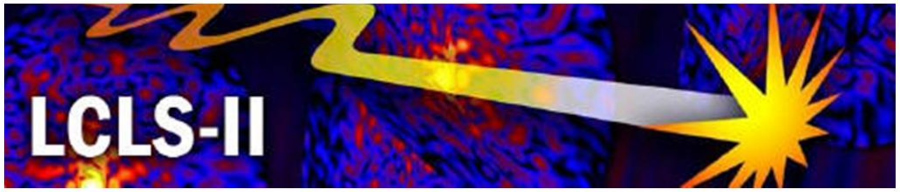


LCLS-II & LCLS, too

November 12, 2012

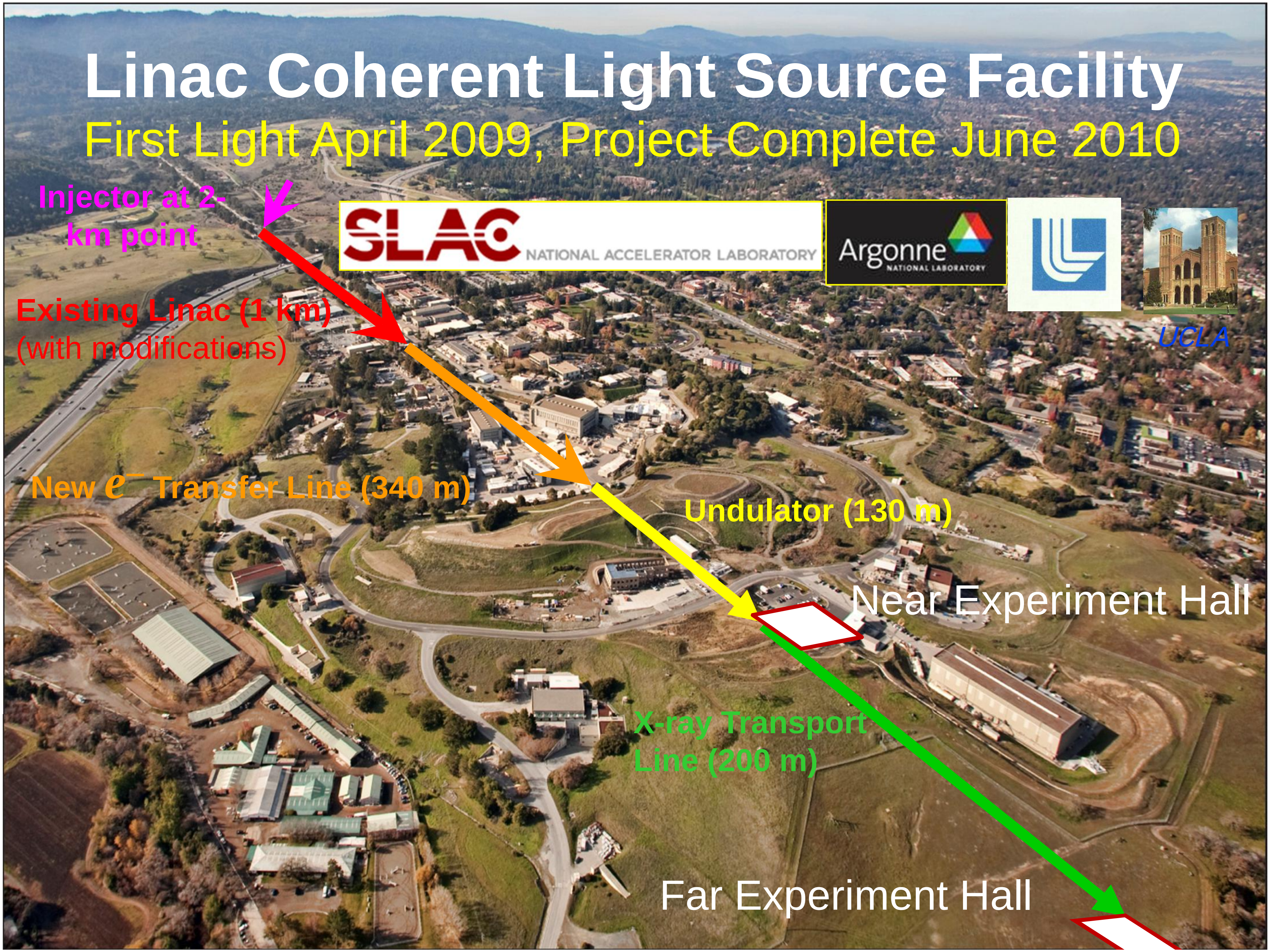
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB

Linac Coherent Light Source Facility

First Light April 2009, Project Complete June 2010

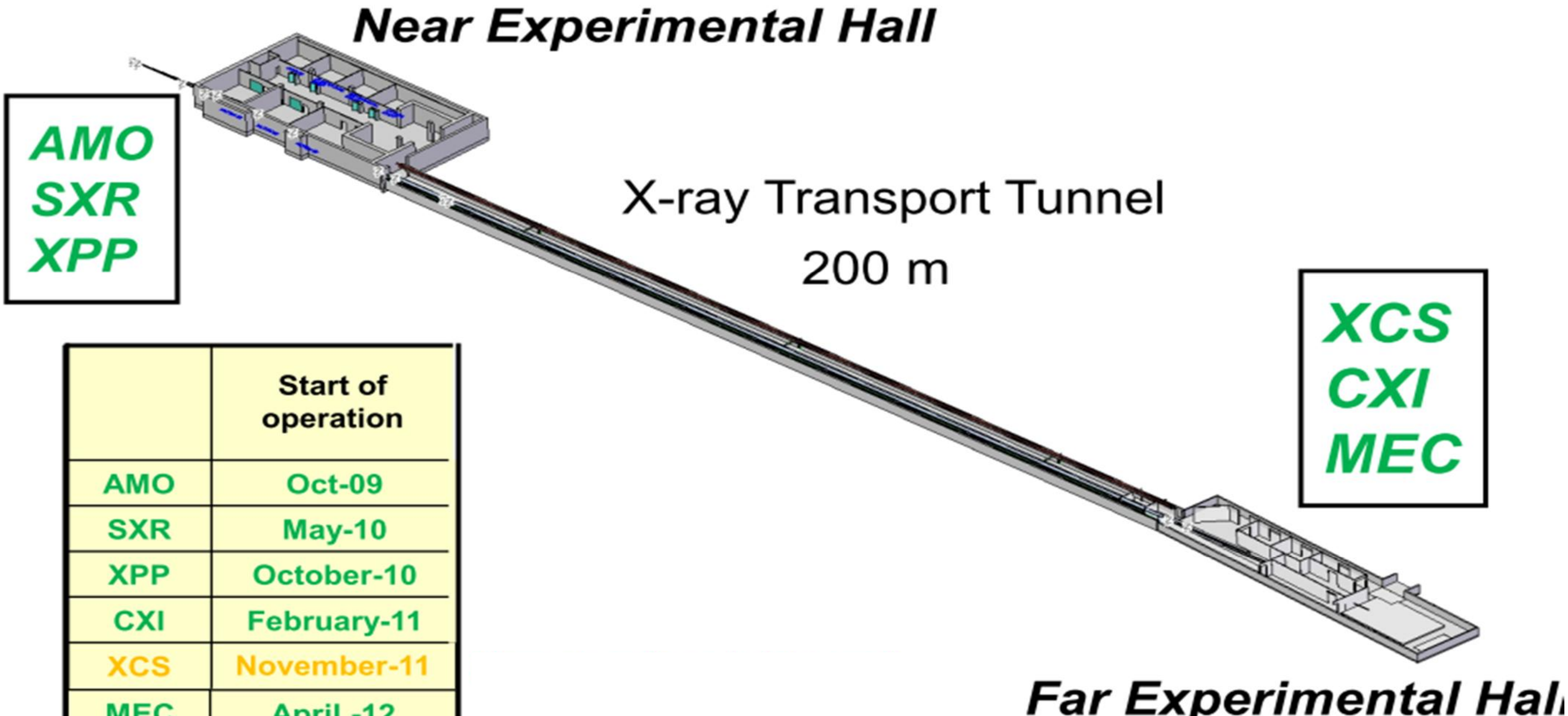


Typical operating parameters

X-RayTuning Range	280 - 10,000	eV
Peak Power	up to 70	GW
Bandwidth, 8,000 eV	0.2 typical; <0.01 seeded	% FWHM
Bandwidth, 800 eV	0.5 typical	% FWHM
X-Ray pulse duration	~3-500	x 10^{-15} sec
Beam size at waist, 800 eV	20, typical	μm, RMS
Beam divergence, 800 eV	20, typical	μrad, FWHM
Beam size at waist, 8,000 eV	15, typical	μm, RMS
Beam divergence, 8,000 eV	3, typical	μrad FWHM
Energy/Pulse	> 2 typical, 6 max	mJ
Energy Jitter/Pulse	5 typical	%
Pulse Repetition Rate	120	Hz

LCLS Experiment Stations Are Now Fully Operational

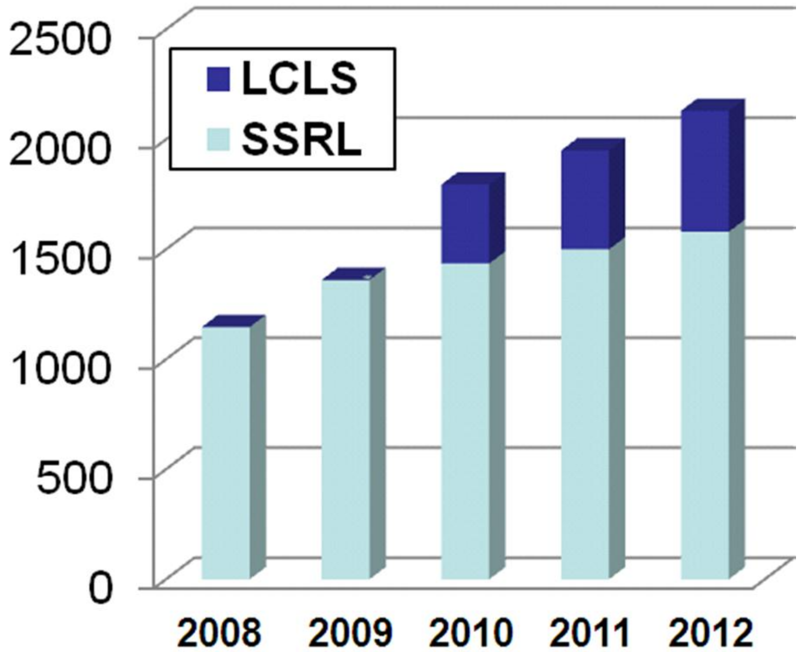
SLAC



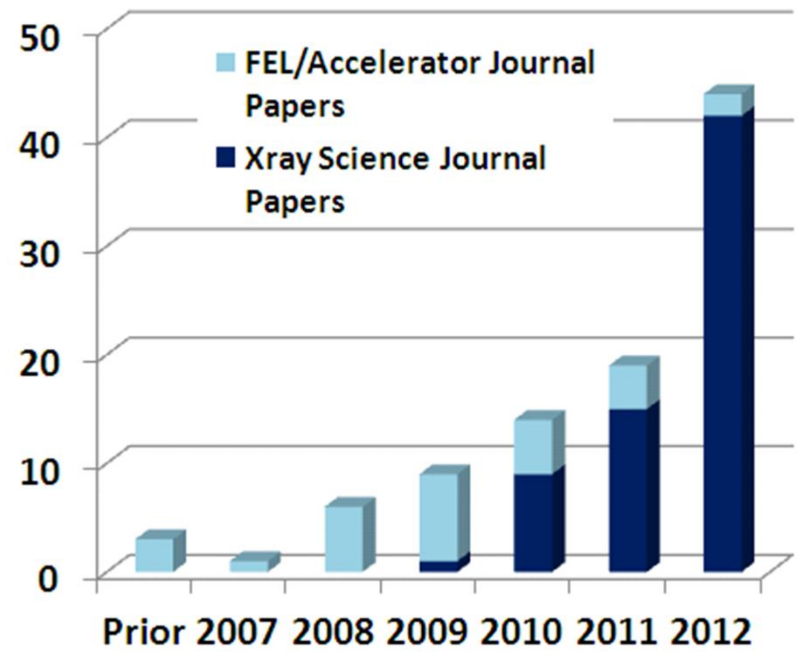
	Start of operation
AMO	Oct-09
SXR	May-10
XPP	October-10
CXI	February-11
XCS	November-11
MEC	April -12

LCLS Operations Summary

On site users



Publications by year



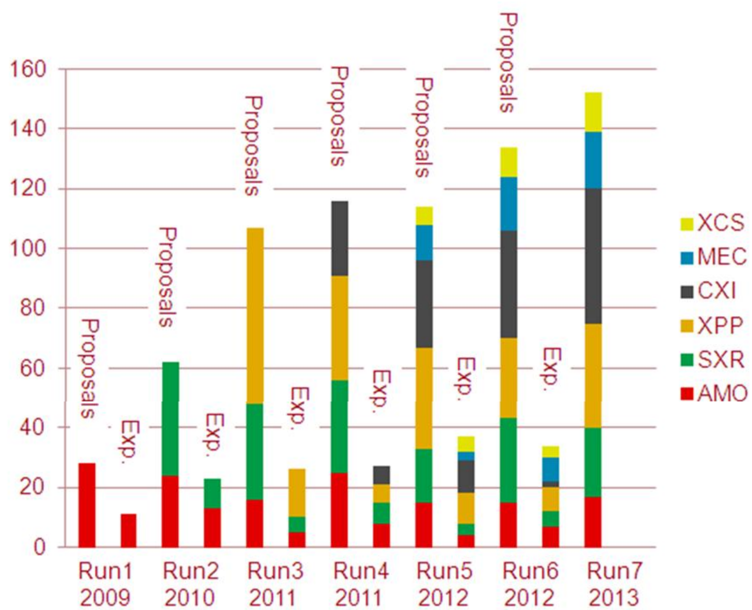
703 proposals (~15 scientists/proposal)

- 31 countries
- only 1 in 5 proposals gets beam time

~ 60% of papers in high impact journals

Beam delivery is ~95% of scheduled beam time

Experiment Program is Oversubscribed



152 proposals for beam time between January and July, 2013

LCLS Proposal Summary							
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Proposals Received	Sept'08	May '09	Nov'09	Jun'10	Jan'11	Sept'11	Jul'12
AMO	28	24	16	25	15	15	17
SXR		38	32	31	18	28	23
XPP			59	35	34	27	35
CXI				25	29	36	45
MEC					12	18	19
XCS					6	10	13
Total Proposals Received	28	62	107	116	114	134	152
	"User Assisted Commissioning"			Dedicated User Facility > August 2010			
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Experiments Performed	Oct-Dec'09	May-Sep'10	Oct-Mar'11	Jun-Oct'11	Nov-May'12	Jun-Dec'12	Jan-Jul'13
AMO	11	13	5	7	4	7	5
SXR		10	5	6	4	5	7
XPP			11	6	9	8	11
CXI			4	6	8	7	12
MEC					2	4	4
XCS					2	2	3
Total Proposals Scheduled	**11**	**23**	**25**	**25**	**29**	**33**	**42**
% Proposals Scheduled	**39%**	**37%**	**23%**	**22%**	**25%**	**25%**	**28%**
Est. User Hours Requested	1680	3720	6420	6960	6840	8040	9120

LCLS Beam-Sharing Demonstration January 2013

SLAC

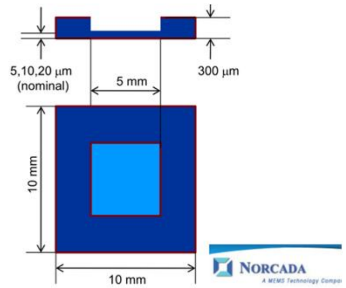
Demonstration in operations targeted for Jan 2013

LCLS beamtime in very high demand

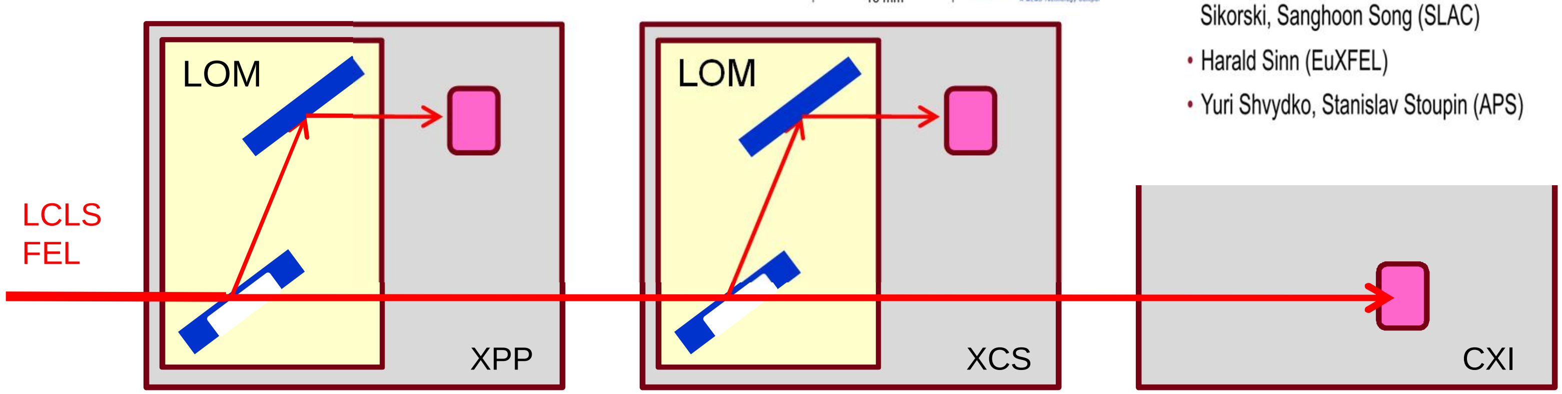
Increase capacity by multiplexing using large offset monochromators (LOM) with thin Bragg crystals

- 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

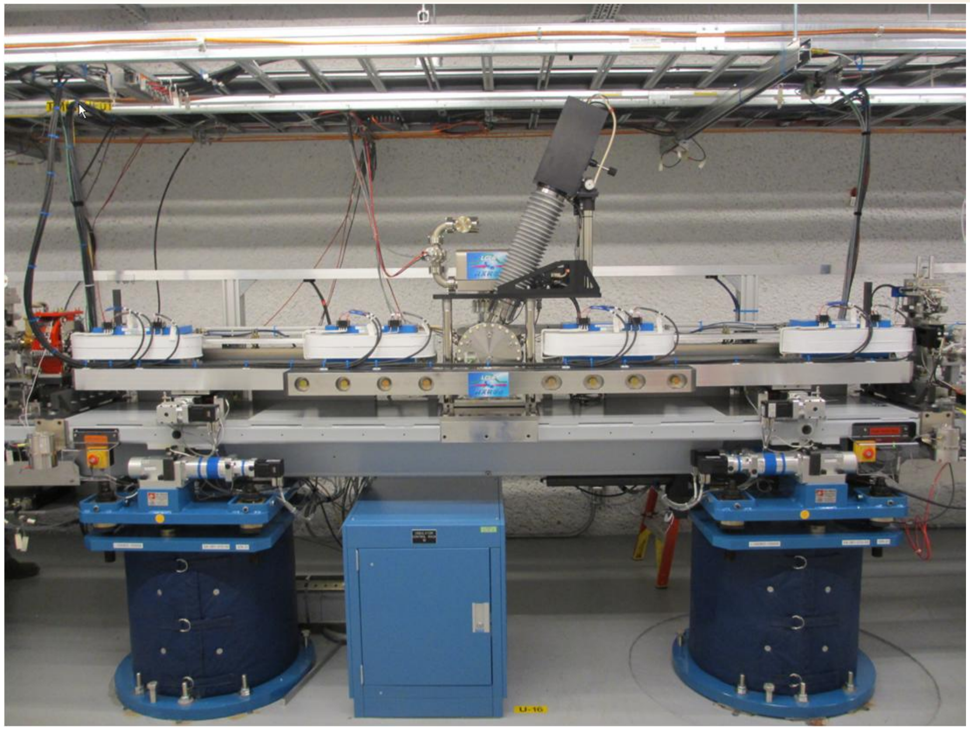
- Etch processes:
  wet etch, DRIE, SOI/wet etch
- Available crystal orientations:
  <400>,<220>,<111>

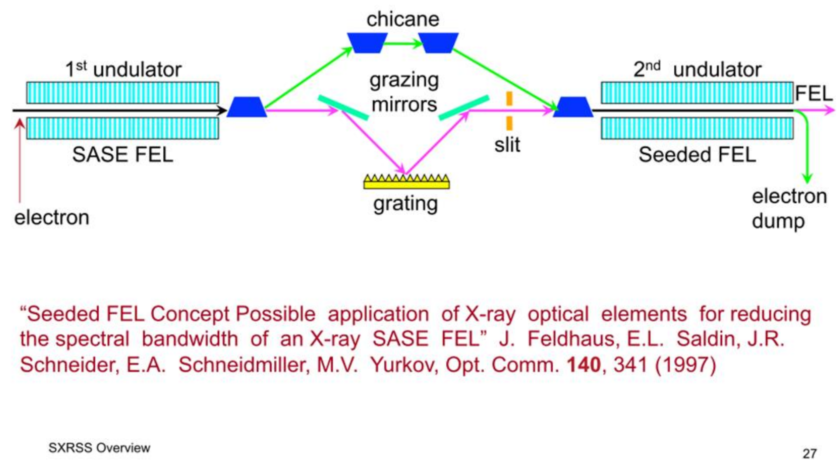


- Yiping Feng, Lead Physicist
- Venkat Srinivasan, Lead Engineer
- Diling Zhu, Henrik Lemke,, Matthieu Chollet, Aymeric Robert, David Fritz, Jim Defever, Jerry Hastings, Paul Montanez, Joseph Robinson, Silke Nelson, Marcin Sikorski, Sanghoon Song (SLAC)
- Harald Sinn (EuXFEL)
- Yuri Shvydko, Stanislav Stoupin (APS)



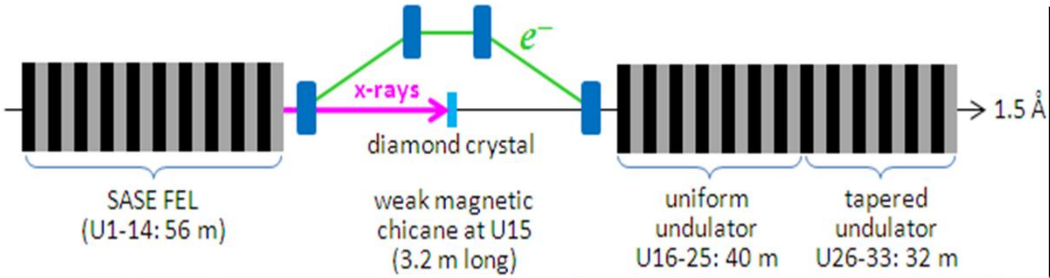
Hard X-Ray Self-Seeding Tests at LCLS

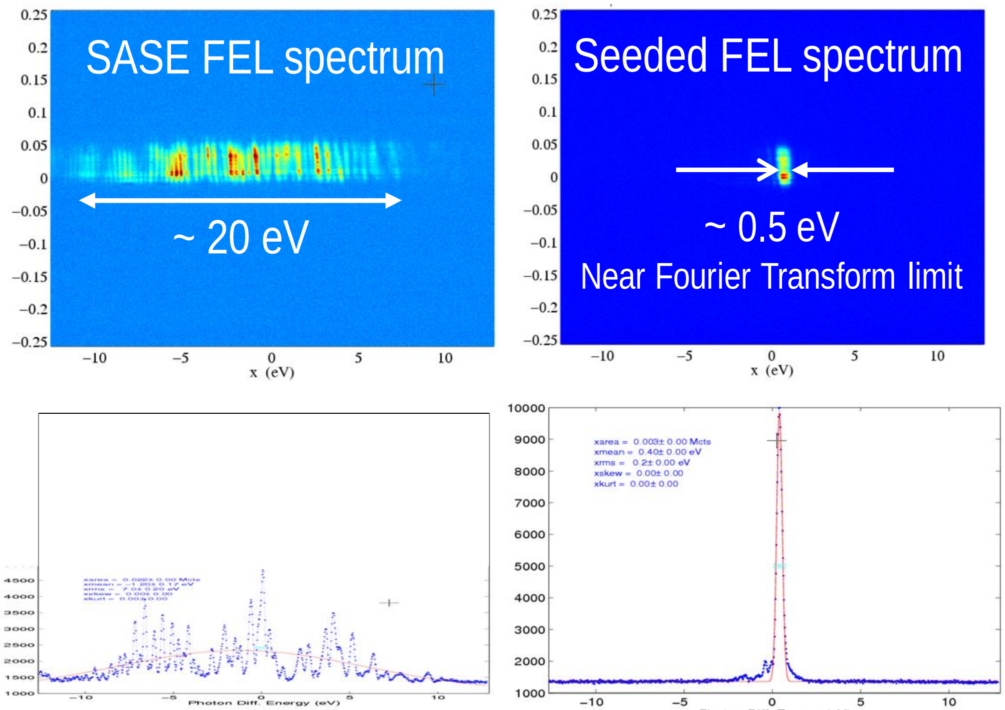




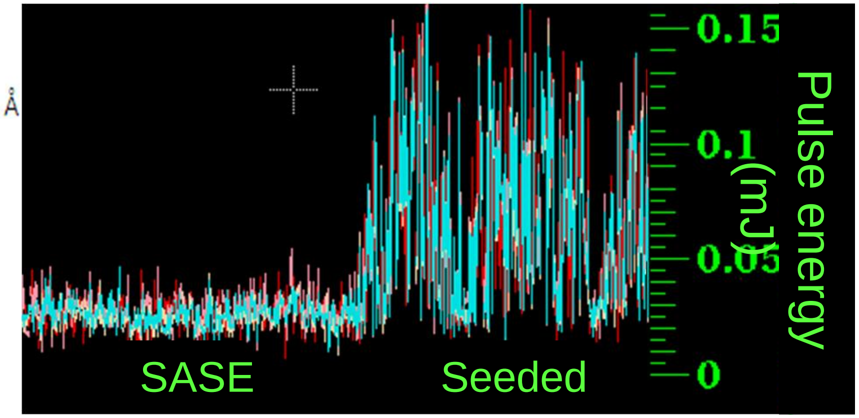
Self-seeded operation of the LCLS
hard X-ray FEL in the long-bunch mode
Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
DESY 10-239

First Demonstration of Hard X-ray Self Seeding at LCLS





SASE and Seeded spectra recorded on single shots. The left panels are SASE with 150 pC, 3kA peak current, un-seeded. The FWHM of the SASE spectrum is 0.2 % Bandwidth. The right panels are the seeded beam with the same electron beam parameters. The FWHM of the seeded beam is 0.5 eV (5×10^{-5} bandwidth)



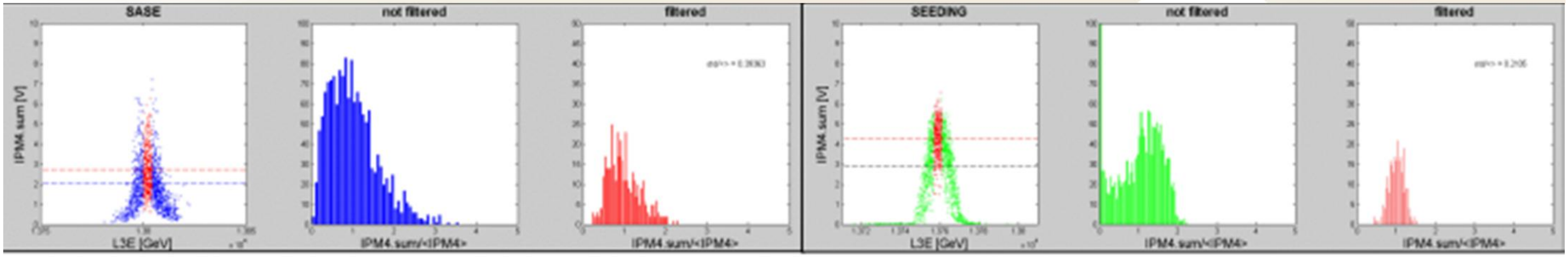
Single shot pulse energy from the gas detectors with 40pC charge

- J. Amman, et al., "Demonstration of self-seeding in a hard-X-ray free-electron laser," Nature Photonics, DOI: 10.1038/NPHOTON.2012.180 (2012).
- 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.

SLAC-Argonne-TISNCM Collaboration

Tested at XCS Beamline- Outperforms Best SASE Intensity

SLAC



SASE after Si(111)

<Gas det> =5mJ

4-6 spikes

<I>mono =2V

No FEE spectro

Seeded after Si(111)

<Gas det> =1mJ

4-6 spikes

<I>mono =3.4V

With FEE spectro

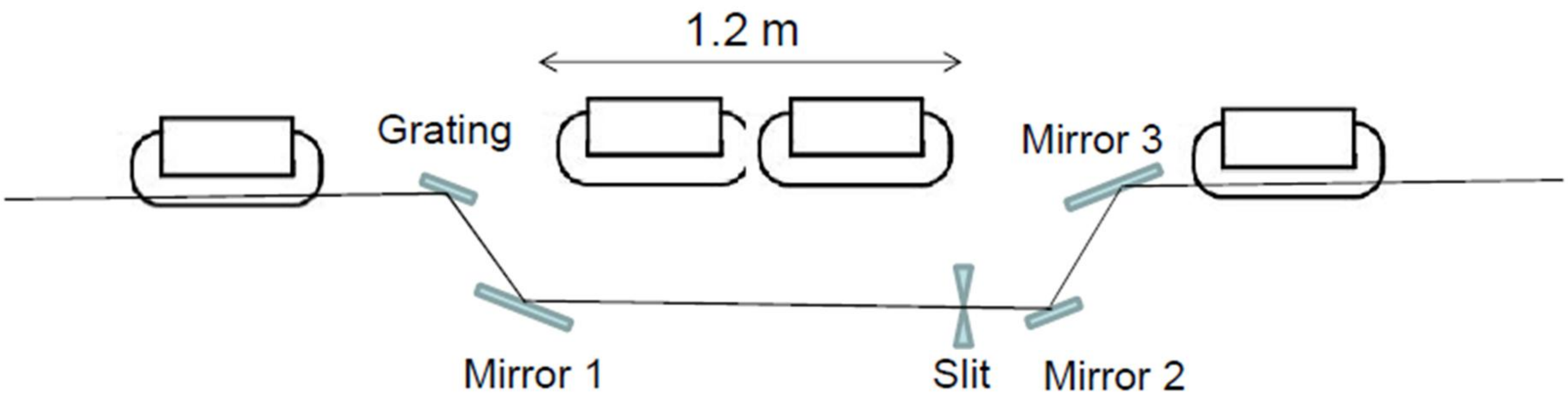
Correction FEE spectro =0.7

$$\frac{\langle I\rangle_{\text{seeded after Si(111)}}}{\langle I\rangle_{\text{SASE after Si(111)}}} = \frac{3.4/0.7}{2} = 2.4$$

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

Soft X-Ray Self-Seeding

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

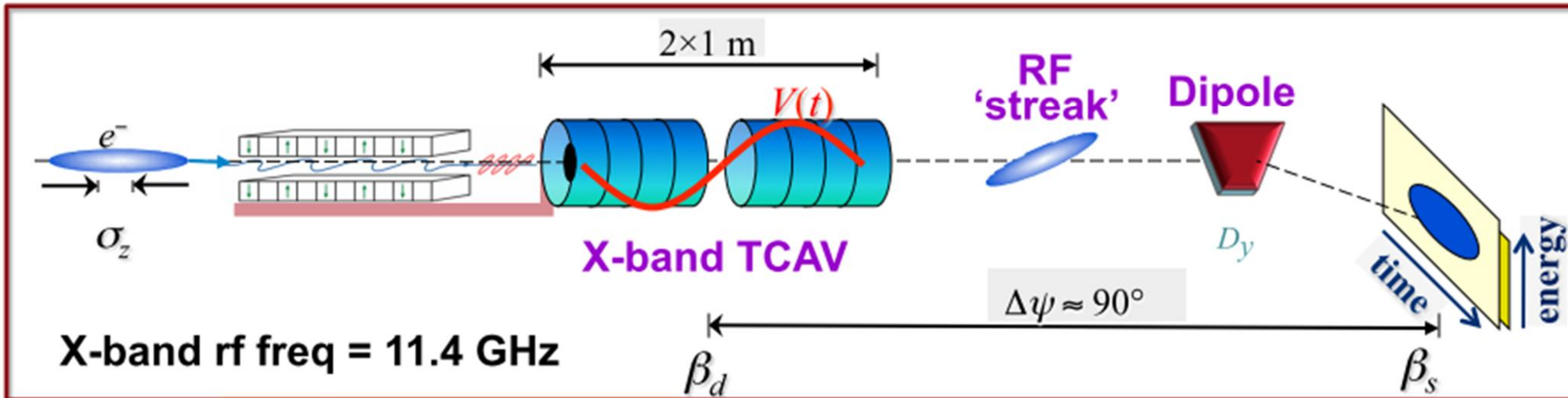


- Fit within the length of one undulator module 4 m.
- Photon energy range 400 - 1000 eV.
- X-ray and electron delay varies from 660 - 850 fs.
- Resolving power from 7800 (400 eV) to 4800 (1000 eV).

P. Heimann

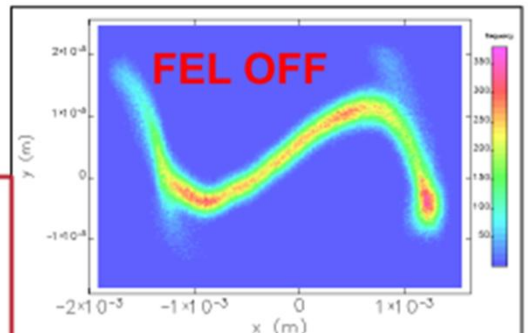
X-band Transverse Cavity (*XTCAV*)

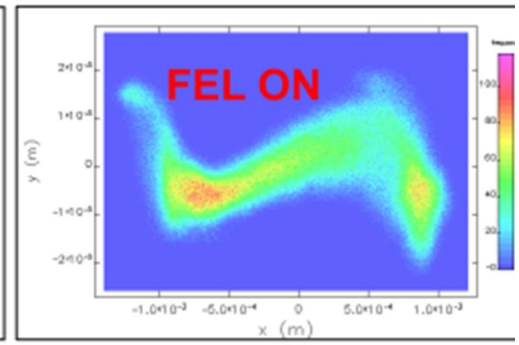
fs electron and x-ray temporal diagnostics – **project started in FY11**

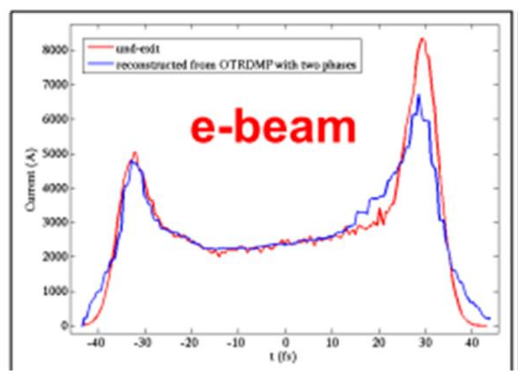


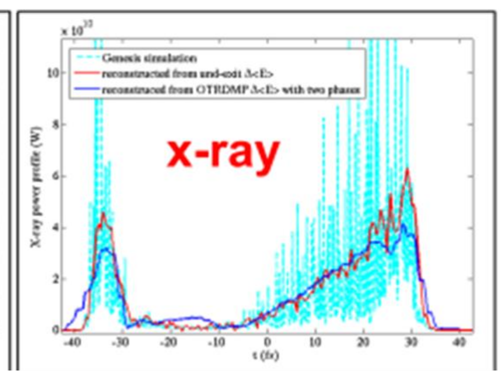
resolution $\propto \dfrac{\lambda_{rf}}{V_0}\sqrt{E\,\dfrac{\varepsilon_{N,x}}{\beta_x(s_0)}}$

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



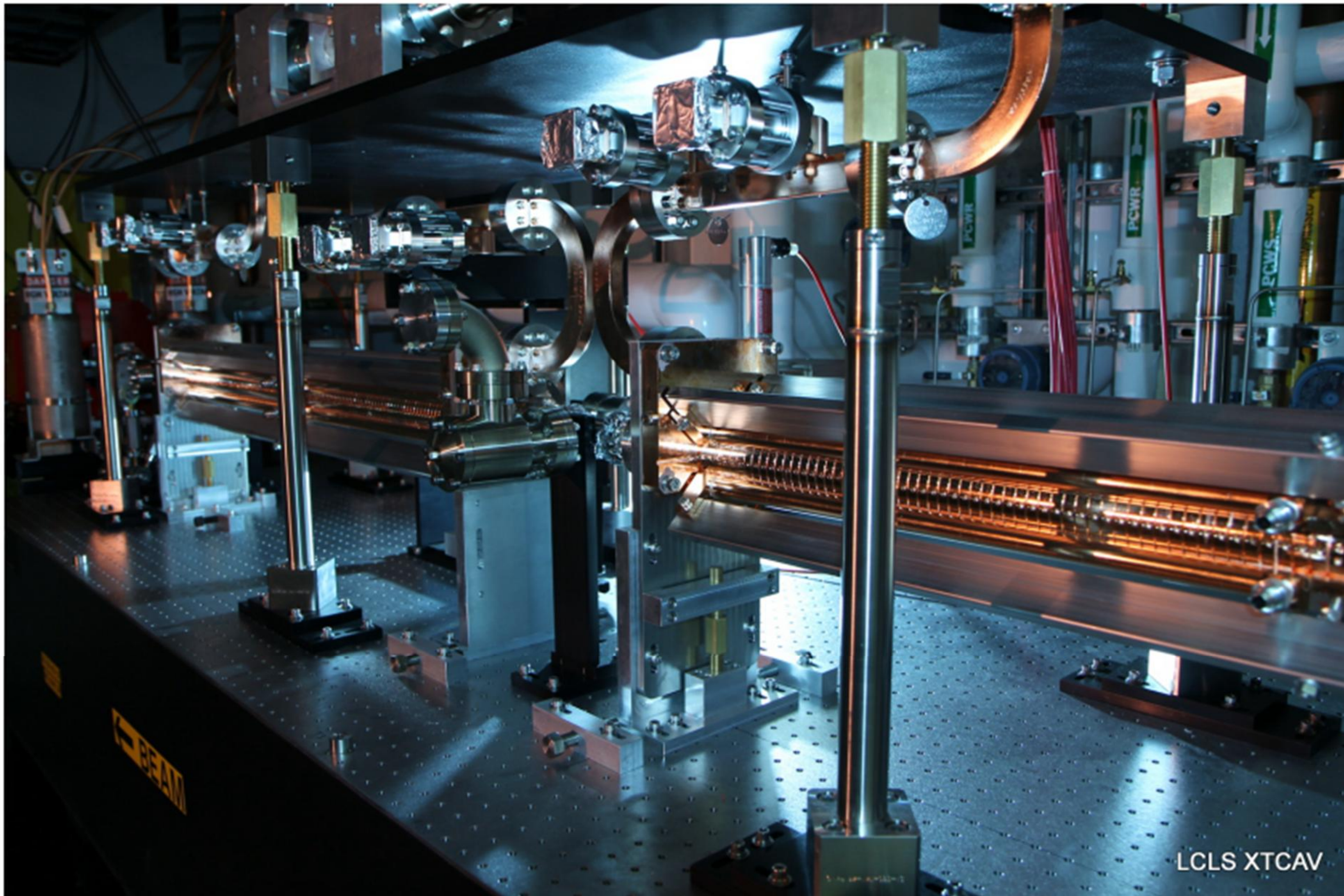






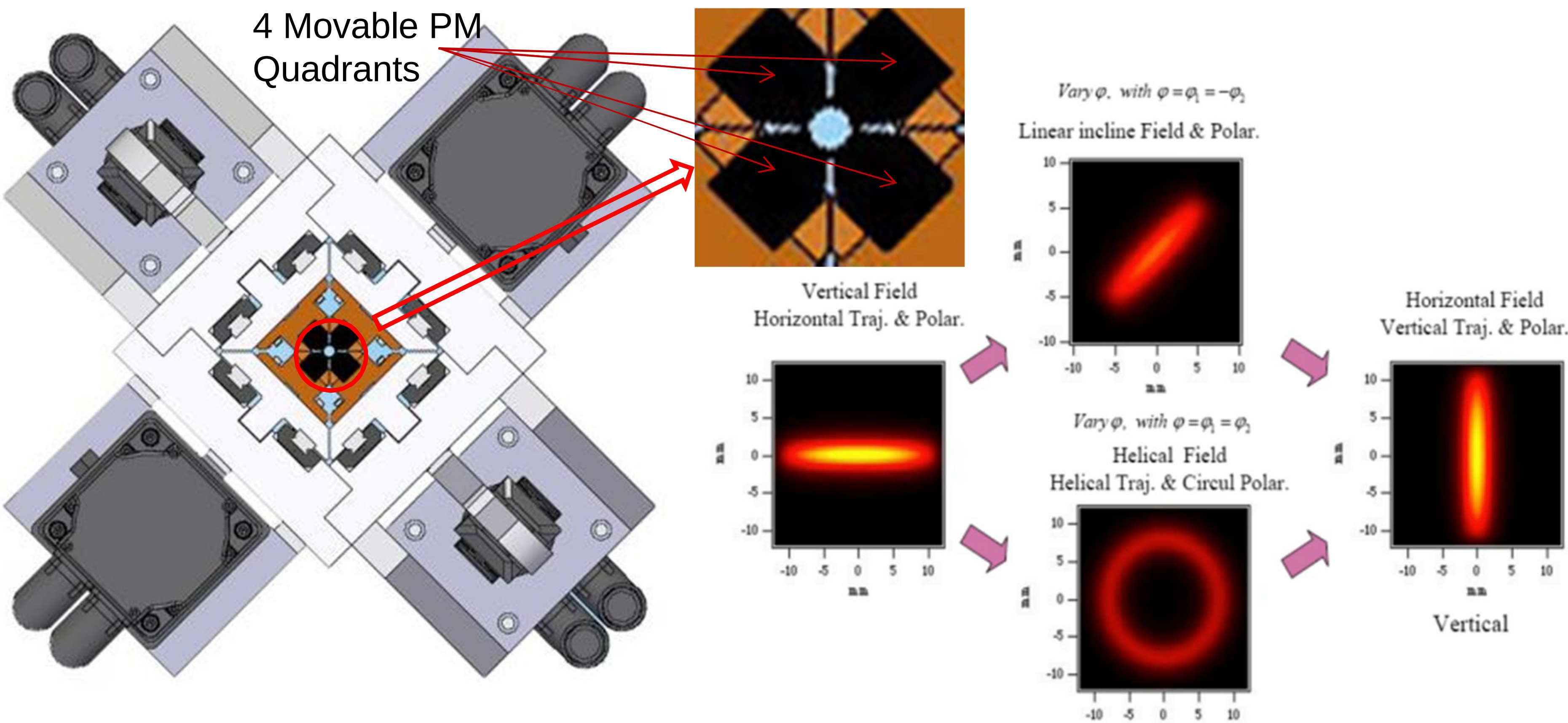
Y. Ding
P. Krejcik

Transverse cavity installed



Variable Phase Undulator for Polarization Control & Terawatt

Proof of principle: autumn 2013



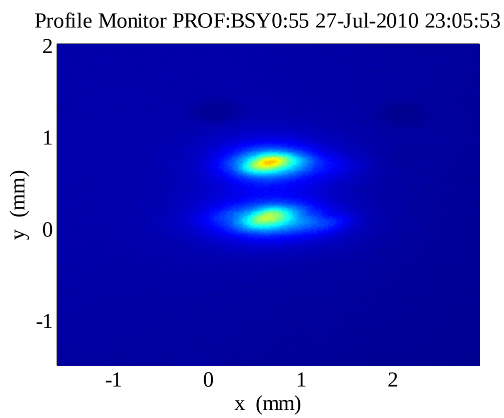
- Four independent quadrants of permanent magnets move longitudinally at fixed gap.
- By sliding the arrays it is possible to control the K from full to zero
- and to control the polarization of the radiation emitted

Multi Bunches – Multiple Lasers – Multiple User

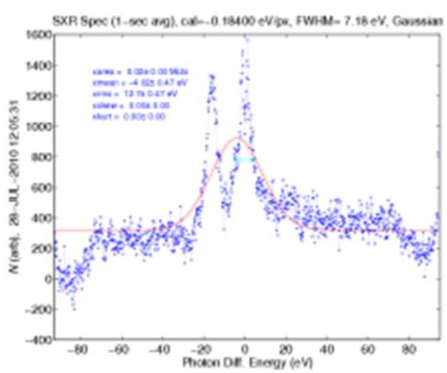
- Two bunch lasing demonstrated 07/2010, 8.4 ns separation, 250 pC
- Single laser, 2 pulses from pulse stacker

- 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

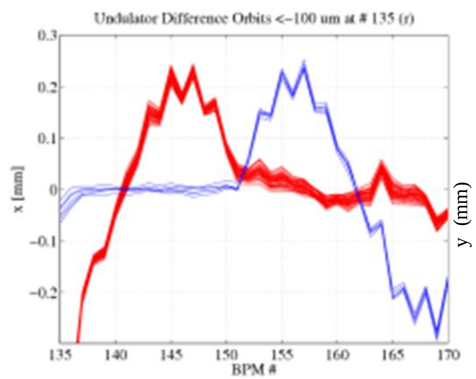
Two bunches separated by TCAV3



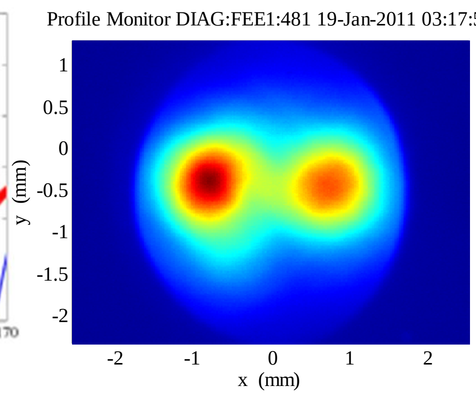
Two X-ray pulses separated energy



Two bunches separated orbit

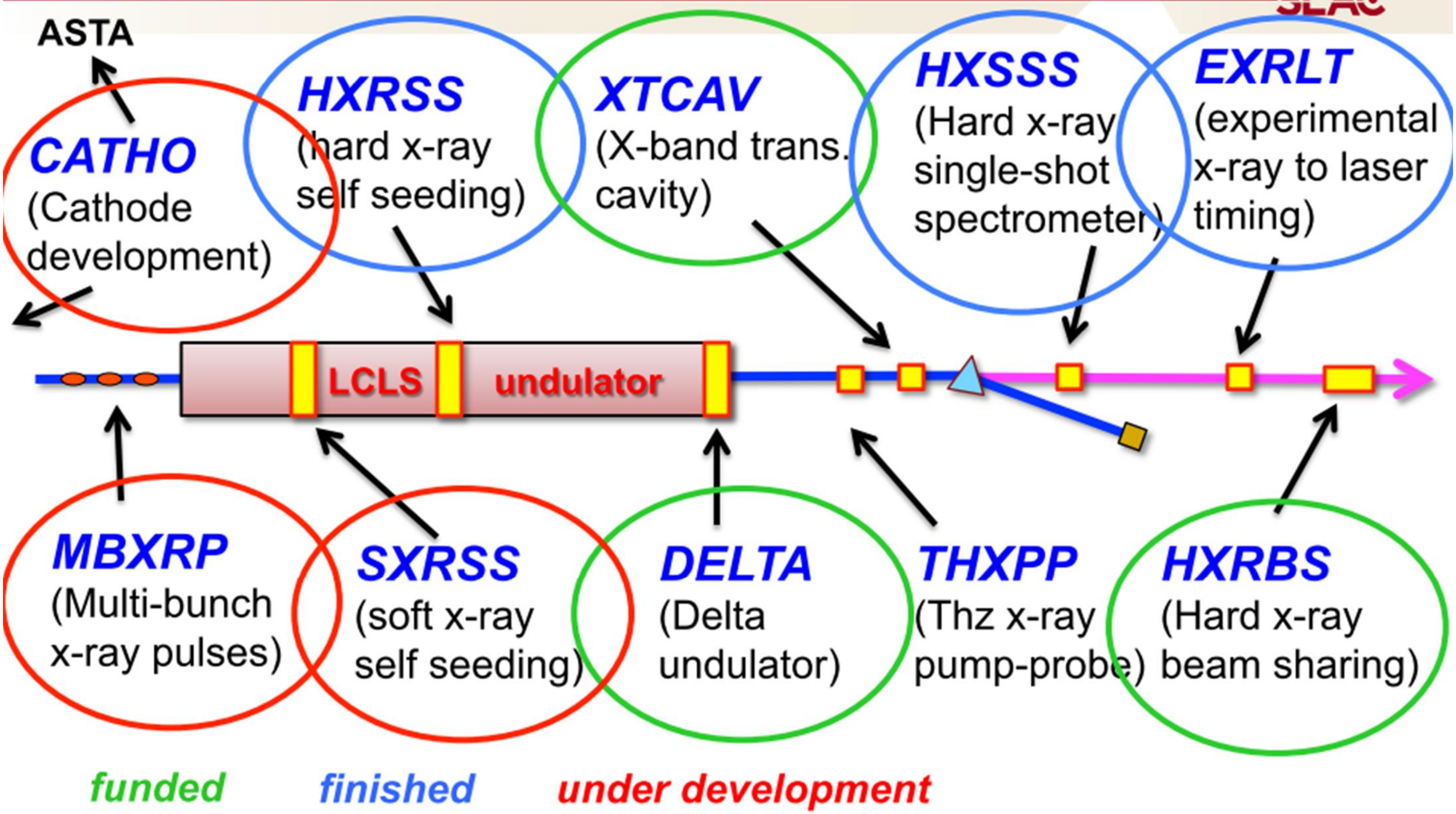


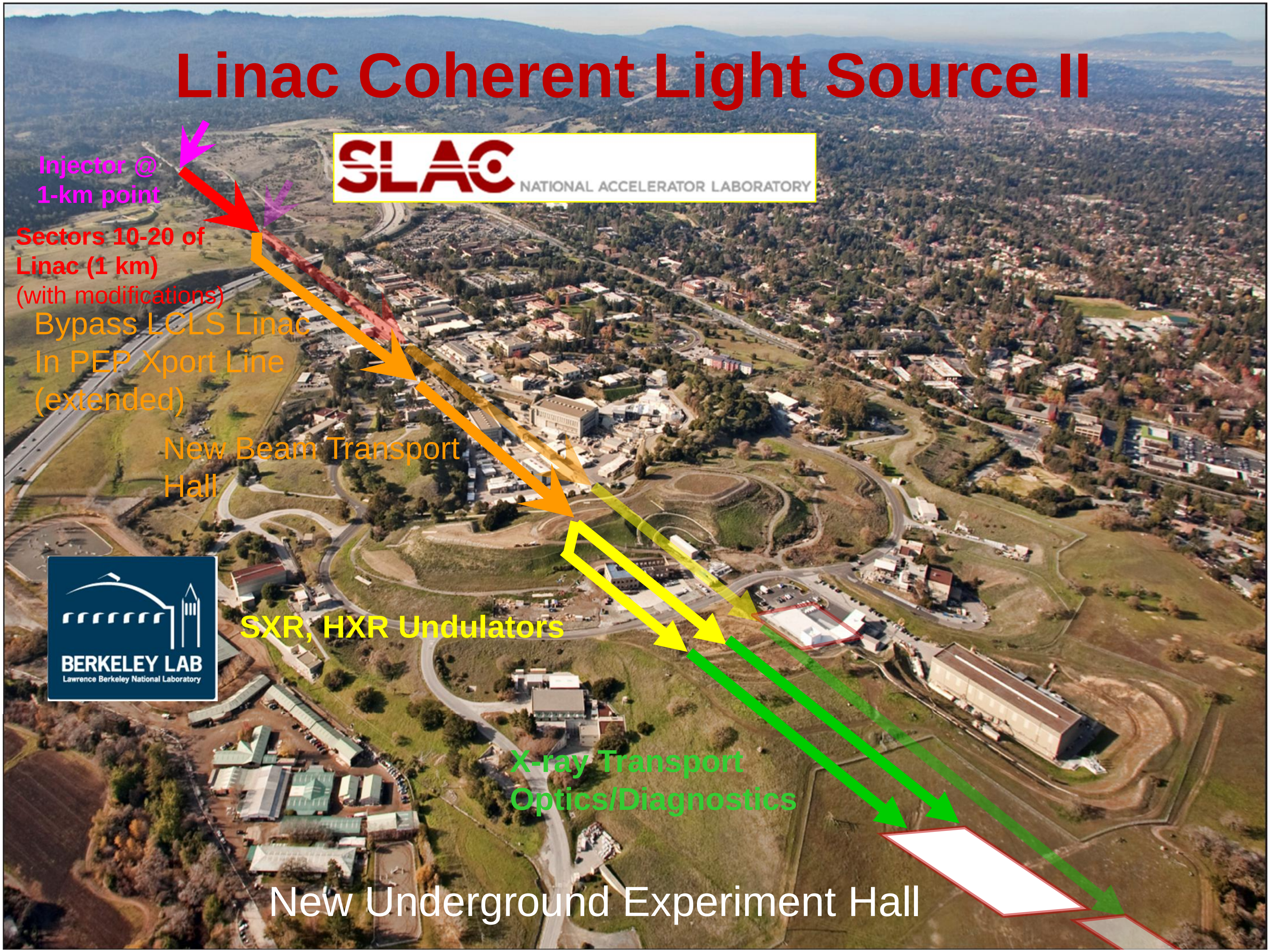
Two X-ray pulses separated transv



F.-J. Decker et al.

LCLS FEL R&D

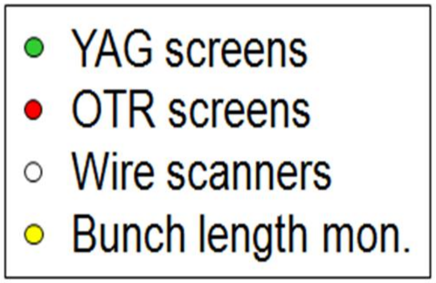

ASTA
CATHO
(Cathode development)
HXRSS
(hard x-ray self seeding)
XTCAV
(X-band trans. cavity)
HXSSS
(Hard x-ray single-shot spectrometer)
EXRLT
(experimental x-ray to laser timing)
LCLS undulator
MBXRP
(Multi-bunch x-ray pulses)
SXRSS
(soft x-ray self seeding)
DELTA
(Delta undulator)
THXPP
(Thz x-ray pump-probe)
HXRBS
(Hard x-ray beam sharing)
funded
finished
under development

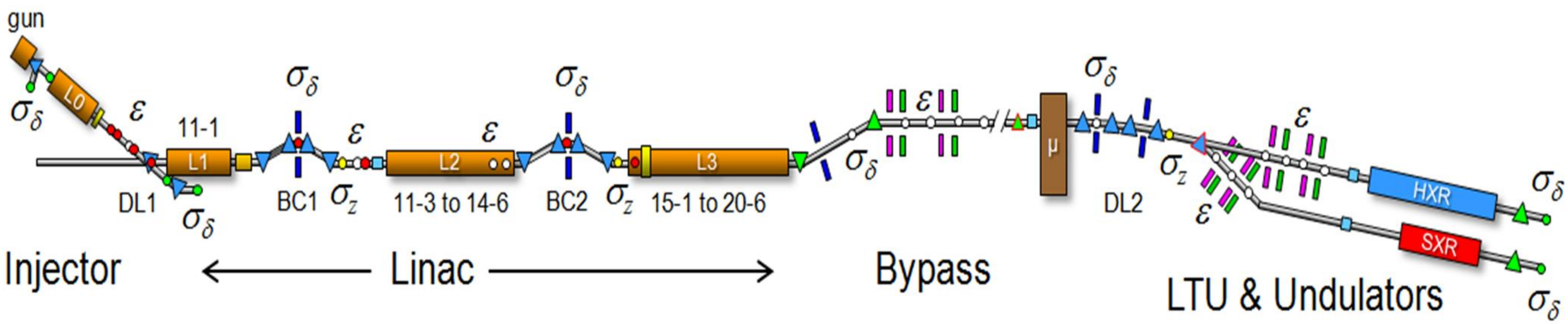

Linac Coherent Light Source II
SLAC NATIONAL ACCELERATOR LABORATORY
Injector @
1-km point
Sectors 10-20 of
Linac (1 km)
(with modifications)
Bypass LCLS Linac
In PEP Xport Line
(extended)
New Beam Transport
Hall
BERKELEY LAB
Lawrence Berkeley National Laboratory
SXR, HXR Undulators
X-ray Transport
Optics/Diagnostics
New Underground Experiment Hall

Overall Layout, LCLS-II

BC-1 moved downstream (375 MeV)

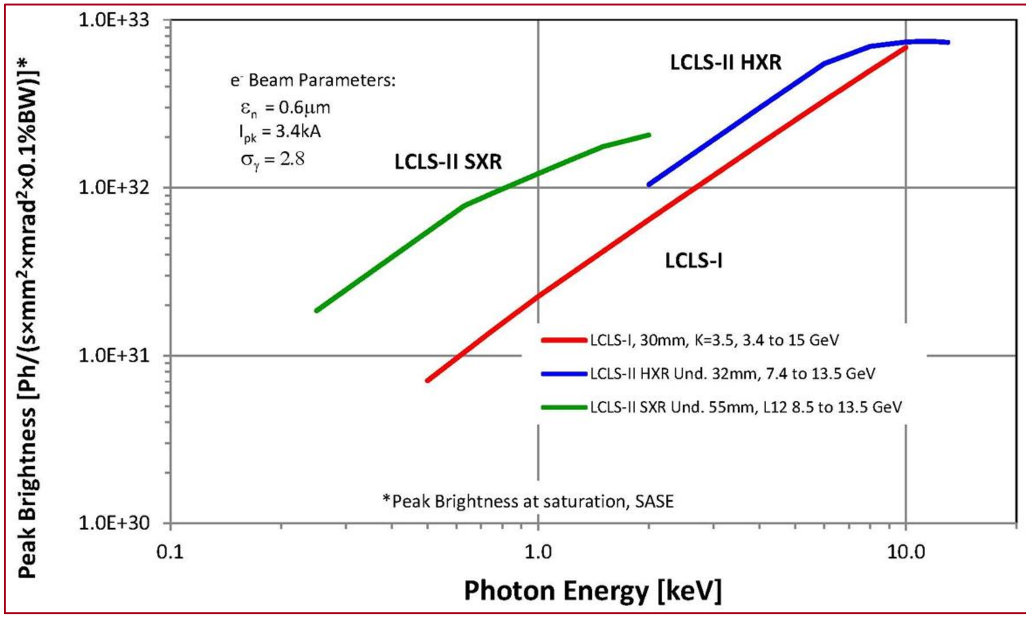
- Less energy jitter
- Compatible with future 360 Hz operation





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



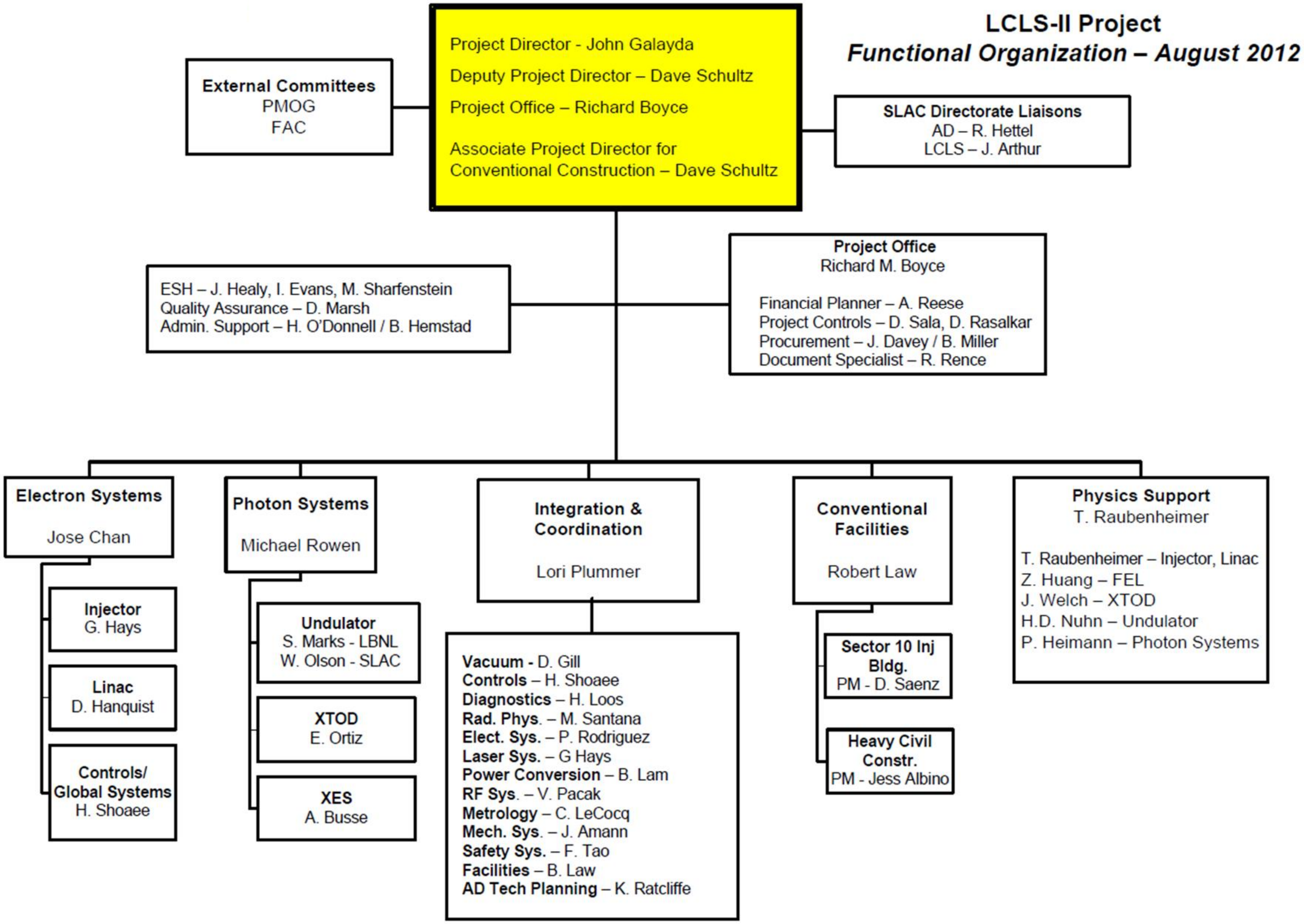
Tuning the X-Rays with both undulator gap and Electron Beam Energy

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 <u>per station</u>
- Future: Room in new experiment hall for up to 6 new instruments

LCLS-II Project Organization

SLAC



Funding/Schedule Overview

Fiscal Year	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17	Total
OPC and Pre-Ops	$1.2	$9.4	$8.0		$0.7		$0.7		$20.0
LLP			$20.0	$20.0					$40.0
Design/ Construction			$ 2.0	$43.5	$80.3	$94.0	$105.3	$19.9	$345.0
Total Project Cost	**$1.2**	**$9.4**	**$30.0**	**$63.5**	**$81.0**	**$94.0**	**$106.0**	**$19.9**	**$405.0**

New funding profile guidance: +14.7 +$10.0 -$4.8 -$19.9

Level I Baseline Milestones	Schedule
CD-0, Approve Mission Need	4/22/10 (actual)
CD-1, Approve Alternative Selection and Cost Range	10/14/11 (actual)
CD-3a, Approve Long Lead Procurement Baseline and Start of Long Lead Procurements	3/14/2012 (actual)
~~CD-2, Approve Performance Baseline (Review 8/21-23)~~	~~10/31/2012~~
CD-2/CD-3b, Approve Start of Construction	6/30/2013
CD-4, Approve Project Completion	9/30/2019

New Guidance on Funding Profile

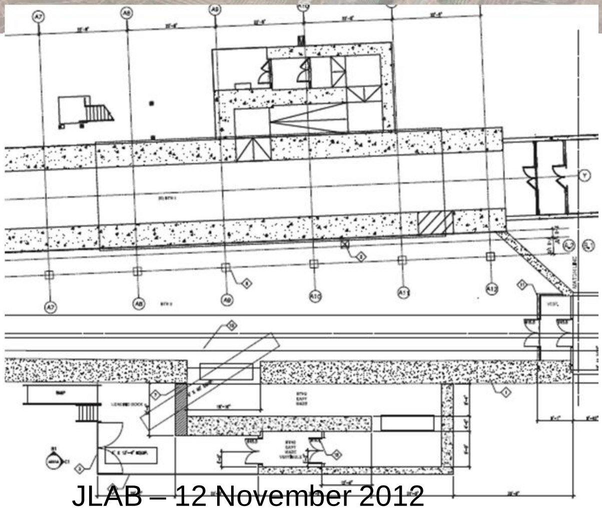
Fiscal Year	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17	Total
OPC and Pre-Ops	$1.2	$9.4	$8.0		$0.7		$0.7		$20.0
LLP			$20.0	$20.0					$40.0
Design/ Construction			$ 2.0	$43.5	$95.0	$104.0	$100.5	$0	$345.0
Total Project Cost	**$1.2**	**$9.4**	**$30.0**	**$63.5**	**$95.7**	**$104.0**	**$101.2**	**$0**	**$405.0**

CF Construction:

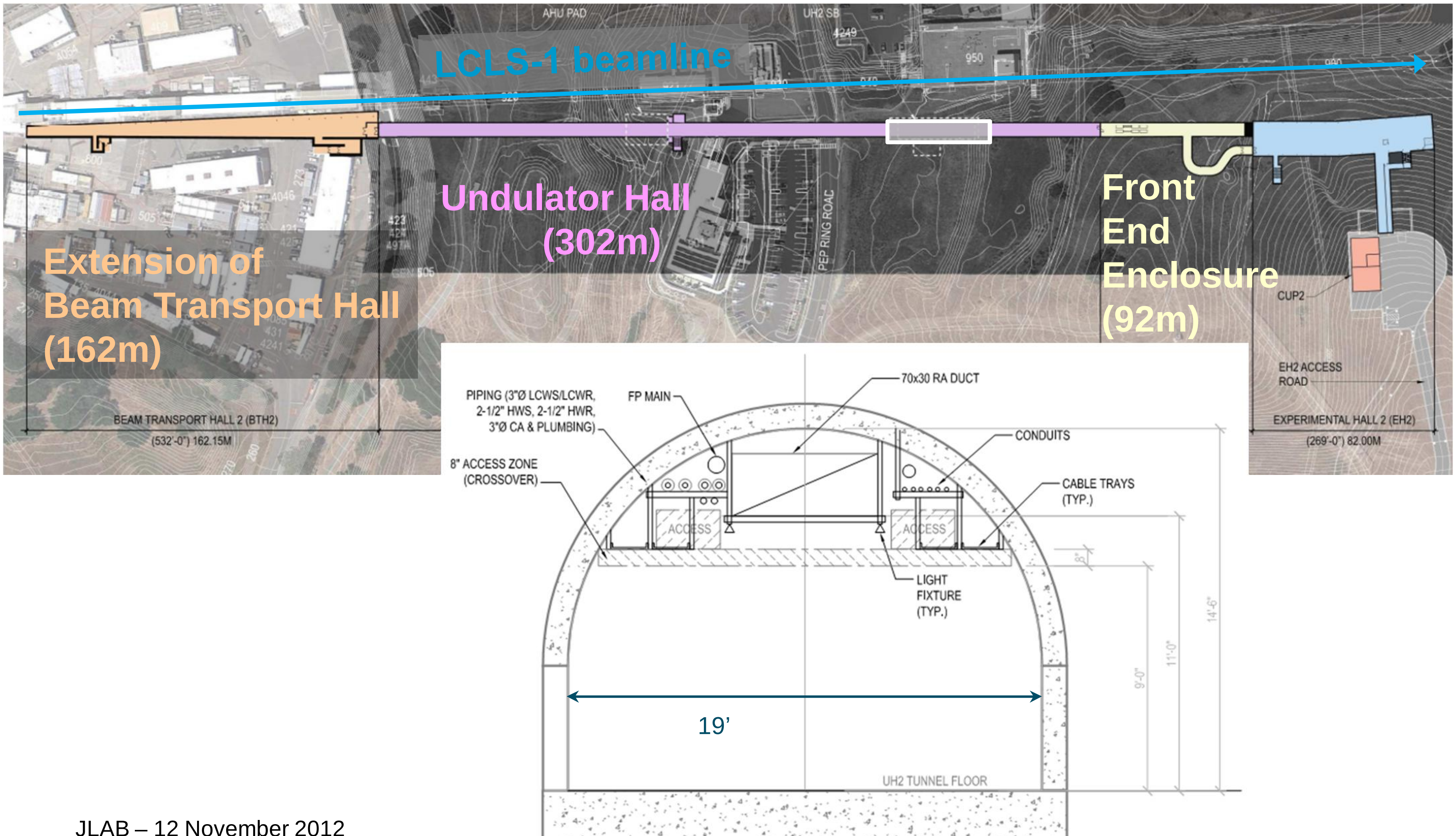
- Should enable acceleration of schedule
  - Undulators, x-ray optics and x-ray experimental systems are candidates for acceleration
  - May gain 6 months on “First Light” milestone

LCLS-II Heavy Civil Construction

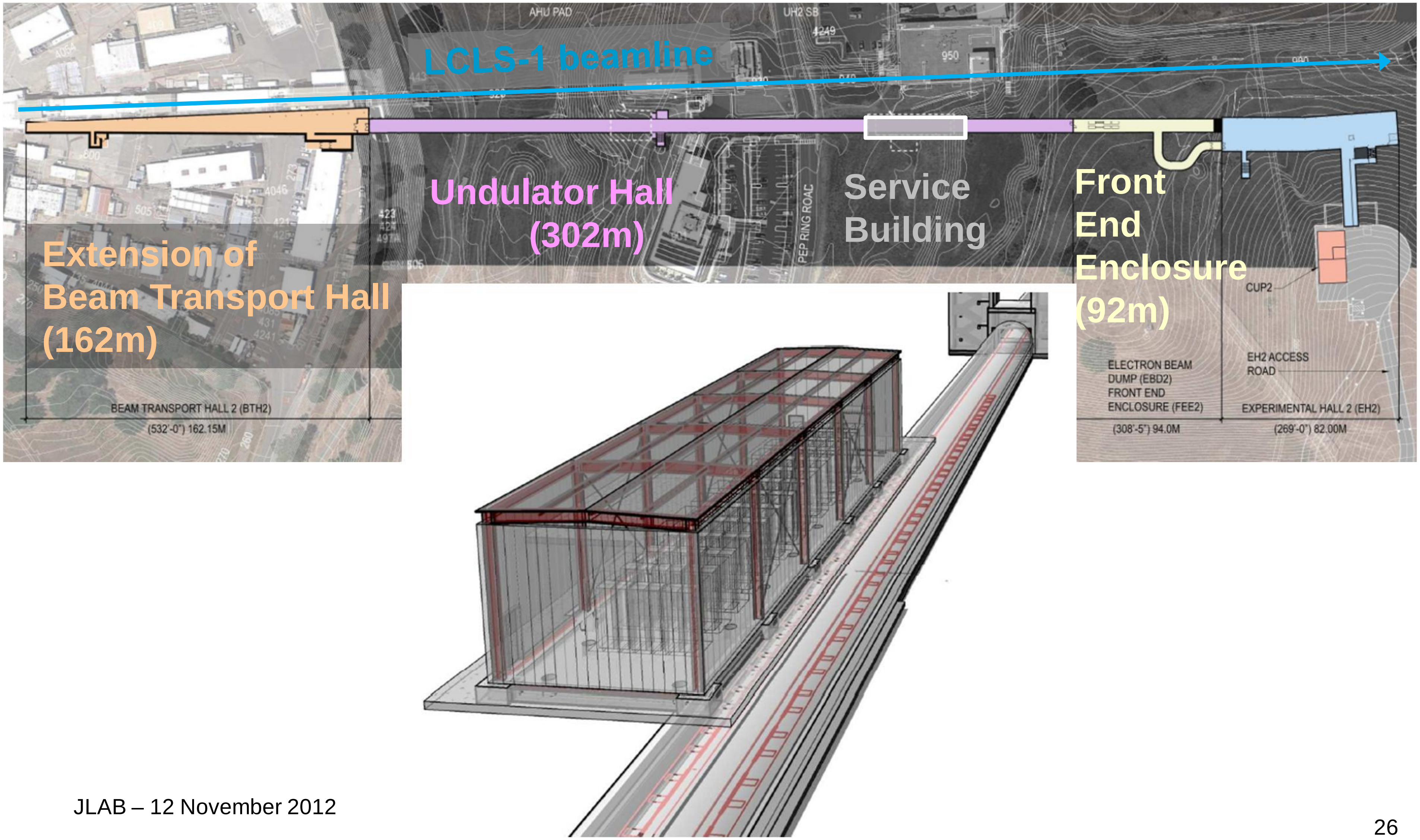
SLAC



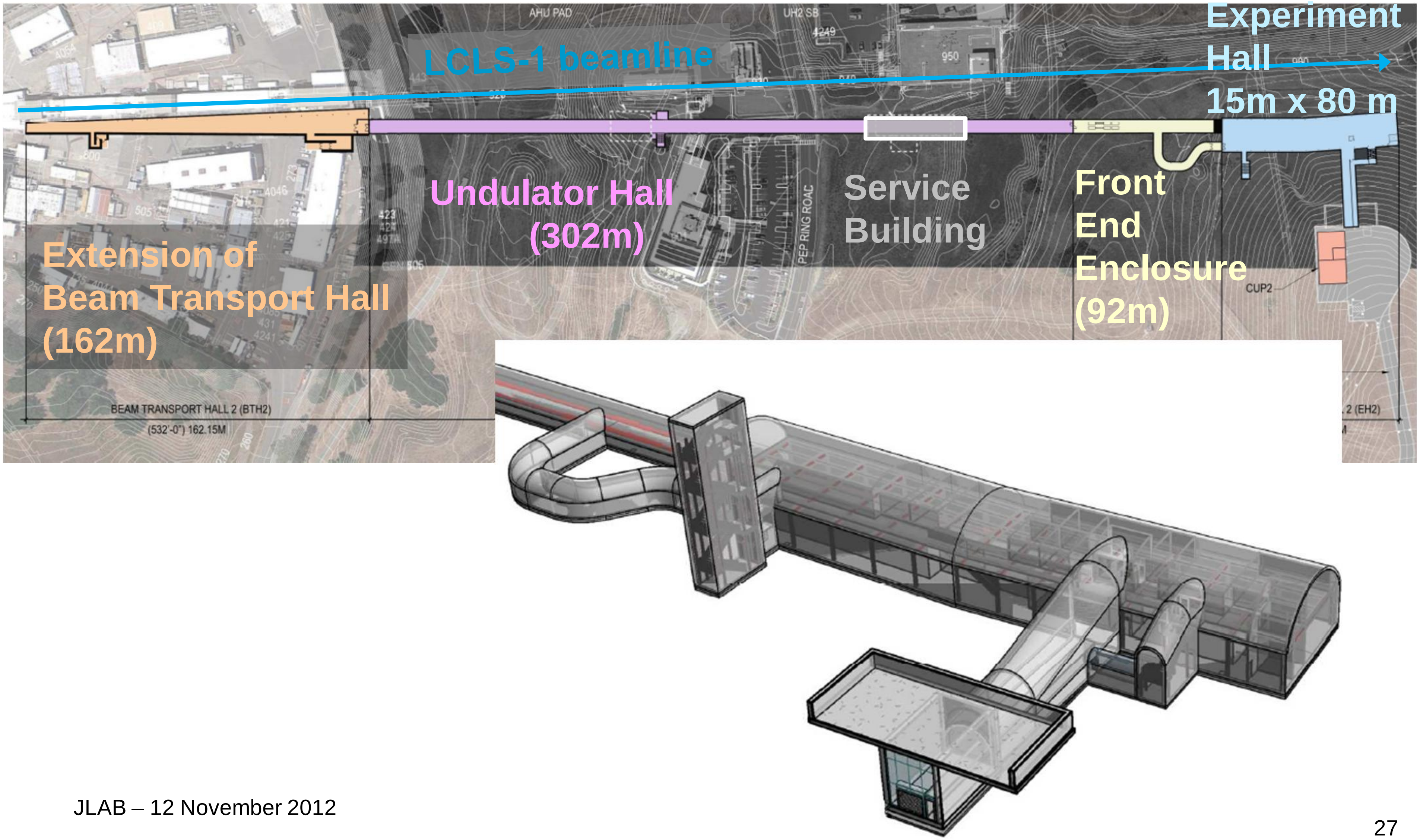
LCLS-II Heavy Civil Construction



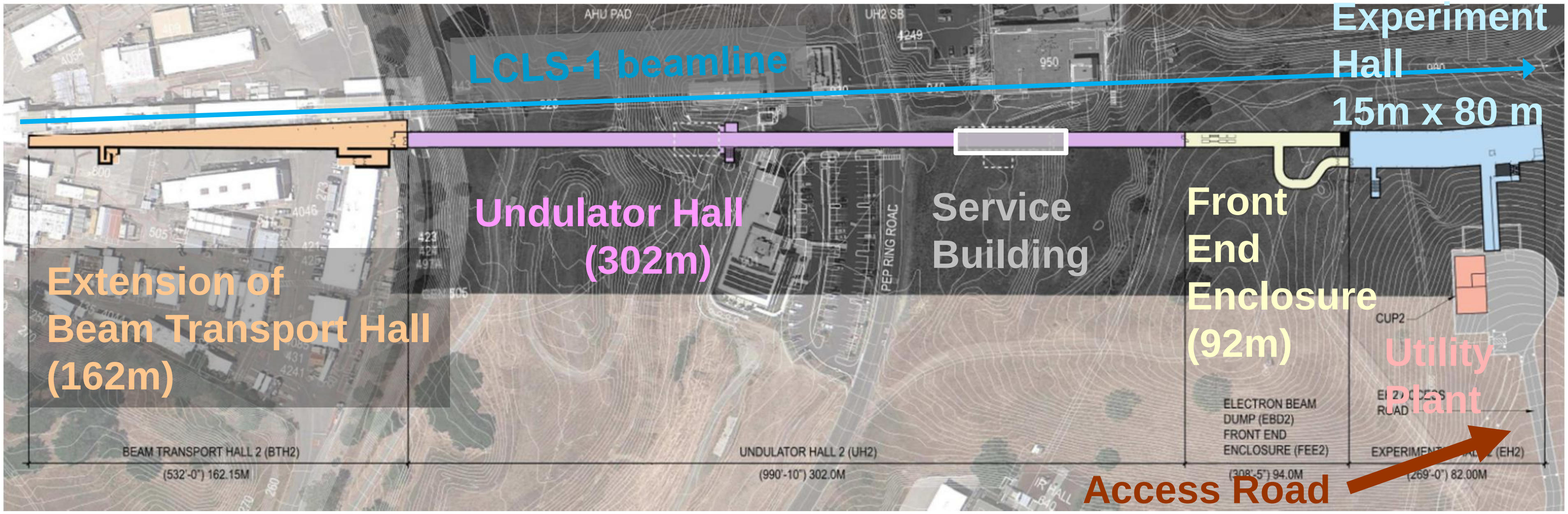
LCLS-II Heavy Civil Construction



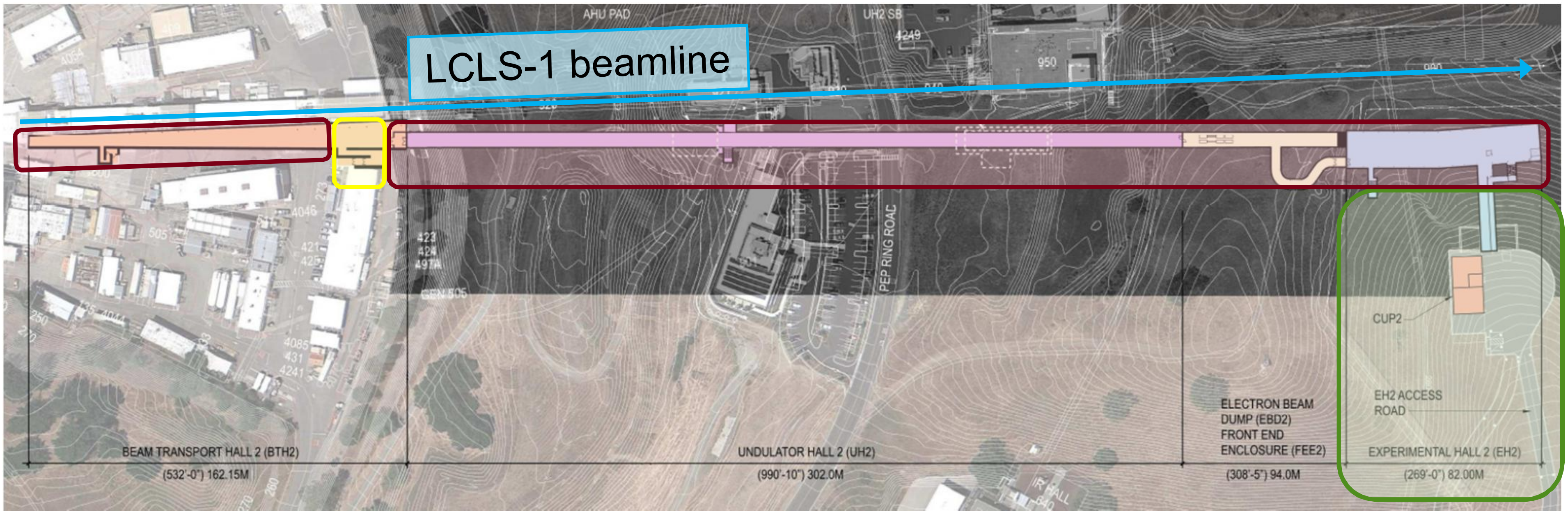
LCLS-II Heavy Civil Construction



LCLS-II Heavy Civil Construction



LCLS-II Schedule - 6-month LCLS outage



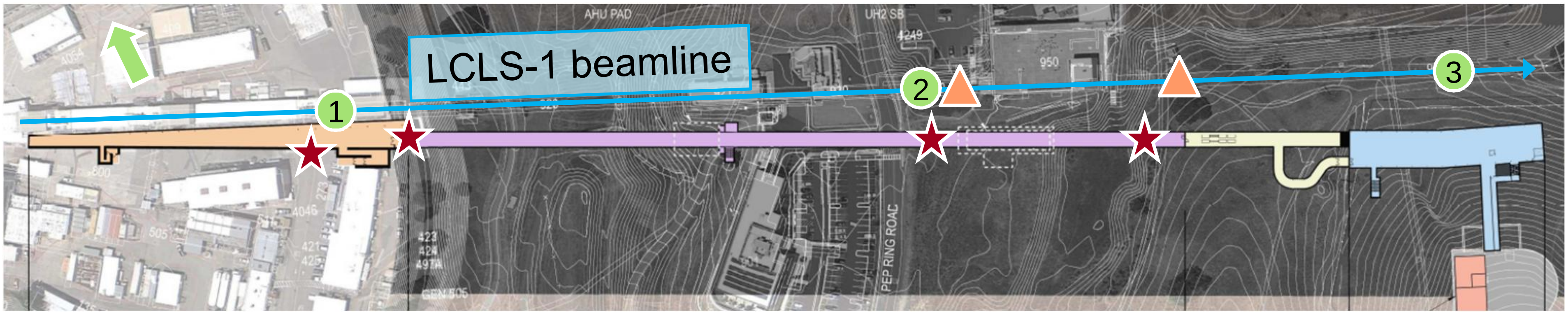
Post-down work:
Finish BTH2 concrete
Finish FEE & EH2 concrete
Construct EH2 2nd floor

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

Pre-down work:
Site work
Start Access Tunnel

Vibration studies with LCLS operating, Aug. 1st

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



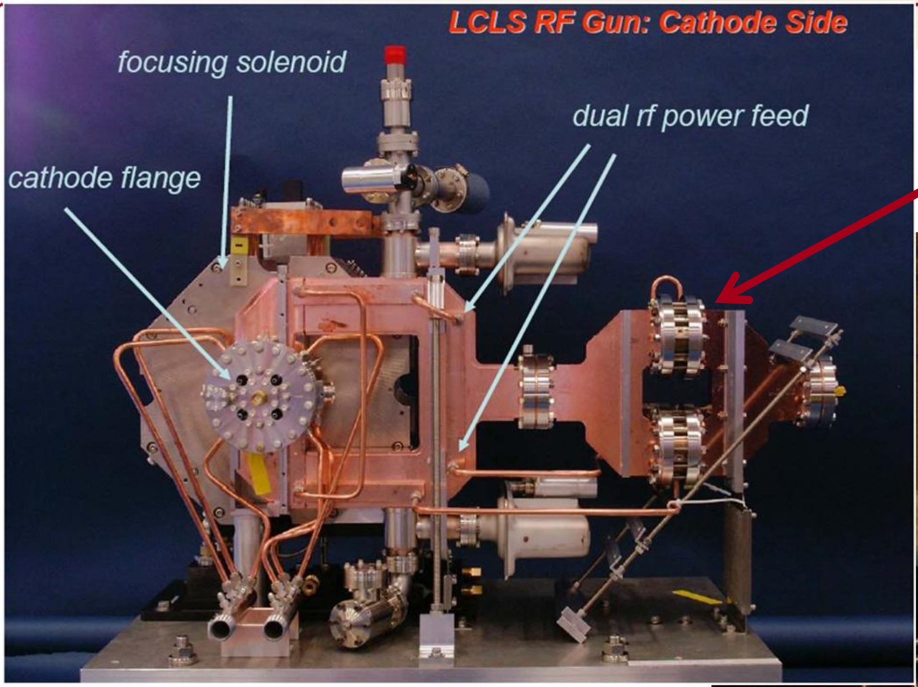
- Instrumented area with 20 accelerometers and seismometers
- No effect seen on SPEAR beams
- 1 No effect seen on LCLS electron beam
- 2 No effect seen of LCLS x-ray beam at FEE direct imager
- 3 No distinguishable effect seen at XCS experiment in the FEH
  - Other effects may mask any construction-driven beam motion
- Impulses detected on FEE & XRT mirrors – under analysis

LCLS-II Long-Lead Acquisitions: Construction Underway

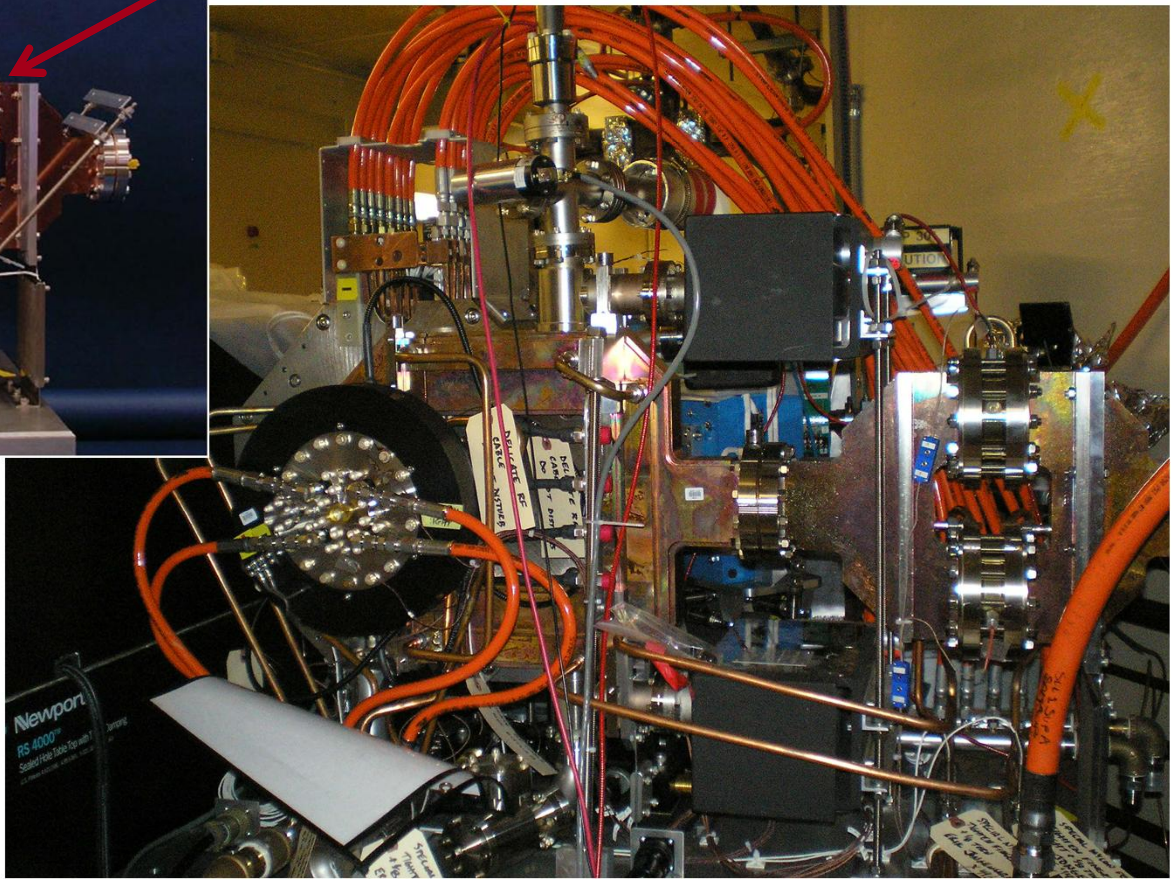
SLAC

- <u>CD-3a (2 x $20M in 2012-2013) approved for:</u>
  - 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

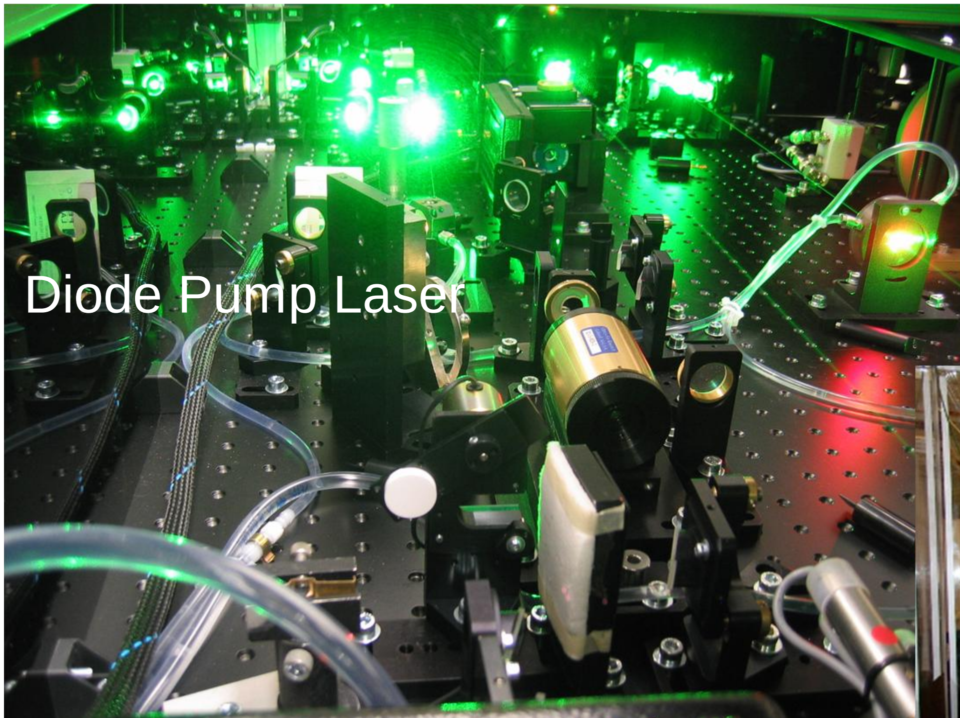


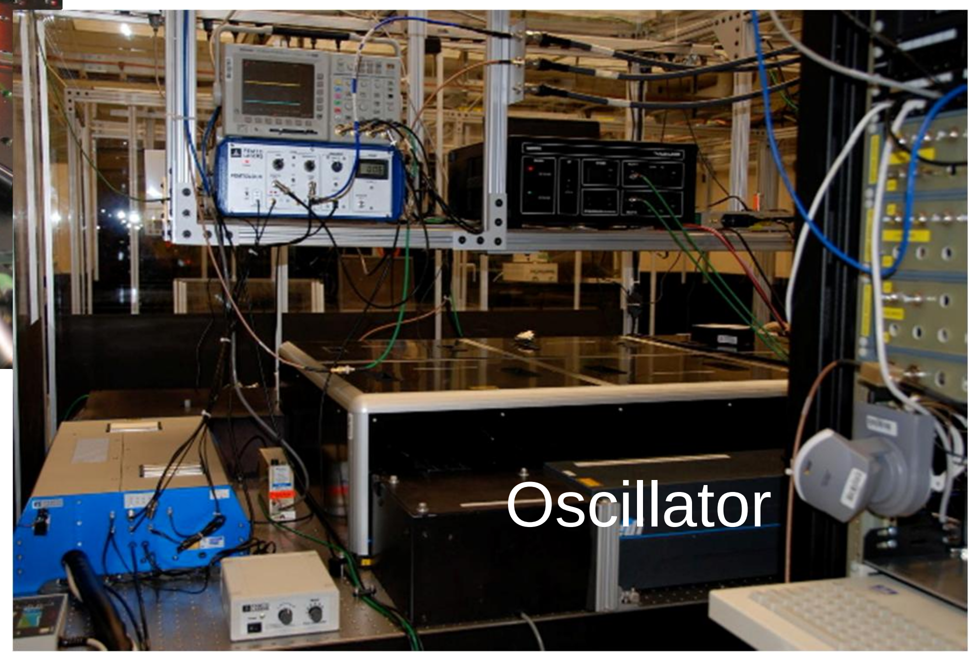
This time, a *single* ceramic window



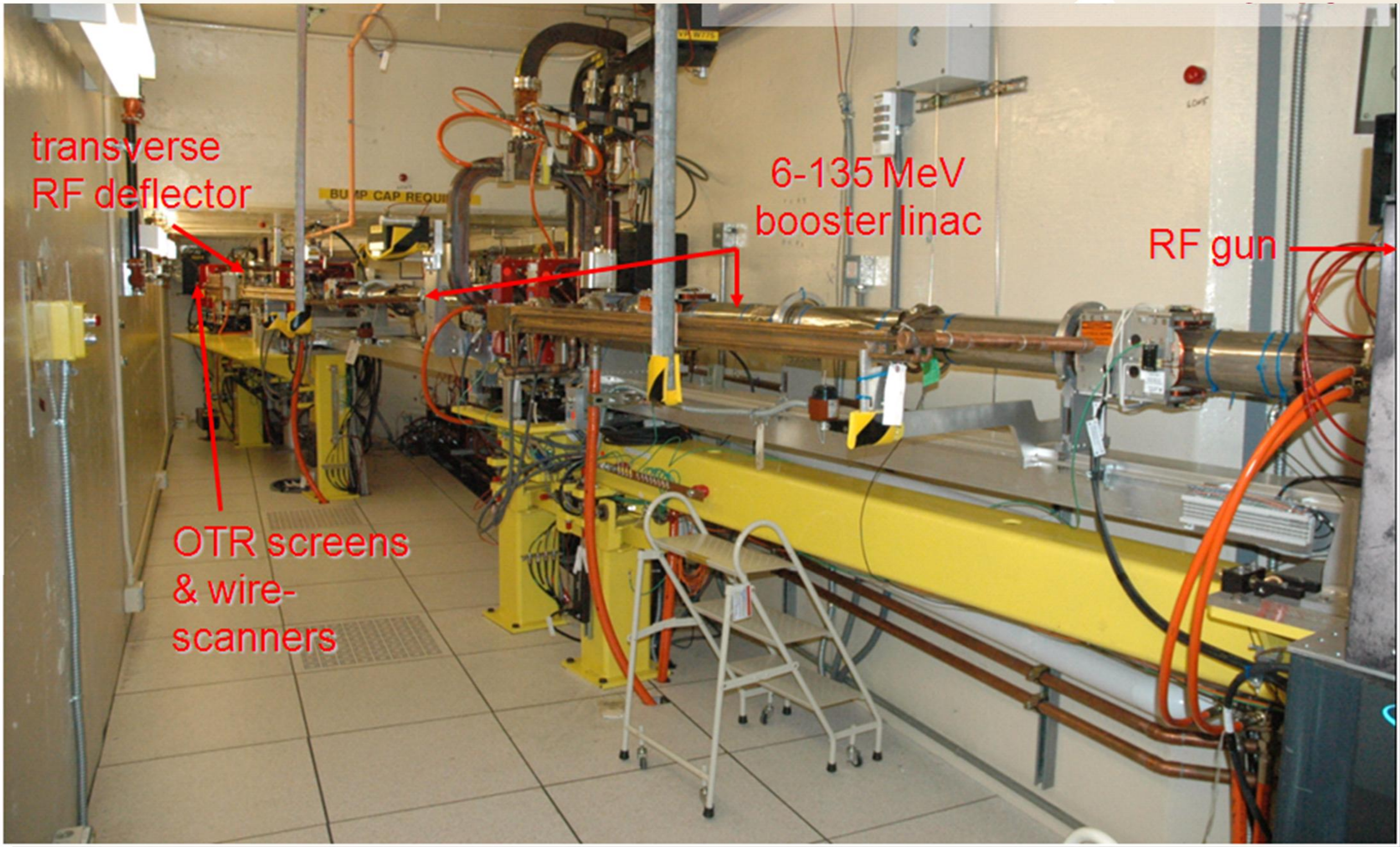
Photocathode Laser- will be identical to many lasers in use now at LCLS

Copper cathode:
QE>$1x10^{-4}$,
2X original design spec
lifetime: years

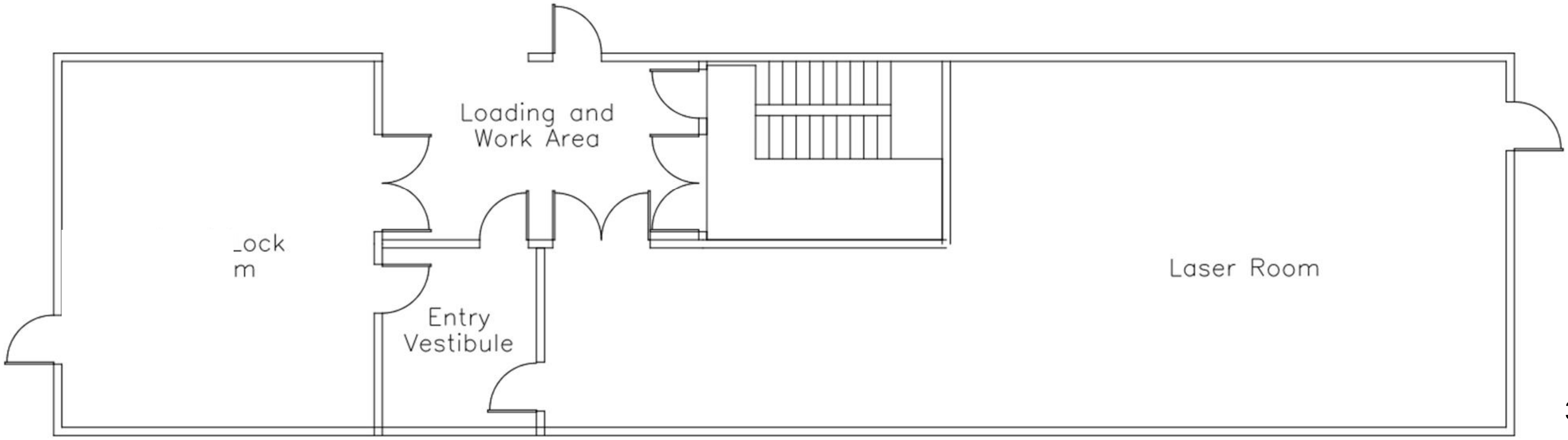




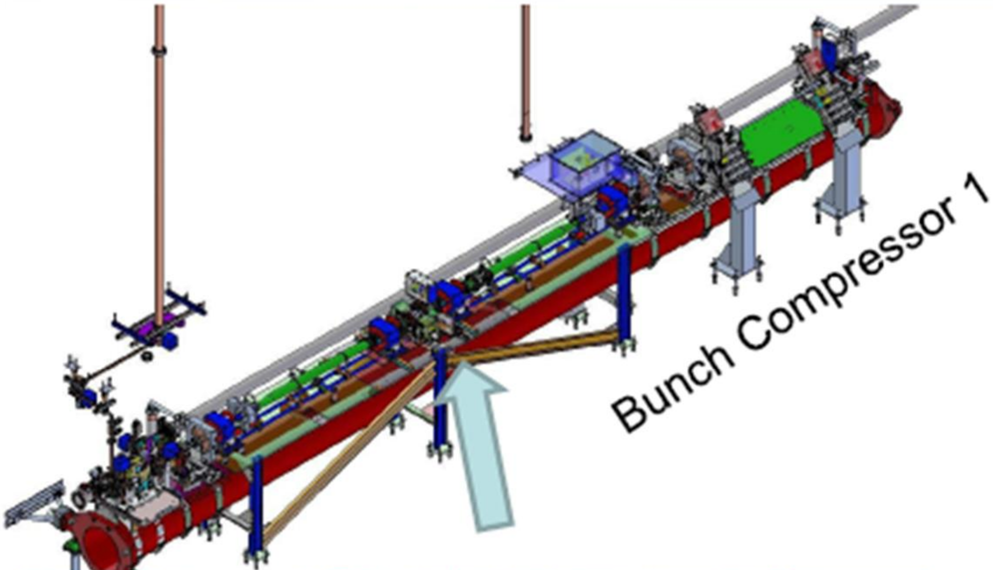
Injector & Laser Heater, Same as LCLS

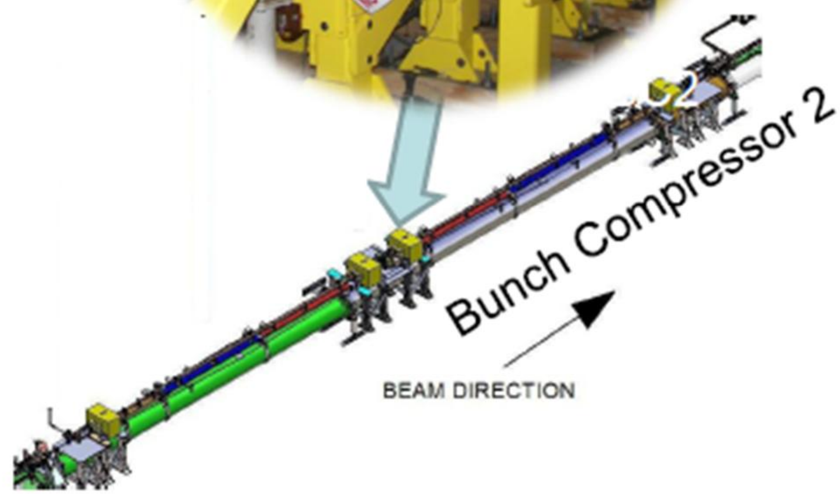


Sector 10 Laser Annex Construction Underway



LCLS-II Linac
BC1 and BC2, Extensive Re-Use of Designs

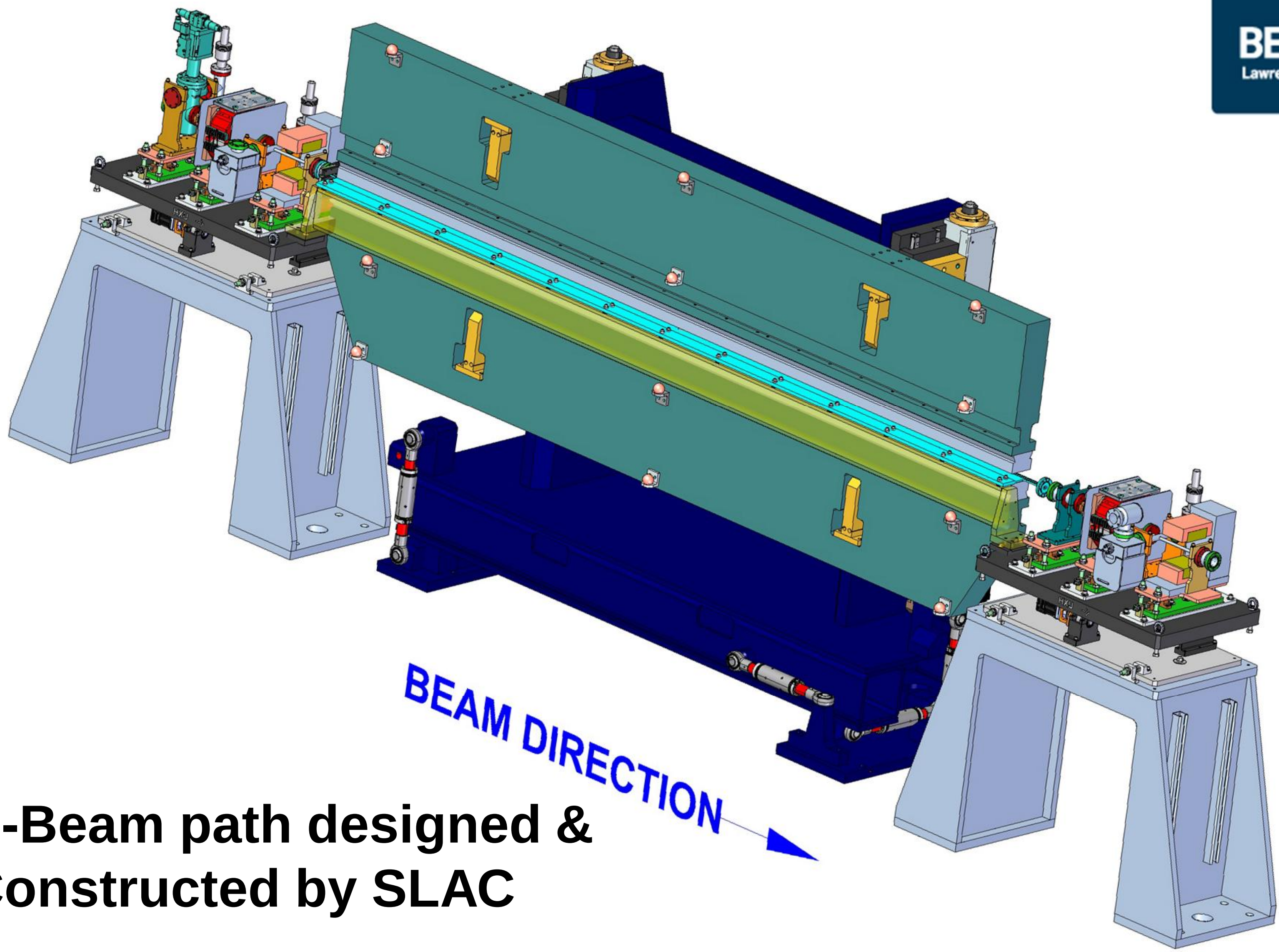




LCLS-1 Bypass, Re-Use PEP-II Transport Line

SLAC

Undulators Designed & Acquired by

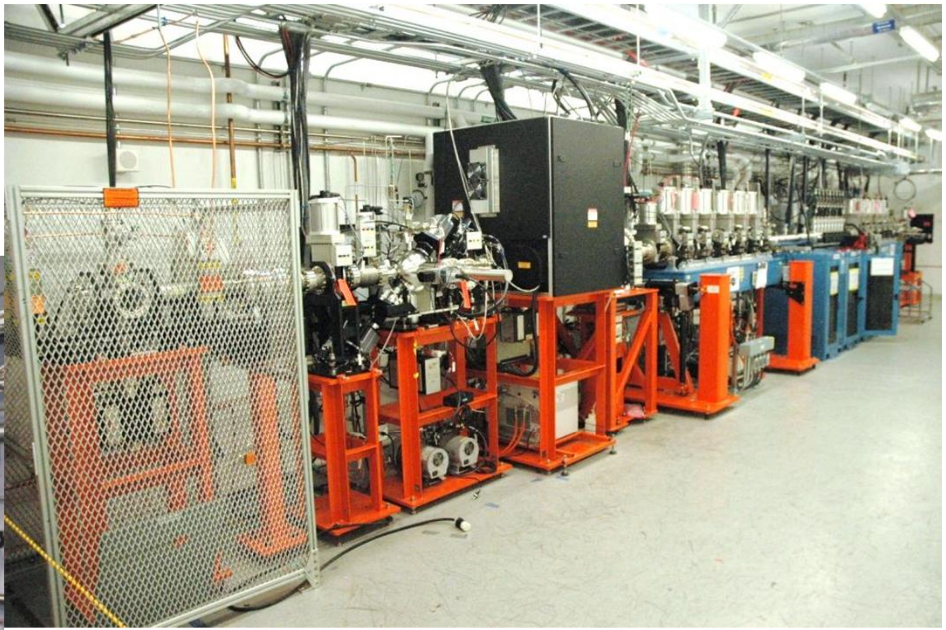


E-Beam path designed & Constructed by SLAC

X-Ray Transport, Optics & Diagnostics
X-Ray Experiment Systems

SLAC

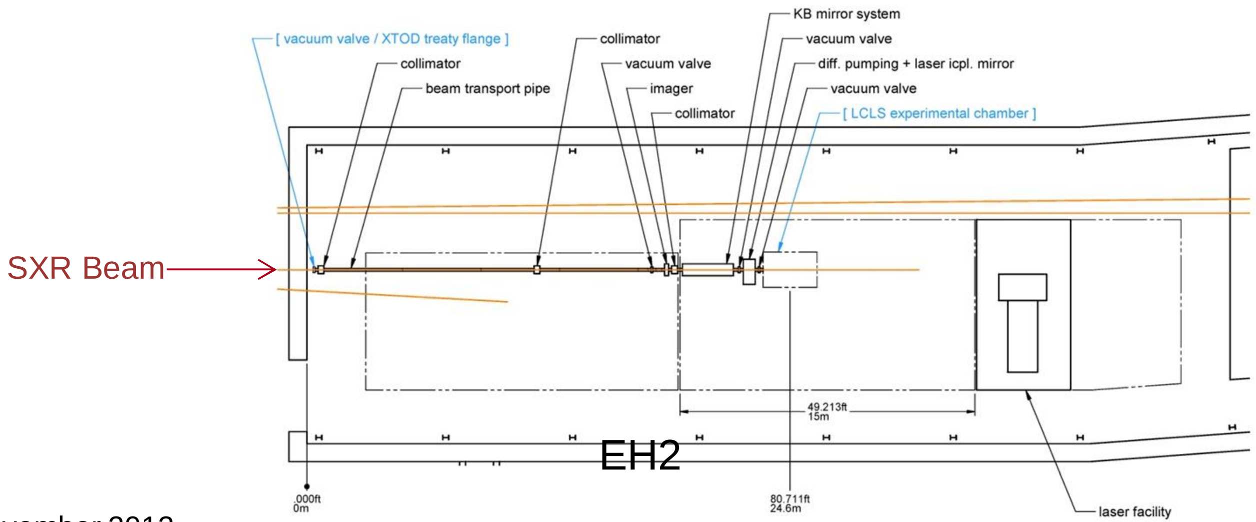
- Based on proven LCLS and LUSI designs



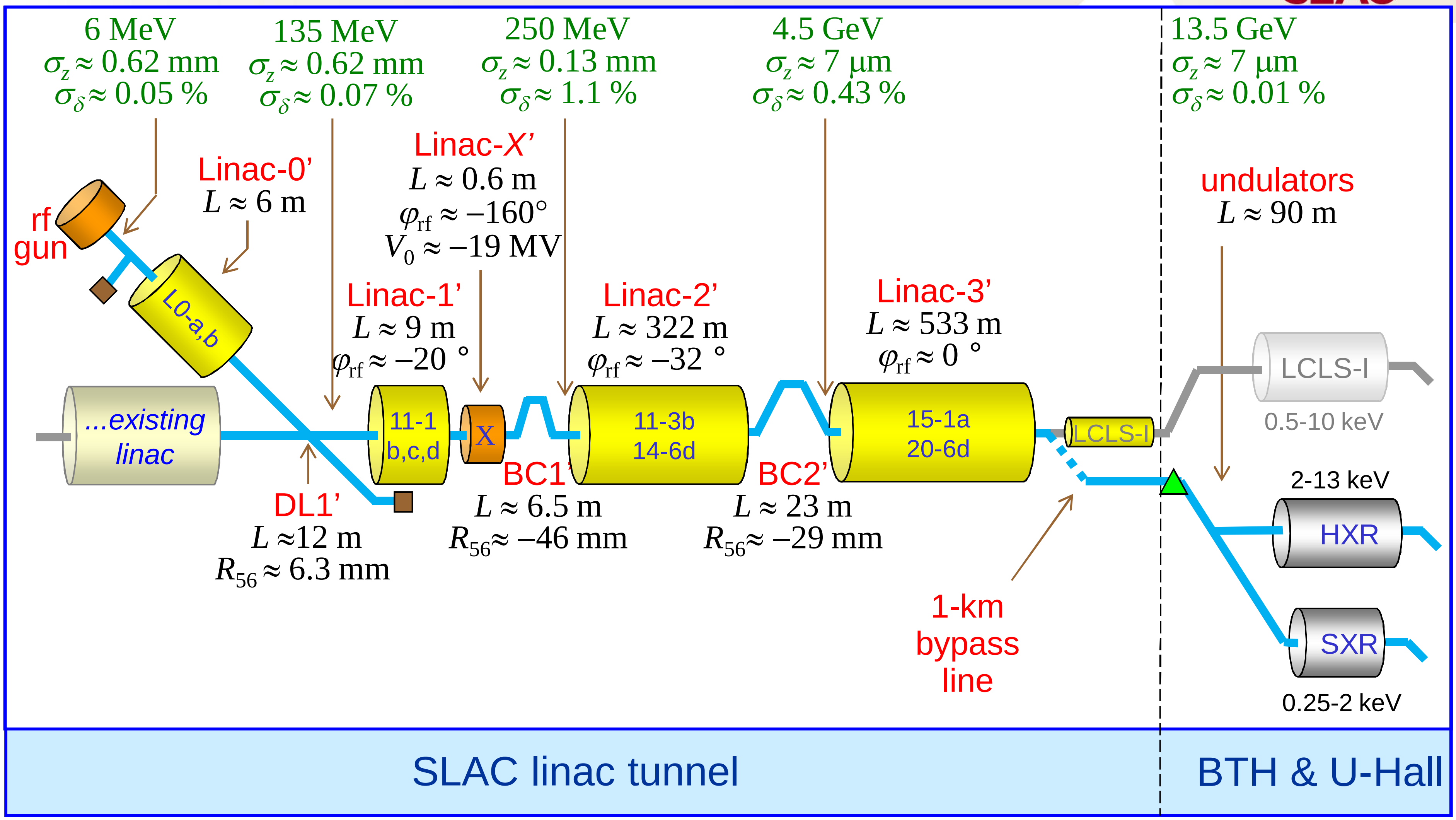
XES

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

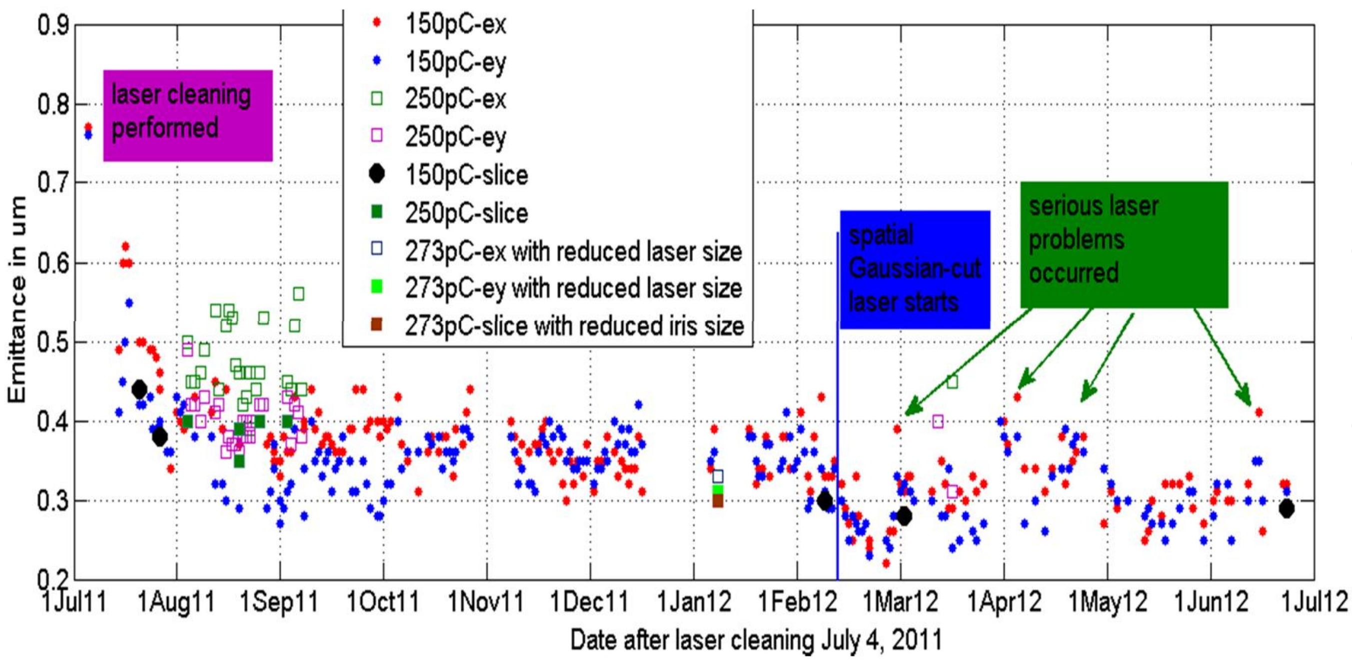
- Primary differences
  - Six fewer rf stations than LCLS-I
    - Roughly 1.5 GeV lower voltage, ok with lower bunch charge
  - 1.2km of additional drift in bypass line
    - Larger chirp at linac end → understand wakefields
  - Two undulator beamlines HXR and SXR
    - Beamline separation with kicker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

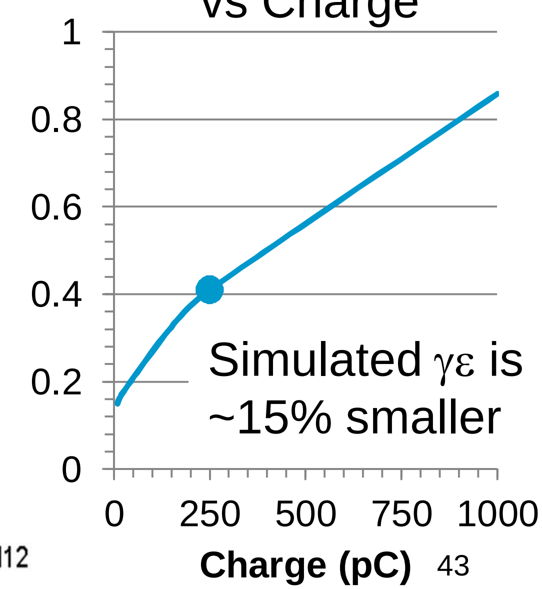
Better performance with lower charge

- 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 → shorter gain lengths and undulators than in LCLS-I original design

LCLS-I Injector emittance measurements

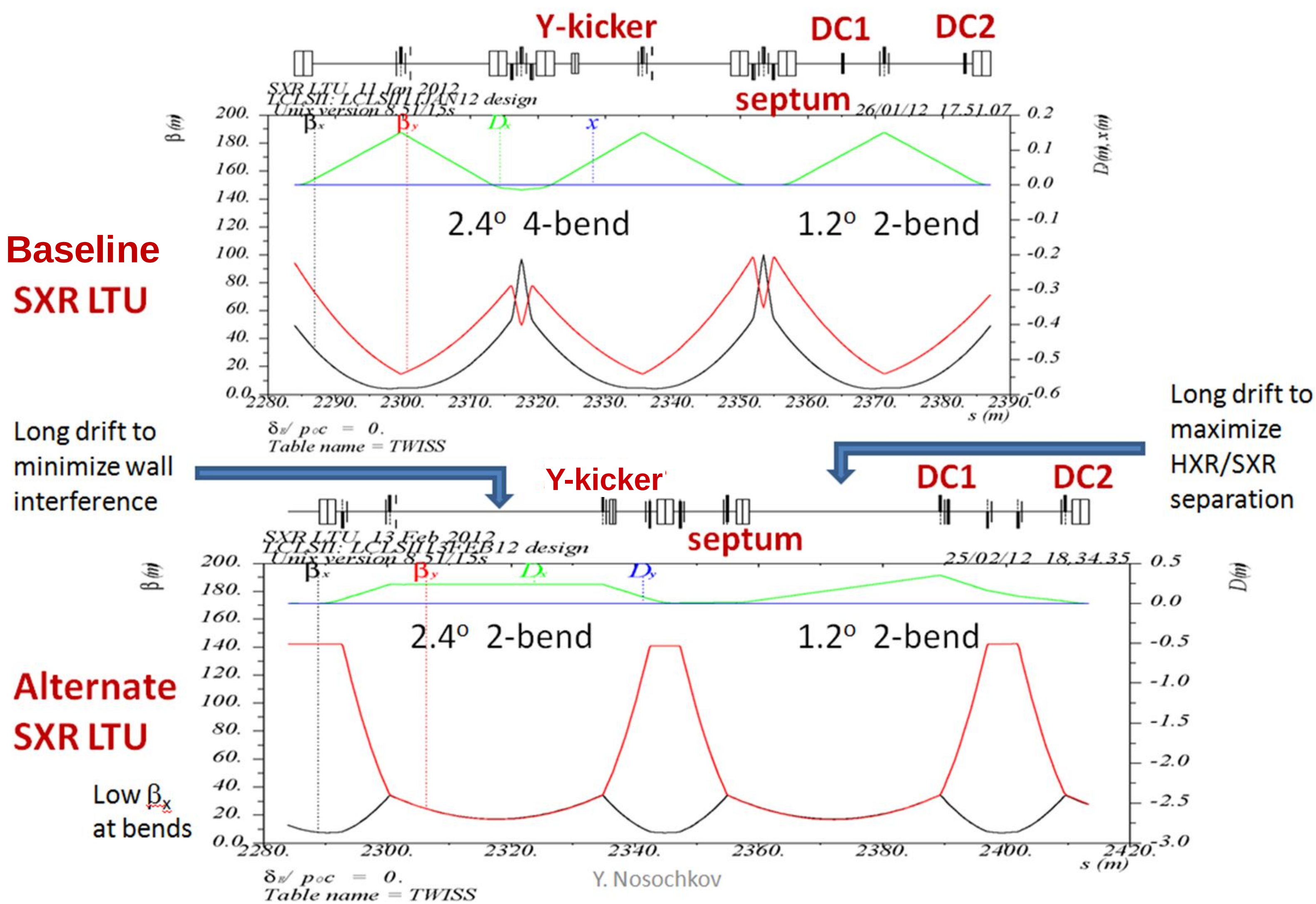


LCLS-II Emittance vs Charge



Alternate Optics layout
Modified LTUS – Eases 2-bunch upgrade

SLAC



Work by Yuri Nosochkov

Baseline Undulator Configuration
Optimized for 250 pC

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

Photon Energy (keV)	Beam Energy (GeV)	Charge (pC)	Emittance (mm-mrad)	Saturation Length (m)	
13	13.5	250	0.4	**87**	← Baseline
13	13.5	150	0.3	75	
13	12.3	150	0.3	74	

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

- 250 pC → 150 pC estimated to reduce gain length by ~15%

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

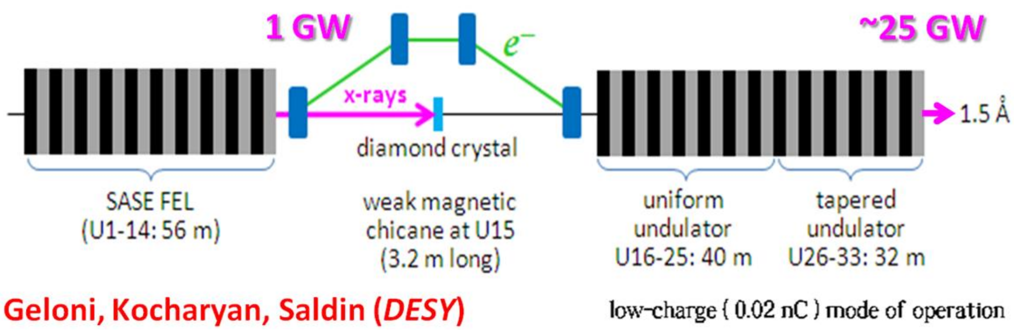
- LCLS-I R&D program to develop DELTA undulator for polarization control
  - Space left at end of SXR for 3 DELTA undulator segments

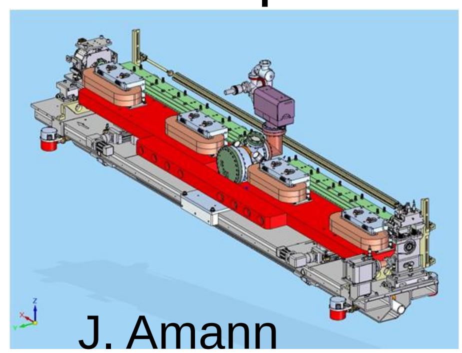
- Three multi-bunch configurations considered:
  - Bunches to both undulators @ 120 Hz (>30 ns separation)
  - Bunch pairs for 2-bunch self-seeding (few ns separation)
  - Bunch train (up to 30 bunches with ~10 ns spacing)
- Studying wakefield limitations and energy control
- Shielding designed for 5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

Seeding Options
Bandwidth limited Operation

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 <u>two-bunch</u> seeding

- Pro: works over wider range of wavelength and bunch parameters → greater flexibility, more x-ray power
- Con: more complicated

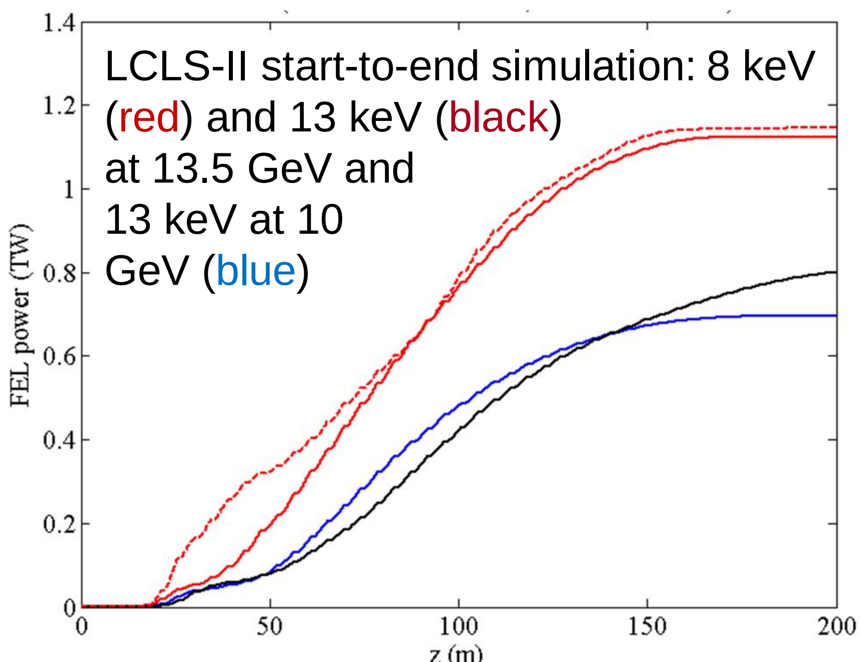
FEL TW Physics with Strong Tapering
Little experience; extensive simulation study

Not many studies:

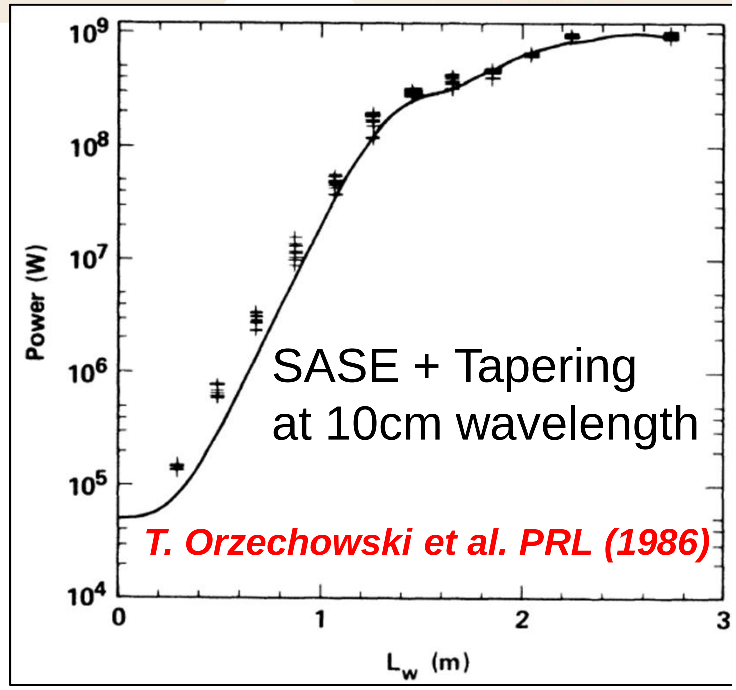
LLNL result →

Simulation studies progressing

Using LCLS-I to benchmark



Undulator length after seeding



- Working to understand saturation mechanisms and tolerance implications

Extended Undulator Hall
Enable Terawatt (TW) Upgrade

SLAC

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

FEL energy (keV)	**SASE Undulator Portion (m)**	**Saturation Full Length (m)**	**Power (TW)** 200 m Full undulator	**Power (TW)** 250 m Full undulator	**Power (TW)** 300 m Full undulator
8	39	220	1.1	1.1	1.1
13	43	270	0.8	1.3	1.4
18	48	330	0.5	0.7	0.9

- 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