LCLS-II & LCLS, too

November 12, 2012
Linac Coherent Light Source Facility
First Light April 2009, Project Complete June 2010

Injector at 2-km point

Existing Linac (1 km) (with modifications)

New e⁻ Transfer Line (340 m)

Undulator (130 m)

X-ray Transport Line (200 m)

Near Experiment Hall

Far Experiment Hall
### Typical operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray Tuning Range</td>
<td>280 - 10,000 eV</td>
</tr>
<tr>
<td>Peak Power</td>
<td>up to 70 GW</td>
</tr>
<tr>
<td>Bandwidth, 8,000 eV</td>
<td>0.2 typical; &lt;0.01 seeded % FWHM</td>
</tr>
<tr>
<td>Bandwidth, 800 eV</td>
<td>0.5 typical % FWHM</td>
</tr>
<tr>
<td>X-Ray pulse duration</td>
<td>~3-500 x 10^{-15} sec</td>
</tr>
<tr>
<td>Beam size at waist, 800 eV</td>
<td>20, typical μm, RMS</td>
</tr>
<tr>
<td>Beam divergence, 800 eV</td>
<td>20, typical μrad, FWHM</td>
</tr>
<tr>
<td>Beam size at waist, 8,000 eV</td>
<td>15, typical μm, RMS</td>
</tr>
<tr>
<td>Beam divergence, 8,000 eV</td>
<td>3, typical μrad FWHM</td>
</tr>
<tr>
<td>Energy/Pulse</td>
<td>&gt; 2 typical, 6 max mJ</td>
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<tr>
<td>Energy Jitter/Pulse</td>
<td>5 typical %</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>120 Hz</td>
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</table>
LCLS Experiment Stations Are Now Fully Operational

Near Experimental Hall

X-ray Transport Tunnel
200 m

<table>
<thead>
<tr>
<th></th>
<th>Start of operation</th>
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<tbody>
<tr>
<td>AMO</td>
<td>Oct-09</td>
</tr>
<tr>
<td>SXR</td>
<td>May-10</td>
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<tr>
<td>XPP</td>
<td>October-10</td>
</tr>
<tr>
<td>CXI</td>
<td>February-11</td>
</tr>
<tr>
<td>XCS</td>
<td>November-11</td>
</tr>
<tr>
<td>MEC</td>
<td>April-12</td>
</tr>
</tbody>
</table>

Far Experimental Hall
LCLS Operations Summary

On site users

- **703 proposals** (~15 scientists/proposal)
  - 31 countries
  - only 1 in 5 proposals gets beam time

---

Publications by year

- ~60% of papers in high impact journals

Beam delivery is ~95% of scheduled beam time

JLAB – 12 November 2012
Experiment Program is Oversubscribed

152 proposals for beam time between January and July, 2013

<table>
<thead>
<tr>
<th>LCLS Proposal Summary</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Run 7</th>
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<td>Sept'08</td>
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<td>Nov.'09</td>
<td>Jan.'10</td>
<td>Jan.'11</td>
<td>Sept.'11</td>
<td>Jul.'12</td>
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<td>18</td>
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<td>6</td>
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<td><strong>Total Proposals Received</strong></td>
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<td>107</td>
<td>116</td>
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</table>

*User Assisted Commissioning*  Dedicated User Facility > August 2010

<table>
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<tr>
<th>Experiments Performed</th>
<th>Oct-Dec'09</th>
<th>May-Sep'10</th>
<th>Oct-Mar'11</th>
<th>Jan-Oct'11</th>
<th>Nov-May'12</th>
<th>Jun-Dec'12</th>
<th>Jan-Jul'13</th>
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<tr>
<td>AMO</td>
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<td>6</td>
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<tr>
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<td><strong>Total Proposals Scheduled</strong></td>
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<td>23</td>
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<tr>
<td><strong>% Proposals Scheduled</strong></td>
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<td>37%</td>
<td>23%</td>
<td>22%</td>
<td>25%</td>
<td>25%</td>
<td>28%</td>
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<tr>
<td><strong>Est. User Hours Requested</strong></td>
<td>1680</td>
<td>3720</td>
<td>6420</td>
<td>6960</td>
<td>6840</td>
<td>8040</td>
<td>9120</td>
</tr>
</tbody>
</table>
Demonstration in operations targeted for Jan 2013

LCLS beamtime in very high demand

Increase capacity by multiplexing using large offset monochromators (LOM) with thin Bragg crystals

- Enables simultaneous operation of multiple instruments
  - XPP/XCS or XPP/CXI or XCS/CXI or XPP/XCS/CXI
- Thin crystal choices
  - Si – 10 μm
    - Vibrations a problem
  - Diamond – 100 μm
    - Latest tests look OK

Etch processes: wet etch, DRIE, SOI/wet etch
Available crystal orientations: \( <400\), \( <220\), \( <111\)
Self-seeded operation of the LCLS hard X-ray FEL in the long-bunch mode
Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
DESY 10-239

First Demonstration of Hard X-ray Self Seeding at LCLS


- The mean seeded FEL power is 8 GW with a 2.5 GW SASE background at 8 keV for 40 pC bunch charge.
- Peak seeded power is in excess of 15 GW, comparable to SASE but with a spectral bandwidth reduction by the factor of 40.
- Next steps include system optimization of the LCLS undulator beamline including additional undulators which should increase seeded power and reduce intensity fluctuation.
Tested at XCS Beamline - Outperforms Best SASE Intensity

Room in the LCLS tunnel for more undulators – “tapering” after seeding could yield ~ 0.4 TW in narrow BW

JLAB – 12 November 2012
Soft X-Ray Self-Seeding

LCLS is developing a compact grating monochromator and chicane that is similar to HXRSS unit in size.

- Fit within the length of one undulator module 4 m.
- Photon energy range 400 - 1000 eV.
- X-ray and electron delay varies from 660 - 850 fs.
- Resolving power from 7800 (400 eV) to 4800 (1000 eV).

P. Heimann

JLAB – 12 November 2012
X-band Transverse Cavity (XTCAV)

fs electron and x-ray temporal diagnostics – project started in FY11

Resolution formula:
\[ \propto \frac{\lambda_{rf}}{V_0} \sqrt{E \frac{\varepsilon_{N,x}}{\beta_x(s_0)}} \]

- High resolution, ~ few fs;
- Applicable in all FEL wavelength;
- Beam profiles, single shot;
- No interruption with operation;
- Both e-beam and x-ray profiles.

Y. Ding
P. Krejcik
Transverse cavity installed
Variable Phase Undulator for Polarization Control & Terawatt

Proof of principle: autumn 2013

- Four independent quadrants of permanent magnets move longitudinally at fixed gap.
- By sliding the arrays it is possible to control the K from full to zero
- and to control the polarization of the radiation emitted

JLAB – 12 November 2012
Multi Bunches – Multiple Lasers – Multiple User

- Two bunch lasing demonstrated 07/2010, 8.4 ns separation, 250 pC
- Single laser, 2 pulses from pulse stacker

- Two FEL demonstration with kinked undulator 01/2011
- Used slow kicker for 2x 5 Hz
- 2 bunches and fast kicker would enable 2x 120 Hz

F.-J. Decker et al.
JLAB – 12 November 2012
Linac Coherent Light Source II

- Injector @ 1-km point
- Sectors 10-20 of Linac (1 km) (with modifications)
- Bypass LCLS Linac in PEP Xport Line (extended)
- New Beam Transport Hall
- X-ray Transport Optics/Diagnostics
- SXR, HXR Undulators
- New Underground Experiment Hall
Overall Layout, LCLS-II

BC-1 moved downstream (375 MeV)

- Less energy jitter
- Compatible with future 360 Hz operation
Enhanced Capability

LCLS-II will provide expanded spectral range

- Up to 13 keV (above Selenium K-edge) @ 10.5-13.5 GeV
- Down to 250 eV (Carbon K-edge) @ 7-10 GeV
- 302m undulator tunnel
  - Space to accommodate future enhancements:
    - Seeding
    - polarization control
    - TW peak power

Tuning the X-Rays with both undulator gap and Electron Beam Energy
Greater Capacity

• Dedicated injector at Sector 10
• Two new SASE undulator systems, both variable gap
• High Field Physics Soft X-Ray Experiment Station
• Sets the stage for
  • 3X increase in hours of operation for soft x-rays
    - Generally, soft x-ray experiments run one-at-a-time
  • ~15%-30% increase in operations hours for hard x-rays, even with no new HXR instruments
    - Since hard x-ray instruments will someday run simultaneously, perhaps 2 or even 3 at a time, this can mean this much more time per station
• Future: Room in new experiment hall for up to 6 new instruments

JLAB – 12 November 2012
LCLS-II Project Organization

LCLS-II Project
Functional Organization – August 2012

External Committees
PMOG
FAC

Project Director - John Galayda
Deputy Project Director – Dave Schultz
Project Office – Richard Boyce
Associate Project Director for Conventional Construction – Dave Schultz

ESH – J. Healy, I. Evans, M. Sharfenstein
Quality Assurance – D. Marsh

SLAC Directorate Liaisons
AD – R. Hettel
LCLS – J. Arthur

Project Office
Richard M. Boyce
Financial Planner – A. Reese
Project Controls – D. Sala, D. Rasalkar
Procurement – J. Dawey / B. Miller
Document Specialist – R. Ronce

Electron Systems
Jose Chan

Injector
G. Hays
Linac
D. Hanquist
Controls/Global Systems
H. Shoaei

Photon Systems
Michael Rowen

Undulator
S. Marks - LBNL
W. Olson - SLAC

XTOD
E. Ortiz
XES
A. Busse

Integration & Coordination
Lori Plummer

Vacuum - D. Gill
Controls – H. Shoaei
Diagnostics – H. Loos
Rad. Phys. – M. Santana
Elect. Sys. – P. Rodriguez
Laser Sys. – G. Hays
Power Conversion – B. Lam
RF Sys. – V. Pacak
Metrology – C. LeCocq
Mech. Sys. – J. Amann
Safety Sys. – F. Tao
Facilities – B. Law
AD Tech Planning – K. Ratcliffe

Conventional Facilities
Robert Law

Sector 10 Inj Bldg.
PM - D. Saenz

Physics Support
T. Raubenheimer
T. Raubenheimer – Injector, Linac
Z. Huang – FEL
J. Welch – XTOD
H. D. Nunn – Undulator
P. Heimann – Photon Systems

Heavy Civil Constr.
PM - Jess Albino

JLAB – 12 November 2012
# Funding/Schedule Overview

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>FY 10</th>
<th>FY 11</th>
<th>FY 12</th>
<th>FY 13</th>
<th>FY 14</th>
<th>FY 15</th>
<th>FY 16</th>
<th>FY 17</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>OPC and Pre-Ops</td>
<td>$1.2</td>
<td>$9.4</td>
<td>$8.0</td>
<td>$0.7</td>
<td>$0.7</td>
<td>$0.7</td>
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<td>Design/ Construction</td>
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<td>$43.5</td>
<td>$80.3</td>
<td>$94.0</td>
<td>$105.3</td>
<td>$19.9</td>
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<td>Total Project Cost</td>
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<td>$9.4</td>
<td>$30.0</td>
<td>$63.5</td>
<td>$81.0</td>
<td>$94.0</td>
<td>$106.0</td>
<td>$19.9</td>
<td>$405.0</td>
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New funding profile guidance: +14.7 +$10.0 -4.8 -$19.9

## Level I Baseline Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-0, Approve Mission Need</td>
<td>4/22/10 (actual)</td>
</tr>
<tr>
<td>CD-1, Approve Alternative Selection and Cost Range</td>
<td>10/14/11 (actual)</td>
</tr>
<tr>
<td>CD-3a, Approve Long Lead Procurement Baseline and Start of Long Lead Procurements</td>
<td>3/14/2012 (actual)</td>
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<tr>
<td>CD-2, Approve Performance Baseline (Review 8/21-23)</td>
<td>10/31/2012</td>
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<tr>
<td>CD-2/CD-3b, Approve Start of Construction</td>
<td>6/30/2013</td>
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<tr>
<td>CD-4, Approve Project Completion</td>
<td>9/30/2019</td>
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JLAB – 12 November 2012
New Guidance on Funding Profile

<table>
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<th>FY 10</th>
<th>FY 11</th>
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<th>FY 13</th>
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<td>$104.0</td>
<td>$101.2</td>
<td>$0</td>
<td>$405.0</td>
</tr>
</tbody>
</table>

**CF Construction:**

- Should enable acceleration of schedule
  - Undulators, x-ray optics and x-ray experimental systems are candidates for acceleration
  - May gain 6 months on “First Light” milestone
LCLS-II Heavy Civil Construction

Extension of Beam Transport Hall (162m)
LCLS-II Heavy Civil Construction

Extension of Beam Transport Hall (162m)

Undulator Hall (302m)

Front End Enclosure (92m)

LCLS-1 beamline

19'

JLAB – 12 November 2012
LCLS-II Heavy Civil Construction

- Extension of Beam Transport Hall (162m)
- Undulator Hall (302m)
- Service Building
- Front End Enclosure (92m)
LCLS-II Heavy Civil Construction

- Extension of Beam Transport Hall (162m)
- Undulator Hall (302m)
- Service Building
- Front End Enclosure (92m)
- Experiment Hall 15m x 80 m

LCLS-1 beamline
LCLS-II Schedule - 6-month LCLS outage

Pre-down work:
- Site work
- Start Access Tunnel

Post-down work:
- Finish BTH2 concrete
- Finish FEE & EH2 concrete
- Construct EH2 2nd floor

6-month down work:
- Utility relocation
- UH tunneling from the west
- BTH2 concrete construction
- Excavate UH2 Access Shaft
- Excavate EH2 cavern
- Tunnel FEE & Maze
- UH and EBD concrete
- Linac installation in LCLS areas

JLAB – 12 November 2012
Vibration studies with LCLS operating, Aug. 1st

- Used a road header, backhoe, jack hammer, concrete vibrator, concrete drill, and truck traffic

- Instrumented area with 20 accelerometers and seismometers

- No effect seen on SPEAR beams

- No effect seen on LCLS electron beam

- No effect seen of LCLS x-ray beam at FEE direct imager

- No distinguishable effect seen at XCS experiment in the FEH
  - Other effects may mask any construction-driven beam motion

- Impulses detected on FEE & XRT mirrors – under analysis
LCLS-II Long-Lead Acquisitions: Construction Underway

- CD-3a (2 x $20M in 2012-2013) approved for:
  - 135 MeV Injector + new annex building at Sector 10
    - Injector fabrication underway
      - Operational during 2015-2016
      - R&D supporting LCLS
      - Connect to LCLS-II linac in 2016
  - Hard x-ray undulator magnet blocks
    - Partial order (1/4 of total)
    - Larger purchase if contingency permits
LCLS RF Gun in fabrication

This time, a single ceramic window
Photocathode Laser- will be identical to many lasers in use now at LCLS

Copper cathode: QE > 1 \times 10^{-4}, 2X original design spec lifetime: years
Injector & Laser Heater, Same as LCLS

- transverse RF deflector
- 6-135 MeV booster linac
- RF gun
- OTR screens & wire-scanners
Sector 10 Laser Annex Construction Underway
LCLS-II Linac
BC1 and BC2, Extensive Re-Use of Designs
LCLS-1 Bypass, Re-Use PEP-II Transport Line
Undulators Designed & Acquired by

E-Beam path designed & Constructed by SLAC
X-Ray Transport, Optics & Diagnostics
X-Ray Experiment Systems

- Based on proven LCLS and LUSI designs
XES

X-ray Experimental Systems (XES):

- Design and build a high field Soft X-ray experimental system
  - Components based on XTOD & LCLS-I
- The high field experimental system provides focused, high-intensity soft x-rays for:
  - Studies of non-linear x-ray physics and other Atomic, Molecular and Optical (AMO) science
  - Single-particle imaging experiments from the water window up to 2000eV
  - Use LCLS sample chambers
LCLS-II Accelerator for 250 pC, 120 Hz

Injector, linac, and compression parameters are all very similar to LCLS-I, but not exact.
Differences between LCLS-I and LCLS-II

The LCLS-II design is heavily based on the LCLS-I

• Primary differences
  - Six fewer rf stations than LCLS-I
    • Roughly 1.5 GeV lower voltage, ok with lower bunch charge
  - 1.2km of additional drift in bypass line
    • Larger chirp at linac end → understand wakefields
  - Two undulator beamlines HXR and SXR
    • Beamline separation with kicker and septum
  - Variable gap undulators
    • Can decouple photon energy from beam energy

• Lots of smaller changes based on LCLS-I experience
LCLS-II Beam Emittances Based on LCLS-I Operation

Better performance with lower charge

- LCLS-I was optimized for 1 nC and 1 mm-mrad but now routinely operates with 150 pC and slice emittances less than 0.3 mm-mrad
- LCLS-II will be optimized around 250 pC and 0.4 mm-mrad \( \rightarrow \) shorter gain lengths and undulators than in LCLS-I original design

---

LCLS-I Injector emittance measurements

![LCLS-I Injector emittance measurements](image)

LCLS-II Emittance vs Charge

![LCLS-II Emittance vs Charge](image)

Simulated \( \gamma \varepsilon \) is \(~15\%\) smaller
Alternate Optics layout
Modified LTUS – Eases 2-bunch upgrade

Baseline SXR LTU

Long drift to minimize wall interference

Alternate SXR LTU

Low $\beta_x$ at bends

Y-kicker

DC1

DC2

2.4° 4-bend

1.2° 2-bend

Septum

Long drift to maximize HXR/SXR separation

JLAB – 12 November 2012

Work by Yuri Nosochkov
Baseline undulators have been chosen to saturate with 250 pC across photon wavelength range:

- **HXR**: 2 – 13 keV and **SXR**: 0.25 – 2 keV
- 15% overhead in SXR undulator length at 250 pC
- Little overhead or margin in HXR baseline at 250 pC

### Table of Results

<table>
<thead>
<tr>
<th>Photon Energy (keV)</th>
<th>Beam Energy (GeV)</th>
<th>Charge (pC)</th>
<th>Emittance (mm-mrad)</th>
<th>Saturation Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>13.5</td>
<td>250</td>
<td>0.4</td>
<td>87</td>
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<tr>
<td>13</td>
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<tr>
<td>13</td>
<td>12.3</td>
<td>150</td>
<td>0.3</td>
<td>74</td>
</tr>
</tbody>
</table>

Rapid reduction of gain length with charge and $\gamma\varepsilon$

- 250 pC $\rightarrow$ 150 pC estimated to reduce gain length by ~15%
Understand Possible LCLS-II Upgrades
Recommendation from LCLS-II CD-1 Review

Understand upgrades to avoid preclusion

- Upgrades may bundled with follow-on instrument project or may come as AIPs
- Also consider if early inclusion can be accommodated with acceptable cost and risk

Possible upgrades include:

- Polarization control
- Multi-bunch and/or higher repetition rate operations
- Self-seeding and Two-bunch seeding
- Terawatt XFEL

LCLS-I R&D will further develop possible options
Polarization and Multi-Bunch Operation

- LCLS-I R&D program to develop DELTA undulator for polarization control
  - Space left at end of SXR for 3 DELTA undulator segments

- Three multi-bunch configurations considered:
  - Bunches to both undulators @ 120 Hz (>30 ns separation)
  - Bunch pairs for 2-bunch self-seeding (few ns separation)
  - Bunch train (up to 30 bunches with ~10 ns spacing)
    - Studying wakefield limitations and energy control
    - Shielding designed for 5 kW beam power
      - Up to 30 bunches of up to 100 pC per rf pulse
    - Will require improvements to diagnostics, gun and laser
Improving understanding of options for hard and soft x-ray seeding

Experiment on HXRSS installed in LCLS-I → user operation

Developing plans for similar SXRSS experiment

Working on options for two-bunch seeding

- Pro: works over wider range of wavelength and bunch parameters → greater flexibility, more x-ray power
- Con: more complicated
FEL TW Physics with Strong Tapering
Little experience; extensive simulation study

Not many studies:
   LLNL result →

Simulation studies progressing
Using LCLS-I to benchmark

LCLS-II start-to-end simulation: 8 keV (red) and 13 keV (black)
at 13.5 GeV and 13 keV at 10 GeV (blue)

• Working to understand saturation mechanisms and tolerance implications

T. Orzechowski et al. PRL (1986)
Extended Undulator Hall
Enable Terawatt (TW) Upgrade

Many S-2-E studies to understand requirements

- Need roughly 270 meters of undulator for 13 keV
- Extended undulator hall has room for 282 meters of undulator

<table>
<thead>
<tr>
<th>FEL energy (keV)</th>
<th>SASE Undulator Portion (m)</th>
<th>Saturation Full Length (m)</th>
<th>Power (TW) 200 m Full undulator</th>
<th>Power (TW) 250 m Full undulator</th>
<th>Power (TW) 300 m Full undulator</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>39</td>
<td>220</td>
<td>1.1</td>
<td>1.1</td>
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<td>48</td>
<td>330</td>
<td>0.5</td>
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</table>

- Extended hall also allows for 2-color generation or other options
Closing Comments

- Design of LCLS-II is well advanced
  - The necessary documentation is ready for CD-2
- LCLS-I lessons learned have been incorporated
  - Parameters based on LCLS-I operation
  - Documented LCLS-I beam physics lessons learned for Injector, Linac and LTU
- Some details to still complete (e.g., balancing tolerance studies, performance across full operational space, ...)
- Studying expansion upgrades to avoid preclusion
  - LCLS-I R&D program will further clarify options
LCLS-II is just the start…

Concepts for new instruments are being developed
Downselect and instrument construction schedule TBD

- “Hard” x-rays
  - Nanocrystallography, 6-13 keV
    - 2 stations, one for imaging and one for screening crystals
      - Stations in series, x-ray beam will be re-focused
- Hard x-ray general purpose
  - Pump/probe, harder x-ray spectrum
- Soft x-rays 250-2,500 eV
  - High-Field Physics (in LCLS-II Scope)
  - Monochromatic (< $10^{-5}$) station
  - Nonlinear/quantum soft x-ray optics
End of Presentation

JNG thanks
-Jerry Hastings
-Zhirong Huang
-Tor Raubenheimer
For hijacked presentation materials