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

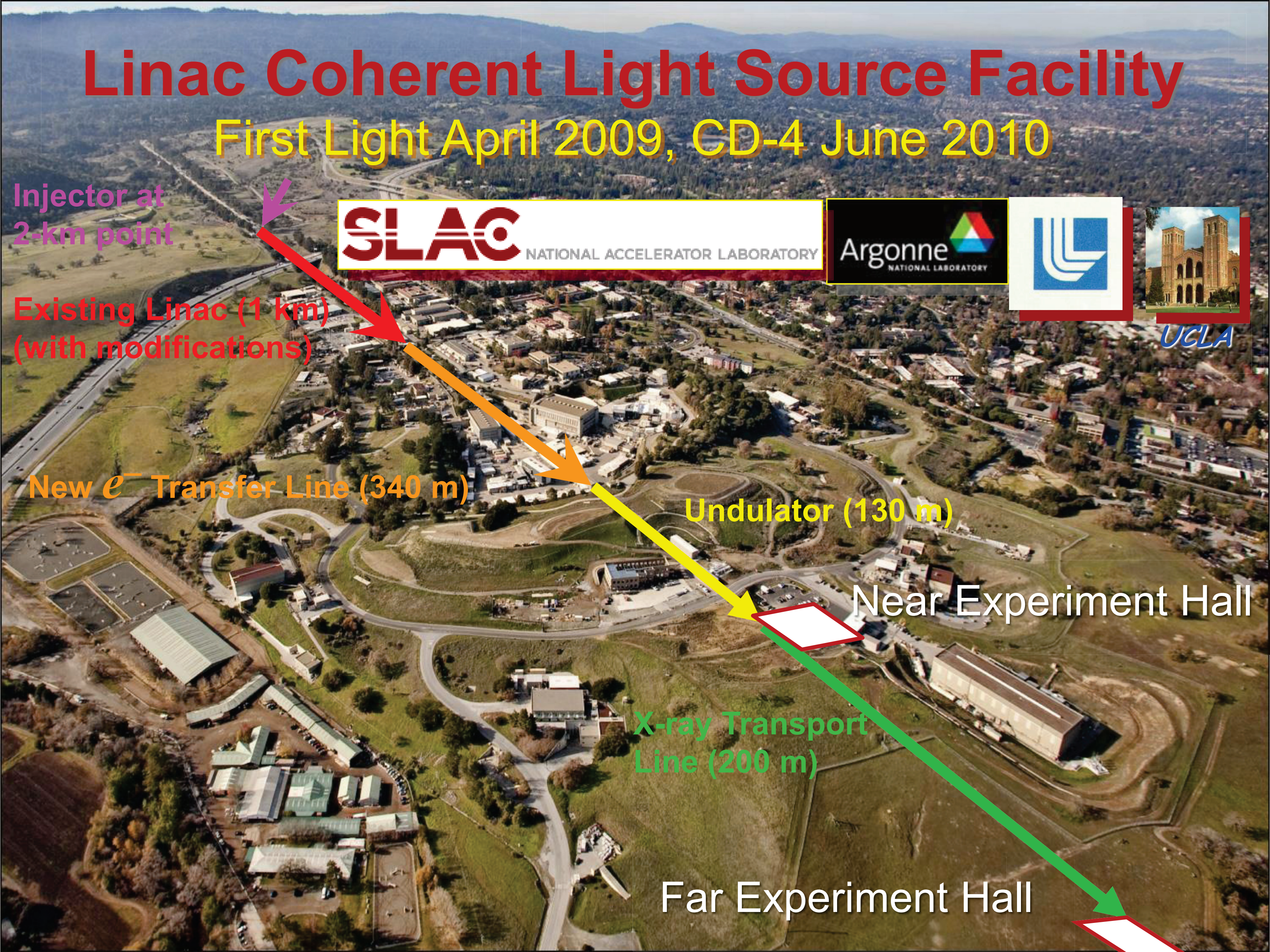
Tor Raubenheimer for LCLS-II Project Team

August 27th, 2014

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

Linac Coherent Light Source Facility

First Light April 2009, CD-4 June 2010



LCLS-II (Phase I: 2010-2013 RIP)

LCLS-II Reborn: July, 2013
(BESAC Subcommittee Outcome)

- Committee report & presentation to BESAC:
  - "It is considered essential that the new light source have the pulse characteristics and **high repetition rate** necessary to carry out a broad range of coherent "pump probe" experiments, in addition to a sufficiently broad photon energy range (**at least *~0.2 keV to ~5.0 keV***)"
  - "It appears that such a new light source that would meet the challenges of the future by *delivering a capability that is beyond that of any existing or planned facility worldwide is now within reach.* **However, *no proposal presented to the BESAC light source sub-committee meets these criteria*.**"
  - "The panel recommends that a decision to proceed toward a new light source with revolutionary capabilities be accompanied by a robust R&D effort in accelerator and detector technology that will maximize the cost-efficiency of the facility and fully utilize its unprecedented source characteristics."

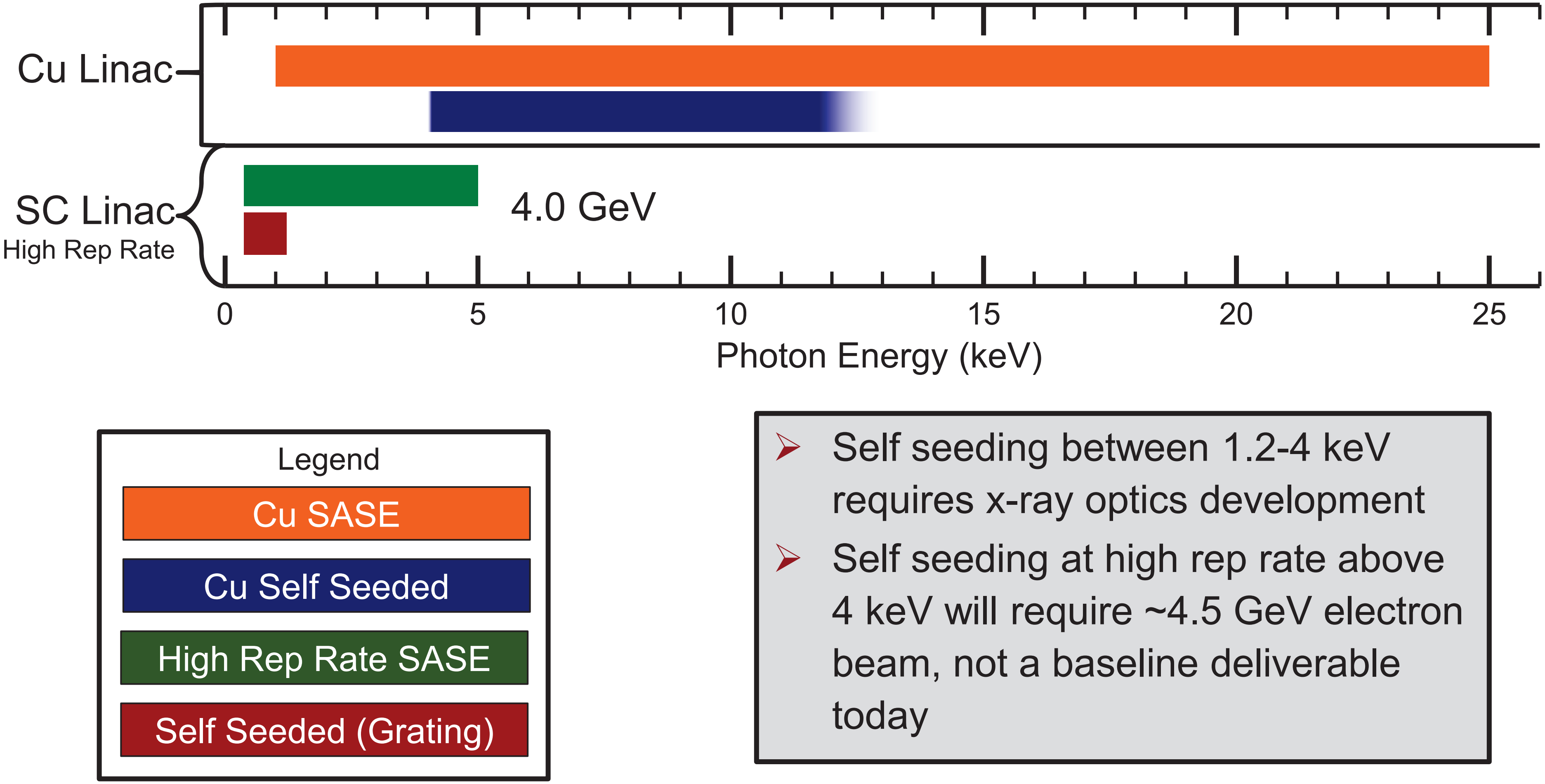
LCLS-II Reborn
(August, 2013)

BESAC Recommendation		Implementation
High repetition rate	✓	CW Linac with MHz capability
Broad energy range	✓	SC and Cu Linacs with variable gap undulators
Transform limited	✓	Self seeding narrows bandwidth; add monochomator to control bandpass
Ultra-bright	✓	14GeV linac & high K undulator
Multiple undulator sources	✓	Two undulators

Parameter choices are driven by performance constraints:

1. Soft X-ray photons from SASE and self-seeding between 0.2 and 1.3 keV at up to MHz rates;
2. Hard X-ray photons from SASE between 1.0 and 5.0 keV at up to MHz rates;
3. Hard X-ray photons with SASE and self-seeding at energies of more than 25 keV at 120 Hz, with performance comparable to or exceeding that of the existing LCLS.

Revised LCLS-II (Phase II) Baseline Deliverables



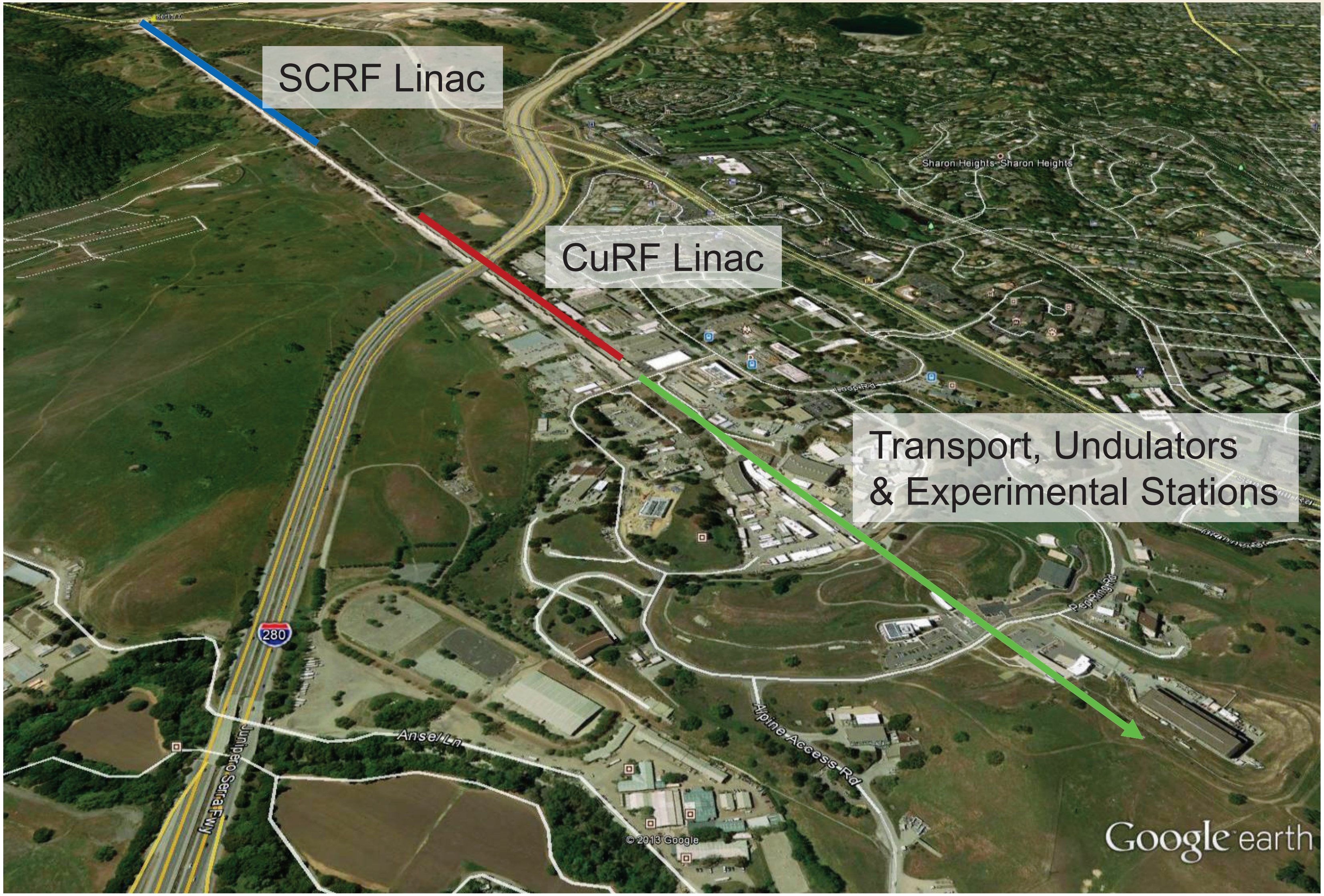
- Self seeding between 1.2-4 keV requires x-ray optics development
- Self seeding at high rep rate above 4 keV will require ~4.5 GeV electron beam, not a baseline deliverable today

LCLS-II Accelerator Design
(Plan for rapid construction)

- New linac based on 1.3 GHz SCRF with MHz beam rate
  - Laser heater, harmonic linearizer and dual bunch compressor with option for third compressor at linac end
  - Link into existing LCLS beamlines
- Dual variable gap hybrid undulators to cover energy range
  - Self-seeding in both HXR and SXR undulators with options for additional photon phase space control
- Leverage extensive work on NGLS, NLS, EU-XFEL, ILC and $\text{LCLS-II}_{\text{Phase I}}$ to develop conceptual design
  - New project definition occurred very rapidly (fall of 2013)
  - Aiming for 1^{st} light at end of 2019

LCLS-II (Phase II) Concept

Use 1st km of SLAC linac for CW SCRF linac

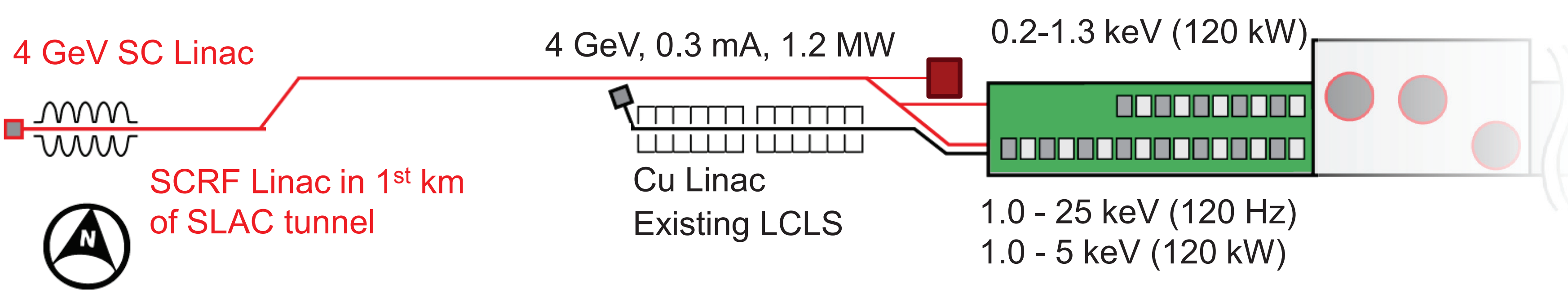


LCLS-II Accelerator Layout
New Superconducting Linac → LCLS Undulator Hall

- 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

- Concurrent operation of 1-5 keV and 5-25 keV is not possible

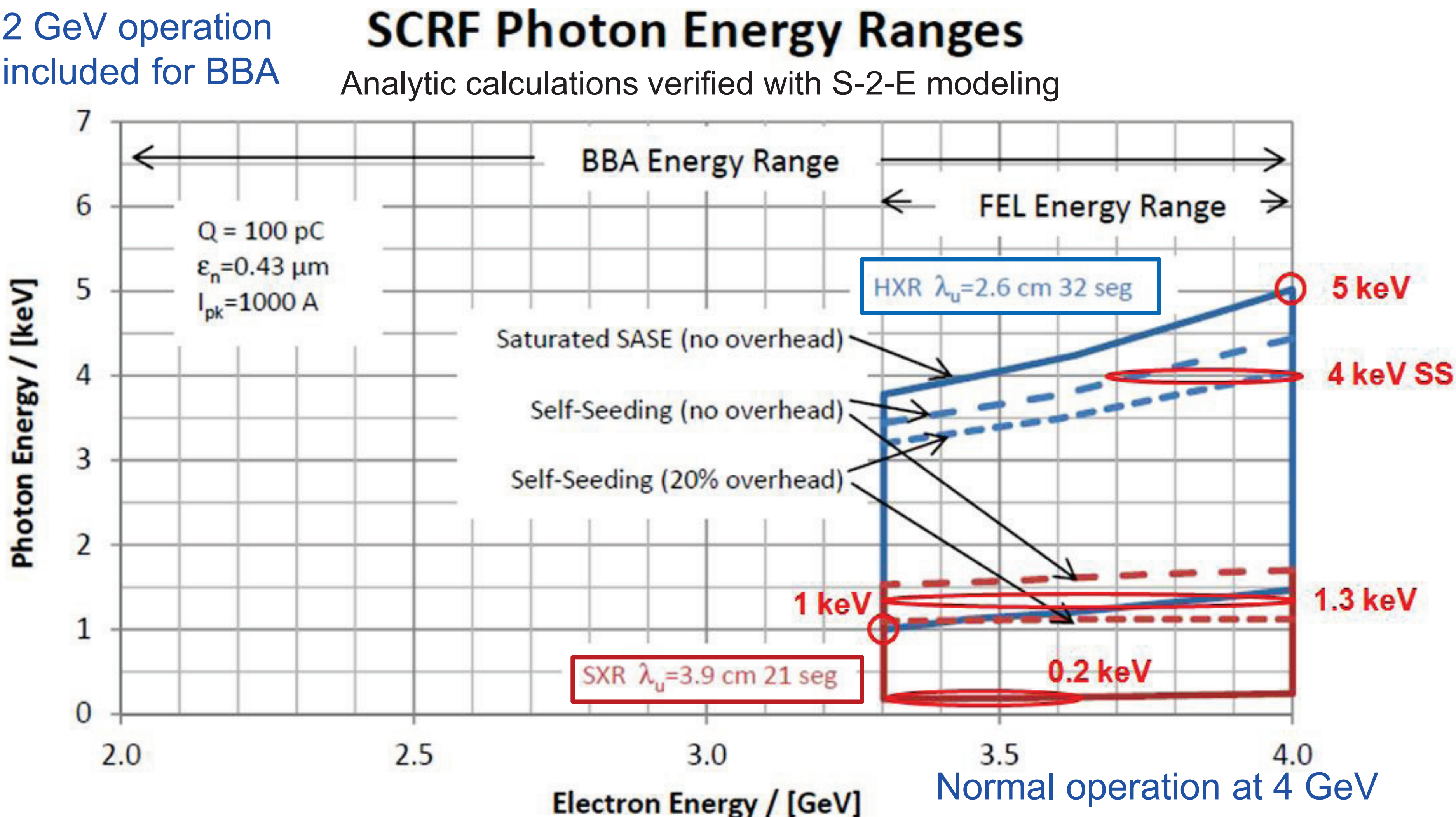


LCLS-II (SCRF) Baseline Parameters

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 - ?e10	-
Photon energy range of SXR (**SCRF**)	E_{phot}	-	**0.2 - 1.2**	keV
Photon energy range of HXR (**SCRF**)	E_{phot}	-	**1 - 5**	keV
Photon energy range of HXR (**Cu-RF**)	E_{phot}	-	**1 - 25**	keV

Baseline High Rate FEL Tuning Range
(HXR between 1 and 5 keV; SXR between 0.2 and 1.3 keV)

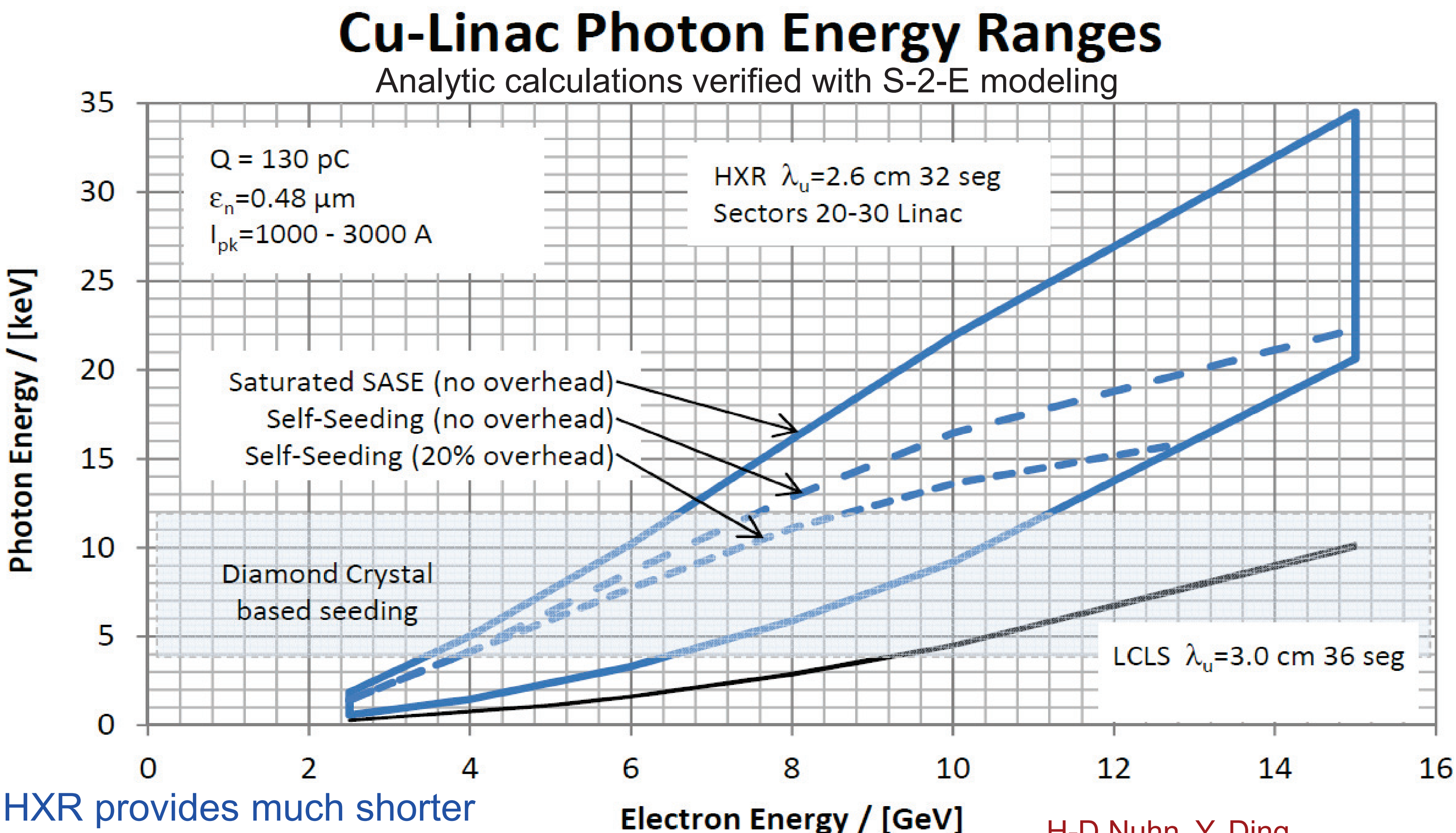
2 GeV operation included for BBA



Normal operation at 4 GeV covers photon range of primary interest

H-D Nuhn, Y. Ding, G. Marcus, J. Wu

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



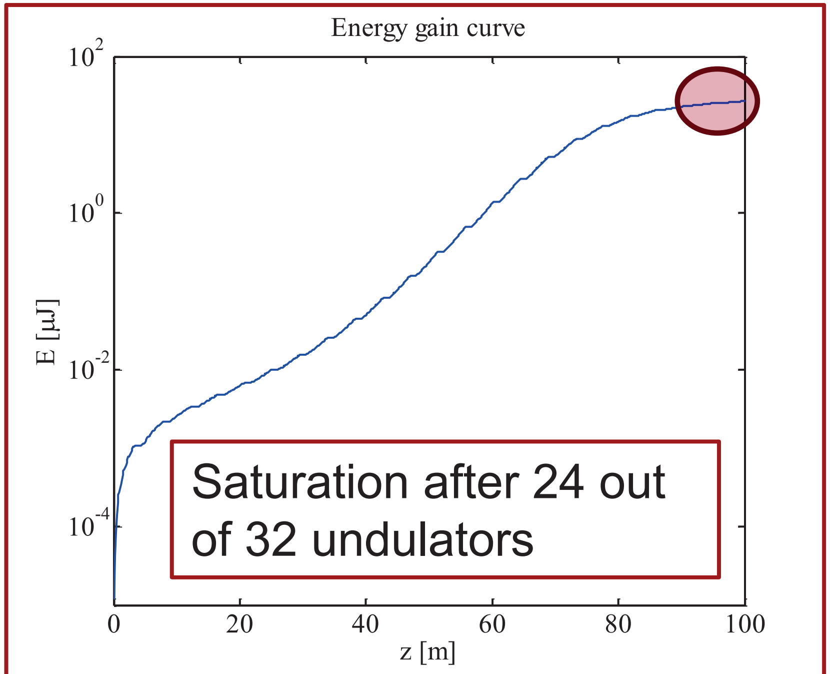
HXR provides much shorter photon wavelength with comparable pulse energy

H-D Nuhn, Y. Ding, G. Marcus, J. Wu

Start-2-End Simulations (examples)

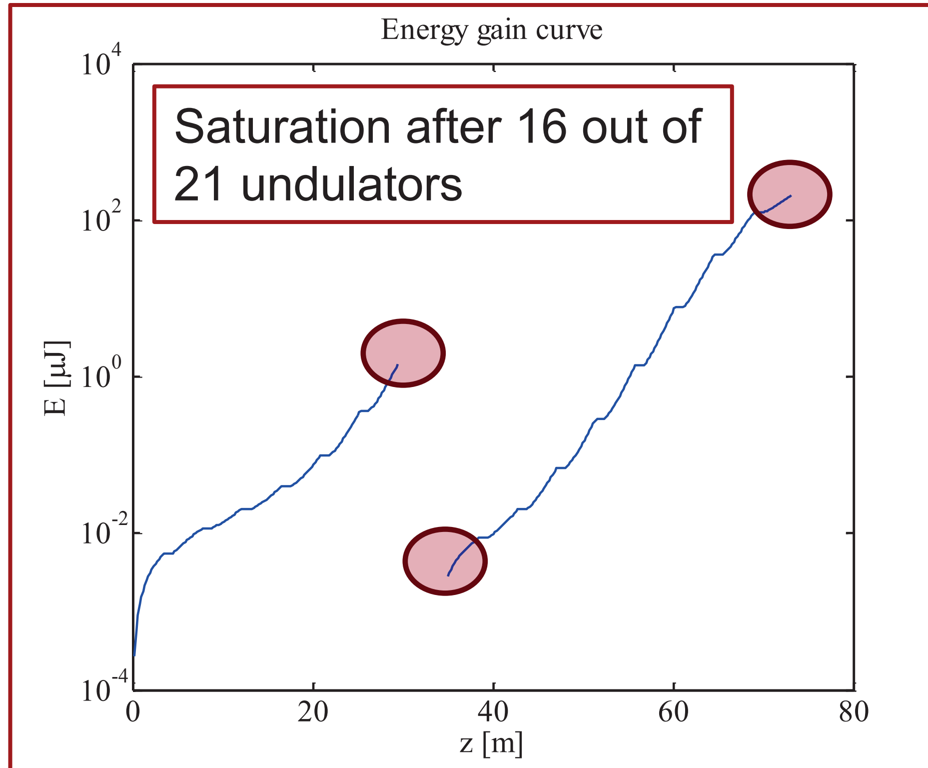
ASTRA → Elegant → Genesis

5 keV X-rays from 20 pC SASE



ΔE_{FWHM} ~ 3.5 eV
$\Delta E_{FWHM}/E_0$ ~ 7.0 x 10^{-4}

1.24 keV X-rays from 100 pC SS



ΔE_{FWHM} ~ 64 meV
$\Delta E_{FWHM}/E_0$ ~ 5.1 x 10^{-5}
TBP ~ 4.3 eV-fs = 2.4 FTL

G. Marcus

Full uBI is not included in simulations

See TUP032

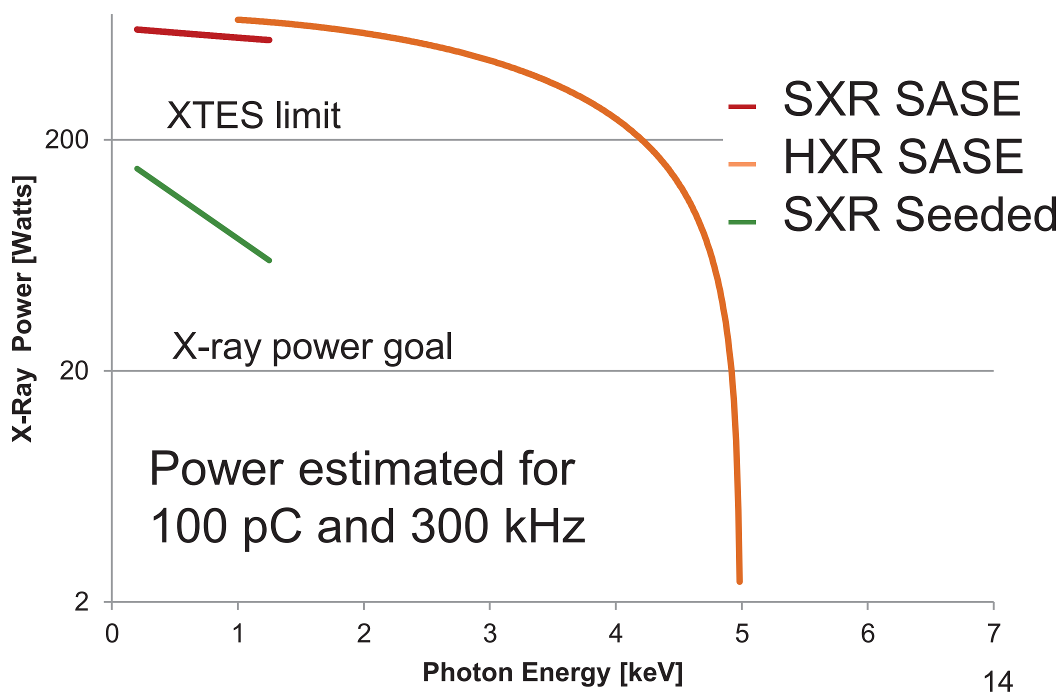
FEL X-ray Power at High rate

SCRF linac can deliver ~1 MHz beam to either undulator

- Goal is to provide >20 Watts over wavelength range
  - Easily met except at 5 keV where limited by energy and ε
    - Simulated performance is better than analytic curve shown

- XTES is designed to handle up to 200 Watts
  - Studying methods of turning down FEL power other than rep. rate

X-ray Power using 4 GeV SCRF Linac

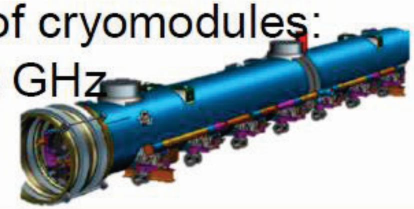


Project Collaboration

SLAC

Fermilab

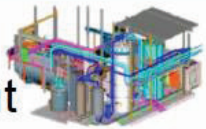
½ of cryomodules:
1.3 GHz



Jefferson Lab
EXPLORING THE NATURE OF MATTER

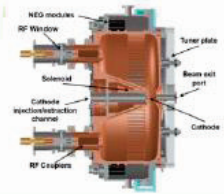
½ of cryomodules:
1.3 GHz

Cryoplant

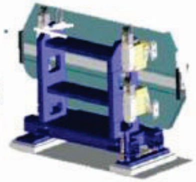


BERKELEY LAB

e⁻ gun & associated
injector systems



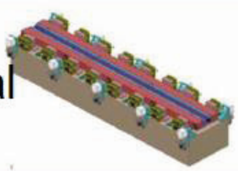
Undulators



Argonne
NATIONAL LABORATORY

Undulator
Vacuum
Chamber

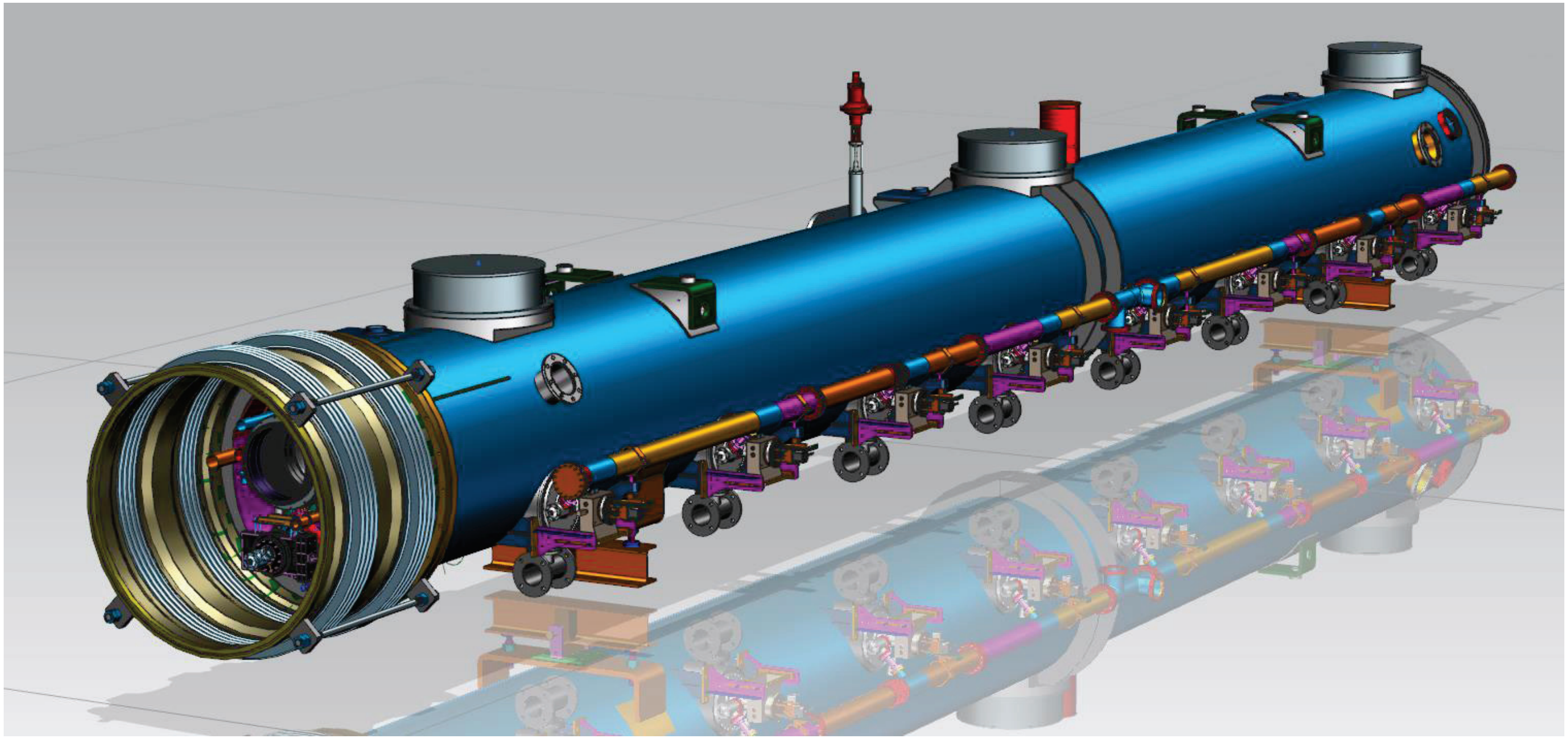
Undulator
R&D: vertical
polarization



CORNELL UNIVERSITY
FOUNDED A.D. 1865

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

LCLS-II Preproduction Cryomodule
1.3 GHz, modified for CW operation



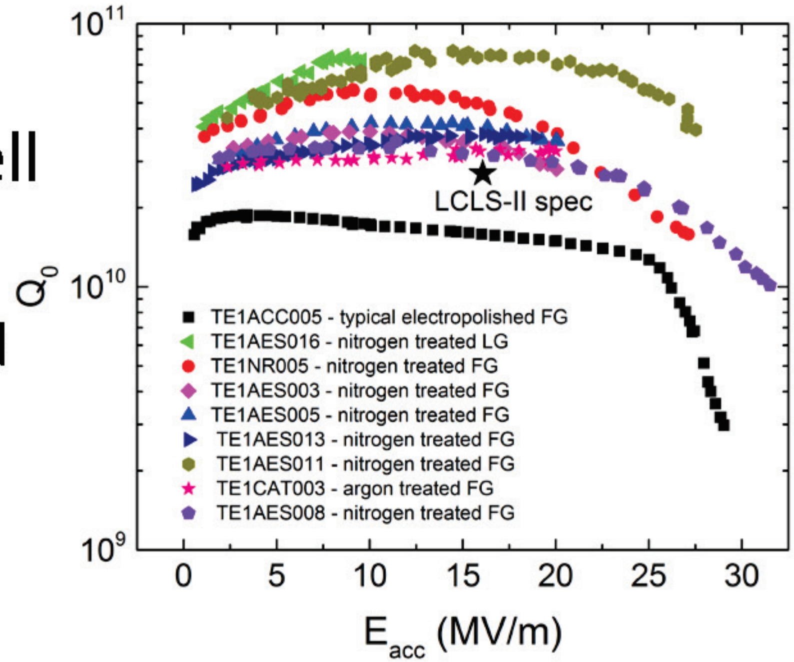
Total length ~12.2 m   Nearly the final LCLS-II cryomodule design

Crymodules will be similar to EuXFEL with small modifications for CW operation

High Q for LCLS-II

From April 2014
TTC Meeting

- The basic phenomenon is well established
  - Early FNAL exploration defined the starting point

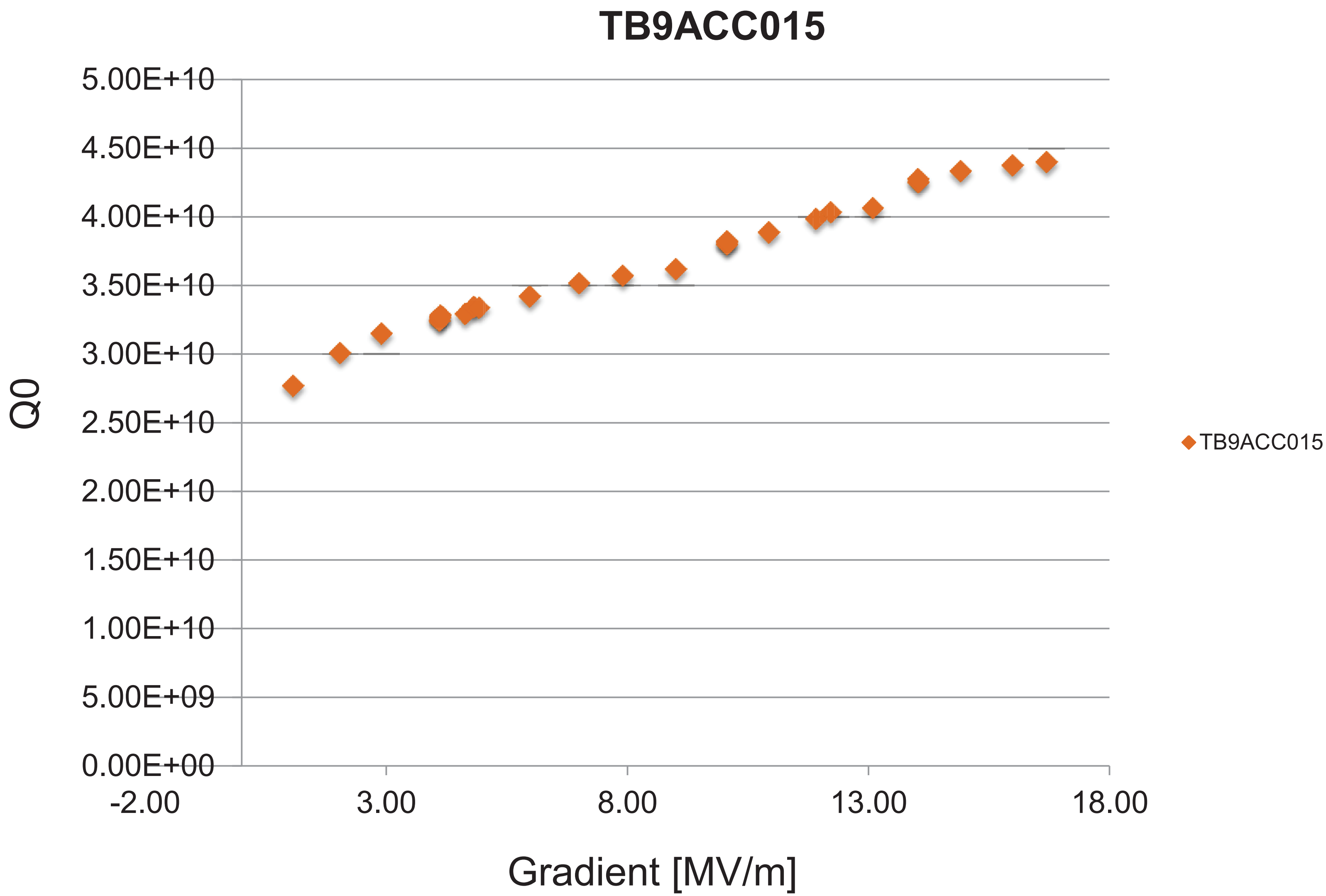


- Present program is refining the parameterization of the "doping" process using single cell cavities.
  - How much gas load per unit area? ~40 torr-liters for single cell?
  - How does duration of subsequent gas-free diffusion time affect performance as a function of EP depth removed?
  - How clean (PP of other species) must the furnace be during 800°C HT?

Progress Towards CW Operation and High-Q_0 Cavities

- The nitrogen-doping recipe was published in 2012.
  - More than 20 single-cell doping / vertical tests completed with results as high as 3.5e10 at 32 MV/m.
- LCLS-II has completed 22 high-Q_0 nine-cell vertical tests; both at Fermilab, Jlab and Cornell.
  - The average Q_0 is 3.1e10 with a limiting gradient of >18 MV/m.
- The high-Q_0 recipe is well established but must be developed for industrial fabrication
  - Residual magnetic field and cooldown rates are critical
- Other modifications for CW operation are straightforward: couplers, cryomodules, etc

9-cell 1.3 GHz TESLA Cavity after N_2 Treatment



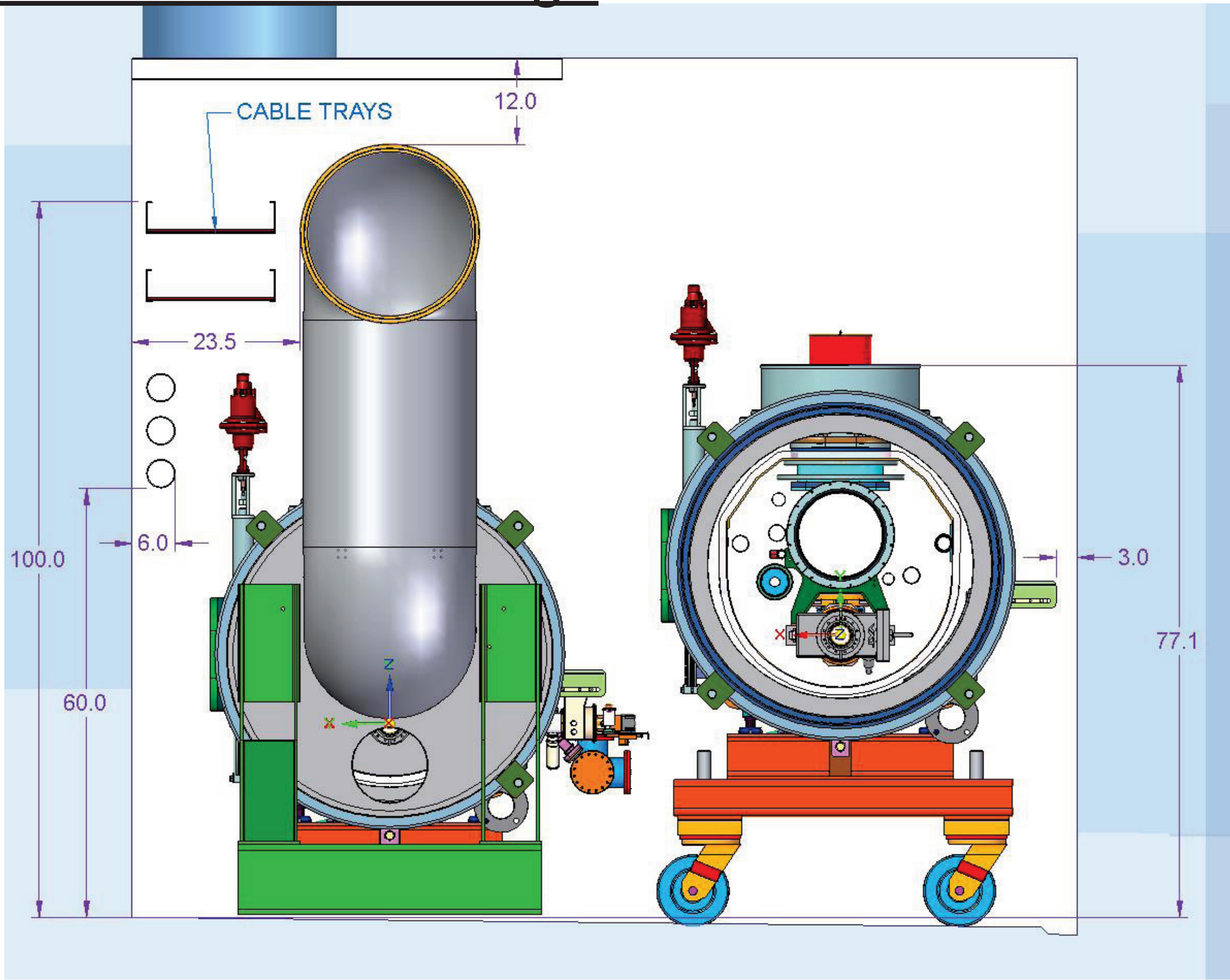
Jlab CEBAF 12 GeV Upgrade 4.5 K cold-box (Linde) 'CHL 2'

SCRF Linac in SLAC Tunnel

SLAC Linac Tunnel: 11 wide x 10 feet high

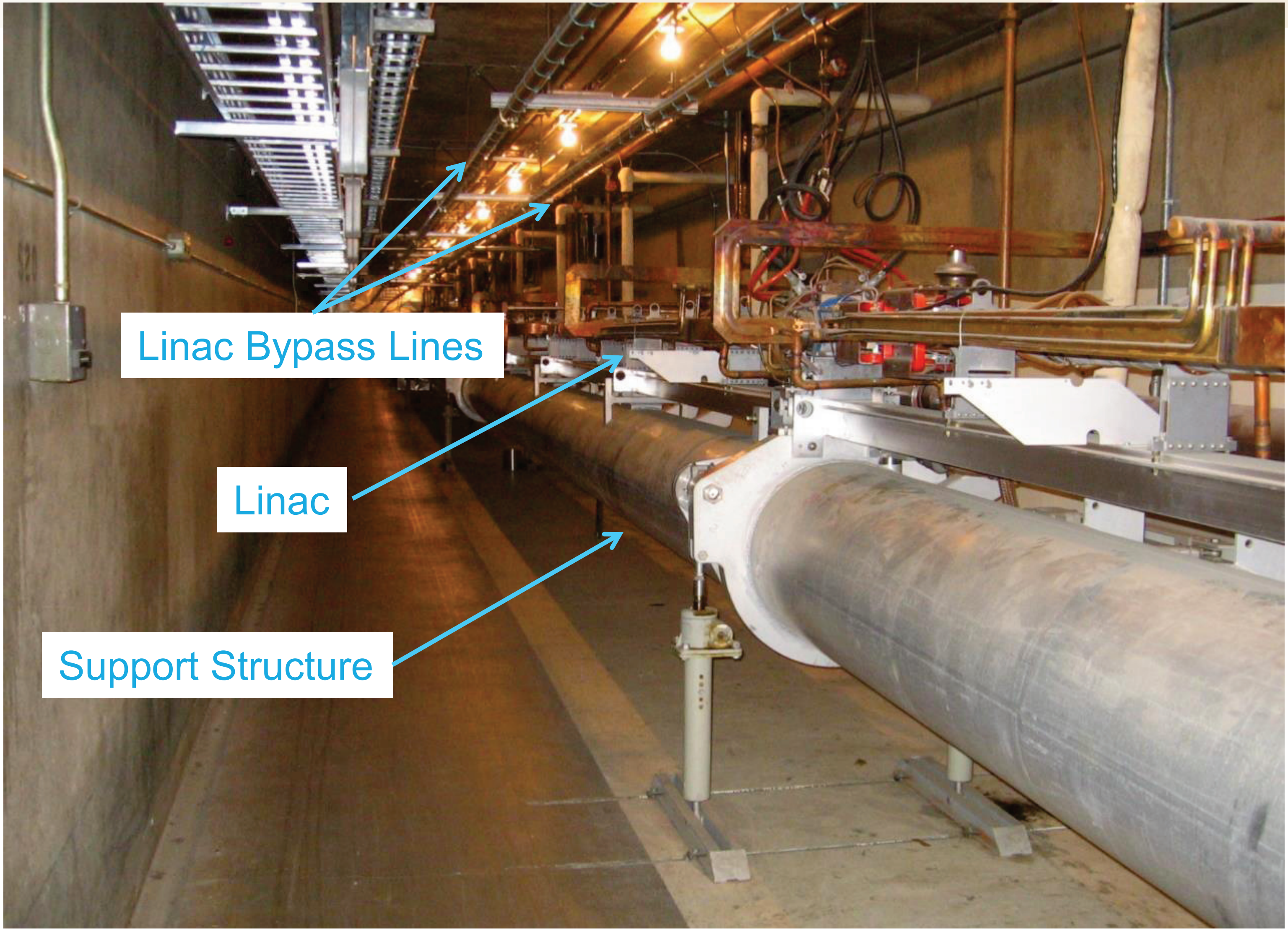
It will be a tight fit!

Working
on detailed
models and
installation
plans

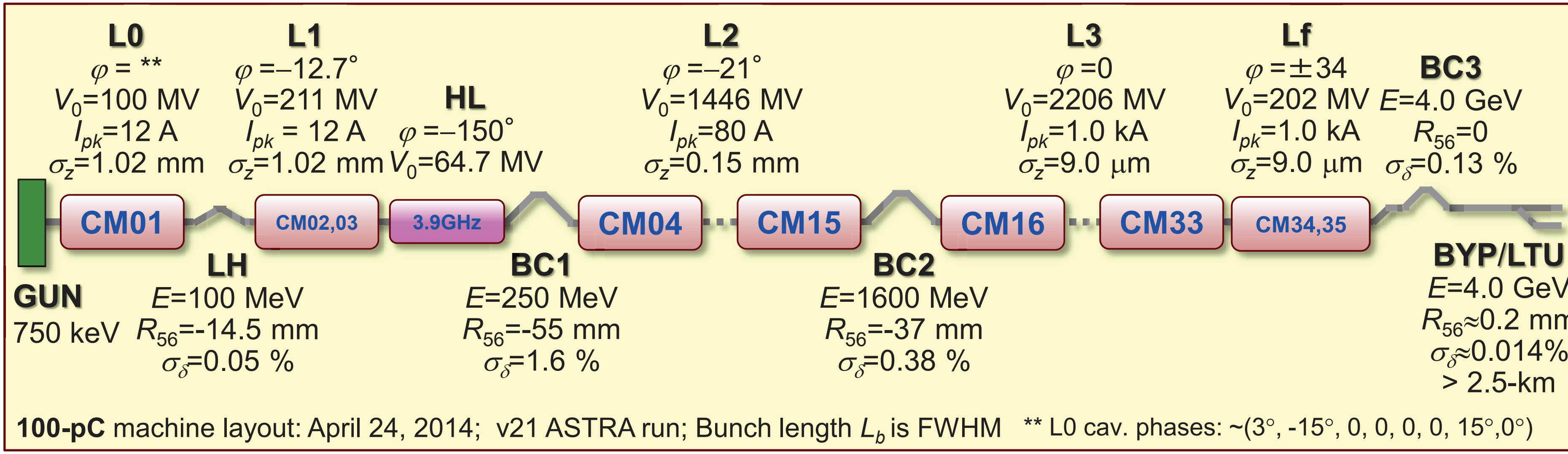


S. Boo, K. Fant, J. Chan

Existing SLAC Linac Tunnel
Remove Linac and Support Pipe; Re-use Bypass line



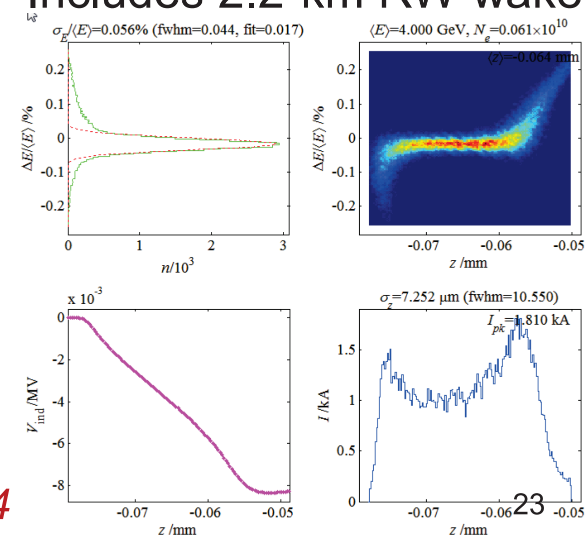
LCLS-II - Linac and Compressor Layout for 4 GeV



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

P. Emma, L. Wang,
M. Venturini

Includes 2.2-km RW-wake



See THP025, THP029, THB04

LCLS-II CW Injector Design

At 4 GeV, emittance is critical for FEL performance

Options for MHz source:

- DC Gun with sub-harmonic bunching (Cornell example)
- VLF Gun operating at sub-harmonic (LBNL and WiFEL examples)
- SRF multi-cell gun (JLAB developing prototypes)
- Different benefits/risks for each

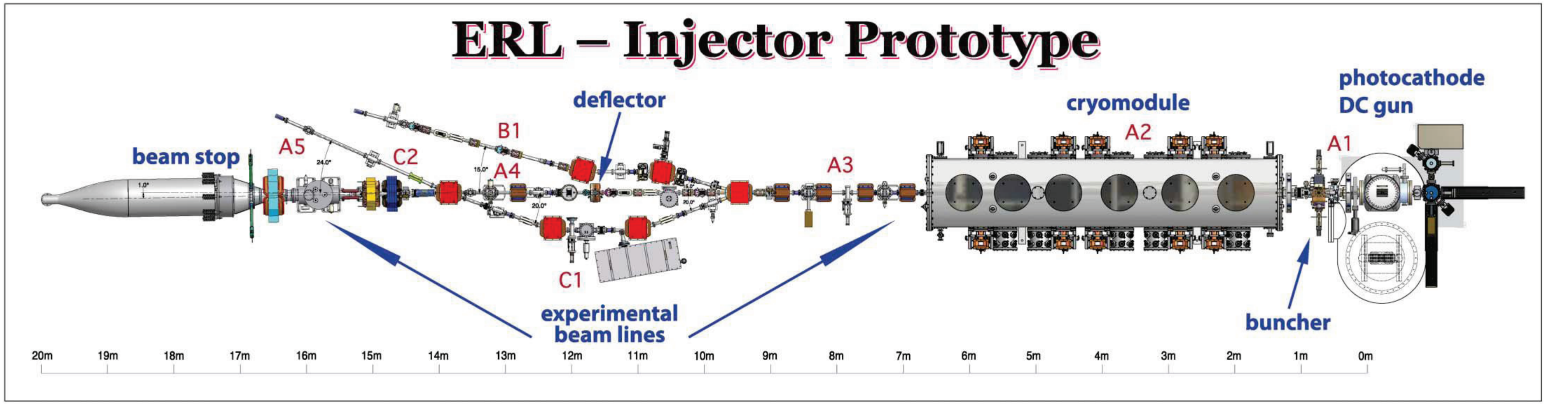
Injector team is evaluating options (John Schmerge)

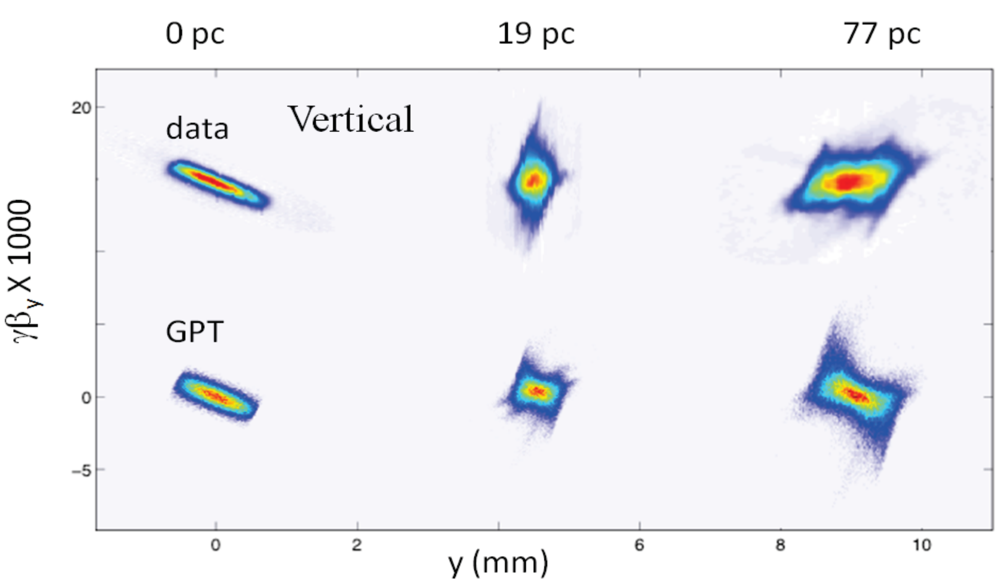
- CDR baseline is 750 kV LBNL APEX gun
    - LBL APEX R&D program aiming for FY15 demonstration
- Will demonstrate ~500 kV DC gun in FY15 as well
- Large team (Cornell, FNAL, LBNL, SLAC) simulating different configurations

See TUA01, THP019, THP042, THP054, THP057

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)

Injector Simulations

Studies over full parameter range 10 pc – 300 pC

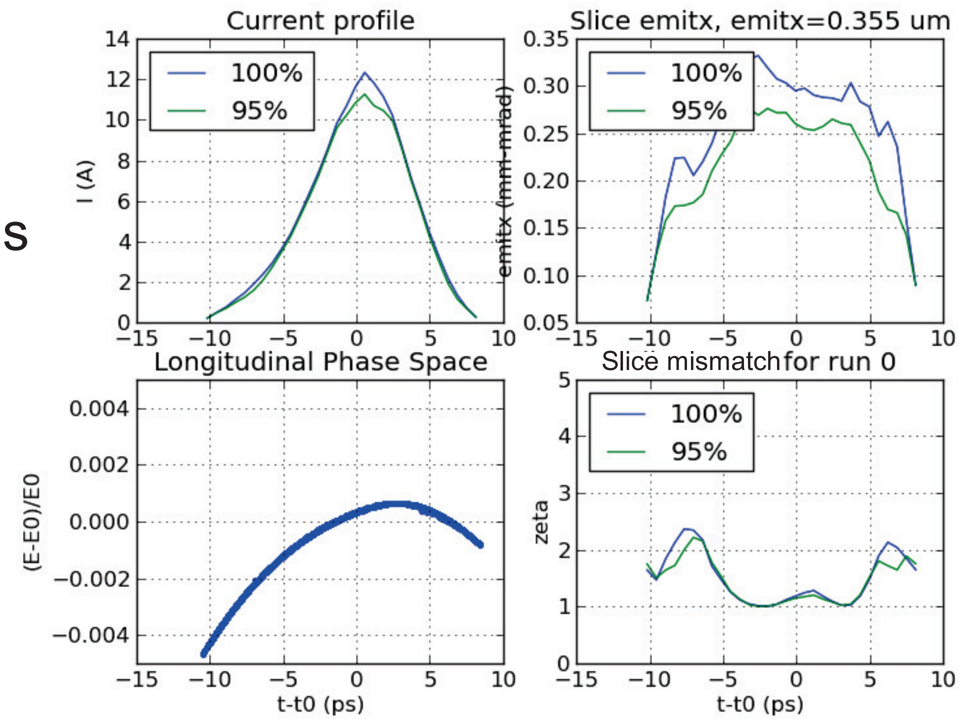
- Simulations of LBL APEX gun and NGLS Injector
  - Re-optimized system to deliver lower charge, lower current, more symmetric bunches (greater use of buncher cavity and less velocity bunching)
  - Solutions for all cases
  - Used for bunch compressor design and S-2-E simulations

<u>100 pC in ~10 Amps</u>

100% proj. emitx = 0.355 μm

95% proj. emitx = 0.26 μm

Final energy = 94.94 MeV



See TUA01

THP019, THP024, THP054, THP057

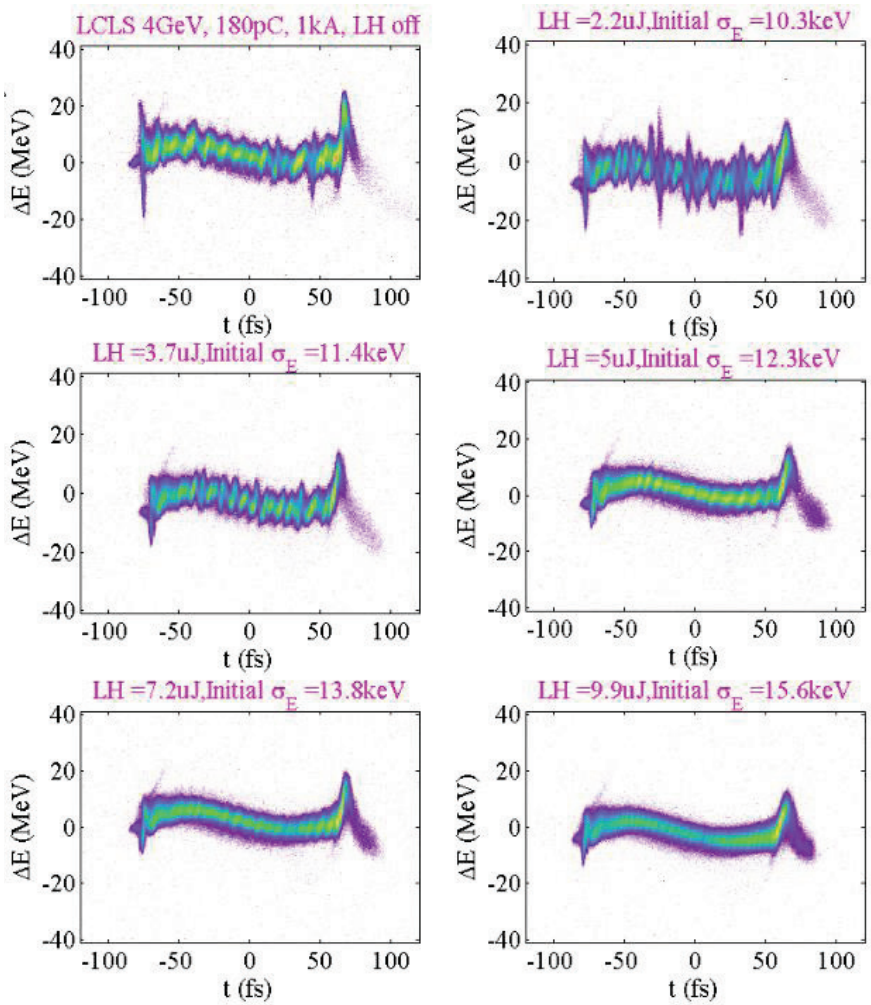
F. Sannibale, C. Papadopoulos, F. Zhou

Benchmarking S-2-E Simulations

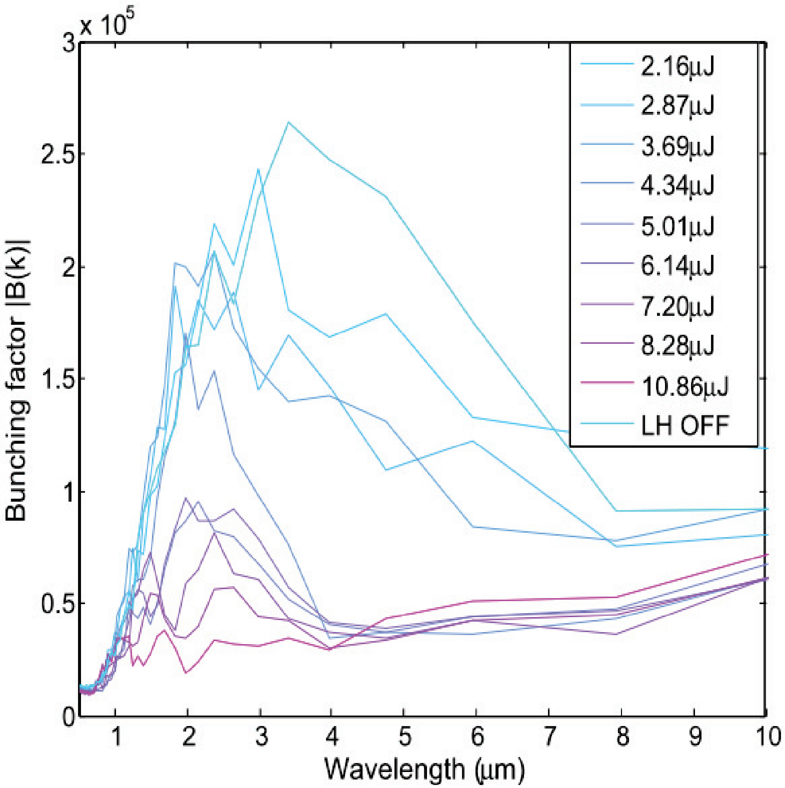
uBI effects will likely be important

LCLS microbunching studies: 4GeV, 180pC, 1kA

Measured final t-p phase space vs laser heater

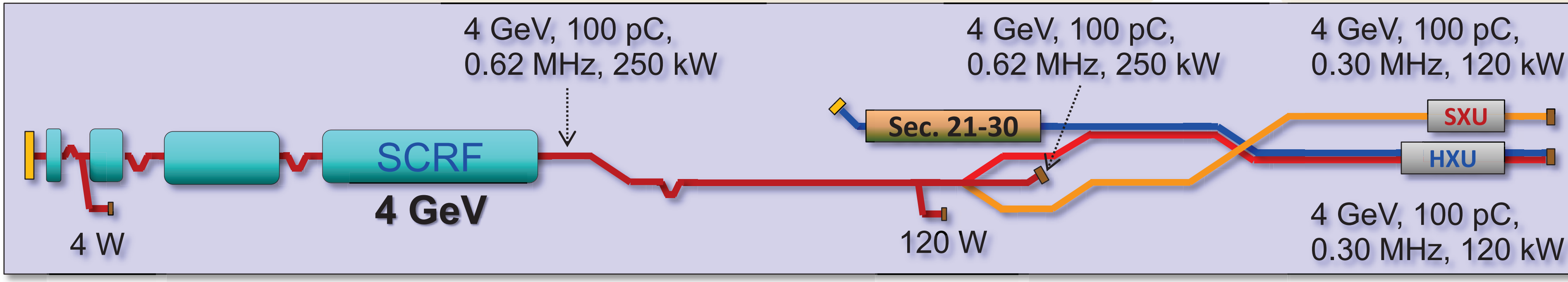


preliminary analysis of bunching factor



(D. Ratner, Y. Ding, et al.)

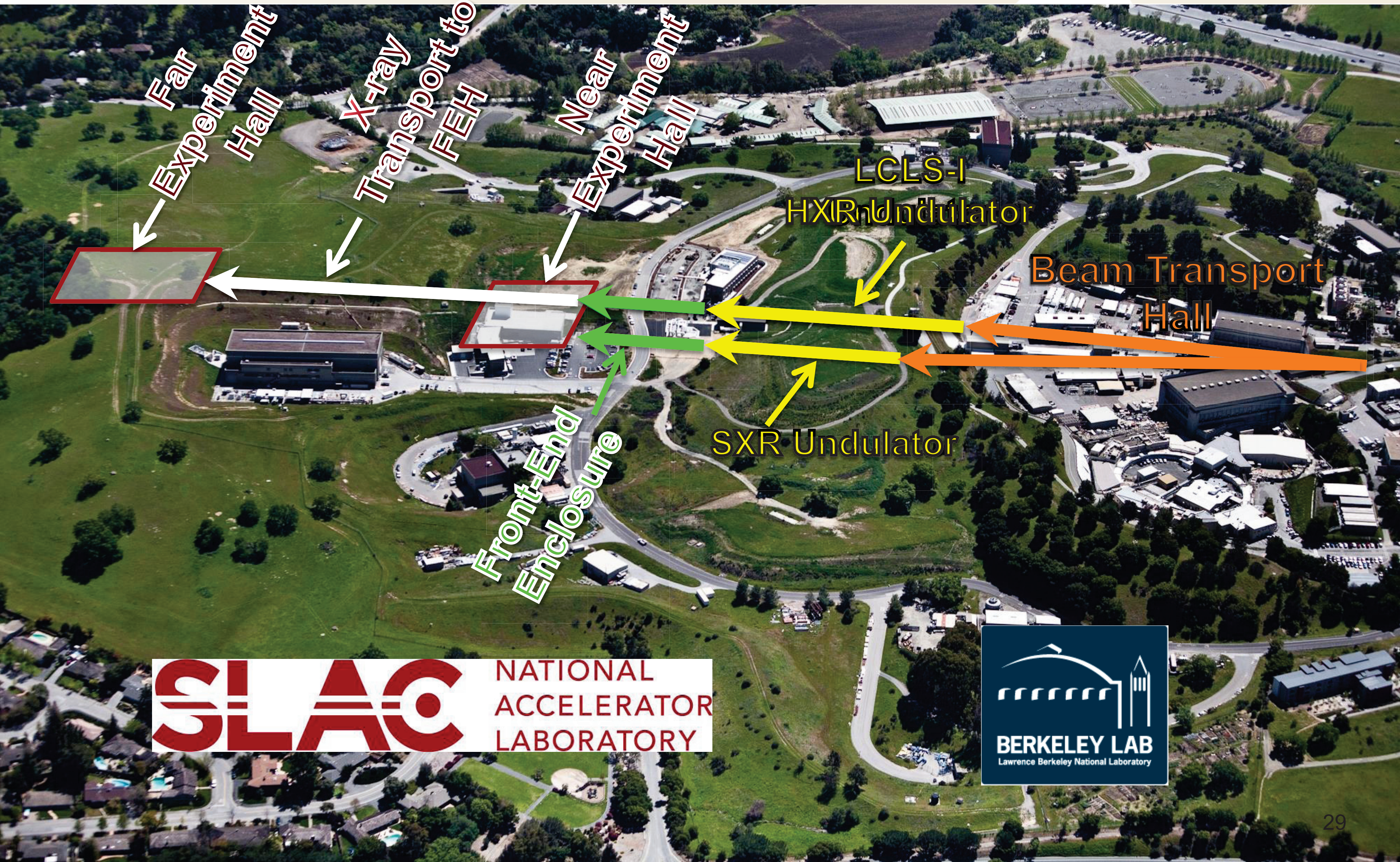
High Power CW Linac
Beam Collimation and Diagnostics



- Beam power and beam loss issues are critical
  - Designing extensive collimation system *See MOP046, MOP050*
  - Hybrid PM undulators sensitive to nearby losses
- Linac designed for 1.2 MW but undulators limited to 120 kW
  - 250 kW maximum power in initial phases
  - Studying dark current and FE effects and radiation limits
- Parasitic injector diagnostic line plus in-line diagnostics

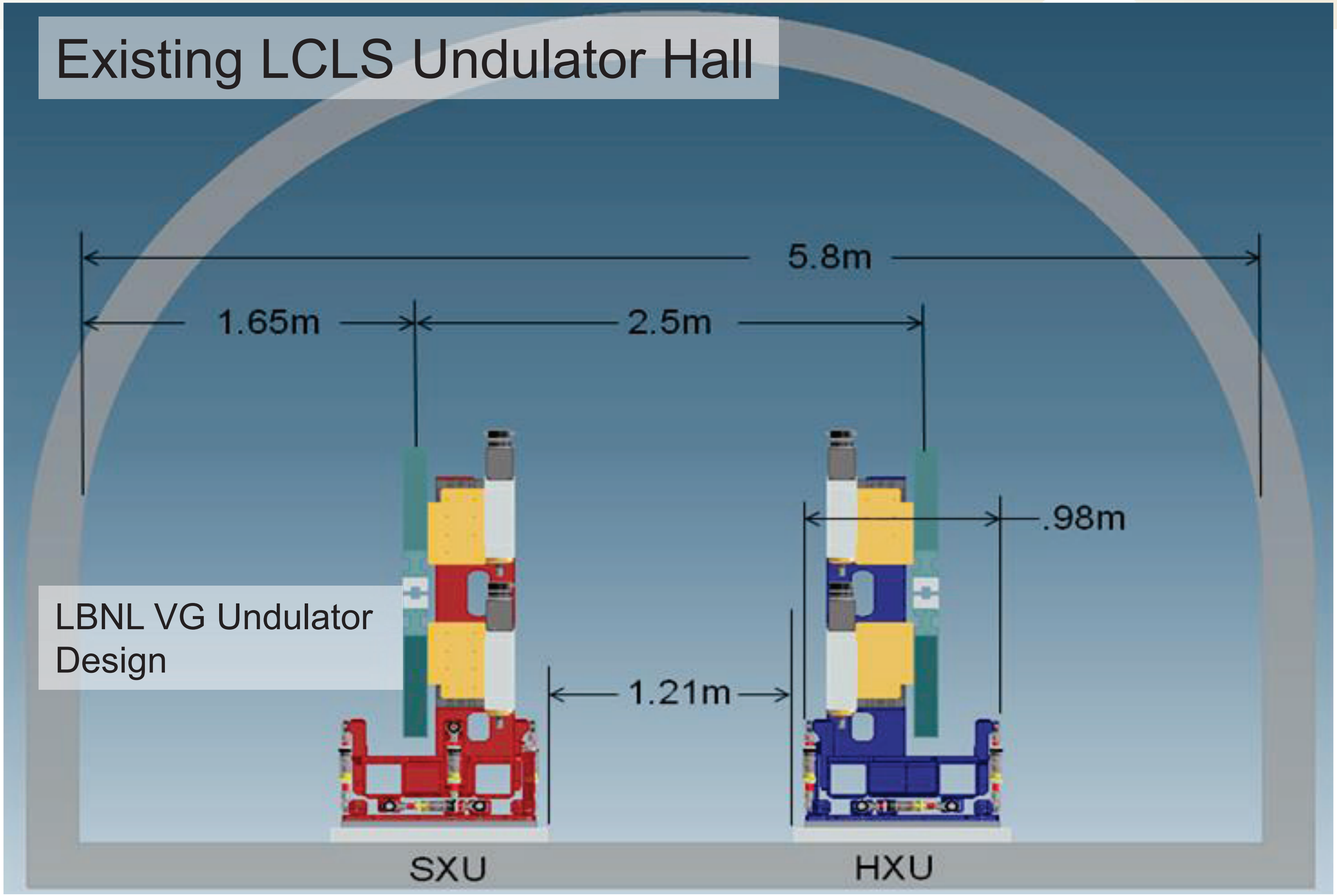
See THB04

LCLS-I/LCLS-II Undulator and Experimental Halls



Undulators in LCLS Undulator Hall

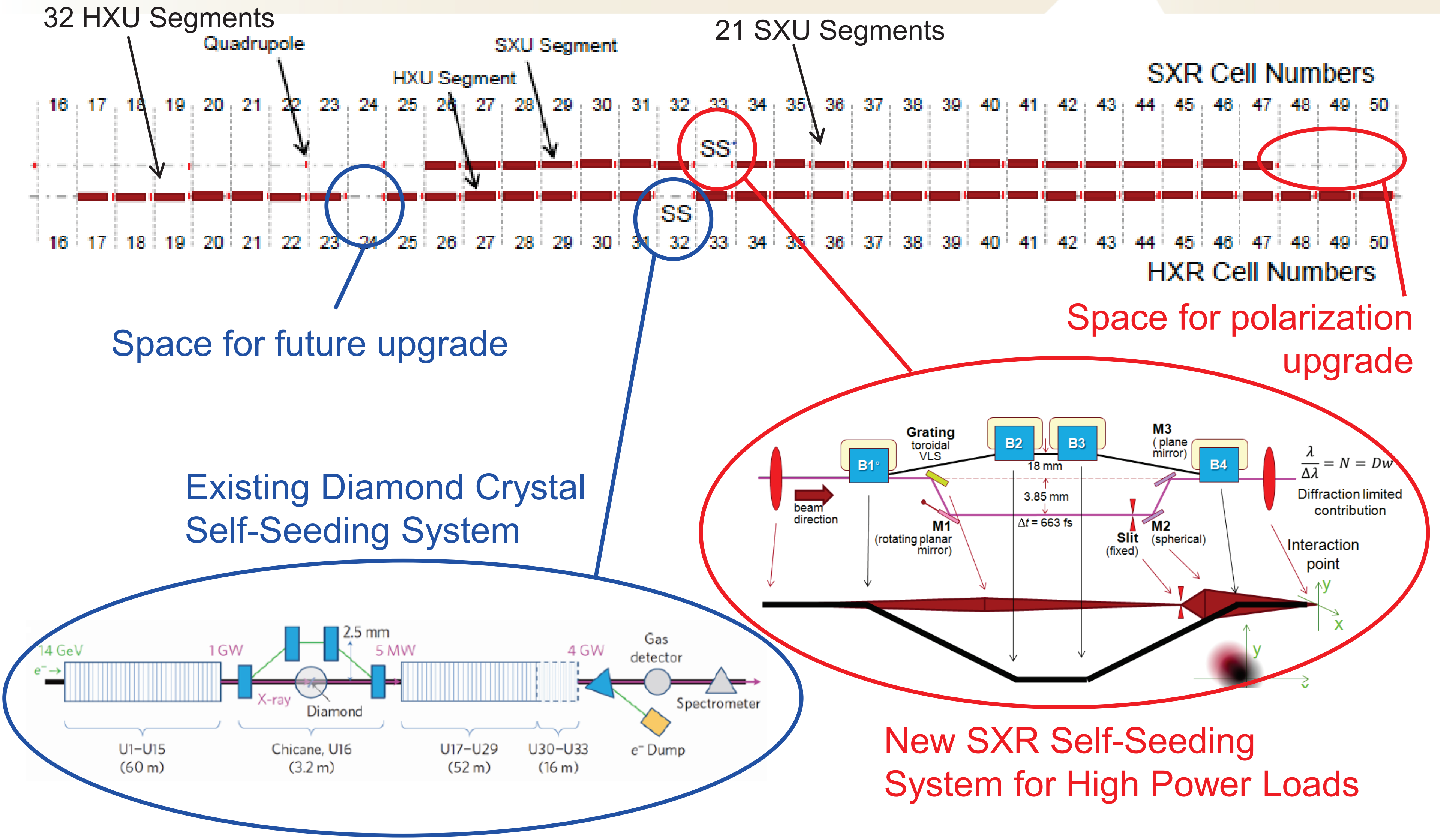
Replace Existing LCLS Undulator with HXR and Add SXR



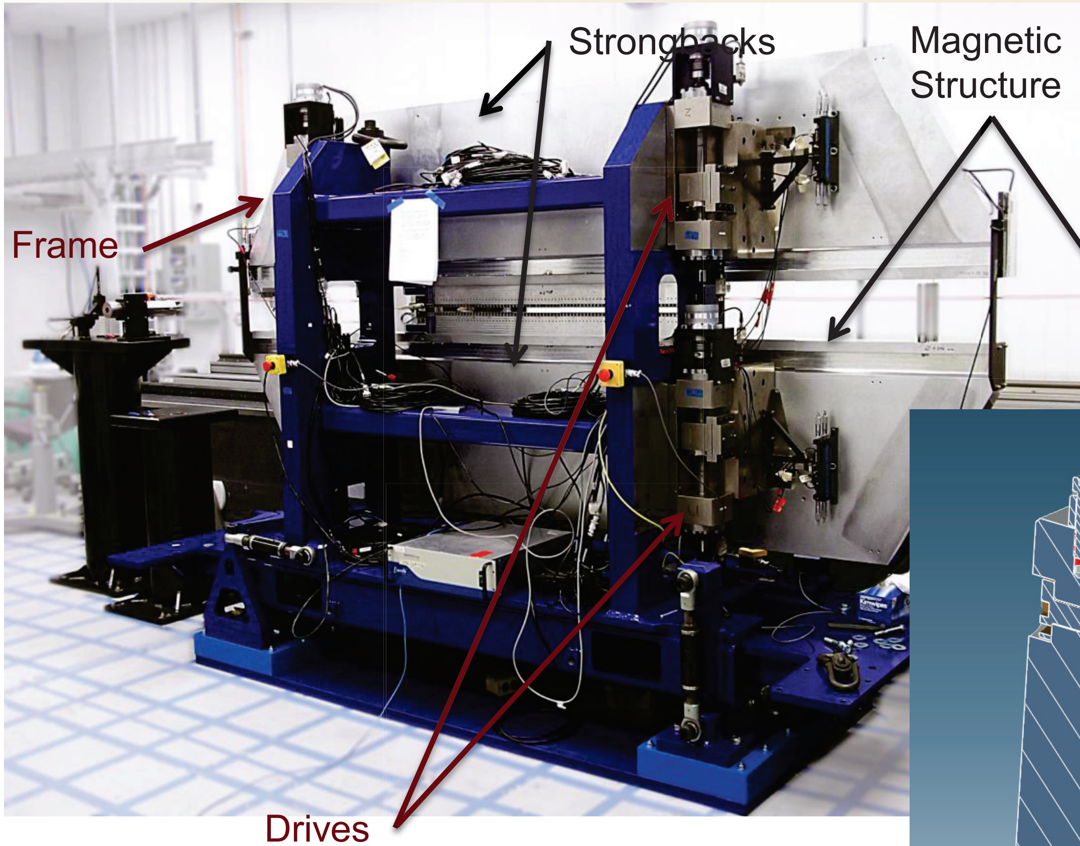
D. Bruch, M. Rowen

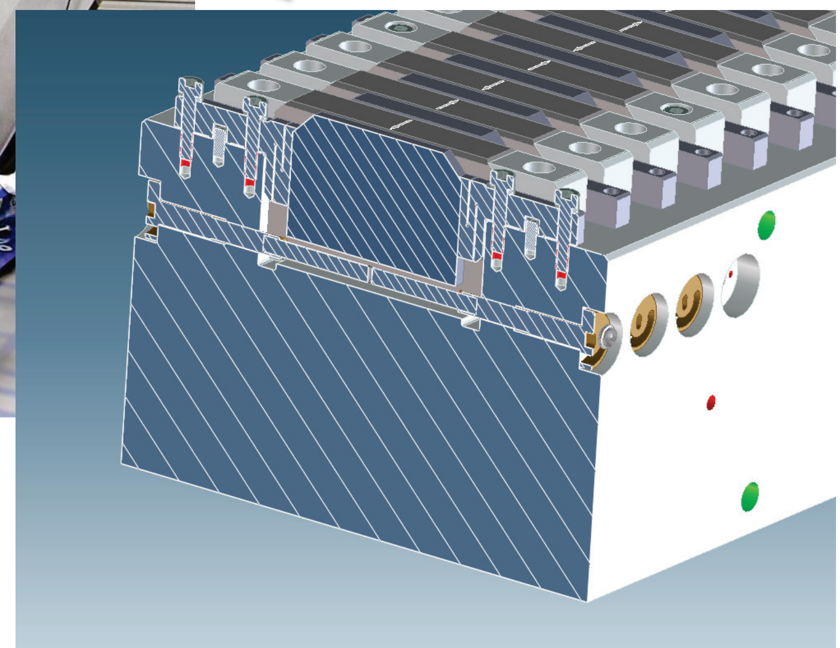
LCLS-II Undulator Layout

150 meter existing Undulator Hall



Variable Gap Hybrid Undulators
Ongoing Development at LBNL





Well on our way to a full scale prototype as part of LCLS-II$_{\text{Phase I}}$

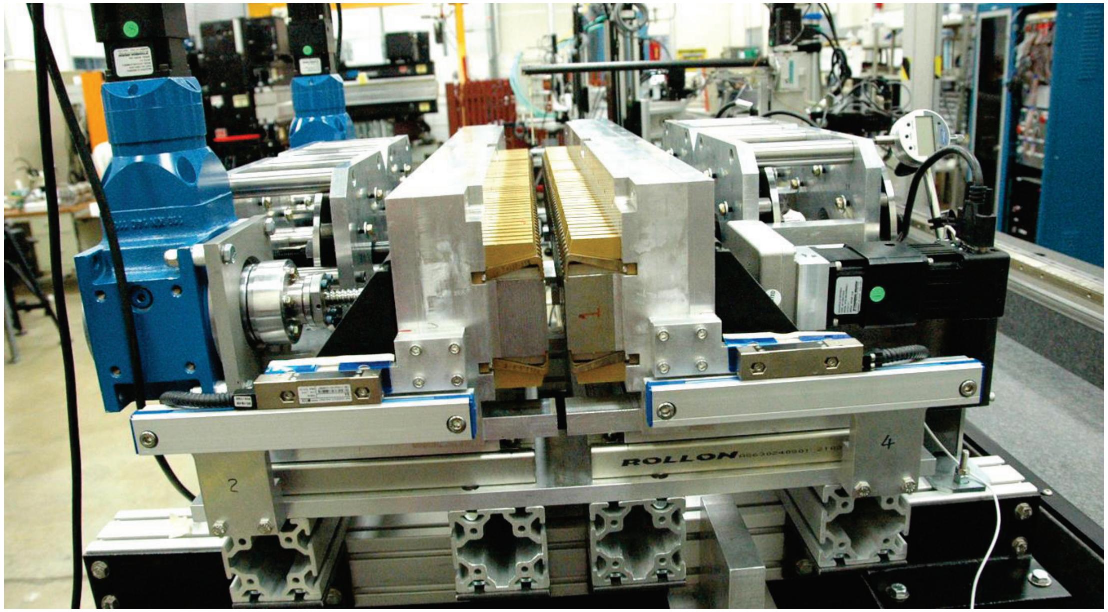
M. Leitner, S. Marks

LCLS-II Undulator R&D

- Developing two alternates: Superconducting undulator (SCU) and a Horizontal gap – vertically polarizing undulator (VPU)

See THA03

  - SCU R&D is a combined Argonne/Berkeley effort
  - VPU R&D is being pursued at Argonne



Argonne 0.8-meter VPU test segment

Plan to have a 3 meter prototype in fall 2014

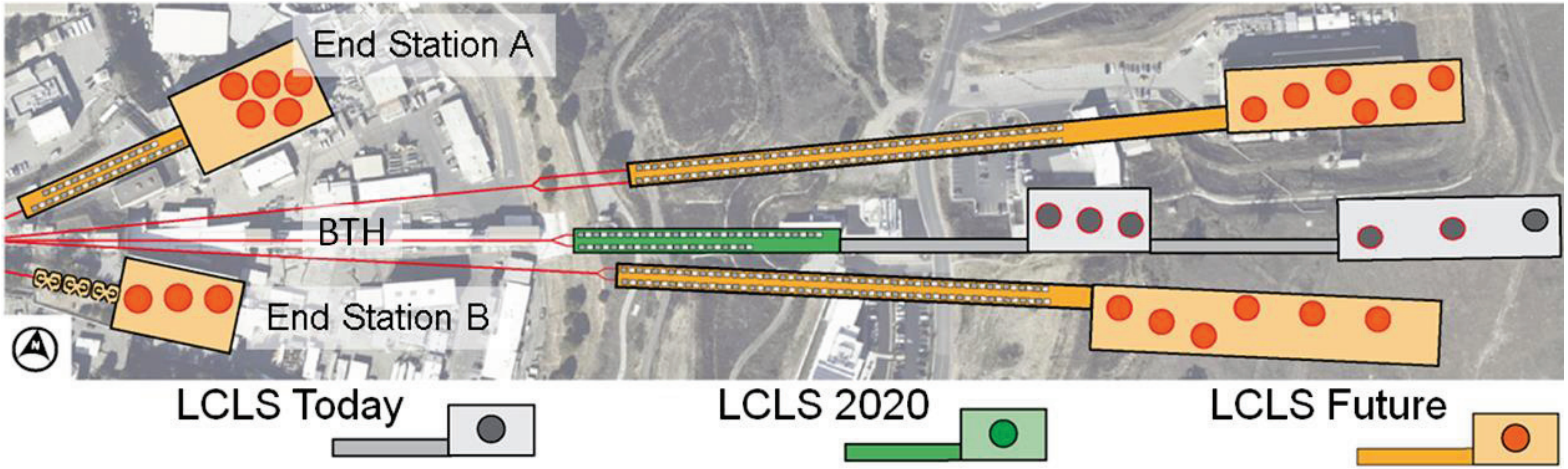
E. Gluskin, S. Prestemon, et al

Future Facility Expansion Options

SLAC has extensive infrastructure that will allow expansion

Working to ensure compatibility with future needs

- SCRF linac will be central element of future SLAC program
- Verifying parameter and layout flexibility
- Support new capability as well as new capacity

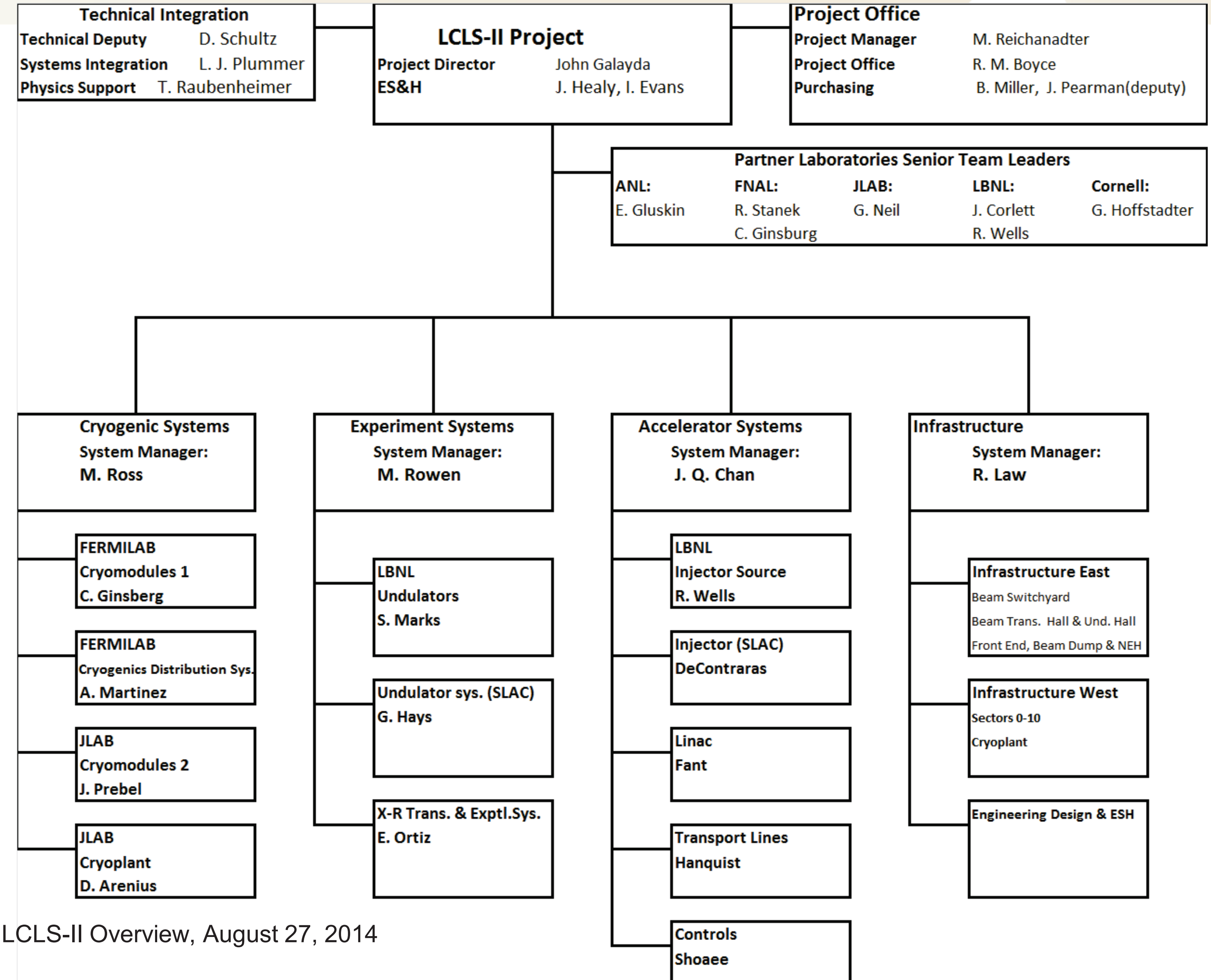


Summary

- LCLS-II design concept has been developed
  - Effort from broad multi-lab collaboration
  - Largely uses existing SLAC infrastructure
  - Based heavily on previous studies by NGLS, NLS, XFEL and ILC
- Conceptual design meets physics requirements
  - Complete e- optics has been developed for primary beamlines
  - Detailed beam physics being verified with S-2-E simulations
  - Developing expansion concepts to ensure compatibility
- Aggressive schedule
  - First light in ~2019 with project completion in 2021
  - Working to define ‘details’
  - User workshops to be held in coming year

End

Organization

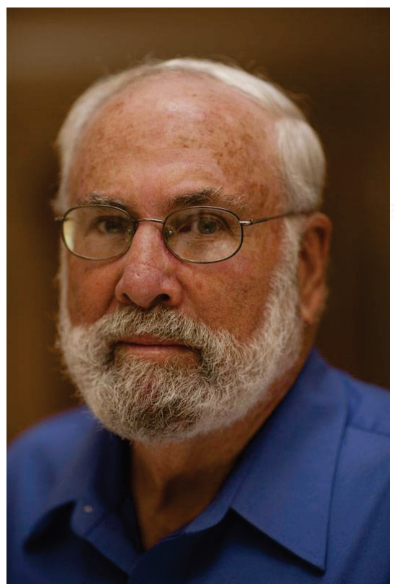


LCLS Concept: Fourth Generation Workshop, 22 Years Ago

C. Pellegrini, A 4 to 0.1 nm FEL Based on the SLAC Linac, Workshop on Fourth Generation Light Sources, February, 1992

Claudio Pellegrini

Herman Winick



Herman Winick's Study Group

SHORT WAVELENGTH FELs at SLAC - STUDY GROUP

SOURCE

Karl Bane
Jeff Corbett
Max Cornacchia
Klaus Halbach (LBL)
Albert Hofmann
Kwang-je Kim (LBL)
Phil Morton
Heinz-Dieter Nuhn
Claudio Pellegrini (UCLA)
Tor Raubenheimer
John Seeman
Roman Tatchyn
Herman Winick

SCIENTIFIC CASE

Art Bienenstock
Keith Hodgson
Janos Kirz (SUNY-Stony Brook)
Piero Pianetta
Steve Rothman (UCSF)
Brian Stephenson (IBM)

Engaged Bjorn Wiik and Gerd Materlik during sabbaticals at SLAC

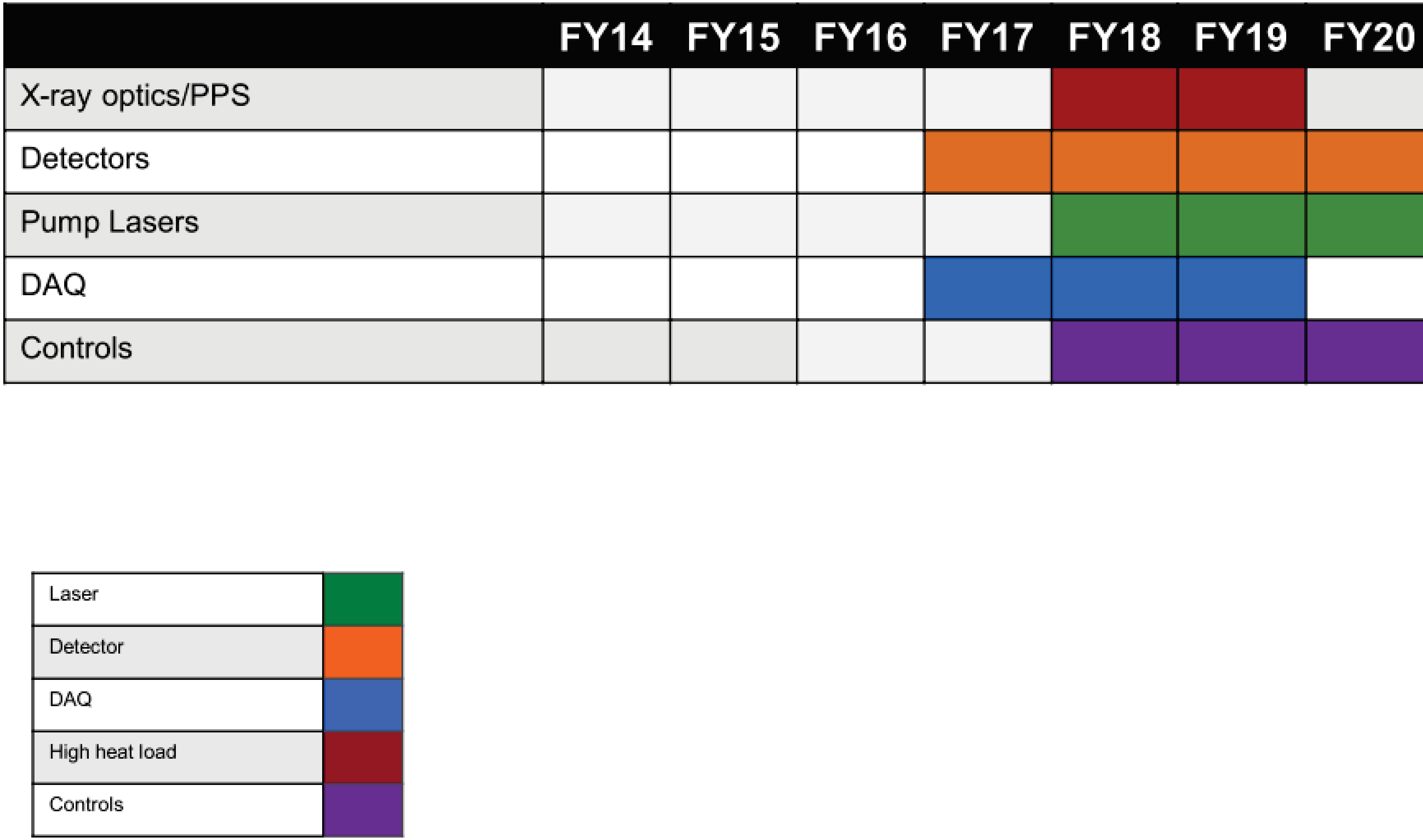
Scientific objectives driving machine capabilities

1. High pulse repetition rate over a broad energy range from ~0.2 to 5 keV
   - Transformative new capability will reduce data acquisition time by several orders of magnitude.
   - Access to the 2-5 keV energy range is ideal for biological imaging
2. Path toward control over the pulse bandwidth and polarization
   - Advanced spectroscopic methods will give new insights into the electronic structure of materials including the spin degree of freedom
3. Increased photon energy range compared to LCLS-I (in particular, exceeding 10 keV)
   - High photon energies enable studies of bulk materials and easier access to smaller length scales.
4. The long term ability to produce multiple pulses with arbitrary delays and full control of pulse energy.
   - Advanced spectroscopies require laser like control of pulse parameters.

Initial Concept for LCLS-II Instruments
Primary instruments will be extensions of existing LCLS

Area/Instrument	X-ray Optics/PPS	Pump Laser	Detector	DAQ	Controls
Transport Tunnel	High power collimators & stoppers				
AMO (soft)		100 uJ @ 100 kHz	Time resolved charge particle det. Soft x-ray area [0.1 mP, >2 kHz]	10 GB/s	New Triggering
SXR (soft)	New monochromator, beamline relocation	1 mJ @ 100 kHz	Soft x-ray area [2.3 mP, >2 kHz] Soft x-ray area [0.1 mP, >2 kHz] Soft x-ray area [0.1 mP, >2 kHz]	10 GB/s	New Triggering
XPP (hard)		10 mJ @ 1 kHz	ePix10k [2.3 MP, >2 kHz] ePix100 [0.2 MP, >1 kHz]	10 GB/s	New Triggering
XCS (hard)	Water cooling for mono	10 mJ @ 1 kHz	ePix100 [2.3 MP, >1 kHz] ePix100 [0.2 MP, >1 kHz]	10 GB/s	New Triggering
MFX (hard)		10 mJ @ 1 kHz	ePix10k [2.3 MP, >2 kHz] ePix100 [0.2 MP, >1 kHz]	10 GB/s	New Triggering
CXI (hard)	Water cooling for KB mirrors, attenuators	100 uJ @ 100 kHz	ePix10k [2.3 MP, >2 kHz] ePix10k [2.3 MP, >2 kHz] ePix100 [0.2 MP, >1 kHz]	20 GB/s	New Triggering
MEC (hard)					New Triggering

Development for LCLS-II Instruments

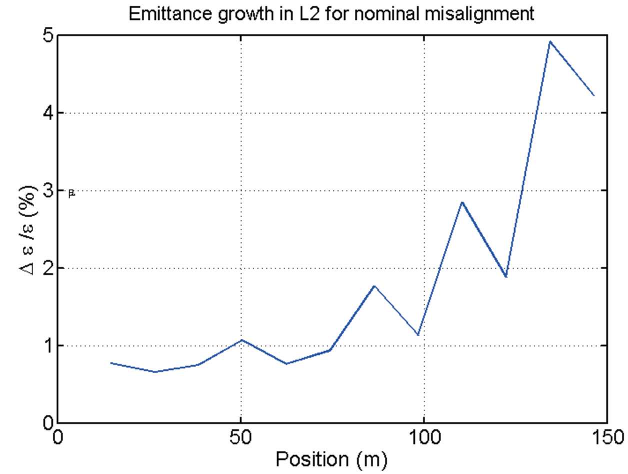


D. Fritz

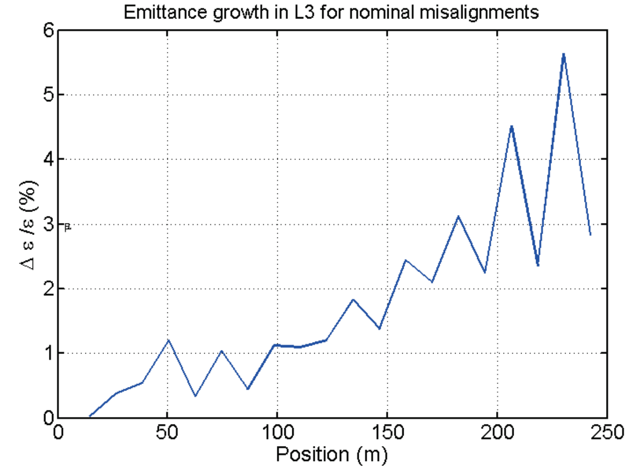
SCRF Linac Tolerances

Present SCRF tolerances similar to European XFEL

Error Source	RMS error	unit
Cavity misalignments wrt. CM	0.5	mm
Cavity tilts	0.5	mrad
Quadrupole misalignments wrt. CM	0.5	mm
BPM misalignments wrt. CM	0.5	mm
Cryomodule misalignments	0.5	mm
Cryomodule tilt	0.05	mrad
BPM resolution	0.01	mm



Multibunch effects are fine even with loaded HOM Q's of 10^7 although HOM heating is a potential issue with large Q's



N. Solyak, A. Saini, A. Vivoli

Superconducting RF Linac Based on XFEL and ILC R&D

- Baseline choices: 1.3 GHz, 9-cell cavities, 16 MV/m and $Q_0 > 2.7 \times 10^{10}$
- 2°K with 110 W per CM using single cryoplant
- SLAC tunnel between Sectors 0 to 10 could fit a 7 GeV linac
- Marc Ross will discuss technology details