MEASUREMENT OF LCLS HARD X-RAY UNDULATOR GAIN UNDER CBXFEL-LIKE CONDITIONS

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Abstract

Cavity-based XFEL, or CBXFEL, is a future highly-coherent photon source under construction at LCLS. In the first phase of the CBXFEL project, we will demonstrate the regenerative amplifier mode of operation with 7 LCLS Hard X-ray Undulators (HXUs). In this paper, we report on the recent measurement of the FEL gain in 7 LCLS HXUs, and hard x-ray self-seeding (HXRSS) under e-beam conditions close to those chosen for the first phase of CBXFEL.

INTRODUCTION

Cavity-based x-ray sources [1, 2] are envisioned to be the next generation of sources due to better temporal and spectral coherence than conventional self-amplified spontaneous emission (SASE) sources. Currently, several efforts are underway to build a cavity-based x-ray source: the CBXFEL and XLO projects at SLAC [3, 4], and the "CBXFEL-demonstrator" project at the EU-XFEL [5]. CBXFEL will operate at 9.831 keV photon energy corresponding to the $C^*(4,0,0)$ crystal reflection at 45.00°, forming a rectangular cavity with 7 LCLS HXUs inside. CBXFEL at LCLS will be using the first 7 undulators, flanked by two in-(out-)coupling e-beam chicanes which will in-couple two 220 ns spaced electron bunches from the LCLS Cu Accelerator [6]. X-rays produced from the first electron bunch with be monochromatized and returned to the beginning of the undulator line by the cavity to provide a seed for the second electron bunch. To ensure high gain in the lasing of the second electron bunch, we must provide a seed of sufficiently high power and spectral purity to overcome the SASE process at start-up. XFEL simulations assert that 7 undulators with ideal performance will provide a sufficiently strong seed to show as high as an 85-100x increase in gain [3]. However, the performance of early undulators is not commonly measured during XFEL tuning, raising concern that the performance of these undulators might not be well optimized during tuning. To characterize the currently installed HXUs, we studied the performance of the first seven LCLS HXUs in a CBXFEL-like configuration with nominal LCLS tuning.

EARLY STAGE XFEL LASING AT 5 KEV

The experimental study of the early stage LCLS HXU lasing was performed at 5 keV photon energy with 7.66 GeV electrons using the transverse kick method [7]. We used a photodiode installed in the X-ray Pump Probe (XPP) user endstation to register the resulting photon flux. In the experiment, we first compared the gain profiles of the LCLS HXR beamline, by consecutively removing individual HXUs for each gain length scan. This measurement allows us to determine the performance of each individual undulator throughout the HXU beamline in the exponential gain regime to see if each undulator(s) is contributing to the lasing process, and measure FEL gain length. The resulting gain curves are shown in Fig. 1. Cell 13 corresponds to the first HXU in the line.

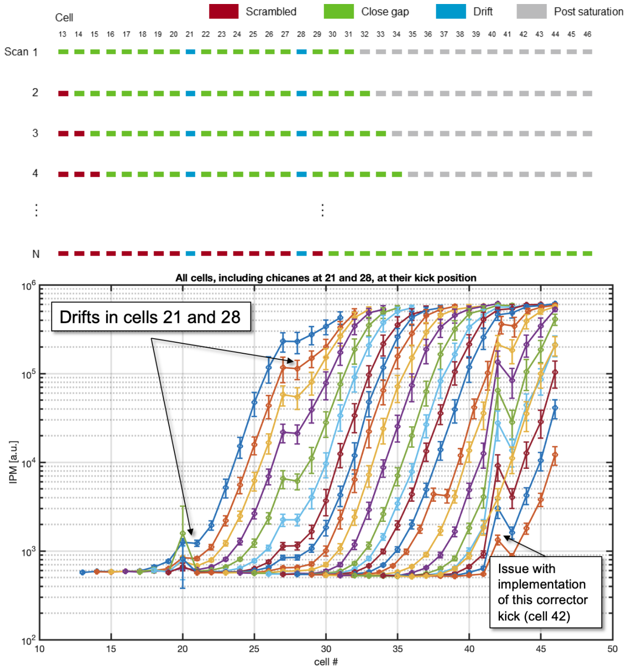

Figure 1: Gain curves for each scan, with consecutively removing HXUs from the beginning of the HXU beamline.

Aligning all the scans lets us determine an "average" gain length of the LCLS HXU system (about 3 m). From this measurement, we concluded the HXU lattice largely behaves as expected, with all undulators equally contributing to the FEL lasing.

We then proceeded with a different measurement. We first closed the first 14 the undulator gaps, then opened one individual cell at a time, starting from the beginning. This effectively interrupts the FEL lasing at different locations and allows us to determine the impact at each HXU cell position; see Fig. 3.

Several other observations can be made. The spread in intensity seems to be relatively large in the exponential regime, converging toward saturation. Some lower-intensity curves

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[*] presently not at SLAC

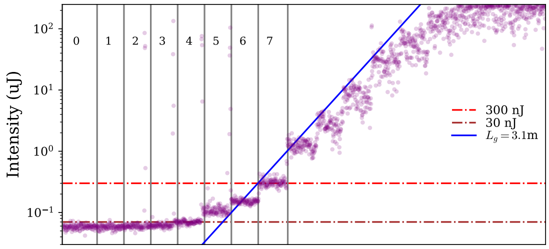

Figure 2: LCLS gain curve with corresponding intensity calibration at 5 keV photon energy. The numbers correspond to the undulator count from the beginning of the HXU beamline.

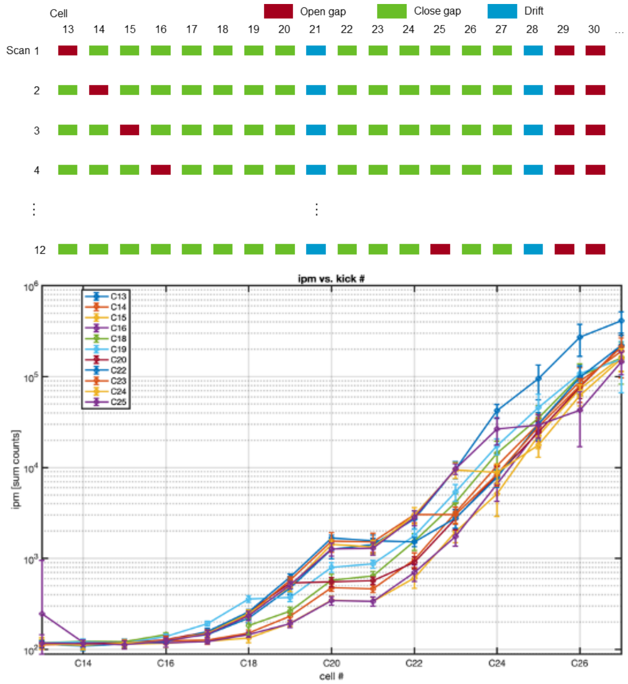

Figure 3: Gain curves for each scan, with consecutively open-gapping one undulator module throughout the HXU beamline, then aligning the gain curves.

represent cases when the FEL process was interrupted during the lethargy regime. On the contrary, interrupting the FEL close to the saturation point doesn't seem to be very impactful.

We then focused on characterizing the gain of the CBXFEL undulators only; see Fig. 2. One can see the FEL gain begin to develop around undulator number 5, which is in agreement with the seeding studies presented below. The FEL gain length has been measured to be 3.1 m, compared to the simulated $L_g = 2.9$ m. Similarly, the saturated pulse energy was found to be about 250 uJ compared to the simulated 300 uJ. Overall, this measurement seems to corroborate the expected performance of the LCLS HXU based on numerical simulations, in line with other facilities that have described early undulator performance as agreeing well with simulation [8]. Assuming the LCLS performance does not significantly drop at 9.8 keV, one can estimate the number of SASE photons at the first CBXFEL crystal is about 10^8. Therefore, based on the input SASE bandwidth, and the bandwidth of the CBXFEL cavity, the cavity will store about $10^5 - 10^6$ photons on the first round trip [9]. These numbers can be refined in future dedicated experiments.

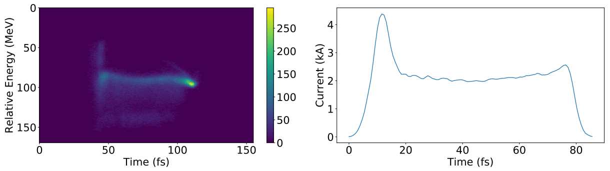

Figure 4: Longitudinal phase-space profile of the e-beam during the gain length studies. One can infer the x-ray pulse duration to be about 50 fs.

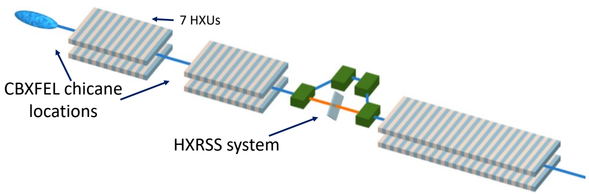

Figure 5: Layout of the LCLS HXU beamline (not to scale).

Finally, we were able to estimate the FEL power after 7 HXUs at 5 keV. From Fig. 4, one can infer the pulse duration of about 50 fs, which then yields about 6 MW of power after 7 HXUs, and about 5 GW in saturation.

HARD X-RAY SELF-SEEDING STUDY AT 9.5 KEV

LCLS HXRSS system contains a single diamond crystal that acts as a monochromator; see Fig. 5. A SASE pulse generated upstream of the HXRSS is filtered and overlapped with the e-beam downstream. Here we discuss recent seeding measurements with the HXRSS performed at 9.530 keV. In the experiment, we first established nominal HXR seeding conditions, with 12 undulators upstream of the self-seeding chicane and 19 downstream undulators for amplification. We have observed a strong seeded line with a bent crystal spectrometer located downstream of the HXU beamline. We then consecutively retracted HXUs one by one from the upstream section, effectively reducing the number of undulators contributing to the seed pulse intensity. The resulting seeded spectra are shown in Fig. 6. The seeded line is seen above the shot noise with 5 HXUs or more upstream of the self-seeding crystal, with a well-defined line above the background with 7 seeding HXUs; see also Fig. 7.

This HXRSS experiment gives practical evidence that, excluding additional losses from the CBXFEL cavity, seeding with as few as 5-7 undulators is possible.

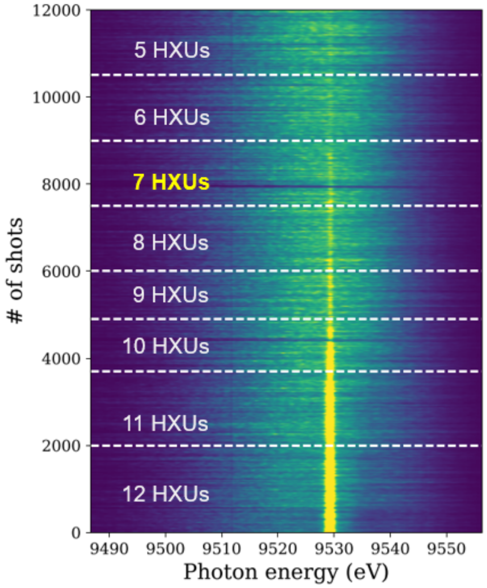

Figure 6: Seeded LCLS spectra as a function of upstream undulator number. The image color palette has been adjusted to enhance the case of seeding with a small number of HXUs.

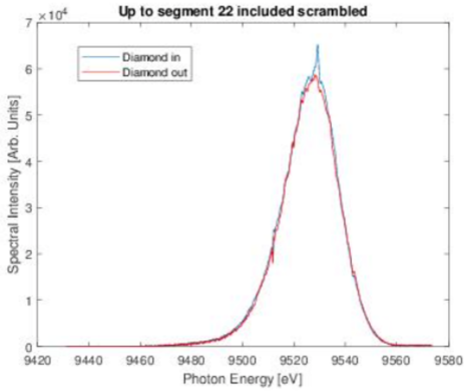

Figure 7: Seeded spectrum with 6 seeding HXUs.

FUTURE PLANNED EXPERIMENTS

Currently, we plan to perform a few more experiments as part of the preparation for CBXFEL. In order to verify in(out-)coupling chicane performance, we will redo the gain length measurements described above with and without the chicanes. This will allow us to establish the unaffected, optimal e-beam trajectory in the HXU when the chicanes are on. We will repeat this measurement with two electron bunches produced via the multi-bunch generation technique previously established at LCLS.

We will also perform an experiment with HXRSS, where we use 7 HXUs for generating the seed pulse at 9.8 keV and another 7 for amplification. This experiment will allow us to establish similar photon flux conditions as envisioned in CBXFEL and will help with commissioning photon diagnostics.

SUMMARY

In summary, we have shown that the CBXFEL demonstration experiment at the LCLS HXU beamline is feasible. We estimated the expected photon numbers in the cavity bandwidth and determined that FEL gain length and saturation power are in agreement with numerical simulations. The latter fact will help to gain confidence in the numerical simulations of CBXFEL as well as other experiments.

ACKNOWLEDGEMENTS

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