ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1C4

THE CXFEL PROJECT AT ARIZONA STATE UNIVERSITY

W. S. Graves* on behalf of the CXFEL collaboration†, Arizona State University, Tempe, AZ, USA

Abstract

The CXFEL Project encompasses the Compact X-ray Light Source (CXLS) that is now commissioning in the hard x-ray energy range 2-20 keV, and the Compact X-ray Free-Electron Laser (CXFEL) designed to lase in the soft x-ray range 250 - 2500 eV. CXFEL has recently completed a 3-year design phase and just received NSF funding for construction over the next 5 years. These instruments are housed in separate purpose-built laboratories and rely on inverse Compton scattering of bright electron beams on powerful lasers to produce femtosecond pulses of x-rays from very compact linacs approximately 1 m in length. Both instruments use recently developed X-band distributed-coupling, room-temperature, standing-wave linacs and photoinjectors operating at 1 kHz repetition rates and 9300 MHz RF frequency. They rely on recently developed Yb-based lasers operating at high peak and average power to produce fs pulses of 1030 nm light at 1 kHz repetition rate with pulse energy up to 400 mJ. We present the current commissioning performance of CXLS, and review the design of the fully coherent CXFEL.

INTRODUCTION

Future light sources aim to improve performance, cost, and accessibility over today's instruments. The CXFEL project is developing femtosecond x-ray light sources at a cost and size that makes the novel time-resolved molecular science they provide accessible to many institutions including universities, medical facilities, and industrial labs. The first instrument produced and now commissioning is the CXLS that produces partially coherent synchrotron-like x-ray pulses at few hundred fs duration in the hard x-ray range. The second instrument, CXFEL, has completed design and is now under construction. It is a further development of CXLS technology that adds novel nanometer-scale electron bunching to produce fully coherent x-rays in the soft x-ray spectrum. These instruments differ from the major XFEL and synchrotron facilities as well as current laboratory scale sources, thus require development of new experimental techniques, sample delivery, detector properties, controls and data analysis methods that are matched to their novel properties. These properties include lower flux than the major facilities as well as improvements in stability and precision of beam properties, and the ability to tailor integrated accelerator, laser, and x-ray beamline operations to optimize particular experiments. We first describe the labs that house the instruments and then the 2 instruments. For illustrations of the various equipment and laboratories discussed here please see oral presentation TU1C4 in the proceedings of the 2023 FLS workshop.

* wsg@asu.edu
† see Annex A

LABORATORY ENVIRONMENT

Environmental factors have a large impact on the stability and performance of experiments at molecular length and time scales. In 2018 we constructed a new laboratory building on campus, Biodesign C, with 2 essentiallly identical groups of labs that are purpose-built for the accelerators, RF systems, lasers, and x-ray endstations used by CXFEL and CXLS. The laser, accelerator, and x-ray labs are in separate rooms each with their own safety and air-handling systems but the 3 rooms share a single 2m thick reinforced concrete foundation that is physically separated from the adjoining building spaces to provide a common stable platform for the beams. These rooms are verified to meet VC-E vibration standards similar to an electron microscope lab. The air temperature stability in the laser labs is $\pm 0.25°$ C, and is $\pm 0.5°$ C in the accelerator lab and x-ray hutch. Air humidity is at 40% $\pm$ 5%.

To mitigate electromagnetic interference we installed the RF systems including the klystrons in a Faraday cage preventing external pickup and suppressing any effects of the high power klystron pulses on sensitive x-ray experiments. The majority of equipment is water-cooled for temperature stability of high power systems. We designed and built a precision processed cooling water system that is tunable and stable to $\pm 0.05°C$ with a future goal to achieve $\pm 0.01°C$.

CXLS

The CXLS is constructed and now commissioning having produced first x-rays in February 2023. The technical components of CXLS including RF and accelerator sections, magnets, lasers, and diagnostics all serve as prototypes for the CXFEL equipment. CXLS will continue commissioning through 2023, transitioning to early science phase in 2024.

CXLS X-ray Performance

The CXLS design performance is given in Table 1. So far for commissioning we are running at lower electron bunch charge (10 - 20 pC) and laser ICS laser power (80 W) resulting in x-ray flux of 3×10^5 photons/shot at 1 kHz repetition rate. The charge is limited by damage to UV photoinjector optics that are currently being replaced with reflective optics. We are being conservative with the ICS laser power while developing automated steering software. In coming months we expect to increase UV and ICS laser powers to their full design specs. Simulations indicate that current x-ray performance (flux, emission angle, energy) is consistent with measured values. We anticipate meeting the full x-ray performance specifications as the power from both lasers is increased.

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1C4

Table 1: CXLS Design Performance at 0.1% and 5% bandwidth. Brilliance units are ph/(s 0.1% mm^2 mr^2.

Parameter	0.1% BW	5% BW
Photon energy (keV)	2 - 20	2 - 20
Photons/pulse	5×10^6	1×10^8
Pulse rate (Hz)	1000	1000
Avg flux (ph/s)	5×10^9	1×10^{11}
Avg brilliance	2×10^{12}	5×10^{12}
Peak brilliance	3×10^{19}	9×10^{18}
Round RMS src size (μm)	3.0	3.0
Round RMS src angle (mrad)	4.0	4.0
RMS pulse length (fs)	< 300	< 300
RMS timing jitter (fs)	< 50	< 50

Interaction Point

The electron and laser beams meet at the interaction point (IP), crossing at an 8° angle from head-on to produce x-rays. The electron bunch length is 300 fs and the Dira is 1 ps. Timing jitter is 100 fs and is stable over timescales of hours. The Dira output is focused by a f=20 cm lens to a ω_0 = 10 µm spot and the electron beam is focused by a quadrupole triplet located 20 cm upstream of the IP to a 4 µm rms spot size at the IP. Spatial overlap is stable over periods of minutes at these spot sizes. We are developing steering feedback to correct slow thermal drift over longer timescales. The x-rays emerge with a 10 mrad opening angle. In current commissioning no collimating x-ray optic is present. An f = 20 cm elliptical Montel x-ray optic at fixed photon energy of 9.3 keV will be installed in coming weeks to collimate the beam. There are several YAG:Ce screens in the vicinity of the IP to image the electron/x-ray/laser beams including one insertable screen directly at the IP. Fitting short focal length optics for all of these beams within a few cm of teh IP as well as the diagnostics was an engineering challenge.

Accelerator and RF Systems

The accelerator consists of a 4.5 cell photoinjector and 3 short linac sections of 20 cells each, all powered by 2 RF transmitters. All of the accelerator structures are high efficiency standing-wave room-temperature copper structures with a repetition rate of 1 kHz and fill time of 170 ns. Peak cathode field in the photoinjector is 120 MV/m for a 3 MW input power. The cathode cell is less than a half-cell so that the laser arrival timing is close to the peak applied electric field. Exit energy is 4.0 MeV.

The linacs are innovative distributed-coupling structures [1] with a high shunt impedance 165 MOhm/m making them very efficient, gradient up to 30 MV/m and peak surface E-field of 120 MV/m. The structures are 20 cells long (32 cm), produce energy gain of 10 MeV each for 2 MW input power and a final maximum linac energy of 34 MeV. This energy is adequate to produce up to 20 keV x-rays via ICS.

The low-level RF (LLRF) system is a hybrid analog-digital system based on IQ modulation/demodulation developed at ASU. It drives 100 W solid-state power amplifiers that in turn drive a pair of L3 L-6145 klystrons to 6 MW saturated output power in 700 ns pulses. Output from klystron 1 is split with a waveguide variable phase-shifter power-divider (VPSPD) between the photoinjector (3 MW) and linac 1 (2 MW) after losses. Klystron 2 output is fed to a 3 dB hybrid that routes 2.5 MW power to each of linacs 2 and 3. We use a total of 3 VPSPDs that can shunt klystron power to water loads so that the klystrons always run at max power and constant thermal load regardless of what final beam energy is required. Scandinova K1 modulators power the klystrons, achieving 100 ppm rms voltage stability. Generally the RF systems are extremely stable over short and long terms with phase jitter of < 0.04° (12 fs) and amplitude jitter < 5×10−4. Typical operations during commissioning are to run for 8-10 hours in a day, shutdown, and then repeat the next day. The facility reaching thermal stability about 45 minutes after startup when running at 1 kHz, or within 10 minutes when running at 100 Hz. The day-to-day stability is excellent requiring only a few minutes of tuning to rephase all the structures and laser.

Lasers and Timing Systems

CXLS includes a photocathode laser that produces the electron beam and the high power ICS laser that collides with the electron beam. The photocathode laser is a Light-Conversion Pharos Yb:KGW amplifier producing 1.5 mJ pulses of 1030 nm light with FWHM 180 fs at 1 kHz repetition rate. The single-box laser has a 4th harmonic module that produces up to 100 µJ of 258 nm light that produces the electron beam at the photocathode. The Pharos oscillator is synchronized to the RF master oscillator via a Menlo Systems RRE-SYNCHRO unit resulting in 120 fs rms timing jitter between RF and UV. This unit runs stably with little tweaking required. However the fs UV pulses at 1 kHz have proved to cause nonlinear effects and damage in optical coatings on the MgF lenses used for transport. These effects limit the charge available in the accelerator to 20 pC. We are in the process of replacing the transmissive optics with reflective optics and are testing damage thresholds to increase the fluence to the cathode.

The ICS laser is a Trumpf Dira 200-1 Yb:YAG thin-disk amplifier producing 200 mJ pulses of 1030 nm light with FWHM of 1.1 ps at 1 kHz repetition rate. The Pharos oscillator sends an optical seed signal to the Dira that is amplified producing good synchronization with the cathode laser and electron beam. Trumpf has also supplied a cross-correlator that measures and corrects the timing difference between the Pharos and Dira amplifier outputs resulting in a net timing jitter of 33 fs between amplified pulses at 1 kHz rate. Pointing stability of the Dira is 4 µrad rms and power stability is 0.2% rms over 24 hours. The Dira has been tested to its full specifications but we are typically using it at 80 mJ/shot in early x-ray commissioning.

CXFEL

CXFEL is a further development of the technologies used in CXLS that is designed to produce fully coherent x-ray pulses. See the illustrations in the TU1C4 oral presentation in these proceedings. The accelerator components are nearly identical to CXLS with the addition of an electron diffraction [2] chamber and emittance exchange [3] line. The components also apply lessons learned with CXLS to improve performance. The purpose of the additional equipment is to create bunches of electrons that are short on the x-ray wavelength scale, i.e., < 1 nm in length so that when they interact with the ICS laser the output is coherent. ICS sources are generally excellent at producing hard x-ray photons with performance decreasing for softer photon energies. However the technique used by CXFEL to produce nanobunches that radiate coherently is currently limited by equipment jitter performance to lower energies (longer x-ray wavelengths) in the soft x-ray range. We believe that with further development this technique will reach hard x-rays, but the scope of CXFEL is currently limited to photon energies less than 2.5 keV with most of the development work focusing on the important energy range from 250 eV to 1.2 keV.

Producing x-rays in this lower energy range is not well suited to the head-on collision geometry of CXLS where the effective undulator period is just 515 nm. Such a short period requires an ebeam energy into the few MeV range to make soft x-rays. Such low energy electrons are subject to strong space-charge forces and difficult to focus to a small interaction spot. Instead we adopt an ”overtaking” collision geometry where the electron beam and laser propagate in the same direction with a 30° angle between them resulting in an effective undulator period of $8\,\mu$m thus raising the ebeam energy to e.g. 29 MeV to produce 1 keV photons. This geometry does however require a substantially more powerful and shorter pulse ICS laser as discussed below.

X-ray Performance

The CXFEL design performance is given in Table 2 across a range of energies. The nanobunching concept that produces coherent emission is very sensitive to space charge forces resulting in the use of very low charge (1 pC) electron bunches vs the 200 pC bunches of CXLS. Thus the flux of CXFEL with its more efficient coherent emission is similar to CXLS. However the coherent photons are emitted into a phase space volume that is orders of magnitude smaller than the incoherent CXLS and thus the brilliance of the CXFEL s orders of magnitude higher. The x-ray pulses are also much shorter, ranging from 0.5 - 10 fs.

Accelerator and RF Systems

The CXFEL accelerator reuses the CXLS photoinjector and has 3 similar linac sections. However the linacs have subtle design changes that improve the symmetry of the cells and allow operation at higher gradient up to 75 MV/m. The RF system uses the same 2 klystrons as CXLS, but combines and compresses the klystron output to make short pulses up to 40 MW. This power is then split among the RF structures. Combining and splitting the power produces a system with redundancy that enables operation with a single RF transmitter, as well as providing the opportunity to reduce ebeam energy and timing jitter by using the correlations in phase and amplitude jitters among the linac sections to partially cancel their effects. The transmitters are upgraded Scandinova K200 units customized with low jitter triggers and additional charging supplies with the goal to reduce high voltage jitter from 100 ppm to 10 ppm at 1 kHz. The compressed high power RF is used to drive the photoinjector cathode gradient up to 150 MV/m.

Table 2: CXFEL Design Performance at several photon energies. Brilliance units are ph/(s 0.1‰ mm^2 mr^2.

Parameter	Photon energy (eV) 250	1000
Photons/pulse	8×10^8	1.1×10^8
Pulse rate (Hz)	1000	1000
Avg flux (ph/s)	8×10^{11}	1.1×10^{11}
Flux/shot (nJ)	32	18
Avg brilliance	1.3×10^{15}	1.2×10^{16}
Peak brilliance	1.2×10^{28}	5.6×10^{28}
Round RMS src size (μm)	0.9	0.5
Round RMS src angle (μrad)	440	188
FWHM pulse length (fs)	9.1	4.6
FWHM bandwidth (%)	0.18	0.09
Arrival timing jitter (fs)	< 10	< 10
Electron beam energy (MeV)	14	29

Lasers and Timing Systems

The photoinjector laser is identical to CXLS except that we will build our own harmonic module to improve the UV mode. The ICS laser is a significant upgrade over CXLS with the final multipass amplifier producing 500 mJ of 1030 nm light in 800 fs pulses at 1 kHz. This output is then spectrally broadened in a large Herriott cell and compressed to 40 fs.

The timing synchronization for CXFEL takes a different approach than CXLS, using BOM-PD components from Cycle Laser with the goal to achieve approximately 20 fs locking between RF and photoinjector and ICS lasers. We anticipate ebeam and x-ray arrival time jitter below 10 fs with proper setup of the accelerator and laser timing.

ACKNOWLEDGMENTS

This work is supported by NSF Awards 2153503 and 1935994, and by ASU.

REFERENCES

[1] S. Tantawi, M. Nasr, Z. Li, C. Limborg, and P. Borchard, “Design and demonstration of a distributed-coupling linear accelerator structure,” *Phys. Rev. Accel. Beams*, vol. 23, no. 9, p. 092 001, 2020. doi:10.1103/PhysRevAccelBeams.23.092001

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1C4

[2] L. Malin *et al.*, “Quantitative agreement between dynamical rocking curves in ultrafast electron diffraction for x-ray lasers,” *Ultramicroscopy*, vol. 223, p. 113 211, 2021. doi:10.1016/j.ultramic.2021.113211

[3] E. A. Nanni, W. S. Graves, and D. E. Moncton, “Nanomodulated electron beams via electron diffraction and emittance exchange for coherent x-ray generation,” *Phys. Rev. Accel. Beams*, vol. 21, no. 1, p. 014 401, 2018. doi:10.1103/PhysRevAccelBeams.21.014401

ANNEX A: CXFEL COLLABORATION

A. Botana, S. Botha, B. Cook, O. Erten, P. Fromme, A. Gardeck, W. Graves, M. Holl, J. Houkal, S. Jachim, R. Kaindl, S. Karkare, R. Kirian, E. Lttman, B. Liebich, S. Rednour, A. Ros, K. Schmidt, D. Smith, S. Teitelbaum, T. Thornton, S. Tilton, S. Tongay, J. Vela, K. Warble, U. Weierstall, D. Winkel, Arizona State University, Tempe, AZ
H. Loos, Yorktown Heights, NY
M. Mitrano, Harvard University, Cambridge, MA
D. Rolles, A. Rudenko, Kansas State University
Y.-D. Chuang, O. Gessner, J. Qiang, S. Roy, T. Weber, Lawrence Berkeley National Laboratory, Berkeley, CA
R. Comin, K. Nelson, Massachusetts Institute of Technology, Cambridge, MA
L. DiMauro, Ohio State University
N. Shivaram, Purdue University
G. Phillips, Rice University
J. Cryan, V. Dolgashev, Z. Li, E. Nanni, S. Tantawi, M. Trigo, SLAC National Accelerator Laboratory, Stanford, CA
R. Fung, A. Hosseinizadeh, A. Ourmazd, M. Schmidt, P. Schwander, University of Wisconsin - Milwaukee, Milwaukee, WI T. Grant, University of Buffalo, Buffalo, NY
M. Brown, A. Sandhu, University of Arizona, Tucson, AZ
M. Frank, T. Kuhl, University of California Davis, Davis, CA
F. Mahmood, University of Illinois Urbana-Champagne, Urbana-Champagne, IL
M. Centurion, University of Nebraska, Nebraska
Undergraduate students: G. Babic, C. Bell, E. Boyd, T. Brown, T. Dela Rosa, R. DeMott, A. Dupre, K. Eckrosh, E. Everitt, A. Eyler, J. Falconer, R. Jaswal, R. Larson, X. Ma, A. Martinez, S. Ramkumar, E. Ros, A. Semaan, A. Staletovic, J. Stanton, S. Tripathi, D. Valentin, Arizona State University, Tempe, AZ