LCLS-II-HE FEL Facility Overview

Tor Raubenheimer

Workshop on Scientific Opportunities for Ultrafast Hard X-rays at High Rep. Rate

SLAC, September 26-27, 2016

Outline

- LCLS and LCLS-II Overview
- LCLS-II-HE Concept
- Performance and Operating Modes

Introduction

LCLS-II starts from the LCLS X-ray FEL

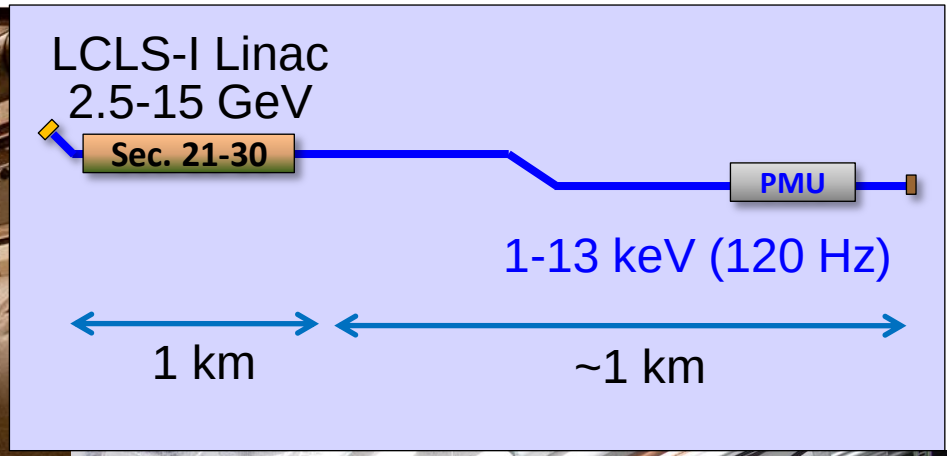
The LCLS is the world's 1st x-ray Free Electron Laser (FEL)

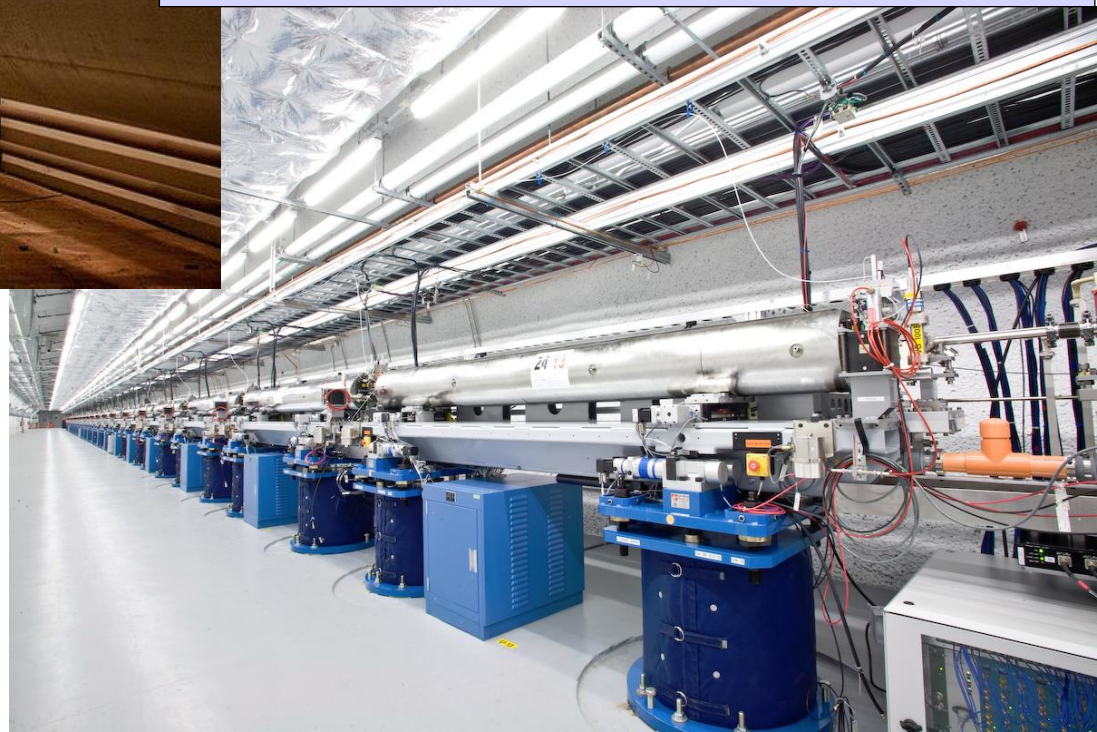
- LCLS electron source is the SLAC *Cu* linac
- Includes one fixed gap undulator
- Six experimental stations

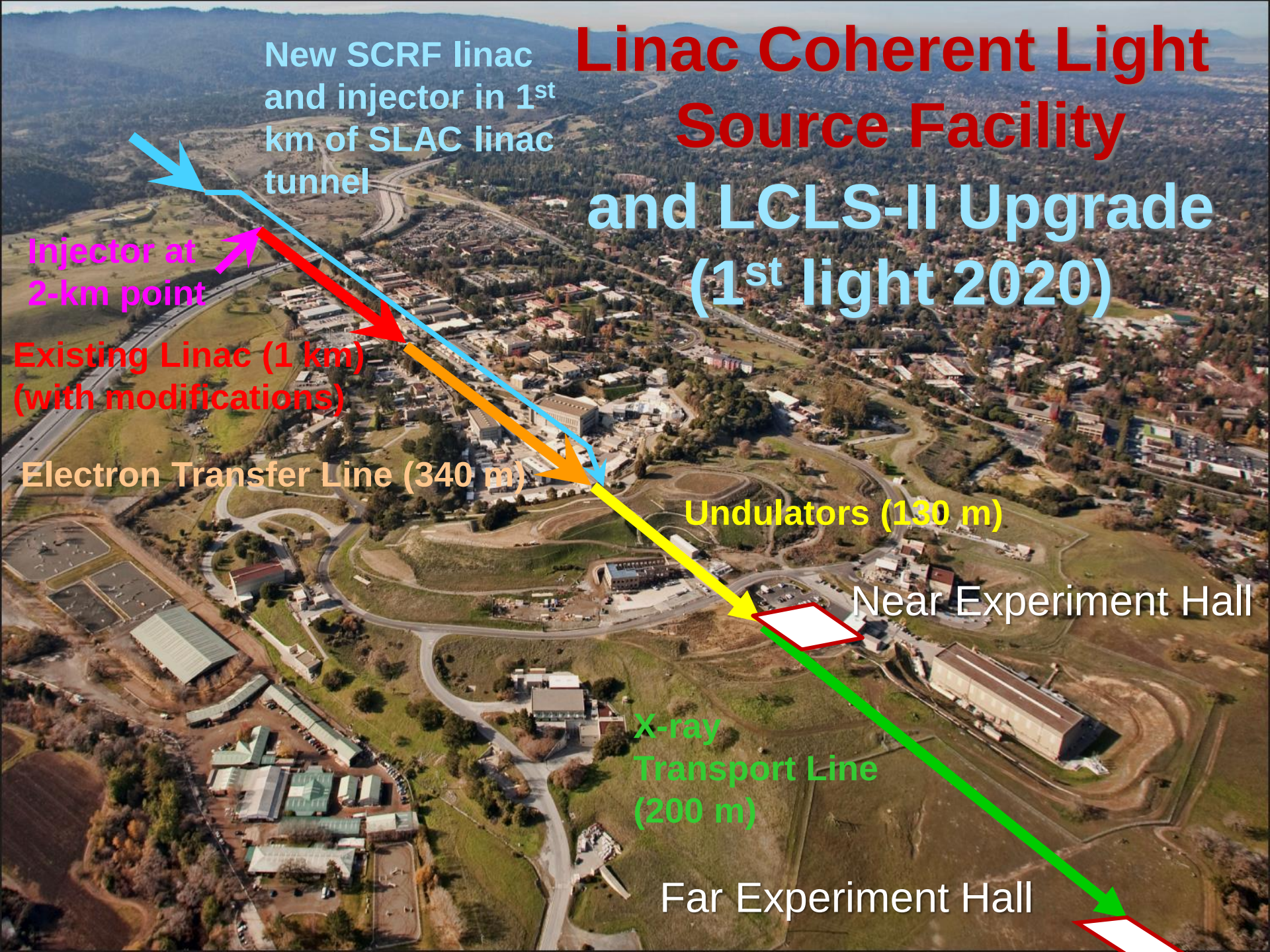
X-ray Range	**250 to 12,600 eV**
FEL Pulse Length	**< 5 - 500 fs**
FEL Pulse Energy	**~3 mJ (2 * 10^{12} @ 10 keV)**
Repetition Rate	**120 Hz**

LCLS

Based on 15 GeV SLAC CuRF linac

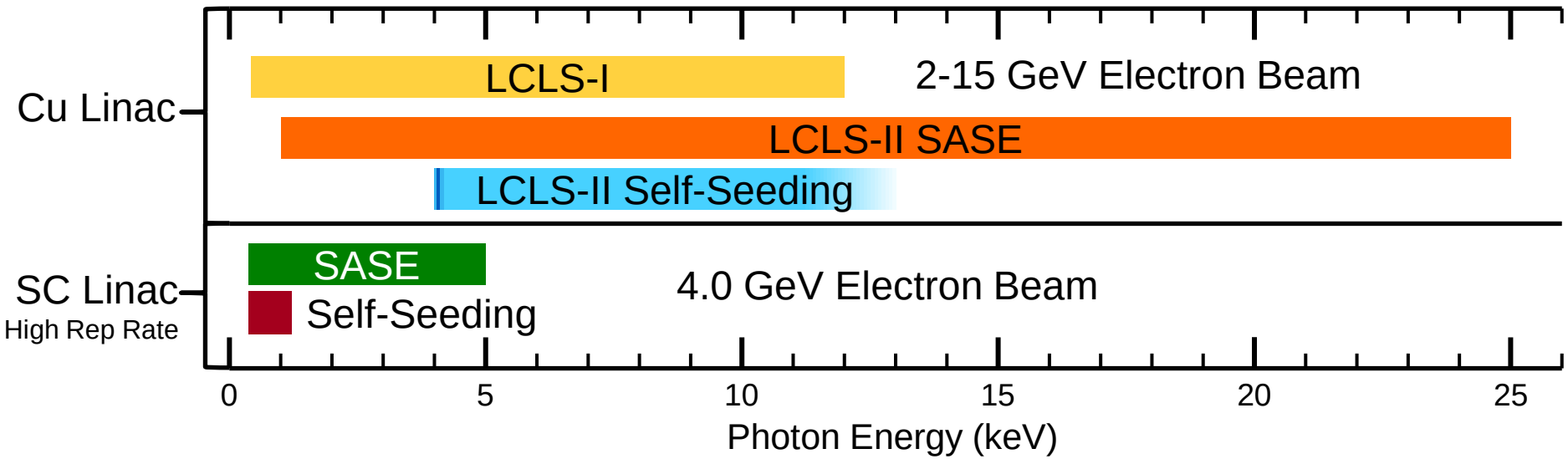


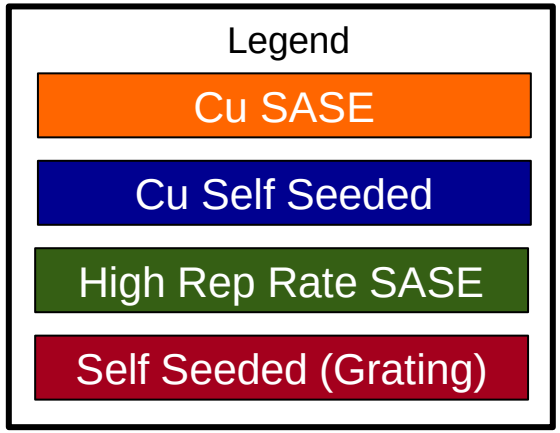



Linac Coherent Light Source Facility
and LCLS-II Upgrade
(1st light 2020)
New SCRF linac and injector in 1st km of SLAC linac tunnel
Injector at 2-km point
Existing Linac (1 km) (with modifications)
Electron Transfer Line (340 m)
Undulators (130 m)
Near Experiment Hall
X-ray Transport Line (200 m)
Far Experiment Hall

LCLS-II X-ray Coverage

Using SASE and Self-Seeding





Future expansion options

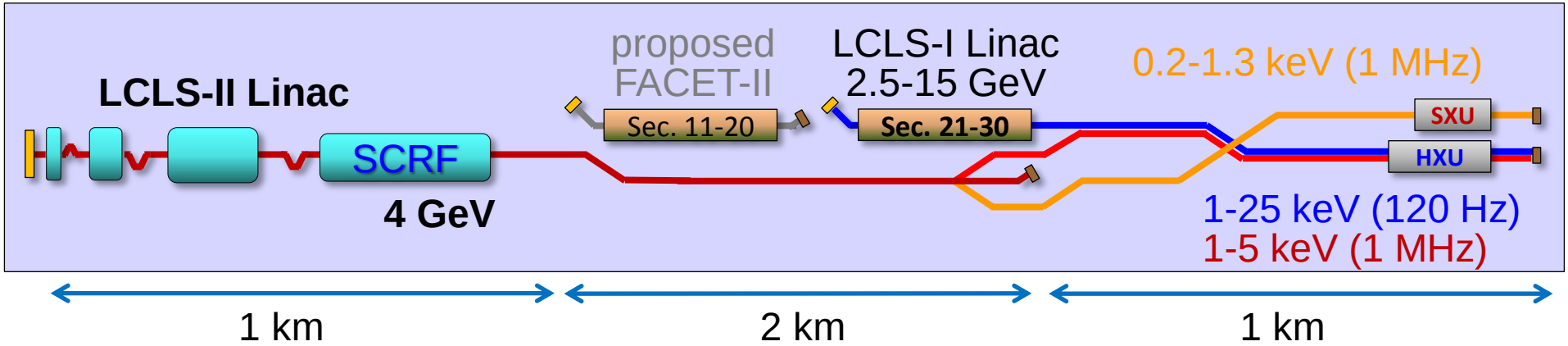
- External seeding below 1 keV
- Self seeding between 1.5 - 4 keV
- X-rays beyond 5 keV from the SCRF linac with >4 GeV beam energy
- Additional FEL's using 1.2 MW e-

LCLS-II Accelerator Layout

New Superconducting Linac → LCLS Undulator Hall

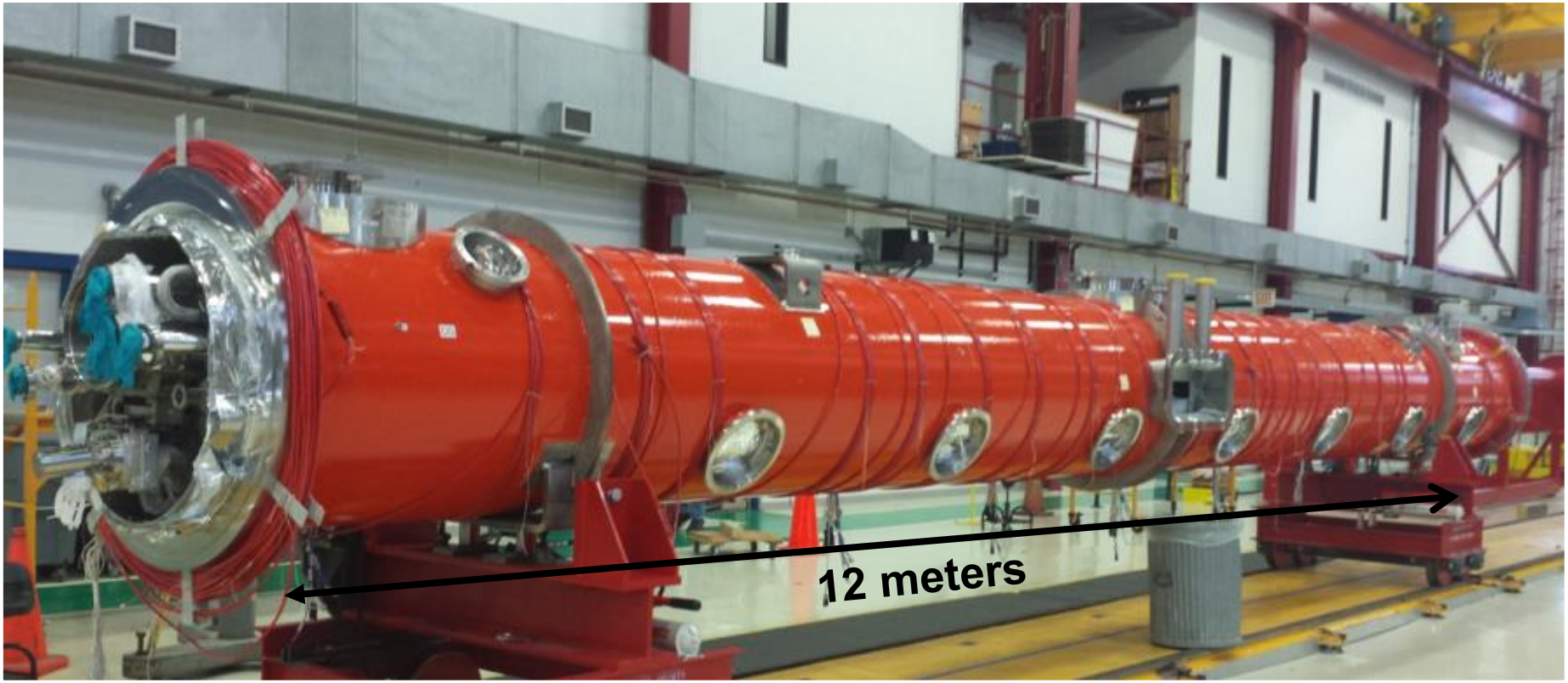
- Two sources: MHz rate SCRF linac and 120 Hz Cu LCLS-I linac
- Hard and Soft X-ray undulators can operate simultaneously in any mode
- SCRF beam destination controlled with fast (μs) magnetic deflector

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



LCLS-II Cryomodule

35 new 1.3 GHz Crymodules to be installed in SLAC linac tunnel

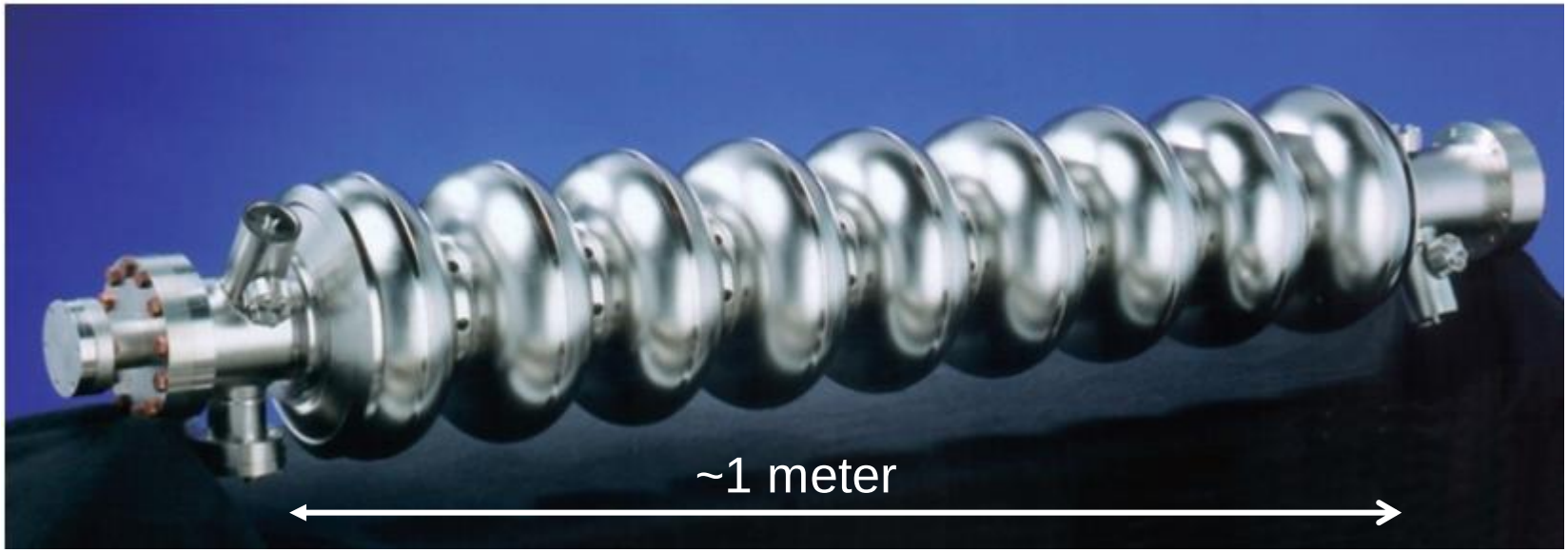


CM to be fabricated at FNAL and JLab; Prototypes are being assembled and tested through Fall 2016. Installation May 2017.

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

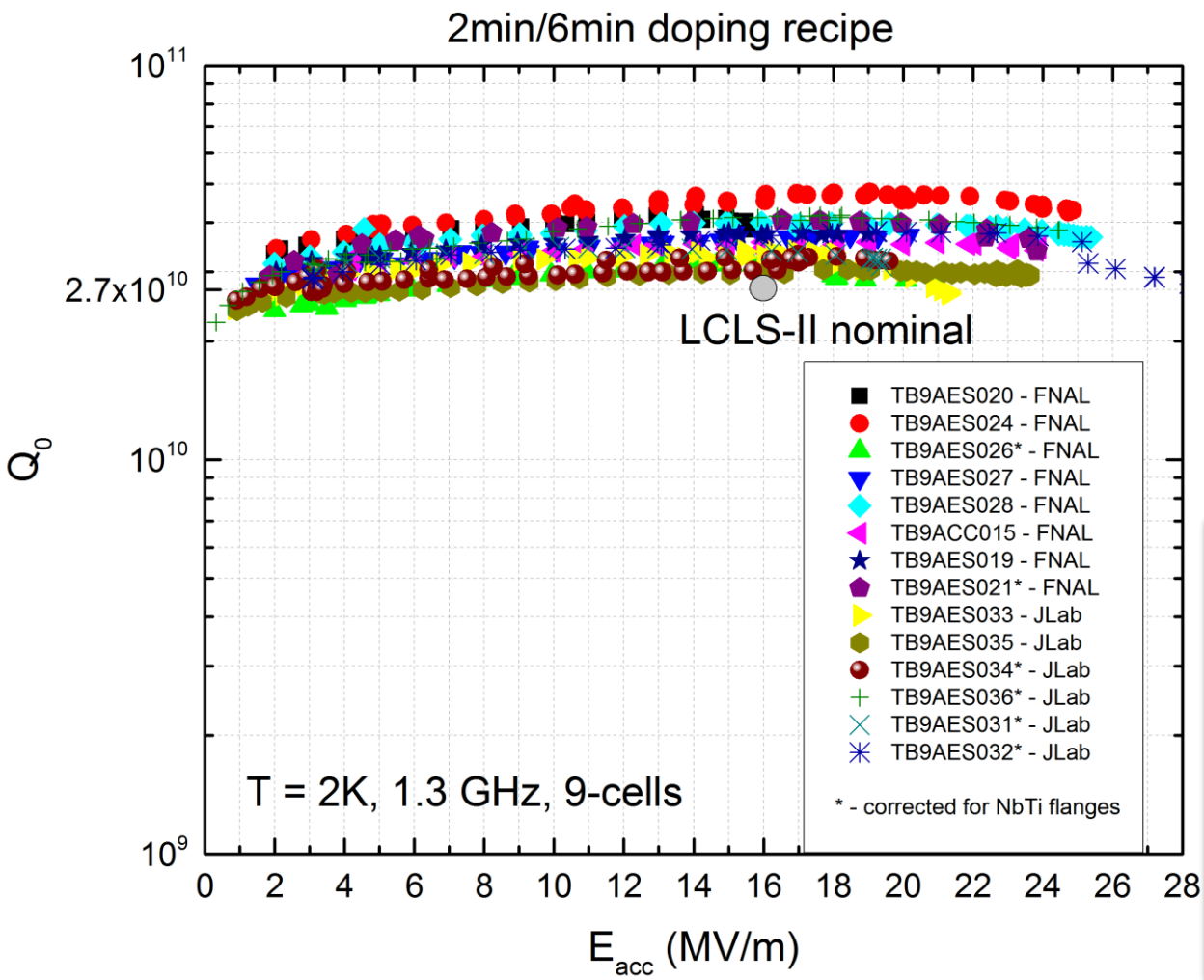


Technology developed in Europe and transferred around world. Hundreds have been fabricated in US, Japan, Europe.

Minor modifications to HOM ports for CW operation

Cryogenic Load → Maximize Q_0

CW linac is dominated by dynamic (RF) losses



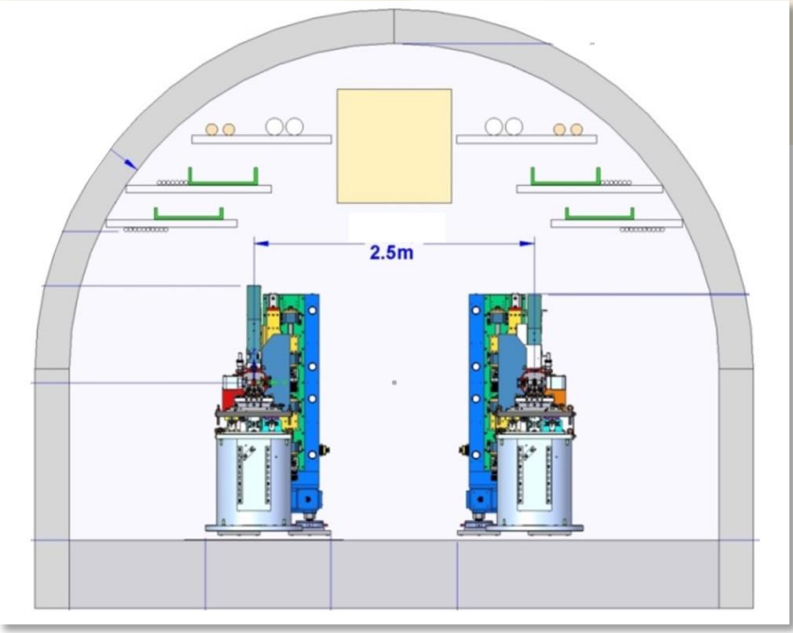
Nitrogen-doping technology developed at Fermilab will have big impact on CW SCRF accelerators

Spec:
Q > 2.7e10 dressed
E_{max} > 19 MV/m

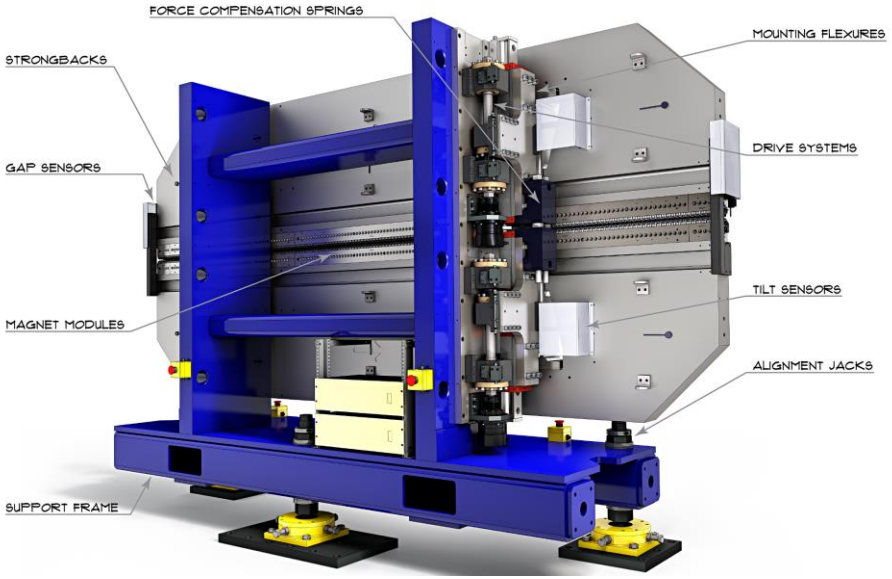
Meas:
<Q> = 3.0e10 dressed
<E_{max}> = 22.2 MV/m

Variable Gap Hybrid Undulators

Will install two new undulators in Hall

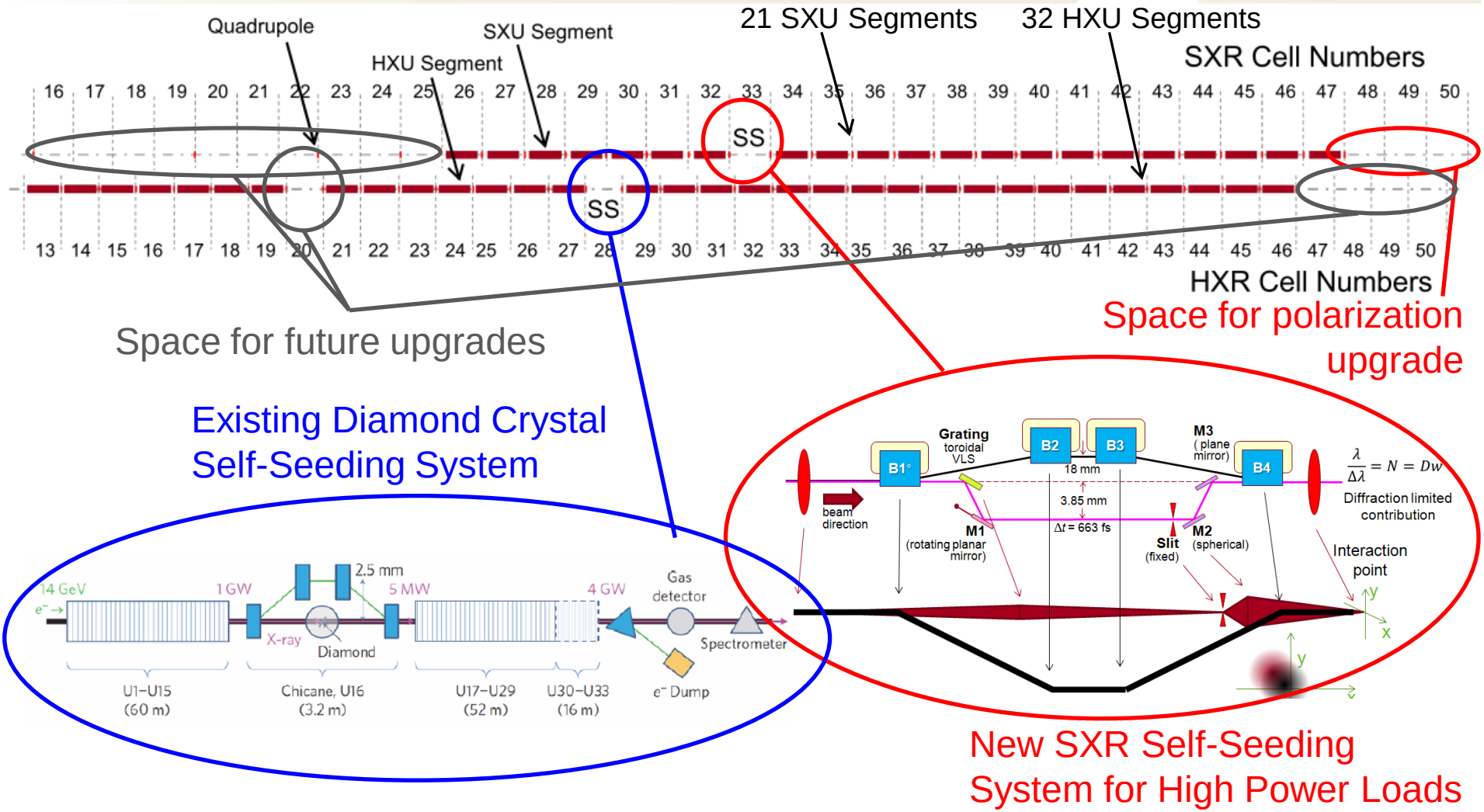


Variable gap undulators used in LCLS-II to provide greater wavelength tuning flexibility: standard vertical gap for SXR and a horizontal gap Vertically Polarized Undulator for HXR.

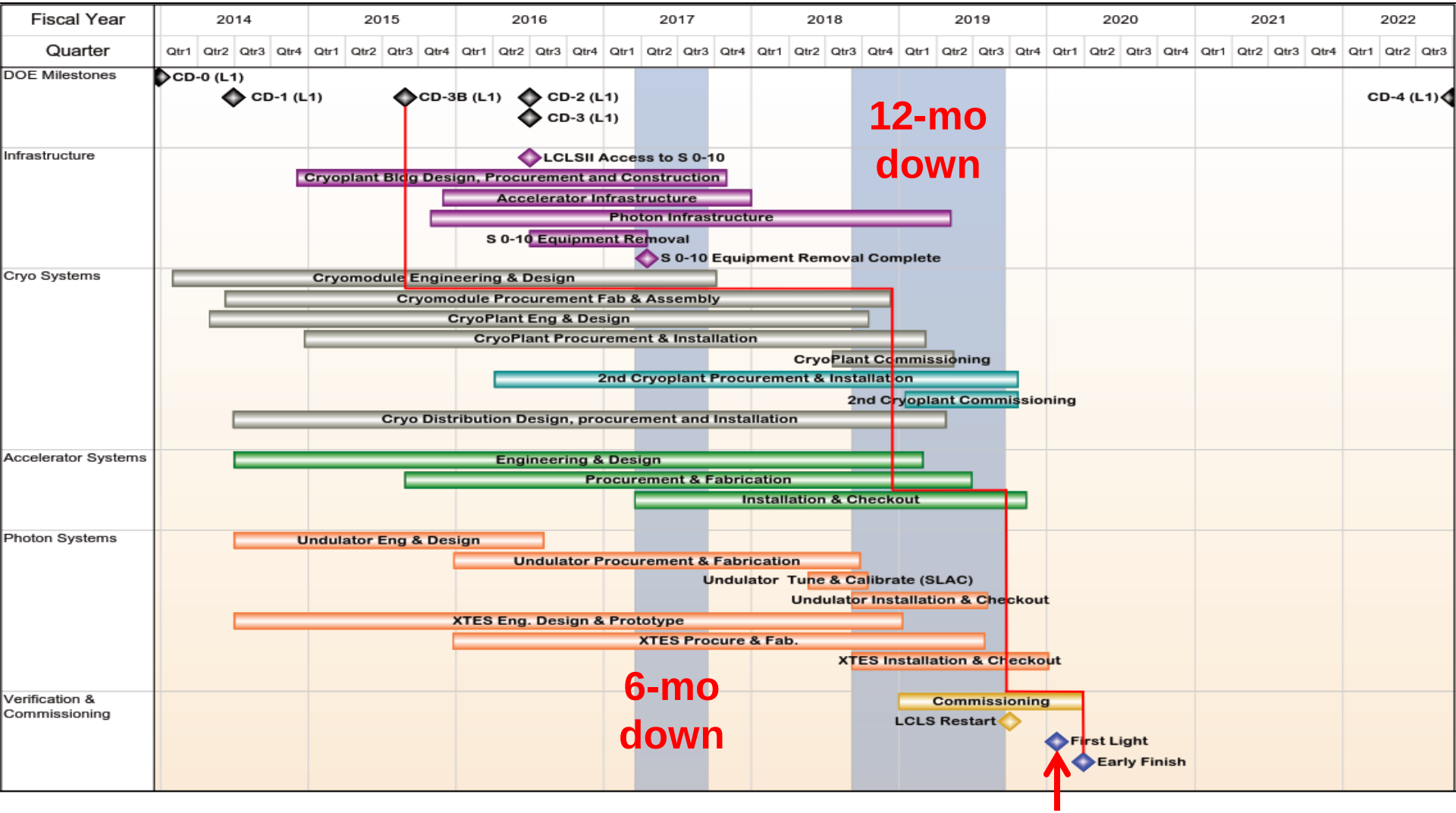


LCLS-II Undulator Layout

Replace Existing LCLS Undulator with HXR and add SXR



LCLS-II Schedule



First light (start FY2020)

LCLS-II High Energy Upgrade

Possible LCLS-II extension to go from 5 keV → 12.8 keV or more

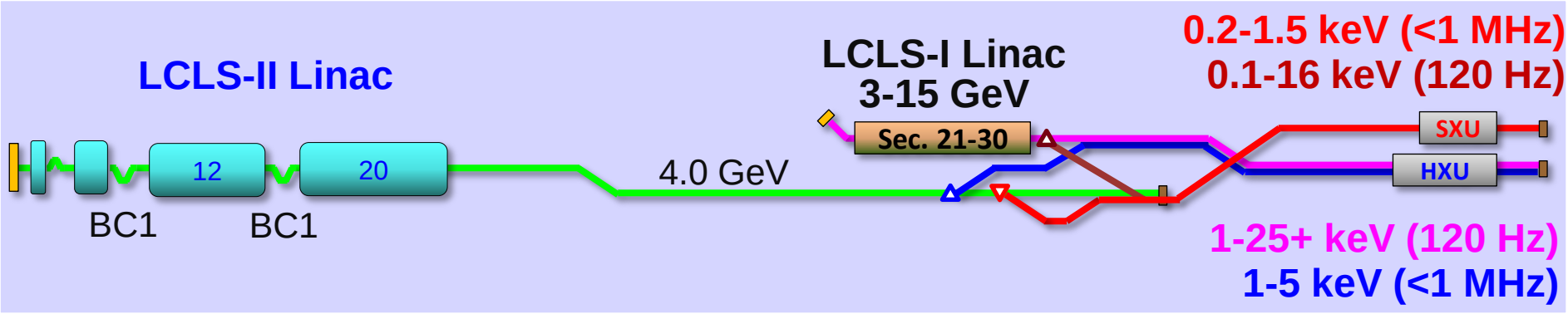
Left space in the LCLS-II for additional cryomodules

→ Add 20 additional cryomodules

Added 2nd cryo-plant to LCLS-II design to reduce risk of poor cryomodule performance

→ Present performance looks good up to 20 MV/m

Increased length and gradient → 8 GeV final energy



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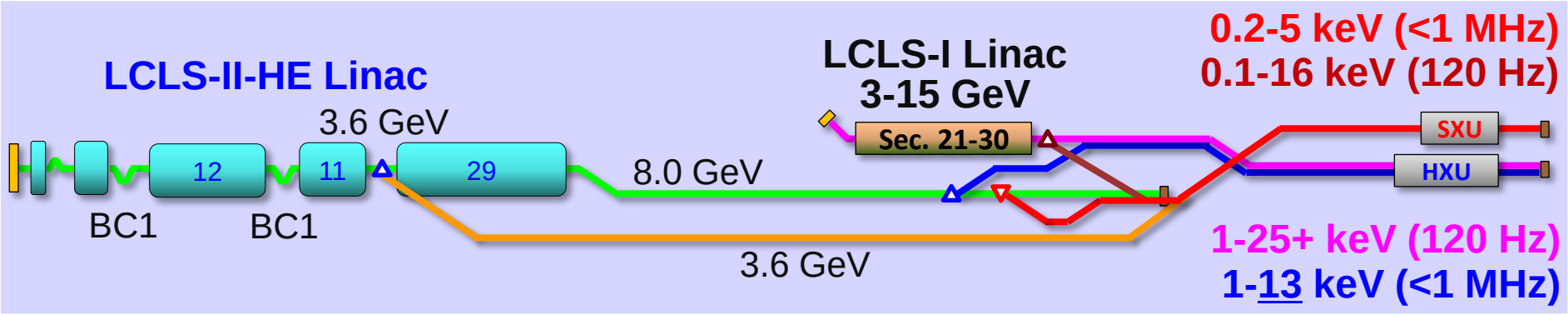


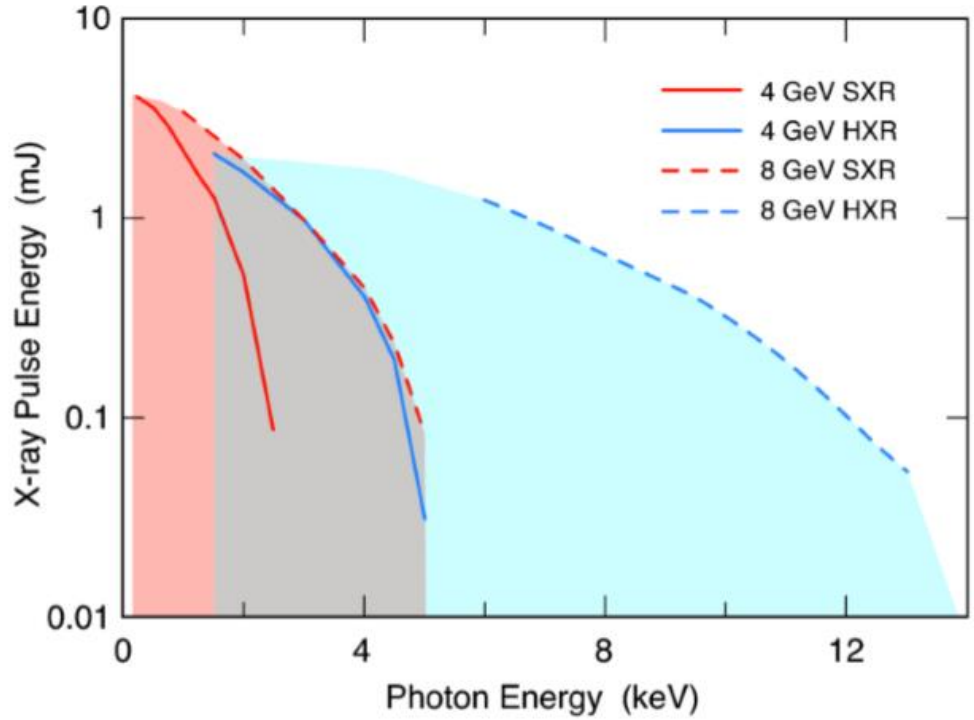
LCLS-II Operating Modes

SXR choices	HXR SC-Linac options	or	HXR Cu-Linac options
3.6 GeV SC-Linac (< 1 MHz) 0.1-1.3 keV with >> 20 W	8 GeV (< 1 MHz) 1-13 keV with >20 W	or	3-15 GeV (≤ 120Hz) 1-25 keV with mJ pulses
8 GeV SC-Linac (< 1 MHz) 0.2-5 keV with >> 20 W	8 GeV (tied to SXR) (< 1 MHz) 1-13 keV with >20 W	or	3-15 GeV (≤ 120Hz) 1-25 keV with mJ pulses
3-10 GeV Cu-Linac (≤ 120Hz) 0.1-16 keV with mJ pulses	8 GeV (< 1 MHz) 1-13 keV with >20 W	or	3-15 GeV (tied to SXR) (≤ 120Hz) 1-25 keV with mJ pulses

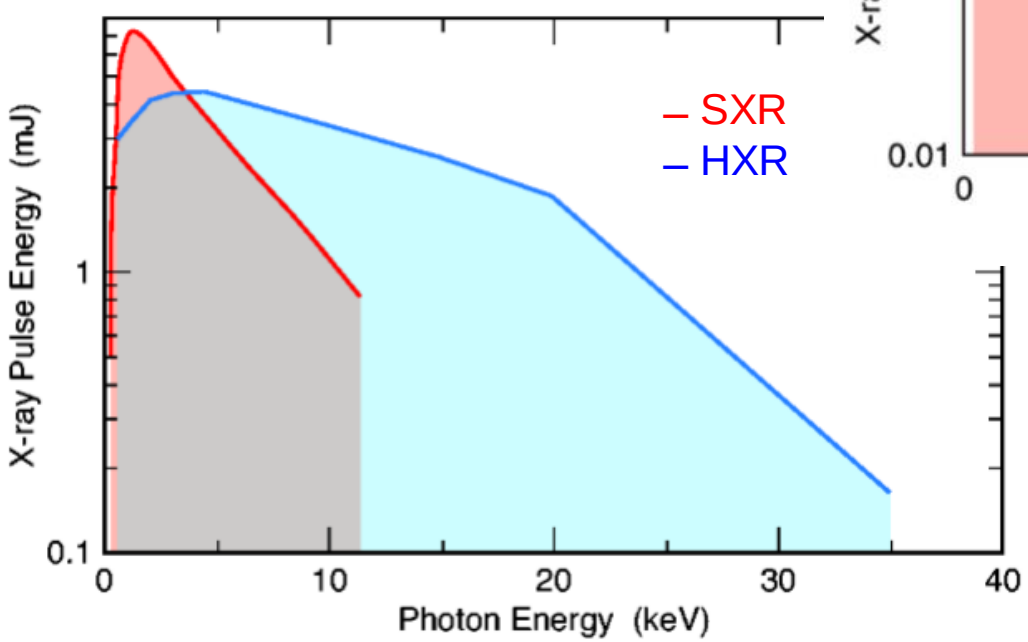
LCLS-II-HE X-ray Performance

LCLS-II-HE will extend the performance from the SCRF linac substantially (total power limited <200W)

SCRF Linac with ~1 MHz rate



CuRF Linac with 120 Hz rate



SCRF-Linac Parameters	LCLS-II	LCLS-II-HE	Unit
Final electron energy	3.3 - 4.0	3.3 - 8.0	GeV
Electron energy at new extraction point	-	3.6	GeV
Total Number of 1.3-GHz Cryomodules	35	55	-
Total Number of 3.9-GHz Cryomodules	2	2	-
Active SCRF accelerator length	296	456	m
Mean RF Gradient (CM01 to CM03)	< 16.0	< 16.0	MV/m
Mean RF Gradient (CM04 to end)	< 16.0	< 18.5	MV/m
RF Overhead (spare cavities)	6	0	%
Max. avg. electron beam power in linac	0.25	0.25	MW
Max. avg. electron current in linac	62	30 - 48	μA
Max. RF power per 1.3-GHz cavity	3.8	4.2	kW
RF cavity detuning (see avg. current)	10	10 - 9	Hz
1.3-GHz Superconducting Cavities	**LCLS-II**	**LCLS-II-HE**	**Unit**
Cavities per cryomodule	8	8	-
Active length 1.3-GHz cavity	1.038	1.038	m
Specified average cavity Q_0	> 2.7	> 2.7	10^{10}
Specified cavity *qualifying* gradient	19	19	MV/m
Installed 2K cryo-capability	8.0	8.0	kW
Expected heat load at max energy	3.7	7.2	kW
Heat Load Margin (excess available)	115	10	%

Basic LCLS-II / LCLS-II-HE X-ray Configurations

Color Code: SC-Linac & Cu-Linac

Photon Energy (0.2-5 keV & 1-25 keV)

- ±1% is fast using e^- energy (10 ms)
- Full range uses gap control (5 min.)
- Cu-Linac is slow if $\Delta\lambda/\lambda$ > 10% (15-30 min)
- Use energy or gap for Cu-Linac (3-15 GeV)

Pulse Duration

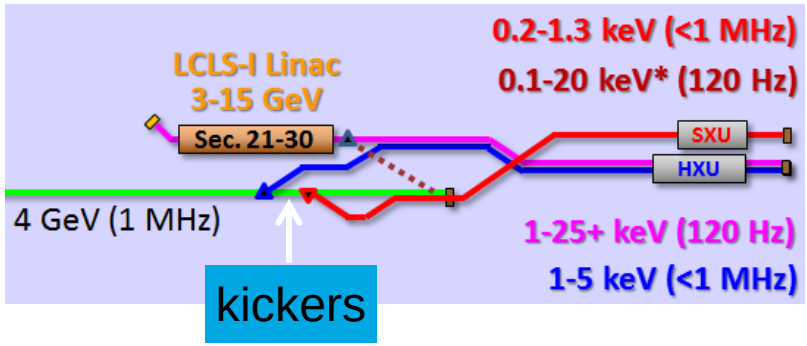
- 20-300 fs (slow changes: 1-2 hrs)
- Use of slotted-foil may limit beam rate
- Cu-Linac as existing (1-min., 60-500 fs)
- < 10 fs with reduced bunch charge

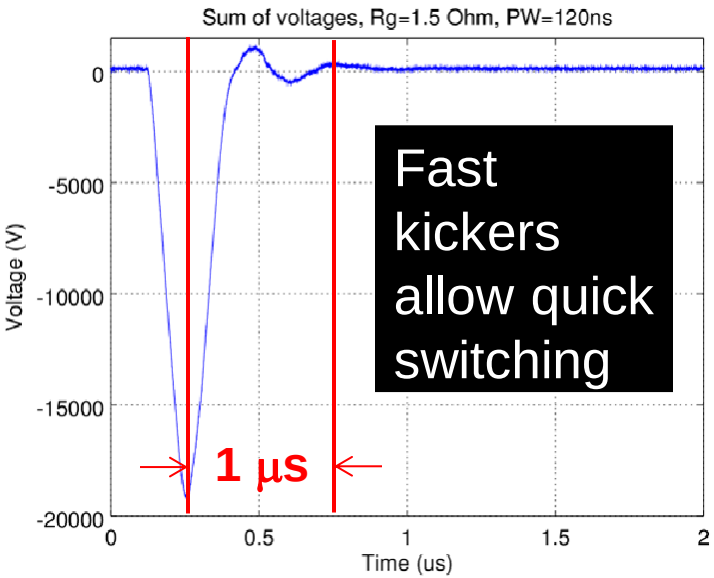
Beam Rate (< 1 MHz & 120 Hz)

- Trigger fast kickers (μsec)
- May be set from 'one-shot' to 1 MHz
- Total beam power < 120 kW/FEL (rate limit)

FEL Pulse Energy

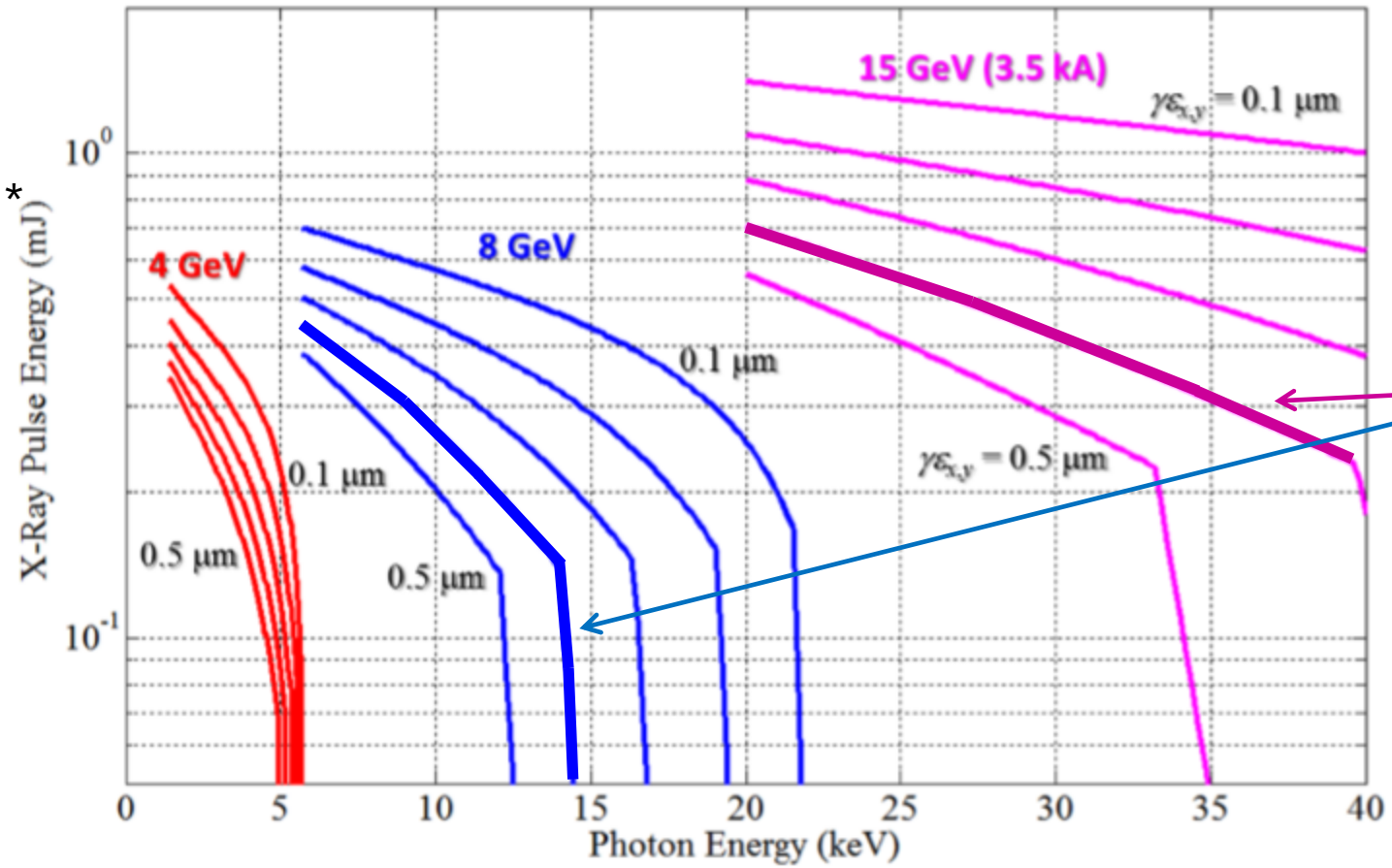
- Up to 8 mJ (250-fs pulse, 800 W, 250 eV)
- Up to 6 mJ (3-6 keV is best), 3-4 mJ typical





Injector R&D Program

Big impact of improved injectors for LCLS-II CuRF and LCLS-II-HE SCRF, extending SCRF reach out beyond 20 keV



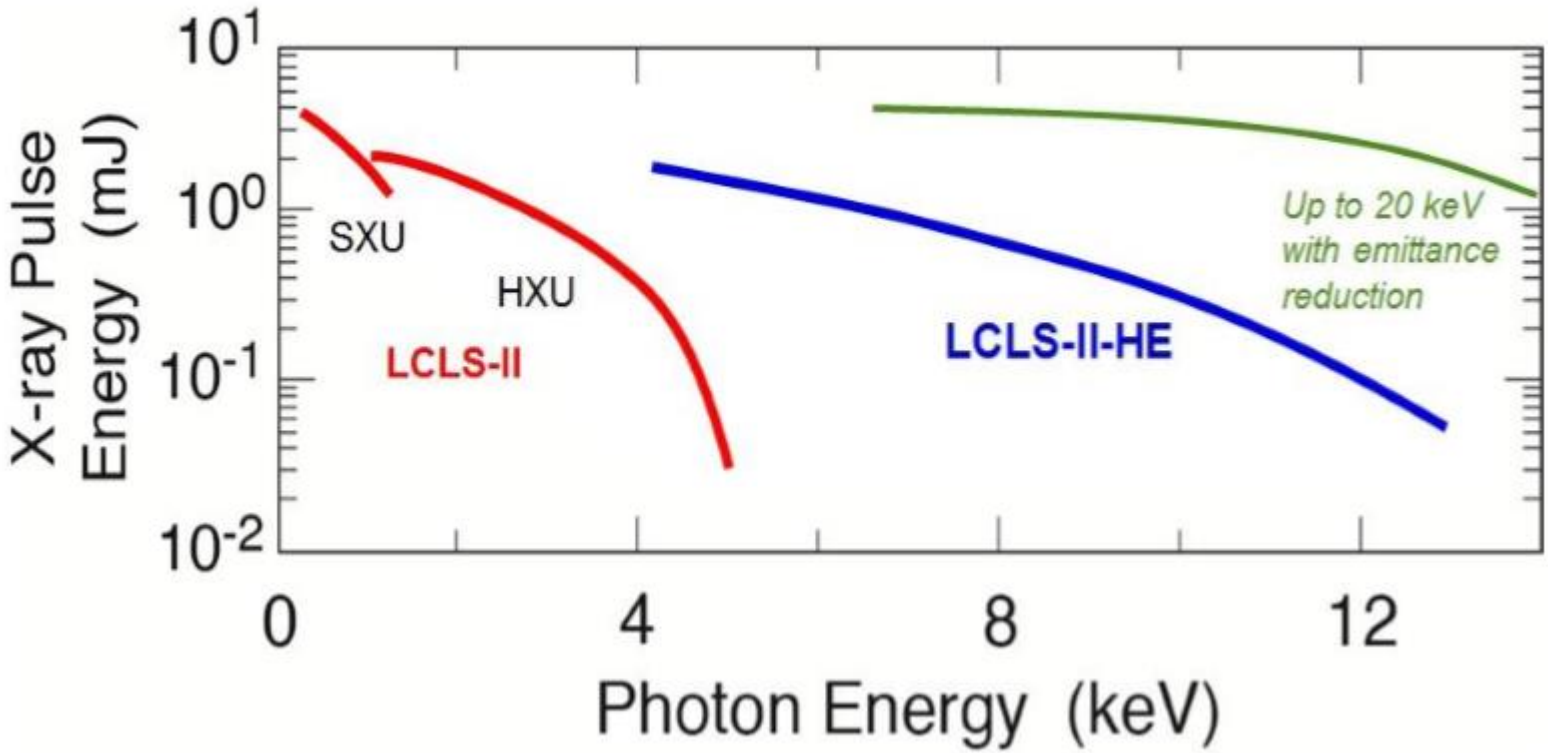
Baseline injector $\gamma\varepsilon$ = 0.4 μm

Injector R&D aimed at $\gamma\varepsilon$ = 0.1 μm

* Note: results do not include taper which can increase energy by factor of a few

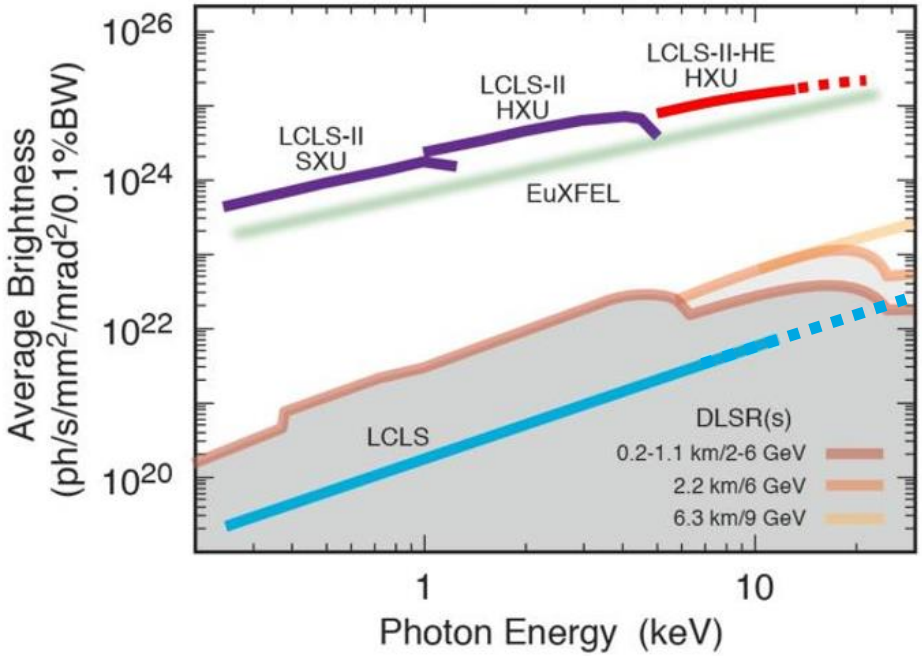
LCLS-II-HE X-ray Pulse Energy

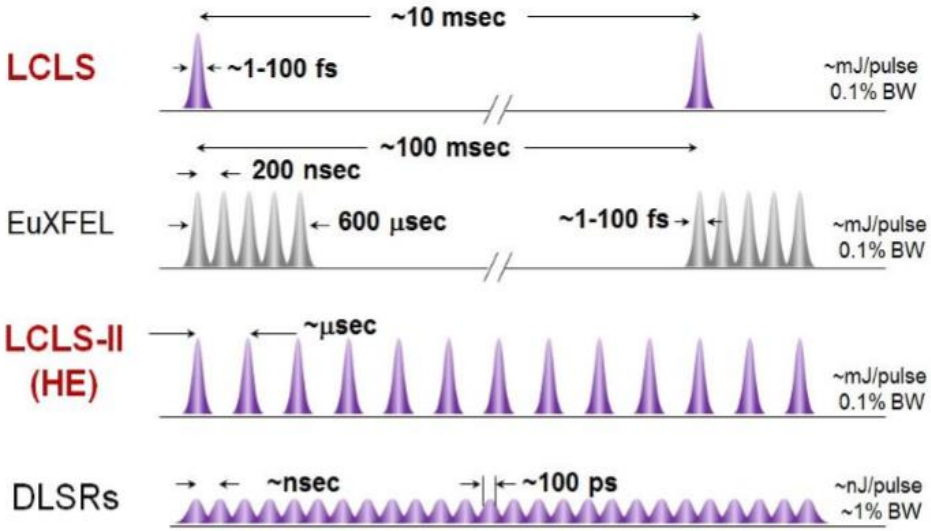
Expected performance, including post-saturation taper, with improved injector is illustrated in green



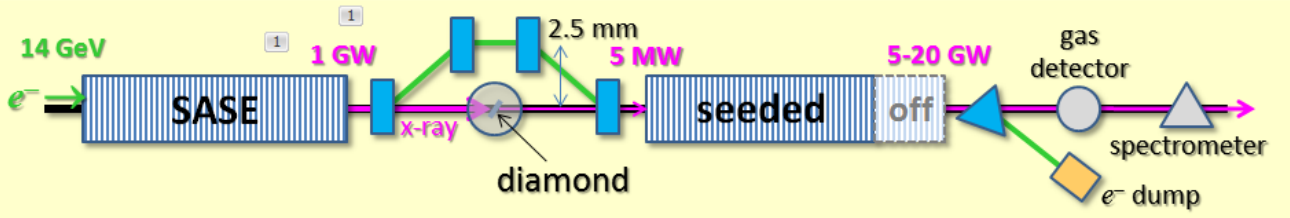
LCLS-II-HE Brightness

Brightness of LCLS-II-HE will exceed 10^{25} at 12.8 keV and extend out to >20 keV with additional injector improvements

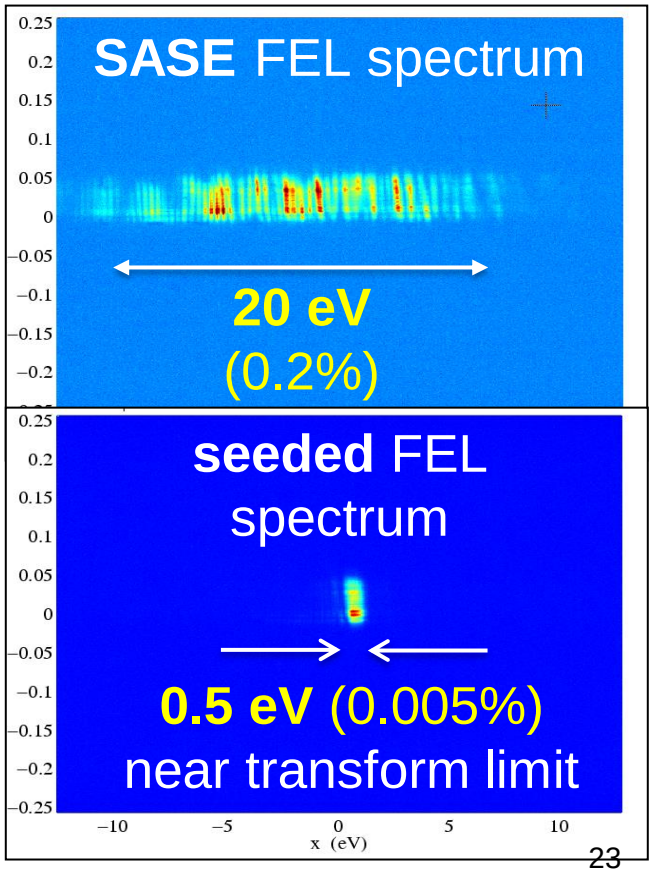




Seeding at LCLS-II / LCLS-II-HE



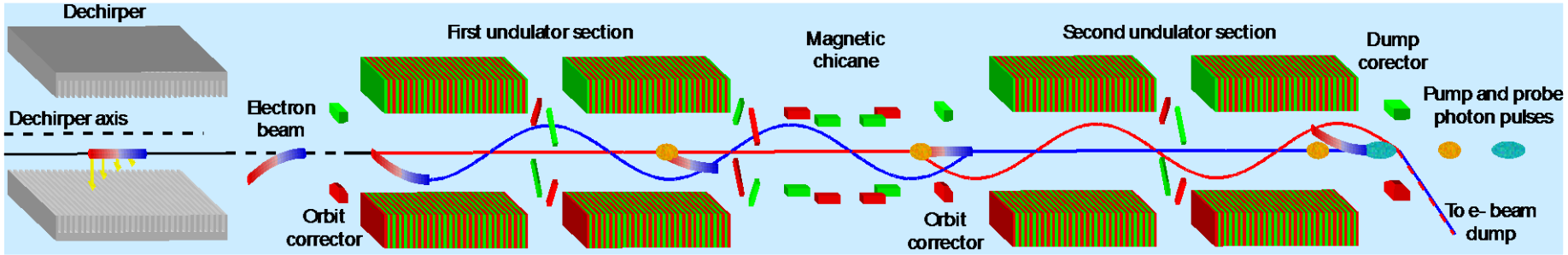
demonstrated at ***LCLS***, *Nature Photonics 6, 693-698 (2012).*



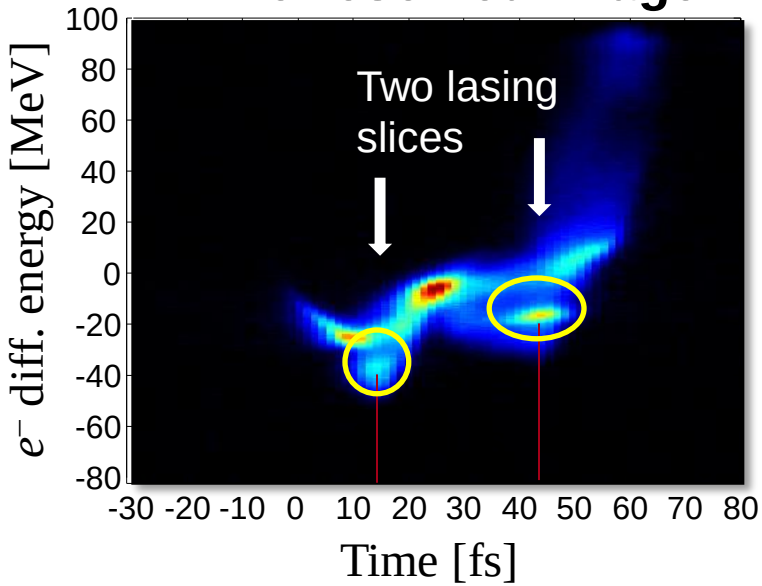
- **Hard X-Ray self-seeding will be possible, as it is now (low rate, Cu-Linac, 4-12 keV). Option to increase rate in future with 2nd mono.**
- **Soft X-ray self-seeding will be designed for high rate.**
- **External seeding options being studied by task force.**

Two-Color Options at LCLS-II / LCLS-II-HE

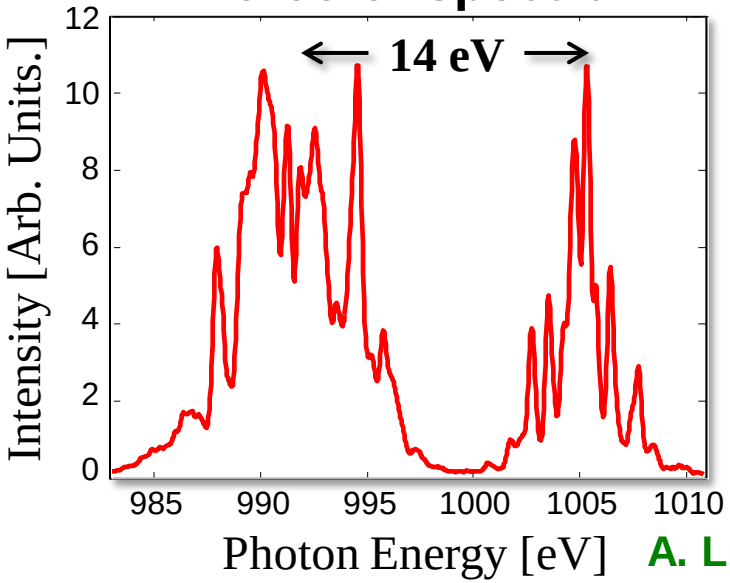
- Fresh-bunch lasing of two slices at different times/energies
- Used for 2-color, time-delayed X-ray pulses for pump-probe studies with up to 1 mJ pulse energy (-15 to 950 fs) – easier in LCLS-II w/ undulators



Time-resolved image



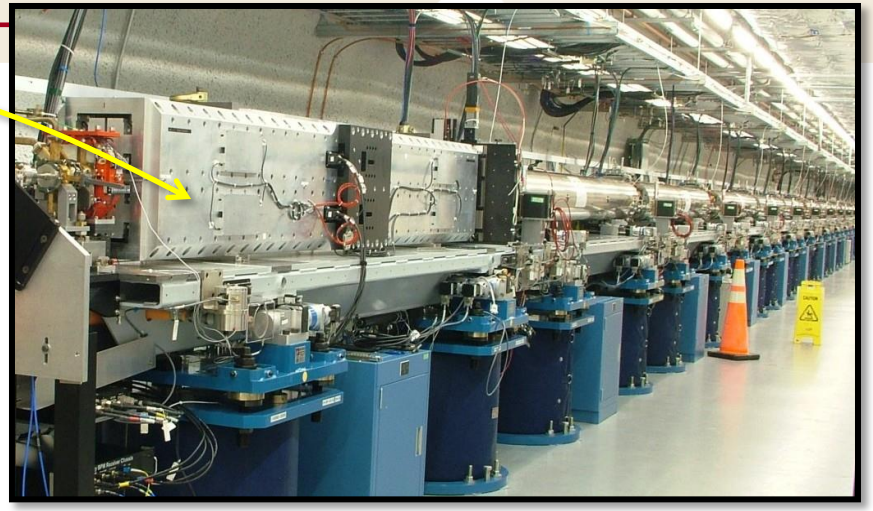
Two-color spectrum

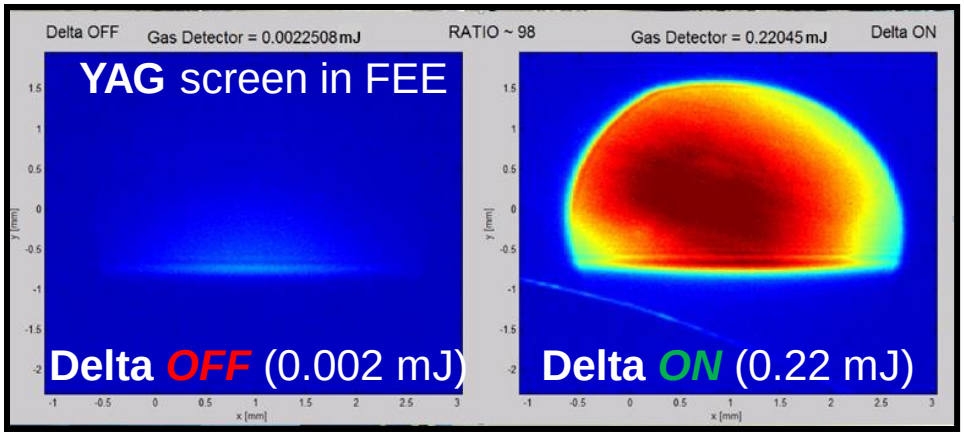


A. Lutman

Polarization Control at LCLS-II / LCLS-II-HE

- Delta-I is operational
- Delta-II for SXR: larger *K* & var. gap
- Add three 3.3-m long Delta-II's at end of SXR und. (not in *LCLS-II* baseline)
- Simulations: 5-7 GW (w/3 Delta-II's)
- 100% polarization (goal <1% stability)
- All orientations possible (planar: x or y; circular: *L* or *R*) – change in ~1 min.





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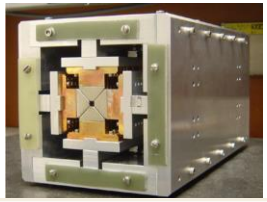
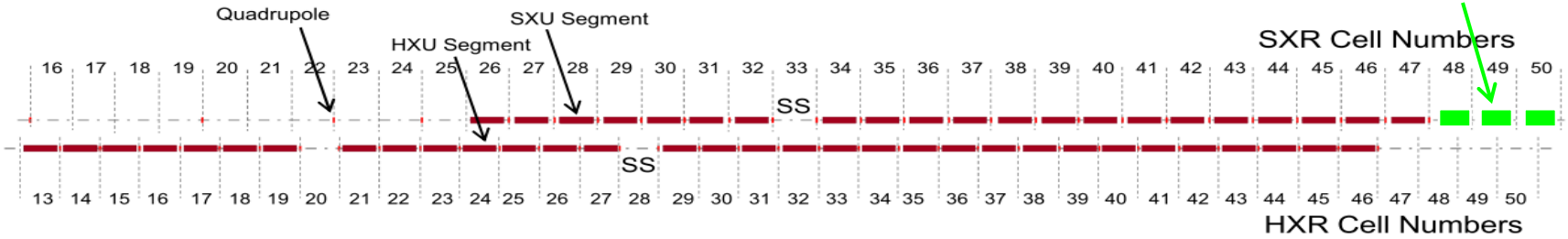
Polarization control in an X-ray free-electron laser

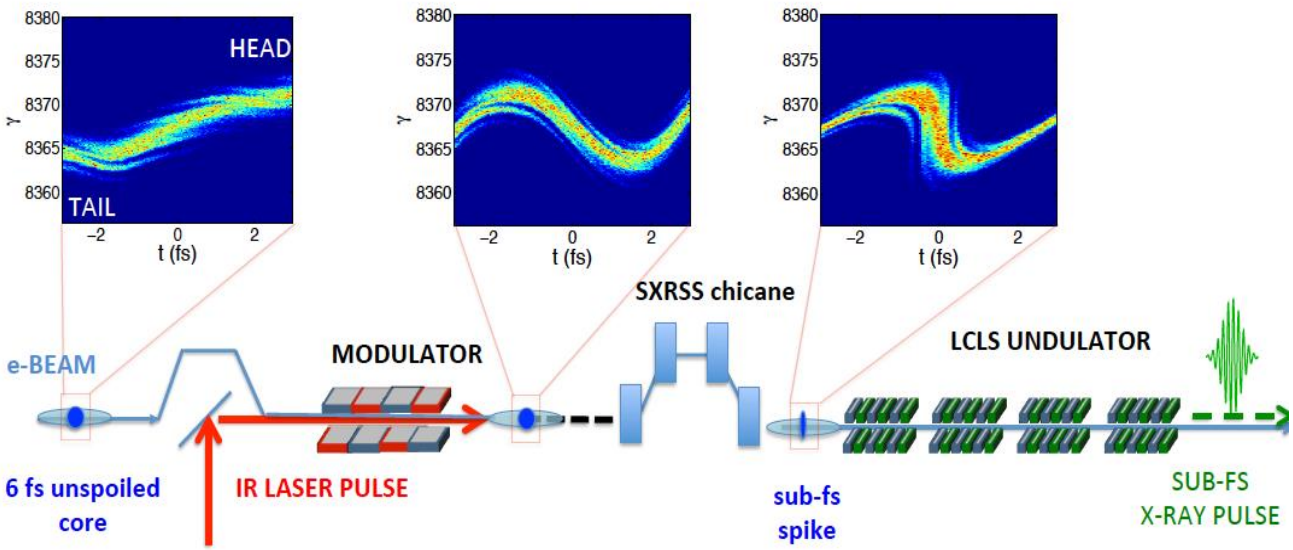
A. Lutman, H.-D. Nuhn, F. Peters, *et al.*



3 new Delta-II's

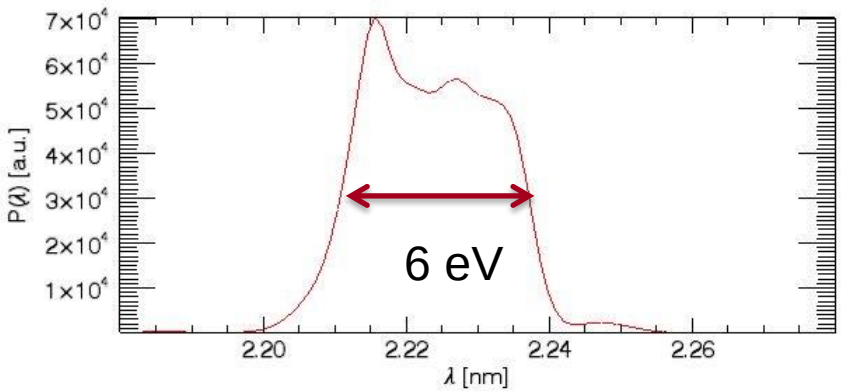


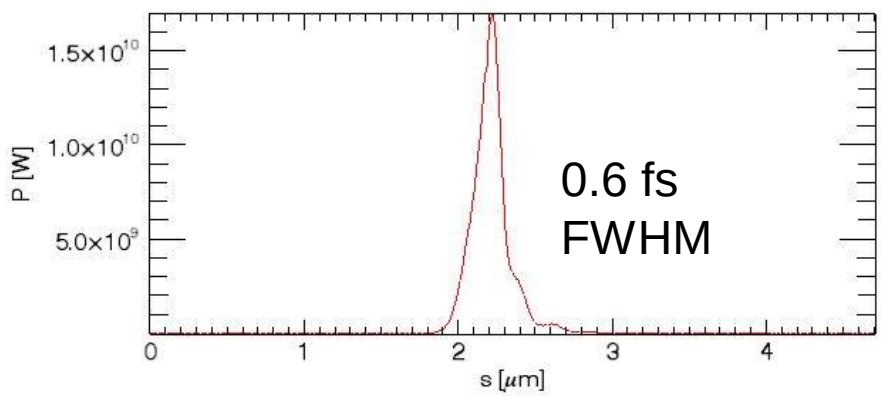
XLEAP – sub-fs X-ray pulse R&D program



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





Summary

- LCLS-II on track to deliver MHz-rate FEL X-ray's from 0.2 to 5 keV with commissioning in 2020
- LCLS-II-HE uses capacity designed into LCLS-II to double electron beam energy and increase spectral reach >12.8 keV
- R&D program to electron beam brightness will further increase spectral range to >20 keV
- Capabilities developed at LCLS should be available at LCLS-II and LCLS-II-HE

Backup Slides

Prototype Cryomodule Status Overview

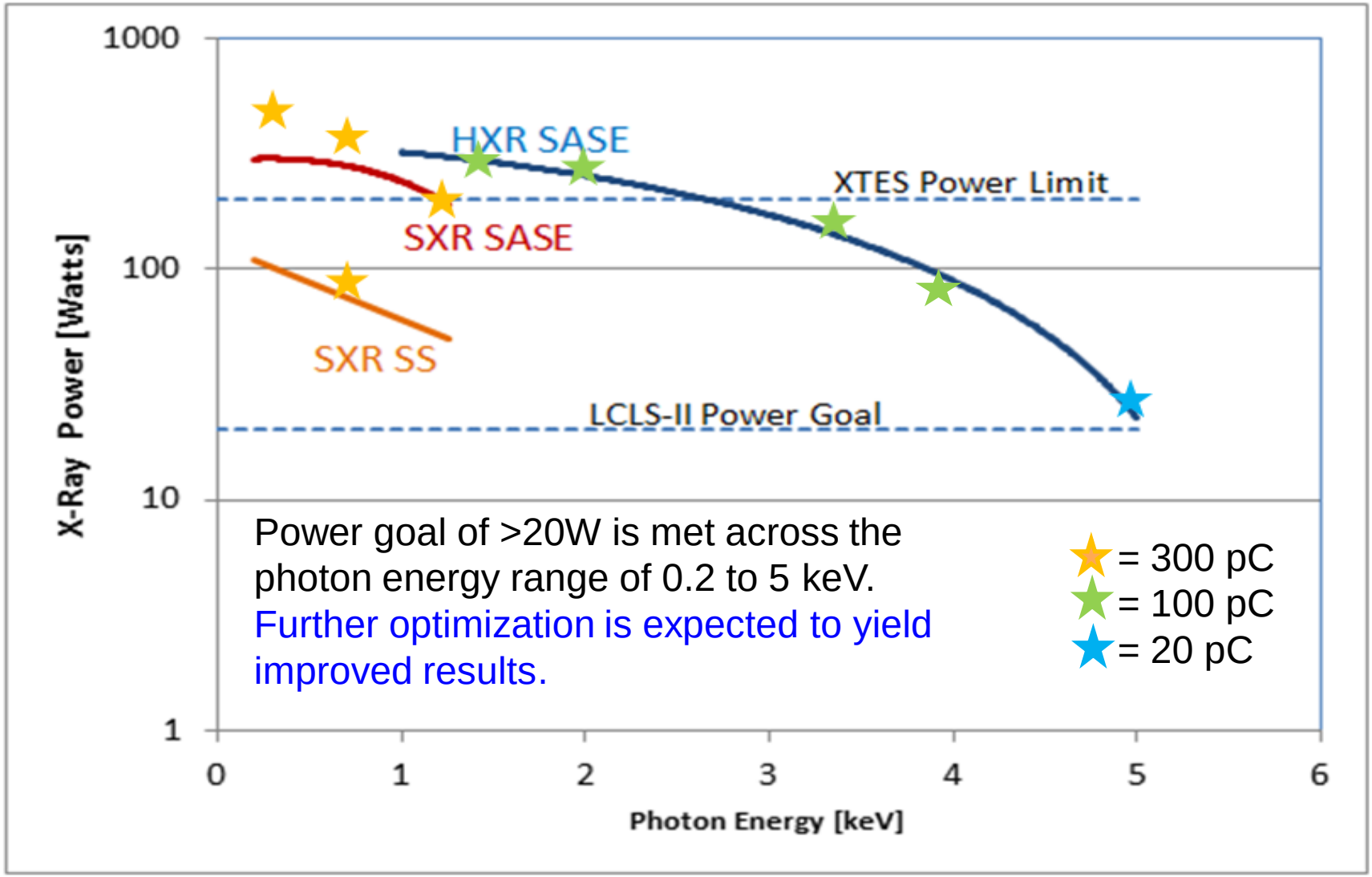
- Cryomodule Assembly complete at FNAL.
- JLab in Phase II of cryomodule Assembly (~70% complete)
- Testing began at FNAL Mid September
- Testing slated to begin in November at JLab

LCLS-II (SCRF) Baseline Parameters

Parameter	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.5	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**	0.0 - 0.3	mA
Avg. e^- beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**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**	8 - 20	MV/m
Avg. Cavity Q0	$Q0$	**2.7e10**	1.5 - 5e10	-
Photon energy range of SXR (**SCRF**)	E_{phot}	-	**0.2 - 1.3**	keV
Photon energy range of HXR (**SCRF**)	E_{phot}	-	**1 - 5**	keV
Photon energy range of HXR (**Cu-RF**)	E_{phot}	-	**1 - 25**	keV

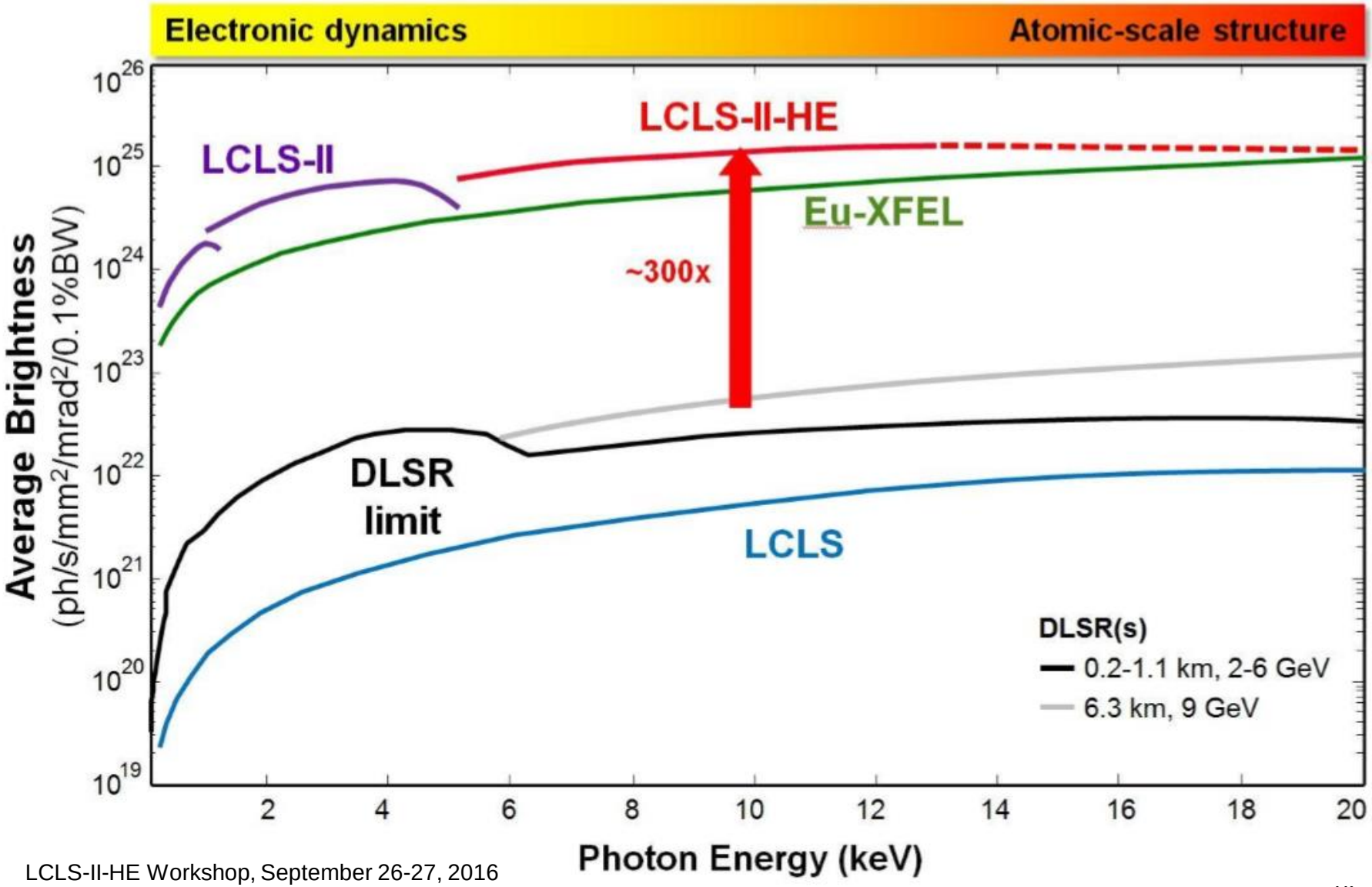
FEL Performance Simulations at 4.0 GeV

Full IMPACT/Genesis S-2-E across parameter range

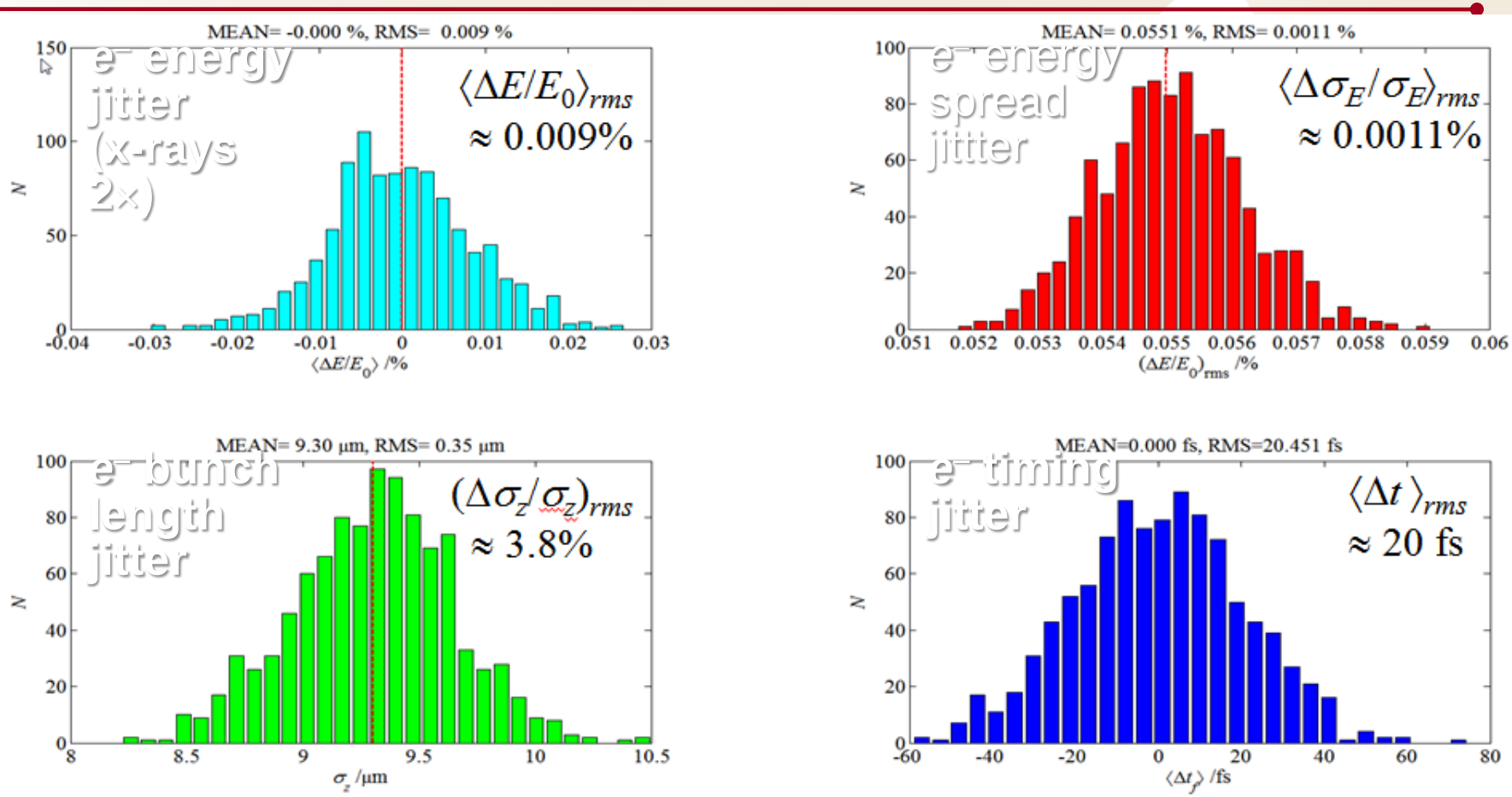


G. Marcus, H.D. Nuhn

LCLS-II-HE Brightness Curve



LCLS-II / LCLS-II-HE Stability Expectations



- Shows estimated *pulse-to-pulse* jitter (rms)
- Slow drift will be removed by using beam-based feedback (as at *LCLS-I*)
- Final jitter may be even better than shown (conservative estimate here)
- Should be considerably better than *LCLS-I*