Light Sources at ~1 Å

H.-D. Nuhn, H. Winnick

SLAC
NATIONAL ACCELERATOR LABORATORY
Why FEL R&D?

• **Seeded** FELs with **Full** Coherence are the next Frontier
  – Narrower bandwidth, stable pulse form
  – FEL efficiency is greatly enhanced with a tapered undulator

• **Smaller** emittance, **higher** peak current
  – Advanced cathodes and guns
  – Bunch compression, mitigation of collective effects
  – Emittance exchange/conditioning

• **Ultrafast** techniques and instrumentations to fully utilize XFELs

• **Average** brightness enhancement

• Special **source** and **polarization** are highly designable
FEL R&D Program with essential components for LCLS II, NGLS and other FELs

LCLS-II injector

2011-12

HXRSS

FEL Seeding schemes

2013-14

ECHO-7+

Laser & phase error control

2015-16

CTF/GTF

Injection studies (LCLS-II injector)

2017-18

ITF (Sector 0-9) to enable advanced beam generation, manipulation, compression and seeding at high energy

2019-20

SXRSS demo

Beam brightness & manipulation

LCLS-II completion

Temporal diagnostics & timing

Ultrafast techniques

Attosecond x-ray generation

THz & Polarization

THz generation

Technology development

Polarization ctrl.

Multi bunches, detectors, short-period undulators, high-rep. rate

Beamline R&D
LCLS R&D Projects

- **HXRSS** (hard x-ray self seeding)
- **XTCAV** (X-band trans. cavity)
- **XRSSS** (X-ray single-shot spectrometer)
- **EXRLT** (experimental x-ray to laser timing)

- **MBXRP** (Multi-bunch x-ray production)
- **SXRPC** (Soft x-ray polarization control)
- **THXPP** (THz/x-ray pump/probe)
- **XRDBL** (X-ray R&D Beamline)
Hard X-Ray Self Seeding

P. Emma, LCLS SAC Meeting, April 18-19

- Would like a narrow bandwidth (0.01%), but how?
- Self-seeding avoids large power fluctuations
- Narrow BW leads to increased peak brightness
- Monochromatic (seeded) beam responds better to tapering providing more pulse energy
The Idea...

- **Great idea from DESY** (Geloni, Kocharyan, Saldin, DESY 10-133, Aug. 2010)
- **SLAC** is collaborating with **ANL/APS** & **TISNCM** (Moscow)
- Will remove one of 33 undulators at U16 (3.4 m)
- Replace with retractable 4-dipole chicane & diamond
- Monochromatic transmitted x-rays seed 2nd half of FEL
- Applicable only in 20-pC mode with 1-μm bunch length
- Increases peak brightness ×15 (or more)
- Generates 10⁻⁴ bandwidth at 1.4 to 1.6 Å
- Switched on or off at any time allowing SASE mode
- Should be installed by Dec. 2011

* Neither is charging labor and in return are full members of the collaboration
Hard X-ray Self-Seeding @ LCLS

Geloni, Kocharyan, Saldin (DESY)

Self-seeding of 1-µm e⁻ pulse at 1.5 Å yields $10^{-4}$ BW with 20-pC mode. Undulator taper provides more power & brightness.

Power dist. after diamond crystal

Wide-band power

5 MW

6 µm ≈ 20 fs

Monochromatic seed power
The chicane does the following:

1. Displaces the electron beam horizontally (2.6 mm) so that only the x-ray beam intercepts the small diamond (2 mm × 2 mm).
2. Delays the electron beam (20 fs) so that it overlaps, in time, the ringing monochromatic x-ray pulse.
3. Smears out the initial SASE µ-bunching on the electron beam so that seeding dominates the output power of the final FEL.

Chicane bends mounted on common raft - sits on existing undulator sliders. C-bends can be fully extracted for SASE mode.
Table 6. Crystal chamber, YAG diagnostic, and crystal positioning parameters.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>x and y position full control range</td>
<td>±2</td>
<td>mm</td>
</tr>
<tr>
<td>x and y position settability (rms)</td>
<td>&lt;0.05</td>
<td>mm</td>
</tr>
<tr>
<td>crystal extraction range (approx.)</td>
<td>0 - 10</td>
<td>mm</td>
</tr>
<tr>
<td>crystal pitch angle full control range</td>
<td>45 - 95</td>
<td>deg</td>
</tr>
<tr>
<td>pitch angle settability (rms)</td>
<td>&lt;0.005</td>
<td>mrad</td>
</tr>
<tr>
<td>crystal yaw (optional) angle control range</td>
<td>±3</td>
<td>deg</td>
</tr>
<tr>
<td>crystal yaw (optional) angle settability (rms)</td>
<td>&lt;0.010</td>
<td>mrad</td>
</tr>
<tr>
<td>crystal temperature stability</td>
<td>~1</td>
<td>degC</td>
</tr>
<tr>
<td>screen and camera position resolution</td>
<td>&lt;0.02</td>
<td>mm</td>
</tr>
<tr>
<td>expected rms spot size on screen</td>
<td>30-50</td>
<td>μm</td>
</tr>
<tr>
<td>max. camera update rate</td>
<td>≥10</td>
<td>Hz</td>
</tr>
</tbody>
</table>

Deming Shu (ANL)

- X-pos control
- Y-pos control
- Pitch angle ctrl
- Yaw angle ctrl
- In-vac. stages
HXRSS Layout at U16

Crystal chamber (ion pump moved)

Sliding raft to move all 4 dipoles IN or OUT (0-8 cm)

J. Amann (SLAC)
D. Shu (ANL)
The Bragg Diagnostic Screen

Located at the center of the chicane for setup of crystal angle

Note: Bragg grazing incidence angle
\[ \theta = 90° - \frac{\psi}{2} \]

W. Berg, R. Lindberg (ANL)

- Sets Bragg angle by locating x-ray beam on screen
- Ni-edge is nominal centered on Be-window (1.488 Å, \( \psi = 66.9° \))
- \( \lambda_r = 1.38 \text{ to } 1.58 \text{ Å} \) (\( \psi = 54.8° \text{ to } 79.1° \) - set by Be window)
Start-To-End HXRSS Simulations (U17-U33)

Simulations from cathode through FEL, with realistic particle distributions, variable field taper, and assuming 5-m gain length. Performance may be better – this is a worst case 5-m gain length.
Bandwidth from Simulations (brightness$\times 15^*$)

* with respect to 20-pC SASE mode of operation
Expected Self-Seeding Performance *(LCLS-I)*

*Low* value is 29 undulators and 5-m gain length. *High* value is 33 undulators and 3-m gain length.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HXR SASE (20 pC)</th>
<th>Self-Seeded (20 pC)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.4 – 1.6</td>
<td>1.4 - 1.6</td>
<td>Å</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>0.1 - 0.2</td>
<td>0.1 - 0.4**</td>
<td>mJ</td>
</tr>
<tr>
<td>$N$ photons/pulse</td>
<td>0.08 - 0.2</td>
<td>0.08 - 0.3</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Peak power</td>
<td>50</td>
<td>10 - 100</td>
<td>GW</td>
</tr>
<tr>
<td>Pulse length (FWHM)</td>
<td>6 - 10</td>
<td>4 - 10</td>
<td>fs</td>
</tr>
<tr>
<td>Bandwidth (FWHM)</td>
<td>30 - 60</td>
<td><strong>1 - 4</strong></td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Peak Brightness</td>
<td>0.01</td>
<td><strong>0.2 - 2</strong></td>
<td>$10^{33}$*</td>
</tr>
<tr>
<td>Power jitter (rms)</td>
<td>5 - 10</td>
<td>10 - 20</td>
<td>%</td>
</tr>
</tbody>
</table>

* Standard brightness units of photons/sec/mm²/mrad²/0.1%BW

** Pulse energy might be increased \(\times5\) by using a multi-slotted foil

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Juhao Wu

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SLAC National Accelerator Laboratory

LCLS SAC Meeting, April 18-19

Hard X-Ray Self-Seeding at LCLS

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Simulations for \textbf{LCLS-II} HXR (optimistic)

- 8.3 keV (13.5 GeV)
- Quadratic tapering starts at 15 m (6.6%) from 15 m to 120 m
- Ideal temporal profile (10 fs FWHM)
- 40-pC bunch charge
- 0.2-μm emittance
- 4-kA peak current
- $\langle \beta_{x,y} \rangle = 20$ m

![Diamond crystal](image-url)

800 GW

$10^{-4}$ BW

Juhao Wu - SLAC
Commissioning Plan Exists (needs more work)

HXRSS Commissioning Procedure
Mar. 3, 2011

- **Do local system check-out in the tunnel**
  - Magnet polarities and connectivity (dipole fields), including trims (use control system)
  - Exercise and verify chicane slider, linear pots, and limit switches (use control system)
  - Exercise and verify crystal position and angle controls, and limit switches (use control system)
  - Check operation of vacuum valves, gauges, and MPS interlocks
  - Confirm camera focused, pointed at YAG, image visible, illumination, etc (use control system)
  - Add system labels and warnings of delicate instrumentation

- **Check chicane orbit closure over many settings**
  - Verify MPS connections (chicane and crystal actuator limit switches)
  - Scan chicane strength from zero to full with beam and measure duty BPMs (x & y)
  - Adjust trim-coil B-to-I polynomials to correct any residual x-orbit effects
  - Confirm no trajectory kicks > 5 μm downstream of chicane over zero to full setting

- **Beam-Based Alignment (BBA) with HXRSS**
  - Measure local quadrupole transverse position changes vs. chicane slider setting using hydro-static levels and wire-position monitors (small enough quad alignment distortions?)
  - Run BBA as normal (but with chicane OFF and extracted) to set BPM offsets properly
  - With beam OFF, turn ON chicane and slide it into the beam position (8 cm)
  - Turn on beam and adjust orbit kicks using XCU15, XCU16, YCU15, YCU16, if necessary (automate this step in software if correction is significant)

- **Align crystal to x-rays**
  - With U1-15 inserted...
  - Set crystal angle to 36.5±1 deg (for 1.4878-Å x-rays – the Ni edge)
  - Setup soft x-rays of 1-4 keV so that attenuation of x-rays through 0.1-mm diamond is a factor of ~2 or more (or try 8.3 keV if more convenient?)
  - Set chicane to at least 2.6-mm x-offset (or more if low e⁺ energy allows?)
  - Extract all undulators after crystal (i.e., U17-U33)
  - Scan x-position of crystal and record total x-ray intensity on YAGXRAY screen (after undulator) to find crystal edge (finds the x-edge nearest e⁺ beam)

- **Two 8-hr ROD days for pre-beam checkout (2 weeks real time)**
- **Six 8-hr shifts for commissioning (assumes no down time)**
- **Use existing FEE monochromator with 1×10⁻⁴ BW**

3 pages (not shown)
Soft X-ray Polarization Control (SXRPC)

Adding APPLE undulators to LCLS for polarization control

1. Crossed Polarizer (Fundamental) – Fast Switching

- Lowest Cost;
- Reduced degree of polarization
- Degree of polarization fluctuates

2. Circular Polarizer (Fundamental) – Slow Switching

- High degree of polarization;
- High intensity;
- Degree of polarization stable

- Photon Energy Range: 500 eV – 2000 eV
- Polarization Degree: 80%-100%
- Minimum energy: ~0.1 mJ/100 fs or better
- Pulse width: Full range <10 fs – 300 fs
THz/X-ray Pump Probe (*THXXP*)

THz in the Undulator Hall

1. Extract and measure THz fields: *Done*
2. THz pump and laser probe: *When LCLS restarts*
3. THz pump and x-ray probe: *Designing now*
Multi-Bunch X-Ray Production (*MBXRP*)

- Two bunches to serve SXR/HXR in LCLS-2
- Two bunches for THz/X-ray
- Multiple bunches (separated by ~10s ns) to increase hit rate on samples
- Develop electron and photon multi-bunch diagnostics for reliable operation

- 8.4 ns 8.4 ns
- 2-Bunch lasing demonstrated
- Higher hit rate of virus in jet

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FEL R&D
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X-band Transverse Cavity (XTCAV)

Y. Ding

X-band rf freq = 11.4 GHz

resolution $\propto \frac{\lambda_{rf}}{V_0} \sqrt{\frac{E}{\beta_x (s_0)}}$

High resolution, ~ few fs;
✓ Applicable in all FEL wavelength;
✓ Beam profiles, single shot;
✓ No interruption with operation;
✓ Both e-beam and x-ray profiles.
X-Ray Single-Shot Spectrometer (XRSSS)

M. Yabashi, J. Hastings et. al. PRL 97, 084802 (2006)

- Provide missing LCLS capability for tuning SASE process
- Measure pulse length similar to soft X-ray statistical method
- Serve as prototype for LCLS-II XTOD spectrometer
- Provide diagnostic for hard X-ray self-seeding

Designed operating range 4 - 13 keV

SASE spectral spikes $1/\Delta T$

$1/\tau_c$
Exp. X-ray to Laser Timing (*EXRLT*)

- Soft x-rays: chirped continuum technique
- Hard x-rays: RF cavity timing
- Chirped continuum uses x-rays to induce a change in refractive index

⇒ 20fs RMS (measured). Goal is <10fs RMS
Other R&D areas

- Echo-7
- ITF for high energy seeding/compression
- Laser
- Detector
- ...
Charge: Evaluate the presented LCLS R&D projects:

1. Are the proposed R&D projects important from a science/LCLS user point of view?

2. Which do you consider the most important?

3. Should other R&D projects be added at this time?
SAC defined categories

- Must do (self-seeding, single-shot diagnostics, Detector)
- General Benefit (multi-bunch, X-ray beamline)
- Smaller subset of users (THz, polarization)
- LCLS-II and wider community (Echo-7+, laser phase error)
- SAC comments that ‘real time’ data analysis/on-line data reduction are crucial for the users