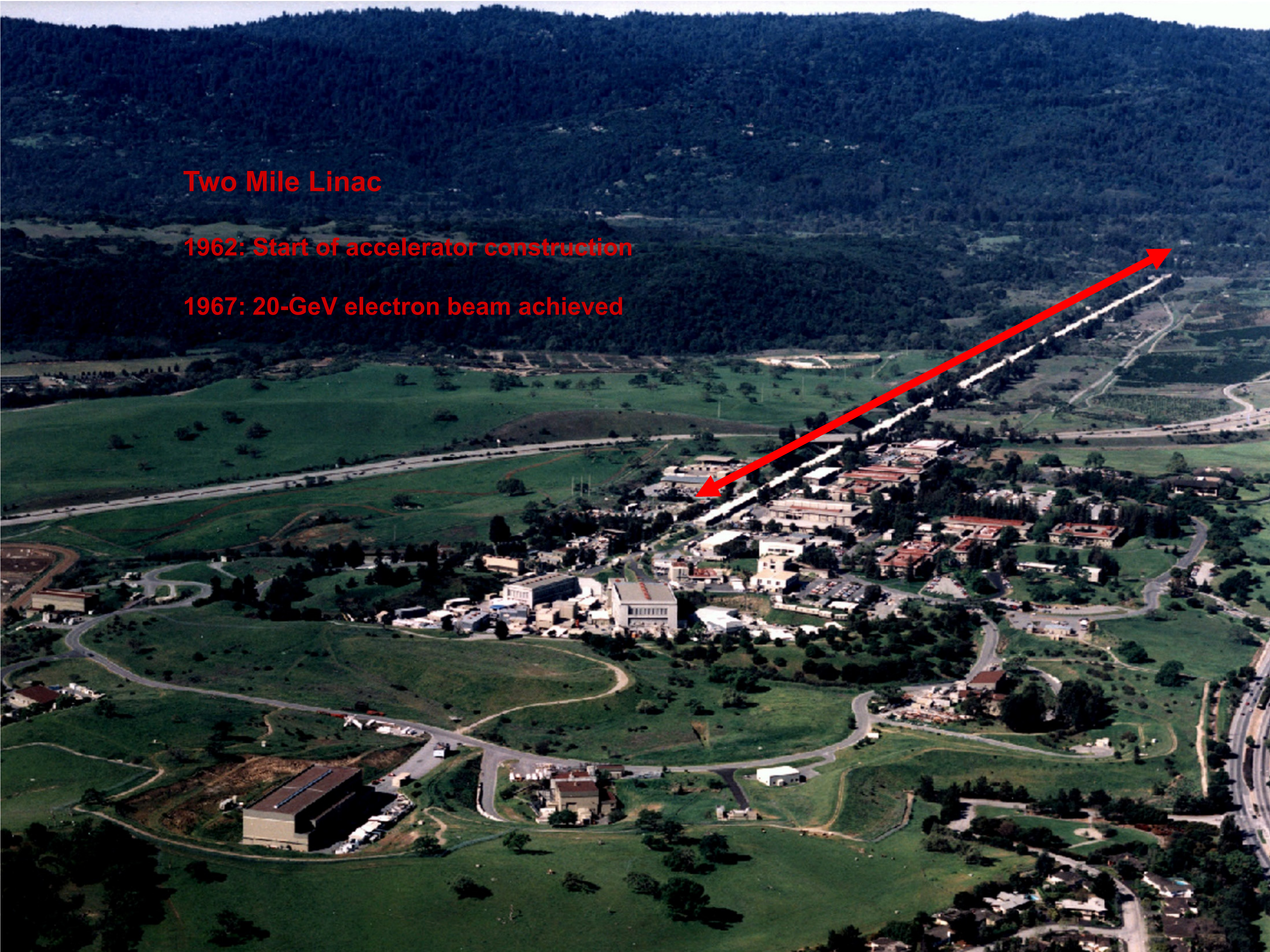
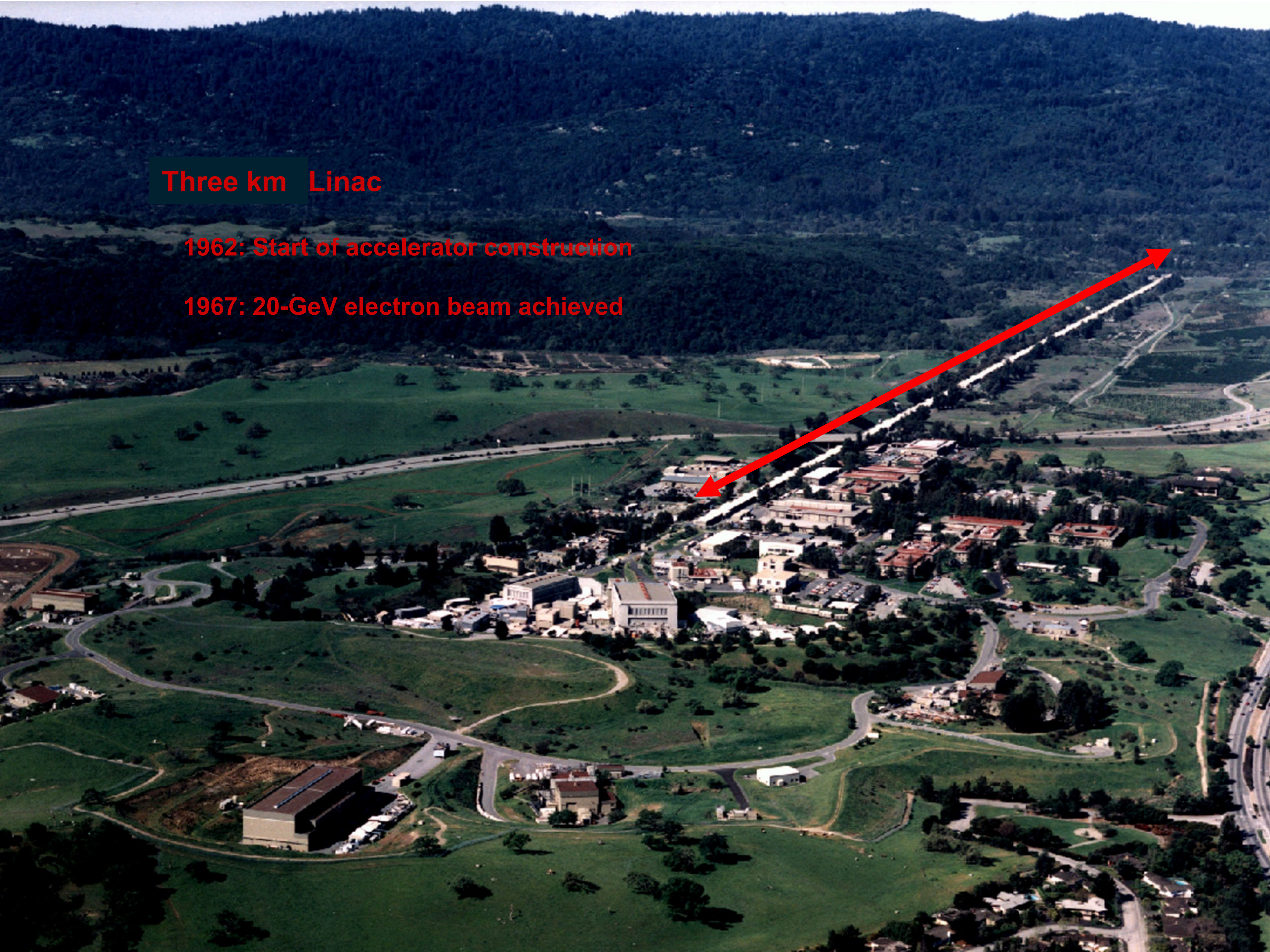
The LCLS-II: a High Power Upgrade to the LCLS

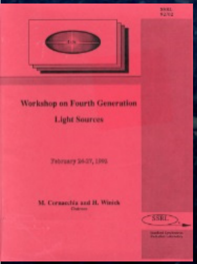
John N. Galayda

30 April 2018


Two Mile Linac
1962: Start of accelerator construction
1967: 20-GeV electron beam achieved


Three km Linac
1962: Start of accelerator construction
1967: 20-GeV electron beam achieved

LCLS: 17 years from idea to first light



1992: Proposal (Pellegrini)

1997: BESAC (Birgeneau) Report

1999: BESAC (Leone) Report

2000: LCLS- the First Experiments (Shenoy & Stohr) SLAC-R-611<< for BES

2001: Critical Decision 0

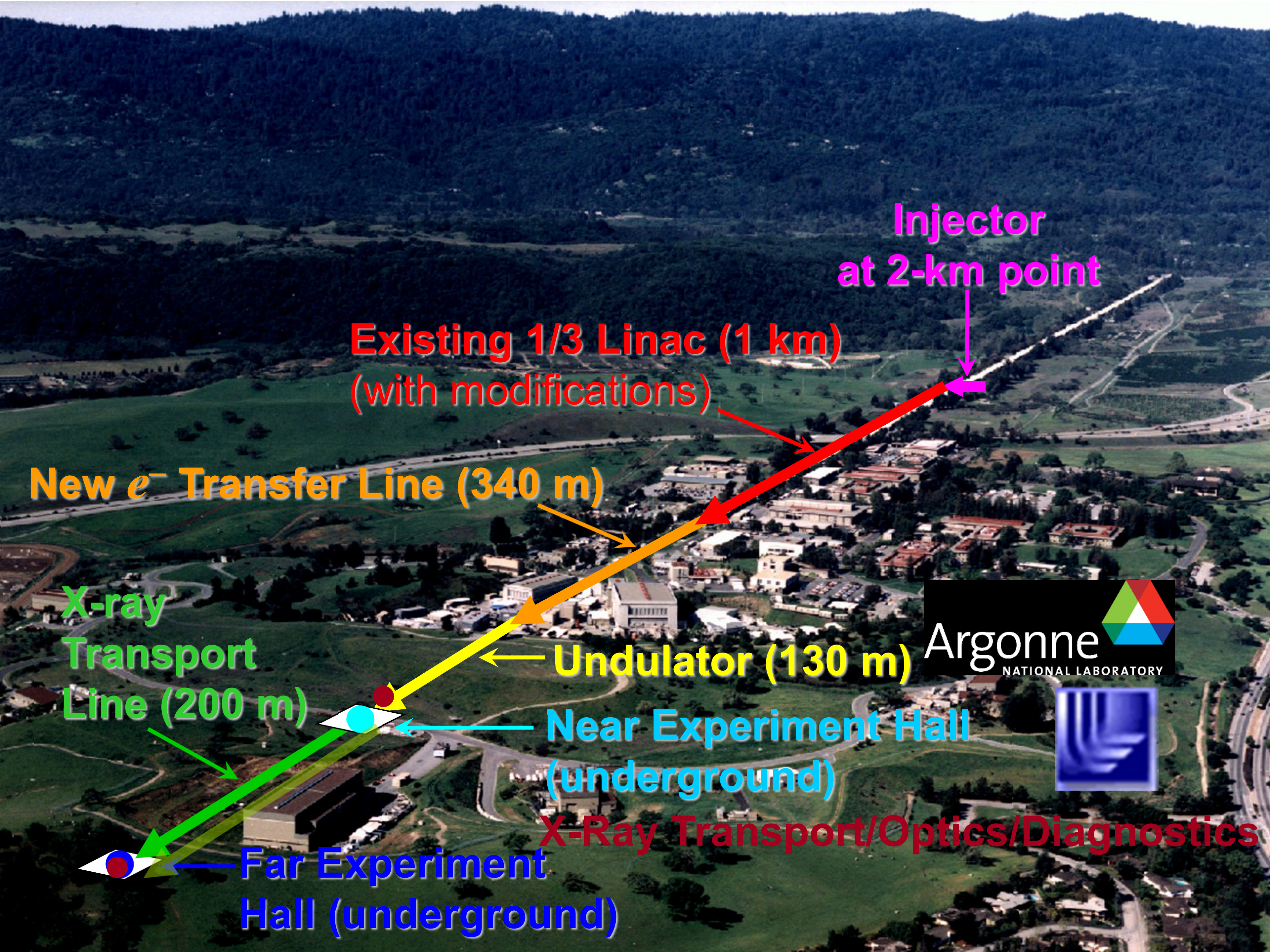
2002: Critical Decision 1

2005: Critical Decision 2

2006: Critical Decision 3

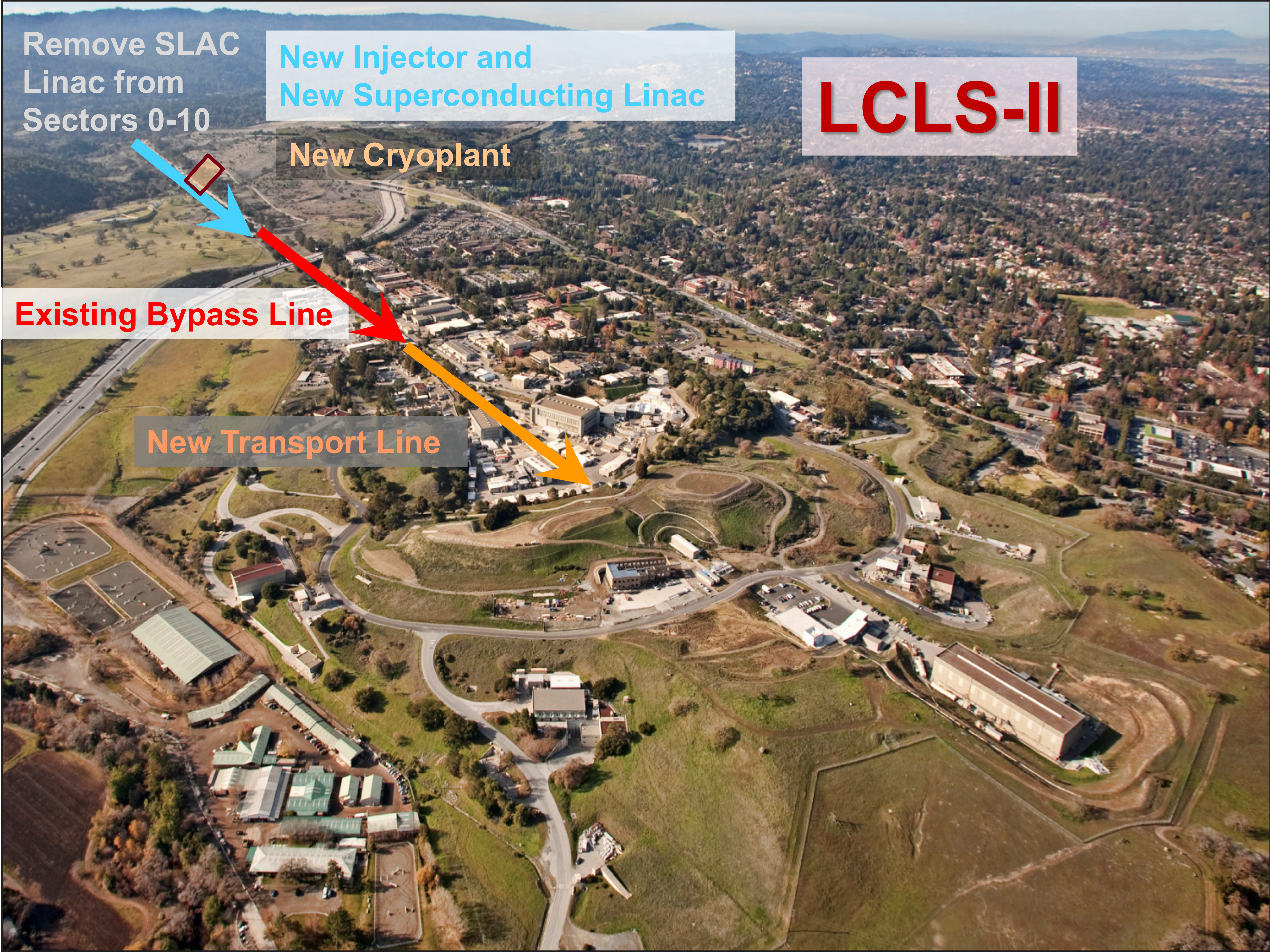
2009: First Light, 10 April

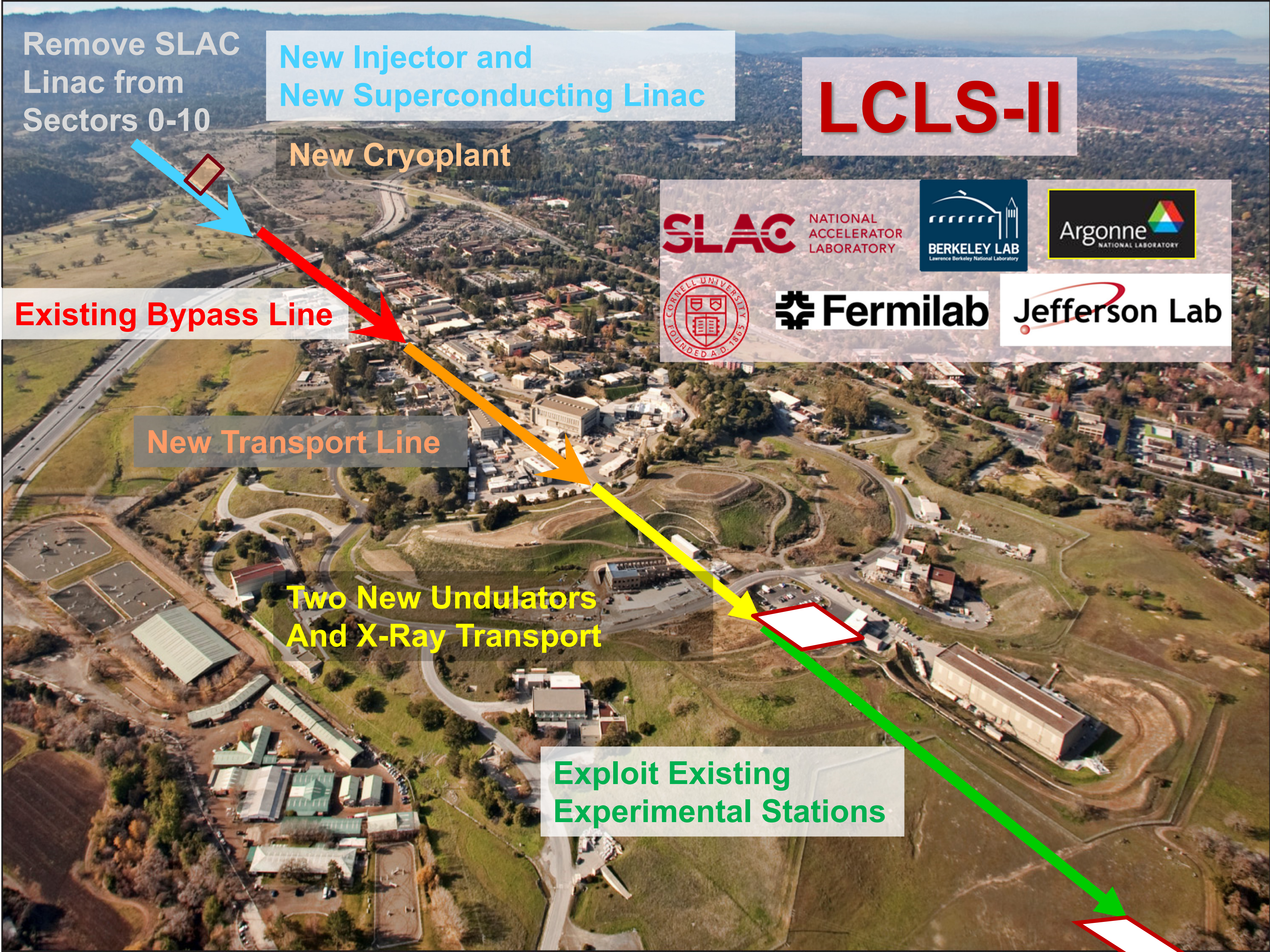
2010: Project Completion


Injector
at 2-km point
Existing 1/3 Linac (1 km)
(with modifications)
New e^- Transfer Line (340 m)
X-ray
Transport
Line (200 m)
Undulator (130 m)
Argonne
NATIONAL LABORATORY
Near Experiment Hall
(underground)
X-Ray Transport/Optics/Diagnostics
Far Experiment
Hall (underground)


Remove SLAC
Linac from
Sectors 0-10
New Injector and
New Superconducting Linac
LCLS-II


Remove SLAC Linac from Sectors 0-10
New Injector and
New Superconducting Linac
New Cryoplant
LCLS-II


Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
LCLS-II
New Cryoplant
Existing Bypass Line
New Transport Line


Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
LCLS-II
New Cryoplant
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Existing Bypass Line
Fermilab
Jefferson Lab
New Transport Line
Two New Undulators And X-Ray Transport
Exploit Existing Experimental Stations

Mission Need, Scope & Key Performance Parameters

Report of the BESAC Subcommittee on Future X-ray Light Sources

U.S. DEPARTMENT OF ENERGY | Office of Science

MISSION NEED STATEMENT

for the

LINAC COHERENT LIGHT SOURCE-II (LCLS-II)

Major Acquisition Project

Office of Basic Energy Sciences

Office of Science

U.S. Department of Energy

Revised and Approved:

September 2013

- LCLS-II adds a 4 GeV SC linac to the first kilometer of the SLAC linac tunnel.
  -The copper linac in that region will be removed
- The new beam will run CW at up to 1 MHz
  -The LCLS-1 linac is not altered, retains performance
- The new beam can be directed at either of two new undulators
  -The LCLS-1 beam can be directed to the new Hard X-ray Undulator

Key Performance Parameters for LCLS-II

Performance Measure	Threshold	Objective
Variable Gap Undulators	2 (SXR & HXR)	2 (SXR & HXR)
Super Conducting Linac Based FEL System		
Super Conducting Linac Energy	3.5 GeV	≥ 4 GeV
Electron Bunch Repetition Rate	93 kHz	929 kHz
Super Conducting Linac Charge per Bunch	0.02 nC	0.1 nC
Photon Beam Energy Range	250-3,800 eV	200-5,000 eV
High Repetition Rate Capable End Stations	≥ 1	≥ 2
FEL Average Power (10^-3 BW)	$5x10^8$ (10x spontaneous @2,500 eV)	>10^{11} @ 3,800 eV
Normal Conducting Linac Based FEL System		
Normal Conducting Linac Electron Beam Energy	13.6 GeV	15 GeV
Electron Bunch Repetition Rate	120 Hz	120 Hz
Normal Conducting Linac Charge per Bunch	0.1 nC	0.25 nC
Photon Beam Energy Range	1,000-15,000 eV	1,000-25,000 eV
Low Repetition Rate Capable End Stations	≥ 2	≥ 3
FEL Photon Energy (10^{-3} BW[a])	10^{10} (lasing @ 15,000 eV)	> 10^{12} @ 15,000 eV

New mission:
CD-0 9/2013

Shooting to
Finish 3/2021

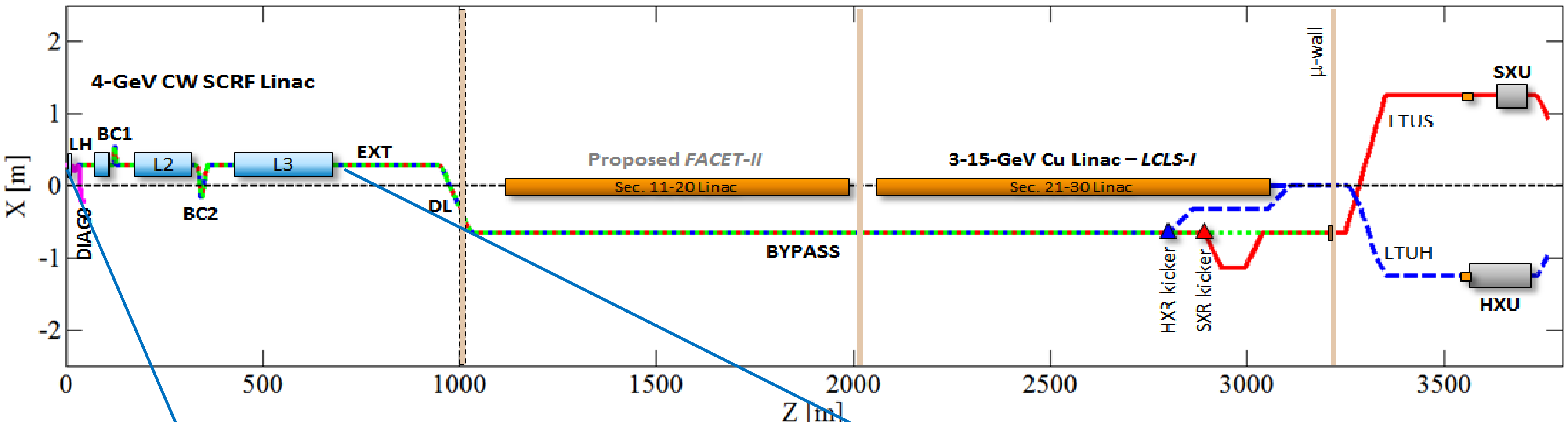
Level 1 Baseline Milestones	Schedule
CD-0 - Approve Mission Need	4/22/2010 (Actual)
Mission Need Statement (Update)	9/27/2013 (Actual)
CD-1 - Approve Alt. Select. & Cost Range	10/14/2011 (Actual)
CD-3a(1) - Approve Long Lead Procurement (LLP)	3/14/2012 (Actual)
CD-1 - Approve Alt. Select. & Cost Range (Update)	8/26/2014 (Actual)
Advanced Procurement of Niobium Material	8/26/2014 (Actual)
CD-3b(2)- Approve LLP	5/28/2015 (Actual)
CD-2 – Approve Performance Baseline	**3/21/2016(Actual)**
CD-3 – Approve Construction Start	**3/21/2016(Actual)**
CD-4 - Project Complete/Start of Operations	**June 30 2022**

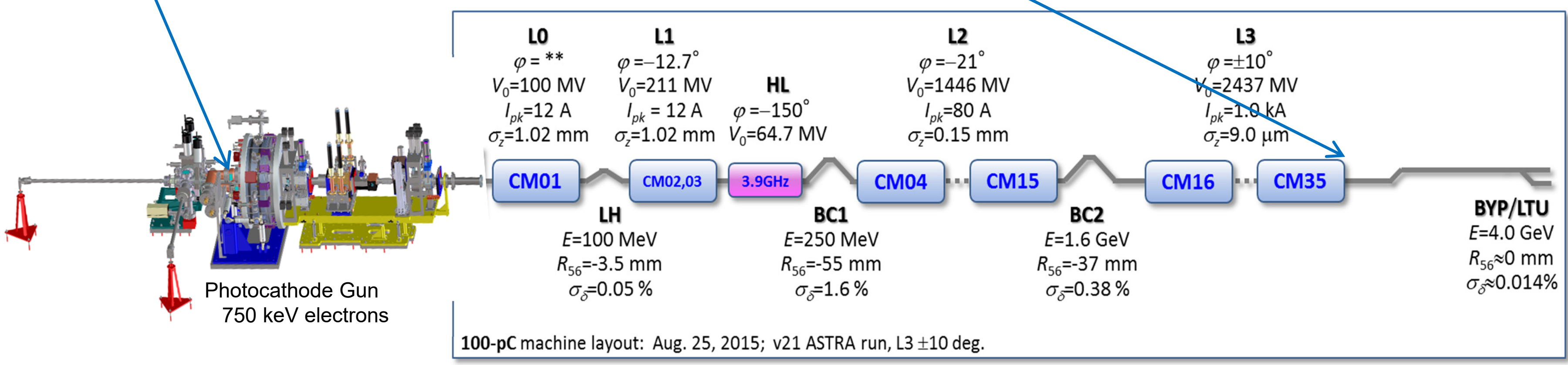
(1) CD-3a LLP for the original LCLS-II scope; authorization included Linac Sector 10 injector and annex, undulator magnet blocks, and Global Interface System.

(2) CD-3b LLP authorizes long-lead procurements proposed at this review.

Fiscal Year	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	Total
TEC - PED			2.0	5.0	4.0	21.0	15.0	0.0	0.0	0.0	0.0	**47.0**
TEC - Construction			42.5	17.5	71.7	117.7	185.3	190.0	192.1	129.3	0.0	**946.1**
OPC	1.126	9.474	8.0	0.0	10.0	9.3	0.0	0.0	7.9	6.1	0.0	**51.9**
Total	**1.126**	**9.474**	**52.5**	**22.5**	**85.7**	**148.0**	**200.3**	**190.0**	**200.0**	**135.4**	**0.0**	**1045.0**

LCLS-II schematic layout





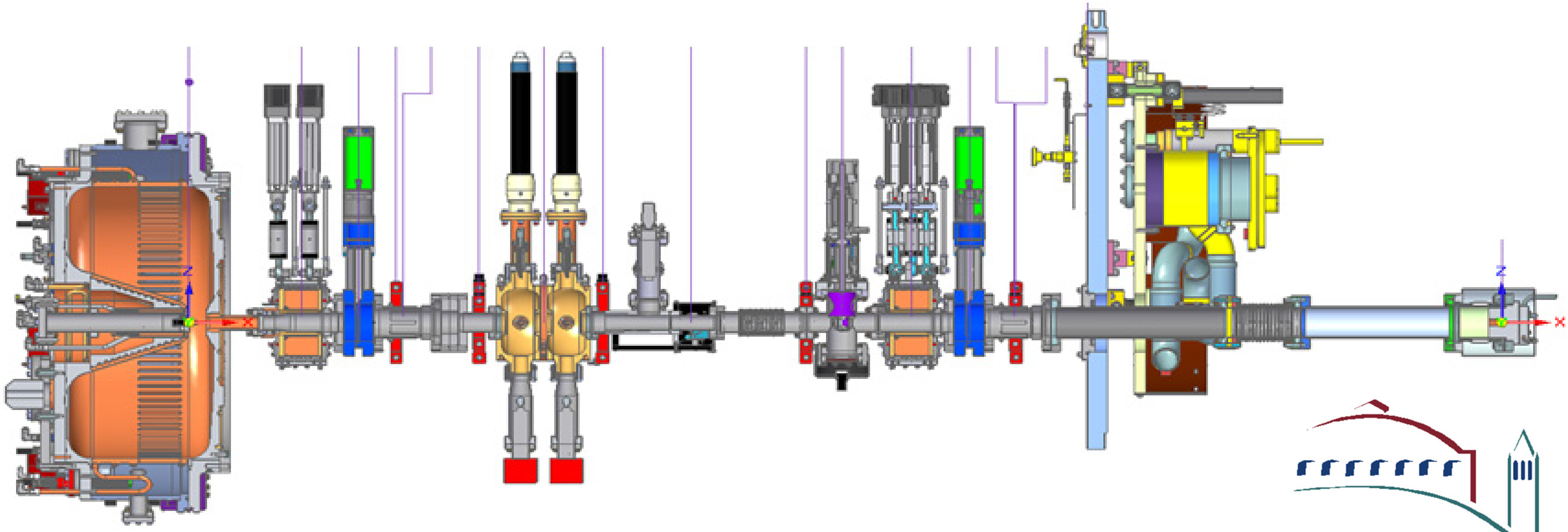
186 MHz RF gun -

750 keV

10-100 pC/pulse

0.2 mm-mr @ 10 pC

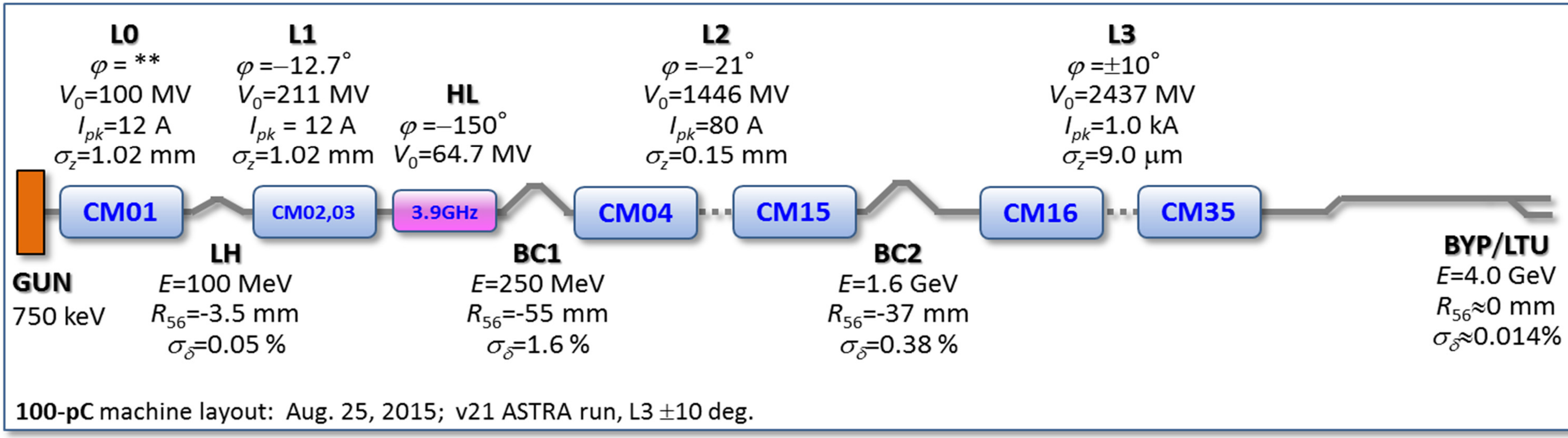
0.35 mm-mr @ 100 pC



Checkout/commissioning underway

First electrons in August 2018 WEPAL039

35 cryomodules



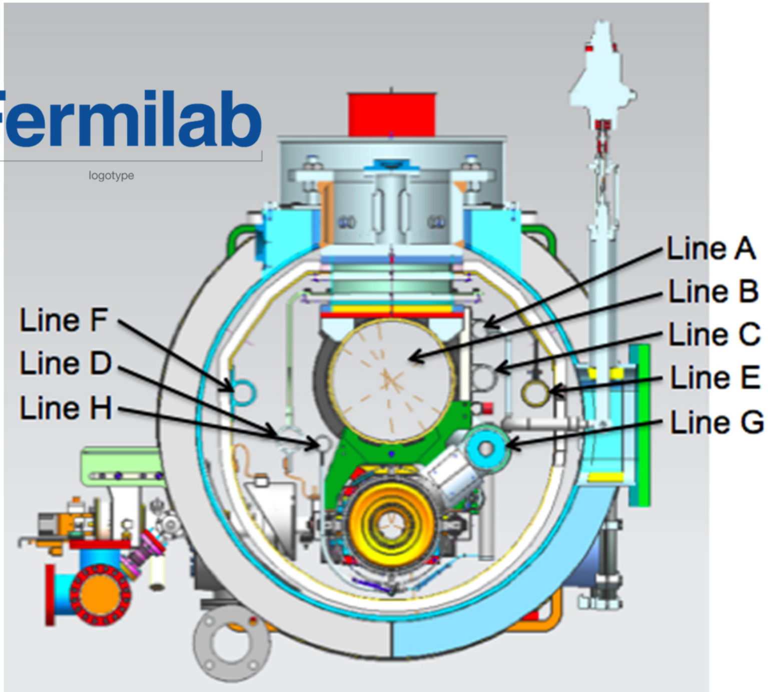
35 cryomodules, each with eight 9-cell XFEL cavities

16MV/m produces 4.25 GeV beam

Laser “heater” to control energy spread

Two bunch compression chicanes

LCLS-II cryomodule design derived from ILC/XFEL FNAL set the design for LCLS-II



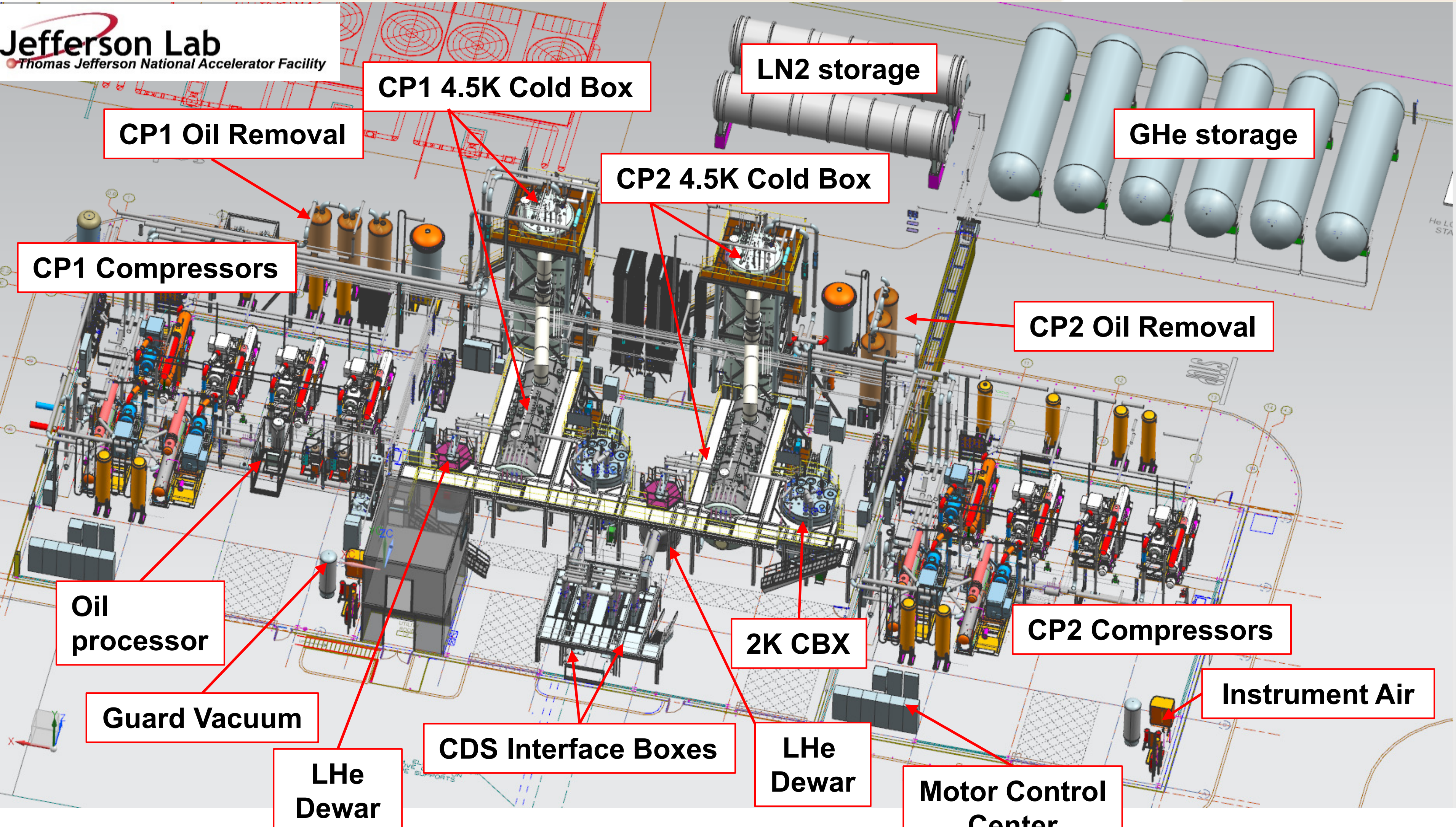
<u>Circuit (Line)</u>

A. 2.4 K subcooled supply
B. Helium gas return pipe (HGRP)
C. Low temperature intercept supply
D. Low temperature intercept return
E. High temperature shield supply
F. High temperature shield return
G. 2-phase pipe
H. Warm-up/cool-down line

Operating Parameters	A	B	C	D	E	F	G	H
Pressure, [bar]	3	0.031	3.2	2.5	3.7	2.7	0.031	3
Temperature, K	2.4	2.0	5.5	8.0*	35	55	2.0	2.0

*Line D returns 1.3 bar, 7.5 K to cryogenic plant after expansion valve

2 x 4kW @ 2K cryoplants



Cryomodule:

- Approximately 6 months to assemble a cryomodule
- Construction ongoing at FNAL and JLAB

Cryomodule Production

- ~6 months to build/test a cryomodule start to finish
  - 5 workstation stops + test stand

- Typically, the pacing item is cryomodule test
- To date
  - JLAB
    - THPAL137 Drury et al, Cryomodules at JLAB
    - 7 Cryomodules built+tested
    - 6 Cryomodules in the production line
  - FNAL:
    - WEPMK010 Arkan et al, Cryomodules @ FNAL
    - MOZGBD3 Solyak, et al
    - 9 Cryomodules built
    - 8 Cryomodules tested

Cryomodule Production

- Design changes, procedural changes during production
  - Reverse JT valve and "wipers"
  - Gate valve support
  - Baffle for Gaseous Helium Return
  - Re-center notch in HOM coupler

- Tightening or replacement of fasteners
  - Reworks will add 3 months to project schedule
  - The work plan for completion of cryomodules is on "critical path" for the completion of the project
- Forecast project completion in March 2021

High Q Nitrogen Doped Cavities

- Very good results in vertical tests:
- Vertical tests of 144 cavities: $\langle Q \rangle = 3.05 \times 10^{10}$
- Usable gradient, averaged: 22.8 MV/m
- Many lessons learned about doping, fabrication
    - Palczwewski et al., THPAL 139,THPAL140
    - Nitrogen doping provides desired high Q for LCLS-II
    - Success in flux expulsion in doped cavities depends on Niobium hardness, grain size for reasons not fully understood
    - Production- <u>control of the “basics” is essential</u>

High Q in Cryomodules with Nitrogen Doped Cavities

- To realize high Q from doping, "fast" cooldown is required to expel magnetic flux from cavities

- At least 30 gm/sec; some cavities require 80 cm/sec
- This can be done at FNAL CMTS
- It will be possible for LCLS-II
- JLAB CMTF is being modified to support "fast cooldown"

- Extrapolating only FNAL cryomodule measurements for now, LCLS-II will run at 4 GeV, cooled by one 4 kW@2K cryoplant

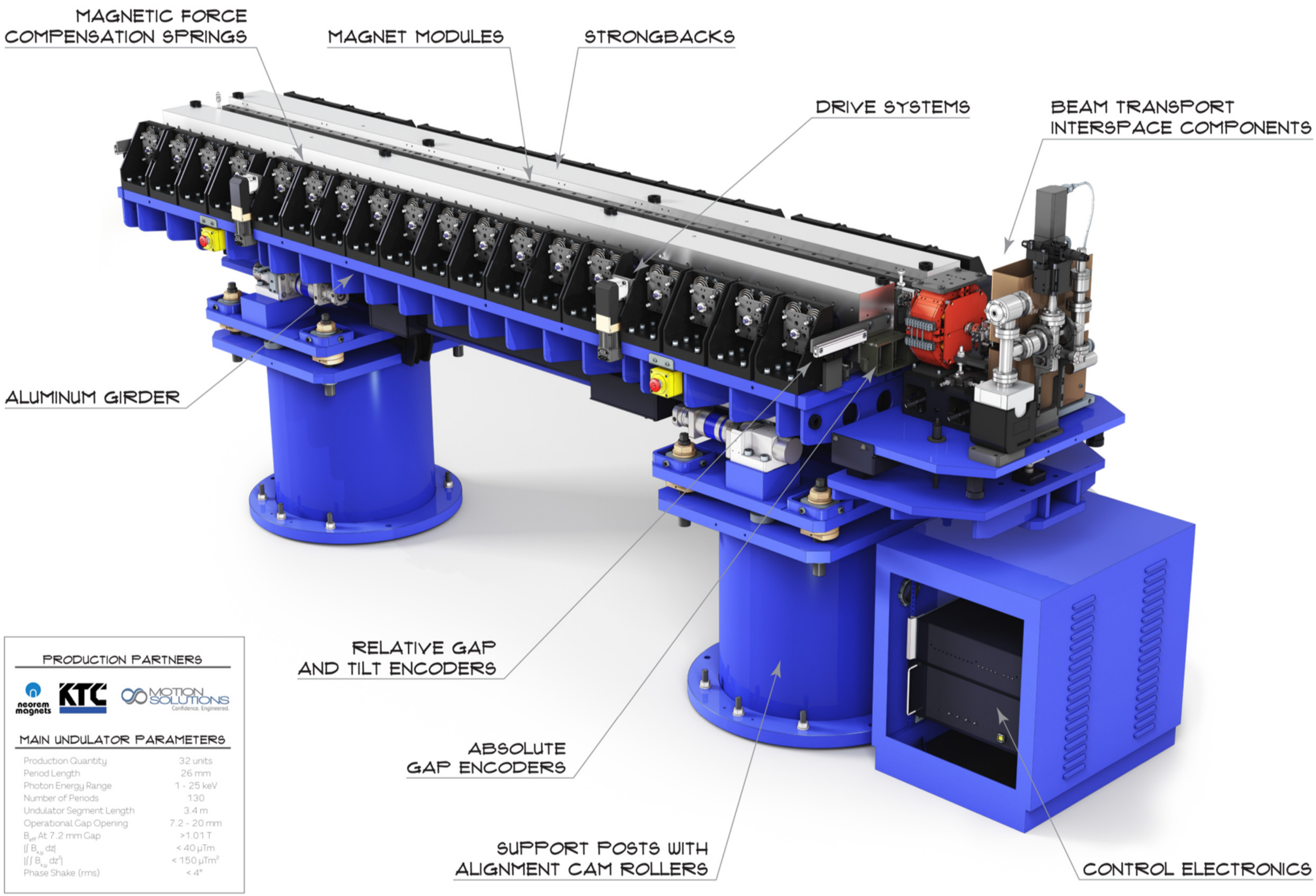
Undulators

Parameter	SXU Values	HXU Values	Unit
Undulator period length (λ_u)	39	26	mm
Segment length	3.4	3.4	m
Number of effective periods per segment (N_p)	87	130	
Number of poles per segment	174	260	
Undulator type	Planar	Planar	
Undulator magnet type	PM Hybrid	PM Hybrid	
Gap type	Variable	Variable	
Magnet material	$Nd_2Fe_{14}B$	$Nd_2Fe_{14}B$	
Linear polarization direction of the xray radiation	horizontal	vertical	
Magnetic Field Symmetry	antisymmetric	antisymmetric	
Minimum operational magnetic gap	7.2	7.2	mm
Maximum operational magnetic gap	22	20	mm
On-axis vertical effective field at min. oper. Gap	>1.49	>1.01	T
K_{eff} at minimum operational gap	>5.43	>2.44	
Minimum full open gap	100	100	mm
Minimum operational K values	1.24	0.44	

Soft X-Ray Undulators

- SXR deliveries on track
- 12 @ SLAC

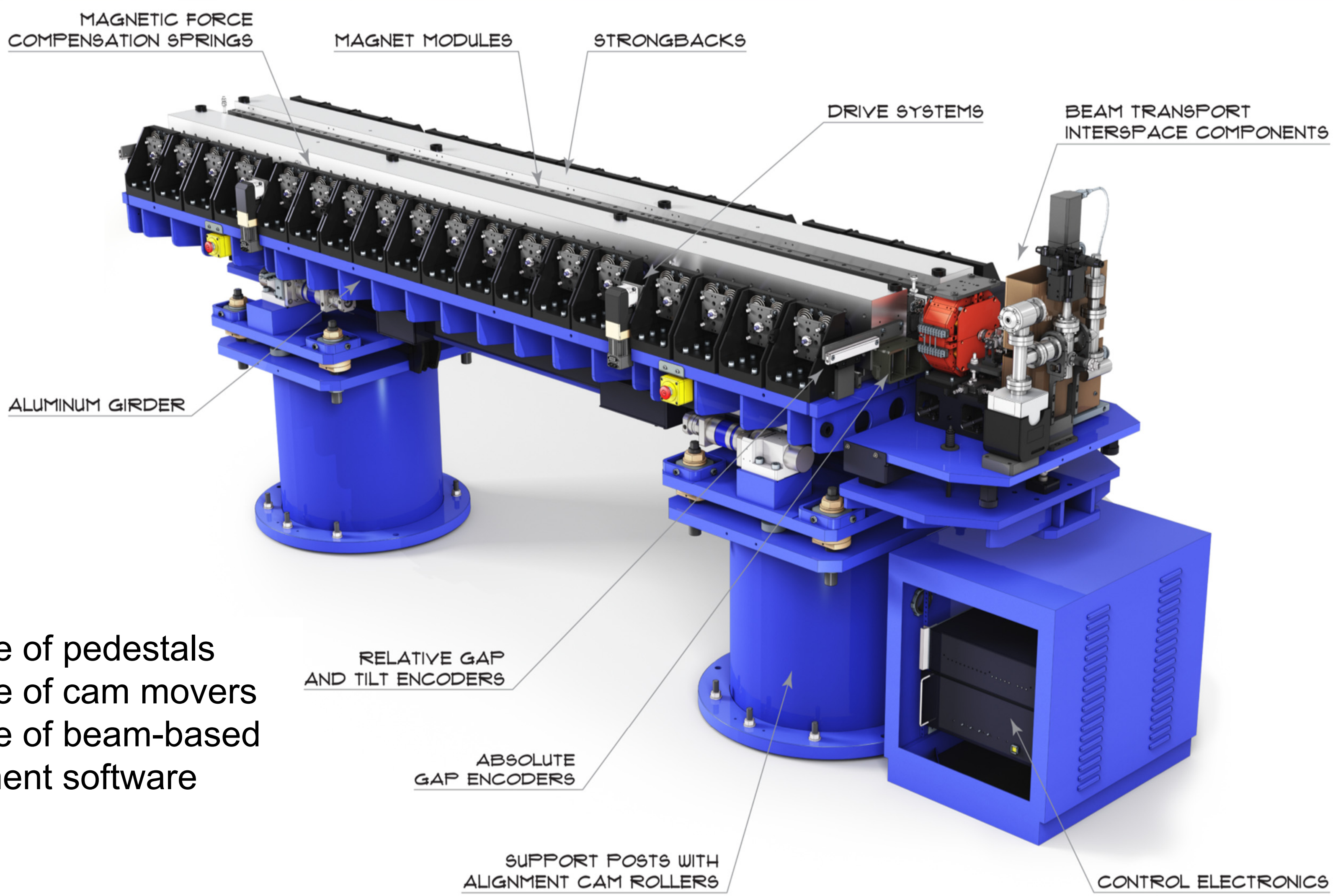
Hard X-Ray Undulators



MAIN UNDULATOR PARAMETERS

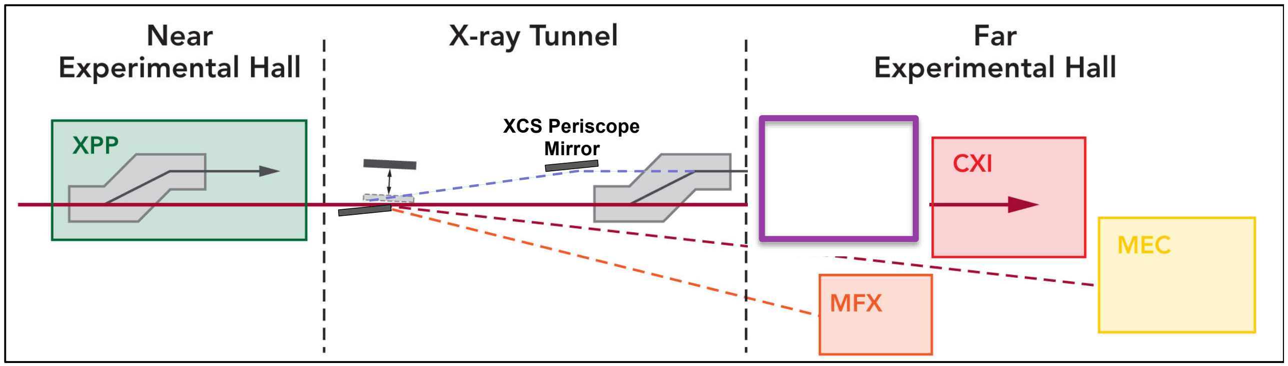
Production Quantity	32 units
Period Length	26 mm
Photon Energy Range	1 - 25 keV
Number of Periods	130
Undulator Segment Length	3.4 m
Operational Gap Opening	7.2 - 20 mm
B_{eff} At 7.2 mm Gap	>1.01 T
$\lvert\int B_{x,y}\,dz\rvert$	< 40 µTm
$\lvert\int\int B_{x,y}\,dz^2\rvert$	< 150 µTm²
Phase Shake (rms)	< 4°

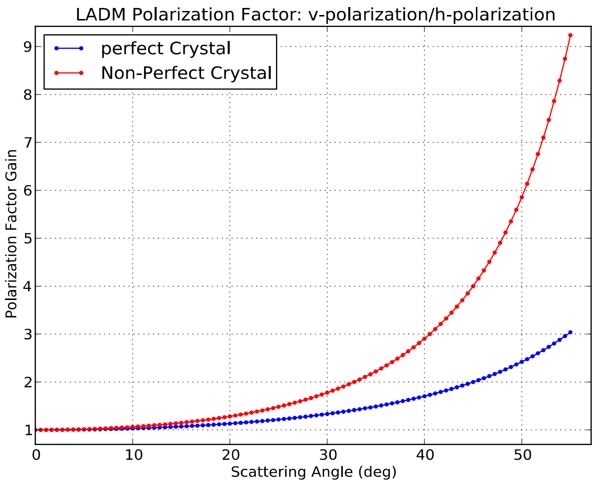
Why build vertical polarization undulator?



Re-use of pedestals
Re-use of cam movers
Re-use of beam-based alignment software

Vertically polarized radiation can be deflected in horizontal plane with much less attenuation





Thanks to D. M. Fritz

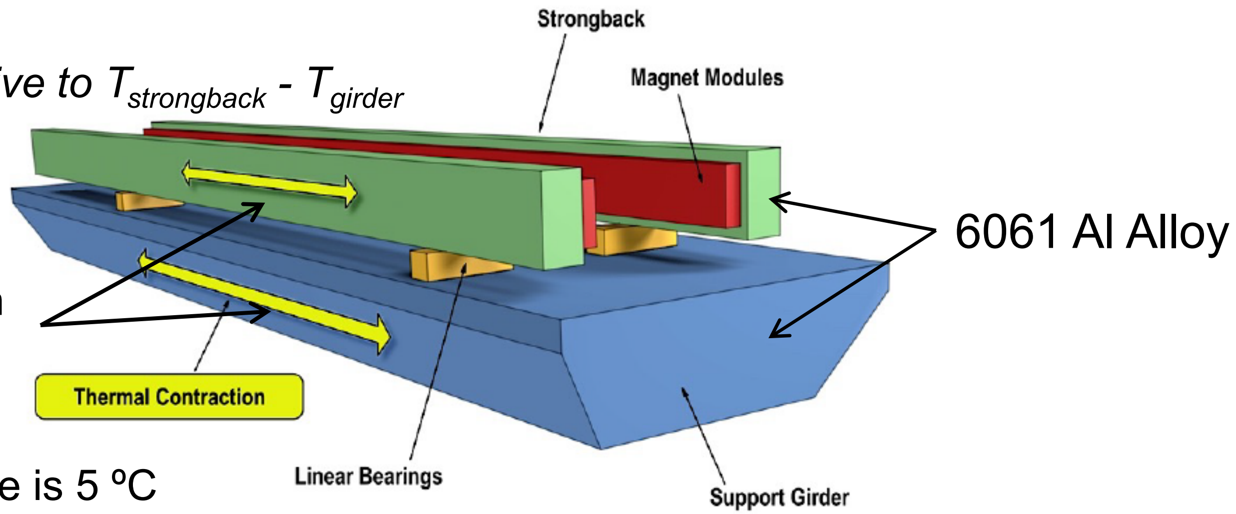
X-Ray Correlation Spectroscopy (XCS) instrument receives a brighter beam

- The XCS detector arm designed to operate in horizontal plane: 0º to 55º
- Vertical polarization is preferred for scattering
    - Gain factor shown in plot: dependent upon scattering angle and type of sample
    - Most XCS samples are non-perfect crystals

The Lack Of Environmental Repeatability Is Attributed To Two Critical Interfaces

Interface between girder and strongbacks needs to accommodate temperature differences that can develop between the strongbacks and girder

Distortions are sensitive to $T_{strongback}$ - T_{girder}



Unconstrained Length Difference of ~250μm

* Maximum expected temperature Difference is 5 ºC

Interface between modules and strongbacks needs to accommodate small material differences between the strongbacks and modules

Unconstrained Length Difference of ~25μm

Distortions are sensitive to $T_{strongback}$ change

* CTE difference is ~ 0.6 μm/(m ºC)
* Maximum temperature excursion of 15 ºC

Thank you

IPAC organizers for inviting me

IPAC attendees for your attention

SLAC and DOE for entrusting me w/LCLS-II

LCLS-II collaboration for dedication and resourcefulness

DESY and XFEL for help in all areas

3/16/2018 assessment reflecting the plan to re-work cryomodules built to date