrade scenarios into one picture: 1) increase the beam current from 950 A to 1250 A, 2) reduce the beam emittance from 4.5/3.5 π mm-mrad to 3/3 π mm-mrad, and 3) correct trajectory to an ideal trajectory. The assumed amount of current and emittance improvement are arbitrary but within an achievable envelope in the near future as gun technology develops. Trajectory control requires improving BPM electronics in terms of sensitivity and gain bandwidth. The combination of improvements in both beam and trajectory is the ideal upgrade path, but we emphasize controlling trajectory could be easy and its effect would be immediate as evidenced by the simulation study shown in Fig. 11.

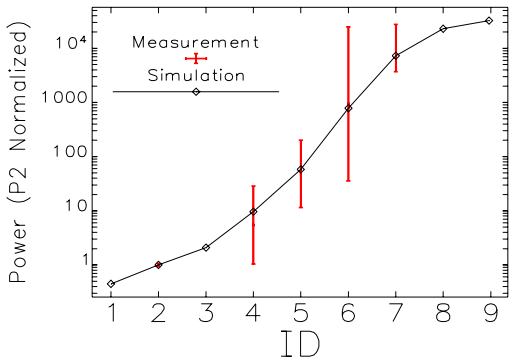

Figure 10: Measured gain at ID-2,4,5,6,7 and the corresponding simulation results. Power is normalized by the power at ID-2 or VUV-2.

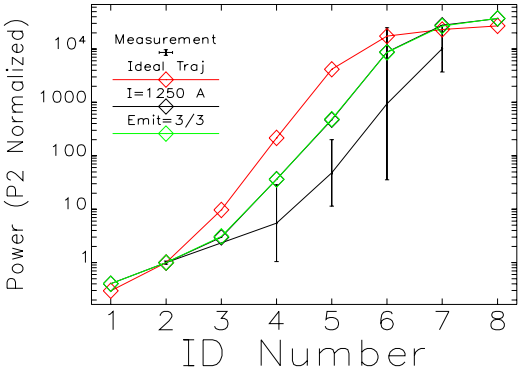

Figure 11: Comparison of performance upgrade options: 1) trajectory correction, 2) current increase, 3) emittance reduction.

SUMMARY

We measured the SKE effect for the first time, and we obtained good agreement between theory, experiment, and simulation. We also analyzed a measured trajectory to show that improving trajectory could be as important as improving the beam qualities.

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