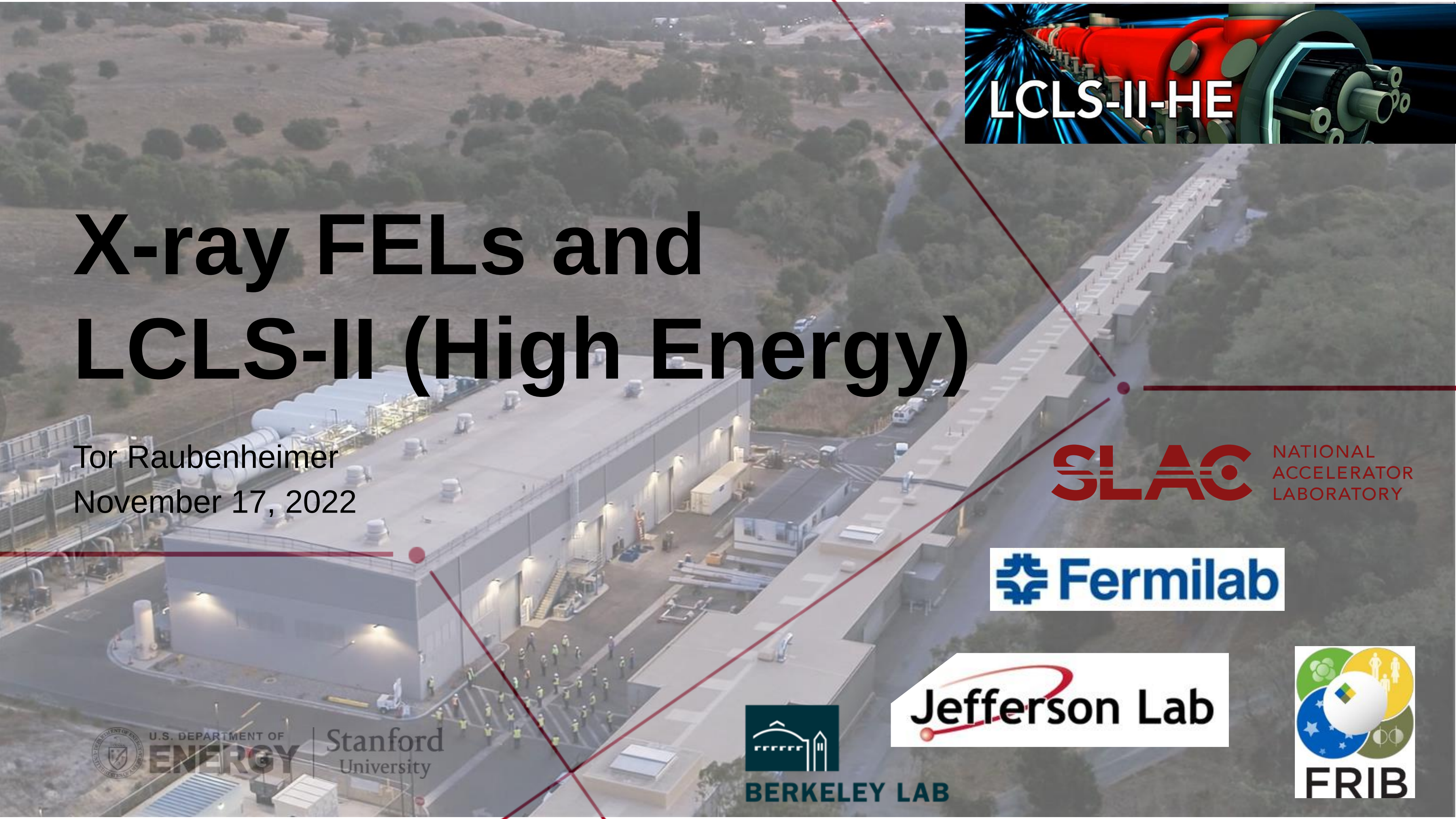


LCLS-II-HE

X-ray FELs and LCLS-II (High Energy)

Tor Raubenheimer
November 17, 2022

SLAC NATIONAL ACCELERATOR LABORATORY

Fermilab

Jefferson Lab

BERKELEY LAB

FRIB

U.S. DEPARTMENT OF ENERGY

Stanford University

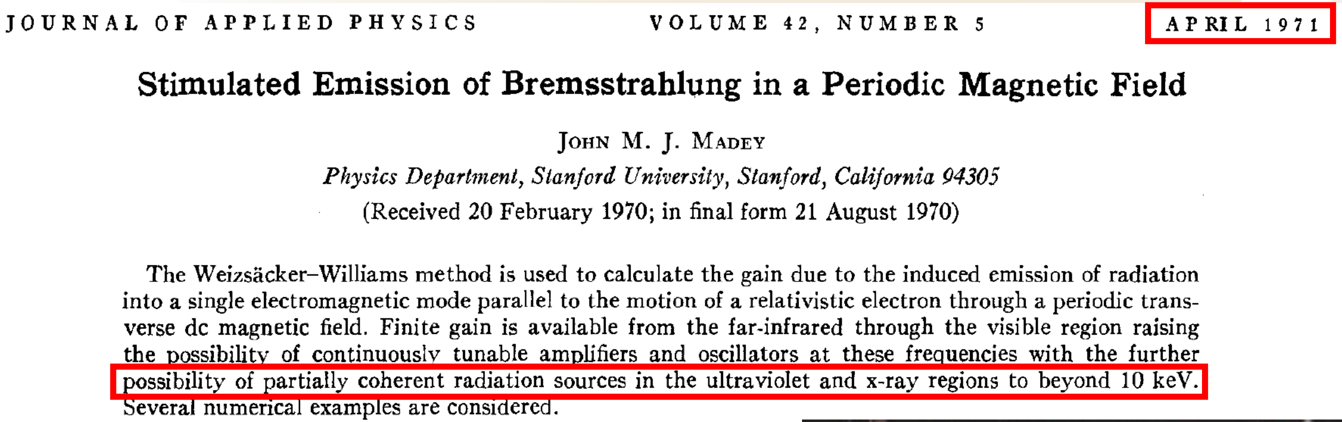
Outline

- X-ray FEL Primer
- LCLS X-ray FEL (15 GeV e- beam in 2009) → 250 eV – 12 keV x-rays
- LCLS-II (4 GeV e- beam in 2023) → 250 eV – 5,000 eV x-rays
- LCLS-II-HE (8 GeV e- beam in 2027) → 250 eV – 20,000 eV x-rays
- LCLS-II Undulator Commissioning (2020-2022)
- SRF Technology
- LCLS-II SRF Commissioning

LCLS was the 1st X-ray FEL and was quickly followed by SACLA, Swiss-FEL, PAL-FEL, EuXFEL

LCLS-II requires advances in 4 critical areas: SRF, CW Injectors, Variable gap undulators, and beam dynamics to increase LCLS brightness by 10,000x.

The Free Electron Laser (FEL)



JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

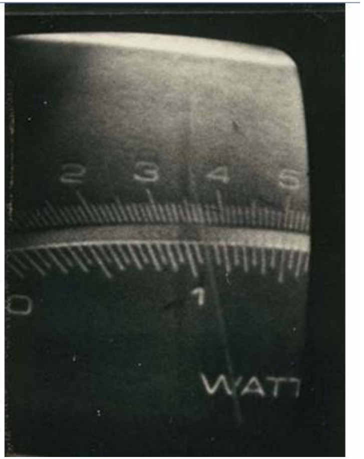
Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

John M. J. Madey
Physics Department, Stanford University, Stanford, California 94305

(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

Output Power of MkI FEL

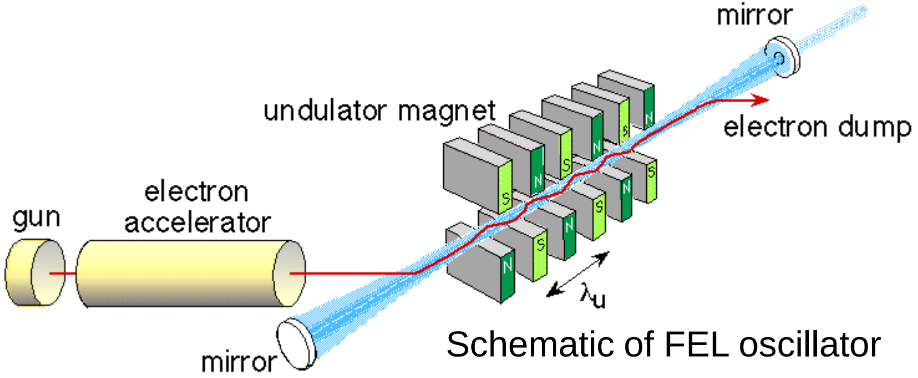


Todd Smith, John Madey, Luis Elias and Dave Deacon

Free Electron Laser (FEL) Primer

Two primary configurations: **low gain oscillator** using mirrors or **high gain single pass amplifier**

3 main elements:
e- gun,
accelerator,
& **undulator**



Schematic of FEL oscillator

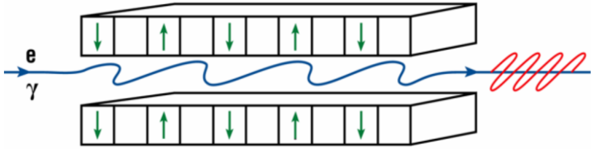
Physics is relatively simple: transverse motion in undulator allows e- to couple to light; light acts back on the electrons and causes beam to bunch, radiating as N^2 rather than N (no need for quantum mechanics).

Lorentz contraction and relativistic Doppler shift of dipole radiation

→ $\boldsymbol{\lambda_r \sim \lambda_u / 2\gamma^2}$ and wavelength easily tunable over wide range

FEL Resonance Condition – Undulator Motion

Looking at motion in an undulator:



$$\frac{dx}{ds} = \frac{e\beta c}{\gamma m \beta^2 c^2} \frac{B}{k_u} \sin(k_u s)$$

$$\beta_x = \frac{K}{\gamma} \sin(k_u s)$$ → trajectory angle in units of 1/γ (SR cone is 1/γ)

where K = 0.93 λ_u [cm] B [T]

Now calculate the 'longitudinal' velocity of the electron

$$\beta_z^2 = 1 - \frac{1}{\gamma^2} - \beta_x^2 = 1 - \frac{1}{\gamma^2}[1 + K^2 \sin^2(sk_u)]$$

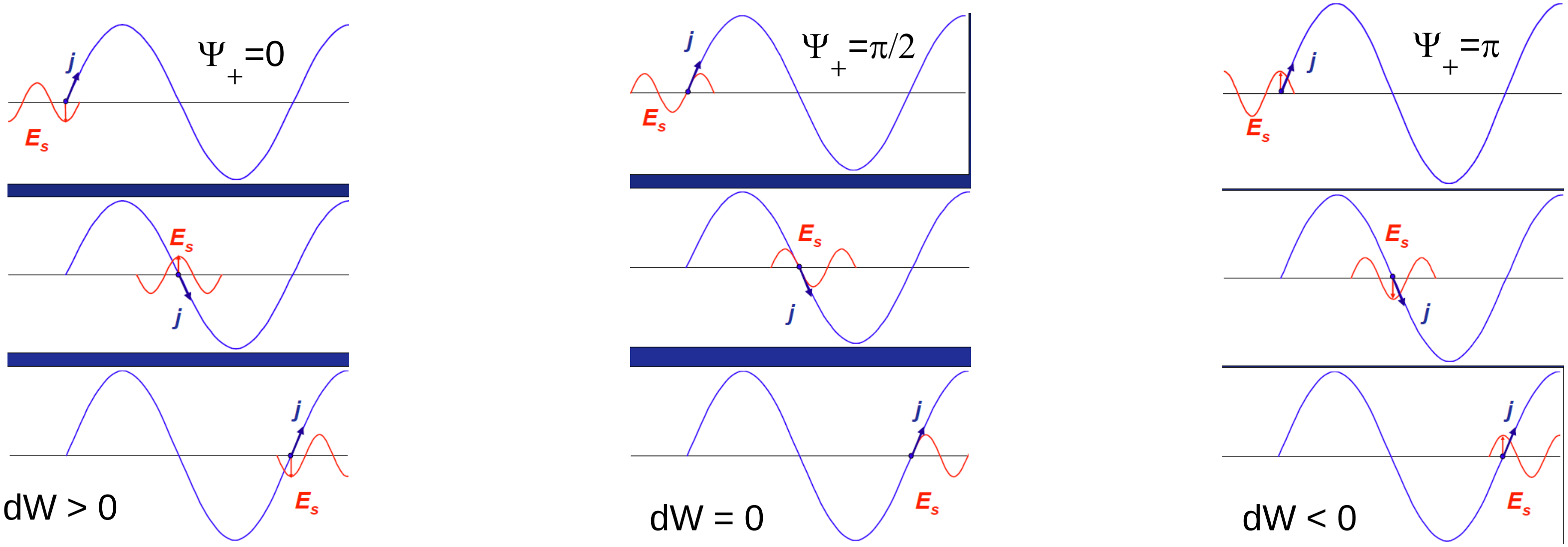
$$\boxed{\beta_z \approx 1 - \frac{1 + K^2/2}{2\gamma^2} + \frac{K^2}{4\gamma^2}\cos(2sk_u)}$$

→ electron slips relative to forward radiation by

$$\Delta L = L\,(1 - \beta_z) \sim L(1+K^2/2)/2\gamma^2$$

FEL Resonance Condition – Energy Transfer

Is there a way to couple the beam to the radiation field?
To transfer energy $dW = \mathbf{F} \cdot \mathbf{ds} = -e\,\mathbf{E} \cdot \mathbf{v}\,dt$

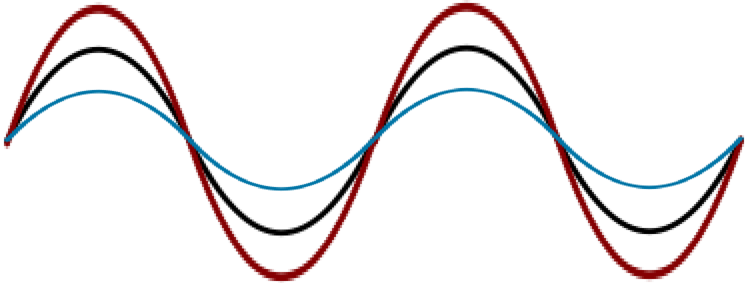


Match the radiation wavelength to the electron velocity so the radiation field slips forward one period every oscillation

$$\boxed{\rightarrow \lambda_r = \lambda_u\,(1 + K^2/2)\,/\,2\gamma^2}$$

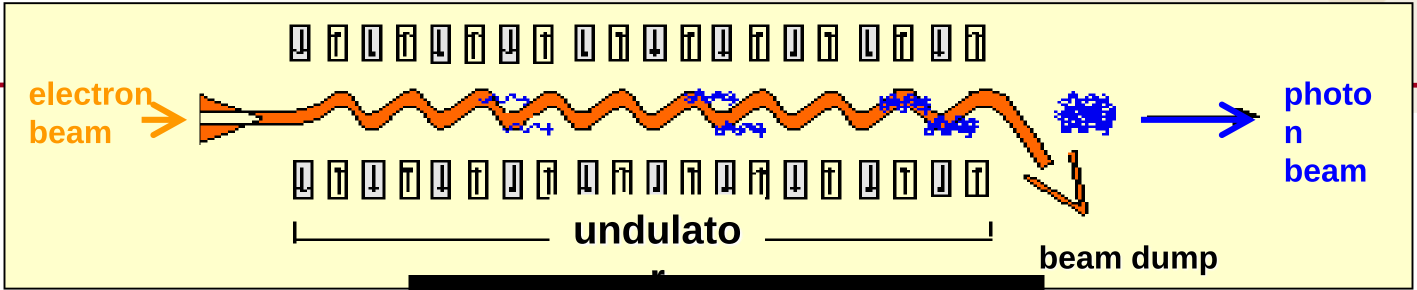
FEL Resonance Condition – Bunching

But the electron bunch is long compared to the radiation λ_r so how do we get net energy transfer to (or from) the radiation?



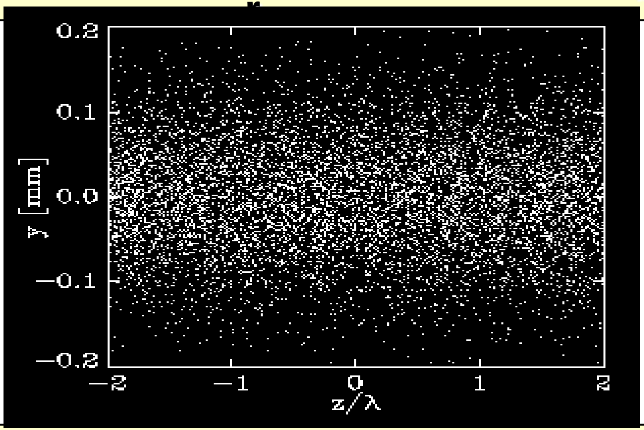
Particles with higher energy are deflected less in the undulator field → gain on nominal energy while low energy particle slip relative to the nominal energy → bunching with lengths << λ_r leading to coherent radiation

SASE FEL Micro-Bunching Along Undulator

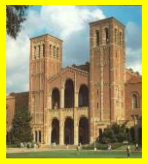


SASE* FEL starts up from noise

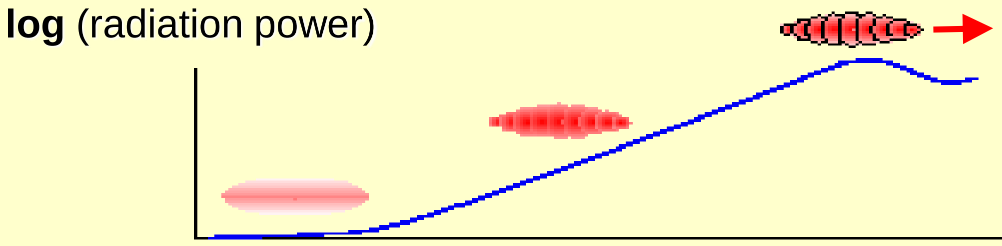
* Self-Amplified Spontaneous Emission



S. Reiche



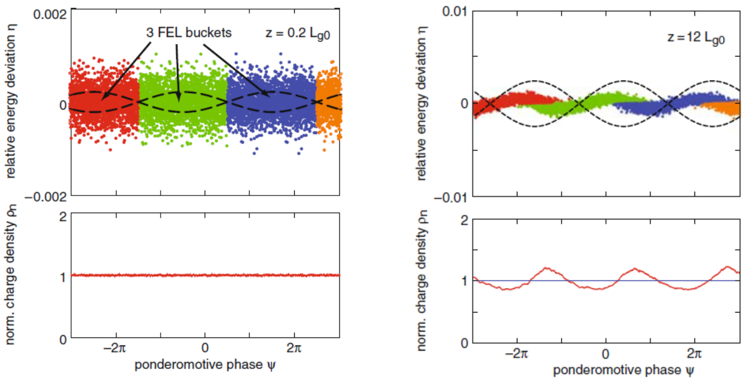
UCLA

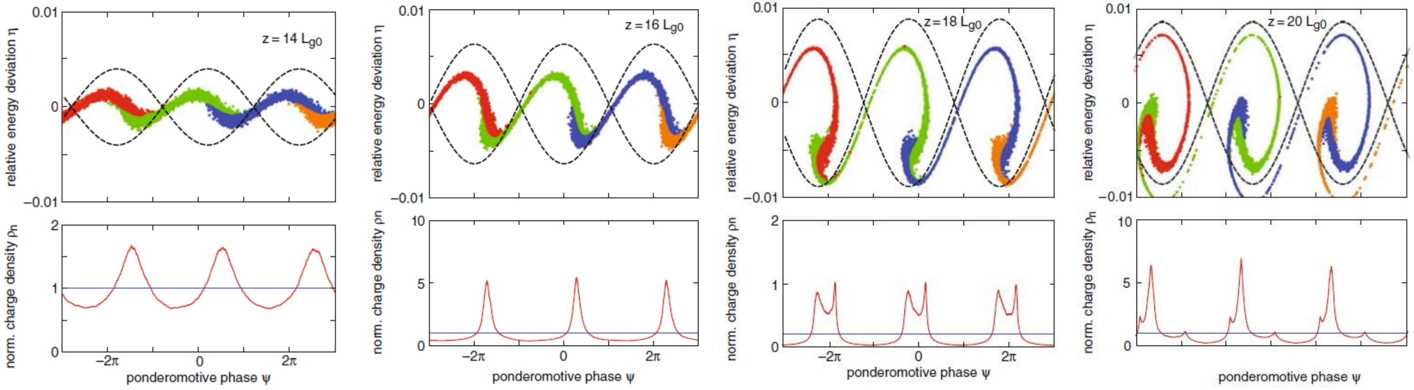


Power comes from last gain length L_g

Evolution of the FEL Microbunching

FEL bucket grows rapidly as the beam begins to bunch and radiate coherently. After a ¼ synchrotron oscillation the bunching begins to Decrease again and the FEL saturates



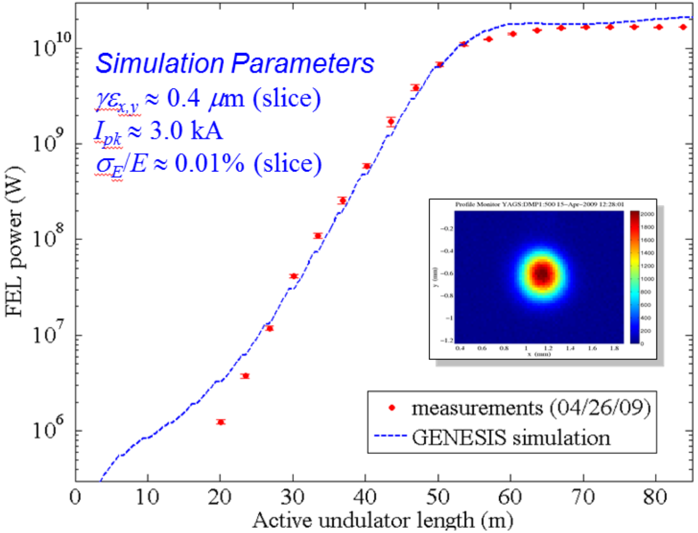


From P. Schmuser et al.

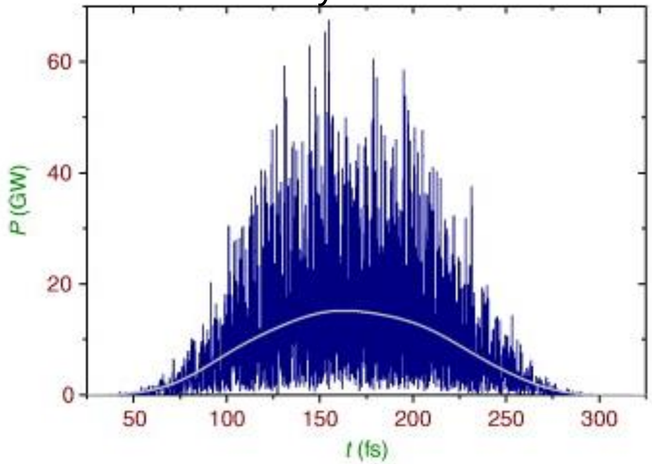
SASE Amplifier FEL Characteristics
Self-Amplified Spontaneous Emission

Amplifiers can start from a seed or noise (SASE)

- Typical SASE bandwidth is ~0.1%; seeded BW >10x smaller
- Transverse coherence usually >50%



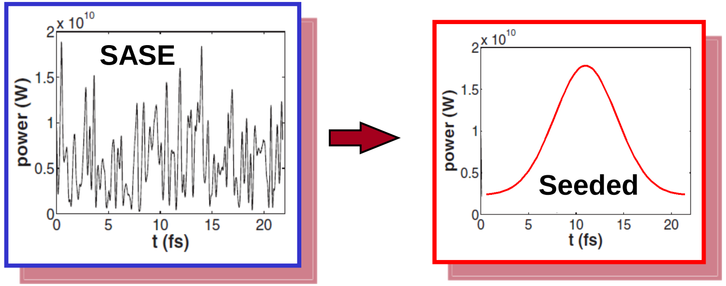
X-ray Pulse



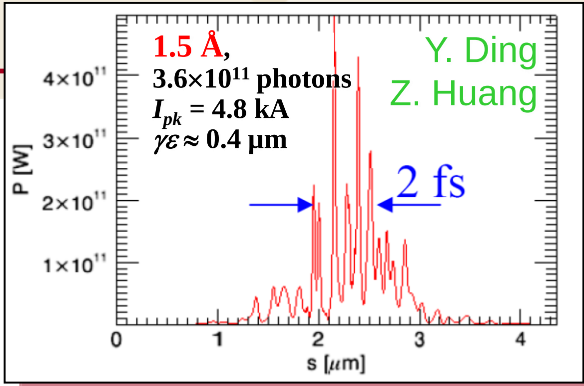
Generate GW’s of peak power in short pulses <1ps

SASE Temporal Coherence

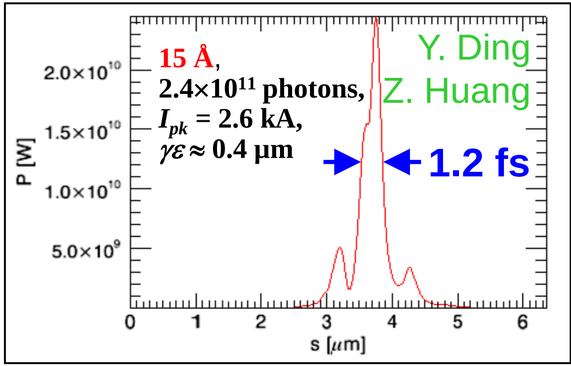
- Single pass SASE FEL starts from noise and the light is still temporally chaotic unless the correlation length is comparable to the bunch length
- Slippage length is ~ $(L_g * \lambda_r / \lambda_u)$ with no phase correlation between portions
- Would like to have transform limited pulses



SIMULATED FEL PULSES



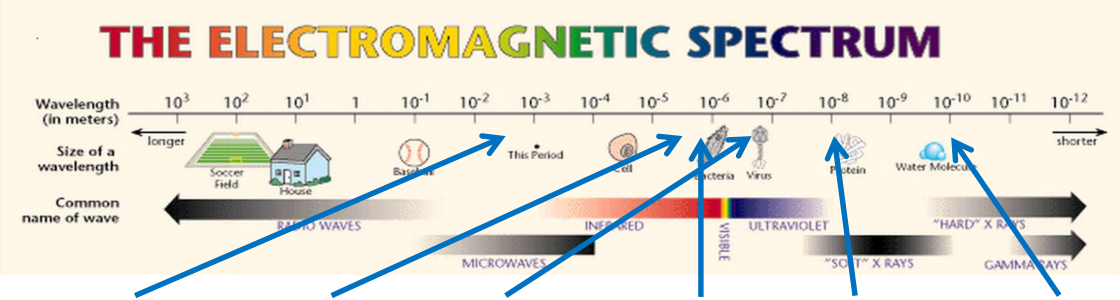
Simulation at 1.5 Å based on measured injector & linac beam & *Elegant* tracking, with CSR, at 20 pC.



Simulation at 15 Å based on measured injector & linac beam & *Elegant* tracking, with CSR & 20 pC.

Operating Free Electron Lasers

FEL History – Modified from Colson, 2006



Motz, Phillips
1950's

Madey
1970's

Duke Ring
1990's

JLAB
2000's

FLASH
2000's

LCLS, SACLA
2010

Over 50 FEL's operating around the world ranging from mm-wavelength to sub-Angstrom.

- JLAB generated 14 kW in IR in oscillator configuration
- LCLS generated 7 mJ in single pulse at a few keV
- EuXFEL has operated with SRF and high beam power since 2017
- SACLA, EuXFEL, and LCLS have lased at sub-Angstrom wavelengths

The Linac Coherent Light Source Concept:
Fourth Generation Workshop, >30 Years Ago

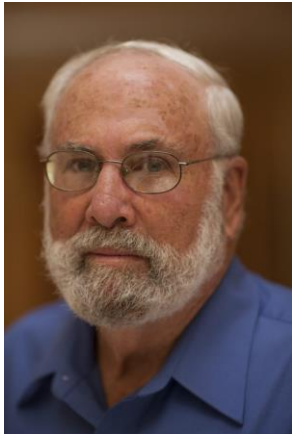
C. Pellegrini, A 4 to 0.1 nm FEL Based on the SLAC Linac,

Workshop on Fourth Generation Light Sources, February, 1992

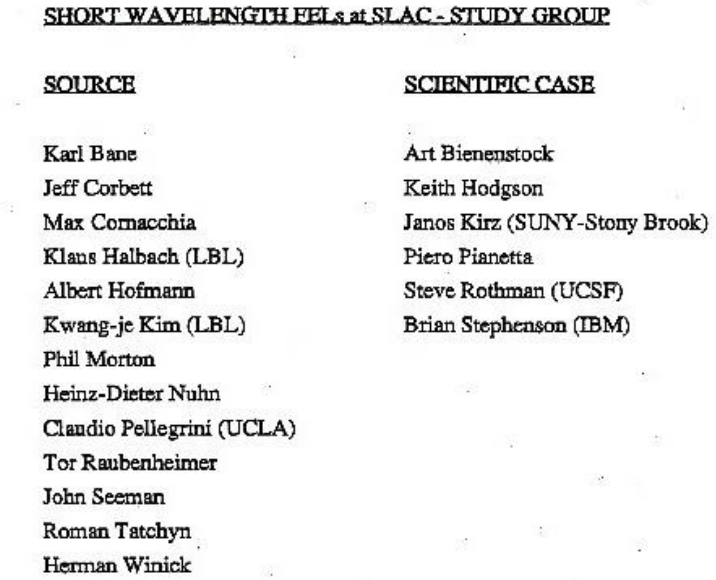
Based on theoretical work done in 80’s

Claudio Pellegrini

Herman Winick



Herman Winick’s Study Group



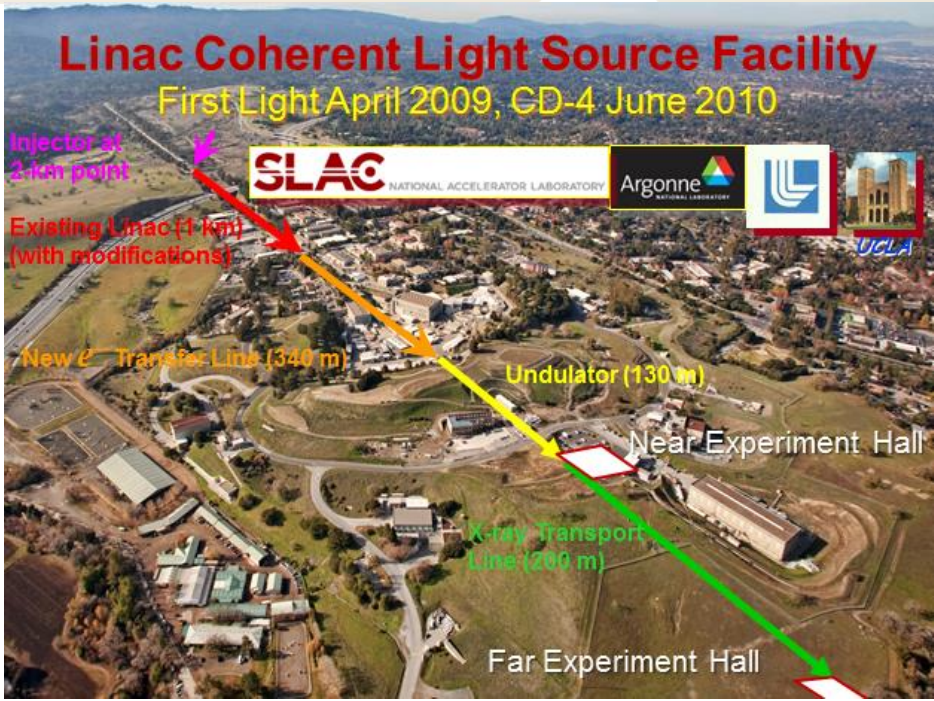
SHORT WAVELENGTH FELs at SLAC - STUDY GROUP

SOURCE	SCIENTIFIC CASE
Karl Bane	Art Bienenstock
Jeff Corbett	Keith Hodgson
Max Cornacchia	Janos Kirz (SUNY-Stony Brook)
Klaus Halbach (LBL)	Piero Pianetta
Albert Hofmann	Steve Rothman (UCSF)
Kwang-je Kim (LBL)	Brian Stephenson (IBM)
Phil Morton	
Heinz-Dieter Nuhn	
Claudio Pellegrini (UCLA)	
Tor Raubenheimer	
John Seeman	
Roman Tatchyn	
Herman Winick	

The Linac Coherent Light Source (LCLS) X-ray FEL

The LCLS was the world's 1st x-ray Free Electron Laser (FEL) in 2009

- LCLS electron source is the SLAC *Cu* RF linac at 120 Hz using ⅓ SLAC linac
- Includes one 3cm fixed gap undulator
- Six experimental stations
- Based on 15 years of focused R&D



Initial Parameter Goals

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**

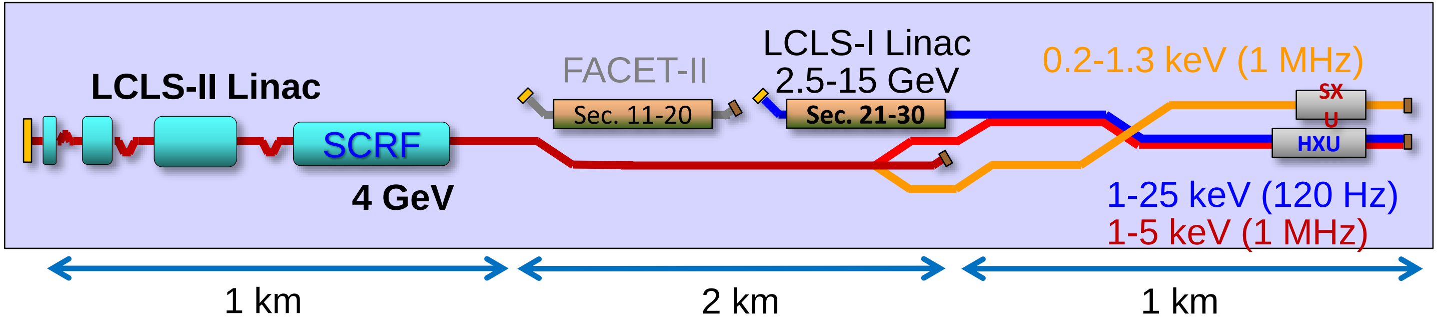
All parameters exceeded

LCLS-II Upgrade

New Superconducting Linac with MHz-rate → 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

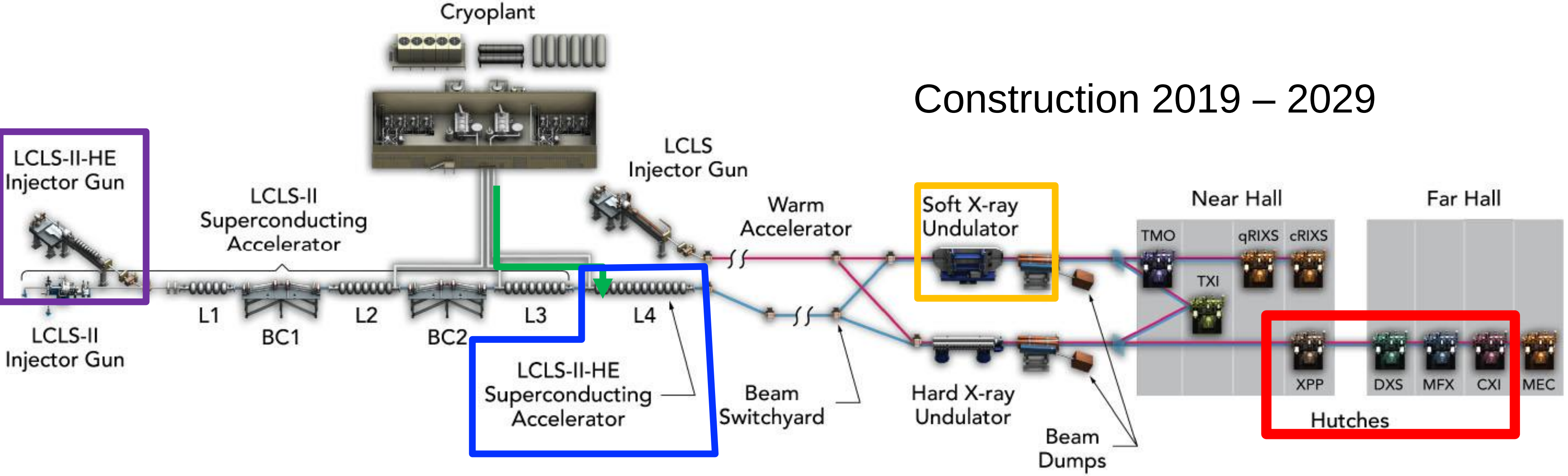
Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
Soft X-ray	0.20 - 1.3 keV with >100 Watts	▨
Hard X-ray	1.0 - 5.0 keV with >20 Watts	1 - 25 keV with mJ-class X-ray pulses



Construction 2013 – 2022

LCLS-II High Energy Upgrade

Increase MHz-rate photon energy from 5 keV → 20 keV



Construction 2019 – 2029

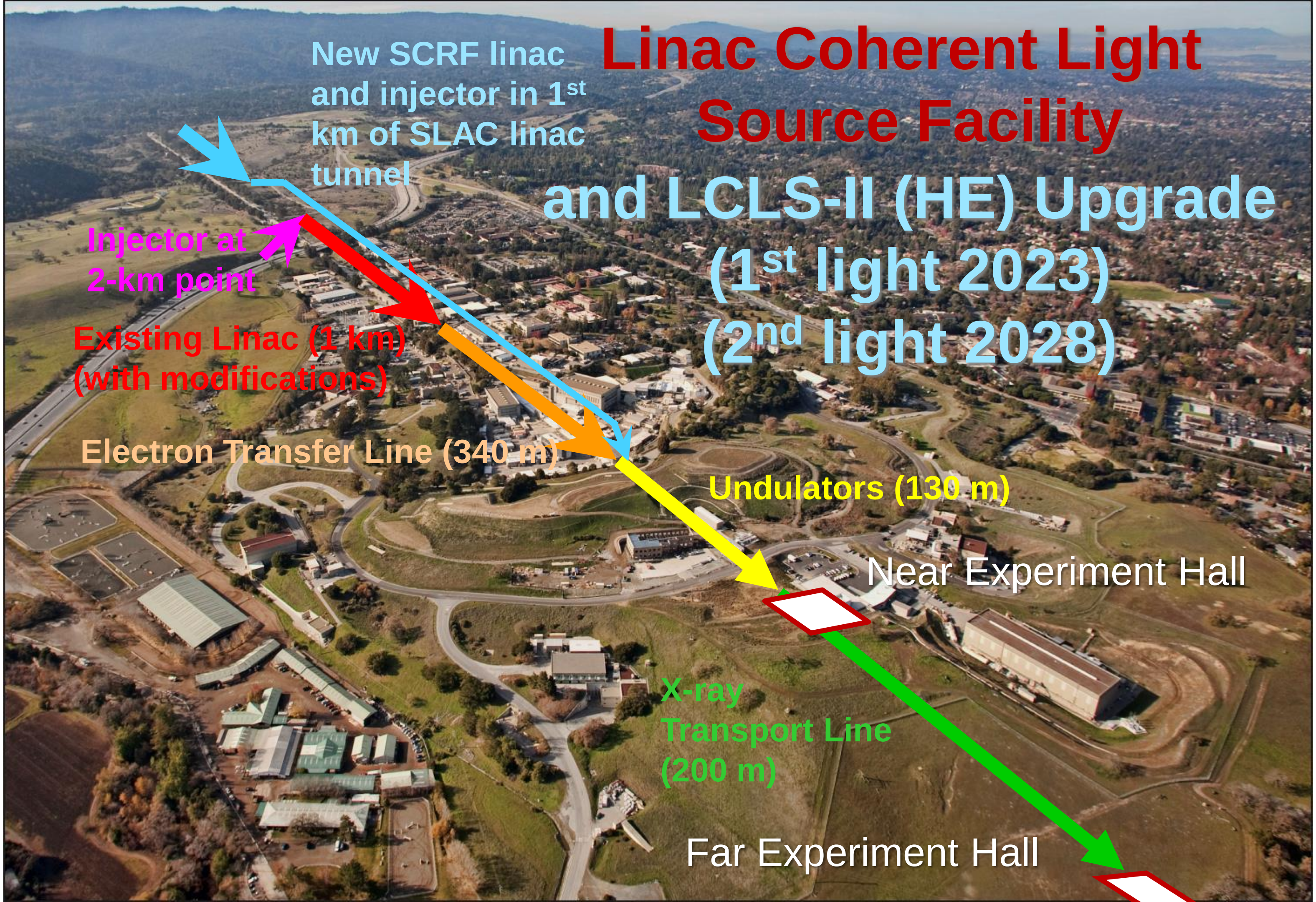
1. Add 23 additional cryomodules (L4 linac) to double the LCLS-II accelerator energy: 4 GeV to 8 GeV
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac
3. New long period soft X-ray undulator
4. Upgrade the LCLS hard X-ray instruments for MHz beam and data rates
5. Design low-emittance injector and SRF gun for extended hard X-ray performance

Linac Coherent Light Source Facility

and LCLS-II (HE) Upgrade

(1st light 2023)

(2nd light 2028)



Technical Challenges of the LCLS-II

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:

- Variable gap undulators → Commissioned
- CW superconducting RF system with >16 MV/m gradient and high Q_0 cavities → Commissioning started
- High brightness CW injector → Commissioned
- Dynamics in high brightness, low-energy electron beams → TBD

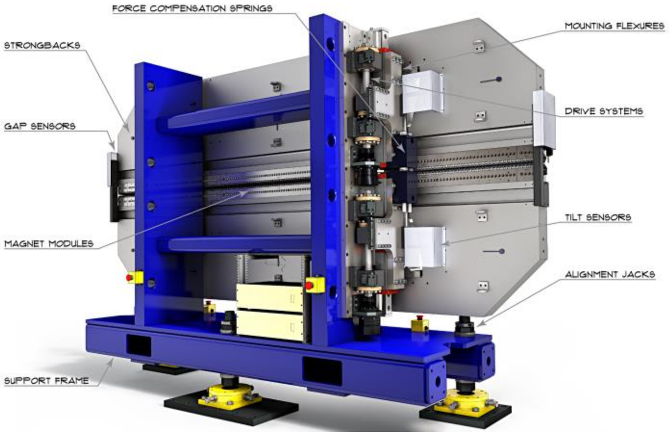
Commissioning started with 1st light from SRF linac expected in 2023

LCLS-II Variable Gap Hybrid Undulators

Installed two new undulators in LCLS Undulator Hall

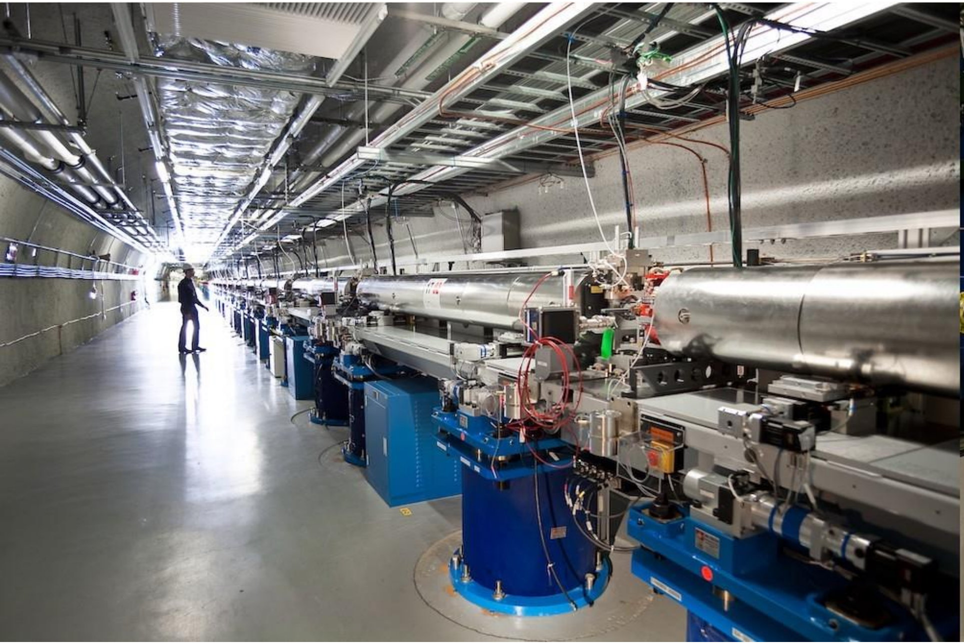
Variable gap undulators used in LCLS-II to provide greater wavelength tuning flexibility than in LCLS:

- standard vertical gap for Soft X-rays with 39 mm period (250 eV – 2 keV)
- a horizontal gap Vertically Polarized Undulator for Hard X-rays with 26 mm period (few keV – 25 keV)



LCLS-II Undulator Installation

SLAC Undulator Hall (May 2015)

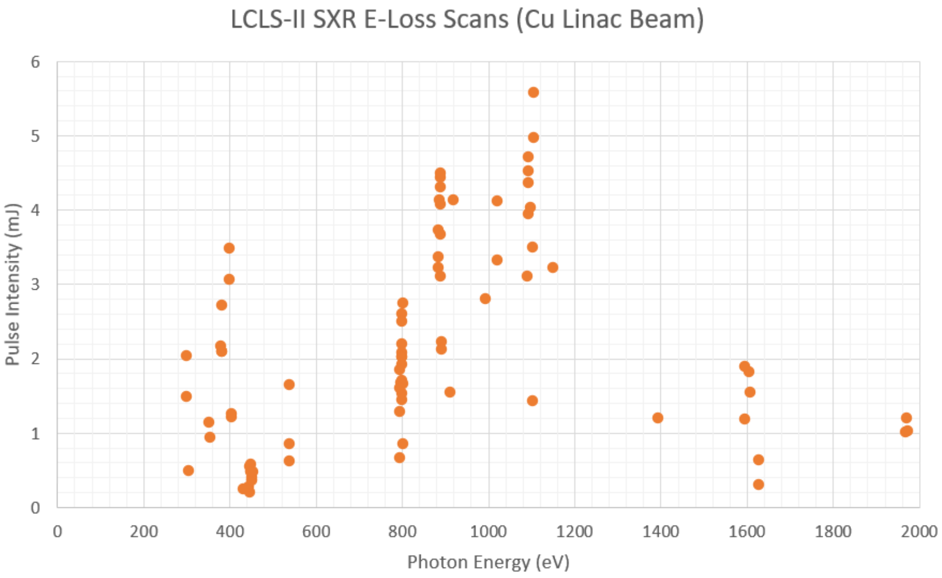


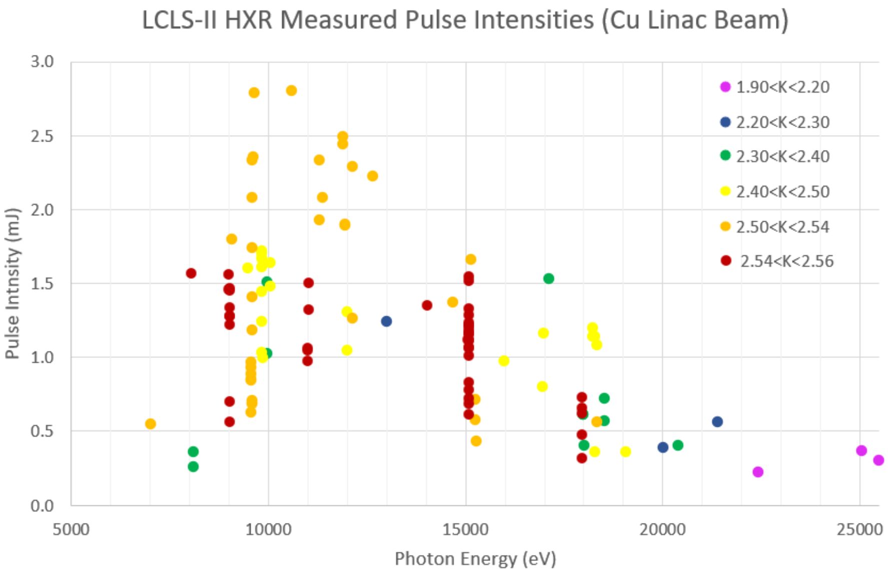
SLAC Undulator Hall (May 2020)

SXR ~ 90 meters HXR ~ 150 meters

HXR and SXR Undulator Performance

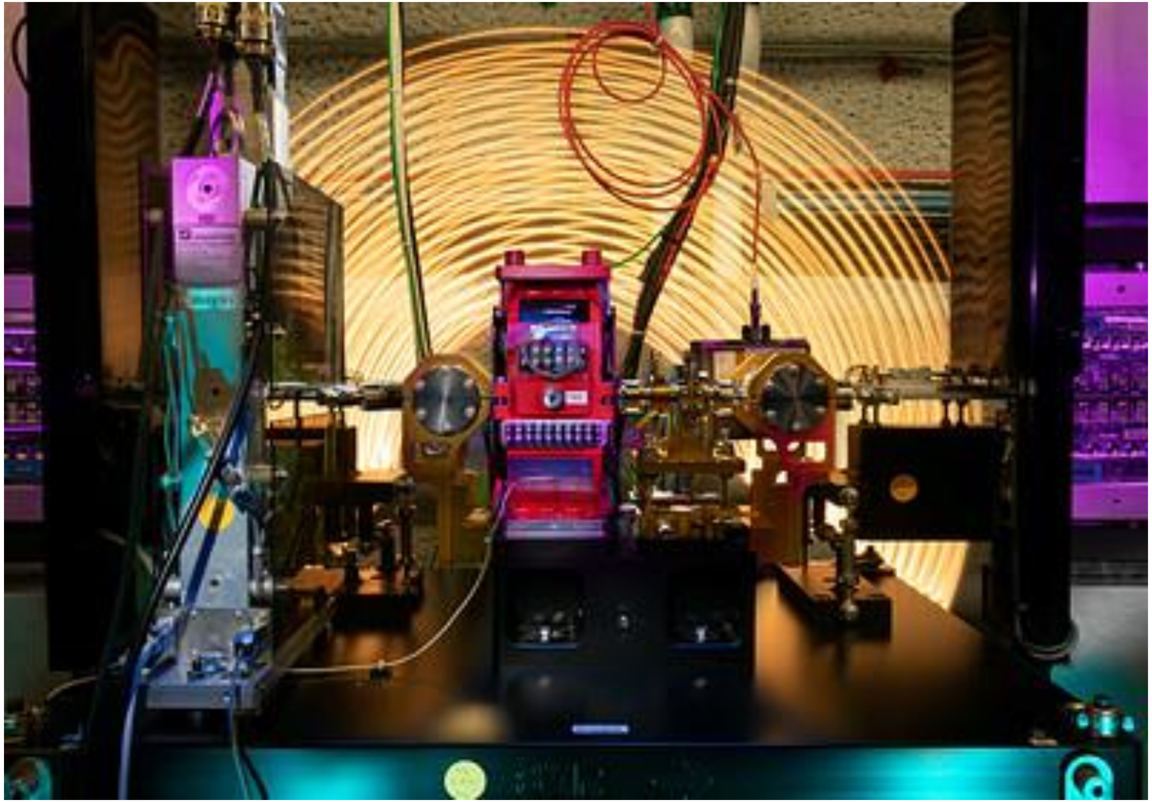
Generating very intense pulses with few 10^{13} photons per pulse at 1 keV to few 10^{11} at 25 keV





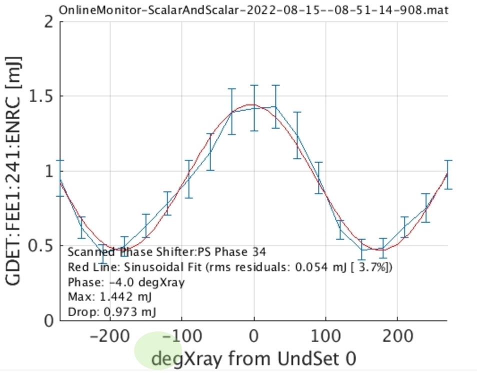
LCLS-II Undulator Segment Interspace

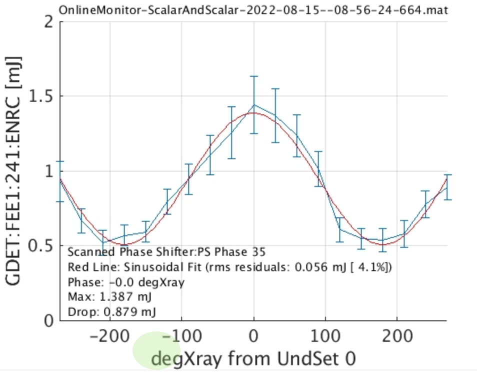
- Undulator segments are ~3.5 meters on movers to position
- Need focusing, diagnostics, and path length control between segments
- BPMs are X-band cavity BPMs with <1um resolution at 10 pC

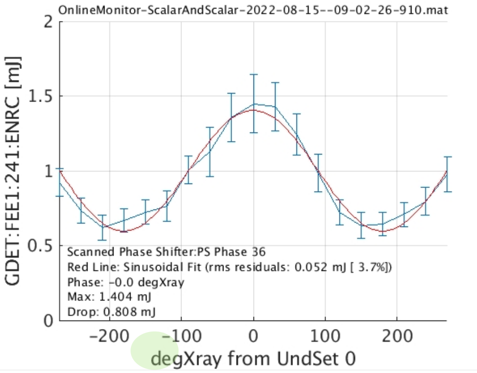


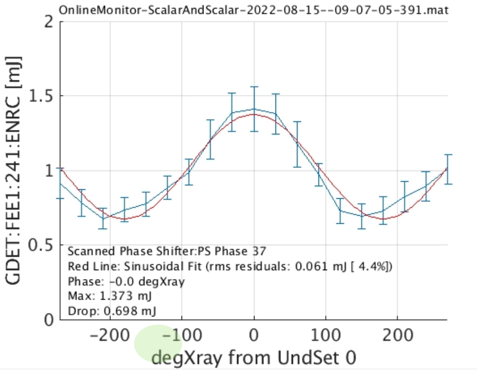
LCLS-II Undulator PM Phase Shifters

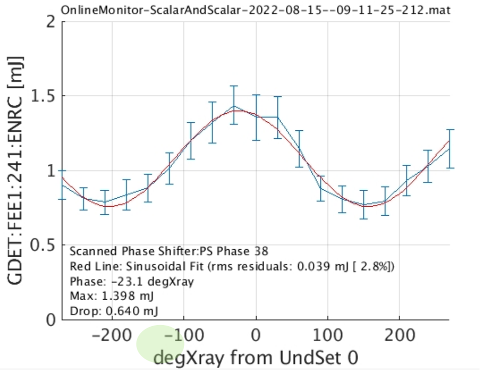
Need to control path length between undulators <<λ_r

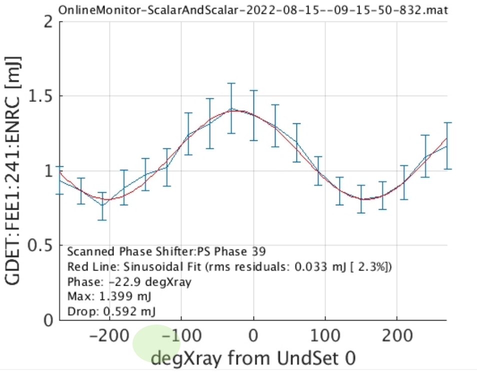




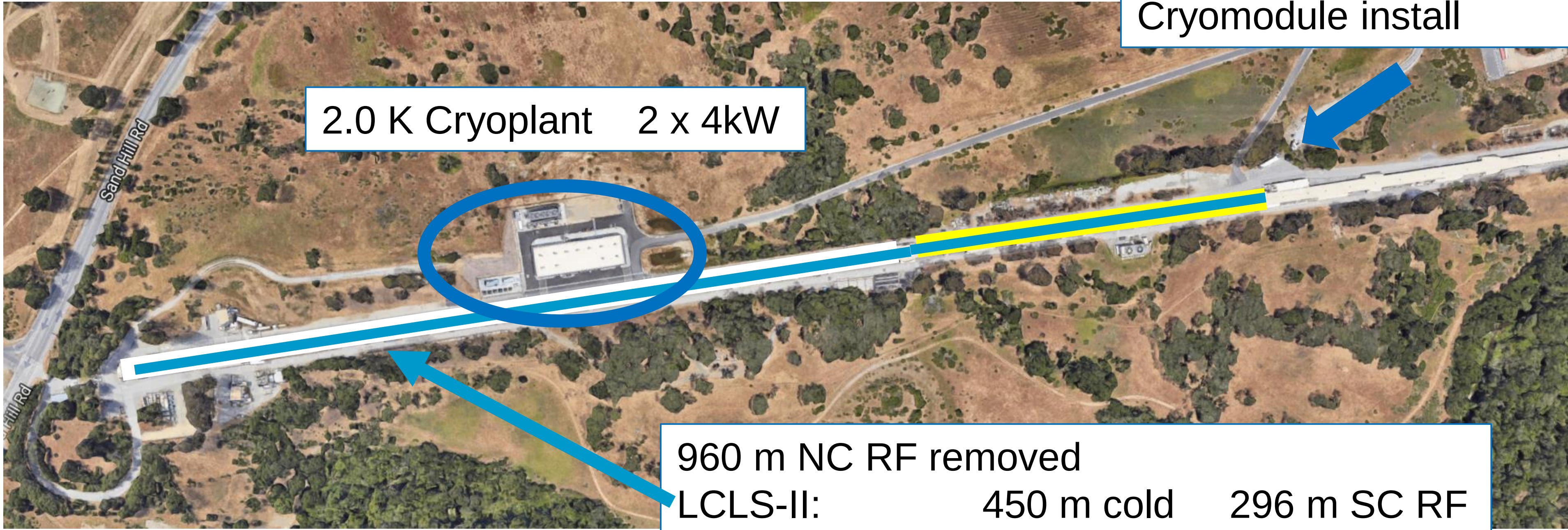








LCLS-II: First 1000m of SLAC Linac



Grade Level Access for Cryomodule install

2.0 K Cryoplant 2 x 4kW

960 m NC RF removed

LCLS-II:	450 m cold	296 m SC RF
LCLS-II-HE:	250 m cold	170 m SC RF
LCLS Total SRF:	700 m cold	466 m SC RF

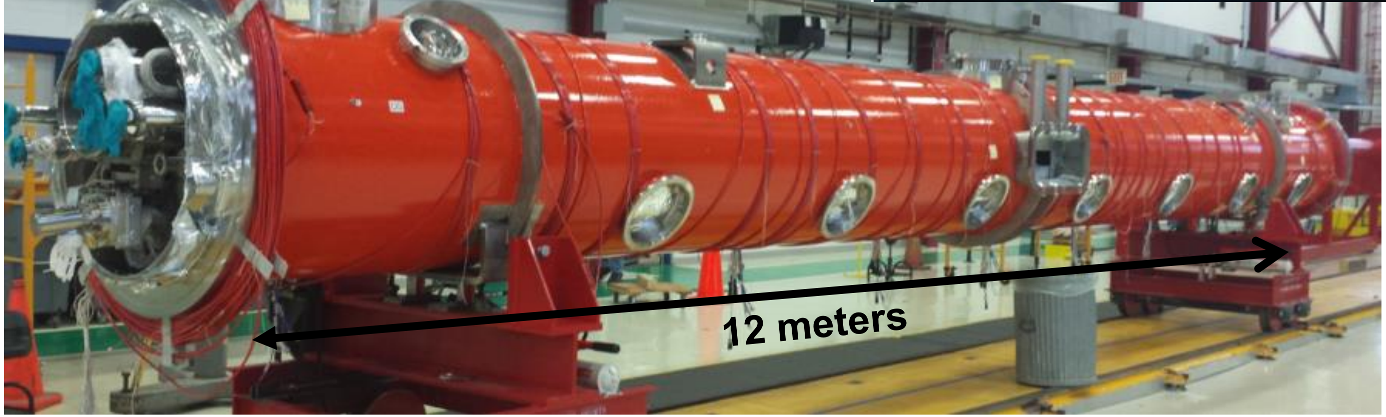
LCLS-II SRF Linac is Installed

LCLS-II (HE) Cryomodules

60 new 1.3 & 3.9 GHz Cryomodules being installed in SLAC linac tunnel

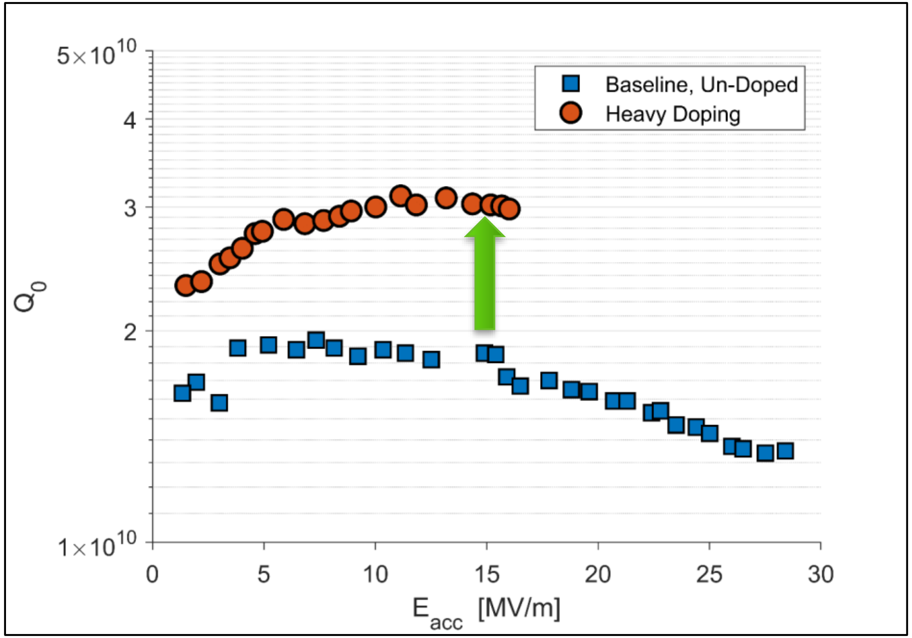
Cryomodules are being fabricated at FNAL and JLab

9-cell $\pi/2$ cavity at 1.3 GHz; L = 1.038m; R/Q ~ 1036; Q > $3\text{x}10^{10}$



Nitrogen-Doping and LCLS-II

Critical development to reduce cryogenics



- All cavities for LCLS-II are produced with nitrogen-doping
- Q is improved by 2 mechanisms:
  - Higher starting Q_0
  - Anti-Q slope
- Both of these are a resulting of a changing R_{BCS}

- Developed by collaboration with Fermi, Jlab, & Cornell

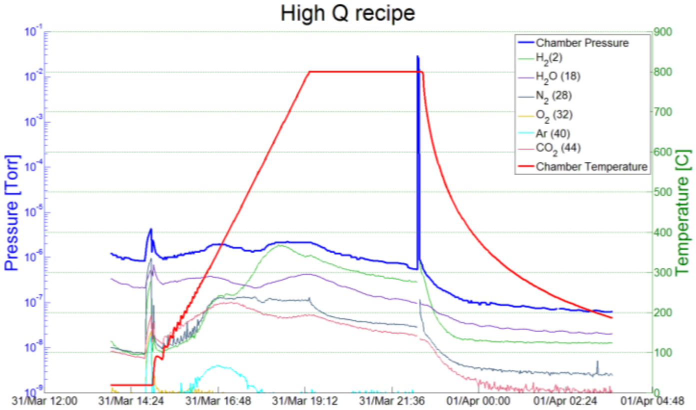
Q_0's of >3×10^{10} can consistently be produced

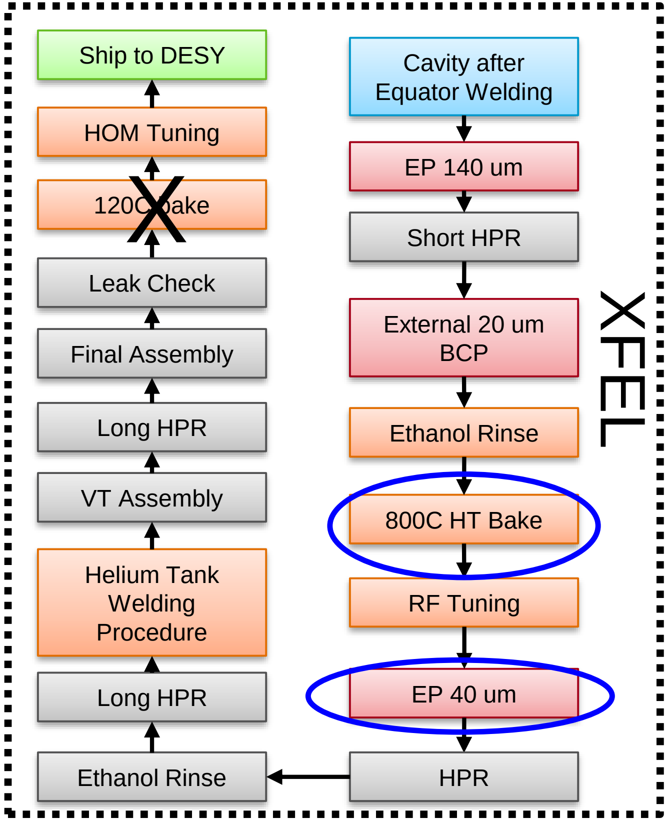
Nitrogen doping treatment

Small variation from standard XFEL/ILC processing recipe

Example from FNAL 2/6 doping process:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





XFEL

Cavity after Equator Welding

EP 140 um

Short HPR

External 20 um BCP

Ethanol Rinse

800C HT Bake

RF Tuning

EP 40 um

HPR

Ethanol Rinse

Long HPR

Helium Tank Welding Procedure

VT Assembly

Long HPR

Final Assembly

Leak Check

~~120C Bake~~

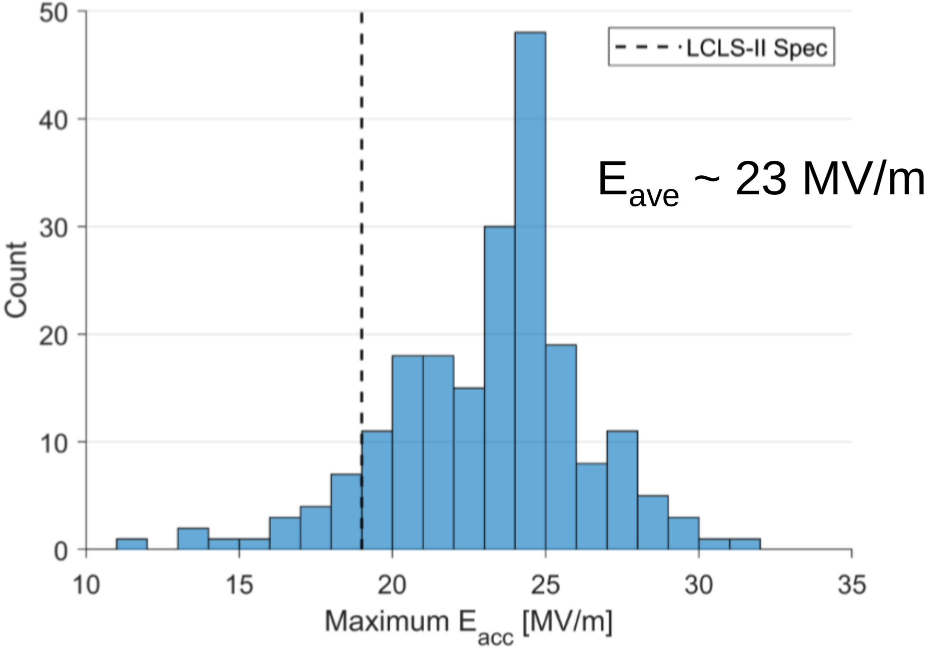
HOM Tuning

Ship to DESY

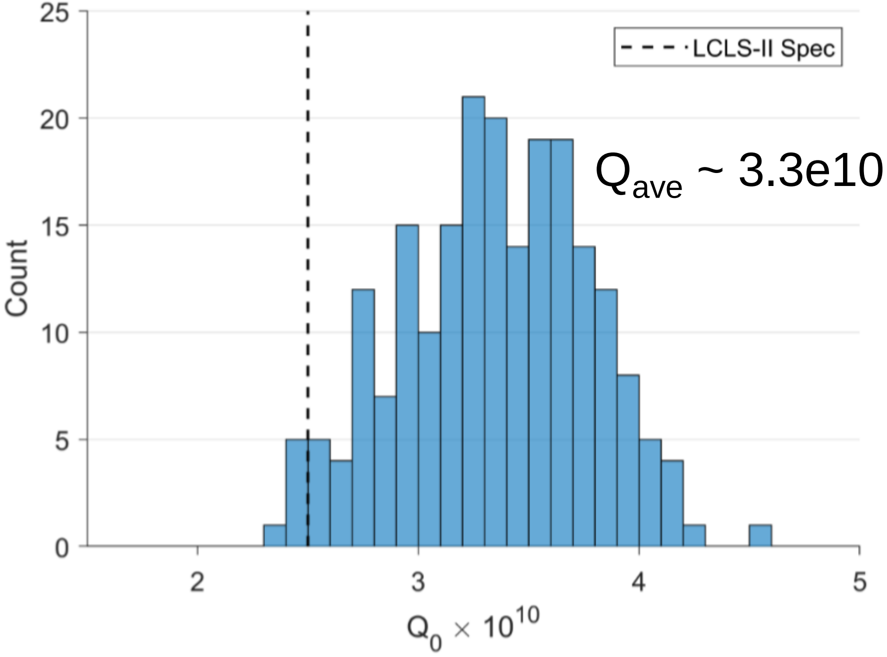
LCLS-II Cavity Production

N_2-doping improved Q_0 by >2x

Cavity E_{acc} and Q_0 for ***final*** LCLS-II production process



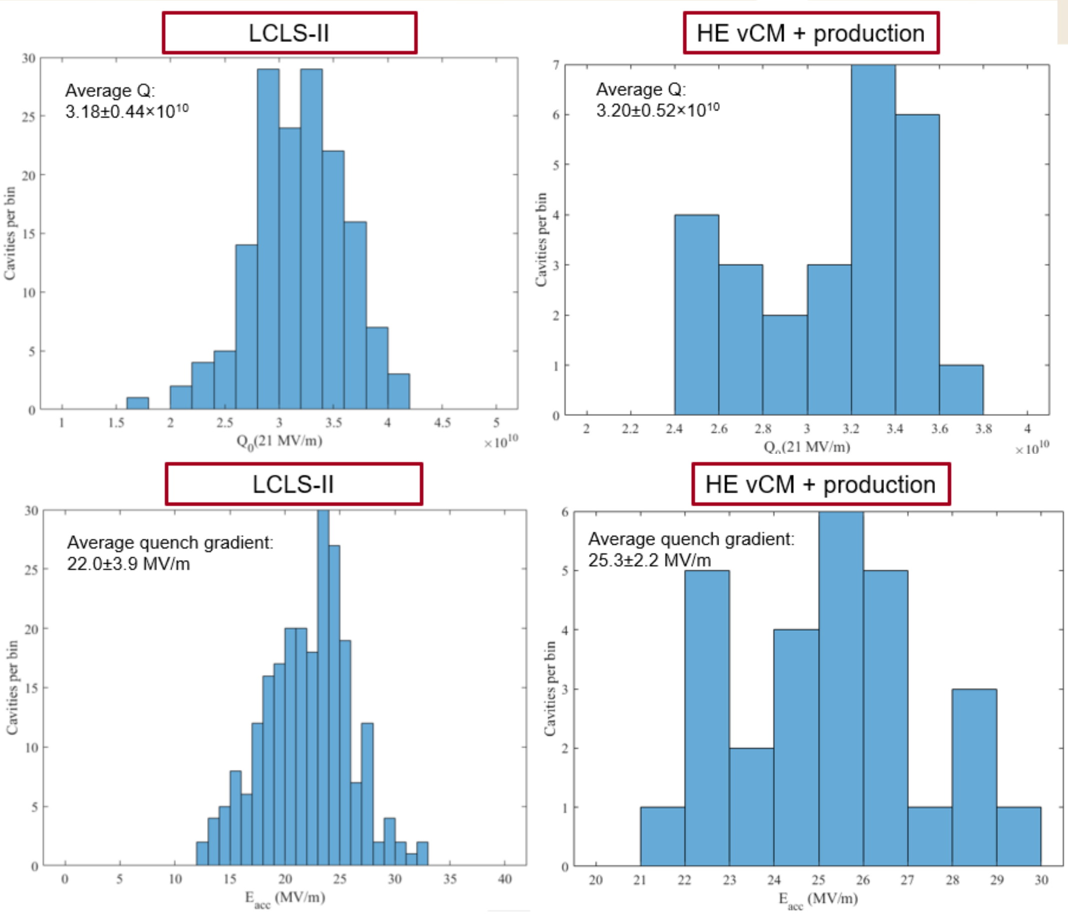
E_{ave} ~ 23 MV/m



Q_{ave} ~ 3.3e10

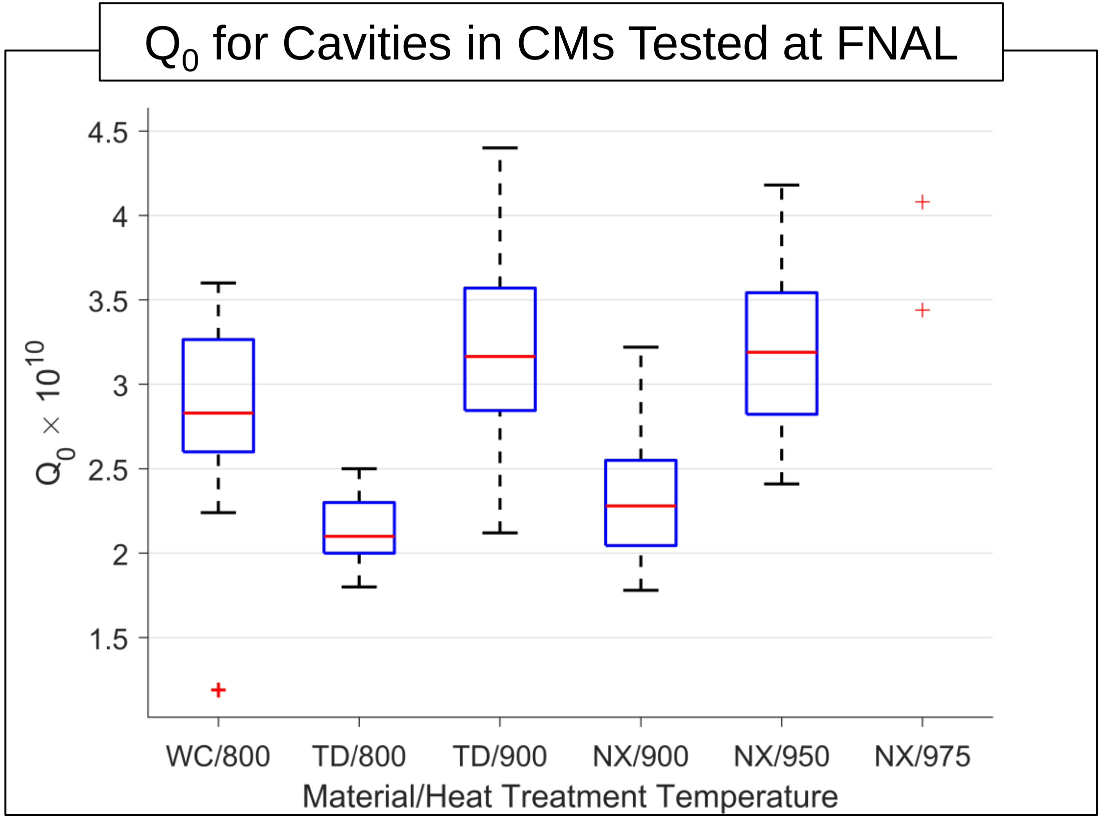
LCLS-II-HE further improved techniques

Choose ***lighter*** N_2 doping, to produce cavities with higher mean free paths than LCLS-II cavities and possibly choose ***longer*** anneal times, to produce a very uniform doped layer. Two new processes: 2 / 0 and 3 / 60 → selected 2 / 0



Cryomodule Q_0 and Flux Expulsion

Q_0 for Cavities in CMs Tested at FNAL



- Prototype cavities typically showed Q_0 above spec
- TD/800 cavities are consistently below spec
- TD/900 cavities consistently far exceed the spec
- NX/900 cavities perform similarly to the TD/800 cavities and do not meet spec
- NX/950/975 cavities perform similarly to TD/900

LCLS-II and LCLS-II-HE Cavity / CM Lessons

1. Vendor oversight and fabrication
   - Many challenges implementing and repeating desired process
2. Cavity material and annealing temperature for flux exclusion
   - Material variations required different treatment process
3. Fast cool-down for high Q0
4. Balance between final EP, N_2-doping, and oxide layer
   - Surface finish sensitivity to EP voltage and **temperature**
5. CM design for microphonics, shipping, stability, …

LCLS-II-HE Cryomodule Development

Testing the vCM (HE 1st unit Cryomodule)

Demonstration of LCLS-II-HE CM

Culmination of High Gradient R&D and development of new N_2-doping protocol

Excellent gradient performance (25.0 MV/m versus requirement of 20.8 MV/m)

Meets Q_0 requirements at PL
(3.0×10^{10} at PL → 2.7×10^{10} installed)

No measurable field emission!
(critical for high gradient CW operation)

LCLS-II-HE Cryomodule Development

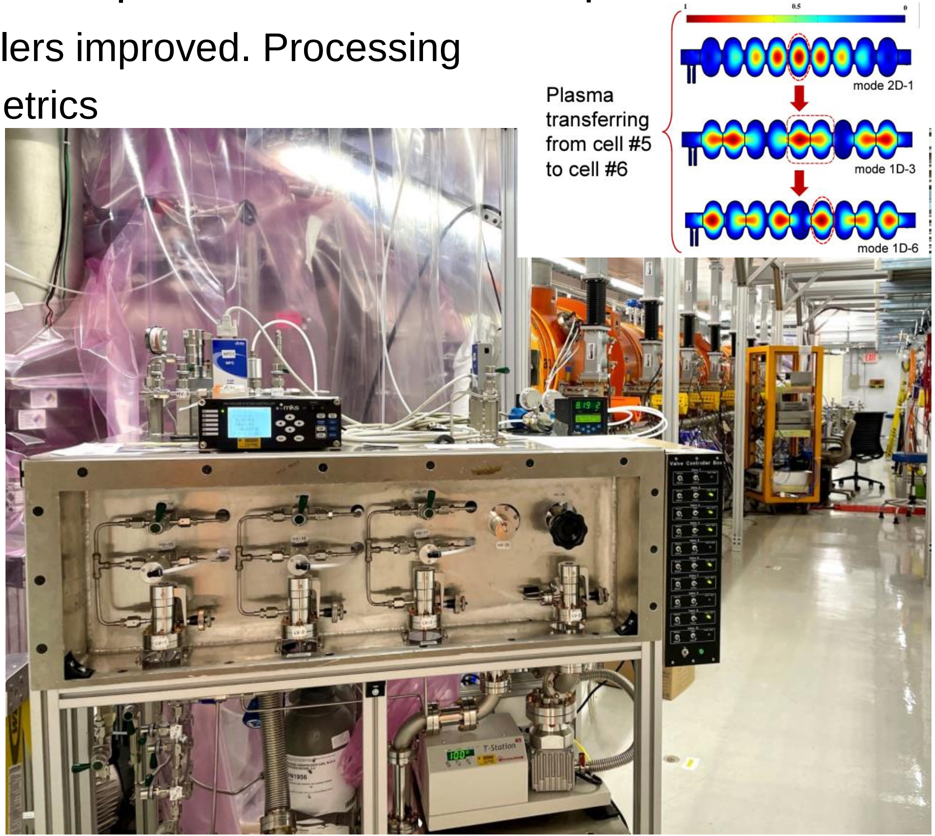
Plasma Processing R&D

Demonstrated Plasma Processing cleaning technique in CM for further improvement

- In 4 cavities processed, multipactoring in couplers improved. Processing did not negatively impact other performance metrics

Plasma Processing is a potential **risk mitigation** tool to improve poorly performing CM for LCLS-II-HE and LCLS-II before or after installation

	Before Plasma Processing				After Plasma Processing			
Cavity #	Max E_{acc} [MV/m]	Usable E_{acc} [MV/m]	Q_0 @ 21MV/m, 2K	MP quenches	Max E_{acc} [MV/m]	Usable E_{acc} [MV/m]	Q_0 @ 21MV/m, 2K	MP quenches
1	**23.4**	**22.9**	**3.0E+10**	**Y**	**23.8**	**23.3**	**3.4E+10**	N
2	24.8	24.3	3.0E+10	Y	25.2	24.8	3.2E+10	Y
3	25.4	24.9	2.6E+10	Y	26.0	26.0	3.4E+10	Y
4	**26.0**	**26.0**	**3.2E+10**	**Y**	**26.0**	**26.0**	**3.2E+10**	N
5	**25.3**	**24.8**	**2.9E+10**	**Y**	**25.5**	**25.0**	**2.8E+10**	N
6	26.0	25.5	3.4E+10	Y	26.0	26.0	3.2E+10	Y
7	25.7	25.2	3.4E+10	Y	25.9	25.4	3.3E+10	Y
8	**24.4**	**23.9**	**2.7E+10**	**Y**	**24.7**	**24.2**	**2.6E+10**	N
Avg	**25.1**	**24.7**	**3.0E+10**		**25.3**	**25.1**	**3.1E+10**	
Total	**209**	**205**			**210**	**208**		

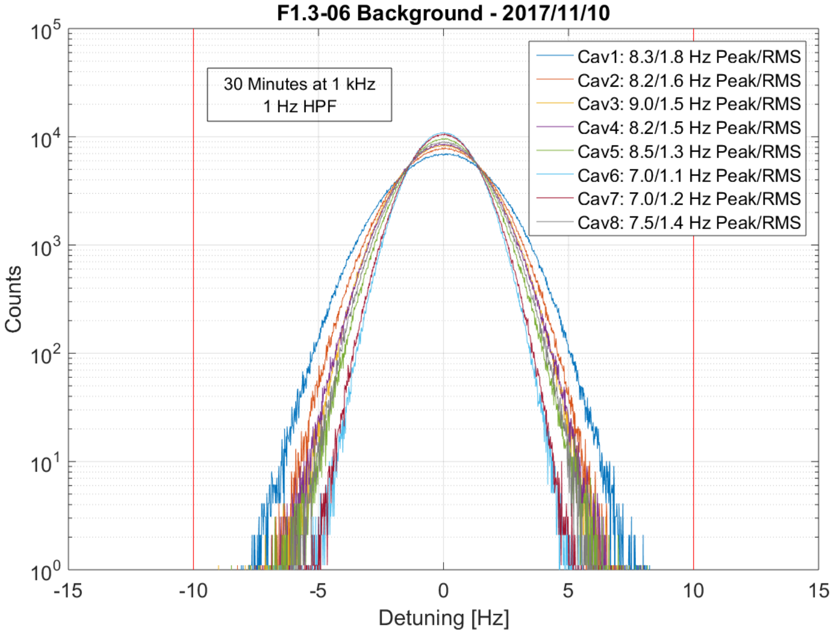

Plasma transferring from cell #5 to cell #6

SRF Cavity Detuning

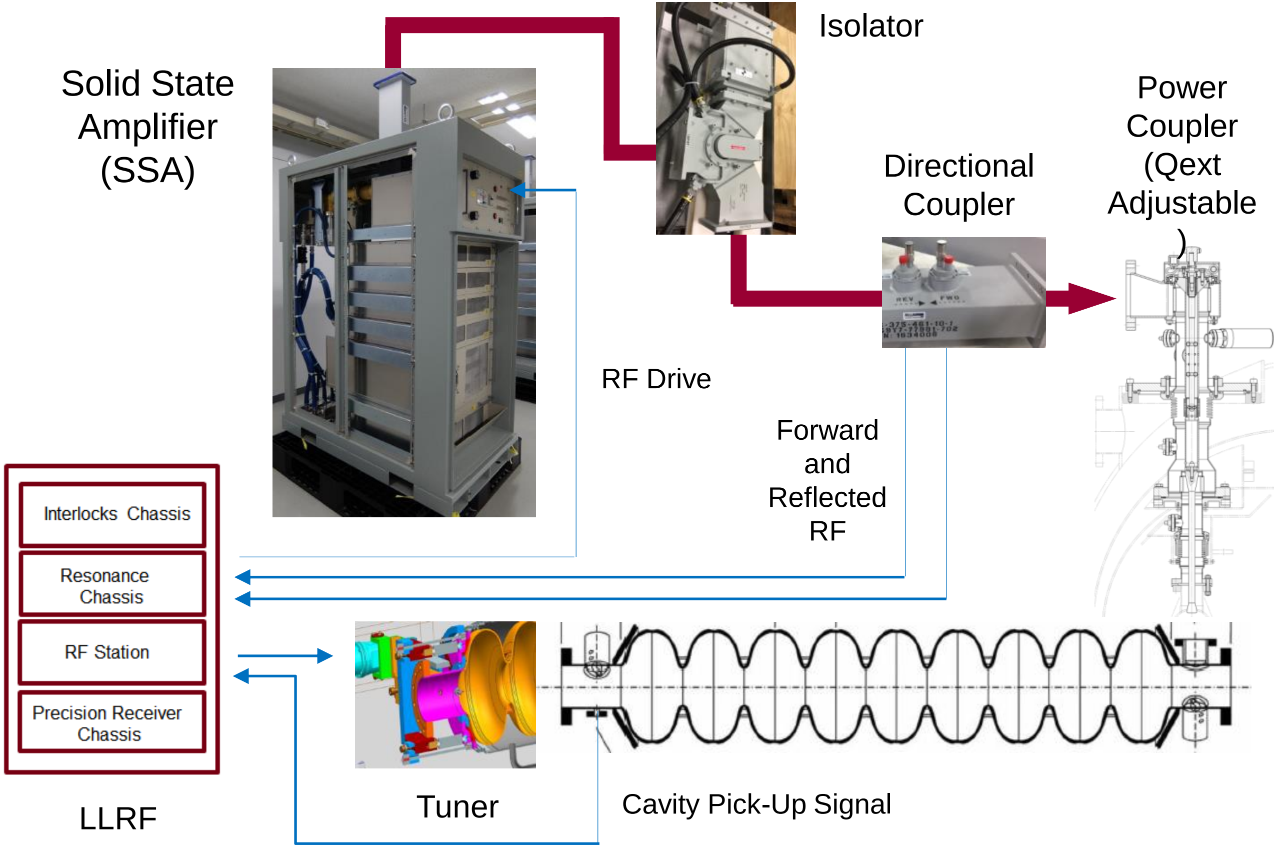
Requires a large RF power overhead

- RF power depends quadratically on microphonic cavity detuning
- For a Gaussian distribution with sigma = 1.7 Hz only one cavity per day in the linac would exceed our 10 Hz max assumption - measured sigma’s are typically < 1.7 Hz
- The LLRF system has ability to allow active detuning compensation with piezo actuators if needed.

Detuning Distribution Measured
at FNAL for CM06



RF Power Generation and Transport

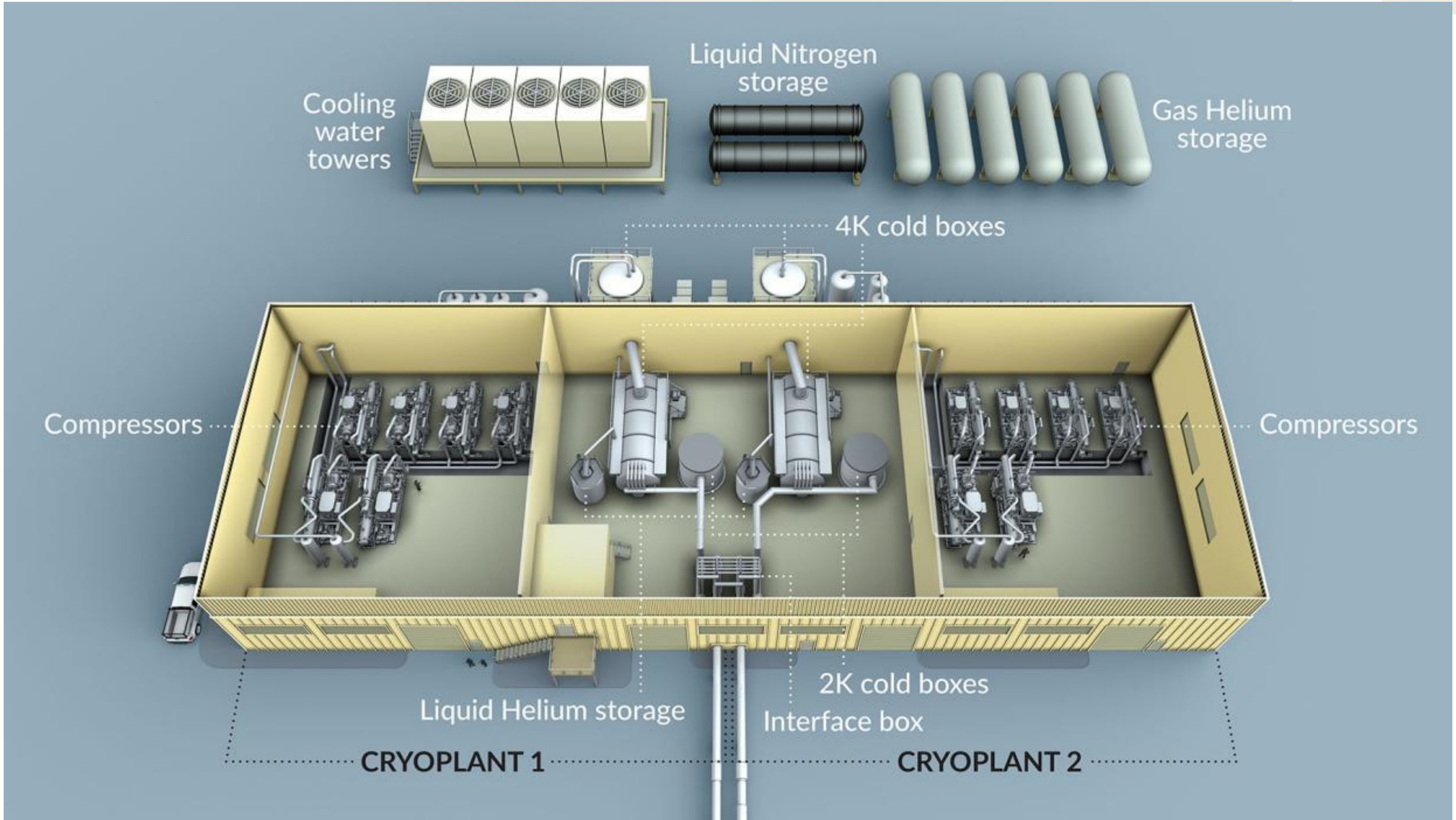


Consider accelerating a 62 uA beam on-crest at 18 MV/m with Qext = 6e7

1.2 kW required to accelerate the beam (i.e., $I_b \times V_c$)
2.1 kW input power required with no detuning or overhead
3.3 kW input power with 10 Hz detuning
3.9 kW source power for 10 Hz detuning and overhead for 8% transport losses and 8% gradient regulation margin

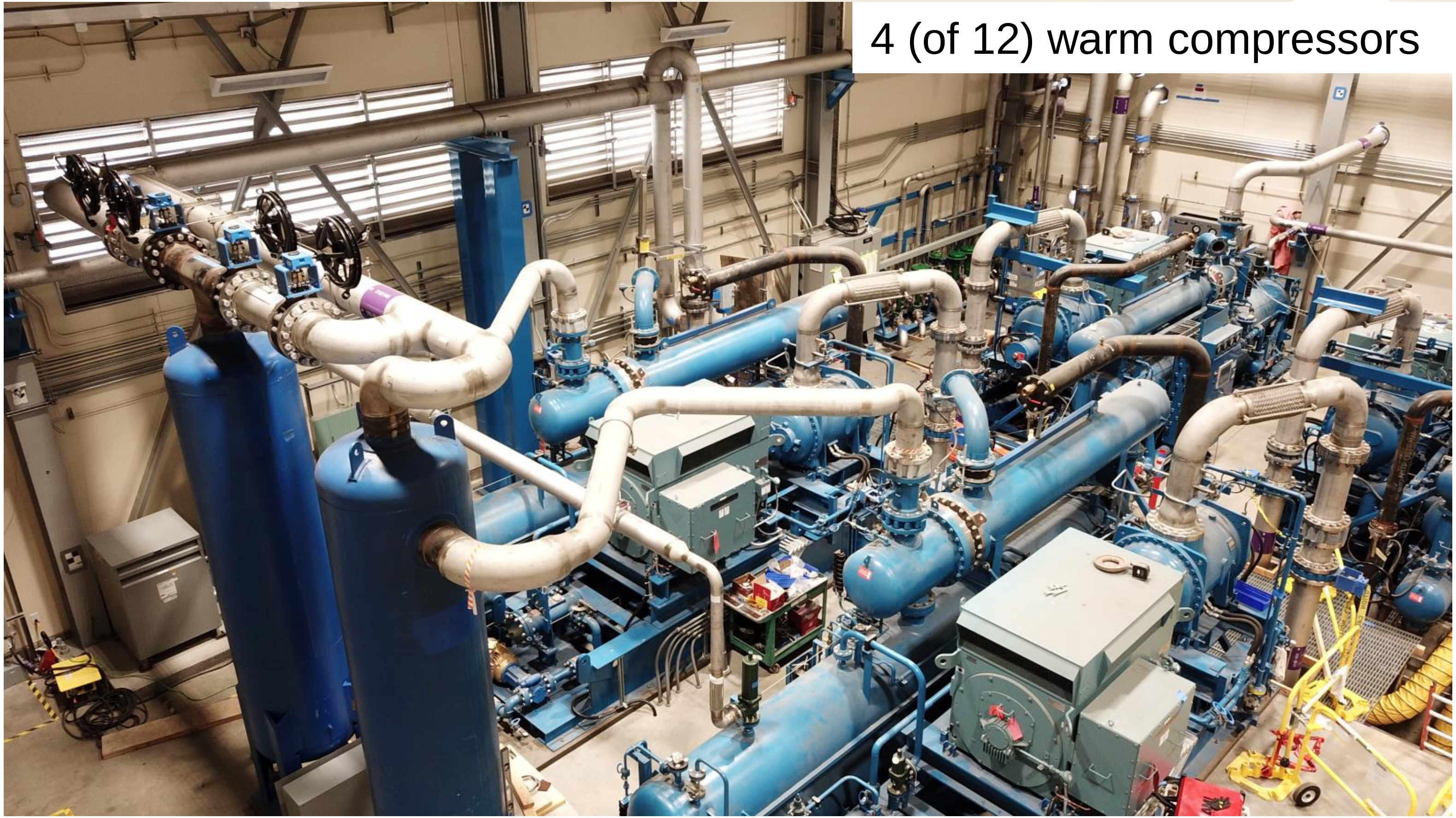
LCLS-II Cryogenics

Cavities must be cooled to 2K and extract ~ 8 kW of heat



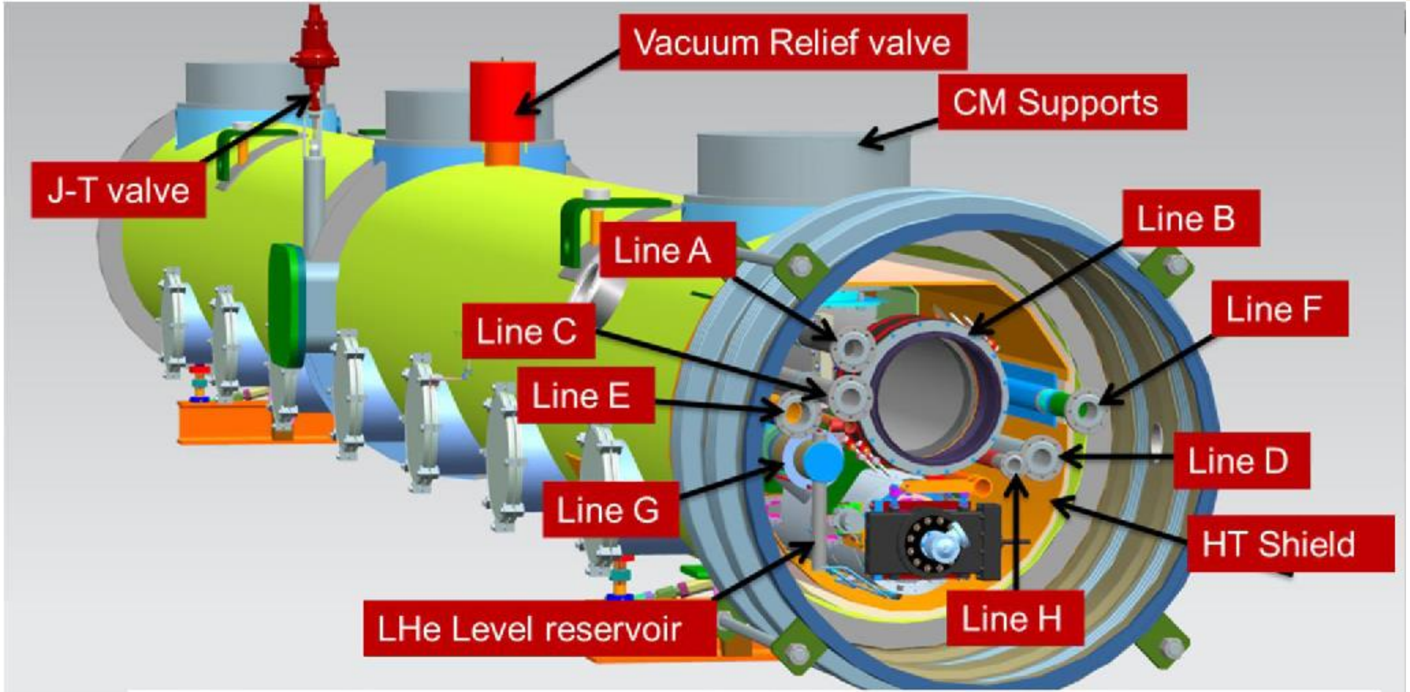
LCLS-II Cryogenic plant

LCLS-II Cryoplant Compressor Room



4 (of 12) warm compressors

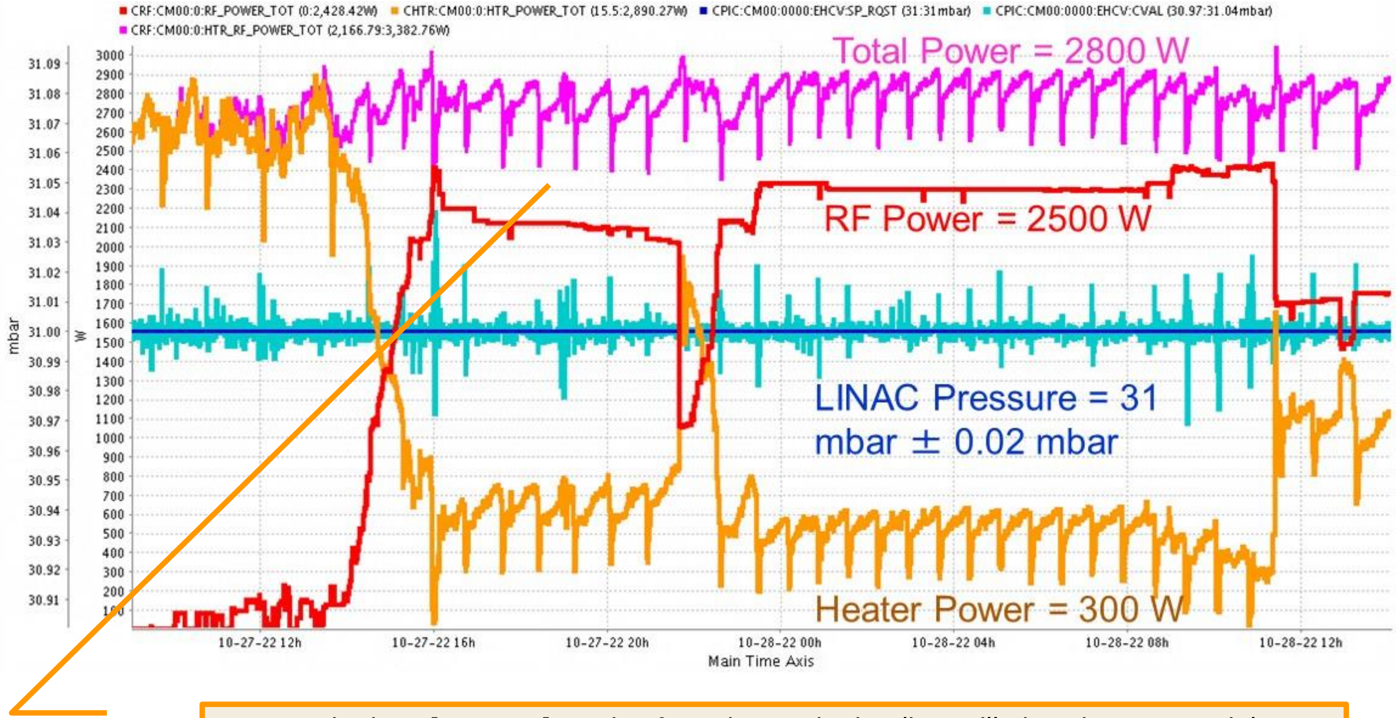
Cryogenic Distribution



A. 2.2 K subcooled supply
B. Gas return pipe (GRP)
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

CRYOPLANT #1: LINAC 2K Refrigeration

Effective 2K Refrigeration for Dynamic Heat Load = 2,800 W

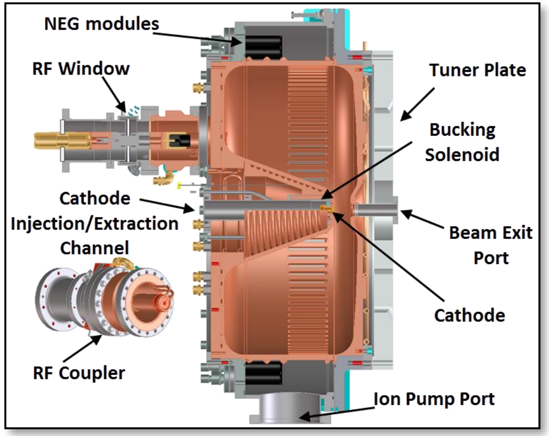


Perturbations [1,000 W] coming from thermo-hydraulic oscillations in Cryo-Modules.

The LCLS-II VHF RF Gun

Based on LBNL APEX NC RF Gun

LBNL normal-conducting scheme satisfies X-FEL requirements



J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006.

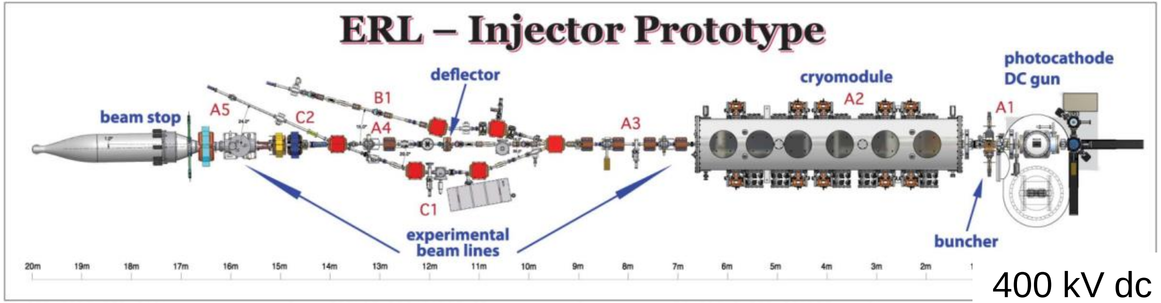
K. Baptiste, et al, NIM A 599, 9 (2009).

Frequency (7th sub-Harmonic of 1.3 GHz)	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.5 MV/m
Q_0 (measured)	>30000
Shunt impedance	6.5 MΩ
RF Power @ Q_0	80 kW
Peak surface field	24.1 MV/m
Peak wall power density	20.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	$\sim 3\ 10^{-10}$ Torr

- At VHF, cavity is large enough to withstand heat load and operate in CW mode at required gradients
- Long λ_{RF} allows large apertures and thus high vacuum conductivity
- Deliver $\gamma\varepsilon$ < 0.4 um-rad at 100 pC with 20 MV/m gradient

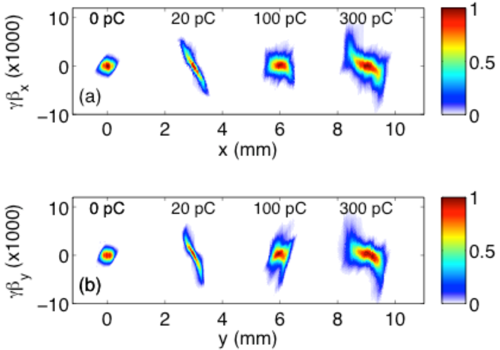
LCLS-II Injector Feasibility R&D

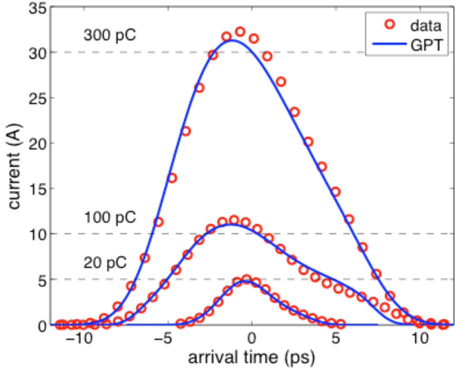
Nominal transverse parameters demonstrated at Cornell



400 kV dc gun

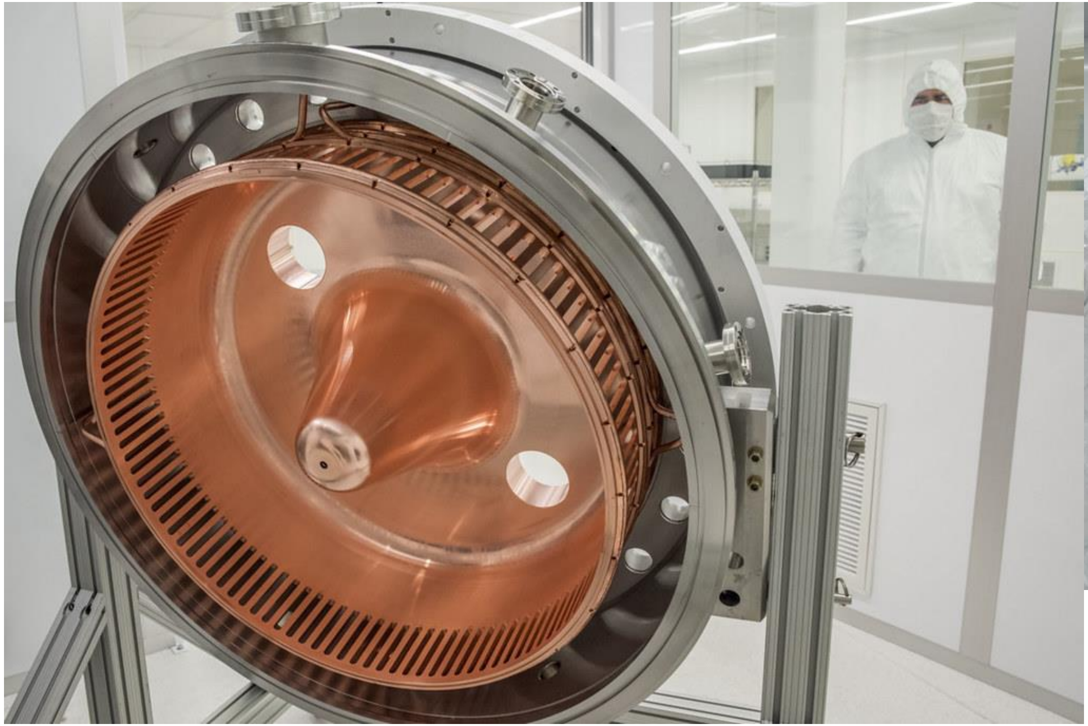
Bunch charge	Peak current	Emittance (95%)
20 pC	5 A	0.25 µm
100 pC	10 A	0.4 µm
300 pC	30 A	0.6 µm





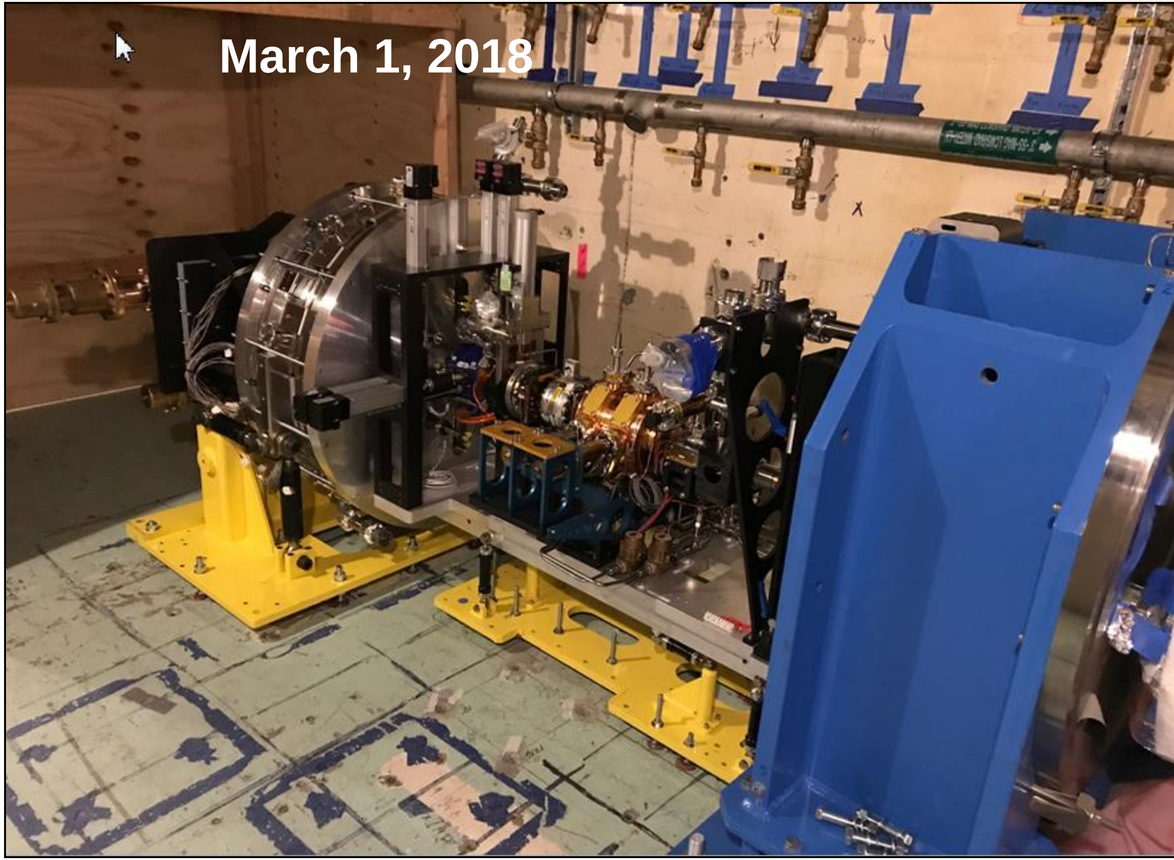
C. Guilliford, *et al*, http://arxiv.org/abs/1501.04081 (2015)

LCLS-II NC RF Gun



LCLS-II Gun and Low-Energy Beamline Installed

- The LCLS-II Injector uses a 750 kV VHF RF (186 MHz) gun based on the APEX gun at LBNL
- Relatively high energy allows higher brightness and simple capture cavities



March 1, 2018

LCLS-II Injector Commissioning

- **Systems operational after addressing many significant problems:**
  - Fully established reliable 24/7 CW RF operation of gun and buncher
  - Commissioned all essential diagnostics which are working
  - Certified all BCS safety systems including ACMs/LBLMs
- **Characterized e-beam performance:**
  - Achieved about 0.75um emittance at 80MeV for 50pC charge, close to 0.4um of design. Further optimization is under way.
  - Measured 0.8mm of bunch length, meeting with design
- **Characterized gun dark current (~4uA), which is much larger than expectation. Effective mitigation is in place:**
  - ~90% of dark current lost on a recently installed circular collimator before CM01 (<1MeV)
  - ~10% dark current lost on a fixed collimator after CM01 (>80MeV)
  - <1% of dark current is measured on ACMs before COL0 collimators

Motivation for an Improved Low Emittance Injector (LEI)

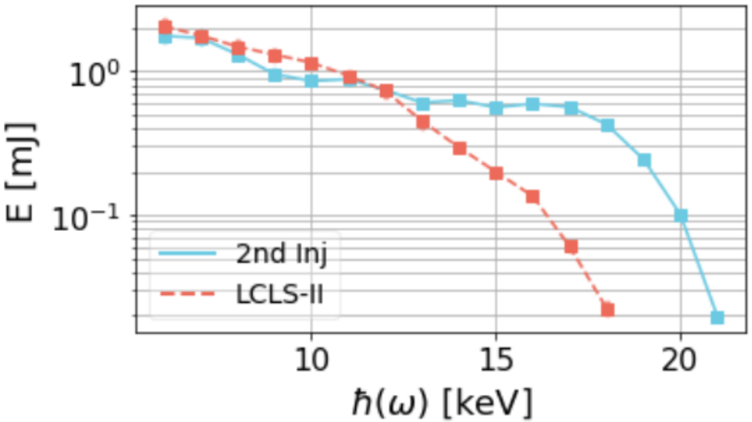
Provide lower emittance beams to extend photon energy reach, enabling a broader photon physics program

- Less costly than increasing beam energy, which is currently limited by space constraints

Provide redundant electron source

- Qualify second injector while current one operates
- Once online, could quickly revert to original injector if problems occur
- In the interim, a spare LCLS-II gun with modest improvements is being built

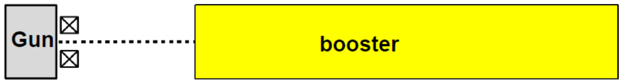
Photon Pulse Energy vs Photon Energy



Injector Approaches for Low Emittance, High Brightness Beams

Low duty → high gradient, high frequency RF

→ short laser pulse → high peak current



- ‘Pancake’ emission brightness

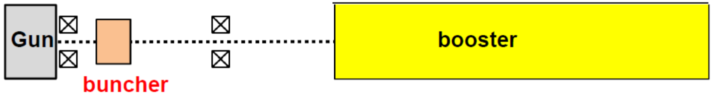
$$\frac{Q}{\epsilon^2} \propto \frac{E_{emission}}{MTE}$$

LCLS (120 Hz):

- 120 MV/m, 2.9 GHz NC Gun
- 6 MeV beam from Gun
- 6 ps FWHM laser pulse
- Copper MTE ~ 400 meV

High duty → low gradient, low frequency RF

→ long laser pulse → buncher → high peak current



- ‘Cigar’ max emission brightness

$$\frac{Q}{\epsilon^2} \propto \frac{E_{emission}^{1.5}}{MTE} \frac{t_{laser}}{\sqrt{R_{laser}}}$$

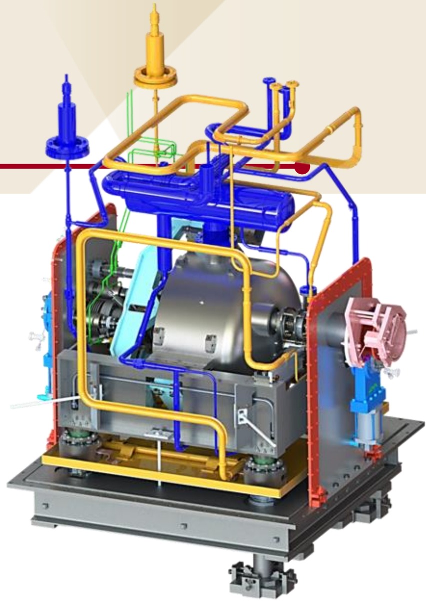
MTE = Mean Transverse Energy of Photo-Emitted Electrons

LCLS-II (CW)

- ~ 20 MV/m, 186 MHz NC Gun
- 750 keV beam from Gun
- 20-60 ps FWHM laser pulse
- Cs2Te MTE ~ 400 meV

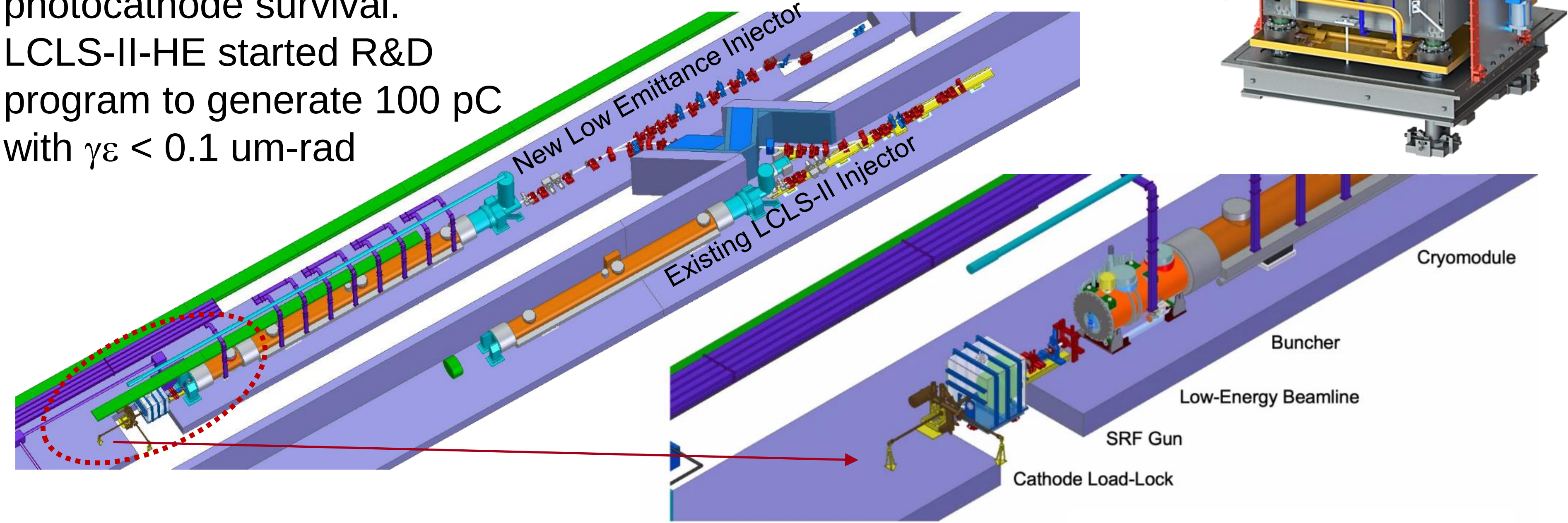
Goals: Increase gradient to 30 MV/m and halve MTE

LCLS-II-HE LEI and LCLS-II Injector Layout



A high-gradient SRF photocathode gun has been an aspiration for decades. Conceptually has many benefits including high gradient operation, low field emission, and good vacuum for photocathode survival.

LCLS-II-HE started R&D program to generate 100 pC with $\gamma\varepsilon < 0.1$ um-rad



Start-to-End FEL Modeling

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

LCLS-II-HE is being extensively modeled using 3D PIC codes

- Using 1-to-1 models with same number of macro-particles as beam electrons
- Simulation runs are made using LBNL Edison Cray XC30

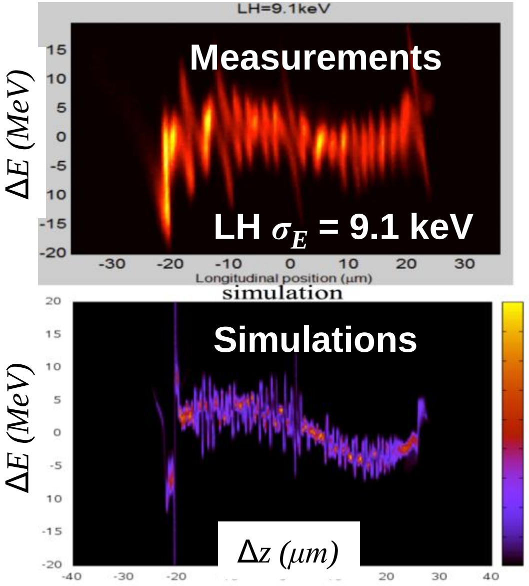
High brightness beams at modest energy and long transport → new longitudinal micro-bunching instabilities

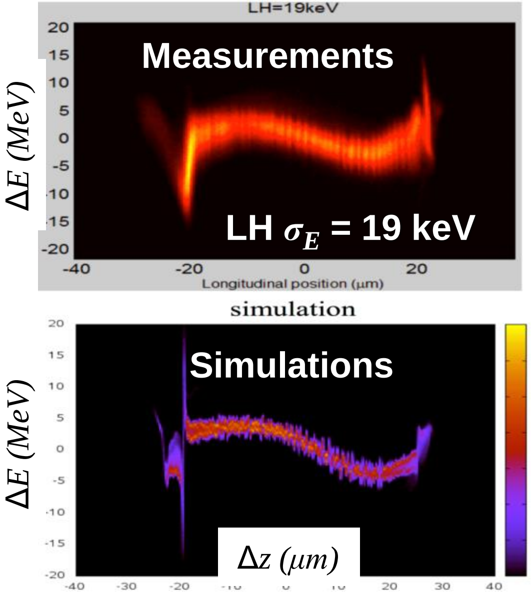
Full S-2-E simulations using IMPACT and GENESIS are being performed

Benchmarking Micro-Bunching (μBI) Effects

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

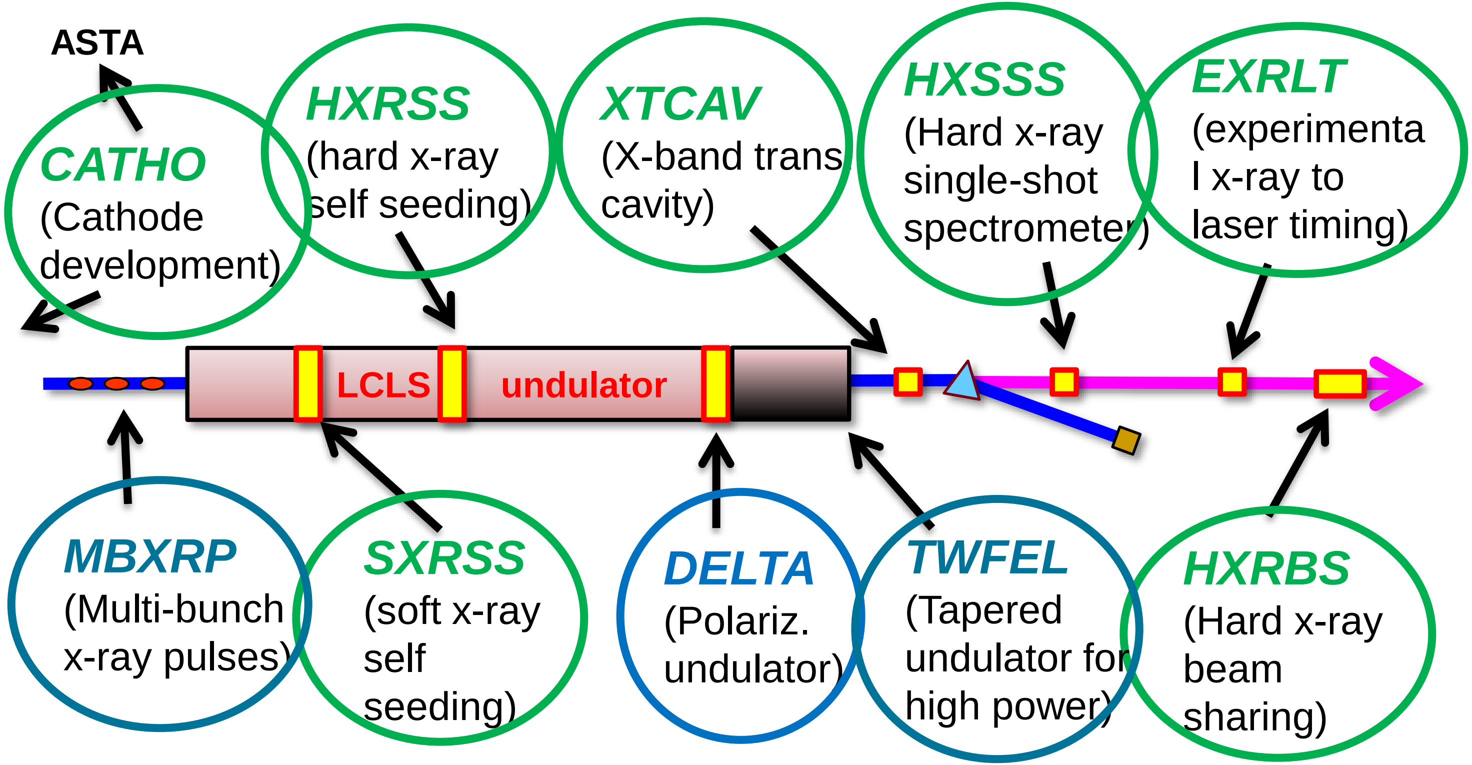
- Benchmarking codes against LCLS measurements





Examples of R&D in support of LCLS Operations/Science

Many additional programs ongoing



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)

MBXRP
(Multi-bunch x-ray pulses)

SXRSS
(soft x-ray self seeding)

DELTA
(Polariz. undulator)

TWFEL
(Tapered undulator for high power)

HXRBS
(Hard x-ray beam sharing)

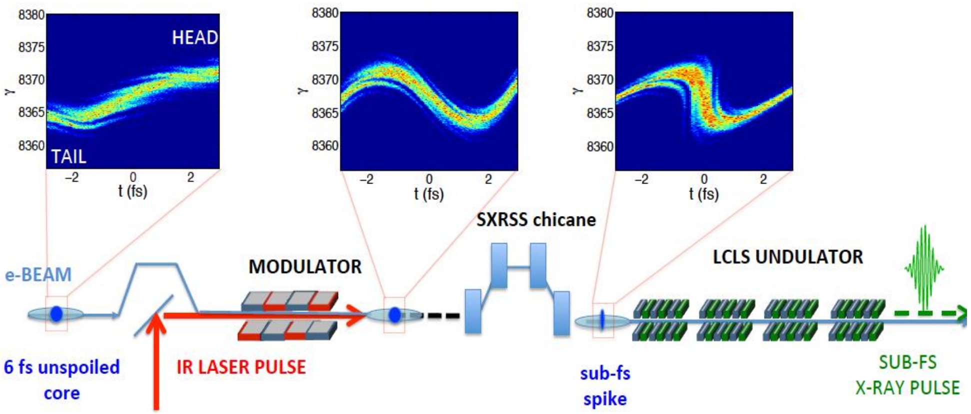
Completed

Ongoing

Under development

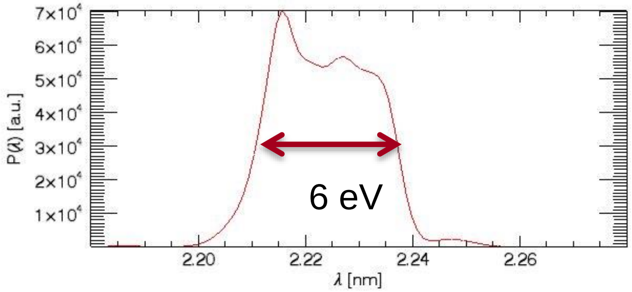
R&D Example: XLEAP – sub-fs X-ray pulse R&D program

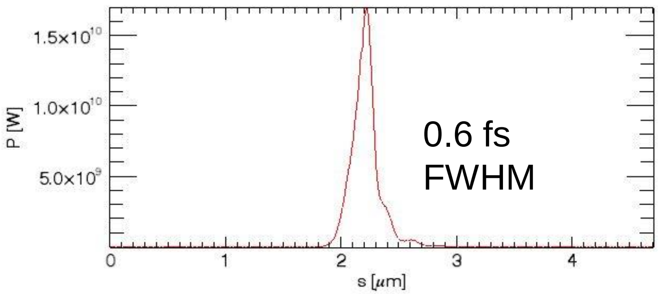
Operating for Users at LCLS and upgrades in planning for LCLS-II/HE



1) <1 fs pulse duration.
2) Multi eV coherent bandwidth.
3) ~20 uJ pulse energy.

Two-color operation with sub-fs jitter for x-ray pump/x-ray probe experiments

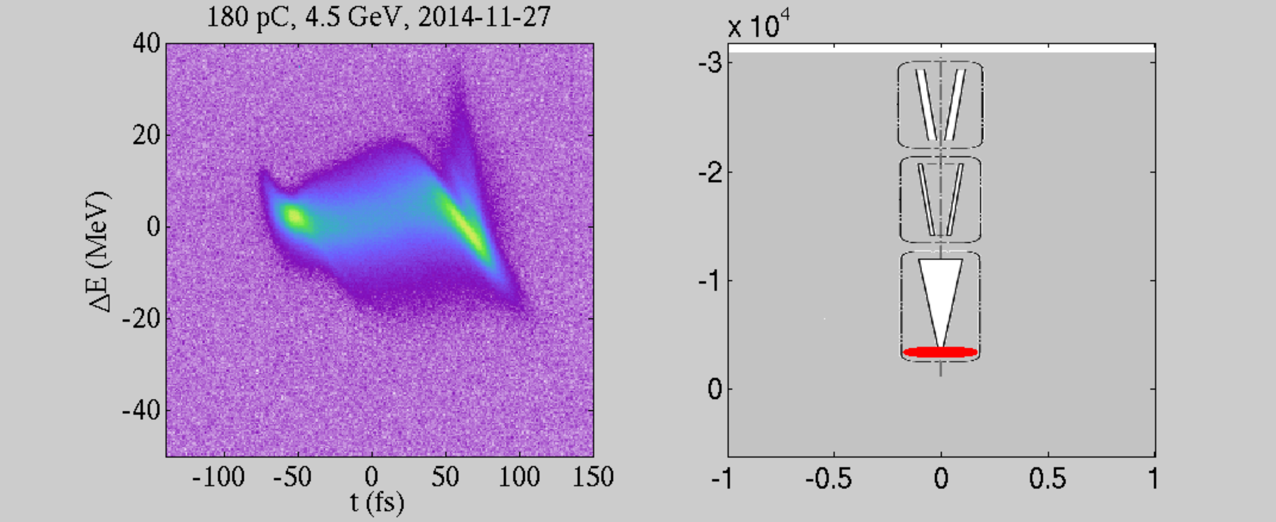




R&D Example: Two bunches and pulse length control

‘slotted’ foil in dispersive region with energy chirp (x-t correlation)

- Added pulsed kickers to control up to 4 bunches on single RF pulse (few - 200 ns sep.)
- Slotted foil for single and double short pulses



- Developing laser heater shaping as well as XLEAP technique for pulse length control in LCLS-II (<1 to 5 fs pulses)

Summary

LCLS-II has begun commissioning with 1st light expected in 2023 with 0.2 – 5 keV

Builds on existing XFEL and SRF development plus:

- High Q0 CW SRF cavities based on N_2-doping process for 4 GeV CW linac
- High brightness injector
- Novel variable gap undulators
- Advanced simulations of high brightness beams

LCLS-II-HE will extend spectral range >20 keV with commissioning in 2027

- Further increase LCLS-II cavity gradients with improved doping to exceed 21 MV/m while limiting field emission will be critical to increase SRF linac energy to 8 GeV
- New SRF gun for 2x reduction of beam emittance and significant improvements in beam brightness at undulator

Ongoing R&D program on beam manipulation and control to expand operating modes

Questions?