LCLS – Update

Axel Brachmann
On behalf of LCLS

8th Hard X-Ray Collaboration Meeting, PAL, Pohang, Korea 2016

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

LCLS Recent Developments

- Continuation of developments to extend LCLS capabilities and robustness, preparing for LCLS-II:
  - Dechirper
  - Multiple Bunches – multiple Energy
  - Polarized beams
  - Atto-second bunches
  - Automated Tuning and Application of AI technology
  - Instrumentation
  - Facility Preparation for LCLS-II

LCLS Beam Performance

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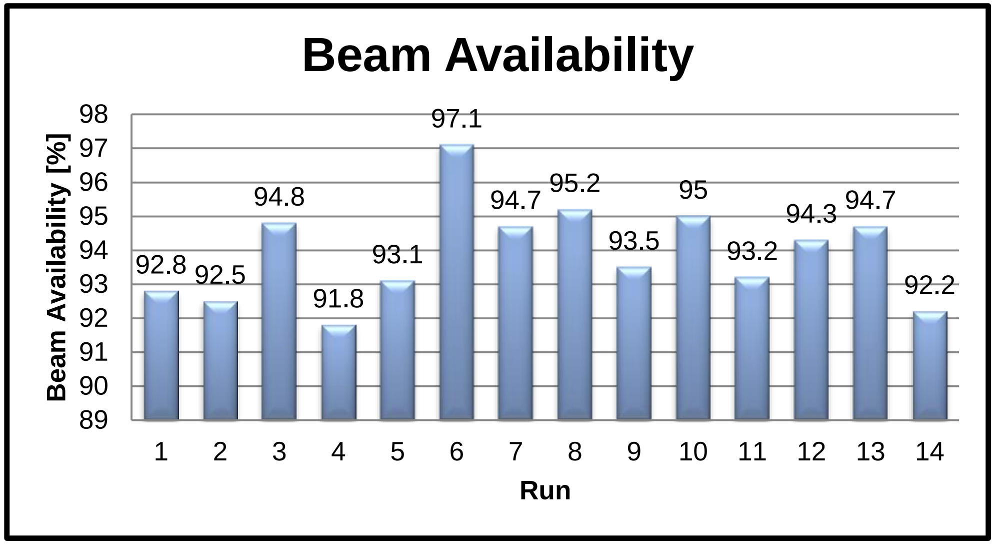
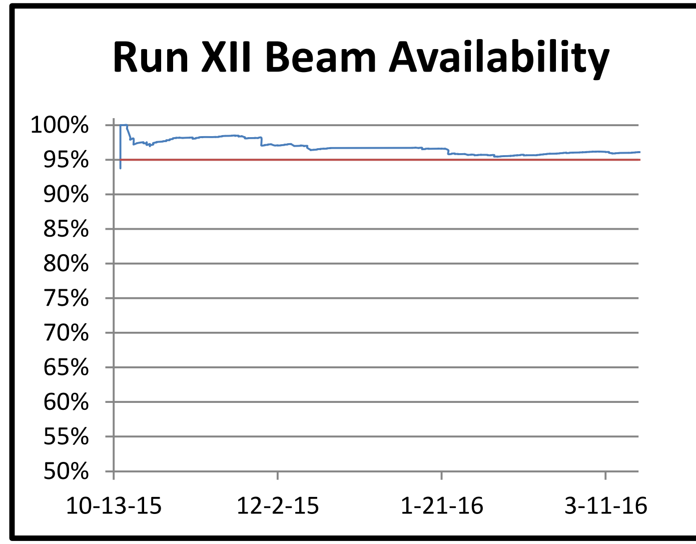
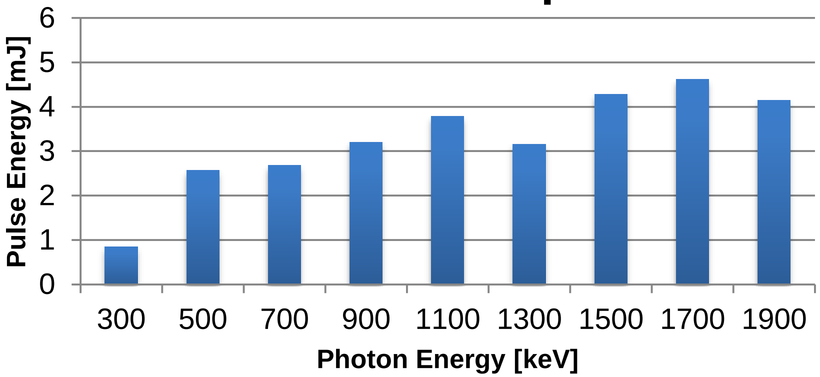
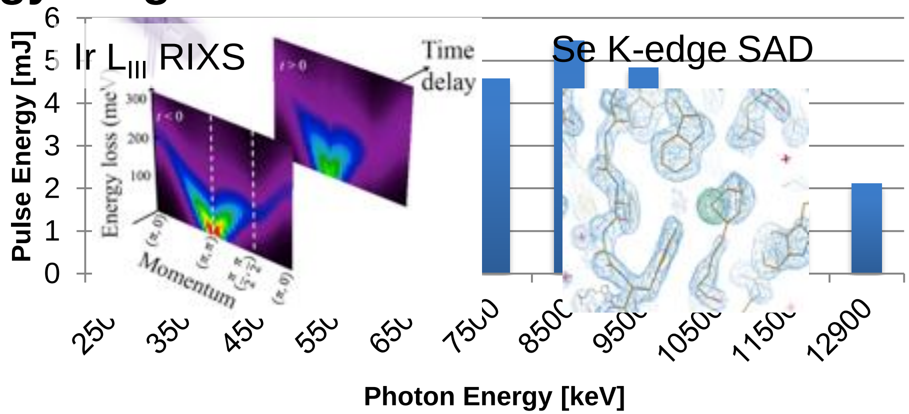


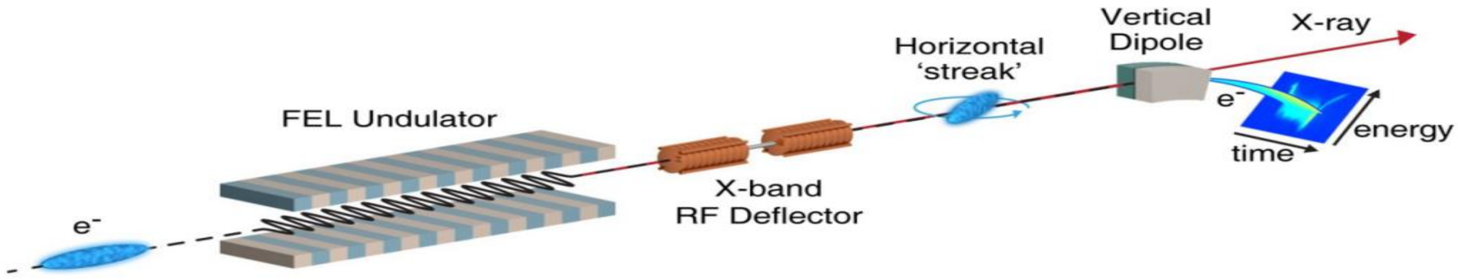


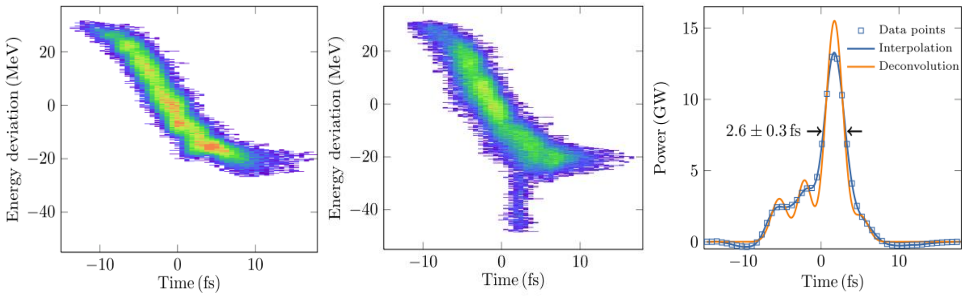
Extended photon energy range: 0.25–12.8 keV

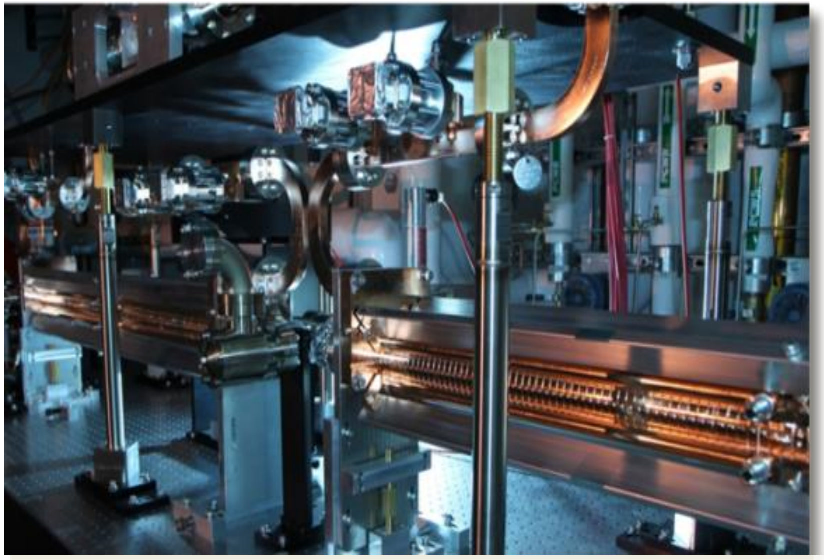




XTCAV X-Band Transverse Deflecting Cavity



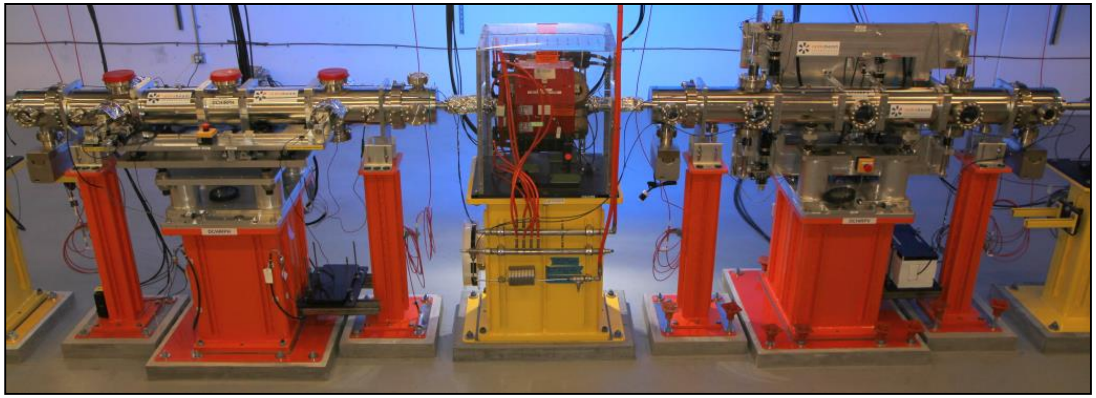


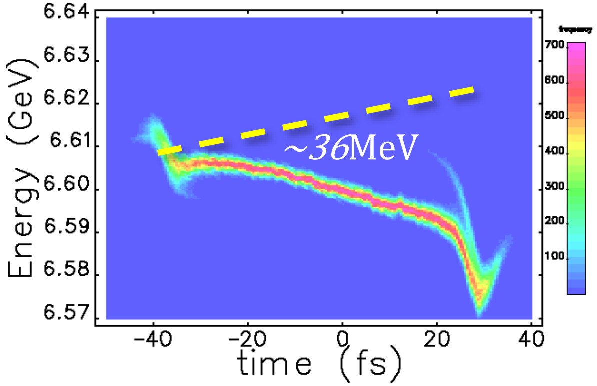


Recent Installation of new spherical cavity increases resolution (almost sub-fs to few fs).

Talk by Y. Ding

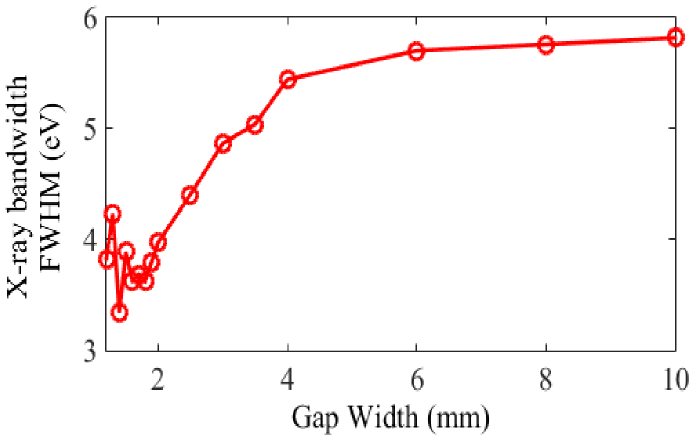
Dechirper - Update



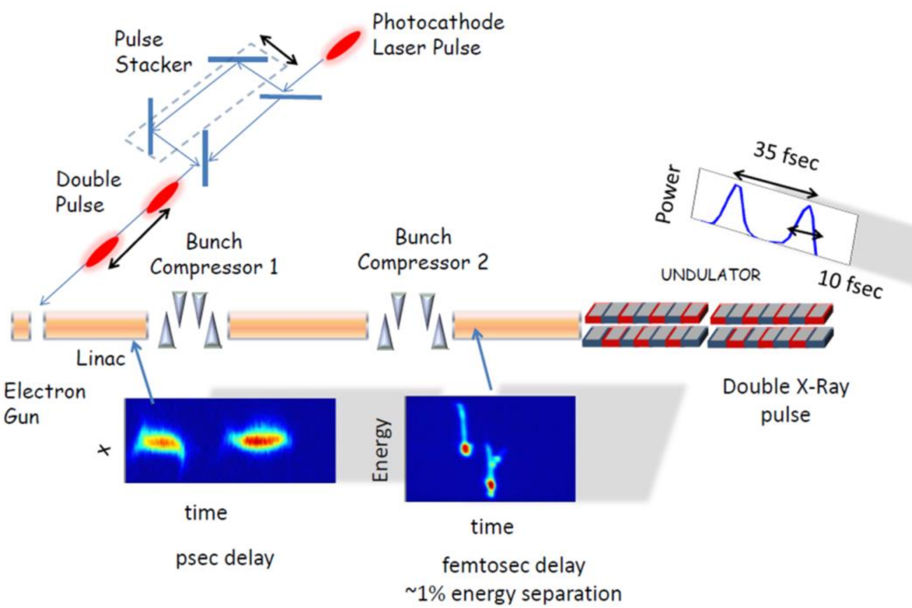


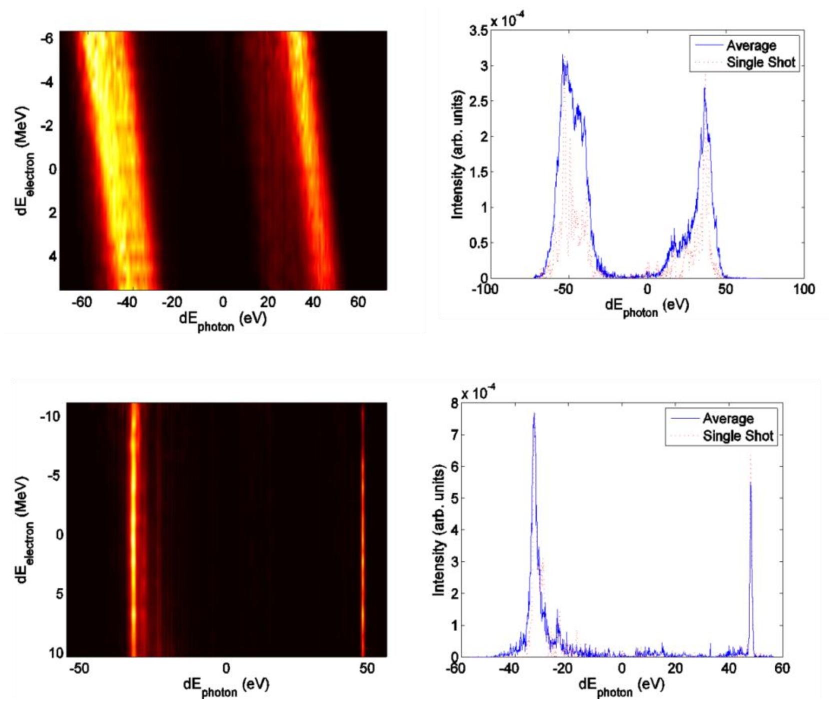
- Chirp control provides bandwidth control
- Creative use for multi-bunch operation
- Successful SBIR Project with RadiaBeam
- Follow – on proposals exist

- ***Talk by A. Lutman***



Multiple Bunches, Multiple Energies





- Many techniques allow fs to ns separation
- Laser based, slotted foil, undulator techniques, dechirper
- Frequent use by LCLS users, pump-probe experiments, structure phasing

Summary of Parameters for Multiple Bunches, Multiple Energies

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SOFT X-RAYS

Technique	Pulse Separation	Min Pulse Duration	Energy Separation	Max Energy/Pulse	Mode	Setup Time	Comments
Fresh Slice							Modes with the dechirper + orbit control.
Two SASE Pulses	~-15 to +850 fs	~5-8 fs	+/-2.5%	200 - 500 uJ (20 fs duraton)	SASE		Probe intensity is higher if the max delay req'd is 35 fs. Pump pulse intensity is higher if the min delay req'd is +15 fs or more (no zero delay).
Linear SASE + Polarization Controlled SASE	~-15 - +850 fs	~5-8 fs	+/-2.5%	300 uJ	SASE		Only pump polarization can be controlled. See also comments re: Fresh-slice, Two SASE Pulses.
One Pulse Self-Seeded, One SASE	0 - 50 fs	~15-20 fs	+/-2.5%	100 uJ seeded, 200 uJ SASE	SASE SEEDED		Only probe polarization can be controlled. See also comments re: Fresh-slice, Two SASE Pulses. Requires longer setup.
Three SASE Pulses	0 - 900 fs (1st to 2nd), 0 - 50 fs (2nd to 3rd)	~5-8 fs	2.5% range for all	100 uJ	SASE		Second pulse has lowest intensity, weak if E > 700 eV.
Split Undulator SASE	0 - 50 fs	40 fs	+/-2.0%	30 uJ	SASE		Minimally invasive, easy to maintain.
Double Slotted Foil	15 - 70 fs	~ 10 fs	+/-1.5%	100-300 uJ	SASE		Minimally invasive, easy to maintain. Delay and energy separation are not independent, minor tuning needed between changes.
Two bucket (ns spacing)	350 ps increments, +/- 120 ns	40 fs	+/-2%	0.5-2 mJ (100 fs duration SASE)	SASE SEEDED		Under development
Twin Bunches (fs spacing)	-	-	-	-	-		Intensity performance comparable to Fresh-slice. Max time separation shorter and tuning more invasive. Recommend Fresh Slice going forward.

HARD X-RAYS

Technique	Pulse Separation	Min Pulse Duration	Energy Separation	Max Energy/Pulse	Mode		Comments
Twin Bunches							Requires long setup (laser stacker/injector tune).
Two SASE Pulses	0 - 125 fs	~ 10 fs	0.2-3%	2 mJ (30 fs duration)	SASE		1st/probe pulse always higher photon energy
Twin bunches + V slotted foil	+/- 50 fs	~5-10 fs	~3%	50 uJ	SASE		
Twin bunches + HXR Self-Seeding	0-100 fs	~ 10 fs	~1 %	150 uJ per pulse	SEEDED		Both colors or a single color can be seeded. Requires longer setup time (hours).
Double Slotted Foil	7-20 fs	~ 10 fs	+/-1.5%	100-300 uJ	SASE		Minimally invasive, faster setup than twin bunches. Delay/energy separation not independent, minor tuning needed between changes.
Two bucket (ns spacing)	350 ps increments, +/- 120 ns	20 fs	~ 2%	1-2 mJ (40 fs duration SASE)	SASE SEEDED		Under development
Fresh Slice / Split Undulator	-	-	-	-	-		Do not apply for hard X-rays (insufficient FEL gain length).

Rapidly growing, check LCLS FAQ frequently!

New R&D project to obtain sub-femtosecond pulses

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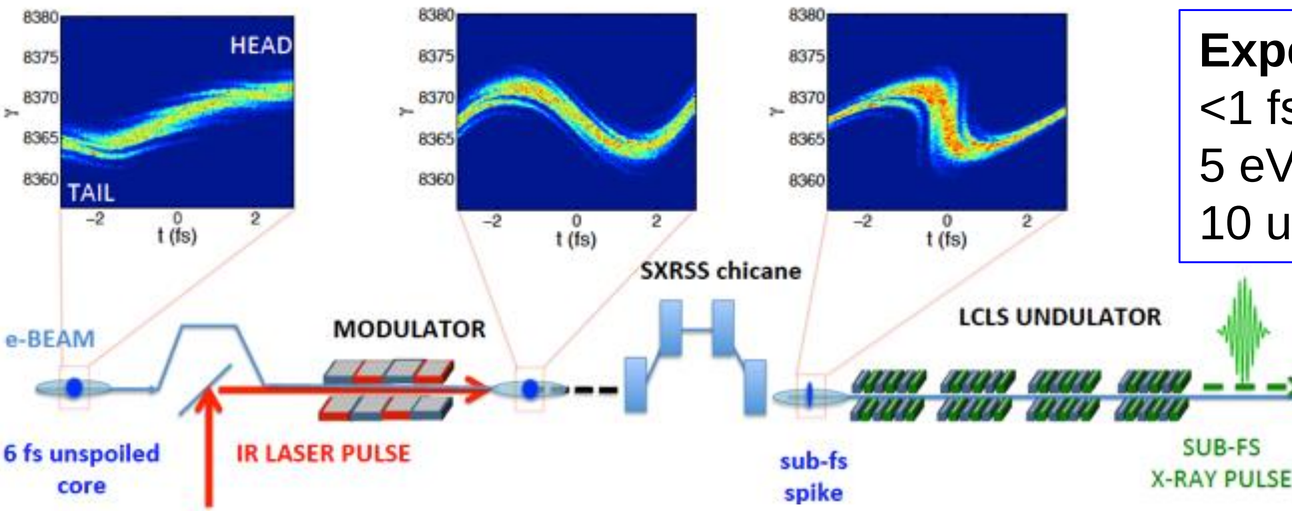
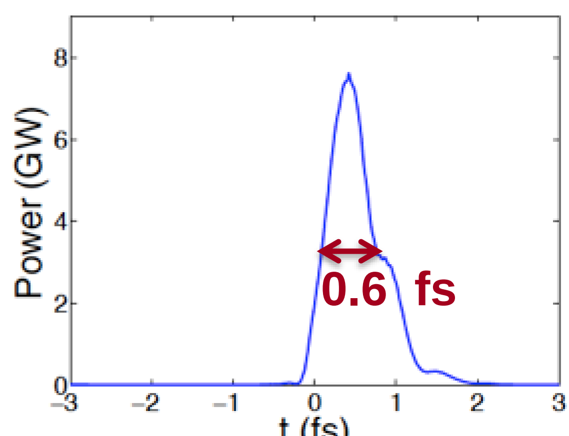
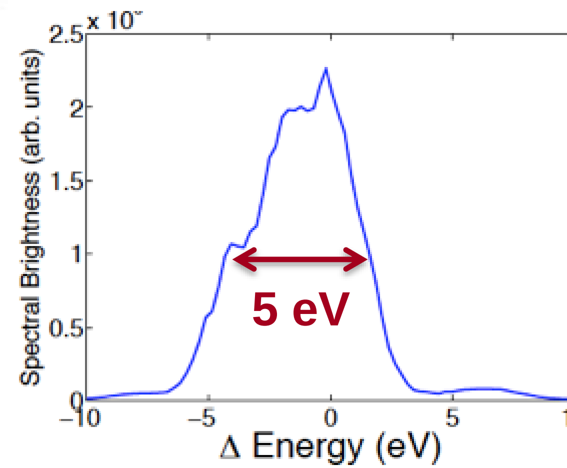
Slotted foil + long pulse laser modulation ➔ isolated single spike



Expected performance:
<1 fs duration
5 eV coherent bandwidth
10 uJ soft X-ray pulses

- Ho:YLF 2 μm laser
- APS Wiggler (reconfigured)
- SXRSS Chicane

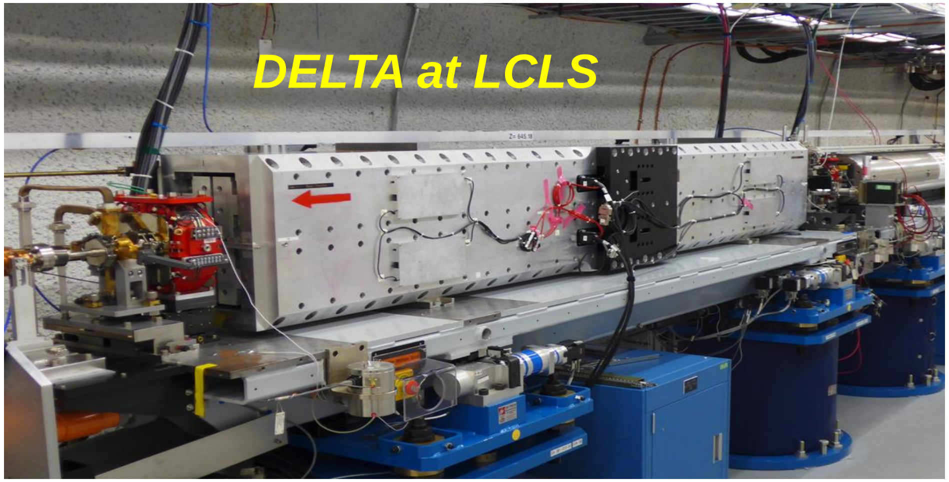


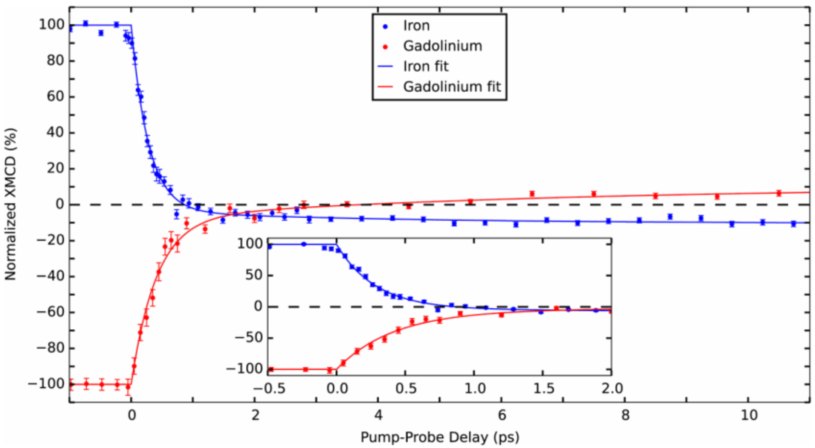


Ago Marinelli – testing in 2017-18

XLEAP (X-ray Laser-Enhanced Attosecond Pulse generation)

Polarized x-ray beam at LCLS

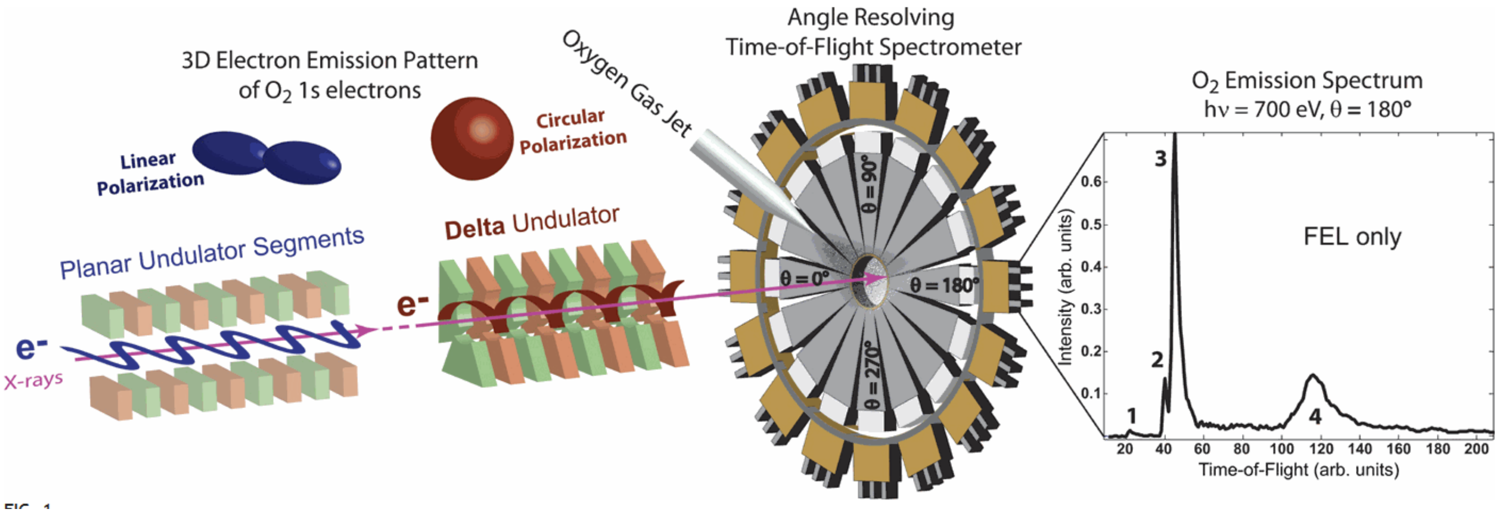




- **Stronger fields (K: 3.5 ⇒ 5.4)**
  match SXR over full range
- **Variable Gap (1.8 < K < 5.4)**
  match SXR over full range
- **Water-Cooled Vacuum Chamber**
  remove heat load due to MHz beams
- **Tighter Tolerances**

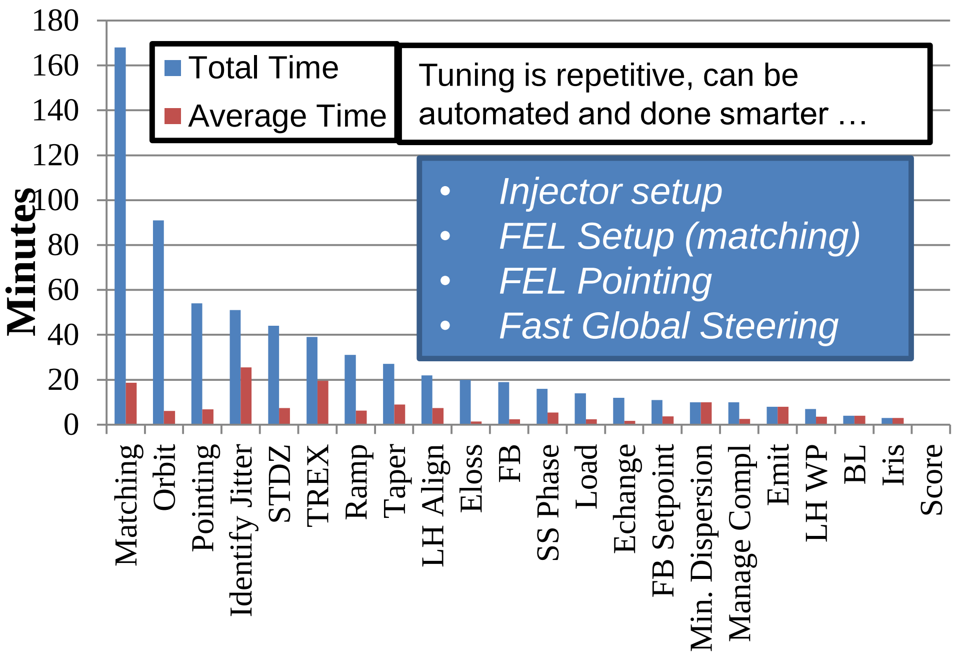
Polarization Measurements Cockie Box Instrument

Polarization experiments can be set up using the eTOF spectrometer as developed at DESY.



Rev. Sci. Instrum. 87, 083113 (2016);

Automation, HLA, AI



Tuning is repetitive, can be automated and done smarter …

- *Injector setup*
- *FEL Setup (matching)*
- *FEL Pointing*
- *Fast Global Steering*

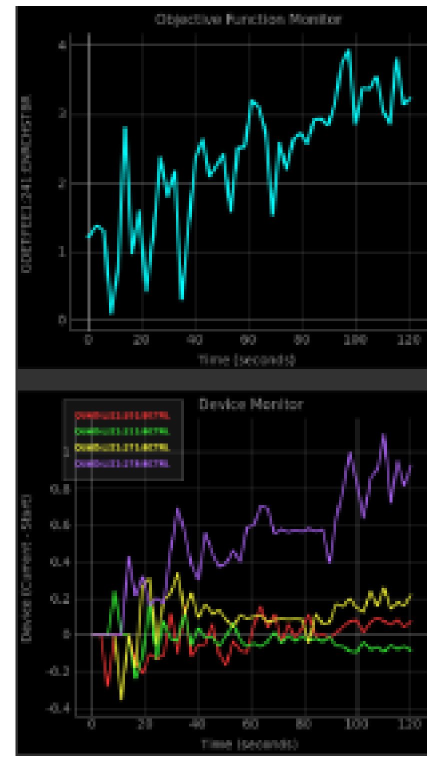
RUN XII	Hours	%
Maintenance	690.0	46.7
Setup	***233.5***	15.8
Capability	201.5	13.7
Photon Setup	***177.5***	12.0
Photon	92.5	6.3
Quality	69.5	4.7
Stability	11.5	0.8
Total	**1476**	

400 hours setup time
~1/2 (200 h) are tuning tasks
50% reduction, **100 h saved**

OCELOT (DESY)
Optimizes matching Quadrupoles

FEL Pulse energy [mJ]

Quadrupole Settings



Talk by D. Daniel Ratner

External Seeding Programs

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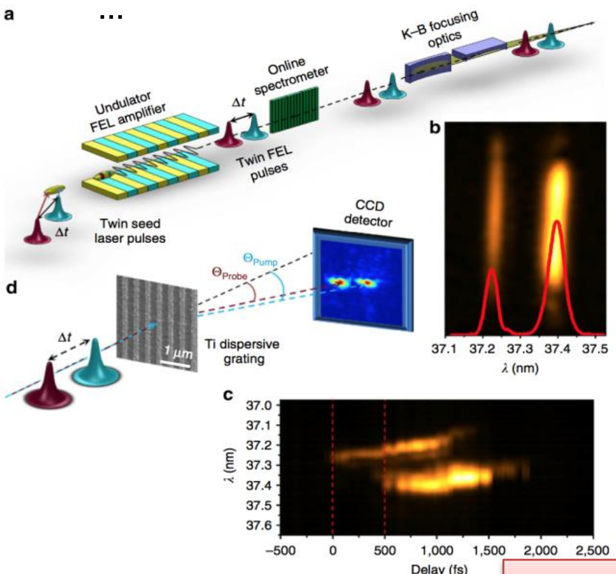
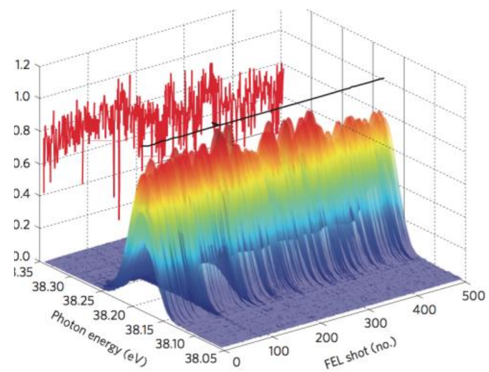
HGHG@ FERMI [4 nm, 65th harm from 260nm]

E. Allaria, et. al., Nature Photonics 6, 699–704 (2012)
E. Allaria, et. al., Nature Photonics 7, 913–918 (2013)
…





EEHG @ SINAP

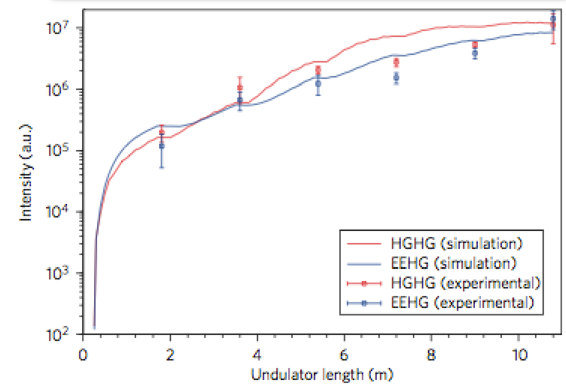
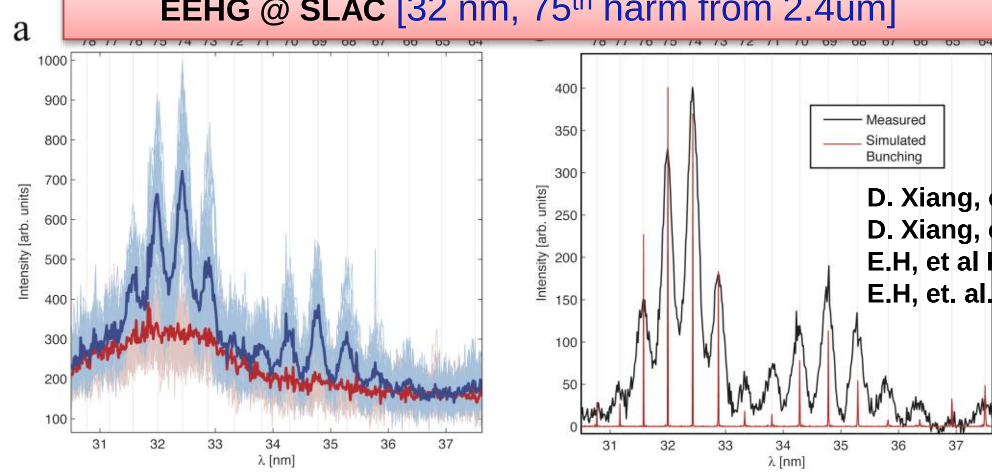


Figure 5 | Gain curves of the EEHG and HGHG FEL at SDUV-FEL. Intensity is measured with a calibrated CCD at the end of the radiator (red open squares, HGHG; blue open squares, EEHG). Error bars correspond to the peak-to-peak intensity statistics of 100 measurements. Simulation results are shown as a red line (HGHG) and a blue line (EEHG).

Z. T. Zhao, et. al., Nature Photonics 6, 360–363 (2012)

EEHG @ SLAC [32 nm, 75th harm from 2.4um]

Task Force at SLAC lead by Erik Hemsing



D. Xiang, et. al., PRL 105, 114801 (2010)
D. Xiang, et. al., PRL 108, 024802 (2012)
E.H, et al PRST-AB 17, 070702 (2014)
E.H, et. al., Nat. Photon. 10, 512–515 (2016)

Leading Seeding Techniques

Direct Seeding - High Harmonic Generation (HHG) – [State Of The Art: 38 nm]

FEL amplification of low power EM input, usu. harmonic of 800nm generated in noble gas

Proof of principle demonstrated. Path to SXRs unclear.

Limited to >20nm by 10^{-6} conversion efficiency. Seed must exceed shot noise in beam.

High Gain Harmonic Generation (HGHG) – [4 nm, 65th harm from 260nm]

Harmonic density bunching. Limited to <15th harmonic in single stage

Cascade multiple stages w/fresh beam to reach soft x-rays. **Demonstrated and in use**

Echo-Enabled Harmonic Generation (EEHG) – [32 nm, 75th harm from 2.4um]

Harmonic density bunching. Small energy modulations required. Reach soft x-rays from UV lasers in single stage. **Proof of principle demonstrated. Tests @ SXRs upcoming.**

Highly nonlinear phase space manipulation and preservation challenging.

Self Seeding (HXRSS & SXRSS)

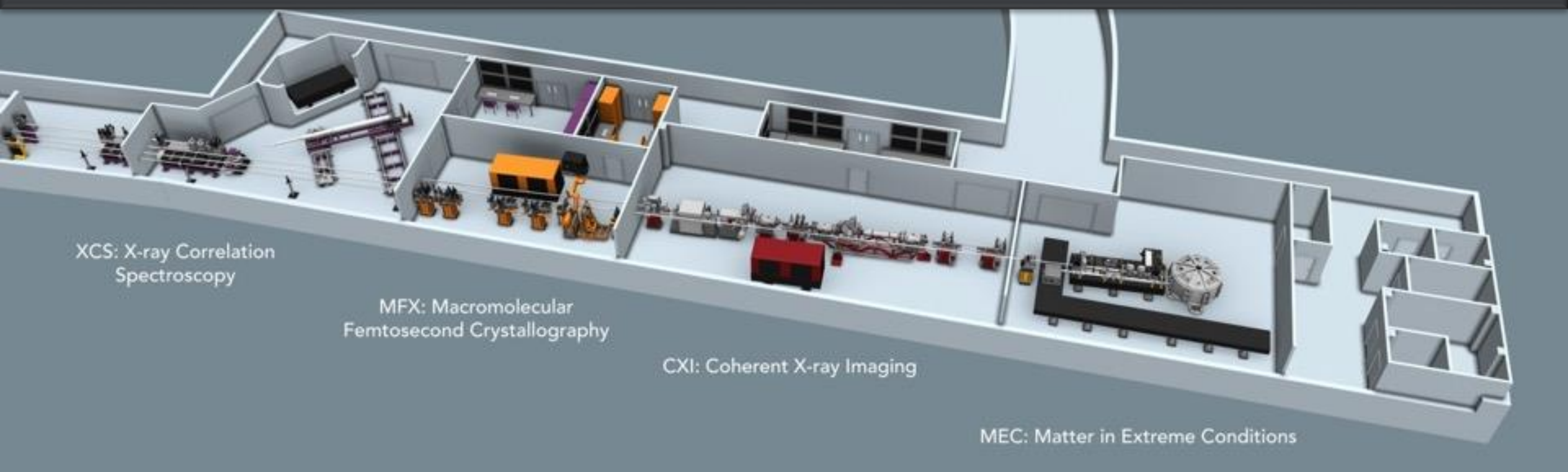
Monochromatized FEL seeds itself. **Demonstrated and in use.**

Damage & rep rate limits. Pedestal/wakefields contribute

Combinations? (HGHG+EEHG, Self-Seeding +?, etc)

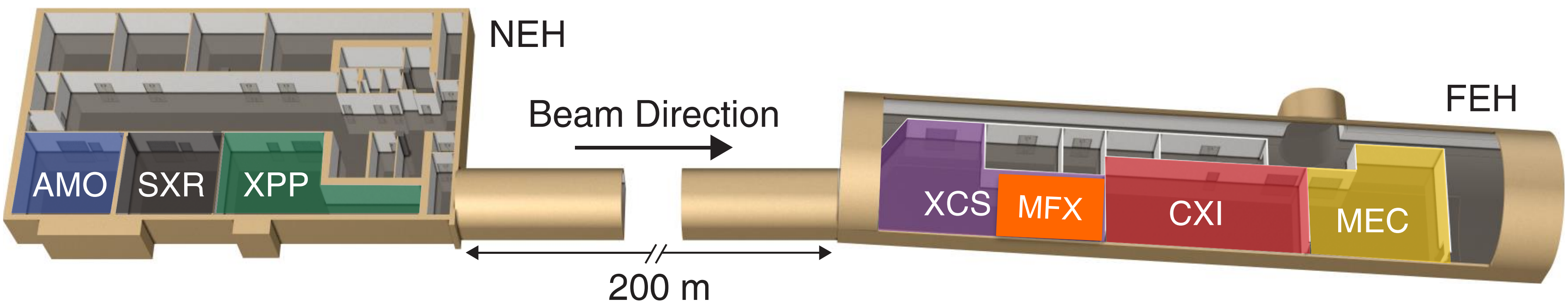
In development

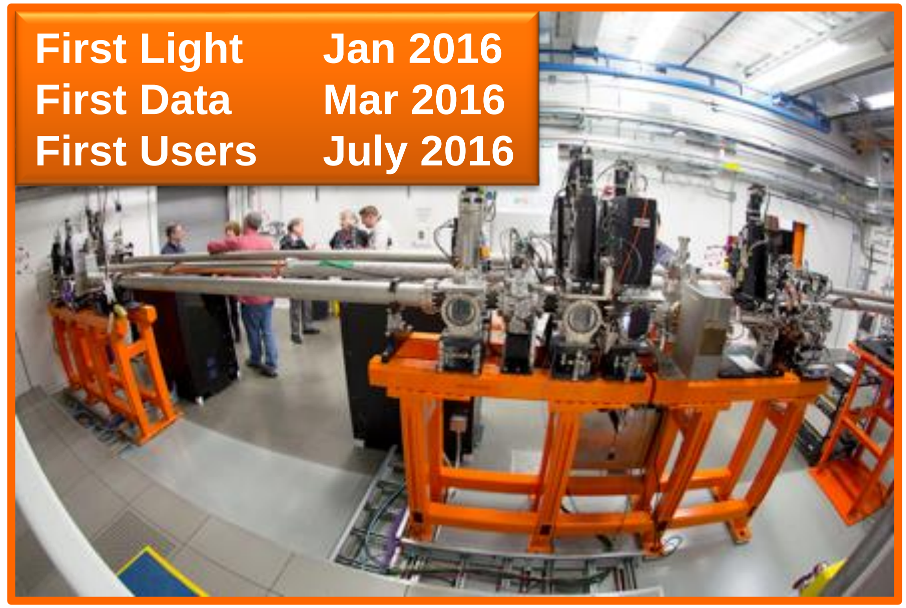
Recent LCLS Instrument Developments



New instrument area: “MFX” in hutch “4.5”

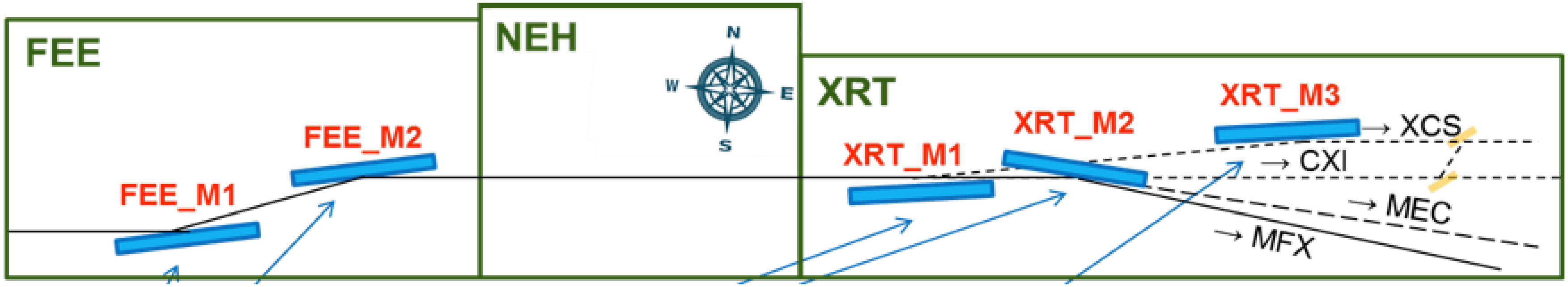
Macromolecular **F**emtosecond **X**tallography

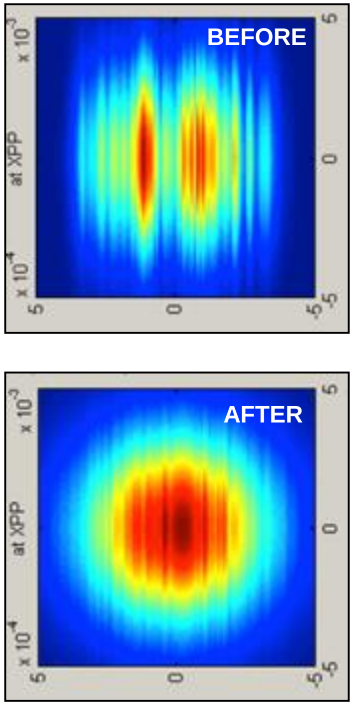


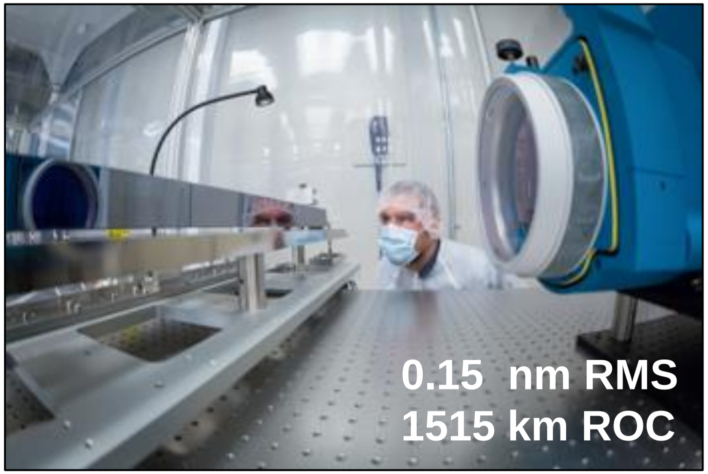


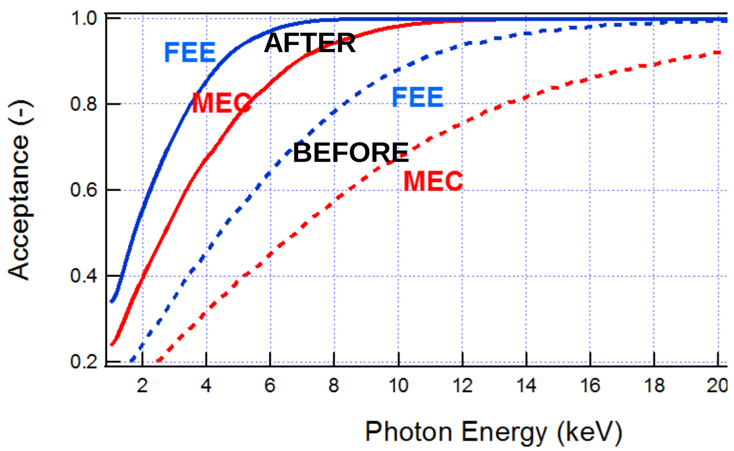
Update: NSF grant awarded for new goniometer endstation

X-ray mirror upgrades (early 2017)



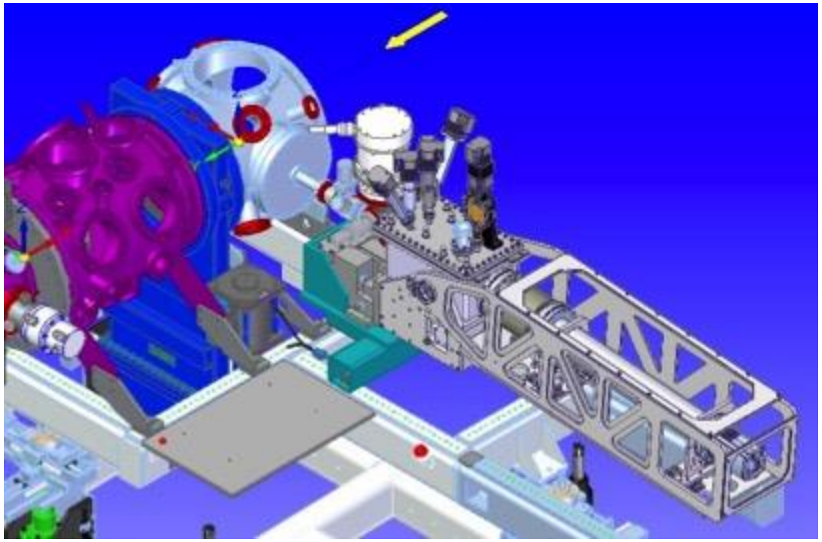




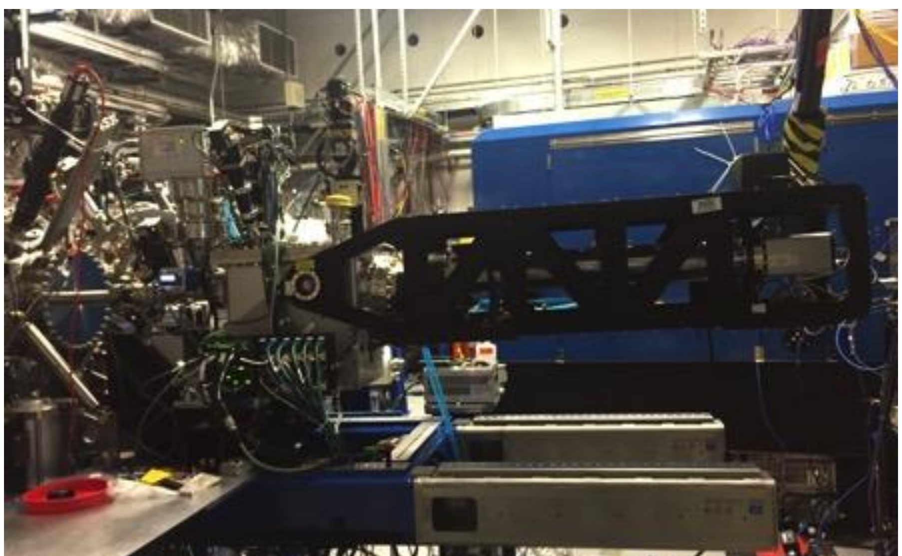


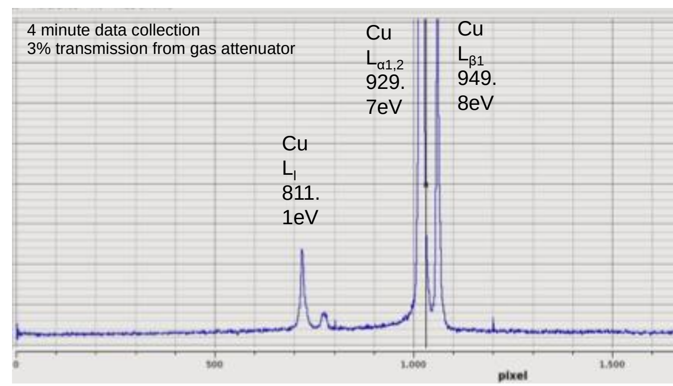
- Substantial impact in HXR near-field quality & efficiency
- New periscope to XCS to create "XPP-like" capability
- Soft X-ray mirrors to be replaced / cleaned

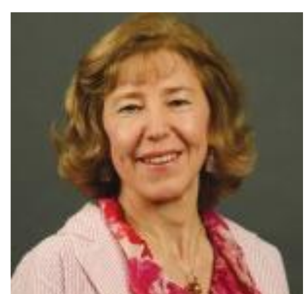
New Soft X-ray Emission Spectrometer Commissioned

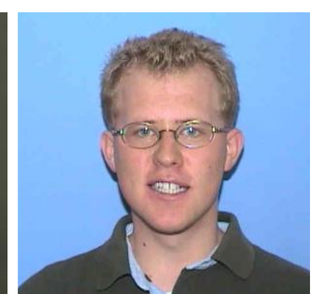


- Portable soft x-ray spectrometer now available
  - ALS Design
  - 1000-3000 resolving power
- Compatible with multiple endstations & LCLS-II
- Part-funded via N. Berrah (UConn) DOE grant



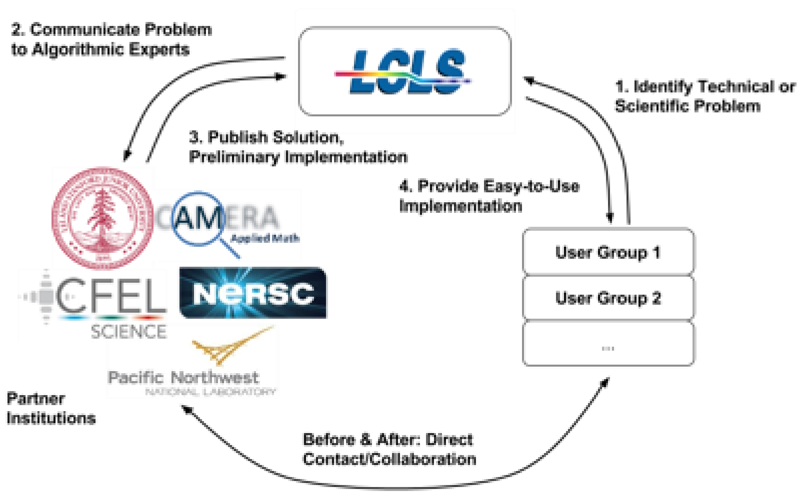






Investment into <u>data science</u> is a critical element of our strategy to ensure high scientific impact from LCLS

- LCLS strategic plan for computational science, theory, and data systems:
  - **Infrastructure** for managing LCLS data
  - Software **tools** for data processing, and fast feedback
  - Advanced **algorithms** specific to LCLS science (hit finding, indexing, diffraction, structures)
- Strategic collaborations with other labs, and DOE “Exascale” computing
- New Computer Science Division at SLAC (2016), with a major focus on LCLS



NERSC

ESnet
ENERGY SCIENCES NETWORK

CAMERA
Applied Math

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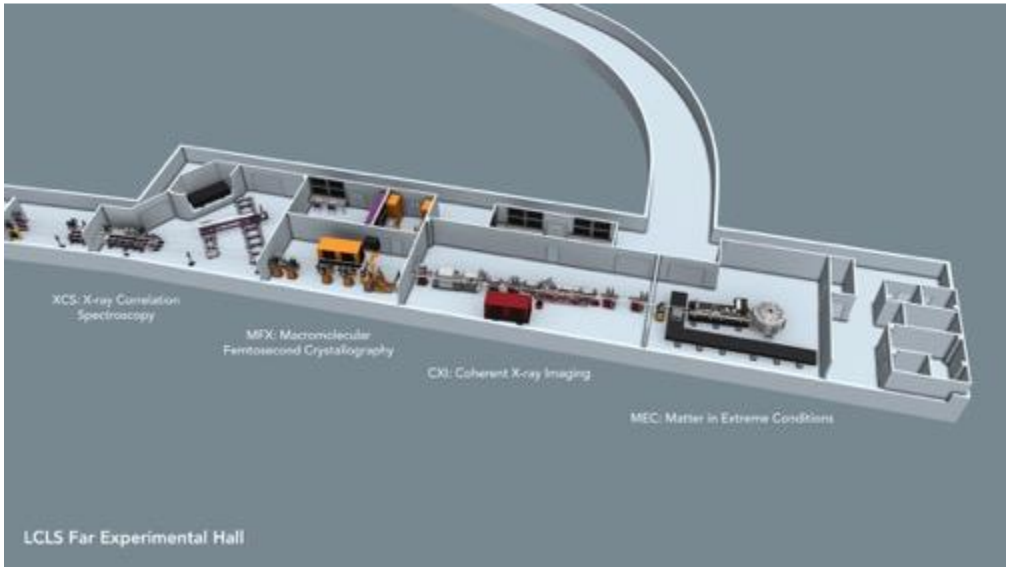
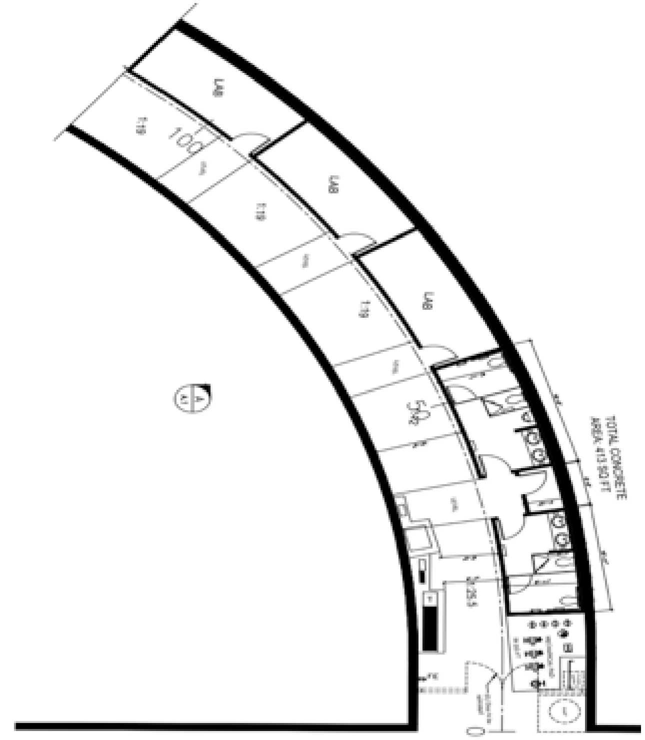
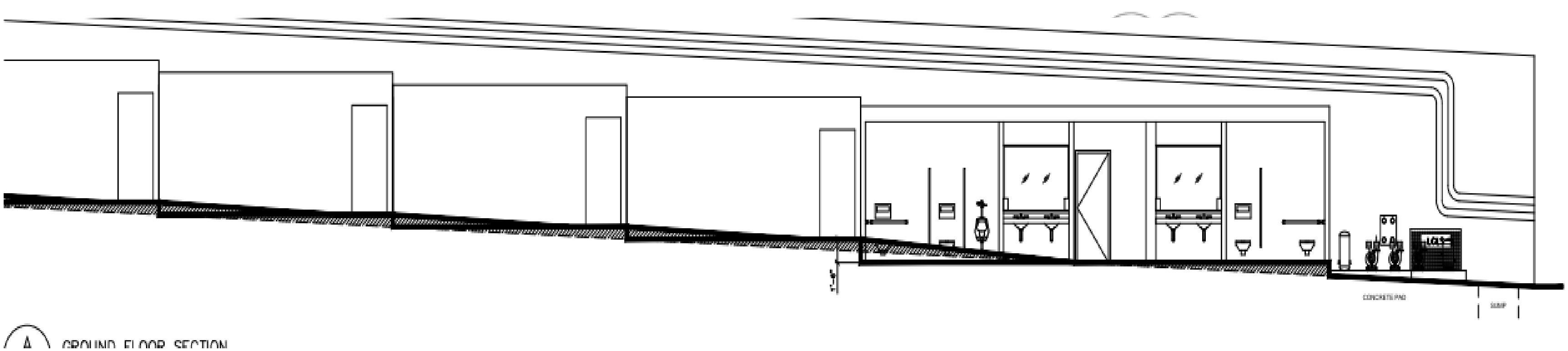
Computer Science

Broad set of partnerships being formed to tie LCLS needs to CS solutions

New support labs planned for the FEH in 2017 – Also enables optimization of the hutches

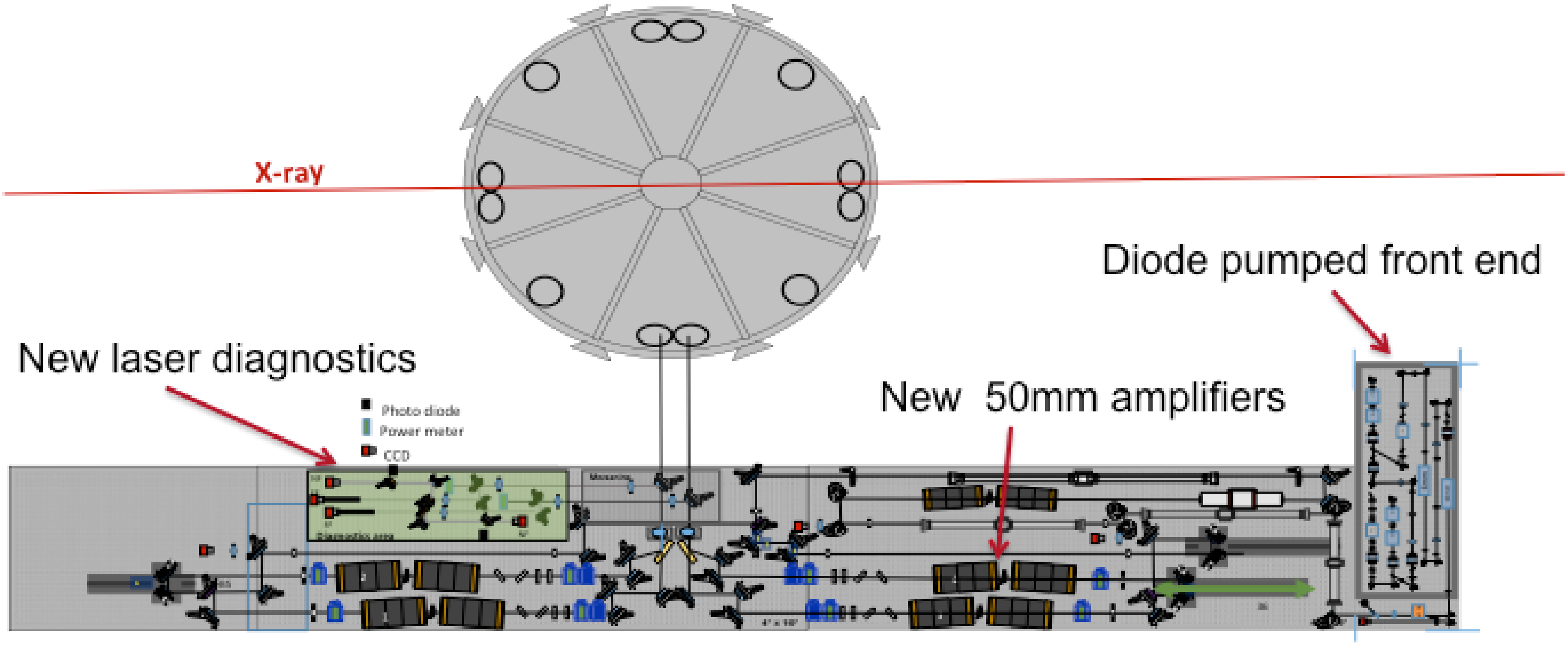






MEC laser upgrade in 2017 will provide 2 beams with 2x energy (40 J), stability, and NIF-like pulse-shaping

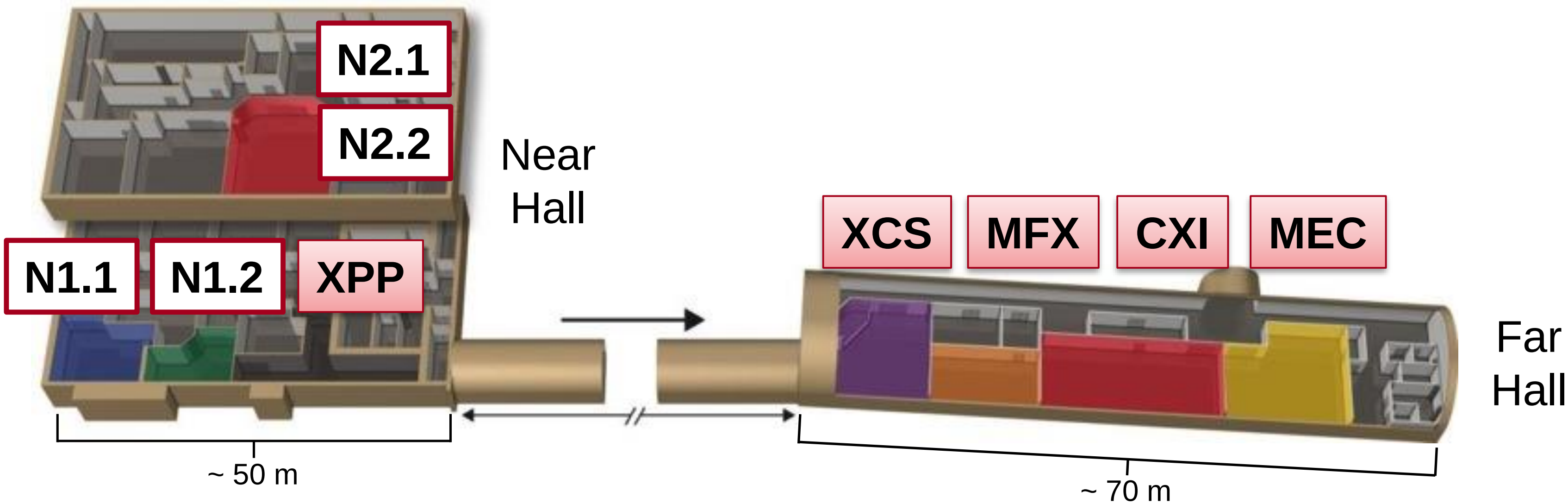
- **Two 'high energy' arms (total 4 J/ns at 351 nm)**
- **Stable, shaped front-end (2-3% RMS)**
- **New laser diagnostic suite incorporated into the DAQ**
- **Appointed a 'Laser manager' to drive robust delivery**



100 TW short pulse system will also be commissioned in the FY17 downtime

4 new instrument areas will be developed for LCLS-II

- **4 new instrument areas are planned**
- **9 instruments available in total for LCLS-II**



SXU → NEH 1.1, NEH 2.1, NEH 2.2, NEH 1.2

HXU → NEH 1.2, XPP, XCS, MFX, CXI, MEC

NEH 1.1: Atomic, Molecular and Optical
NEH 2.1: Resonant Inelastic X-ray Scattering
NEH 2.2: Soft X-ray Research
} 3 Soft X-ray

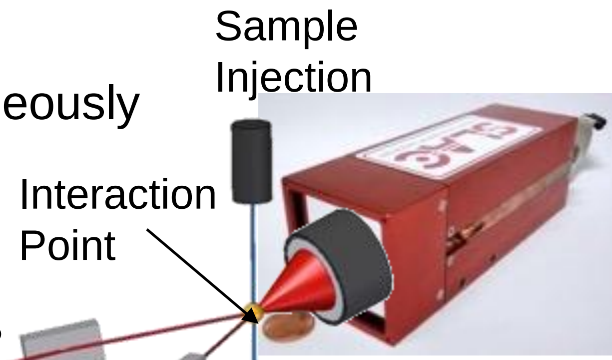
NEH 1.2: Tender X-ray Instrument
} 1 "tender" x-ray

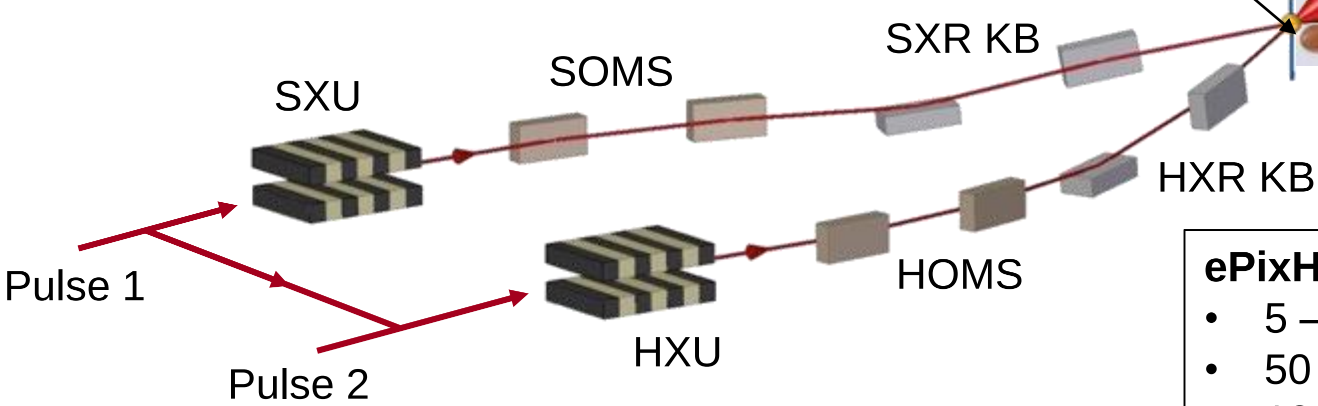
XPP: X-ray Pump Probe
XCS: X-ray Correlation Spectroscopy
MFX: Macromolecular Femtosecond Crystallography
CXI: Coherent X-ray Imaging
MEC: Matter in Extreme Conditions
} 5 Hard X-ray

Example – NEH1.2: Tender X-ray Instrument (TXI)

Being designed as a very flexible instrument:

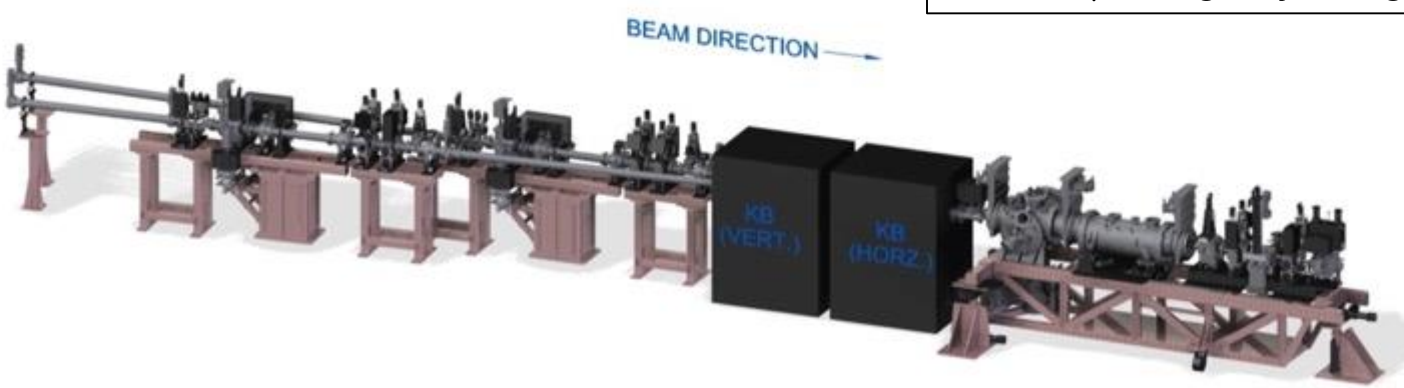
- Capable of using HXU, or SXU, or both simultaneously
- Tender x-ray imaging
- Tender x-ray spectroscopy





ePixHR detectors

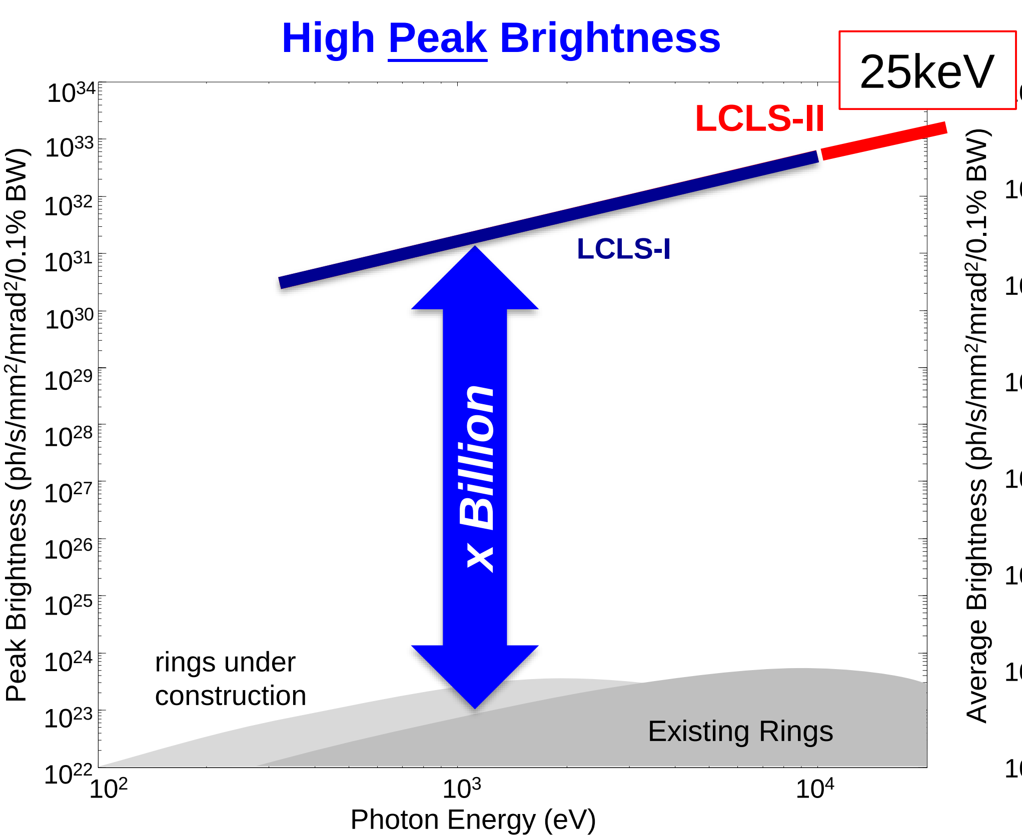
- 5 – 50 kHz development
- 50 µm pixels for low noise
- 100 µm high dy. range

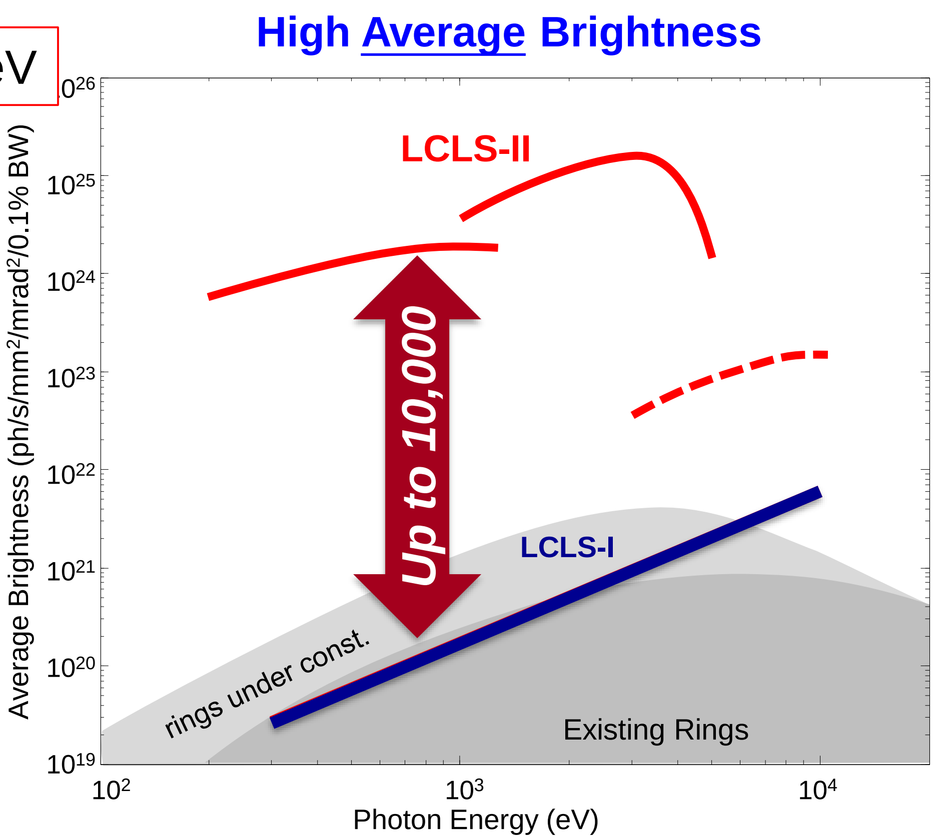


LCLS-II, a major (B$) upgrade to LCLS is fully underway.
CD2/3 was approved in 2016.
Online in 2020.

LCLS-II provides a factor >10^3 in average brightness (to 5 keV), and extends the reach of the Cu linac to 25 keV

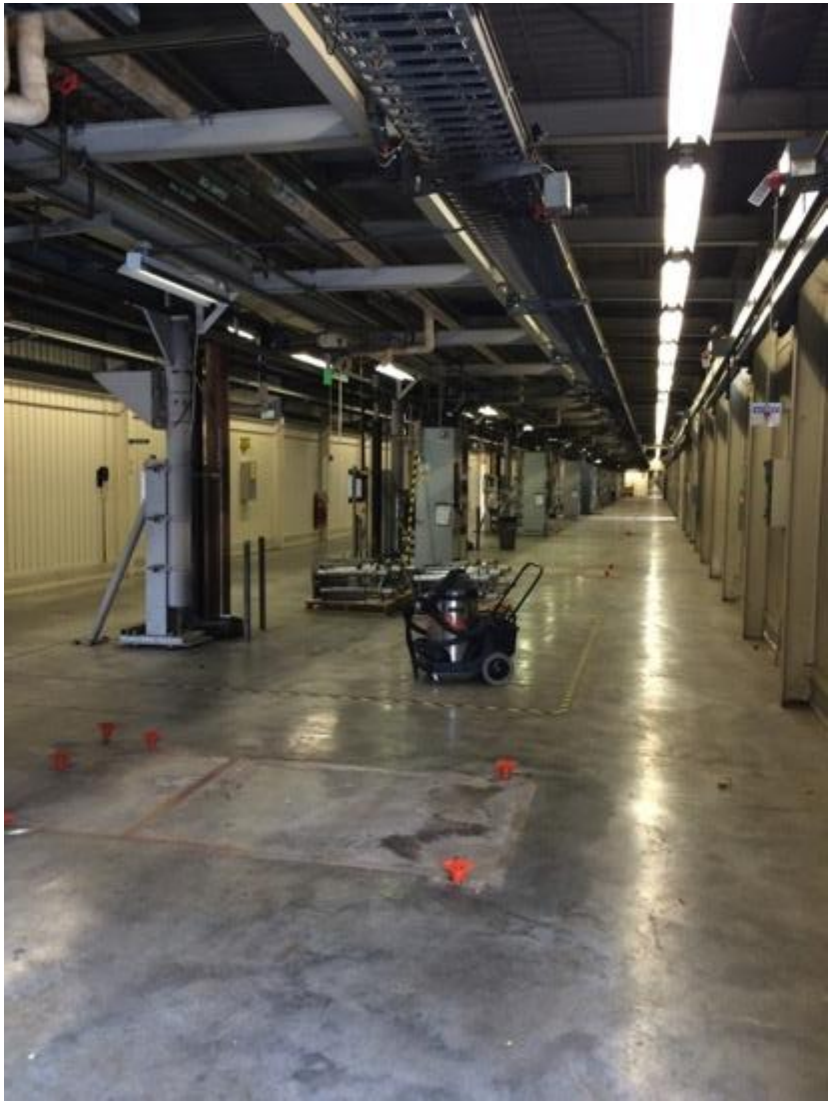
SLAC





The leap from 120 Hz to up to 1 MHz, and access to >25 keV drives development across the entire facility

Sector 0 to 10 equipment removal – phase 1 completed



LCLS-II Project is progressing well

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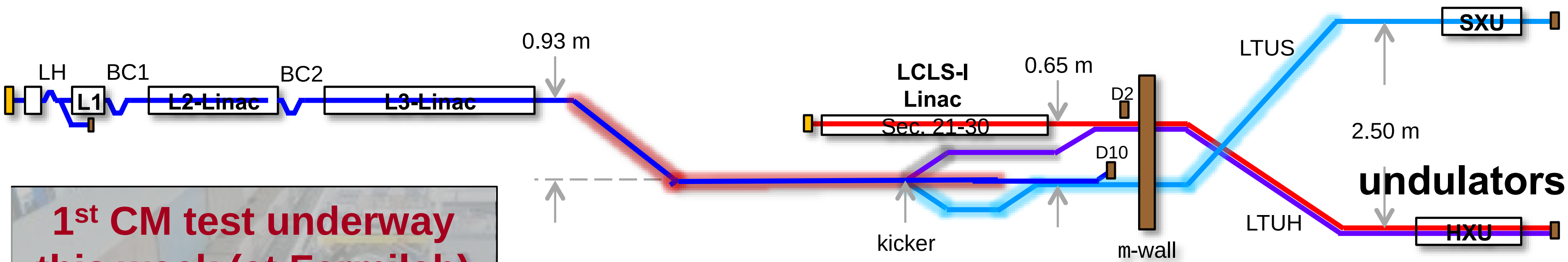
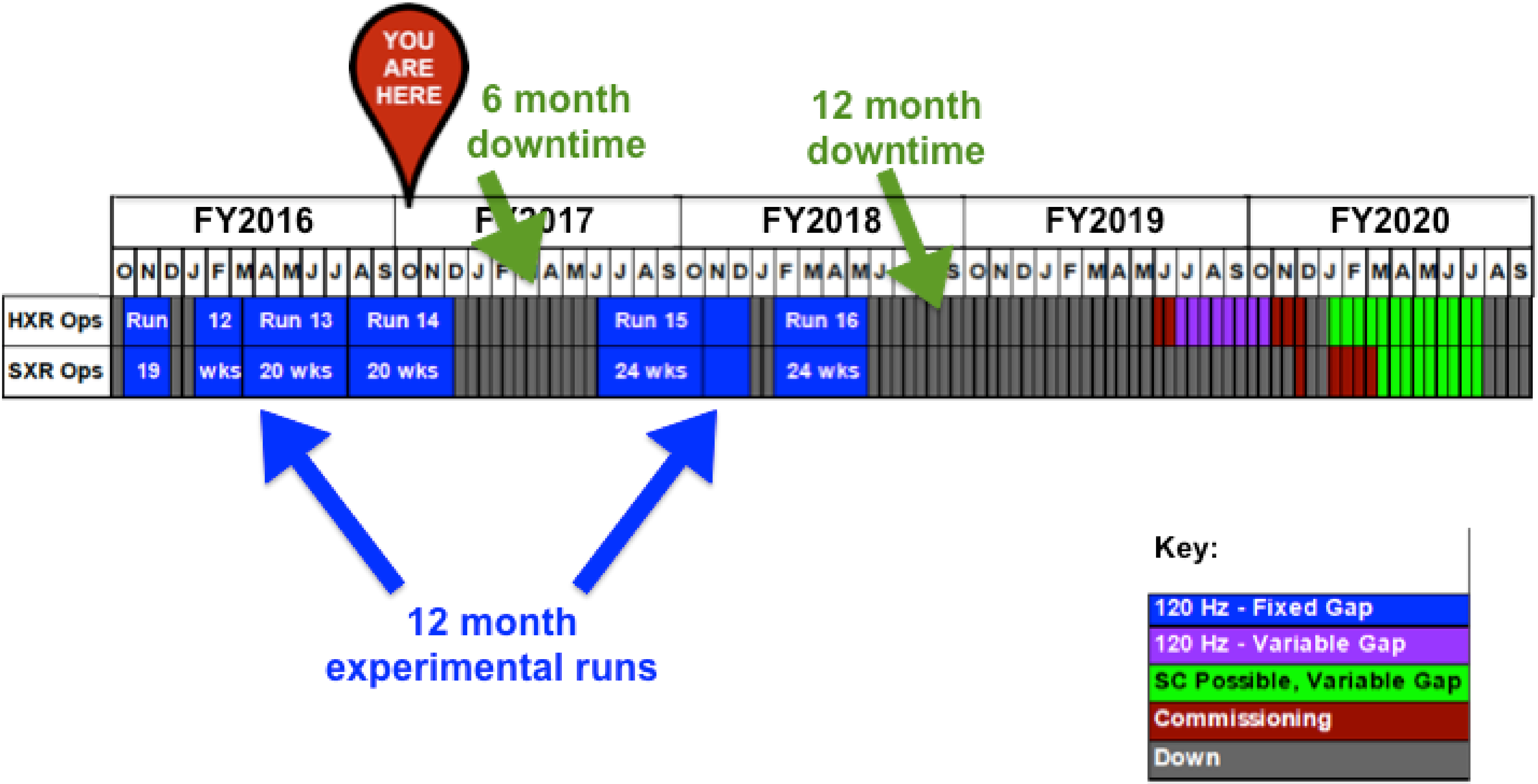


1st CM test underway this week (at Fermilab)

- **4 GeV SC linac in the 1st km of the SLAC tunnel**
  - Exploits new “Nitrogen doping” technique
  - Will run CW up to ~ 1 MHz
  - Dual cryoplant to provide substantial margin
- **Two new variable-gap undulators**
  - Recent choice of vertical polarization for HXU
- **Modified experimental hall**
- **LCLS-1 linac is retained**
  - Parallel activity to increase its robustness, stability, and extend performance
- **Critical Decisions 2 and 3 approved (April 2016)**

Timeline



Proposals for Run 15 due 7 November

Future plans …

A high energy extension, LCLS-II-HE, is currently being designed, able to provide high repetition rate in the hard x-ray regime

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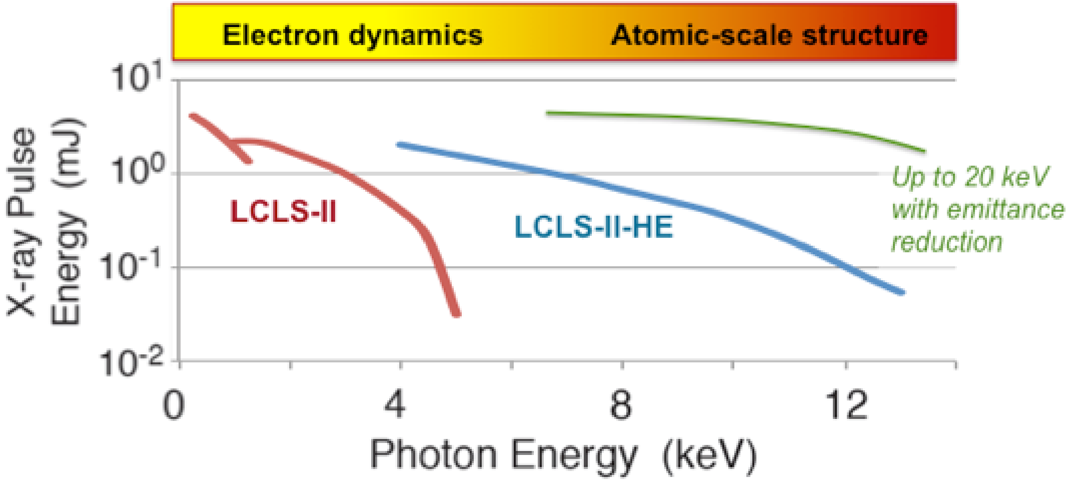
- Extend energy reach from 5 keV to 12 – 20 keV (in the fundamental)

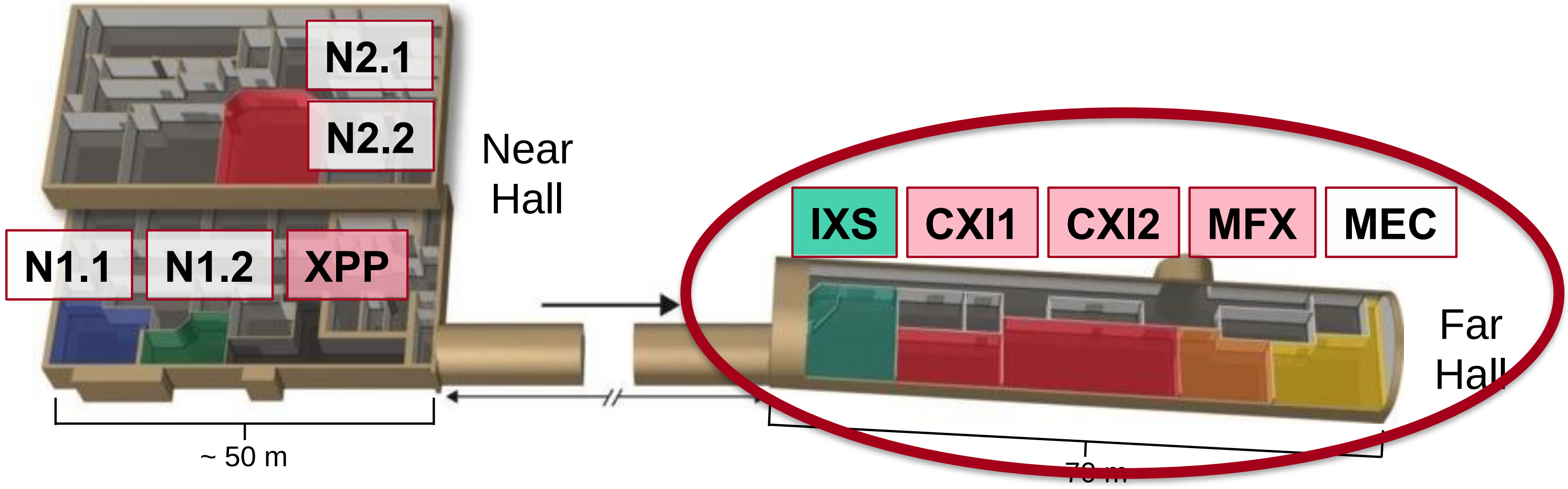


- Additional cryomodules in the newly refurbished space in the existing tunnel

BESAC facilities prioritization: LCLS-II-HE is "absolutely central" and "ready to initiate construction"

LCLS-II-HE scope includes instrumentation to take full advantage of the transformative nature of the new source

- Combined sources for simultaneous atomic and electronic structure
- Enables a variety of new instrumentation for:
  - High resolution (~1 meV) spectroscopy
  - Atomic-scale imaging of fluctuating systems
  - MEC



These extensions will be implemented within the existing infrastructure

Final remarks

- **The next 5 years will see major development at LCLS**
- **In the past year, significant attention has been paid to increasing user access, and improving the efficiency of operations**
- **Implementation of LCLS-II will actively develop:**
  - Automation of beamlines and instruments
  - Major steps in detector, sample delivery, and data analysis capabilities
  - Offline support laboratories
- **Your feedback on these developments is critically important**