Expanding the Boundaries of X-ray Lasers:

LCLS Upgrades and the Future

Greg Hays / Director, LCLS-II and LCLS-II-HE Projects

08 August 2022

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

1. The Linac Coherent Light Source (LCLS): 2009 to 2022
2. LCLS-II Project: The first upgrade
3. LCLS-II High Energy (LCLS-II-HE)
4. Matter in Extreme Conditions Upgrade Project
5. The Future of X-ray FELs
6. Summary

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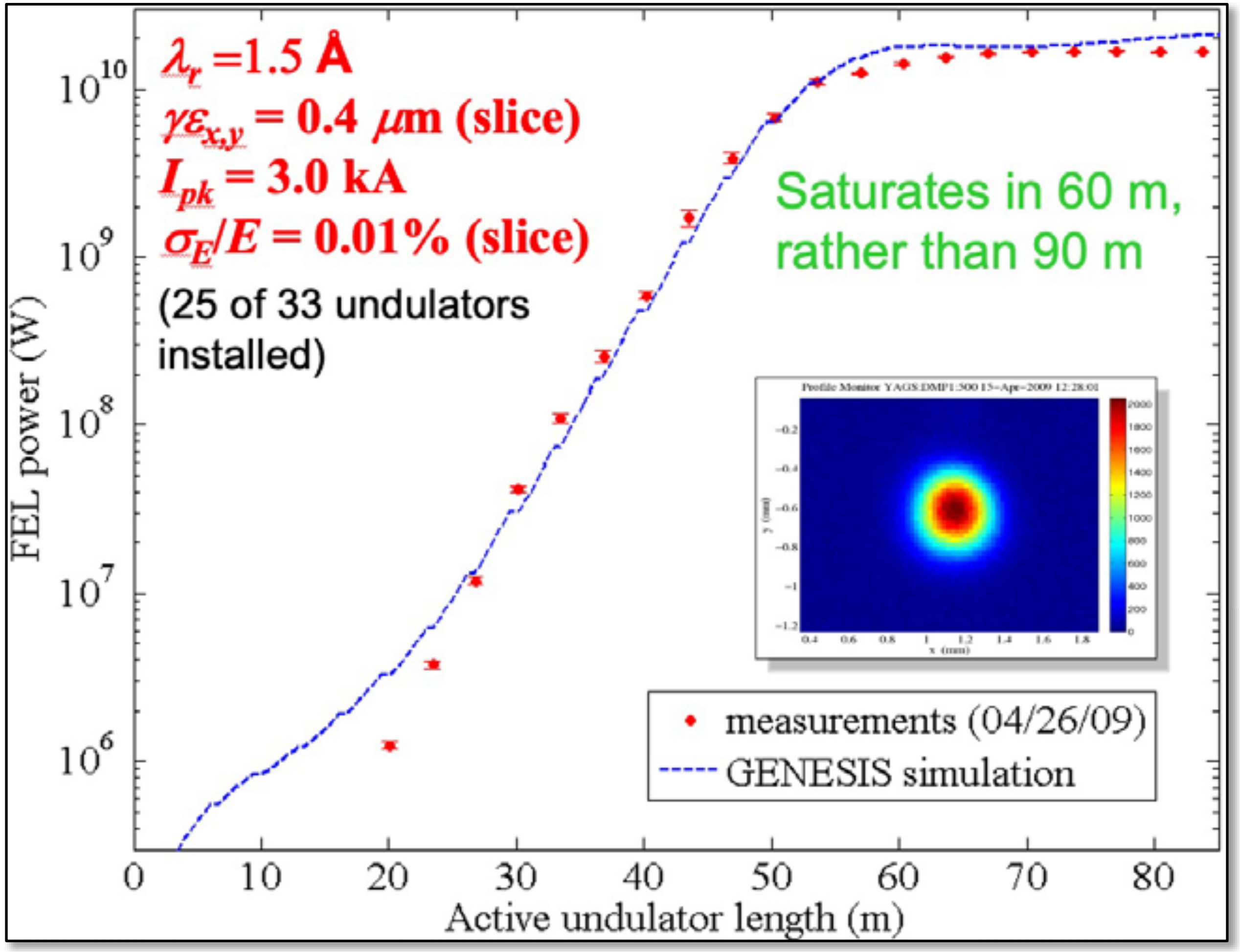
The Linac Coherent Light Source: 2009 to 2022

The era of Hard X-ray FELs began on April 10th, 2009.

The LCLS FEL lases in just “2 shots” through the undulator!

From left: H.D. Nuhn, P. Emma, R. Bionta, J. Galayda, S. Moeller, Z. Huang, D. Ratner



LCLS today

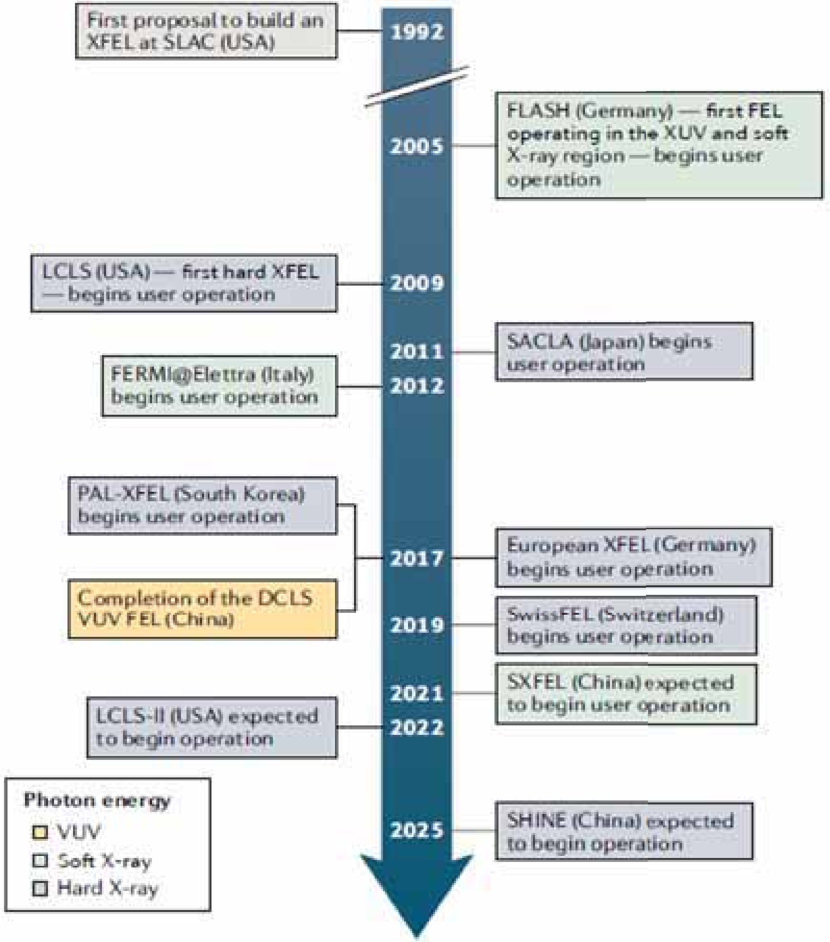
SSRL
LCLS Accelerator
FACET-II (Planned)
LCLS-II Accelerator
LCLS Experimental Halls

LCLS-II Cryoplant

Injector
Linac
LCLS Experimental Facilities
e- Beam Transport
Undulator
Office Building
Near Experimental Hall
X-ray Transport
Far Experimental Hall

Courtesy of N. Holtkamp

Higher average power is the way of the future.



New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu

EuXFEL, Germany

FLASH

SACLA, Japan

SwissFEL, Switzerland

PAL-FEL, Korea

Under construction

SHINE, SXFEL

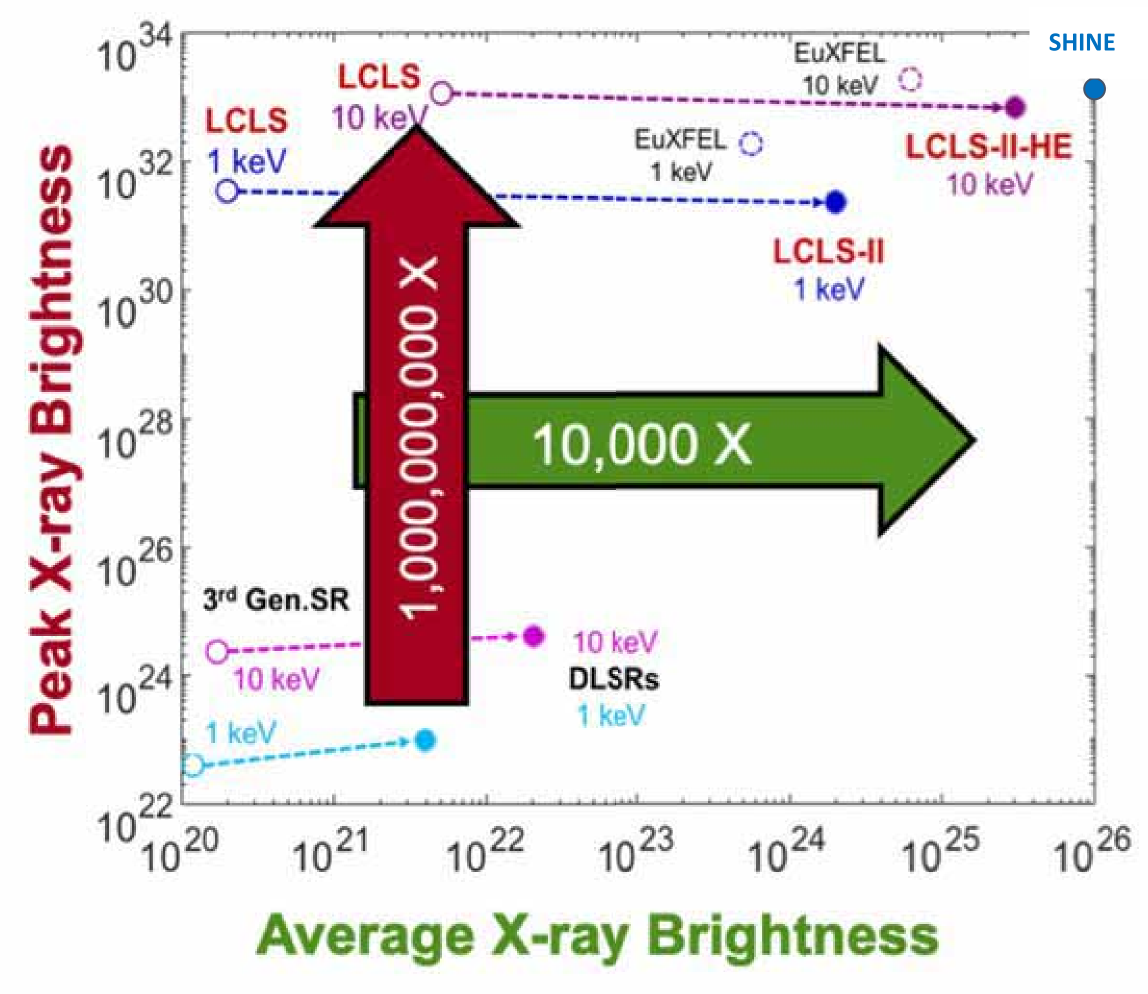
Nature Reviews Physics | https://doi.org/10.1038/s42254-020-0204-6; 3 July 2020

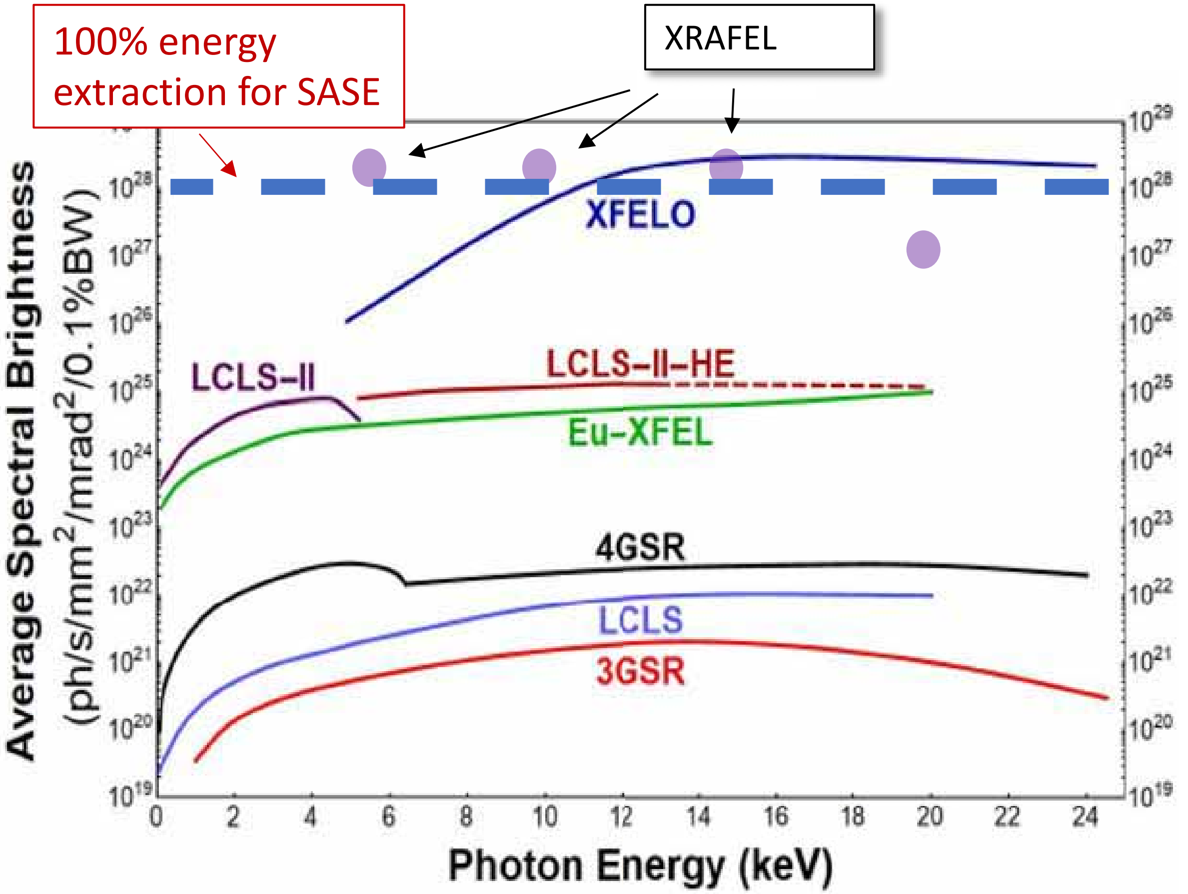
Approx. average pulse repetition rate is shown (note: EuXFEL is 4.5 MHz burst at 10 Hz)

XFEL, SHINE and LCLS-II/HE are leading the development of high average power FEL facilities

Courtesy of M. Dunne & Z. Huang

Ever Higher Performing FELs





Another three orders of magnitude – Where does it end?

2 LCLS-II Project: The first upgrade

LCLS-II Installation: 2017 to 2022

LCLS-II Project Collaboration

Fermilab	• Cryomodule engineering/design • Manufacture 50% of cryomodules: 1.3 GHz • Design and manufacture 2+1 Cryomodules: 3.9 GHz • Design and acquisition of helium distribution • Processing for high Q (FNAL-invented gas doping)	✓
Jefferson Lab — EXPLORING THE NATURE OF MATTER	• Manufacture 50% of cryomodules: 1.3 GHz • Design and acquisition of two 4 kW Cryoplants • Processing for high Q	✓
BERKELEY LAB	• Undulators • e^- gun & associated injector systems	✓
Argonne NATIONAL LABORATORY	• Undulator R&D: vertical polarization prototype • Undulator Vacuum Chamber • Assisting in tuning undulators • Also supports FNAL w/ SCRF cleaning facility	✓
CORNELL UNIVERSITY FOUNDED A.D. 1865	• R&D planning, prototype support • processing for high-Q (high Q gas doping)	✓

- Additional support through many other collaborations:

CERN, DESY., cea, cnrs, SNS SPALLATION NEUTRON SOURCE

LCLS-II Project Timeline

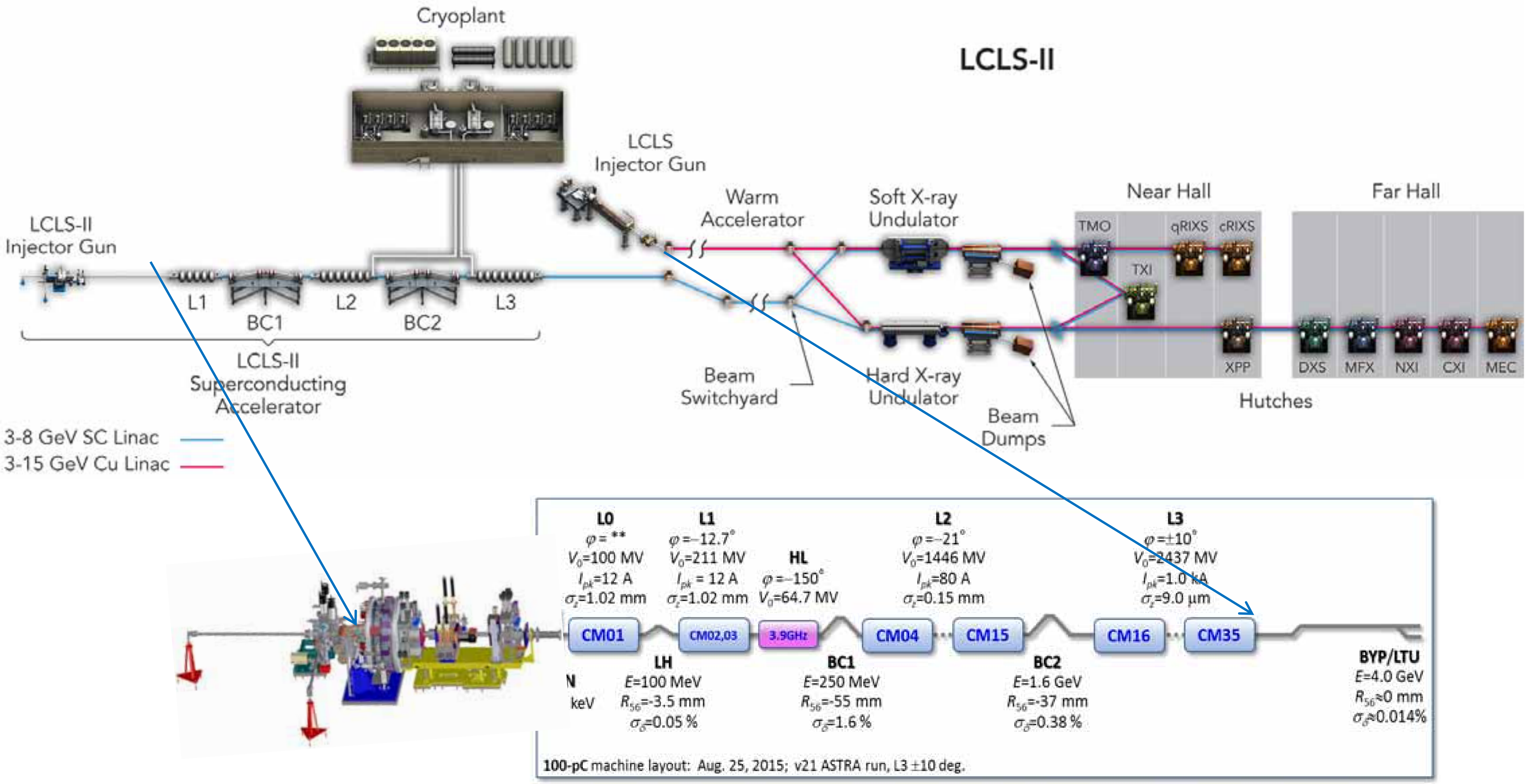
Milestone	Date Due or Complete (A)
CD-0 (Original scope)	22-April-2010 (A)
Mission Need Statement (Update)	27-Sep-2013
CD-1 (Original scope)	14-Oct-2011 (A)
CD-3A (Original scope)	14-Mar-2012 (A)
CD-1 (Update)	22-Aug-2014 (A)
CD-3B (Update)	28-May-2015 (A)
CD-2/3 (Update)	21-Mar-2016 (A)
BCP Approval (Update)	13-Oct-2020 (A)
CD-4 (Update)	31-Jan-2024

Normal Conducting Accelerator

SCRF Accelerator

- **SC Linac First Light: Jan 2023**
- **Project Early Finish: Apr 2023**

LCLS-II Layout



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LCLS-II Key Performance Parameters

Threshold and Objective

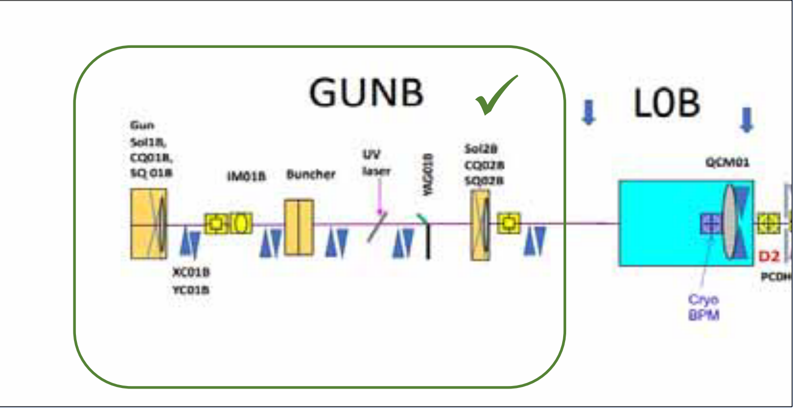
Performance Measure	Threshold (5 kW beam)	Objective (120 kW beam)	Measurements
Variable gap undulators	2 (soft and hard x-ray)	2 (soft and hard x-ray)	
Superconducting linac-based FEL system			
Superconducting linac electron beam energy	3.5 GeV	≥ 4 GeV	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	93 kHz	929 kHz	BPM's, laser rate
Superconducting linac charge per bunch	0.02 nC	0.1 nC	Toroid, Faraday cup
Photon beam energy range	250–3,800 eV	200–5,000 eV	Absorption edges, spectrometer
High repetition rate capable end stations	≥ 1	≥ 2	N/A
FEL photon quantity (10^{-3} BW) per bunch	$5x10^8$ (10x spontaneous) @2,500 eV	> 10^{11} @ 3,800 eV	Gas energy monitor, GMD, Spectrometer
Normal conducting linac-based system			
Normal conducting linac electron beam energy	13.6 GeV	15 GeV	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	120 Hz	120 Hz	BPM's, laser rate
Normal conducting linac charge per bunch	0.1 nC	0.25 nC	Toroid, Faraday cup
Photon beam energy range	1–15 keV	1–25k eV	Absorption edges, spectrometer
Low repetition rate capable end stations	≥ 2	≥ 3	N/A
FEL photon quantity (10^{-3} BW[a]) per bunch	10^{10} (lasing @ 15 keV)	> 10^{12} @ 15 keV	Gas energy monitor, GMD, Spectrometer

Achieved

Normal Conducting Commissioning completed 2021

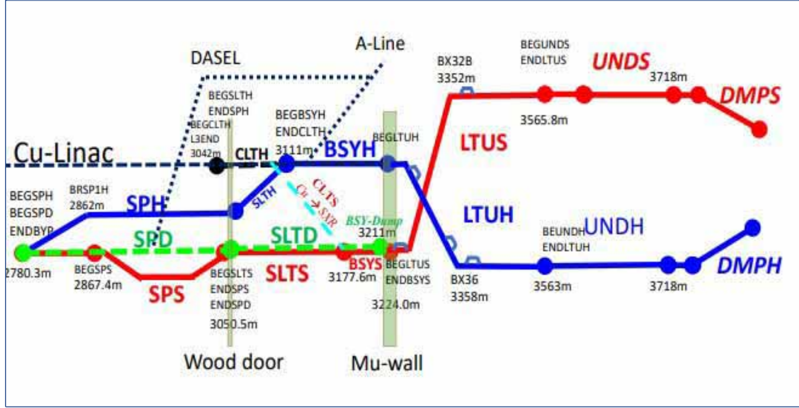
Electron Gun

- Gun and LEB
- Laser
- Gun is commissioned,
- upgrades are complete
- Loadlock repair is complete



Beam Transport

- LTUH
- LTUS
- CLTS (Ops) beamline allowed early commissioning of SXR systems:
    - Beam Transport
    - Undulators and Instruments



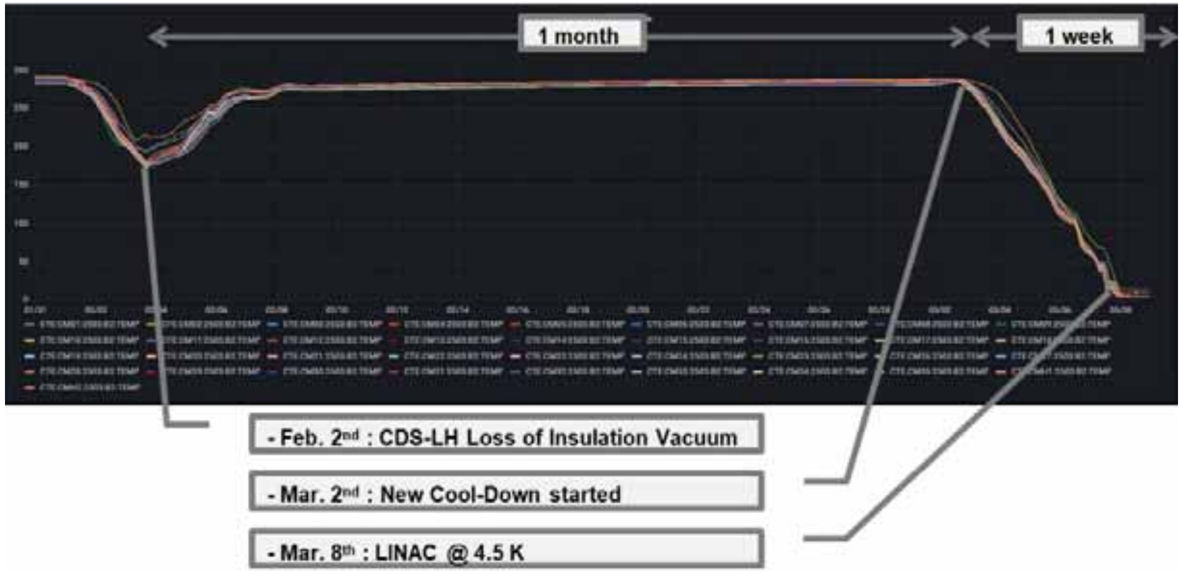
SXR and HXR Undulators

- HXR Undulator
- SXR Undulator
- HXRSS-II
- SXRSS-II (Ops)

Cu-Linac operation allowed commissioning of warm beamline systems, undulators and instruments

Cryoplant #1 has achieved stable operation at 2K

Cooldown to 4.5K and then to 2K



Cryoplant #2 online by February 2023

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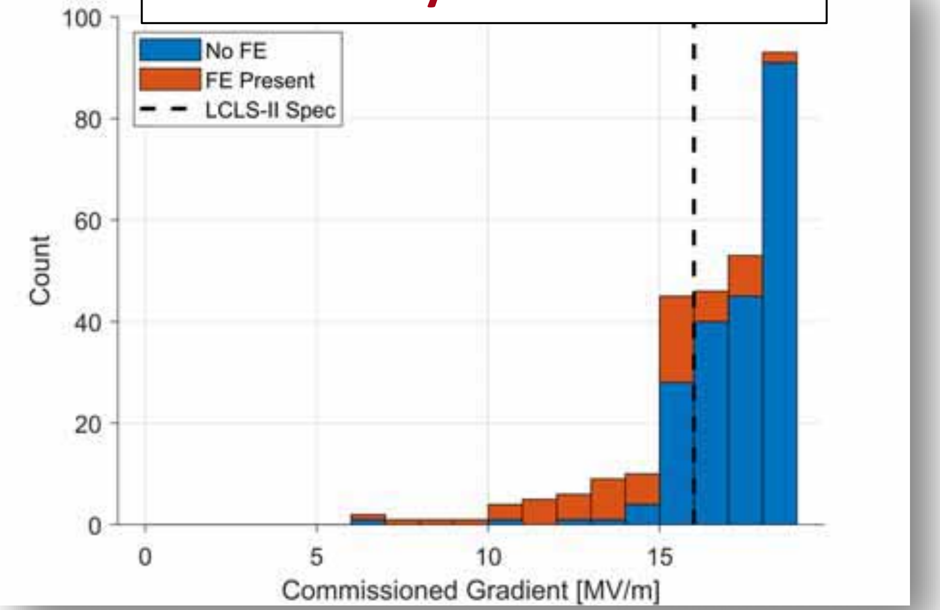
Courtesy of D. Gonnella

SRF Commissioning is underway

- LCLS-II SRF Cavities have been fully commissioned
- Performance has shown **no degradation in field emission performance from installation**

SRF Cavity Performance

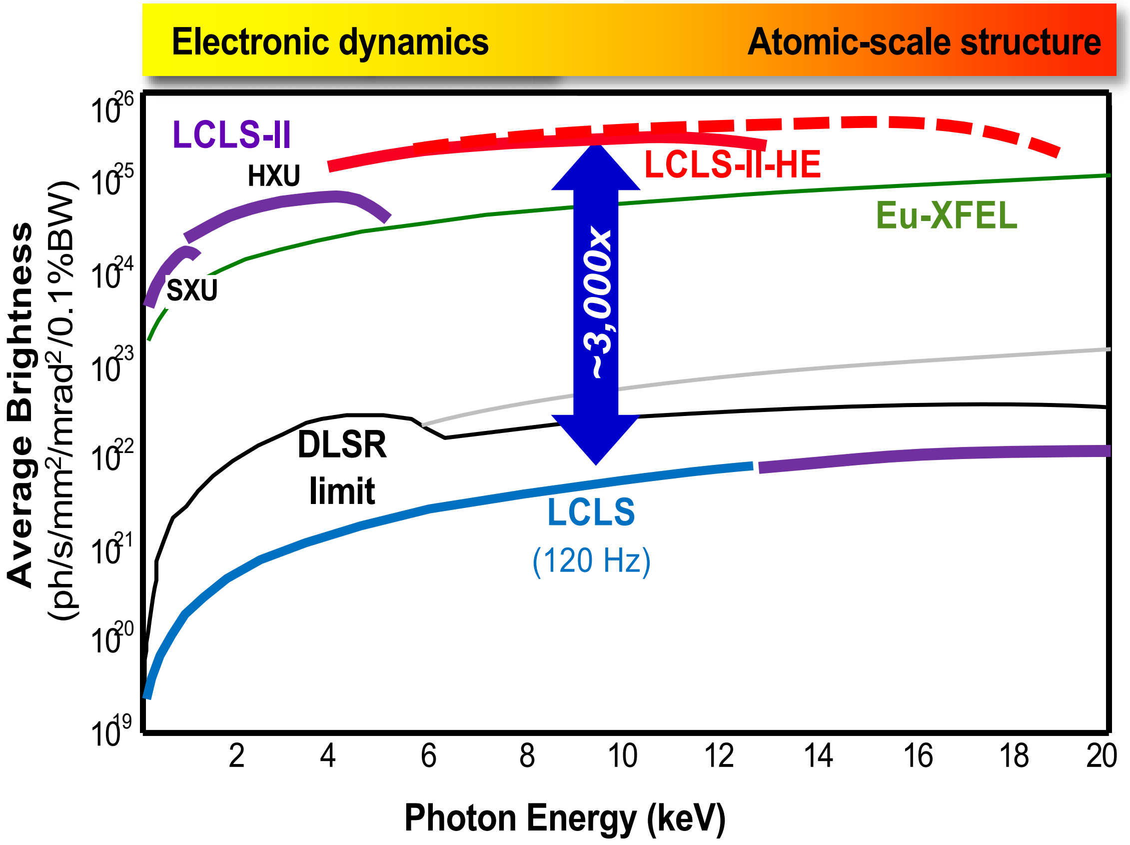


- Injector commissioning has propagated 100 MeV beam through the first Cryomodule
- Plan to run beam through full linac in mid-September

1st SCRF X-rays planned January 2023

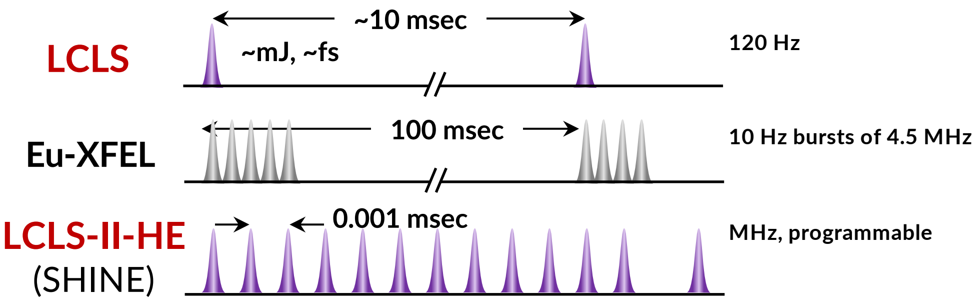
Courtesy of M. Dunne

LCLS-II-HE will provide a step-jump in capability



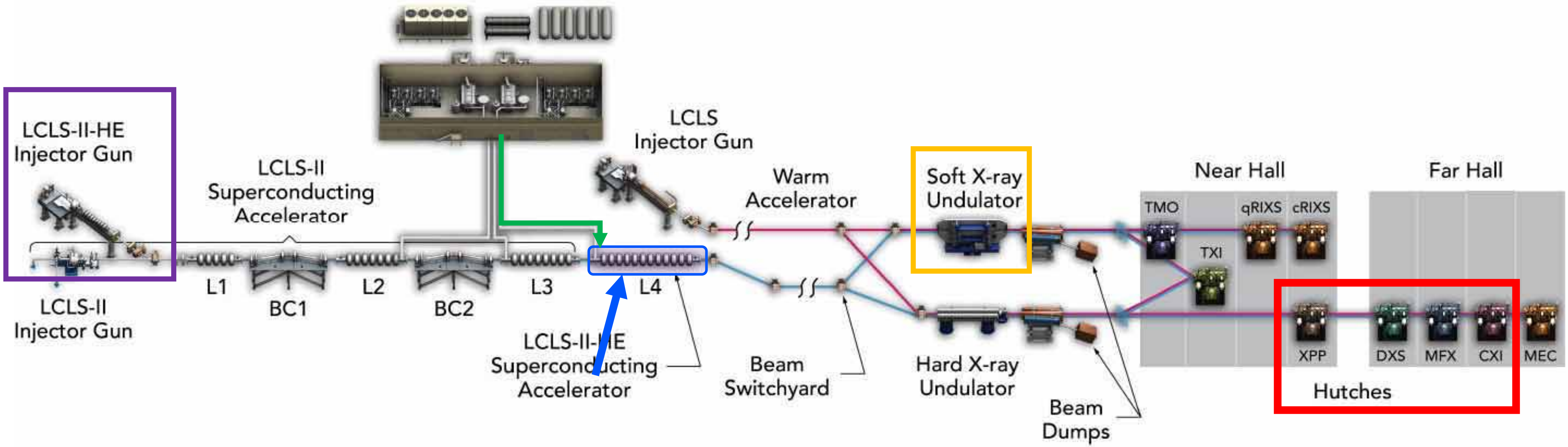
LCLS-II-HE will provide:

- Ultrafast, coherent, hard X-rays
- ~3,000-fold increase in average spectral brightness
- ~8000-fold increase in repetition rate
- Programmable time structure
- Dual source X-ray capability



This provides a qualitatively new capability, unique in the world, delivering ultrafast, Ångström performance at high average power.

LCLS-II-HE Project Scope



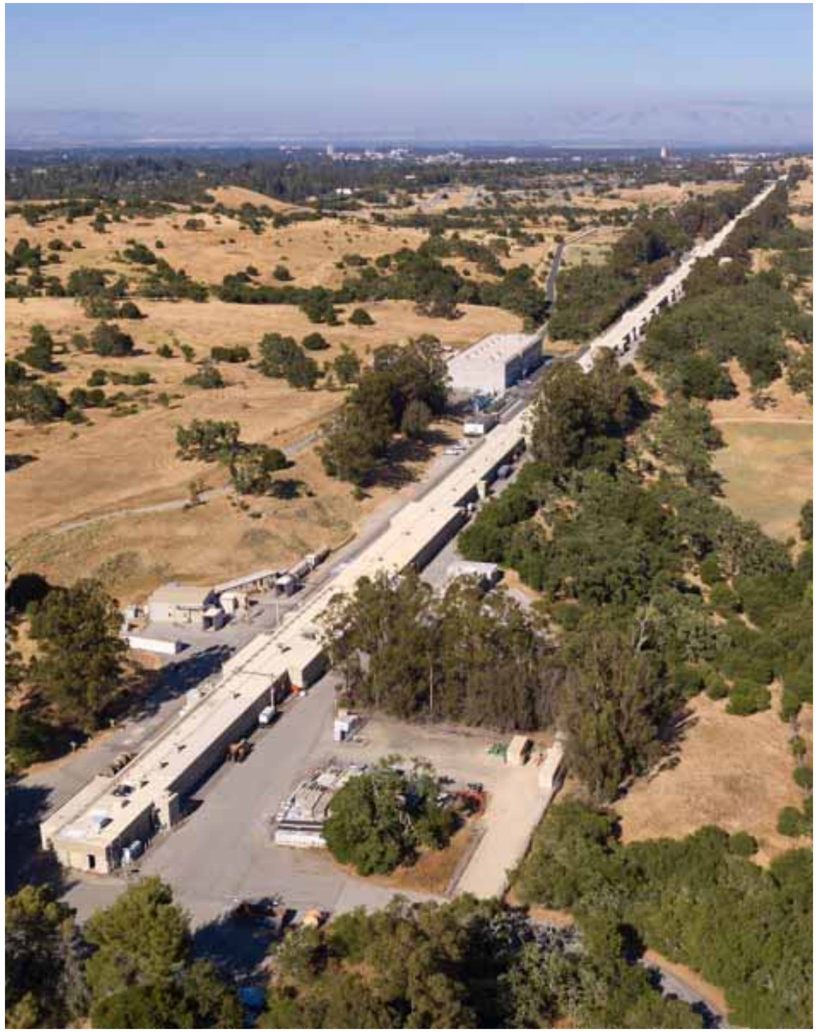
1. Install low-emittance injector and SRF gun for extended hard X-ray performance
2. Add 23 additional cryomodules (L4 linac) to increase the LCLS-II accelerator energy to 8 GeV.
3. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac.
4. New long period Soft X-ray Undulator
5. Upgrade the LCLS Hard X-ray endstations for MHz beam and data rates

LCLS-II-HE Key Performance Parameters

Preliminary Threshold and Objective Parameters

Performance Measure	Threshold	Objective
Superconducting linac electron energy	7 GeV	8 GeV
Electron bunch repetition rate in linac	93 kHz	929 kHz
Charge per bunch in SC- linac	0.02 nC	0.1 nC
Photon energy range	200 – 8,000 eV	200 to ≥ 20,000 eV
High rep-rate-capable HXR endstations	≥ 3	≥ 5
FEL photon quantity per bunch (10^{-3} BW)	5□10^8 (50□ spont. @ 8 keV)	> 10^{11} @ 8 keV (200 mJ) AND > 10^{10} @ 20.0 keV (20 mJ)

LCLS-II-HE Collaboration



SLAC NATIONAL ACCELERATOR LABORATORY	• Accelerator and FEL Design & Installation • High Power RF, low-level RF, and Controls • X-ray instruments design & installation
Fermilab	• High Q0 & High Gradient R&D • Cryomodule design 50% of cryomodule production • Capture Cavity Cryomodule design & production
Jefferson Lab EXPLORING THE NATURE OF MATTER	• High Q0 & High Gradient R&D • 50% of cryomodule production
BERKELEY LAB	• Accelerator Physics • Undulator design & procurement
FRIB	• SRF Gun Design & Prototype Demonstration • Production SRF Gun
CORNELL UNIVERSITY FOUNDED A.D. 1865	• High Q0 & High Gradient R&D

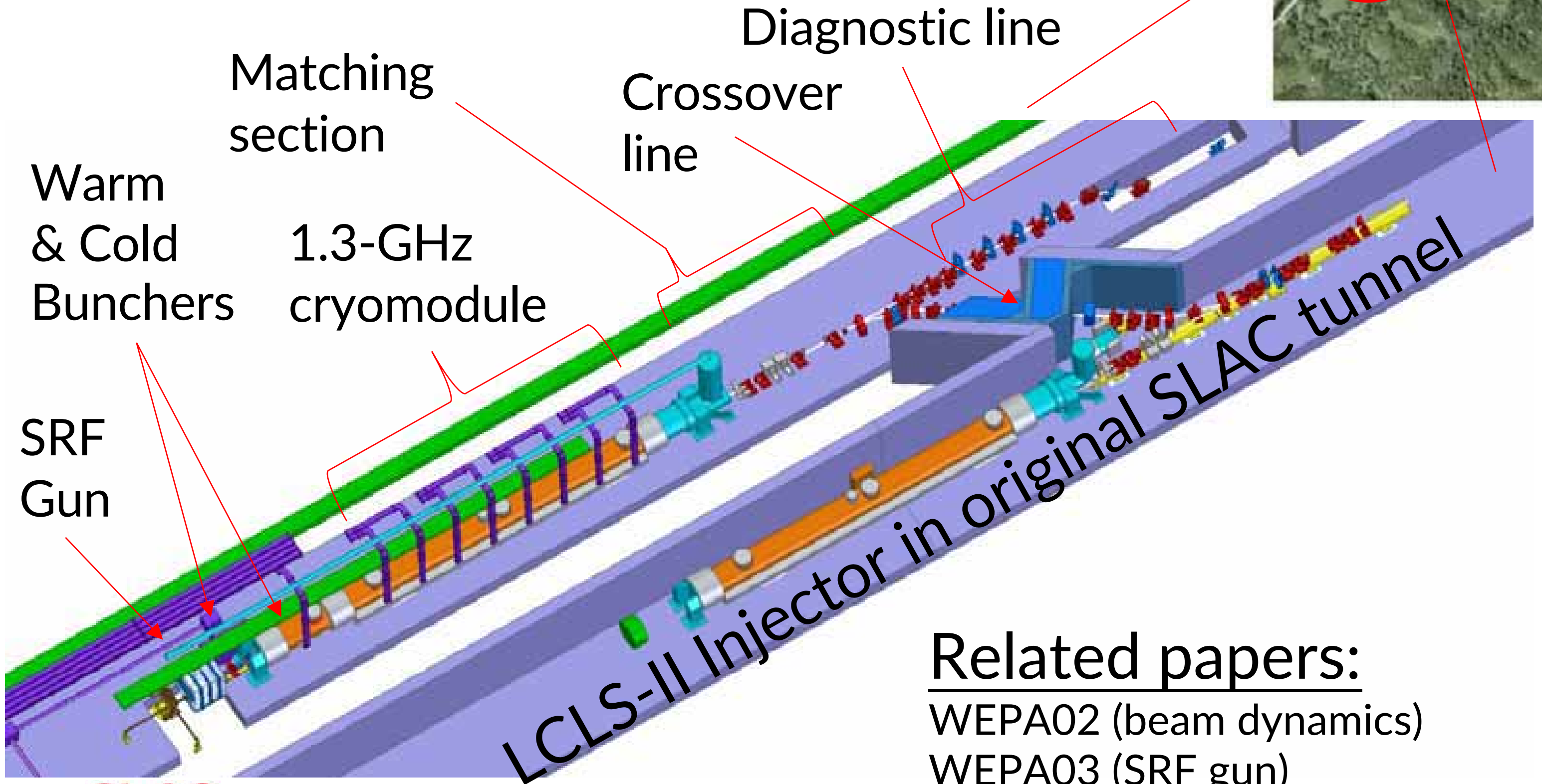
Verification Cryomodule Exceeds Performance Specs

vCM in Fermilab CMTS

- ✓ **vCM exceed the HE specifications**
  - ➢ Avg Q_0: $3x10^{10}$
  - ➢ Avg Gradient: 25 MV/m
- ✓ **Field emission free up to admin limit**
- ✓ **Max gradient near admin limit**
- ✓ **Plasma processing significantly reduced the multipacting quench behavior**

Low Emittance Injector (LEI) for LCLS-II-HE

- New tunnel at west end of SLAC linac
- Injects into LCLS-II linac at 100 MeV



Other notable features

- Dedicated cryoplant
- Operable independently of LCLS-II linac
- Factor of 2-4 lower beam emittance

Related papers:

WEPA02 (beam dynamics)
WEPA03 (SRF gun)

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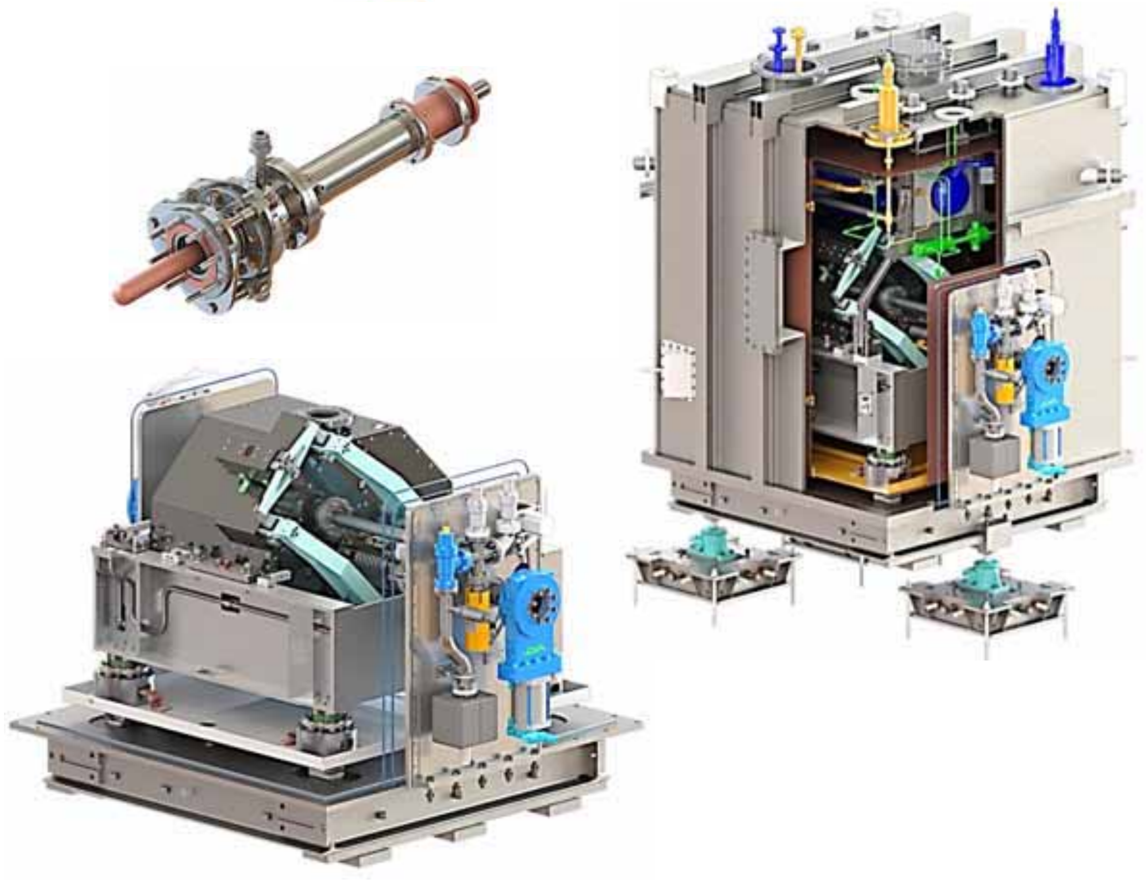
SRF Injector Design Progress

SRF Gun Model & Design

HZDR



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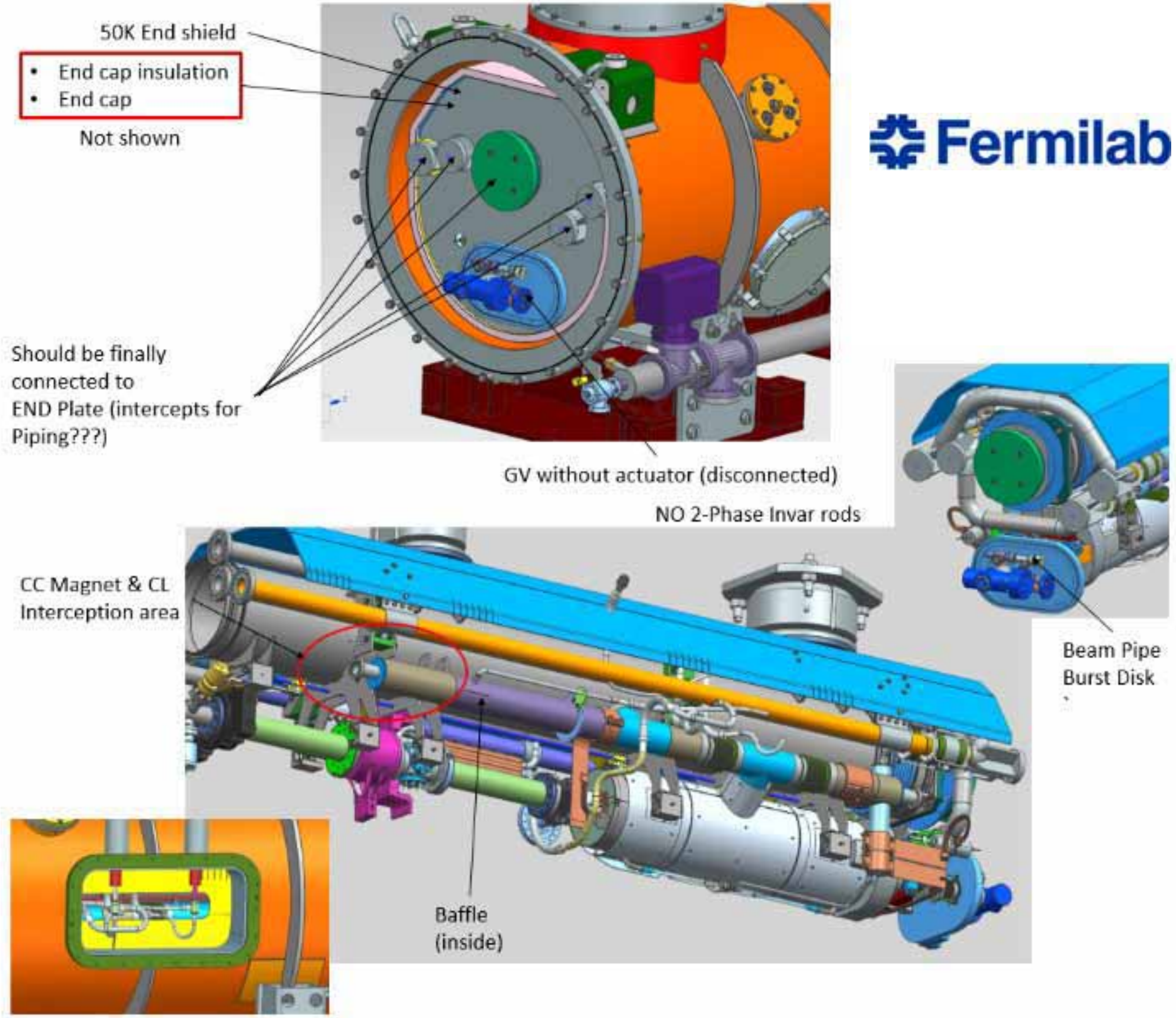
SRF Buncher CM Model & Design

Fermilab



LCLS-II-HE Timeline

Level 1 Milestones	Date	☑
CD-0 - Approve Mission Need	5-Dec-16	☑
CD-1 - Approve Alternative Selection & Cost Range	21-Sep-18	☑
CD-3A - Approve Long Lead Procurement	12-May-20	☑
CD-3B - Approve Long Lead Procurement (proposed)	Dec-22	
CD-2 – Approve Performance Baseline	Aug-23	
CD-3 – Approve Construction Start	Aug-23	
CD-4 – Project Completion	Jun-31	

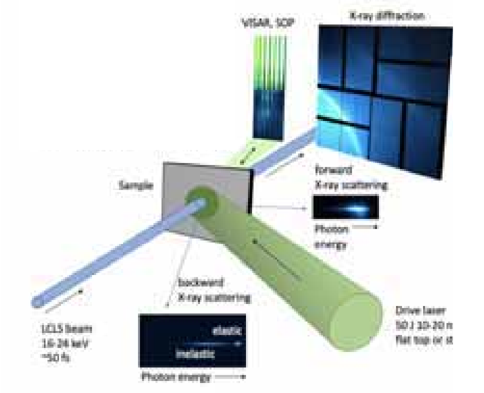
- Linac TTO (science Operations resume): Jan 2028
- Project Early Finish (Injector TTO): Aug 2029

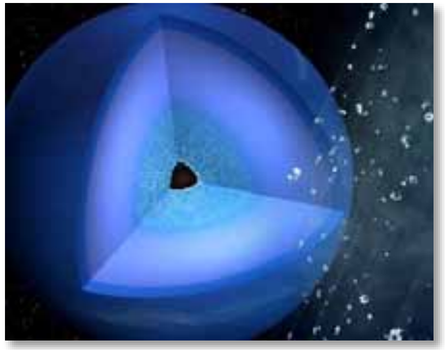
Courtesy of R. Sandberg

Matter in Extreme Conditions (MEC) at LCLS

MEC revolutionized the field of HEDP

Combined high power optical lasers with XFEL for the first time; great materials work; good warm dense matter; a few short pulse examples

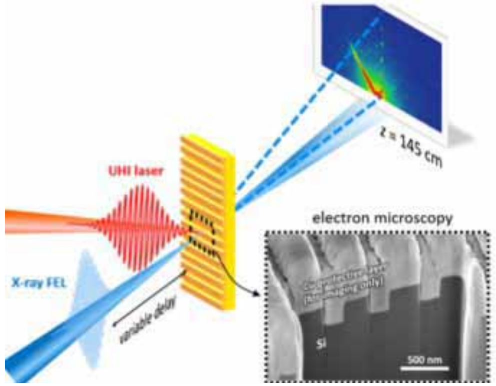


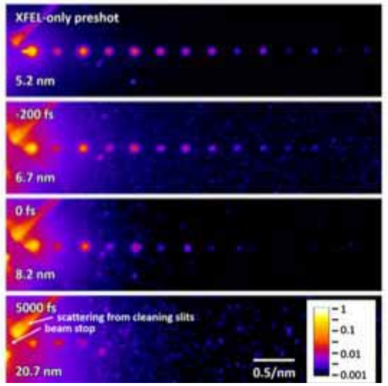


"Diamond rain" evidence

To further advance the field of HEDP science, MEC needs higher power:

- Hotter plasmas
- Brighter and higher energy particle sources
- Higher intensity, larger, more sustained laser-plasma interactions





Relativistic flows in pre-structured targets

T. Kluge *et al*. Phys. Rev. X **8**, 031068 (2018).

Courtesy of A. Fry

MEC-Upgrade will transform HED science at the LCLS XFEL

Driven by the community:

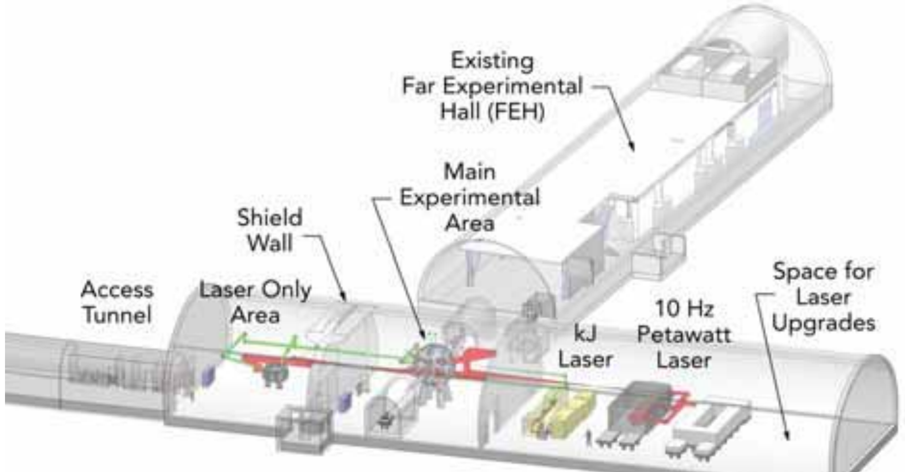
- User workshops over 5 years
- National Academy of Sciences report
- Brightest Light Initiative
- APS community strategic planning

Enable the next generation of extreme matter science by combining LCLS XFEL with:

- 10x higher power laser (petawatt)
- 10x higher energy laser (kilojoule)
- Dedicated underground facility for experimental operations

Partnership between SLAC, LLNL, and UR LLE; funded by DOE Office of Fusion Energy Science

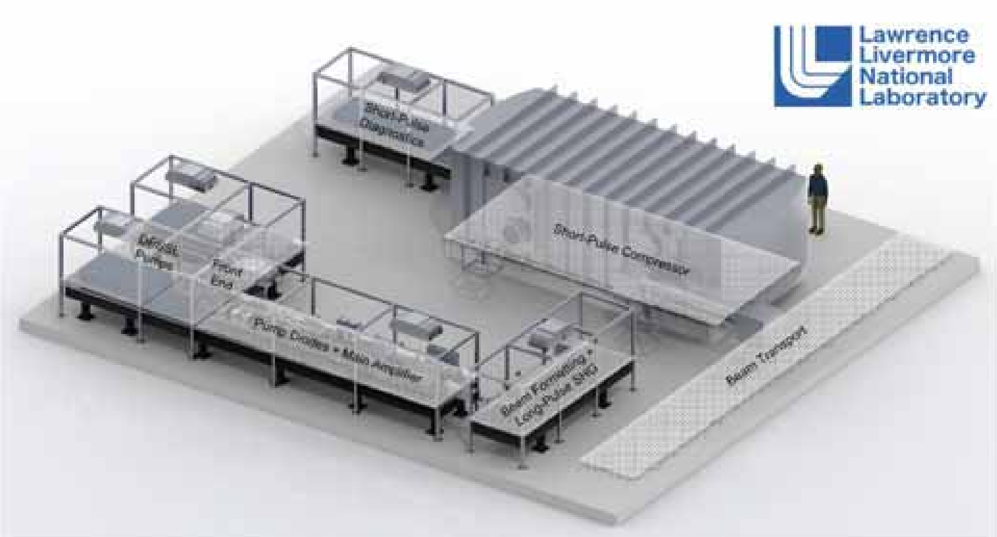
- Critical Decision 1 (CD-1) approved, October 2021
- Start of construction, FY2025; project completion (CD-4) FY2030

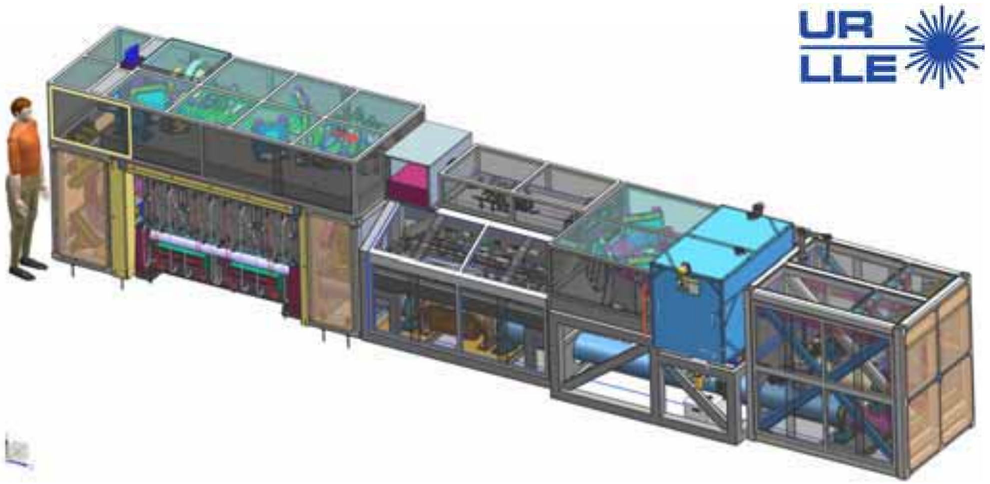


U.S. DEPARTMENT OF ENERGY | Office of Science | SLAC | Lawrence Livermore National Laboratory | UR LLE

State of the art lasers through partnership with LLNL and LLE

SLAC, LLNL, and University of Rochester Laboratory for Laser Energetics (LLE) are partnering to build the MEC-U laser systems based on field-deployed technology





HRR petawatt laser: 150J, 150 fs, 1 μm, 10 Hz

HRR long pulse laser: 200J, 20 ns, 0.527 μm, 10 Hz

High energy long-pulse laser:
1 kJ, 20 ns, 0.527 μm, 2-shot/hour

State of the Art Specifications; no specific R&D required.
World's leading teams for high power lasers.

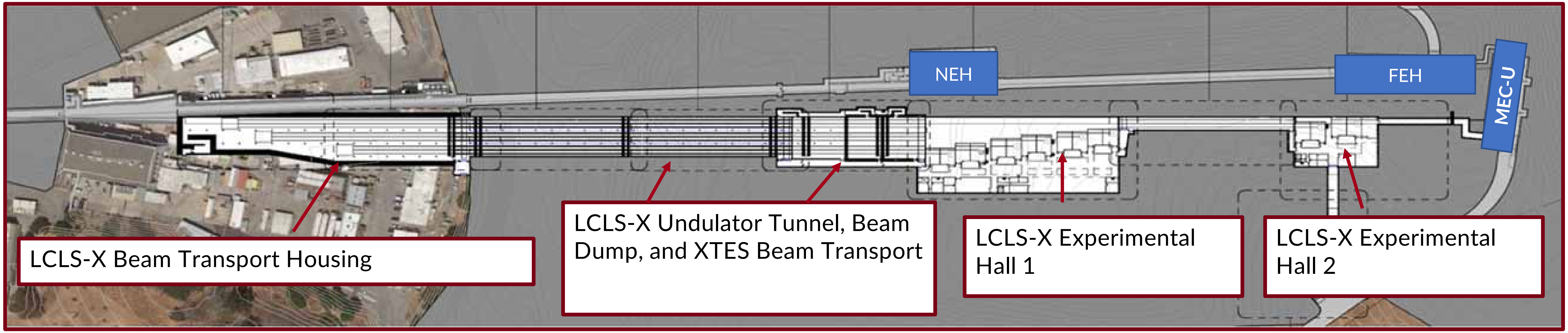
The next evolution… multiple FEL sources

SC XFEL accelerators have the power to feed 10 ++ independent sources

Courtesy of D. Fritz

A Multi-beamline XFEL Enables a Synchrotron-like Operation

- The existing LCLS-II-HE accelerator will be sufficiently powerful to feed 10 undulators
- Expand LCLS from 2 beamlines to ~10, and thus number of instruments to >30
- Enable the highest performance beamlines (superconducting undulators, RAFEL, …)
- Phase the delivery to allow staged growth, responsive to emerging priority directions



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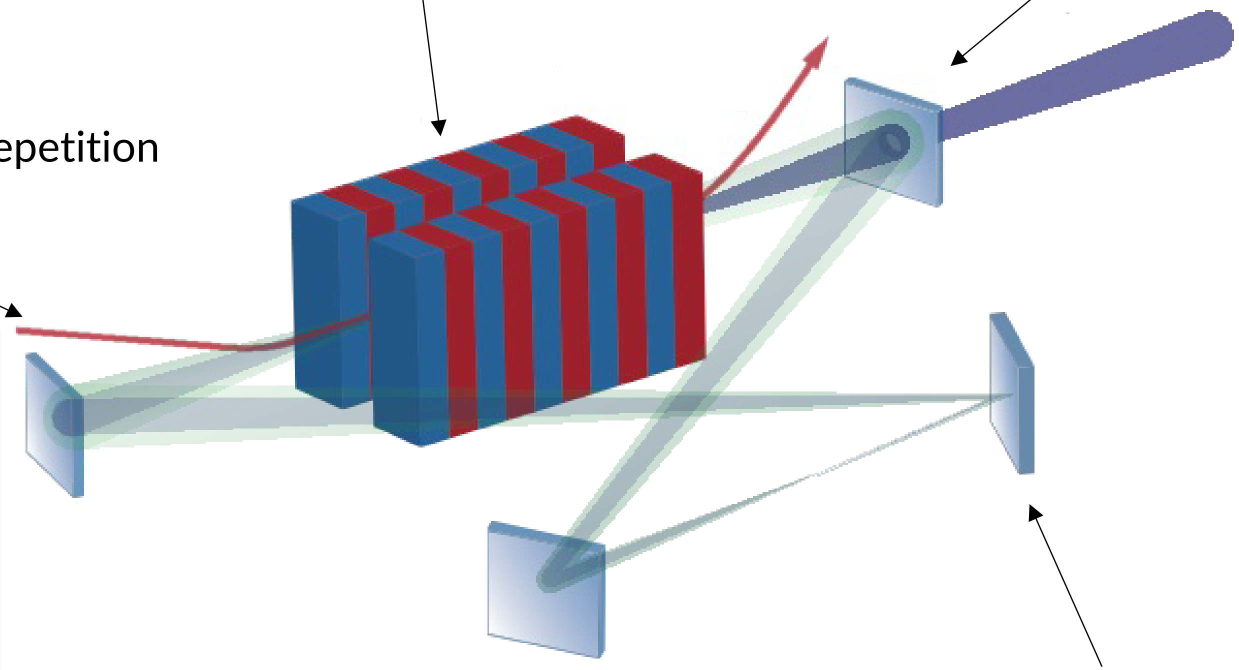
Courtesy of G. Marcus

Cavity-based FELs offer a path to high spectral brightness



One must consider

- FEL gain and *e*-beam brightness
- Undulator length
- Repetition rate
- Cavity round trip efficiency

Trade-offs exist in the above parameters to optimize the system for a particular application (external constraints also drive options)

Targeted R&D is underway to realize an X-ray regenerative amplified FEL (XRAFEL) at the LCLS FEL complex.

Summary

- LCLS launched the era of the 4th generation X-ray light source and has spawned the rapid proliferation of X-ray FELs around the world.
- The current technological push is for higher average power which will open new areas of science.
- Future efforts will focus on increasing scientific throughput and reducing operating costs by creating synchrotron-like modes of operation.
- Research on coupling classical laser cavity architecture with FELs is underway.

Where will we go next?

Acknowledgements

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FRIB

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B. Sims