CXFEL Project

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LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS
CXFEL Project – What is it?

A two-phase project to build a compact fully coherent x-ray laser

CXLS
Phase 1 Hard X-ray ICS Source

Built and now commissioning. First x-rays Feb 2, 2023

CXFEL
Phase 2 Soft X-ray Coherent Laser

5 year construction began March 15, 2023 under $90.8M NSF midscale RI-2 award
The CXFEL Project includes two lab spaces for independent instruments:

- Hard x-ray CXLS is commissioning; prototype of CXFEL technologies
- CXFEL under construction

- 2 m thick slab separate from building
- Vibration rated VC-E (TEM quality)
- 0.25 - 0.5 C temperature stability
- Class 100k conditions throughout
- Low background B-fields
- Faraday cage RF room
CXFEL includes 80+ People in 16 Institutions

**Biochem**
- Fromme, Petra (Science Dir)
- Botha, Sabine
- Brown, Michael (U AZ)
- Frank, Matthias (UC Davis)
- Grant, Tom (U. Buff.)
- Kirian, Rick
- Kuhl, Tonya (UC Davis)
- Lattman, Eaton
- Liu, Wei
- Ourmazd, Abbas (UW-Mil)
- Phillips, George (Rice)
- Ros, Alexandra
- Schmidt, Kevin
- Schwander, Peter (UW-Mil)
- Weierstall, Uwe

**Quantum Materials**
- Teitelbaum, Sam (QM lead)
- Kaindl, Robert (CXFEL Lab Dir)
- Tongay, Sefaatin
- Abbamonte, Peter (UIUC)
- Botana, Antia
- Comin, Riccardo (MIT)
- Chuang, Yi-De (LBL)
- Erten, Onur
- Gedik, Nuh (MIT)
- Mahmood, Fahad (UIUC)
- Mitrano, Matteo (Harvard)
- Reis, David (Stanford)
- Roy, Sujoy (LBL)
- Trigo, Mariano (SLAC)

**Attosecond AMO**
- Sandhu, Arvinder (U AZ, AMO lead)
- Berrah, Nora (UConn)
- Centurion, Martin (U Neb)
- Cryan, James (SLAC)
- DiMauro, Louis (OSU)
- Gessner, Oliver (LBL)
- Nelson, Keith (MIT)
- Rolles, Daniel (KSU)
- Rudenko, Artem (KSU)
- Weber, Thorsten (LBL)

**Instrument**
- Graves, William (Proj Dir)
- Karkare, Siddharth
- Li, Zenghai (SLAC)
- Loos, Henrik
- Malin, Lucas
- Messerschmidt, Marc
- Nanni, Emilio (SLAC)
- Qiang, Ji (LBL)
- Tantawi, Sami (SLAC)
- Thornton, Trevor

**Management**
- Winkel, David (Prog Mgr)
- Clark, Deanna
- Cottrell, Erica
- Reichanadter, Mark
- Staletovic, Anastasia

**Engineering**
- Holl, Mark (Chief Eng)
- Brown, Paul (MIT)
- Cook, Brandon
- Gardeck, Alex
- Houkal, Jeff
- Jachim, Steven
- Liebich, Brett
- Ness, Richard
- Rednour, Steven
- Smith, Dean
- Vela, Juan

**Education**
- Warble, Kelli (Lead)
- Babic, Gregory
- Boyd, Elena
- Brown, Taryn
- Dela Rosa, Trixia
- Dupre, Alan
- Eckrosh, Kevin
- Everett, Eric
- Eyler, Aaron
- Falconer, Jasmin
- Jaswal, Rejul
- Larsen, Rae
- Leonard, Nicholas
- Ma, Xinyi
- Martinez, Anastasia
- Ros, Elena
- Semaan, Antonella
- Stanton, Jade
- Tilton, Sean
- Valentin, Dariannette

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Basic Layout for Inverse Compton Scattering (ICS)
**LightConversion Yb:KGW**
- 1030/515/258 nm
- 1.5 mJ/shot at 1030
- 0.15 mJ/shot at 258
- 200 fs, 1 kHz

**ASU-Tibaray photoinjector**
- 9.3 GHz
- 1 kHz
- 120 MV/m
- 4.5 cell
- 4 MeV energy
- 200 pC
- 1 ps

**Tibaray linac**
- 9.3 GHz standing wave
- 1 kHz
- 25-30 MV/m
- 20 cells/section X 3 sections
- 30 MeV final energy

**Scandinova K1 modulators**
- Stellant (L3) L6145 klystrons
- 9.3 GHz
- 1 kHz rep rate
- 6 MW for 1 us

**X-ray chambers**
- 1e8 photons/shot
- 2-20 keV
- 300 fs
- 1 kHz

**Final focus and interaction point**
- Electron diffraction
- 1030 nm
- 200 mJ/shot
- 1 ps
- 1 kHz
- M^2 = 1.2

**CXLS Layout**

CXLS length is 10 m from cathode to beam dump
CXLS Construction

Late 2019

Accelerator Vault

Early 2022

RF Room

First X-rays Feb, 2023
**CXLS Laser Systems**

### Photoinjector laser
- LightConversion Pharos
- 1 mJ at 1000 Hz, 165 fs FWHM
- 1030/515/258 nm Yb:KGW regen

### ICS laser
- Trumpf Dira 200-1
- 200 mJ at 1000 Hz, 1.1 ps FWHM
- 1030 nm Yb:YAG thin disk regen amplifier

Timing of PI laser oscillator to RF MO via Menlo Systems Sync achieves 100 fs rms jitter

Timing of ICS laser amplifier to PI amplifier has 33 fs rms jitter

Up to 150 uJ of UV for cathode.

Optics challenges with short UV pulse and high rep rate of PI laser.
ICS Laser Test Results

- 33 fs timing jitter relative to photoinjector laser
- ~0.2% power stability
  - mean = 205.75 W
  - rms = 0.29 W
- 3-4 µrad pointing stability
- FWHM = 0.75 nm

Graphs showing the test results for jitter, power stability, and beam pointing stability.
Low Level RF

Rapid and inexpensive prototyping of microwave circuits using modular waveguide components from X-Microwave. Much student involvement in design, test, commission.

Complete IQ Modulator. Similar boxes for downconverter, IQ demod, and machine protection.
LLRF performance to Klystron input

Microwave Amps Ltd
AM73-9.3S-50-50R
9.3 GHz, 100 W, 1 us, 1 kHz

25 W to saturate klystron output

Fast RMS jitter $\Delta \phi = 0.02^\circ$ (6 fs)
High Power RF Layout

Scandinova K1 modulators
L3 L6145 klystrons
9.3 GHz
1 kHz rep rate
700 ns pulse
6 MW

Operating with 700 ns pulses at 1 kHz
RMS phase jitter < 0.04 RF degrees (12 fs)
RMS amplitude jitter ~500 ppm at 6 MW
Variable Phase Shifter Power Divider (VPSPD)

- Divide or combine high power
- Move plungers together for phase shift
- Move plungers separately for power shift among output ports

Tibaray

- Linear Actuator
- Plunger
- WR 112 Flange
Scandinova K1
130 kV
98 A
2.5 us
1 kHz

RMS shot-to-shot jitter = 1.0E-4 over 10k shots

RMS shot-to-shot jitter = 1.1E-4 over 10k shots
Klystron Performance

Stellant (ex L-3)
L-6145
6 MW, 1 us, 1 kHz
59 dB small signal gain

RMS $\Delta \phi = 0.031$ deg (9 fs)
RMS $\Delta \phi = 0.036$ deg (11 fs)
RMS $\Delta P/P = 7 \times 10^{-4}$
RMS $\Delta P/P = 6 \times 10^{-4}$
kHz X-band Photoinjector

- V. Dolgashev (SLAC) RF design
- Mode converter with quad RF feeds
- 4.5 cells
- 9.3 GHz RF
- 3 MW peak power
- 4 MeV final energy
- 120 MV/m on cathode
- 1 kHz repetition rate
- Embedded in tape-wound solenoid

**Typical ops**
- 2.4 MW
- 3.6 MeV
- 105 MV/m
Photoinjector Performance

Commissioned to
- 2.8 MW delivered
- 117 MV/m gradient
- 3.8 MeV energy
- 1000 Hz rep rate
- 700 ns pulses
- Conditioning time ~3 days
- Zero breakdowns/day

- 20 pC (limited by UV optics)
- ~0.3 um emittance
- Few hundred fs pulse
9.3 GHz Distributed-Coupling SW Linac
Tantawi and Li (SLAC and Tibaray)

- 20-cell structure 35 cm long
- 9.3 GHz
- 165 MOhm/m shunt impedance
- 170 ns fill time
- 3 mm apertures
- $E_{\text{surface}}$ to $E_{\text{accel}} = 4:1$
- 1 kHz rep rate
- Distributed coupling to each cell
- Inexpensive

Tantawi et al, Phys Rev Accel and Beams 23, 092001 (2020)

Linacs 2 & 3 fed by 3dB hybrid
Linac Performance

Commissioned to
- 27 MV/m gradient
- 108 MV/m surface field
- 1000 Hz rep rate
- 700 ns RF pulse
- 2 MW delivered to each structure

- ~10 pC per 700 ns RF pulse dark current
- 29 MeV final beam energy (still tuning)
- RMS dE/E = 50-200 ppm
### CXLS Hard X-ray Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.1% Bandwidth</th>
<th>5% Bandwidth</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy range</td>
<td>2 – 20 keV</td>
<td>2 – 20 keV</td>
<td></td>
</tr>
<tr>
<td>Average flux</td>
<td>5x10⁹ photons/s</td>
<td>1x10¹¹ photons/s</td>
<td></td>
</tr>
<tr>
<td>Average brilliance</td>
<td>2x10¹² photons/(s .1% mm² mrad²)</td>
<td>5x10¹² photons/(s .1% mm² mrad²)</td>
<td></td>
</tr>
<tr>
<td>Peak brilliance</td>
<td>3x10¹⁹ photons/(s .1% mm² mrad²)</td>
<td>9x10¹⁸ photons/(s .1% mm² mrad²)</td>
<td></td>
</tr>
<tr>
<td>RMS horizontal size</td>
<td>3.0 microns</td>
<td>3.0 microns</td>
<td></td>
</tr>
<tr>
<td>RMS vertical size</td>
<td>3.0 microns</td>
<td>3.0 microns</td>
<td></td>
</tr>
<tr>
<td>RMS horizontal angle</td>
<td>4.0 mrad</td>
<td>4.0 mrad</td>
<td></td>
</tr>
<tr>
<td>RMS vertical angle</td>
<td>4.0 mrad</td>
<td>4.0 mrad</td>
<td></td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>5x10⁶</td>
<td>1x10⁸</td>
<td></td>
</tr>
<tr>
<td>RMS pulse length</td>
<td>&lt;500 fs</td>
<td>&lt;500 fs</td>
<td></td>
</tr>
<tr>
<td>RMS timing jitter</td>
<td>&lt;500 fs</td>
<td>&lt;500 fs</td>
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<tr>
<td>Repetition rate</td>
<td>1000 Hz</td>
<td>1000 Hz</td>
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</tbody>
</table>

Initial experiments produce ~3e5 15 keV photons/shot at 1 kHz operating at 80 mJ ICS laser energy and Q = 20 pC
Accelerator components very similar to CXLS with upgraded RF system

Laser systems are higher power and shorter pulse compared to CXLS.
**CXFEL Accelerator Layout**

- **Scandinova K200 modulators**
  - 9.3 GHz
  - 1 kHz rep rate
  - 6 MW for 2 us

- **Stellant L6145 klystrons**
  - 9.3 GHz
  - 1 kHz rep rate

- **Power combiner**

- **Compact SLED RF Compressor**

- **LightConversion Yb:KGW**
  - 1030/515/258 nm
  - 1.5 mJ/shot at 1030
  - 0.15 mJ/shot at 258
  - 200 fs, 1 kHz

- **Photoinjector**
  - 9.3 GHz
  - 1 kHz
  - 150 MV/m
  - 4.5 cell
  - 5 MeV energy
  - 1 pC
  - 100 fs

- **3-cell linac & RF transverse kicker**

- **3 high gradient linac sections, 60 MV/m**

- **Power splitters/phase shifters X7**

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**ASU Biodesign Institute**

**CXFEL Labs**

**NSF**
Additional Slides
ICS: replace undulator with a laser

Undulator Radiation

Inverse Compton Scattering

\[ \lambda_x = \frac{\lambda_u}{2\gamma^2} \]

\[ \lambda_u \approx 3 \text{ cm} \]

\[ E = \gamma mc^2 \approx 10 \text{ GeV} \]

Undulator/laser wavelength

\[ \lambda_{\text{laser}} \approx 1 \mu\text{m} \]

X-ray wavelength

E-beam energy required

1000 m long accelerator

1 m long accelerator

X-ray wavelength

Electron

Laser field

X-ray radiation