International Symposium on Extreme Ultraviolet Lithography

October 27-29, 2014 • Washington, D.C.

The LCLS-II: A New High Power X-ray FEL Facility at SLAC

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October 29th, 2014

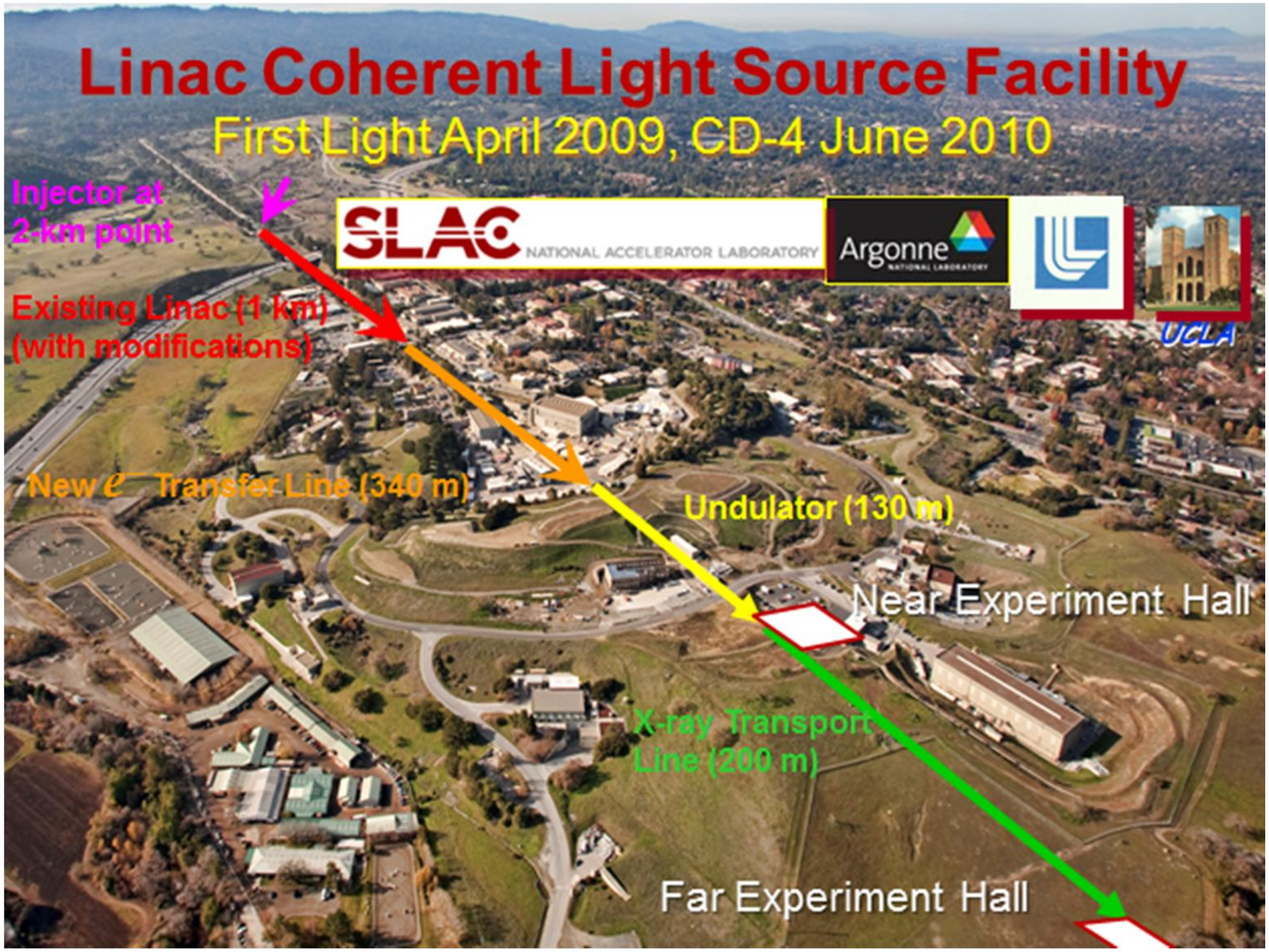
SLAC NATIONAL ACCELERATOR LABORATORY · BERKELEY LAB · Argonne NATIONAL LABORATORY · Fermilab · Jefferson Lab

Linac Coherent Light Source (LCLS) and LCLS-II

The LCLS is the world's 1st x-ray Free Electron Laser (FEL)

and the LCLS-II upgrade will be the 1st CW x-ray FEL (~2020)

High brightness x-ray sources pushing the boundaries in photon science supported by DOE



Why is LCLS-II Relevant to EUV Lithography?

LCLS and LCLS-II FEL's are designed to operate over the x-ray range 60 – 0.4 Angstrom with mJ's per pulse.

LCLS-II will have CW superconducting (SCRF) accelerator system based on technology that has been developed around the world

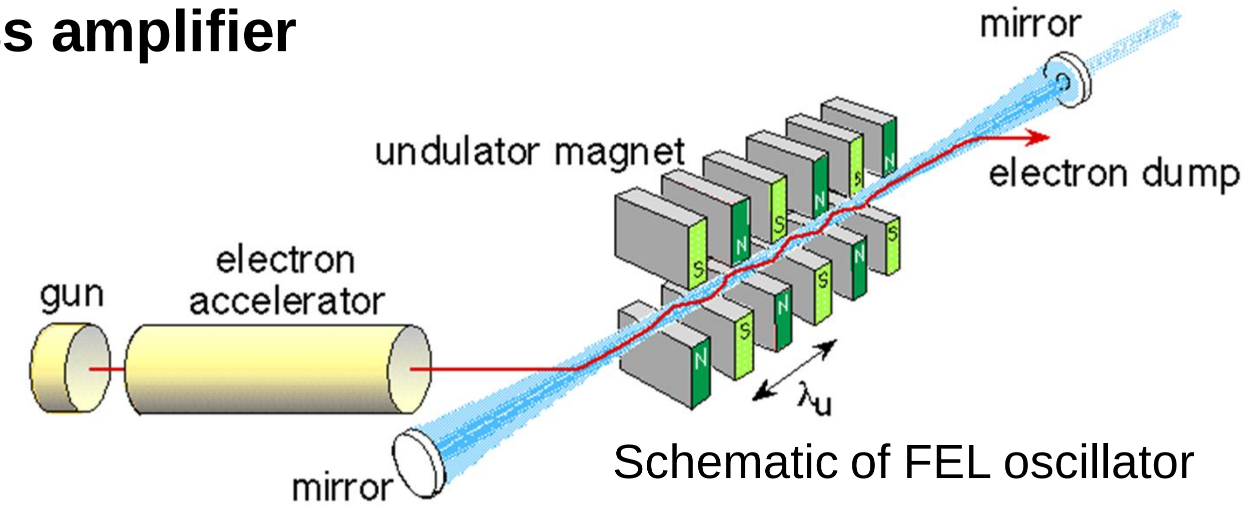
LCLS-II could be operated to generate ~kW at 13.5 nm in an non-optimal configuration

Technology and design concepts being used for LCLS-II could be utilized to generate >10 kW in EUV

Free Electron Laser (FEL) Primer

Two primary configurations: **low gain oscillator** using mirrors or **high gain single pass amplifier**

3 main elements:
e- gun,
accelerator,
& **undulator**



Schematic of FEL oscillator

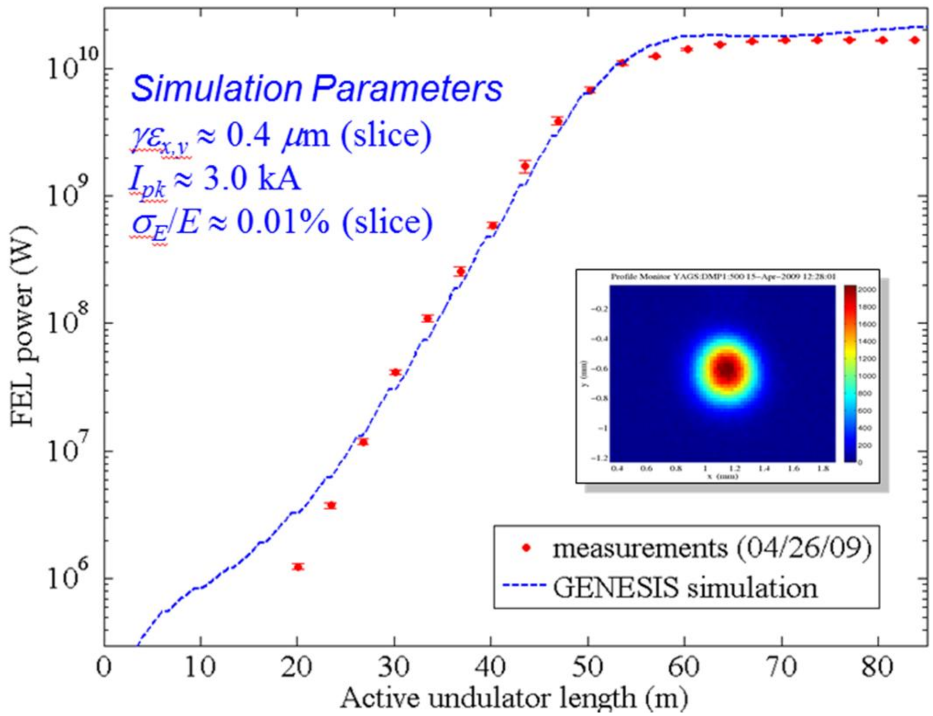
Physics is relatively simple: transverse motion in undulator allows e- to couple to light; light causes beam to bunch and radiate as N^2 rather than N (no need for quantum mechanics).

Lorentz contraction and relativistic Doppler shift of dipole radiation → $\lambda_r \sim \lambda_u / 2\gamma^2$ and wavelength easily tunable over wide range

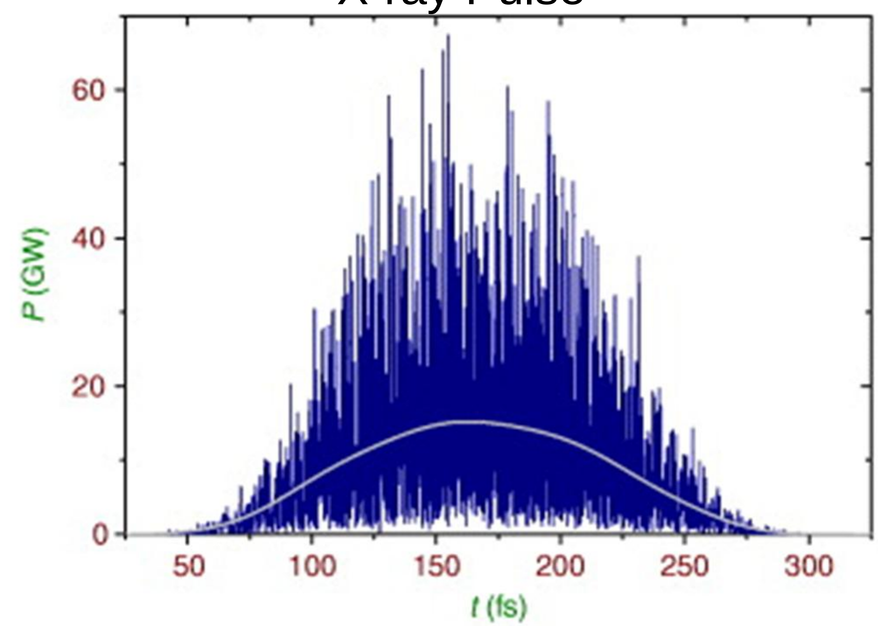
Amplifier FEL Characteristics (i)

Amplifiers can start from a seed or noise (SASE)

- Typical SASE bandwidth is ~0.1%; seeded BW >10x smaller
- Transverse coherence usually >50%



X-ray Pulse



Generate GW's of peak power in short pulses <1ps

Amplifier FEL Characteristics (ii)

Pulses are determined by electron beam

- LCLS operates at 120 Hz → 100 fs burst every 8 ms with an average power <1W

Saturated extraction efficiency of laser from electrons is ~0.1%

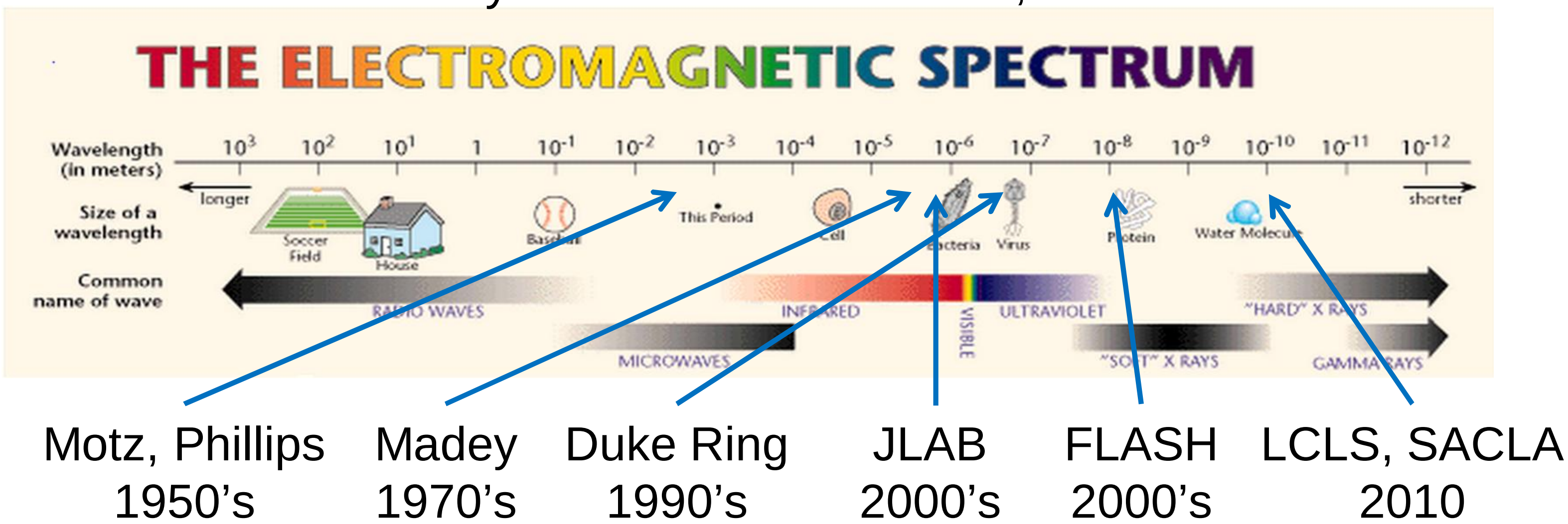
- More possible with high quality beams and tapered undulators
- Livermore extracted 34% in 1986 (at 10 cm-wavelength)
- LCLS has achieved 0.4% at 5 keV with 6 mJ in a pulse

CW SCRF accelerators can achieve repetition rates limited by RF frequency (ns-bunch spacing) and max beam power

- Accelerators (PSI, SLAC, SNS) have operated with MW beams but do need to be aware of activation and radiation handling

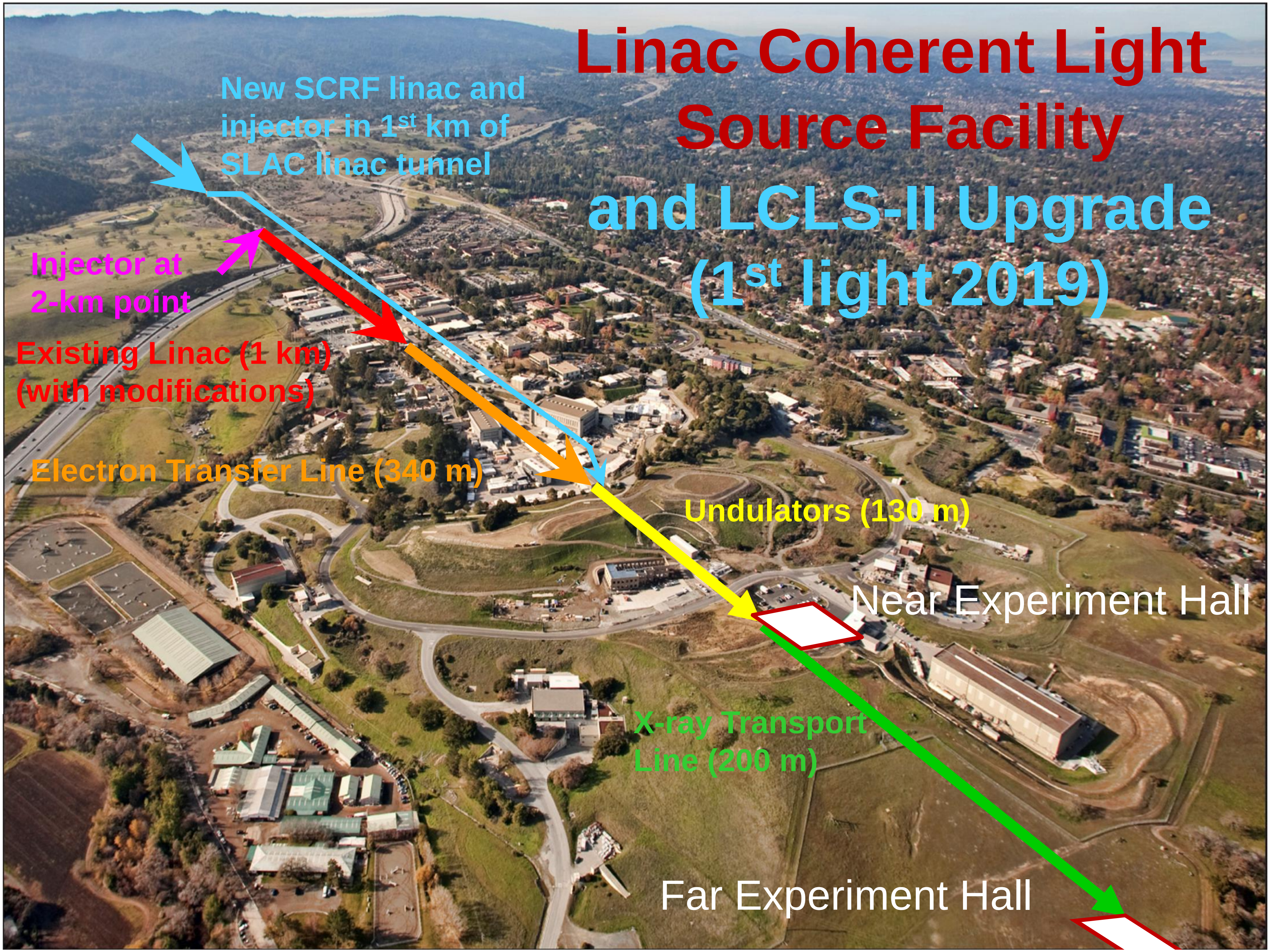
Operating Free Electron Lasers

FEL History – Modified from Colson, 2006



Over 50 FEL's operating around the world ranging from mm-wavelength to sub-Angstrom.

- JLAB generated 14 kW in IR in oscillator configuration
- LCLS generated 6 mJ in single pulse at a few keV
- SACLA has lased at sub-Angstrom wavelengths



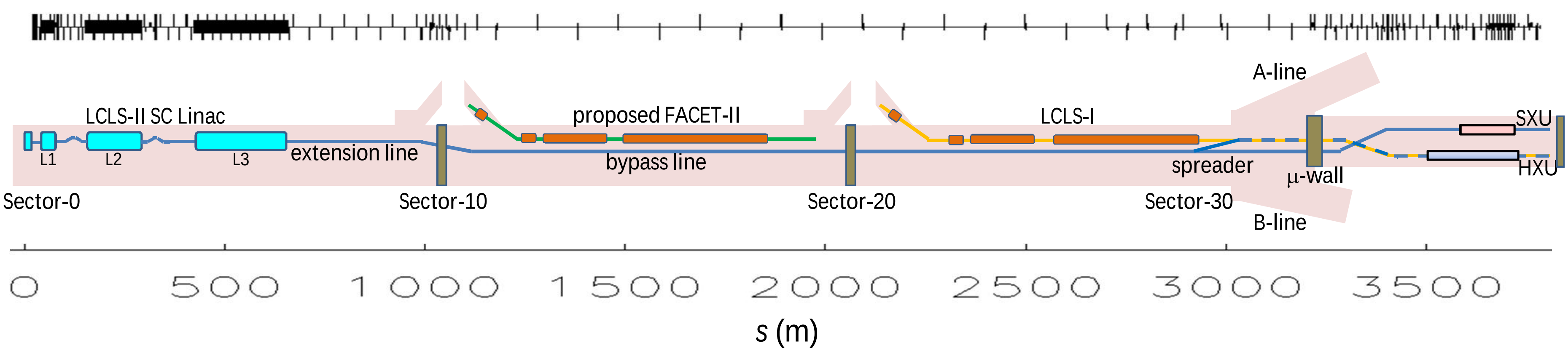
Linac Coherent Light Source Facility
and LCLS-II Upgrade
(1st light 2019)
New SCRF linac and injector in 1st km of SLAC linac tunnel
Injector at 2-km point
Existing Linac (1 km) (with modifications)
Electron Transfer Line (340 m)
Undulators (130 m)
Near Experiment Hall
X-ray Transport Line (200 m)
Far Experiment Hall

LCLS-II Accelerator Layout

New Superconducting Linac → LCLS Undulator Hall

- Two sources: high rate SCRF linac and 120 Hz Cu LCLS-I linac
- North and South undulators can operate simultaneously in any mode

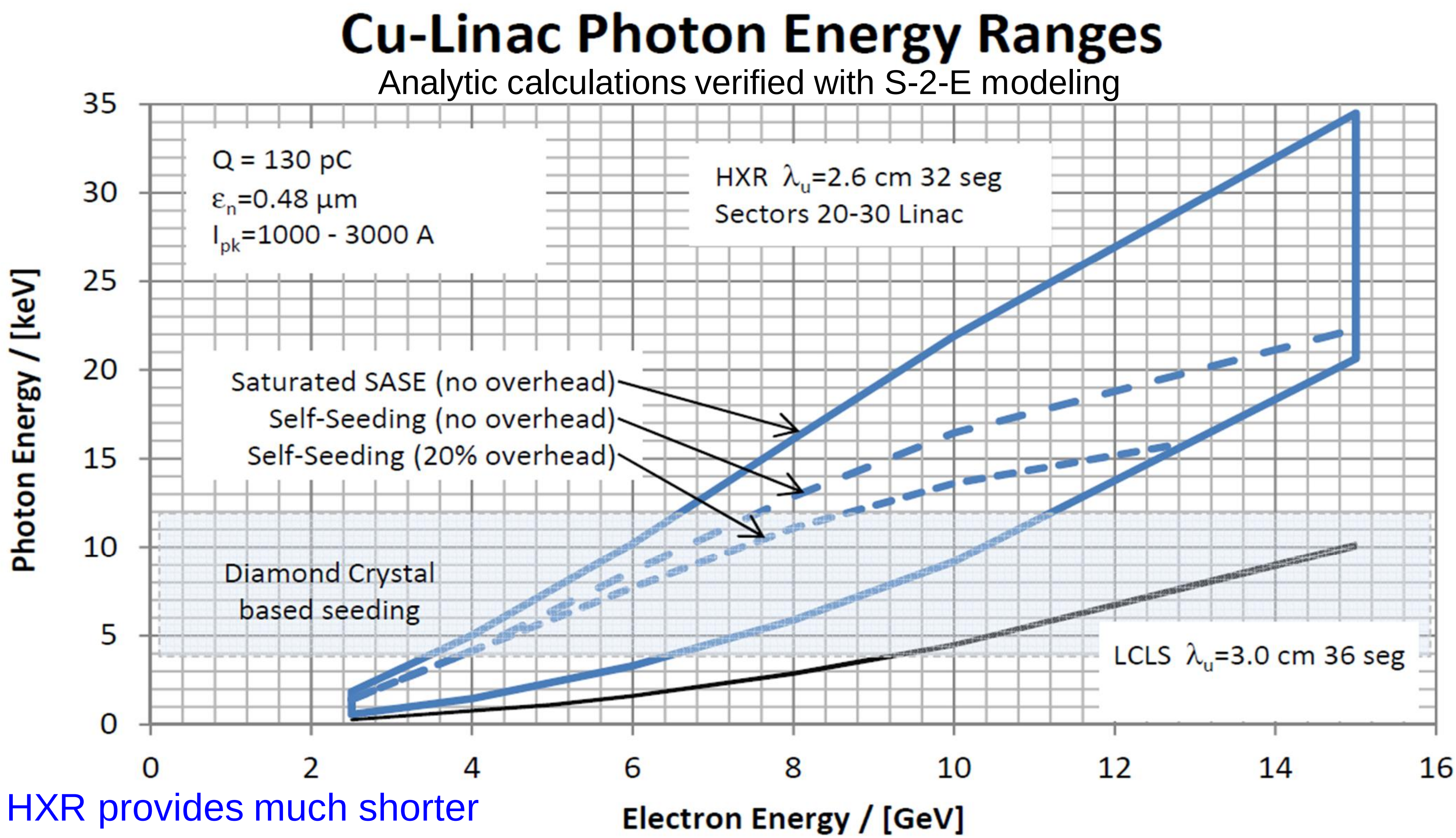
Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
North	0.20 - 1.3 keV	
South	1.0 - 5.0 keV	up to 25 keV higher peak power pulses



LCLS-II (SCRF) Baseline Parameters

Parameter	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.14	GeV
Bunch Charge	Q_b	**100**	10 - 300	pC
Bunch Repetition Rate in Linac	f_b	**0.62**	0 - 0.93	MHz
Average *e*⁻ current in linac	I_{avg}	**0.062**	0.001 - 0.3	mA
Avg. *e*⁻ beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2 - 0.7	μm
Final peak current (at undulator)	I_{pk}	**1000**	500 - 1500	A
Final slice E-spread (rms, w/heater)	σ_{Es}	**500**	125 - 1500	keV
RF frequency	f_{RF}	**1.3**	-	GHz
Avg. CW RF gradient (powered cavities)	E_{acc}	**16**	-	MV/m
Avg. Cavity Q0	$Q0$	**2.7e10**	1.5 - 6e10	-
Photon energy range of SXR (**SCRF**)	E_{phot}	-	**0.2 - 1.2**	keV
Photon energy range of HXR (**SCRF**)	E_{phot}	-	**1 - 5**	keV

LCLS-II versus LCLS performance at 120 Hz
(LCLS-II Performance between 1 and 25 keV)

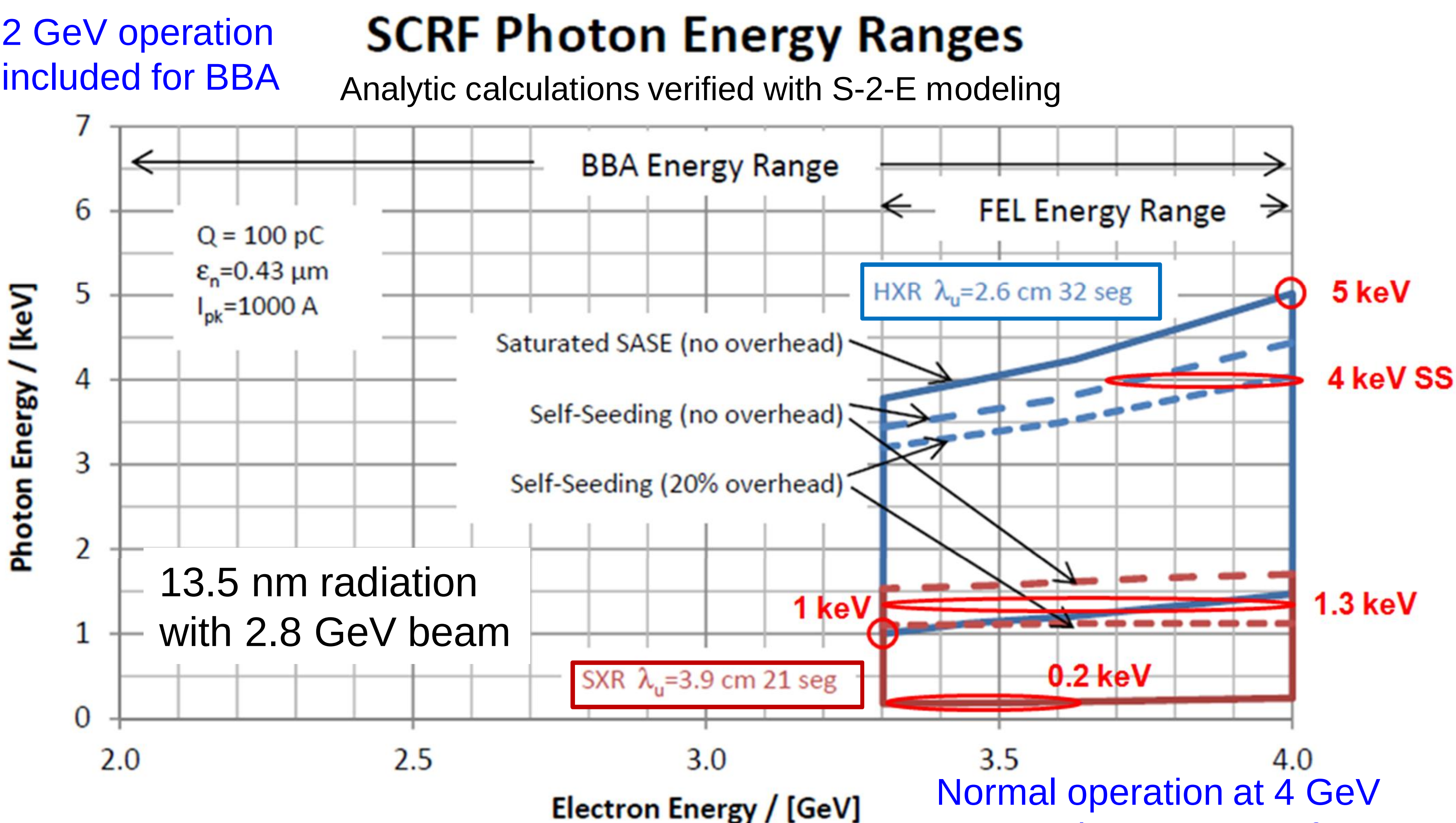


HXR provides much shorter photon wavelength with comparable pulse energy

LCLS-II High Rate FEL Tuning Range

(HXR between 1 and 5 keV; SXR between 0.2 and 1.3 keV)

2 GeV operation included for BBA



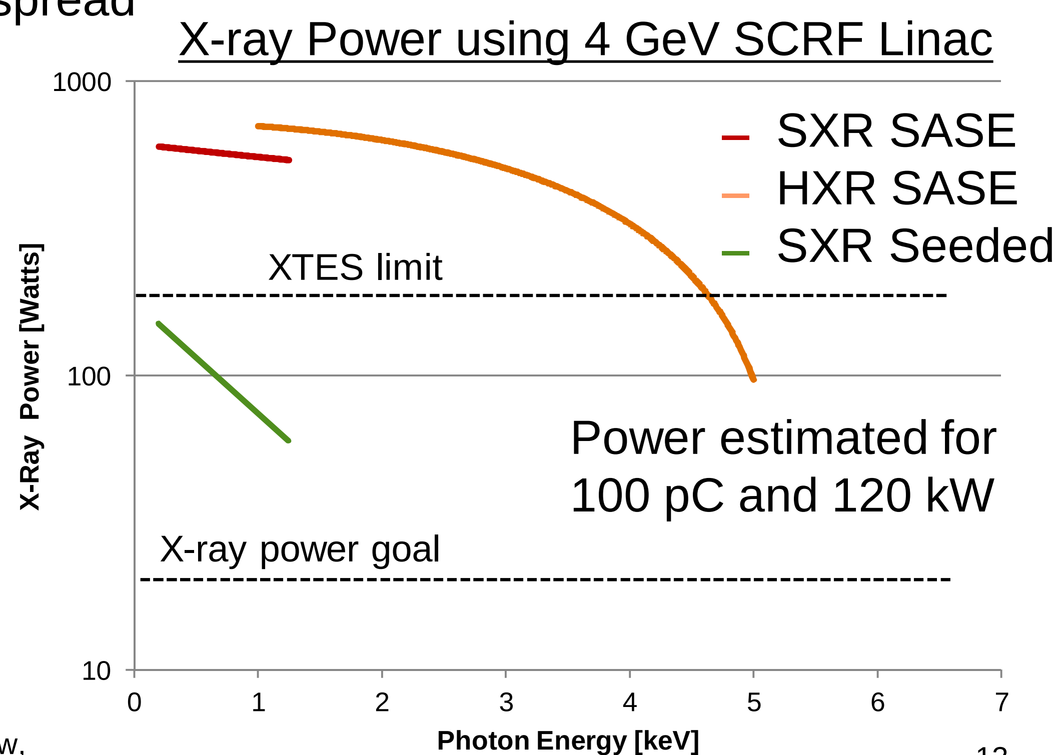
Normal operation at 4 GeV covers photon range of primary interest

LCLS-II X-ray Power using SCRF Linac

SCRF linac can deliver ~1 MHz beam to either undulator

- Goal is to provide >20 Watts over wavelength range
  - Easily met across photon range 0.2 to 5 keV
    - Performance above 5 keV is limited by emittance and energy spread

- XTES is designed to handle <200 Watts
  - Studying methods of turning down FEL power other than the repetition rate

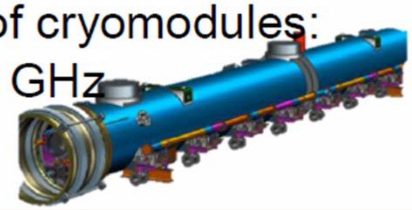


Project Collaboration

SLAC

Fermilab

½ of cryomodules:
1.3 GHz



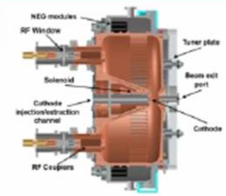
Jefferson Lab
EXPLORING THE NATURE OF MATTER

½ of cryomodules:
1.3 GHz

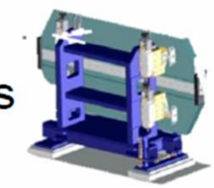
Cryoplant

BERKELEY LAB

e^- gun & associated injector systems

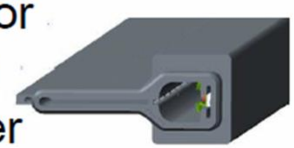


Undulators

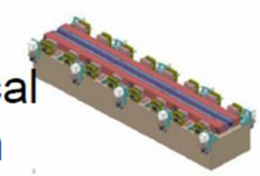


Argonne NATIONAL LABORATORY

Undulator Vacuum Chamber



Undulator R&D: vertical polarization

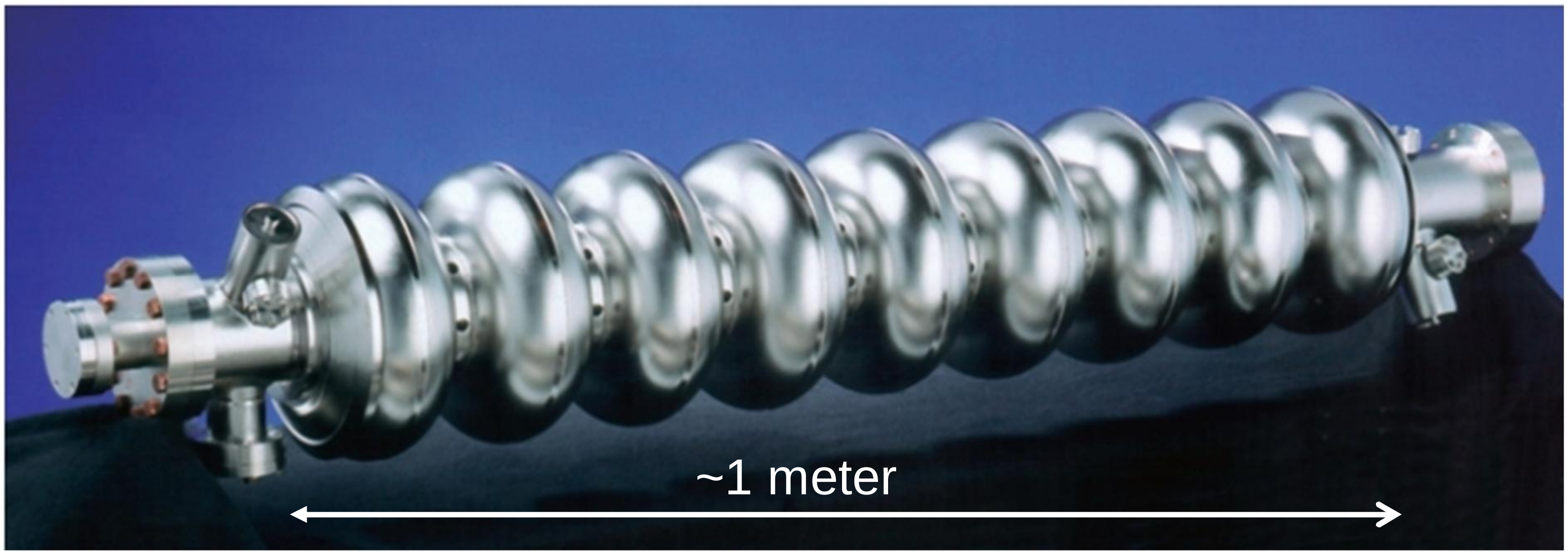


CORNELL UNIVERSITY FOUNDED A.D. 1865

R&D planning, prototype support
e^- gun option

Superconducting RF Cavities

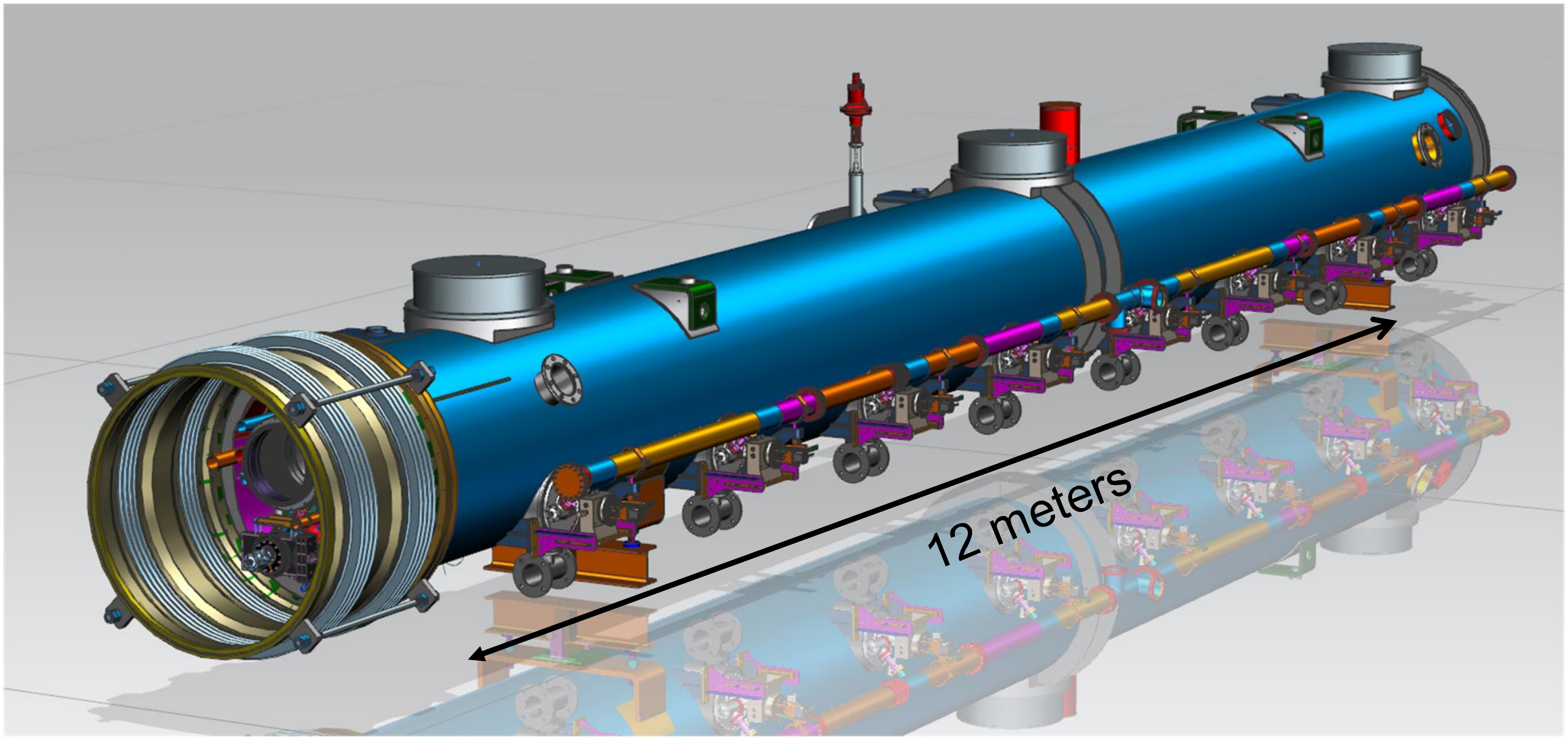
Backbone of the LCLS-II accelerator are the 9-cell 1.3 GHz superconducting rf cavities



Technology developed in Europe and transferred around world. Hundreds have been fabricated in US, Japan, Europe.

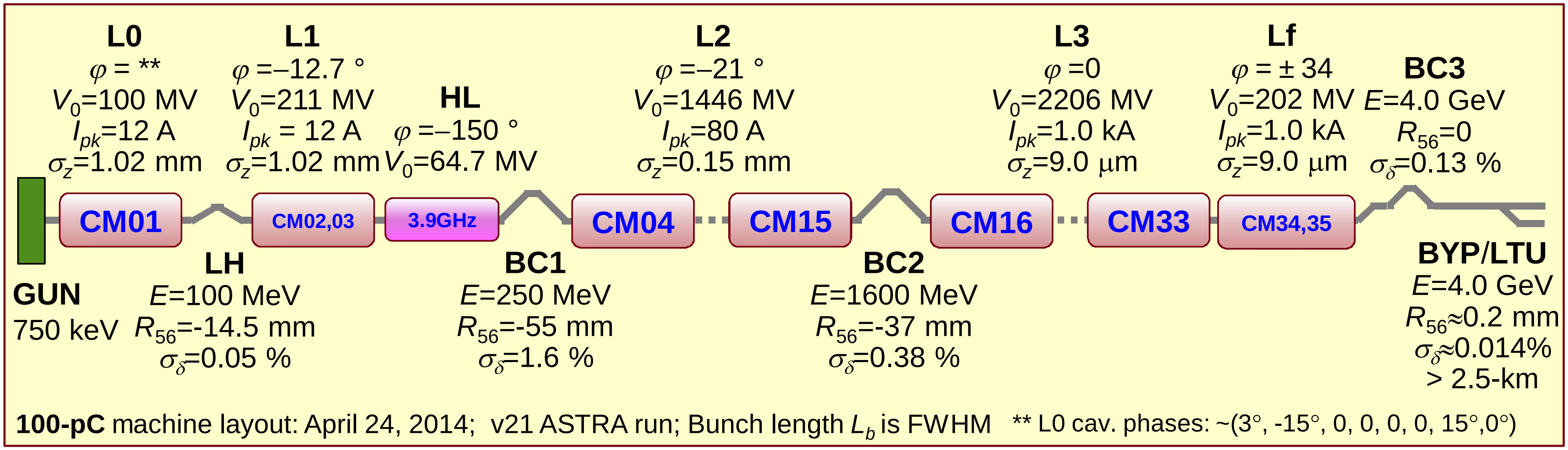
LCLS-II and EuXFEL will use ~1200 combined

LCLS-II Cryomodule
1.3 GHz, modified for CW operation



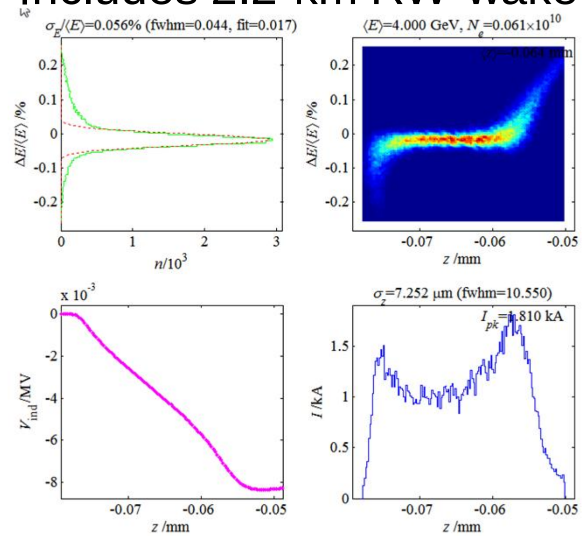
Crymodules will be similar to EuXFEL with modifications for CW operation.   EuXFEL producing 1 module/per week.

LCLS-II - Linac and Compressor Layout for 4 GeV



Linac Sec.	V_0 (MV)	φ (deg)	Acc. Grad.* (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cav's per Amp.
L0	100	**	16.3	1	8	1	1
L1	211	-12.7	13.6	2	16	1	1
HL	-64.7	-150	12.5	2	16	1	1
L2	1446	-21.0	15.5	12	96	6	1
L3	2206	0	15.7	18	144	9	1
Lf	202	±34	15.7	2	16	1	1

Includes 2.2-km RW-wake



2014 Symposium on EUV Lithography: LCLS-II Overview,
October 29, 2014

RF Power System

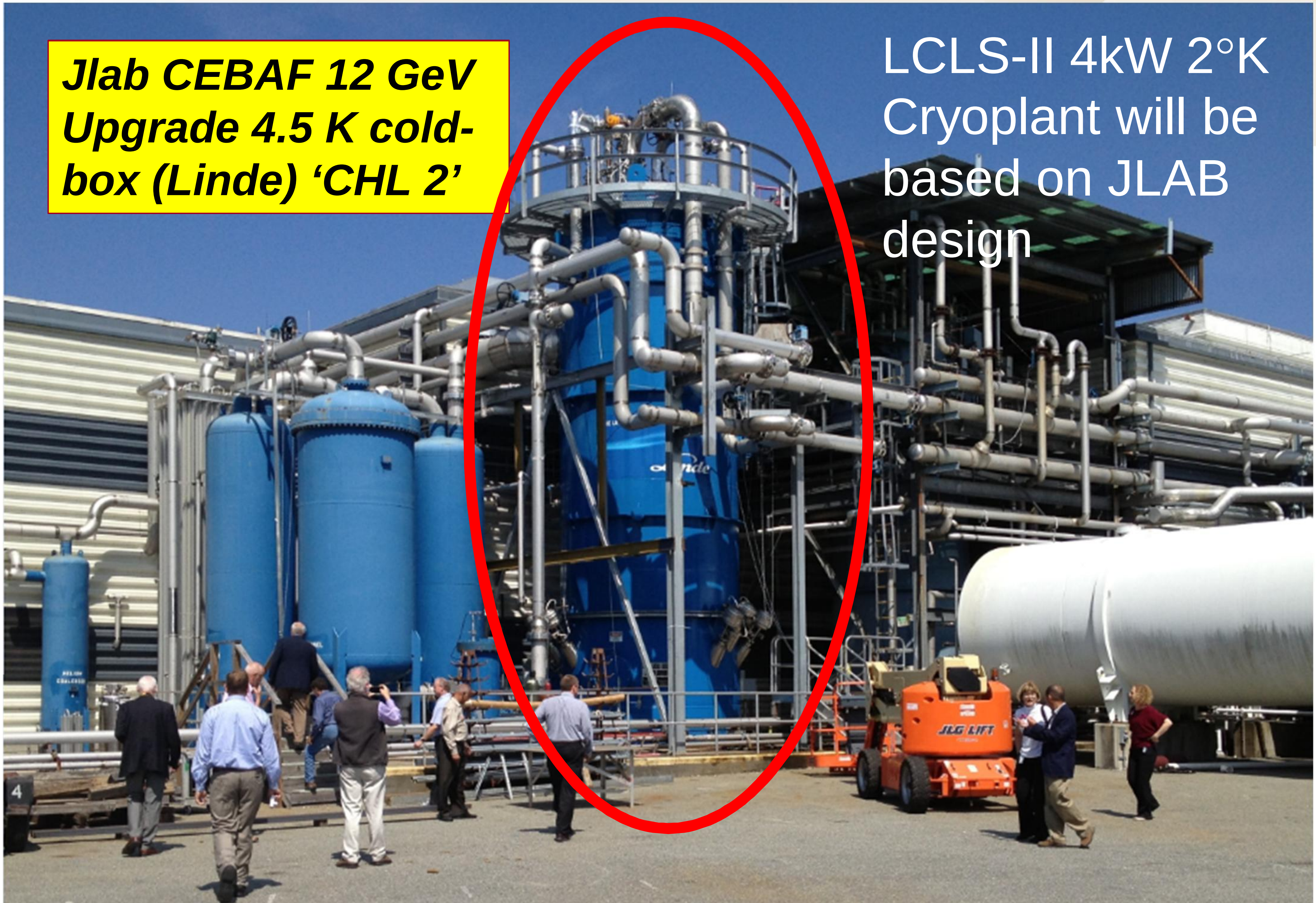
More than 1MW 1.3 GHz RF power

Each cavity individually powered with 4 kW Solid-State Amplifier

- Specified for 0.01% energy stability and 20 fs timing stability

10 kW SigmaPhi Amp

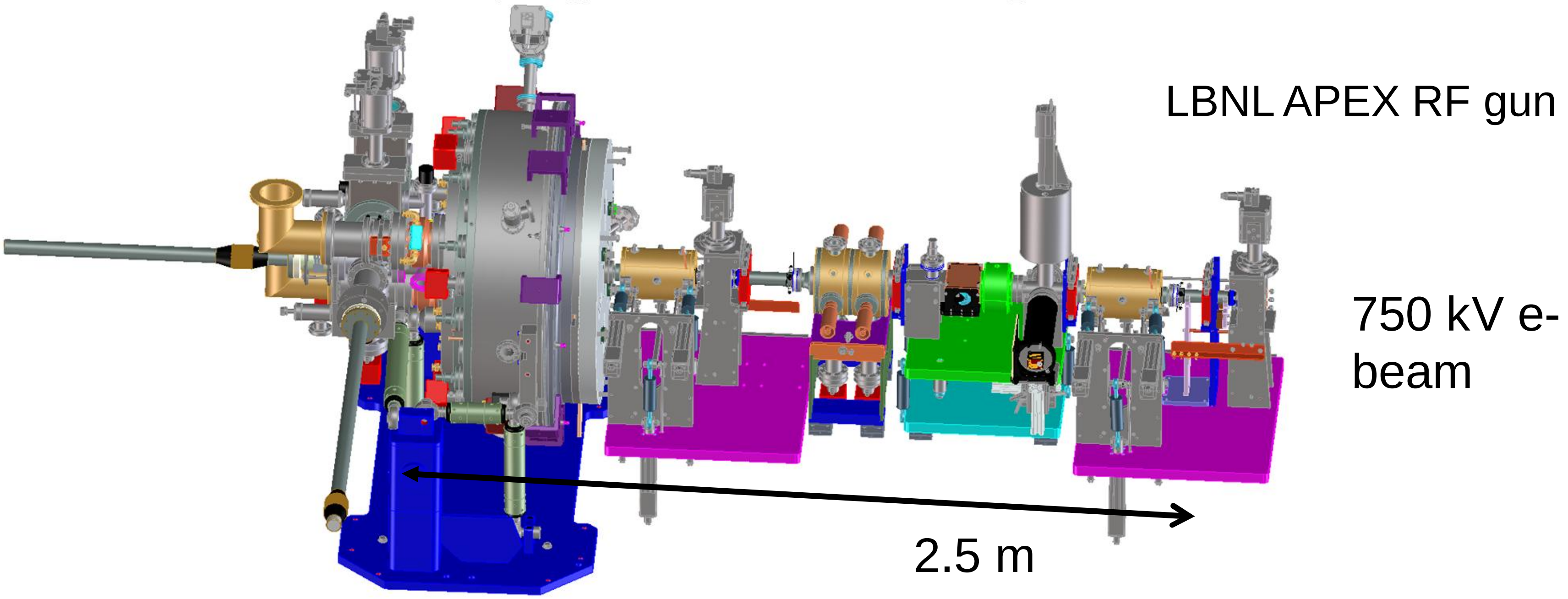
Waveguide distribution system through 25' penetrations into linac tunnel


Jlab CEBAF 12 GeV Upgrade 4.5 K cold-box (Linde) ‘CHL 2’
LCLS-II 4kW 2°K Cryoplant will be based on JLAB design
JLG LIFT

FEL Electron Beam Source

High quality beam is critical for FEL performance

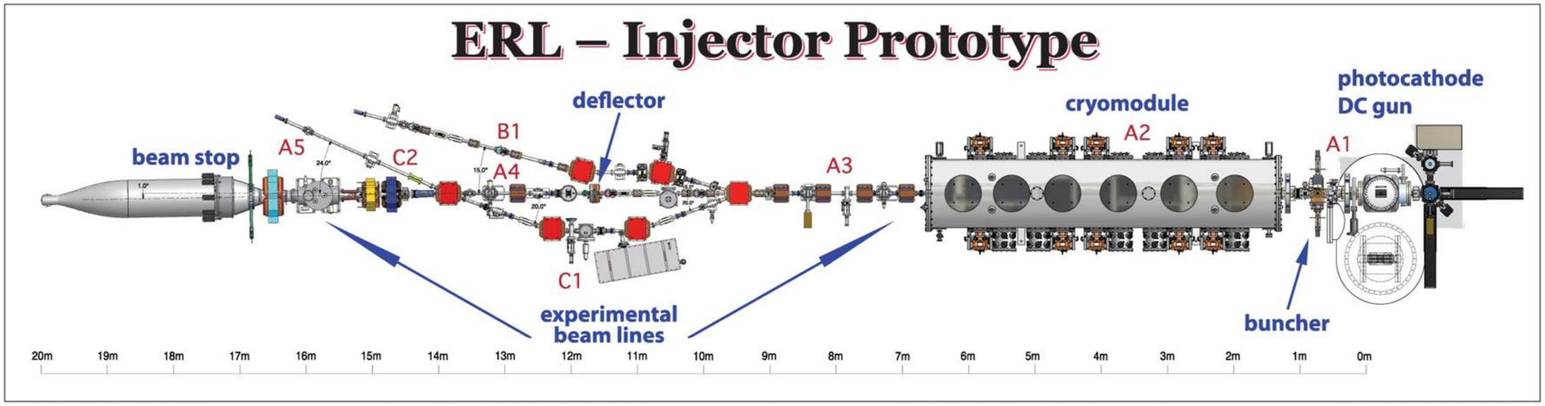
- RF guns create beams with sub-micron emittances for low duty-cycle accelerators
- LBNL developing an RF gun for CW operation
- Cornell developing an alternate DC gun

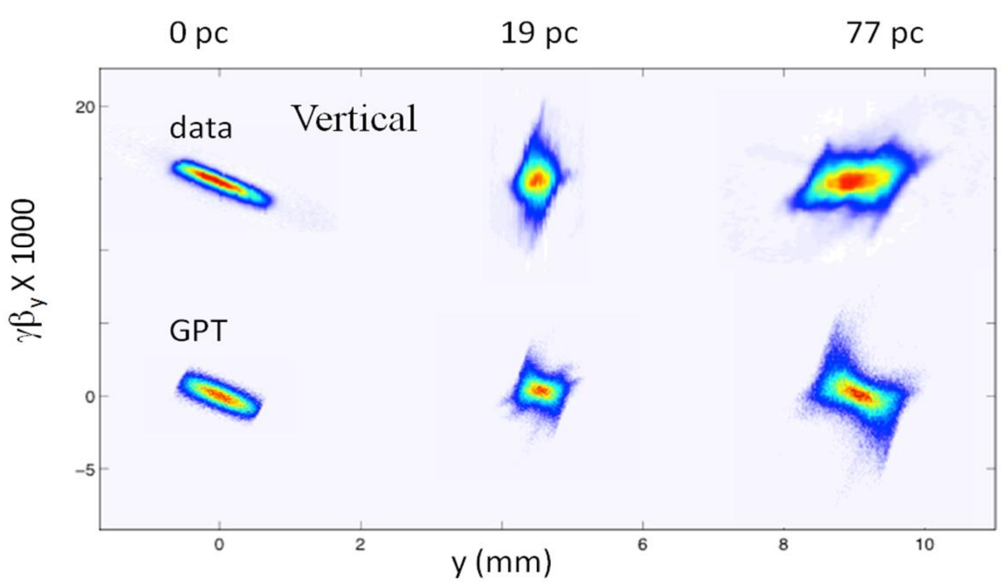


CW Injector Feasibility

Nominal parameters (nearly) demonstrated at Cornell

C. Guilliford, *et al*, PRST-AB **16**, 073401 (2013)





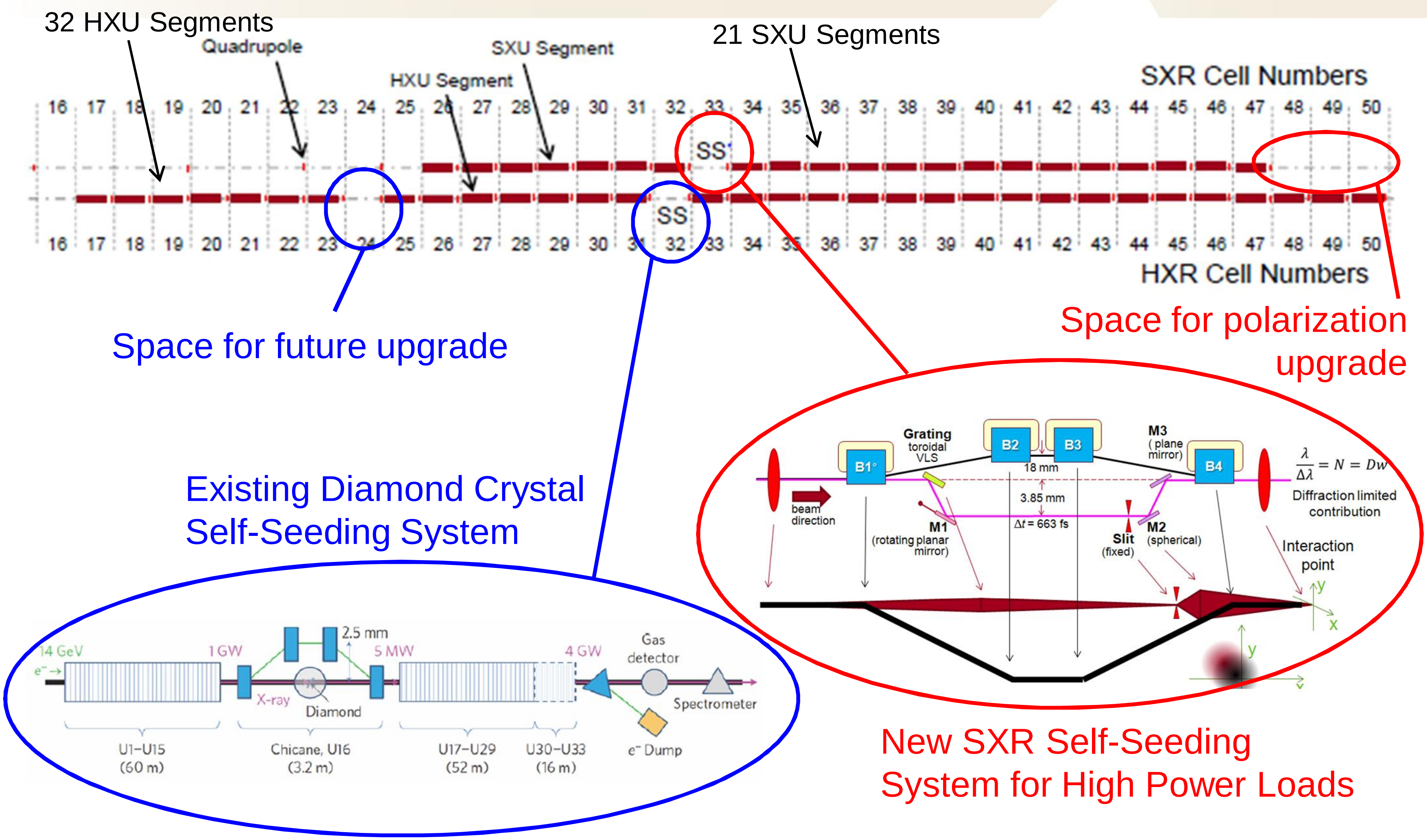
Projected Emittance for 19 (77) pC:

Vertical Phase Space

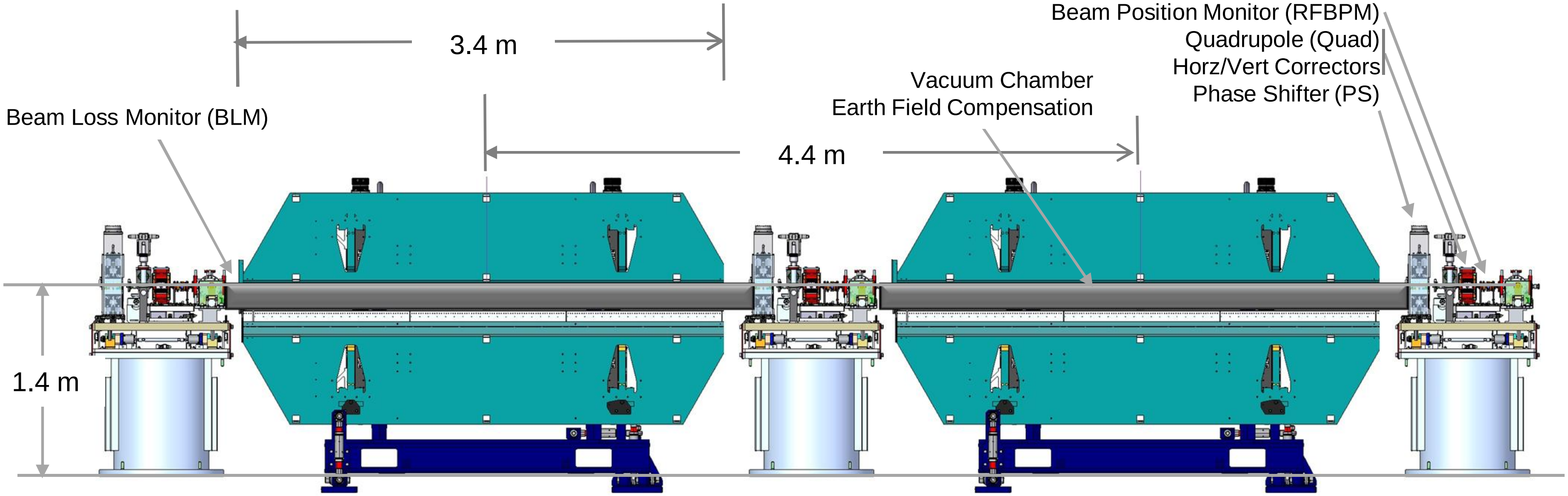
Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.20(0.40)	0.14(0.29)
GPT	0.16(0.37)	0.11(0.25)

LCLS-II Undulator Layout

150 meter existing Undulator Hall



LCLS-II Undulator Segments

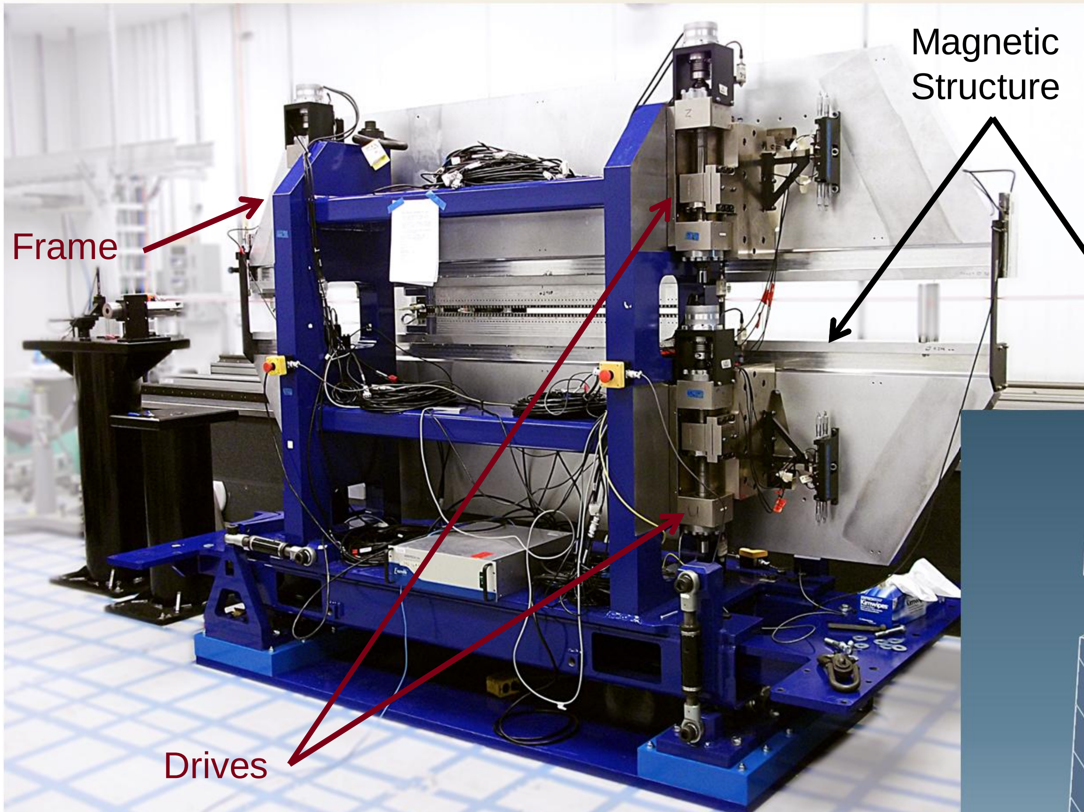


Layout shown for two individual undulator segments and three break sections for the HXR and SXR undulator lines.

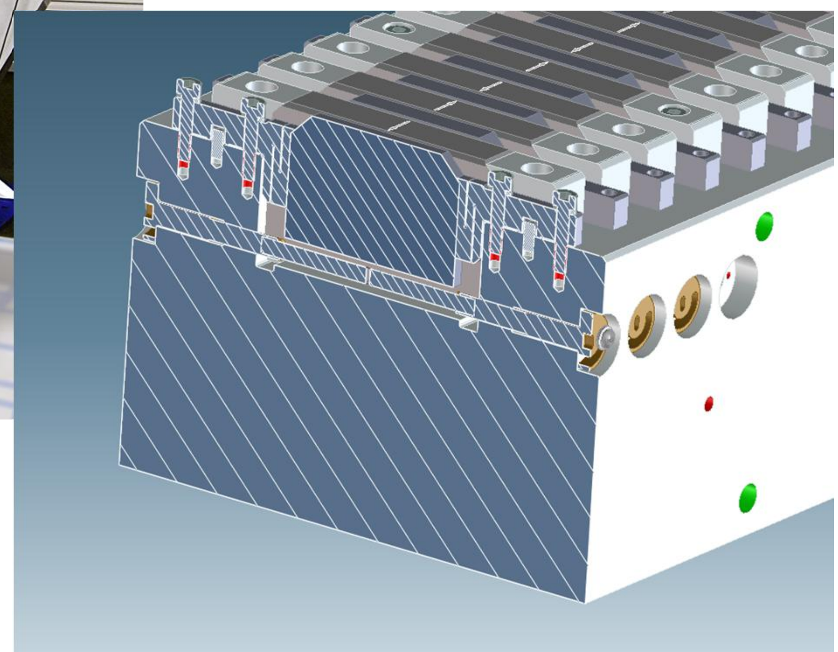
LCLS Undulator hall

Variable Gap Hybrid Undulators

Ongoing Development at LBNL



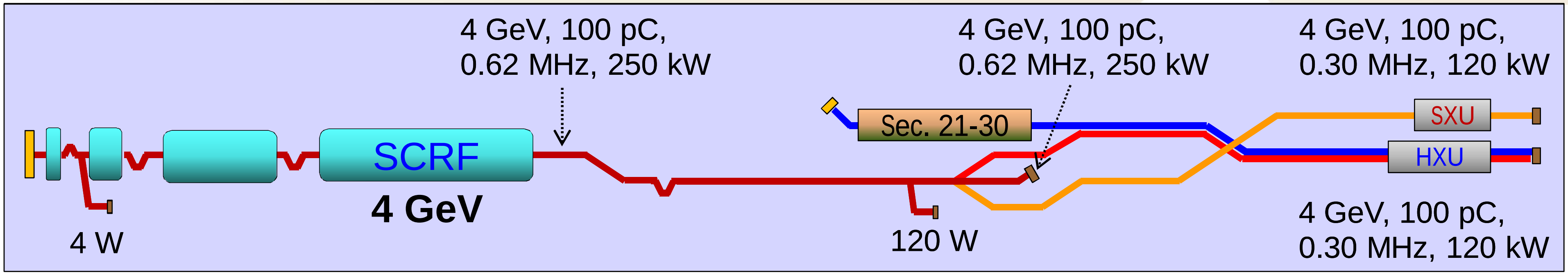
Variable gap undulators used in LCLS-II to provide greater wavelength tuning flexibility



Developing two alternates: Superconducting undulator (SCU) and a Horizontal gap vertically polarized undulator (VPU)

High Power CW Linac

Beam Collimation and Diagnostics

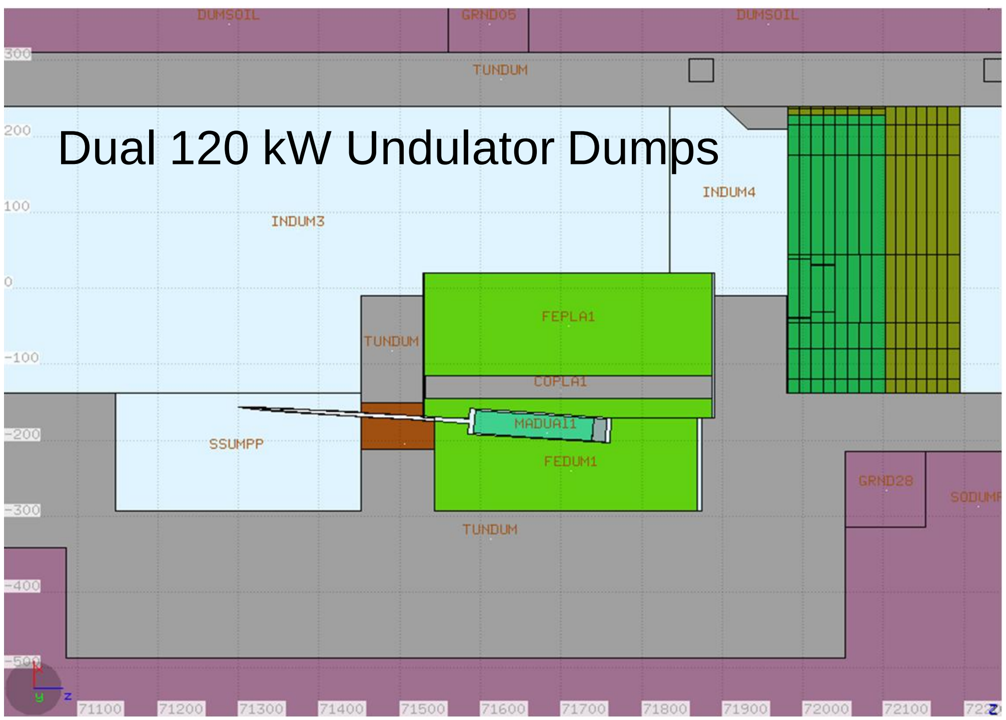


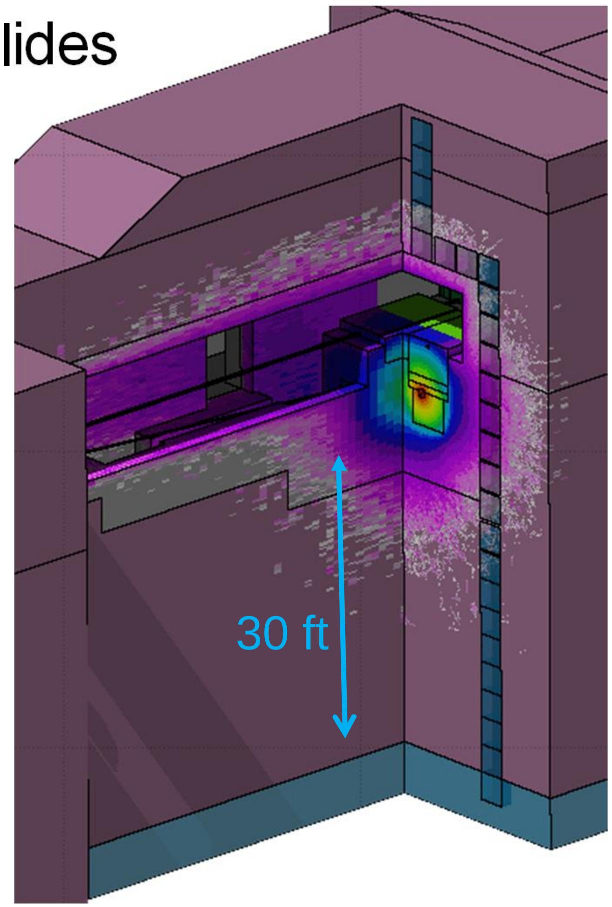
- Diagnostics are based on existing designs
- Beam power and beam loss issues are critical
  - Designing multi-stage collimation system to control losses
  - Hybrid PM undulators sensitive to nearby losses
- Linac designed for 1.2 MW but undulators limited to 120 kW
  - 250 kW maximum power through linac in initial phases
  - Studying dark current and FE effects and radiation limits
- Beam dumps are modified versions of existing MW dumps

MW-class Beam Dumps

SLAC has a number of MW beam dumps constructed over decades of operation

- Require separated water systems with tritium separation and careful treatment of other radionuclides
- Designed to be replaceable





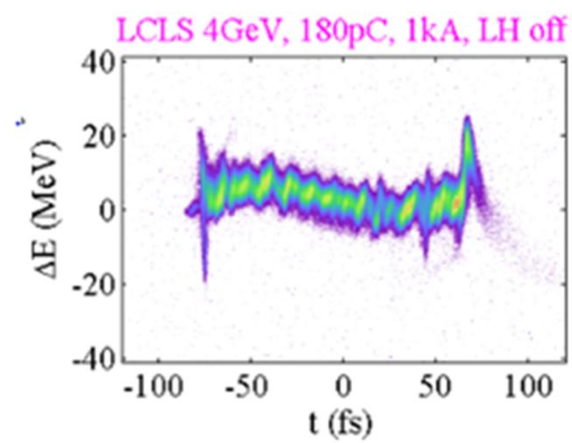
Start-to-End FEL Modeling

LCLS-II is being extensively modeled using 3D PIC codes

- Using 1-to-1 models with same number of macro-particles as beam electrons
- Verification runs are 11 hrs using LBNL Edison Cray XC30

Simulations are being benchmarked using LCLS

- Benchmarking configurations are chosen to exacerbate relevant physics



FEL physics is well understood **provided** beams are well modeled

LCLS-II Photon Availability

LCLS-II is being designed for 95% user availability

- Similar to achieved in SR storage rings and LCLS

System	Availability	Description
Lasers	99.73 %	Injector Laser and Laser Heater
Magnets	99.997 %	Bends, Quadrupole, Horizontal and Vertical Correctors, Kickers. Includes mechanical fabrication. It excludes any magnet inside the cryomodule.
PS controllers	99.57 %	Power supplies and power supply controllers for magnets.
RF power sources	99.85 %	Klystrons, Solid State Amplifiers and high power RF distribution.
SCRF Linac	99.87 %	Super Conductive RF cryomodule, Cavities, cavity tuners, RF input coupler, cryomodule vacuum.
Vacuum	99.88 %	Vacuum pumps, valves, gauges and controllers. Not to include vacuum components inside the cryomodule.
Tuning and Diagnostic	99.16 %	Beam Position Monitor, Wire Scanner and Time spent tuning machine performance to previously defined X-Ray parameters.
Water system	99.77 %	Water pumps, cooling water temperature regulation.
AC power	98.96 %	Power distribution system
Cryogenics Plant	98.62 %	
Controls	99.62 %	Input/output controllers, Machine Protection System, Personnel Protection System, controls backbone, timing, feedback, LLRF.
Photon Controls	99.89 %	Front End Enclosure (FEE) diagnostics and controls.
All	95.00 %	

EUV FEL Consortium

Group from national labs, universities, and industry studying options for a high power EUV FEL

- Considering a relatively conservative configuration based on LCLS-II technology

Contact Alex Murokh <murokh@radiabeam.com>

Summary

- FEL's have become mainstream scientific light sources
  - Both low gain (oscillators) and high gain (amplifiers)
  - Physics is well understood from mm's to Angstrom's
  - Advanced technologies are being aggressively developed and industrialized around the world
- LCLS and LCLS-II are state-of-the-art x-ray FEL's
  - LCLS has generated 6 mJ in single pulse
  - LCLS-II will generate 100's W from 0.2 to 5 keV
- LCLS-II technologies could be used for EUV source
  - Single-pass amplifier design is robust with capability for >10kW's
  - Alternate configurations possible to improve performance
  - FEL technology provides natural path to shorter wavelengths

Thanks for your attention!

LCLS-II Collaboration