Technical Challenges of the LCLS-II CW X-ray FEL

Tor Raubenheimer for the LCLS-II Collaboration

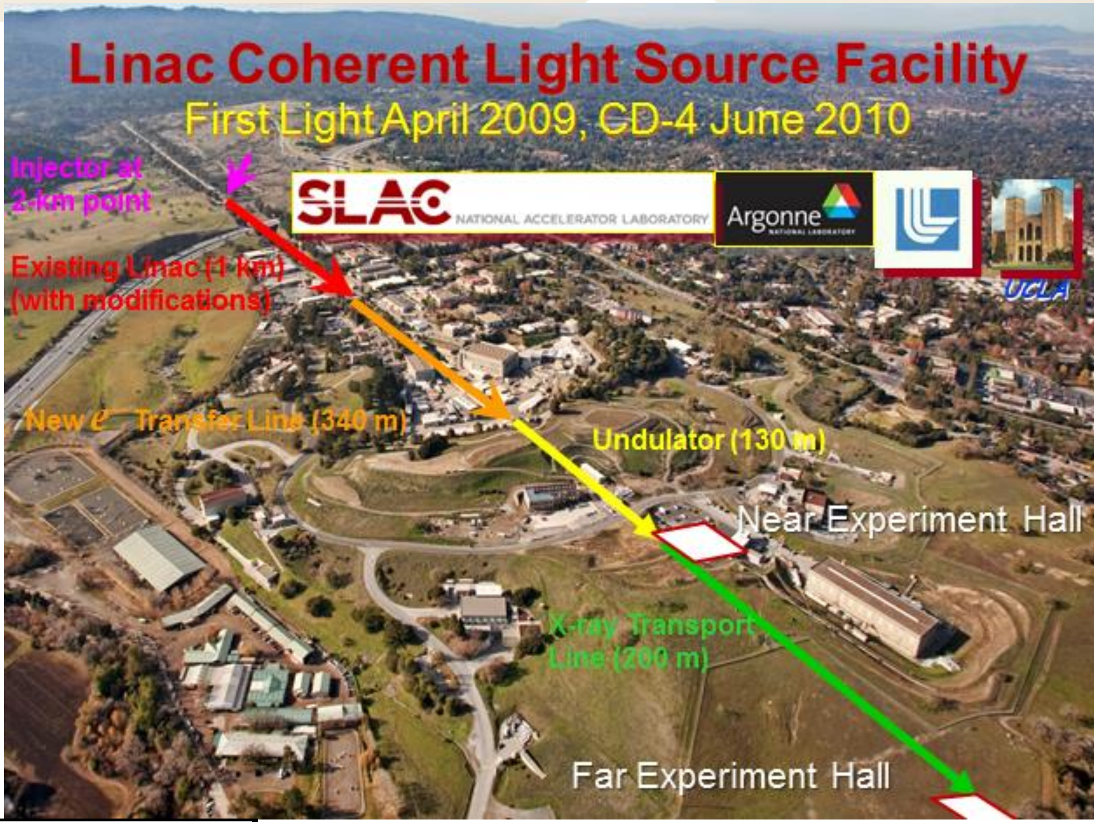
May 6th, 2015

Introduction

LCLS-II starts from the LCLS X-ray FEL

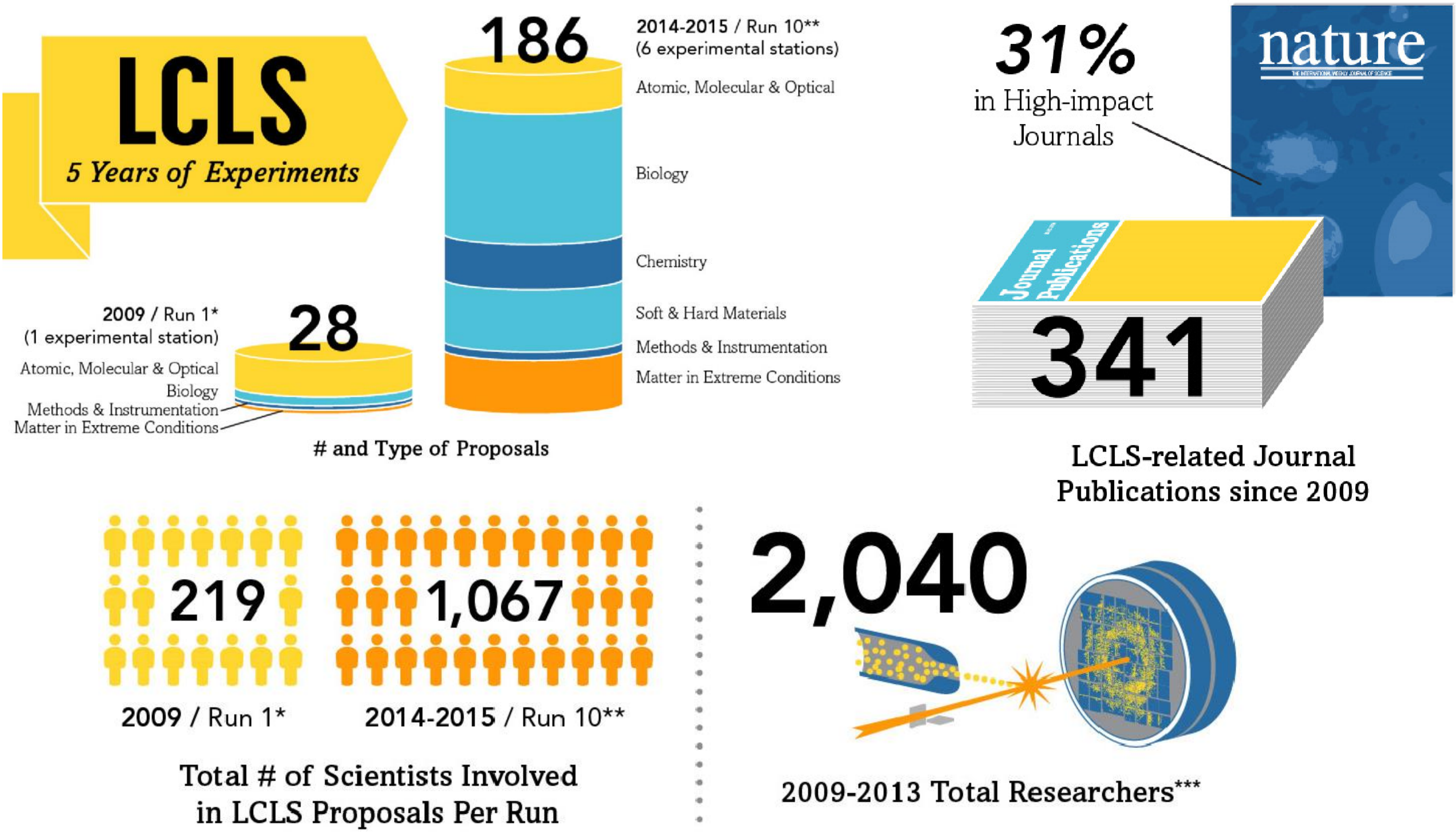
The LCLS is the world's 1st x-ray Free Electron Laser (FEL)

- LCLS electron source is the SLAC *Cu* linac
- Includes one fixed gap undulator
- Six experimental stations



X-ray Range	**250 to 11,300 eV**
FEL Pulse Length	**< 5 - 500 fs**
FEL Pulse Energy	**~3 mJ (2 * 10^{12} @ 10 keV)**
Repetition Rate	**120 Hz**

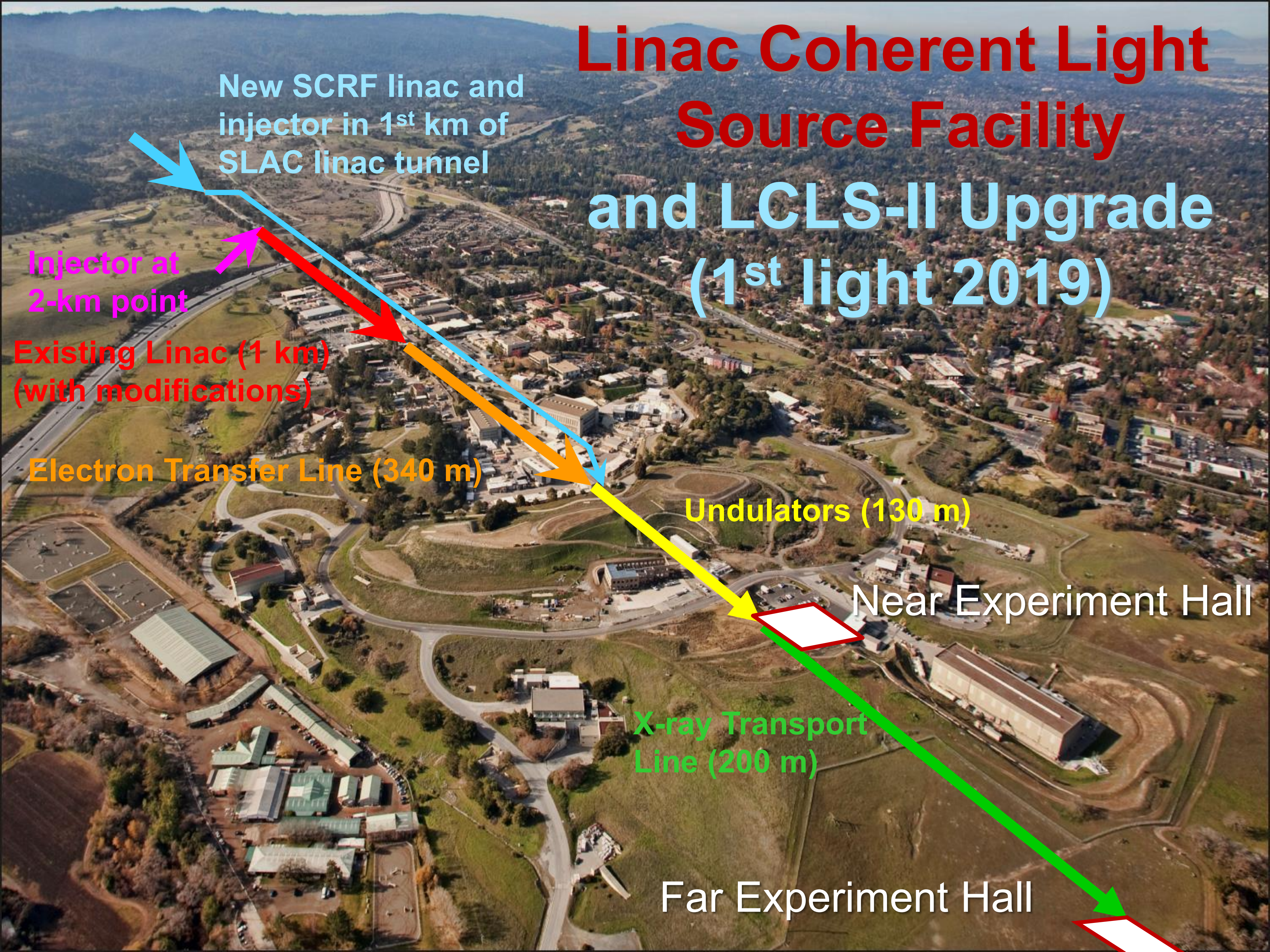
LCLS Operations
Photon Science and Accelerator Science



* Run 1, the first operating period at LCLS, was October-December 2009.

** The Run 10 operating period is scheduled October 2014-March 2015.

*** October 2009-October 2013 total number of scientific researchers engaged in approved research at LCLS.



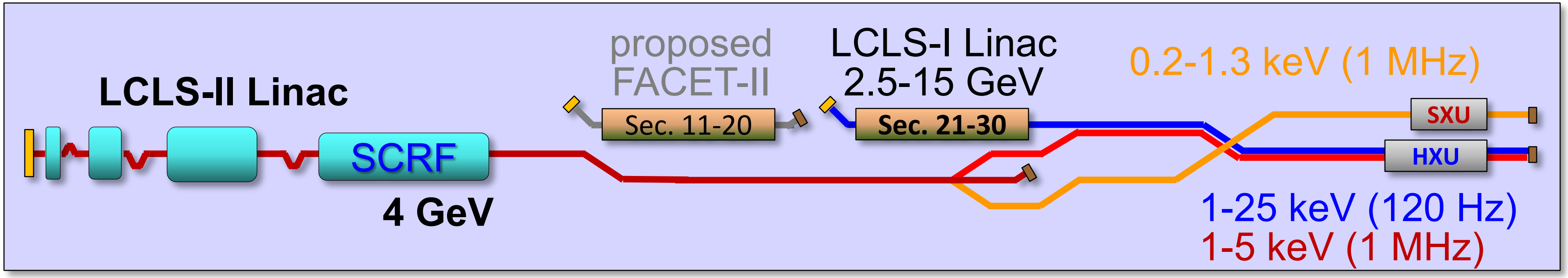
Linac Coherent Light Source Facility
and LCLS-II Upgrade (1st light 2019)
New SCRF linac and injector in 1st km of SLAC linac tunnel
Injector at 2-km point
Existing Linac (1 km) (with modifications)
Electron Transfer Line (340 m)
Undulators (130 m)
Near Experiment Hall
X-ray Transport Line (200 m)
Far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

LCLS-II Accelerator Layout

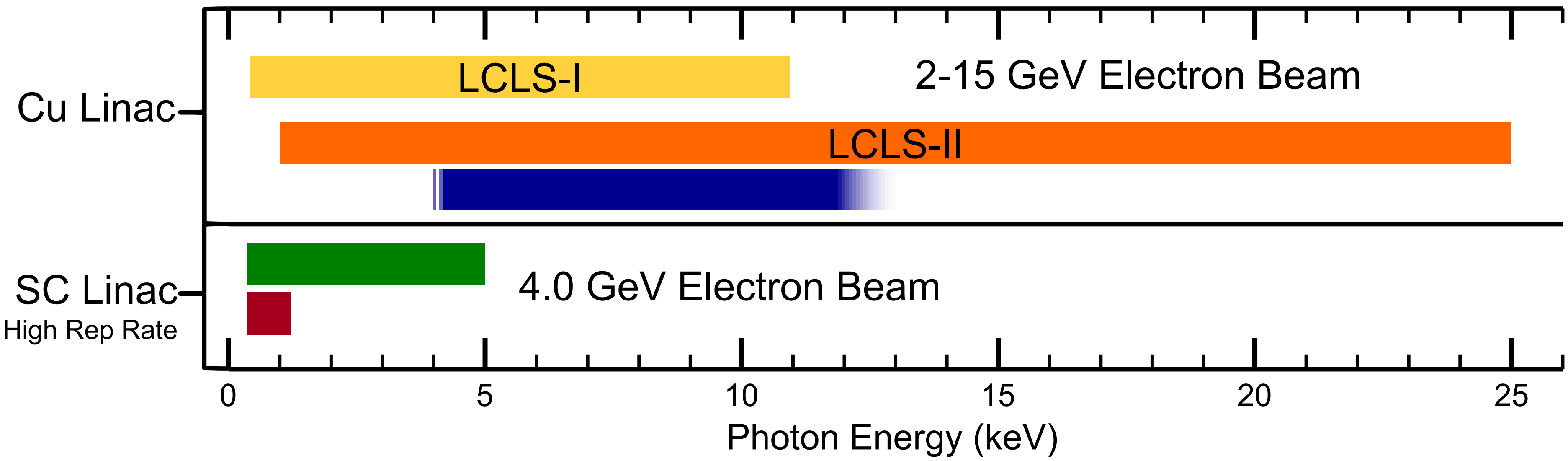
New Superconducting Linac → LCLS Undulator Hall

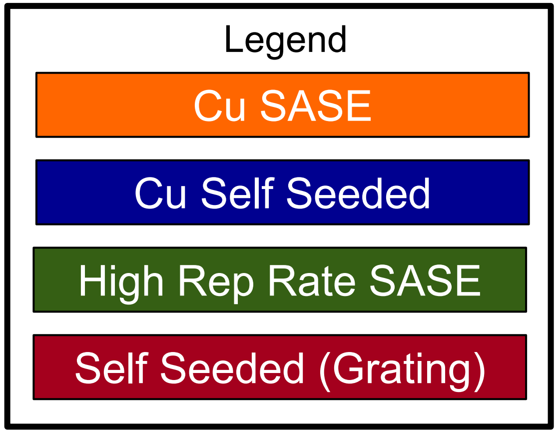
- Two sources: MHz rate SCRF linac and 120 Hz Cu LCLS-I linac
- Hard and Soft X-ray undulators can operate simultaneously in any mode

Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
Soft X-ray	0.20 - 1.3 keV with >100 Watts	
Hard X-ray	1.0 - 5.0 keV with >20 Watts	1 - 25 keV with mJ-class X-ray pulses



LCLS-II X-ray Coverage
Using SASE and Self-Seeding





Future expansion options

- External seeding below 1 keV
- Self seeding between 1.5 - 4 keV
- X-rays beyond 5 keV from the SCRF linac with >4 GeV beam energy
- Additional FEL's using 1.2 MW e-

LCLS-II Scientific Opportunities Workshop

- Upgrades paths for existing LCLS instruments
- Enhancements for beam operations
- Guidance on operating modes for science opportunities

Project Collaboration

SLAC

Fermilab

½ of cryomodules:
1.3 GHz

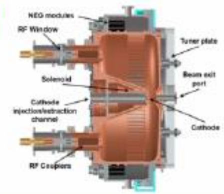
Jefferson Lab
EXPLORING THE NATURE OF MATTER

½ of cryomodules:
1.3 GHz

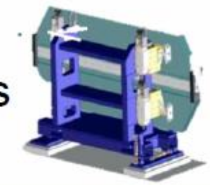
Cryoplant

BERKELEY LAB

e⁻ gun & associated injector systems



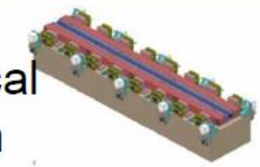
Undulators



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

Technical Challenges

The LCLS-II builds on the developments from the X-ray FEL program around the world

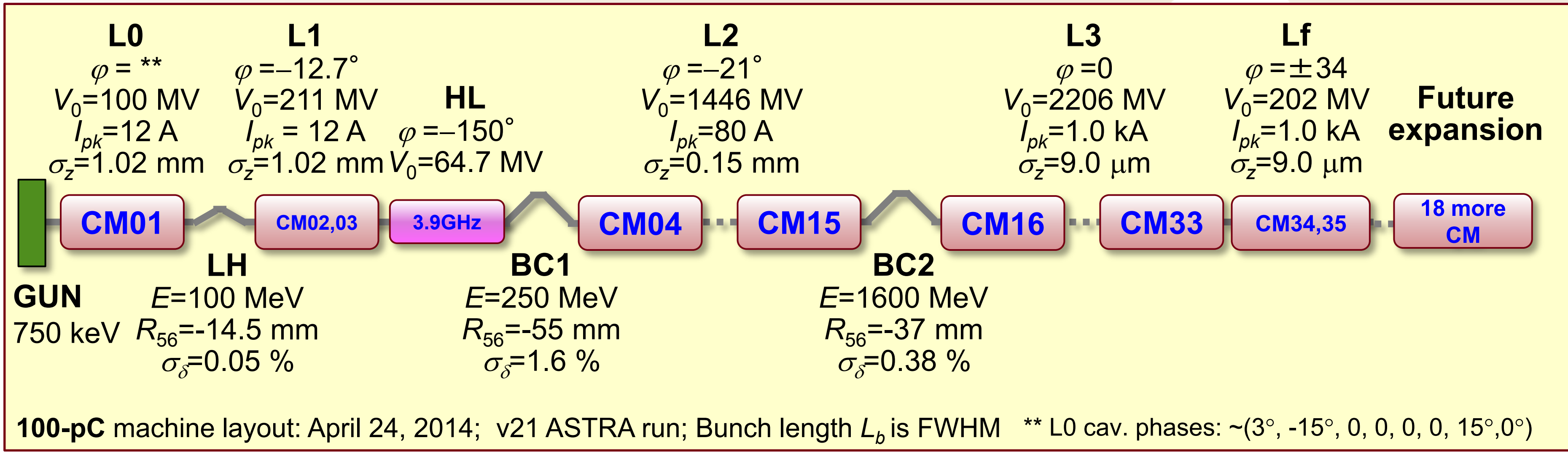
- Leveraged many of the LCLS design concepts

New challenges:

- CW superconducting RF system
- High brightness CW injector
- Variable gap undulators
- High beam power
- Dynamics in high brightness, low-energy electron beams

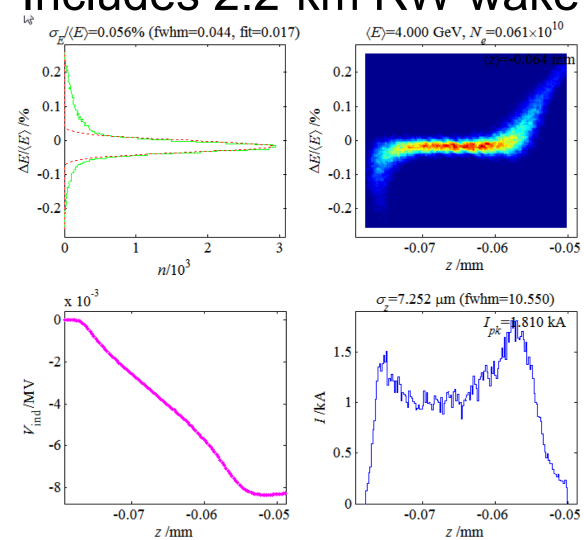
LCLS-II SCRF Linac Layout

Layout similar to LCLS (except SCRF)

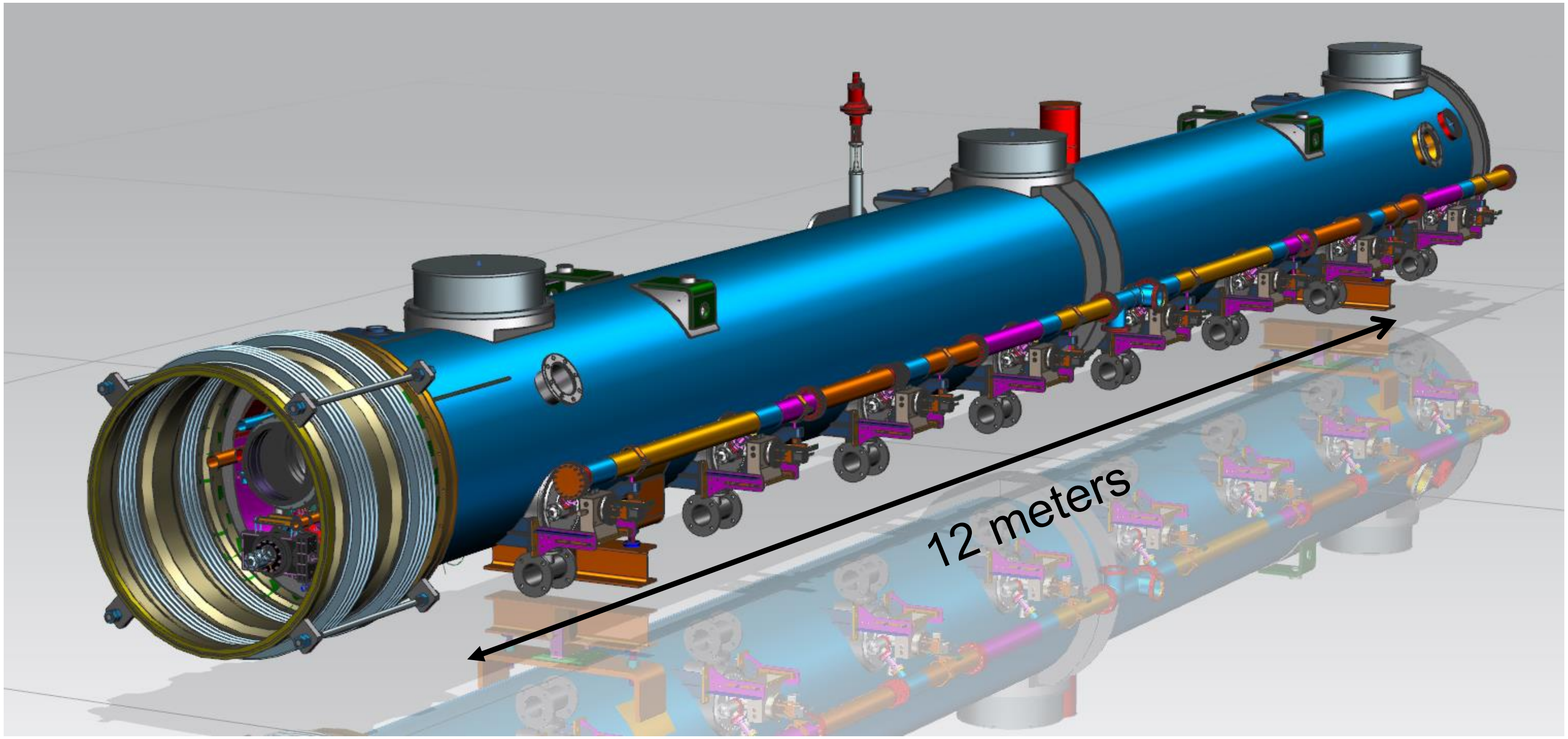


- Two-stage BC w/ linearizer plus laser heater
- Uses (35) 1.3 GHz and (2) 3.9 GHz CM
  - CM design adopted from ILC/XFEL design and adapted for CW operations
  - Fabricated and tested at FNAL and Jlab
  - Prototype assembly complete December 2015 and testing through May, 2016

Includes 2.2-km RW-wake



LCLS-II Cryomodule
1.3 GHz, modified for CW operation

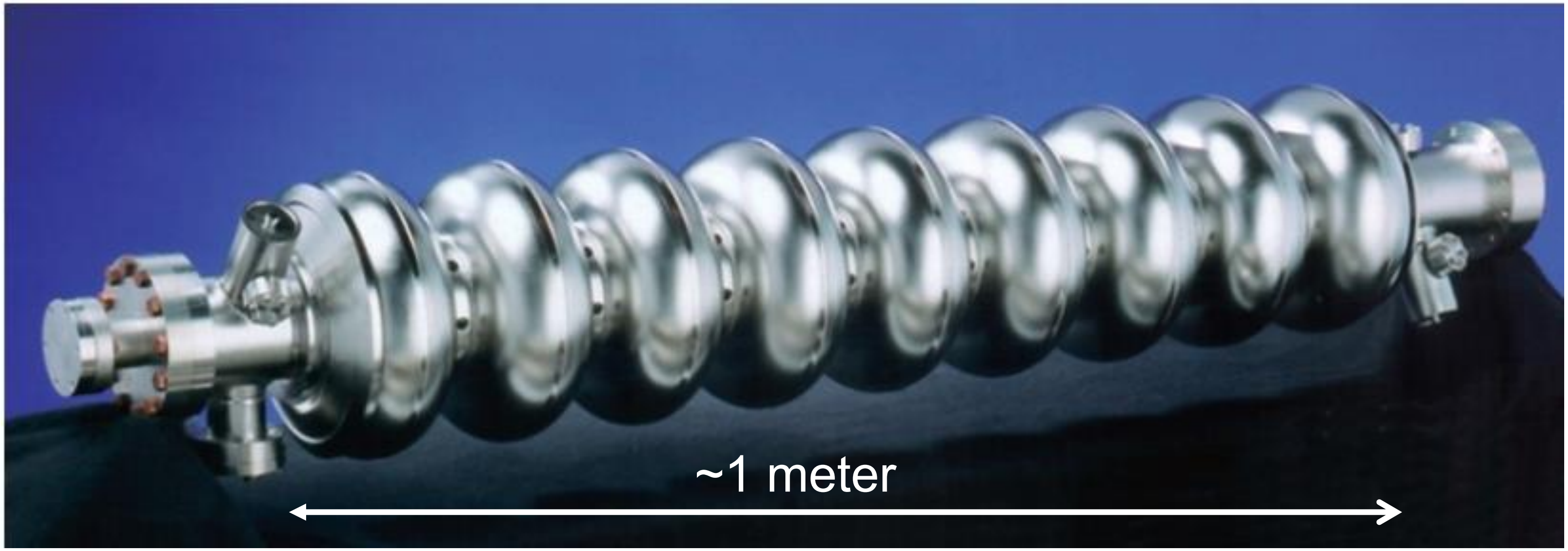


Crymodules will be similar to EuXFEL with modifications for CW operation.   EuXFEL producing 1 module/per week.

Superconducting RF Cavities

Eight 1-m 1.3 GHz cavities within each CM for 280 cavities total

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

RF Power System

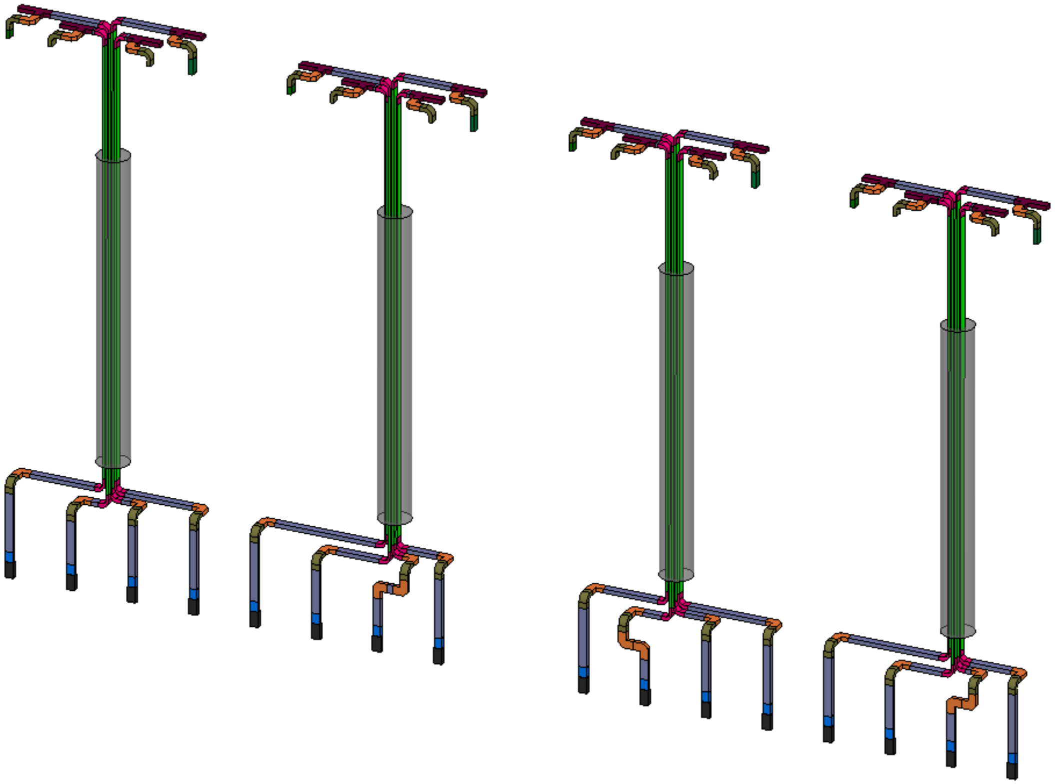
More than 1MW 1.3 GHz RF power for initial phase

Each cavity individually powered with 4 kW Solid-State Amplifier

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

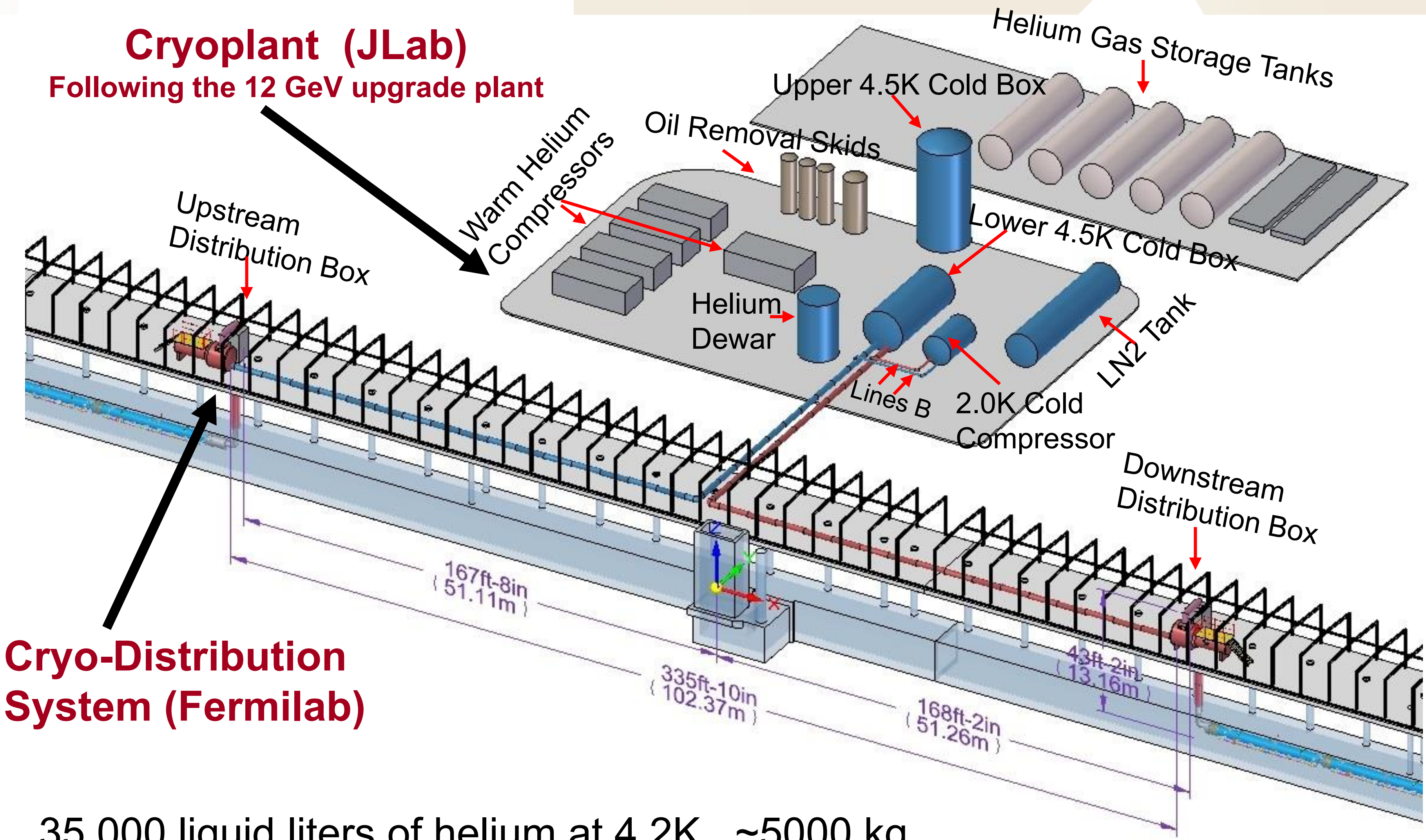
Example: 10 kW SigmaPhi Amp

Waveguide distribution system through 25' penetrations into linac tunnel

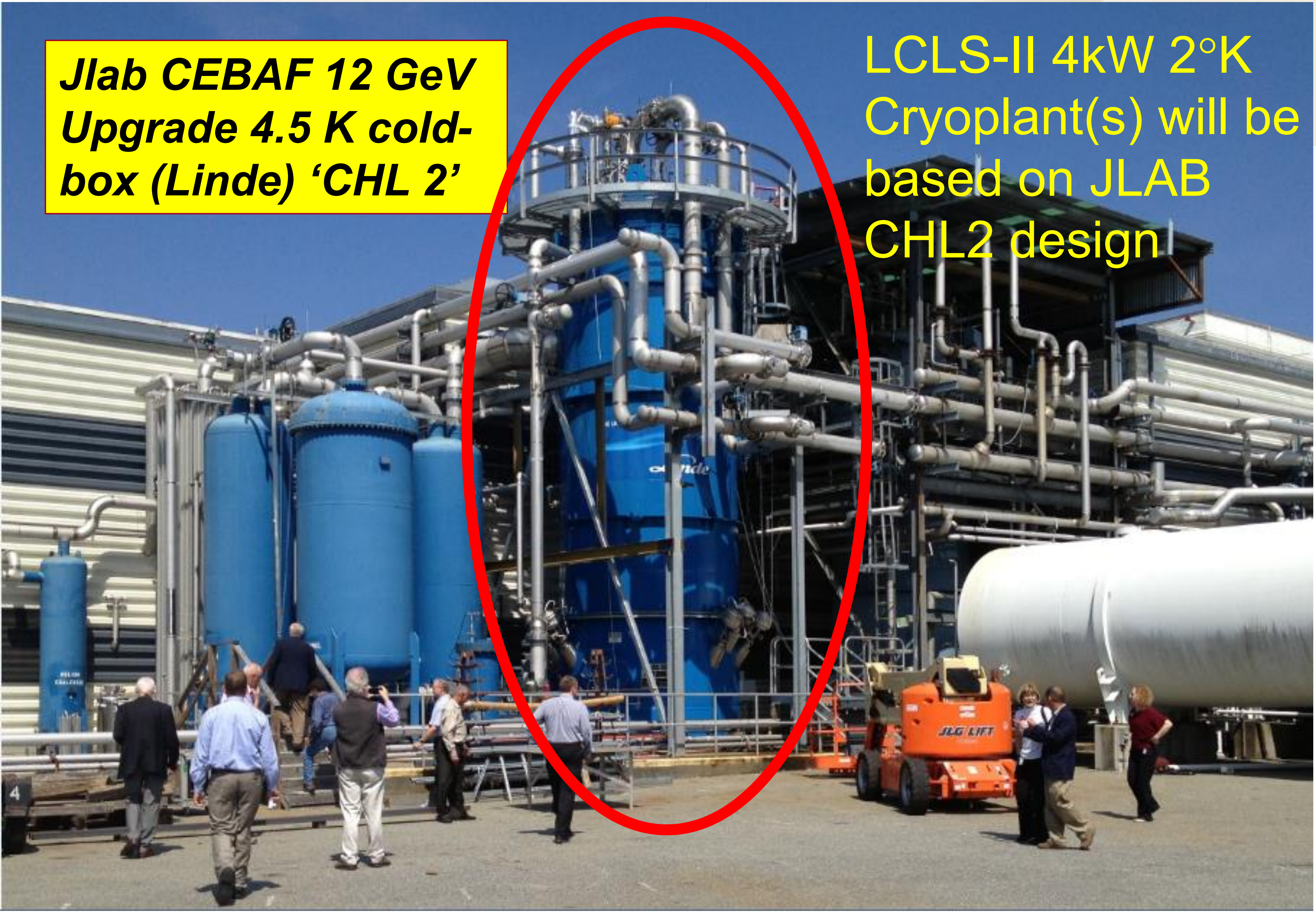


Cryoplant and Cryogenic Distribution System

Exploring single and double cryoplant options

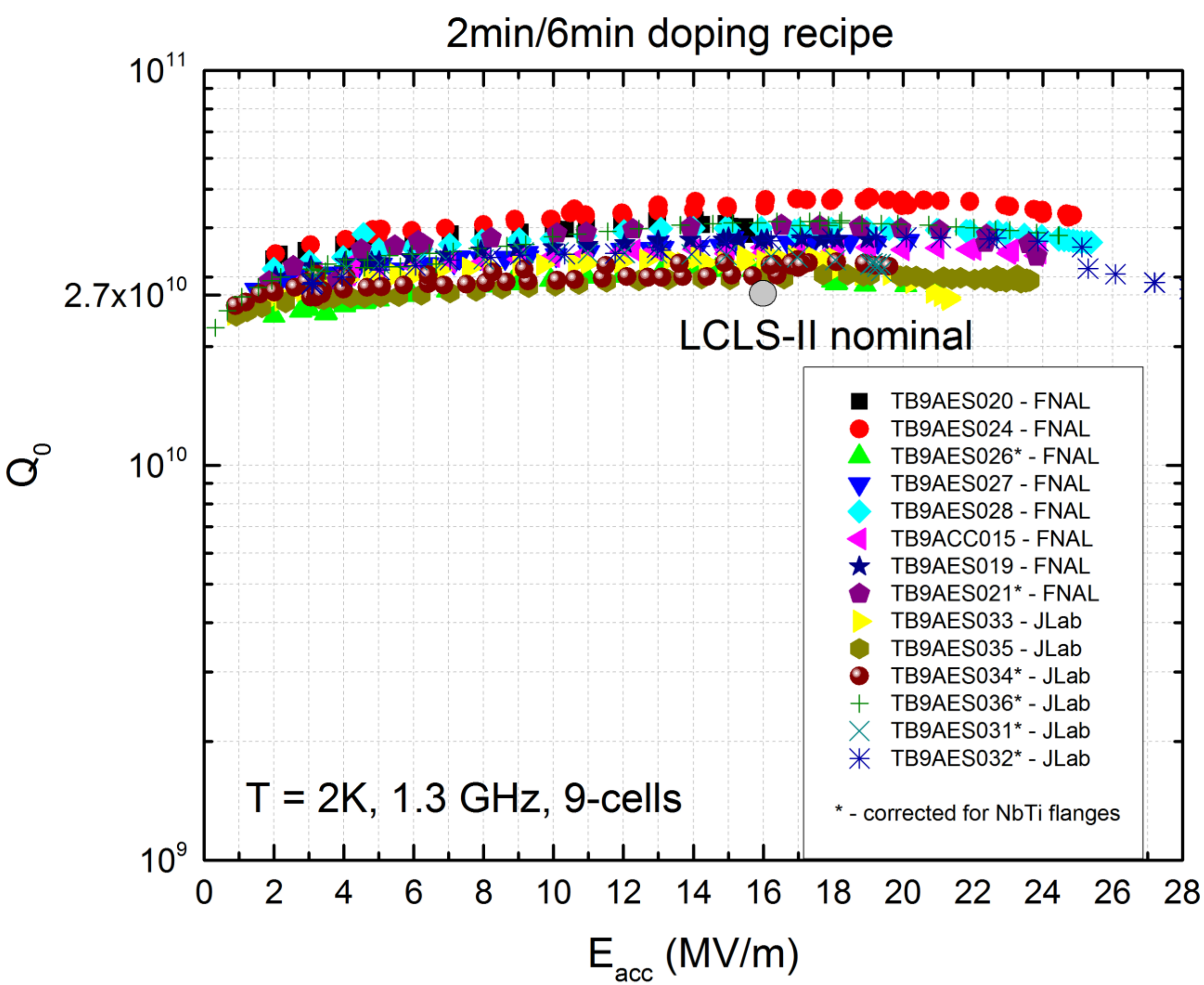


35,000 liquid liters of helium at 4.2K, ~5000 kg


Jlab CEBAF 12 GeV Upgrade 4.5 K cold-box (Linde) ‘CHL 2’
LCLS-II 4kW 2°K Cryoplant(s) will be based on JLAB CHL2 design
JLG LIFT

Cryogenic Load → Maximize Q_0

CW linac is dominated by dynamic (RF) losses

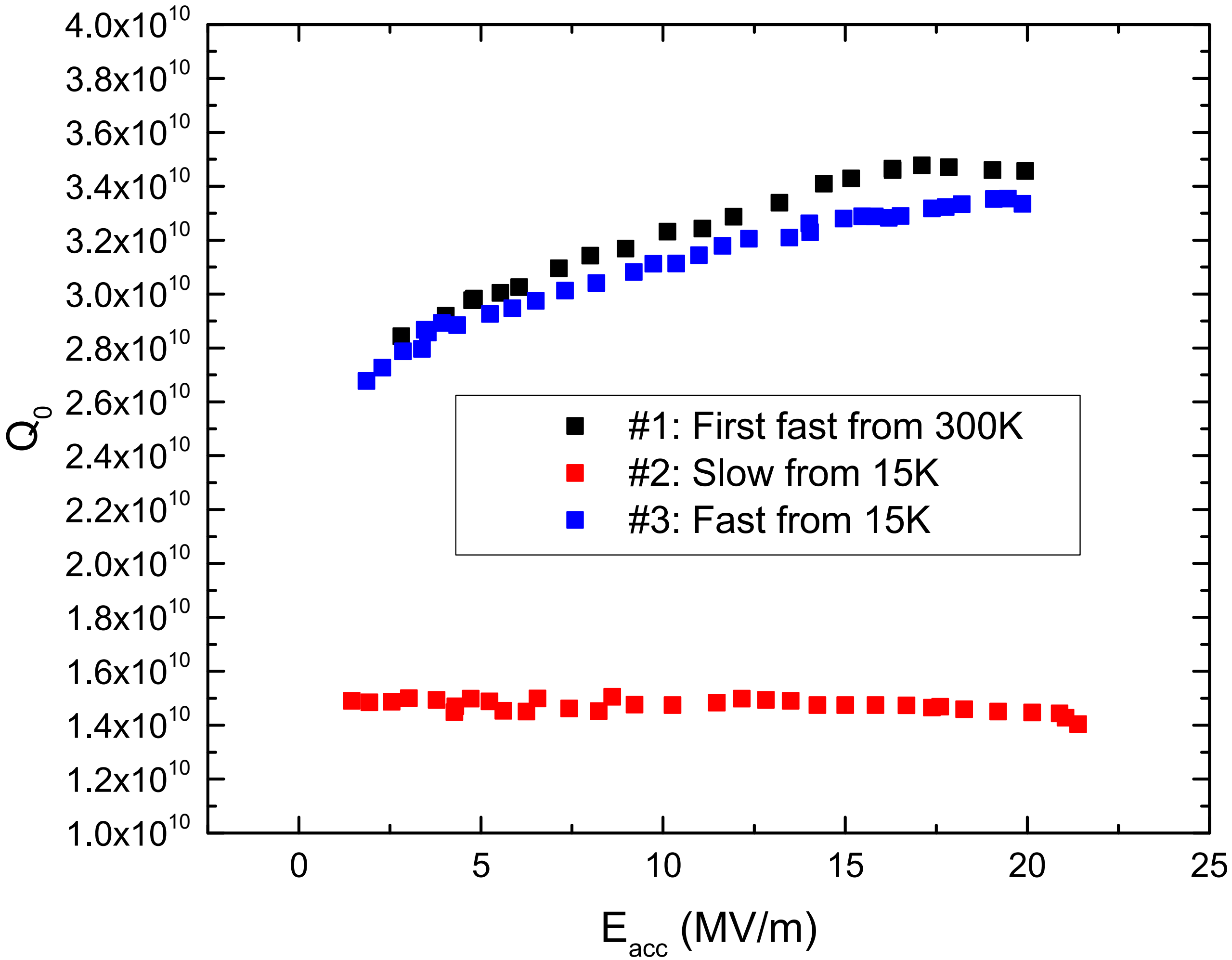


Nitrogen-doping technology has huge impact on CW SCRF accelerators

See A. Grassellino's plenary talk from Monday: MOYGB2

Working to understand Q_0 preservation into CM

Details of residual field, cooldown, geometry, …

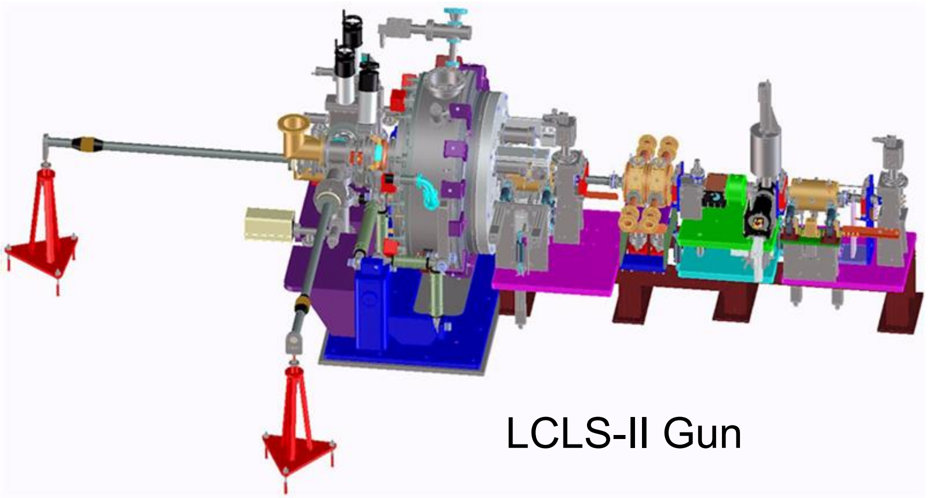


Dressed Nitrogen-doped nine cell cavity vertical test at T=2K

Tests at FNAL, Cornell, and Jlab

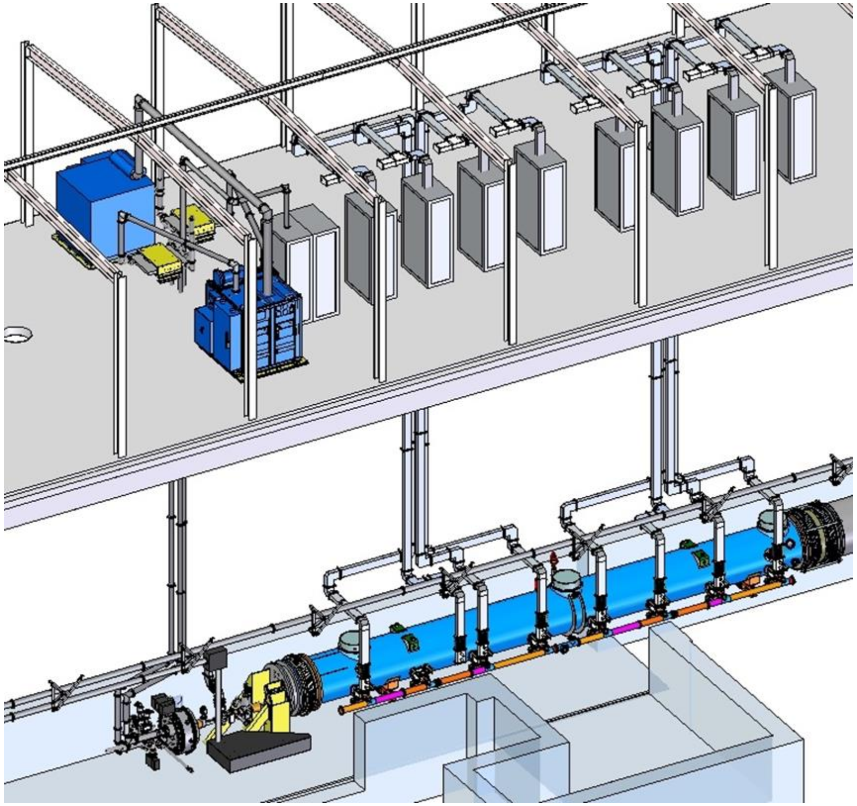
LCLS-II Electron Injector

- The LCLS-II Injector uses a 750 kV VHF RF gun based on the APEX project gun at LBNL



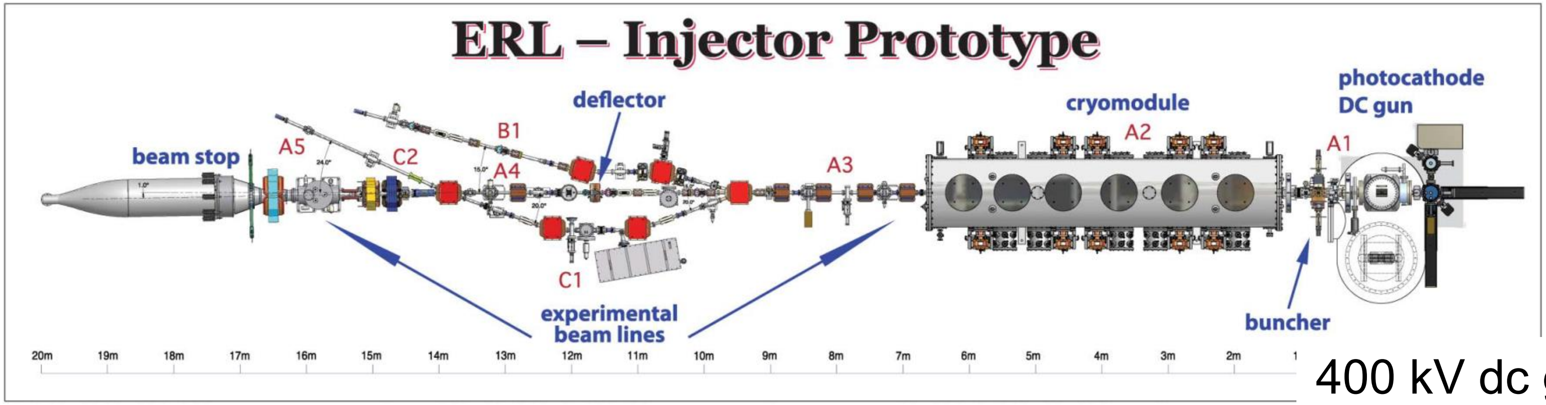
LCLS-II Gun

LCLS-II Injector



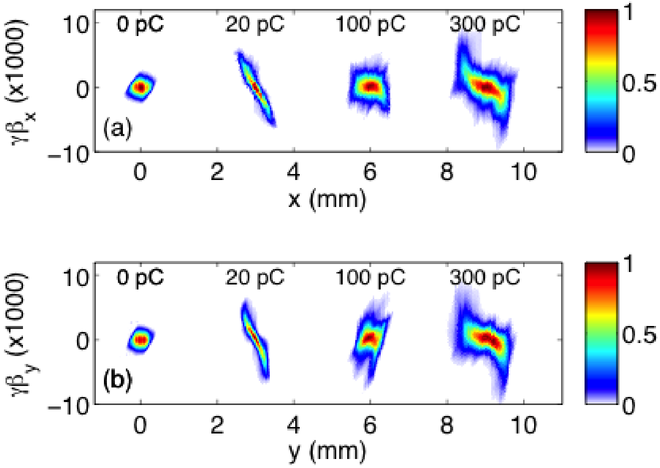
- Current APEX performance
  - Low dark current
  - Good cathode lifetime
  - Beam properties – October 2015

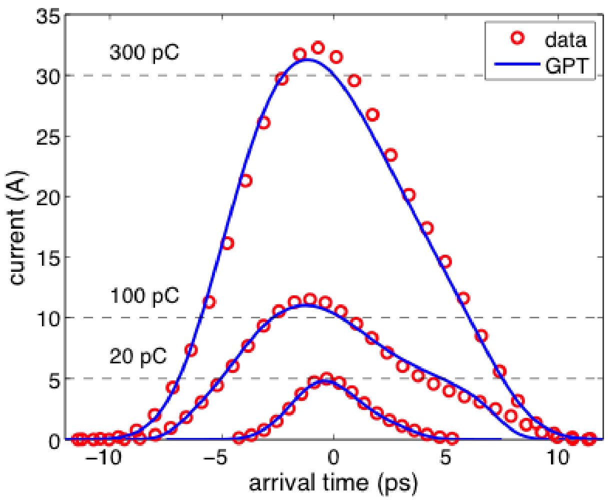
Injector Feasibility R&D
Nominal transverse parameters demonstrated at Cornell



400 kV dc gun

Bunch charge	Peak current	Emittance (95%)
20 pC	5 A	0.25 μm
100 pC	10 A	0.4 μm
300 pC	30 A	0.6 μm



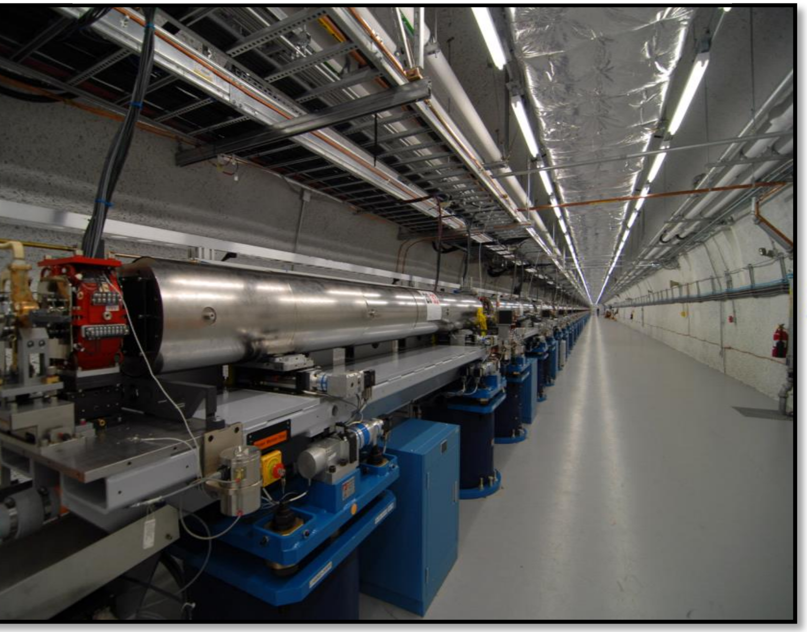


C. Guilliford, *et al*, http://arxiv.org/abs/1501.04081 (2015)

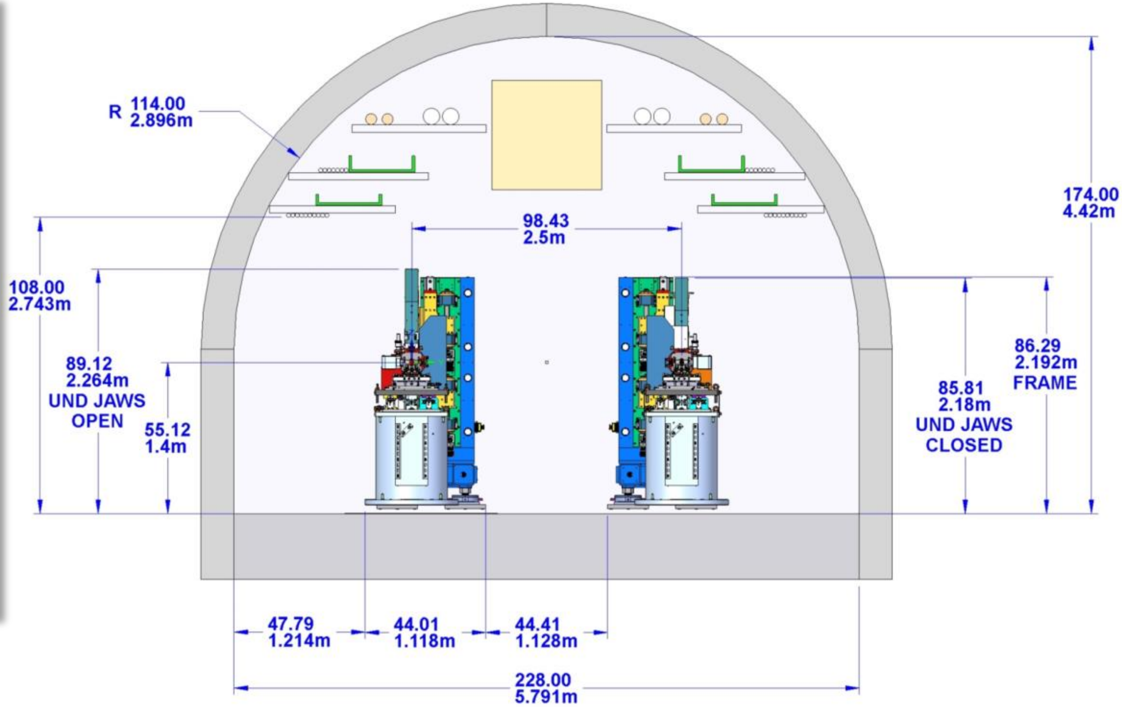
LCLS-II Undulator Hall

- The existing LCLS undulator will be removed from the hall
- LCLS-II adds two new variable gap undulators
  - X-ray energy tunability at a fixed electron beam energy

Existing LCLS Undulator

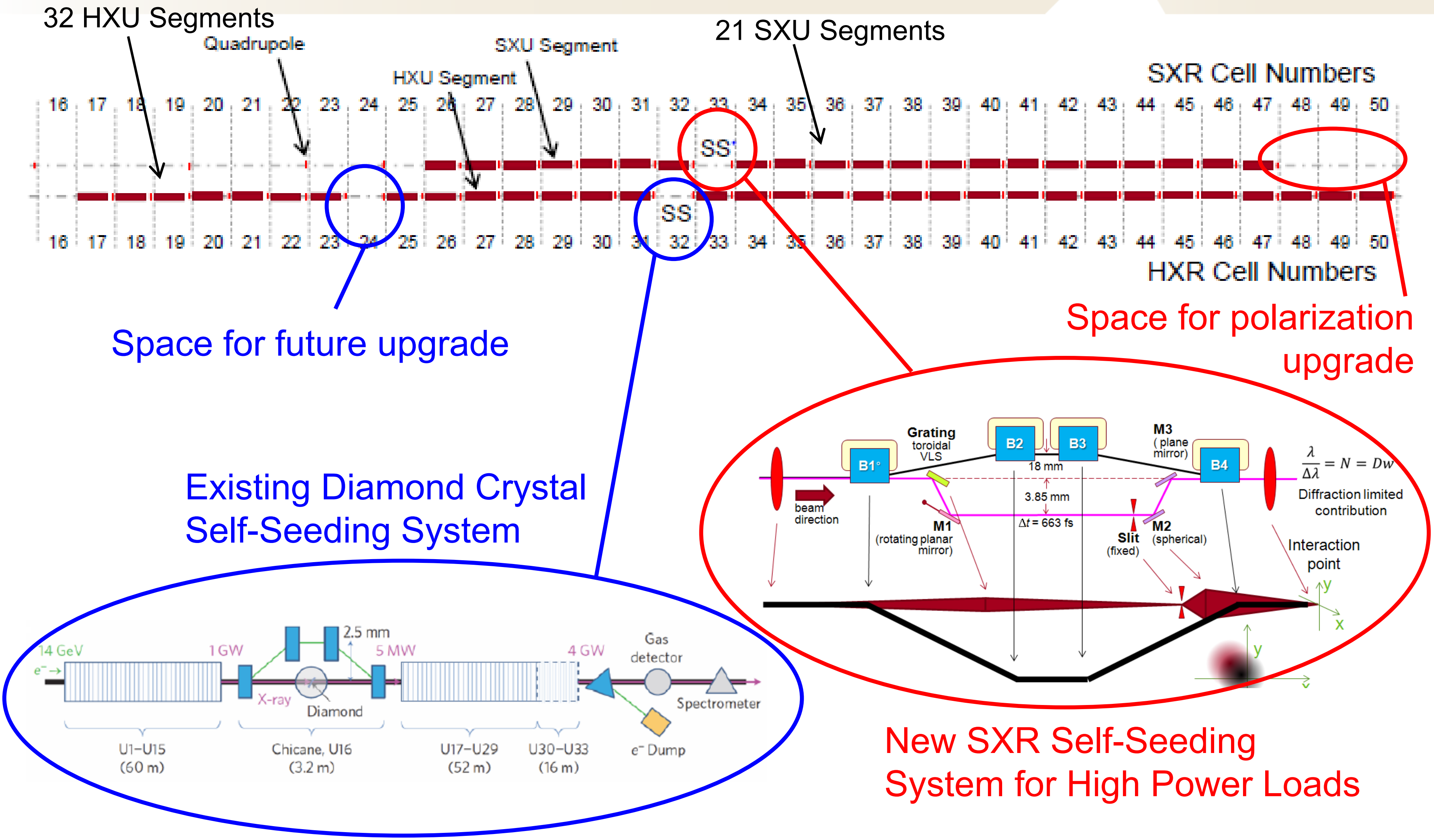


Two new LCLS-II Undulators in the tunnel

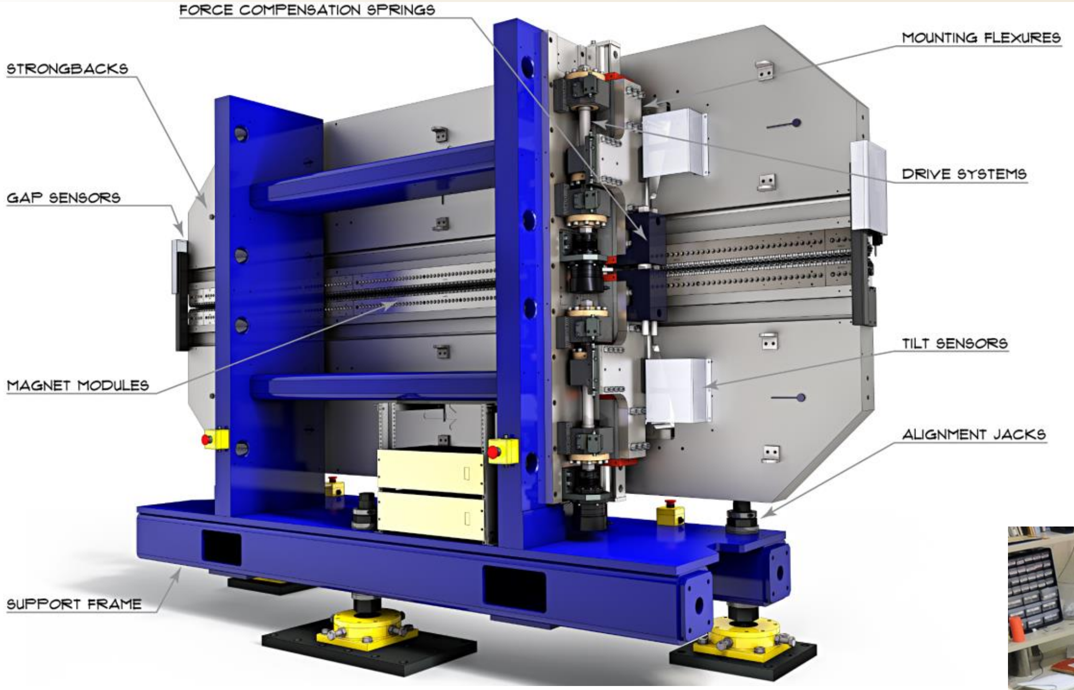


LCLS-II Undulator Layout

150 meter existing Undulator Hall



Variable Gap Hybrid Undulators
Ongoing Development at LBNL and ANL

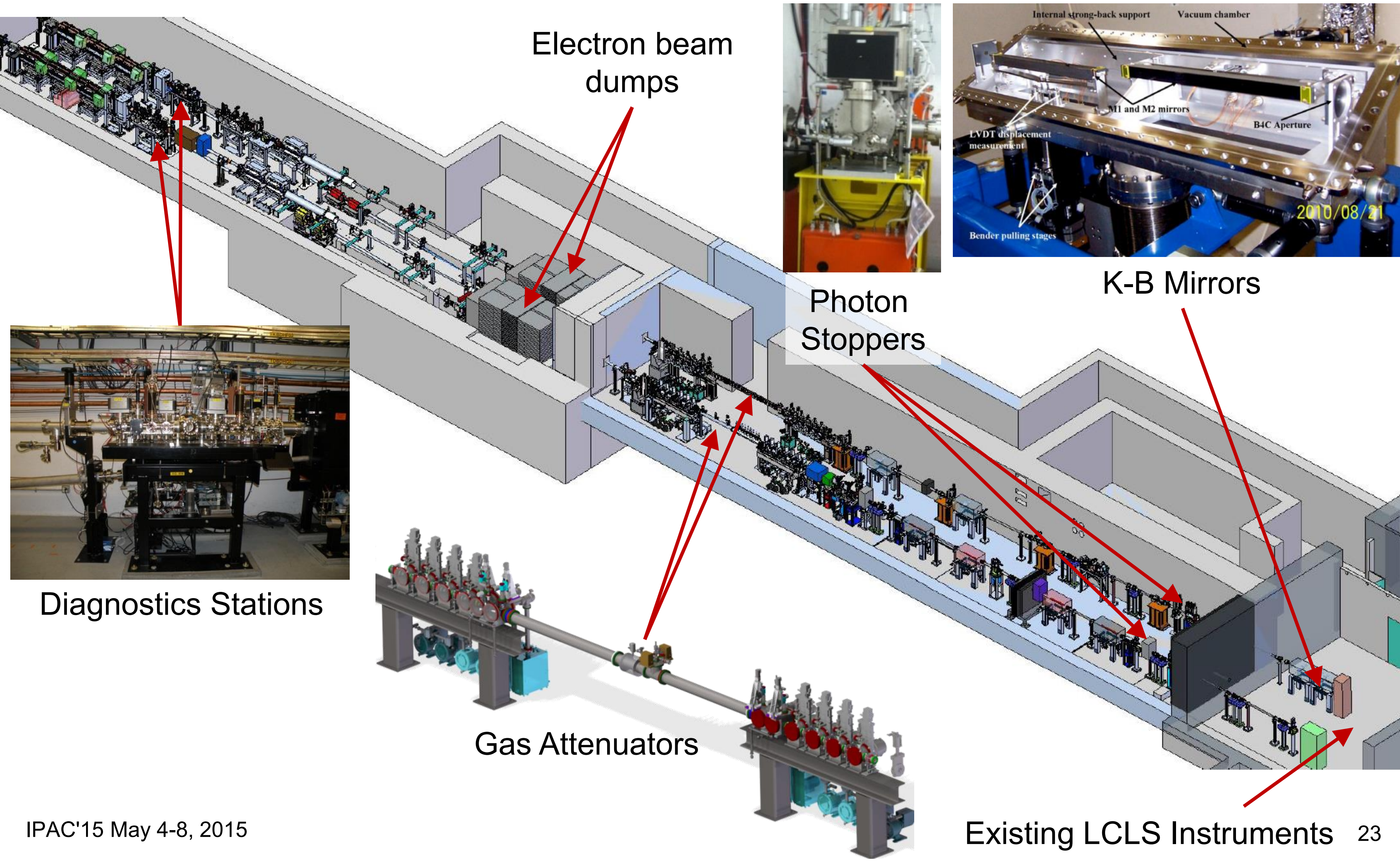


Variable gap undulators used in LCLS-II to provide greater wavelength tuning flexibility

Developing two alternates: Superconducting undulator (SCU) and a Horizontal gap vertically polarized undulator (VPU). See: E. Gluskin, TUXC1

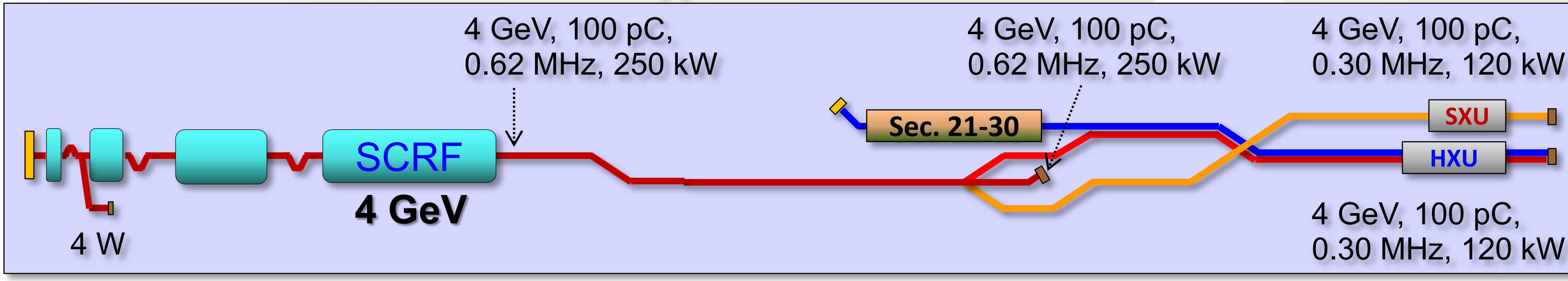
X-ray Transport

Designed for 10 mJ peak and 200 W average X-ray power



High Power CW Linac

Beam Collimation and Diagnostics



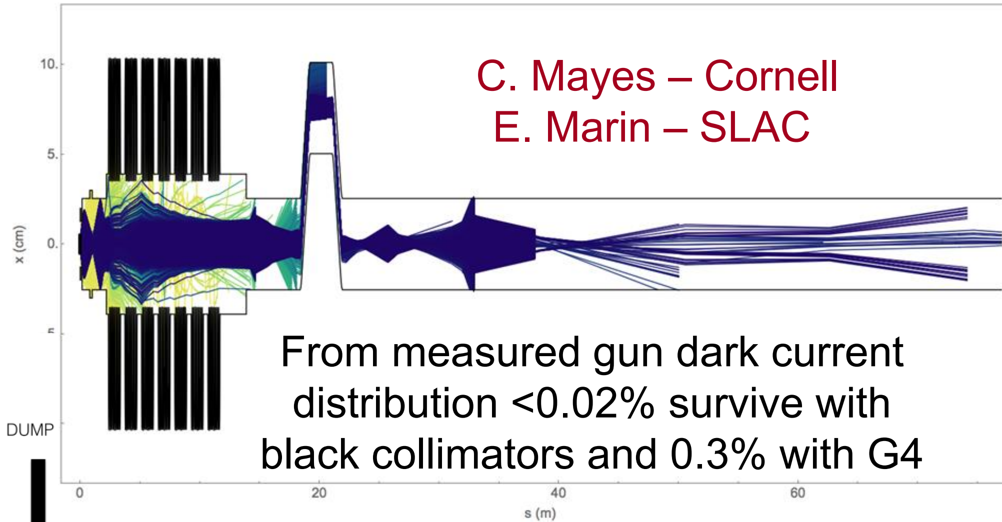
- Diagnostics are based on existing for 10-300 pC/bunch
- Beam power and beam loss issues are critical
  - Designing multi-stage collimation system to control losses
  - Hybrid PM undulators sensitive to nearby losses (3 pA)
- Linac designed for 1.2 MW but undulators limited to 120 kW
  - 250 kW maximum power through linac in initial phase
  - Studying dark current and FE effects and radiation limits
- Beam dumps are modified versions of existing MW dumps

Collimation Studies

Reduce halo to 3pA loss in undulators

- Four or five stages of (x, x’, y, y’, ΔE) collimation
- Could add Δt collimation in Bypass and COL0

Tracking cathode → COL0

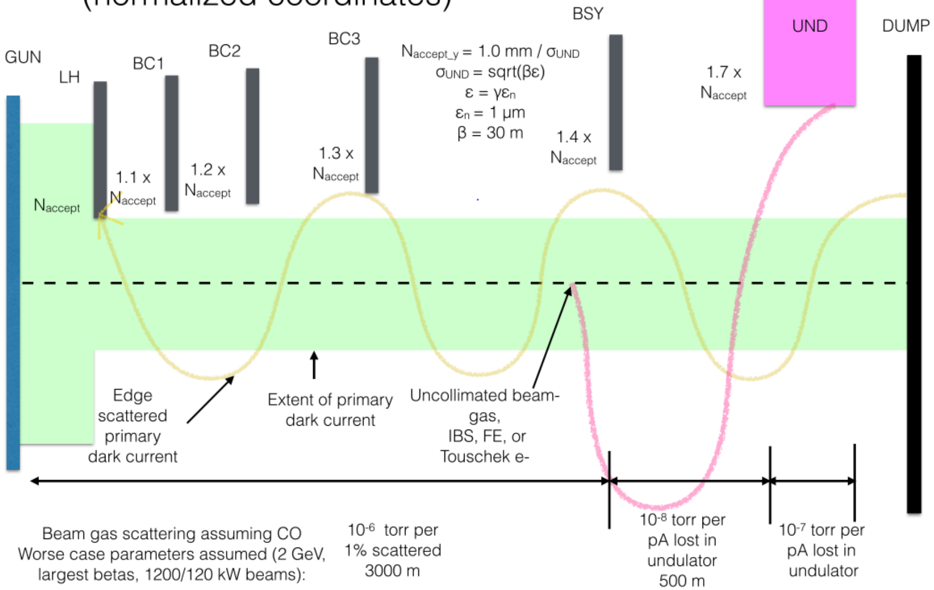


C. Mayes – Cornell
E. Marin – SLAC

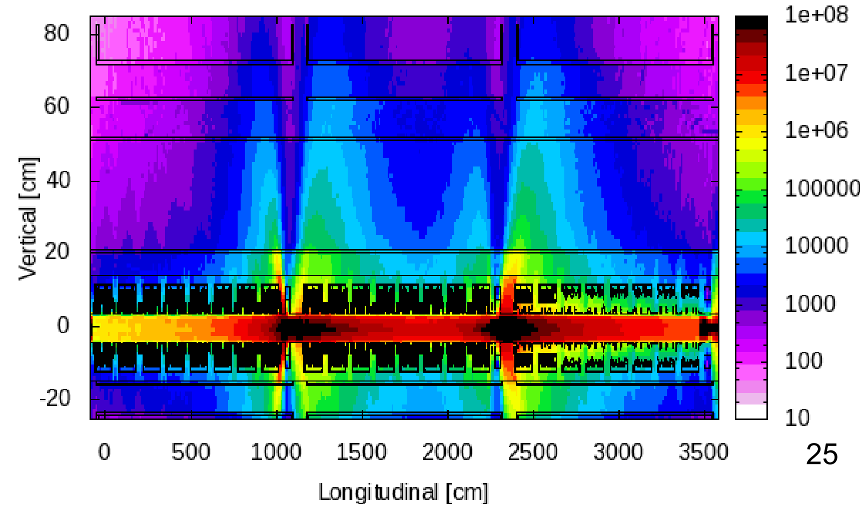
From measured gun dark current distribution <0.02% survive with black collimators and 0.3% with G4

Schematic of Collimation System (normalized coordinates)

J. Welch



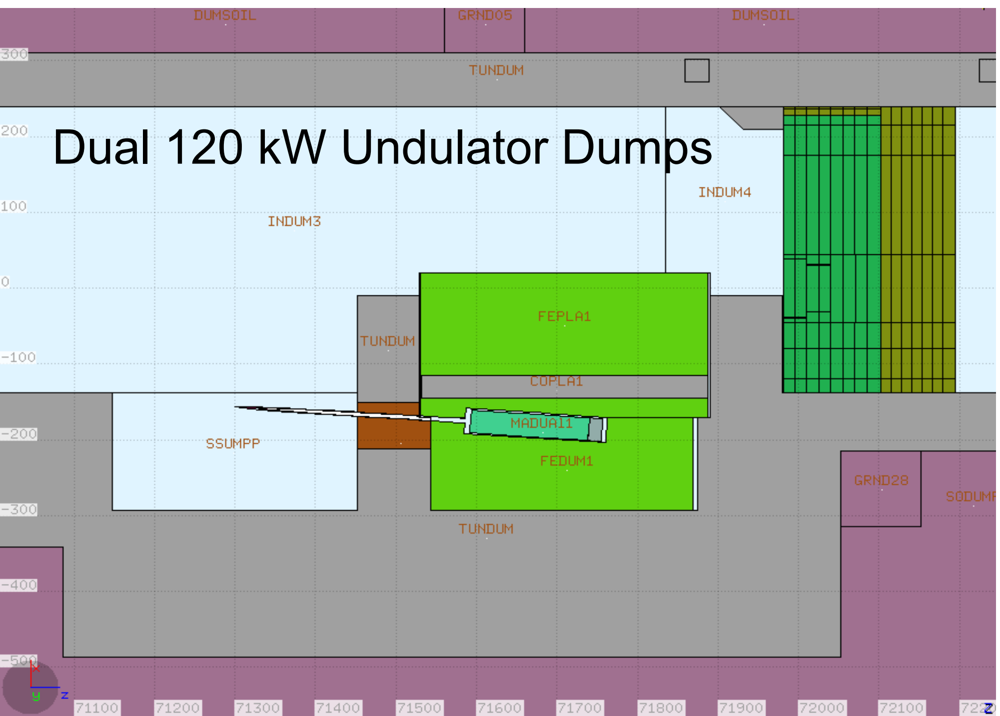
FE Simulation: Z. Li, C. Xu, L. Ge, M. Santana

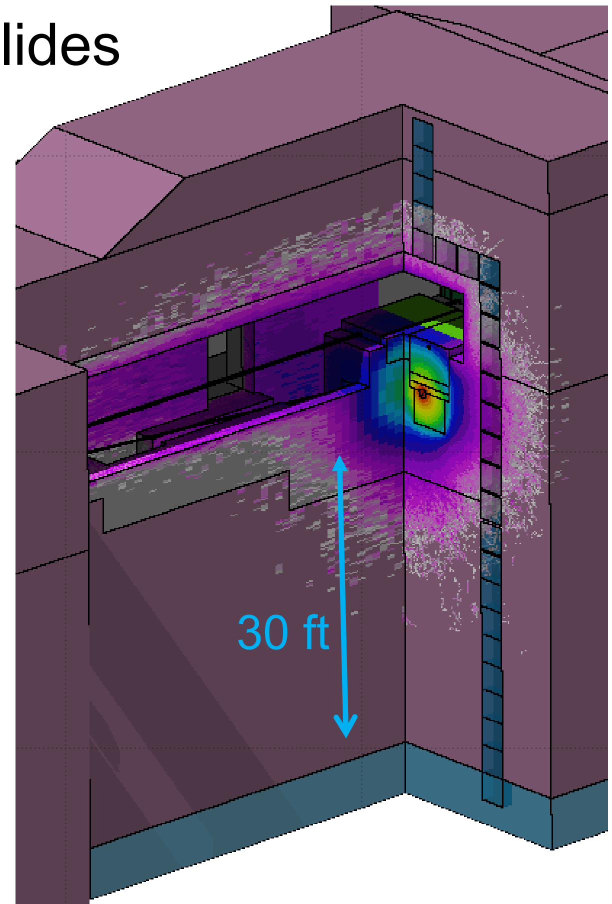


MW-class Beam Dumps

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

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

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 made using LBNL Edison Cray XC30

High brightness beams at modest energy and long transport

→ new longitudinal micro-bunching instabilities

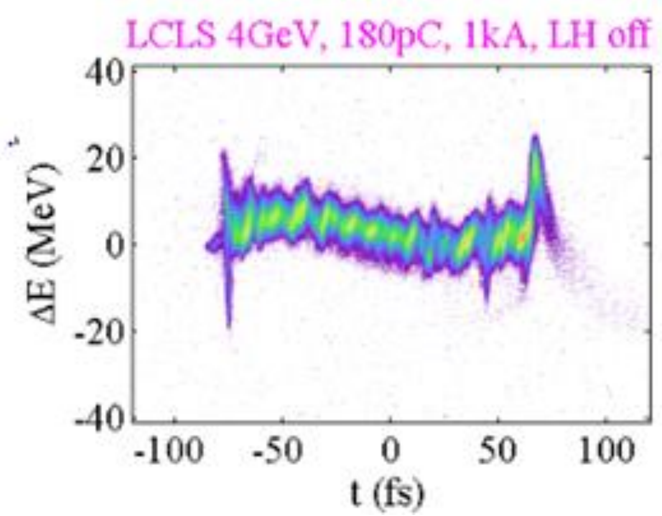
Micro-Bunching Effects

Micro-bunching seen at LCLS and suppressed with laser heater → adopted similar approach for LCLS-II

New effects being studied for LCLS-II using high-fidelity simulation codes (IMPACT and Elegant) and analytic models

- Sensitivity to higher-order optics
- Coupling to transverse fields
- …

M. Venturini, J. Qiang, C. Mitchell



Simulations are being benchmarked using the LCLS at low energy

- Benchmarking configurations are chosen to exacerbate relevant physics

Y. Ding, J. Qiang, D. Ratner

Summary

LCLS has been a great success and has verified much of the critical electron beam dynamics and FEL physics

- LCLS-II being designed and constructed with strong US collaboration and support from international partners
- LCLS-II will expand beyond LCLS with:
  - CW SCRF technology
  - High brightness CW injector
  - Variable gap undulators
  - High power beams
  - Transport of ‘low’ energy high brightness beams

Thank you for your attention