Progress on the LCLS-II and the High Energy Upgrade LCLS-II-HE

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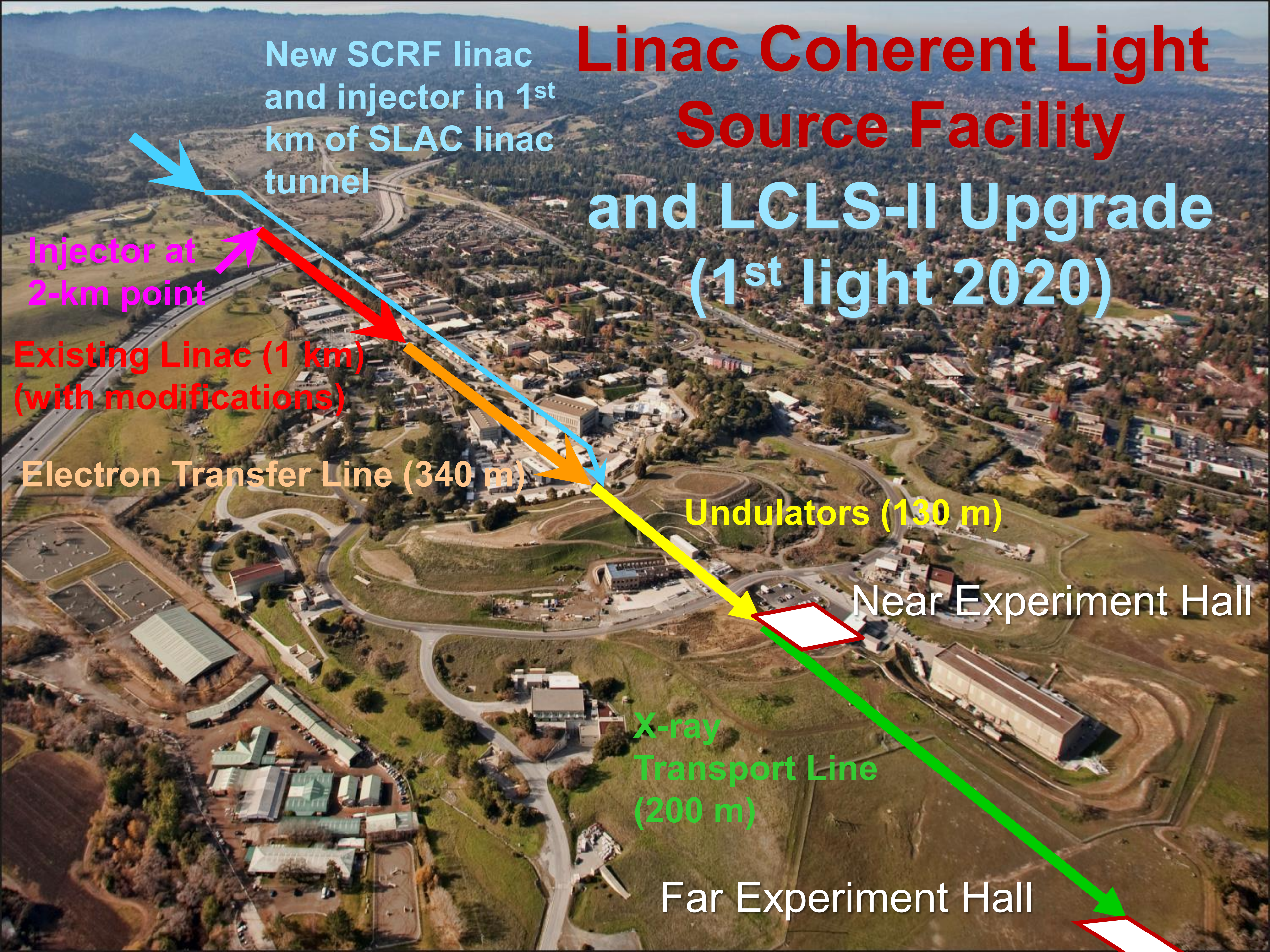
Future Light Sources Workshop 2018, March 5-9, 2018

Outline

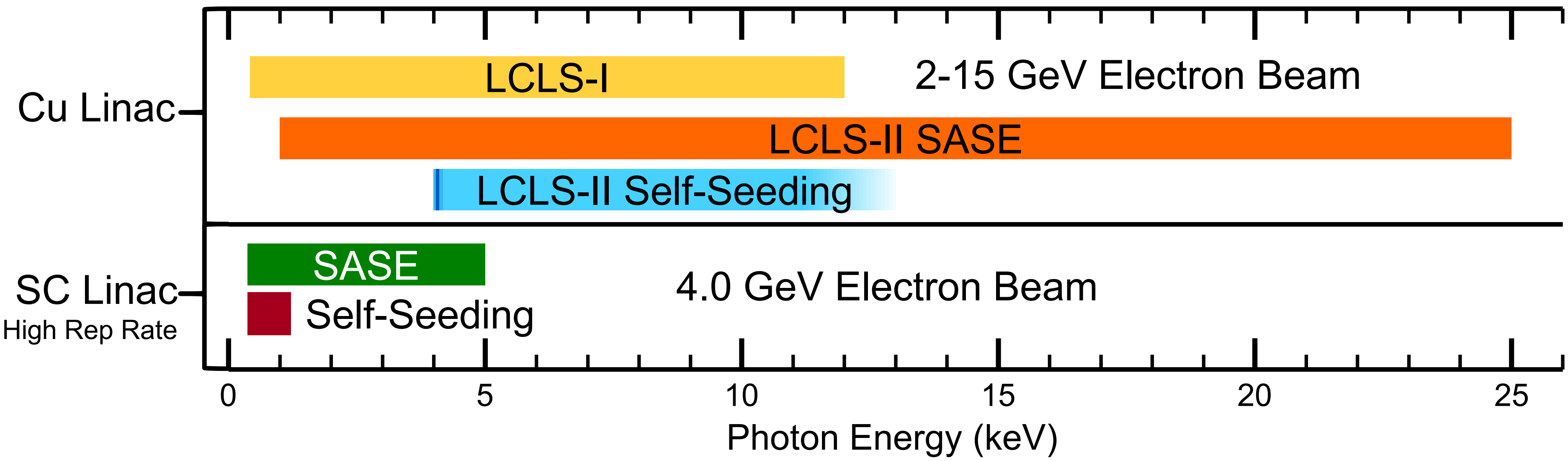
- LCLS-II Overview
- LCLS-II-HE Concept
- Performance and Operating Modes



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



Legend

- Cu SASE
- Cu Self Seeded
- High Rep Rate SASE
- Self Seeded (Grating)

Future expansion options

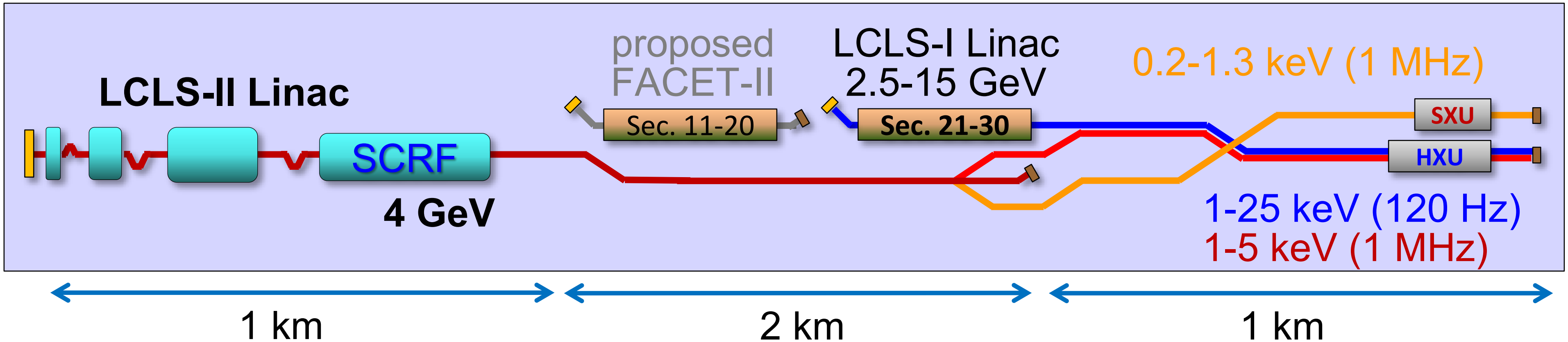
- External seeding below 1 keV
- Self seeding between 1.5 - 4 keV
- X-rays beyond 5 keV from the SCRF linac with >4 GeV beam energy
- Additional FEL's using 1.2 MW e-

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

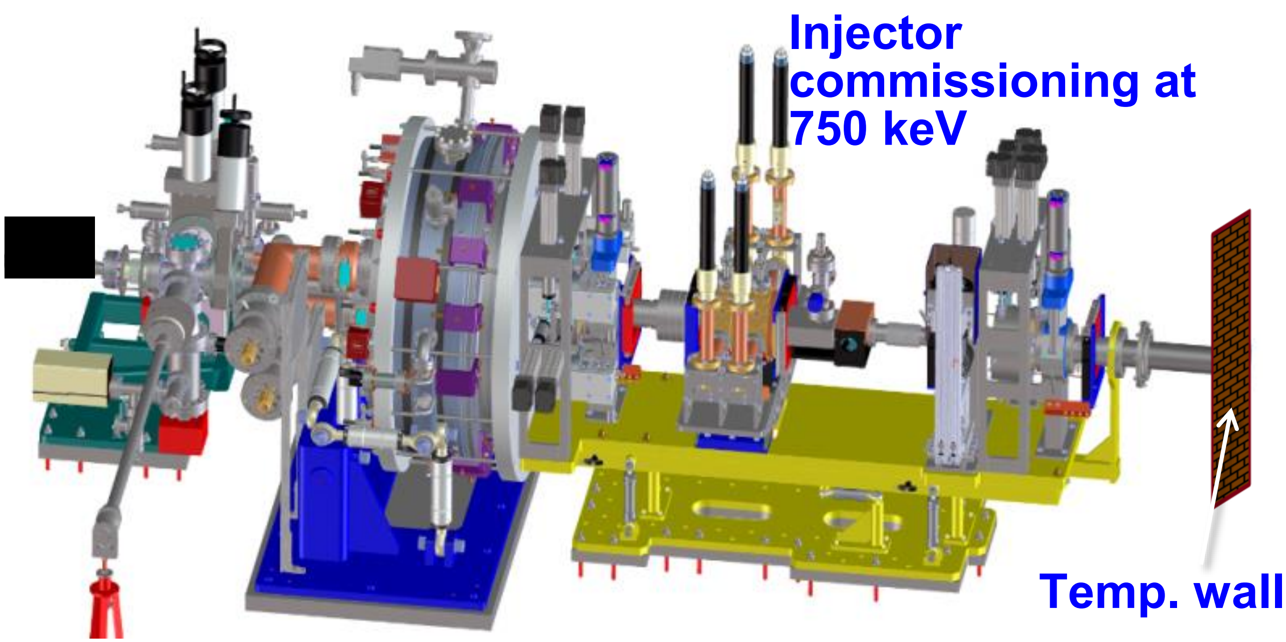
Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
Soft X-ray	0.20 - 1.3 keV with >> 20 Watts	
Hard X-ray	1.0 - 5.0 keV with > 20 Watts	1 - 25 keV with mJ-class X-ray pulses

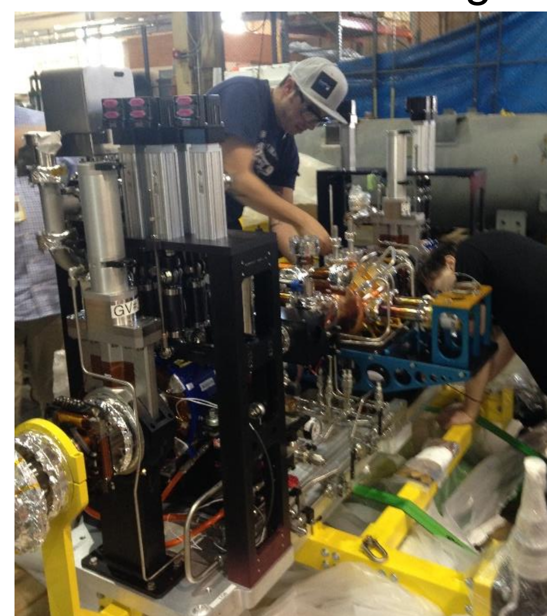


LCLS-II Injector Status

- Laser temporarily installed and running at SSRL
- Gun delivered to SLAC
- Early injector commissioning starts spring 2018

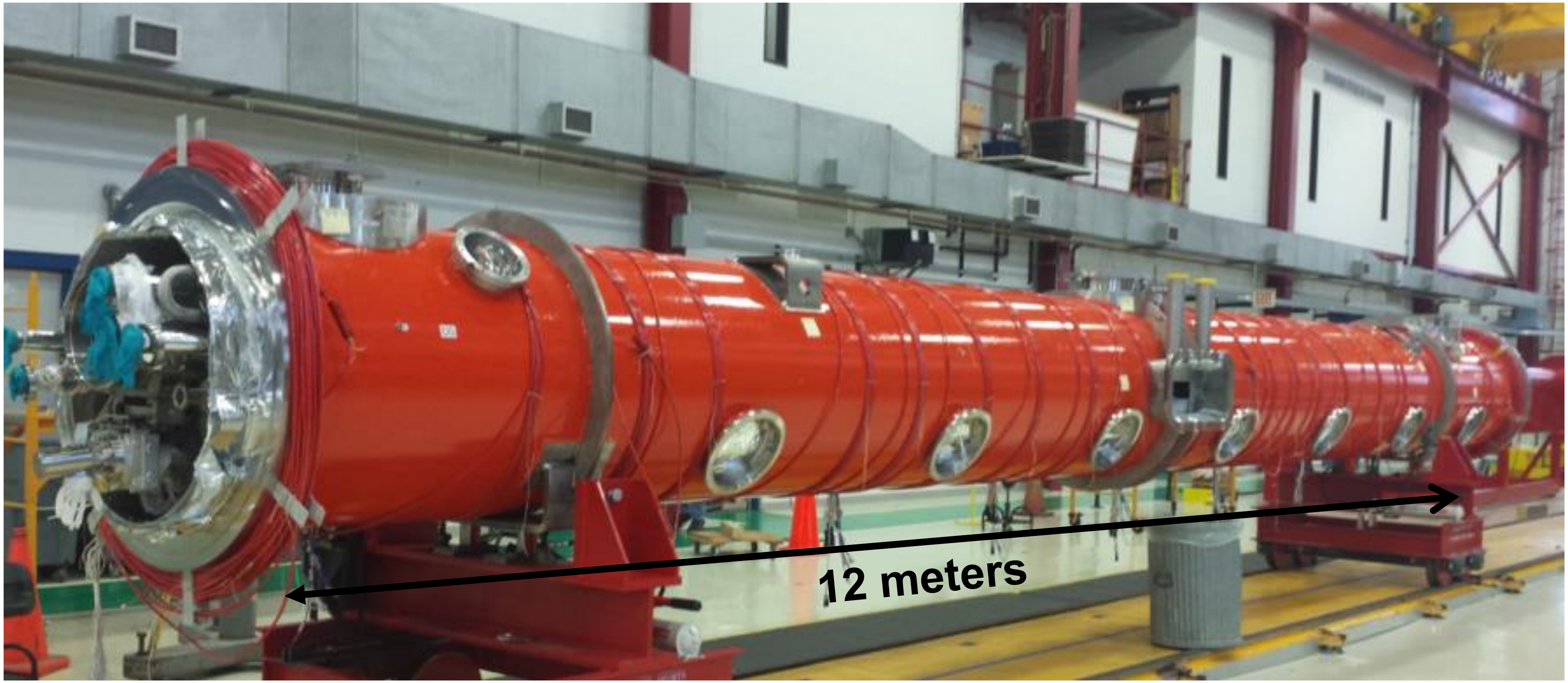
186 MHz CW RF gun





Injector low energy beamline

LCLS-II Cryomodule
Based on ILC and XFEL 1.3 GHz Cryomodules

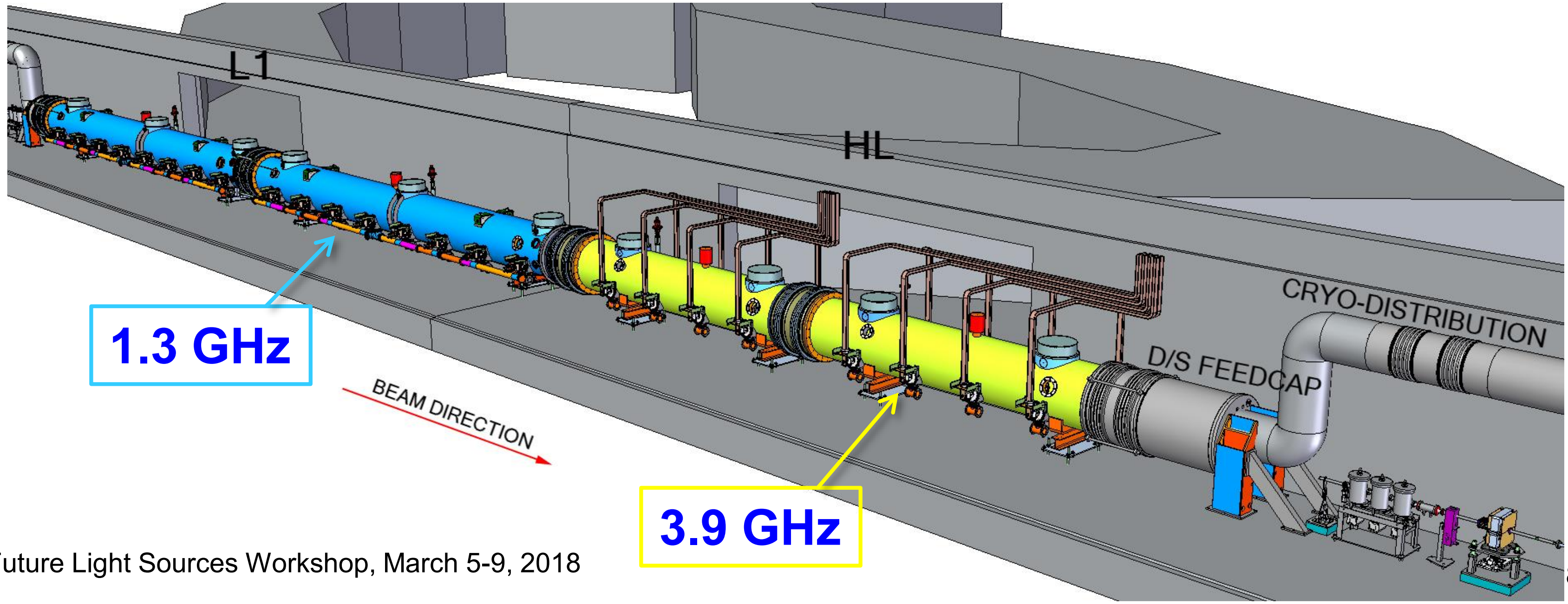


CM to be fabricated at FNAL and JLab; Prototypes have been assembled and tested in 2017. Installation 2018.

LCLS-II Cryomodule Status

37 CMs to be installed

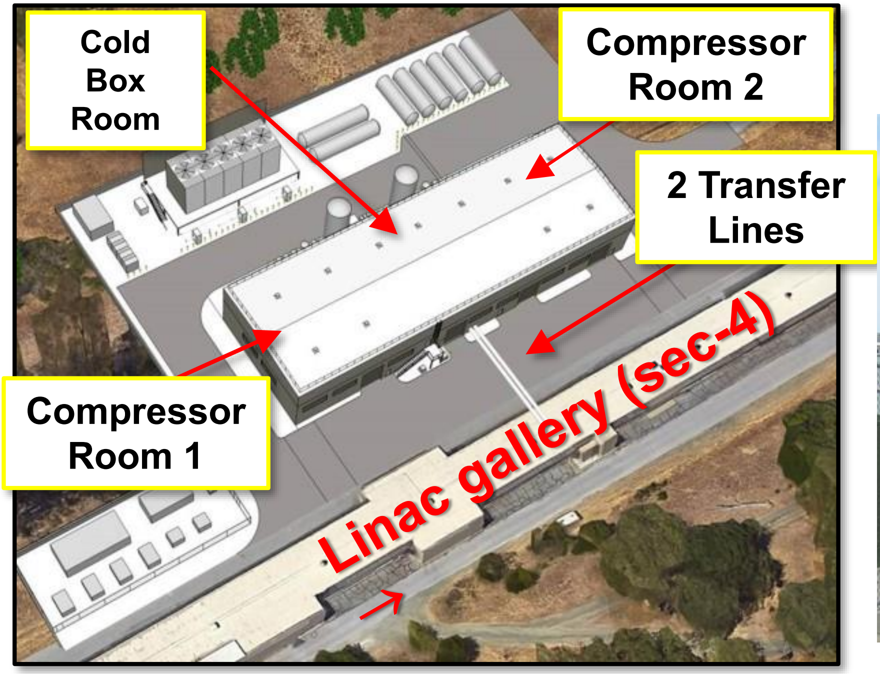
First 1.3 GHz CM at SLAC but have had vacuum problems



Cryoplant Building – Two 4-kW plants (2K)

- Building nearly complete
- Warm compressor installation started

Warm Helium Compressor Installed

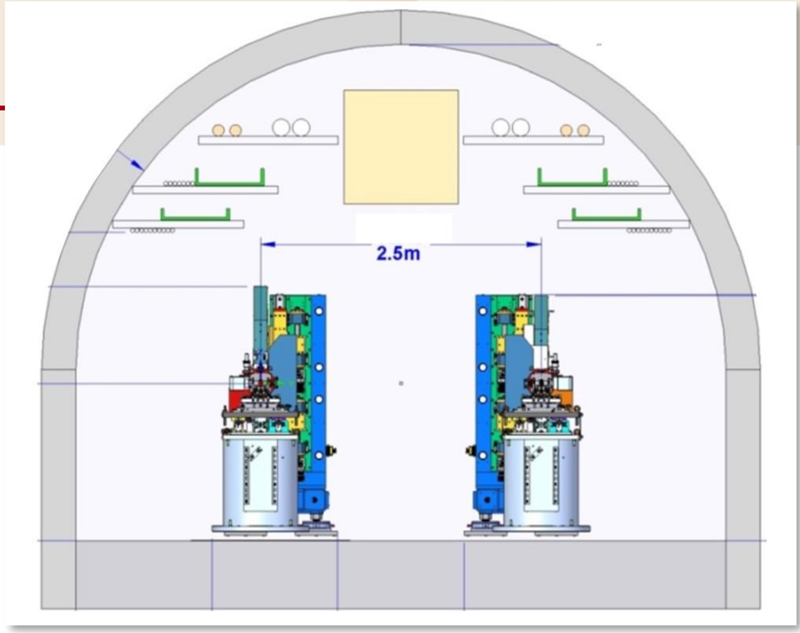


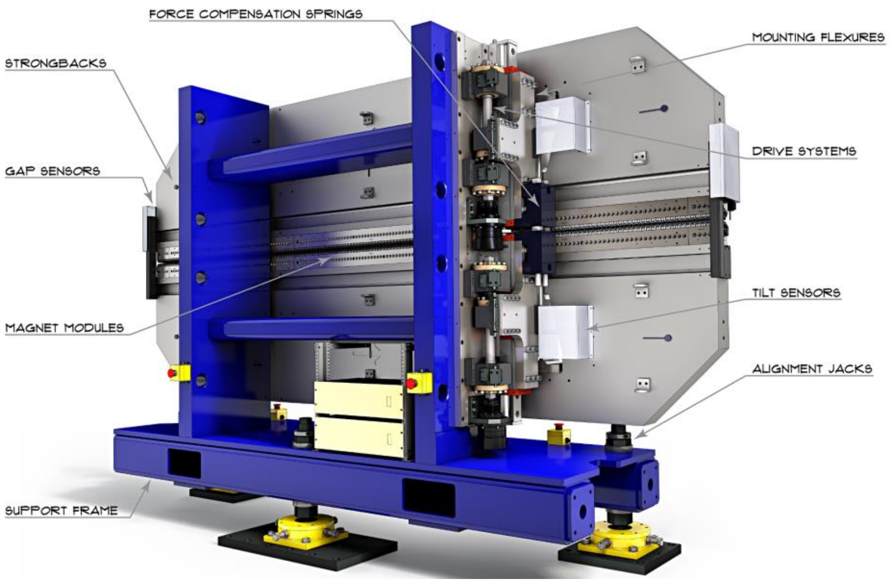
CryoPlant Building at Sector 4

Variable Gap Hybrid Undulators

Will install two new undulators in Hall

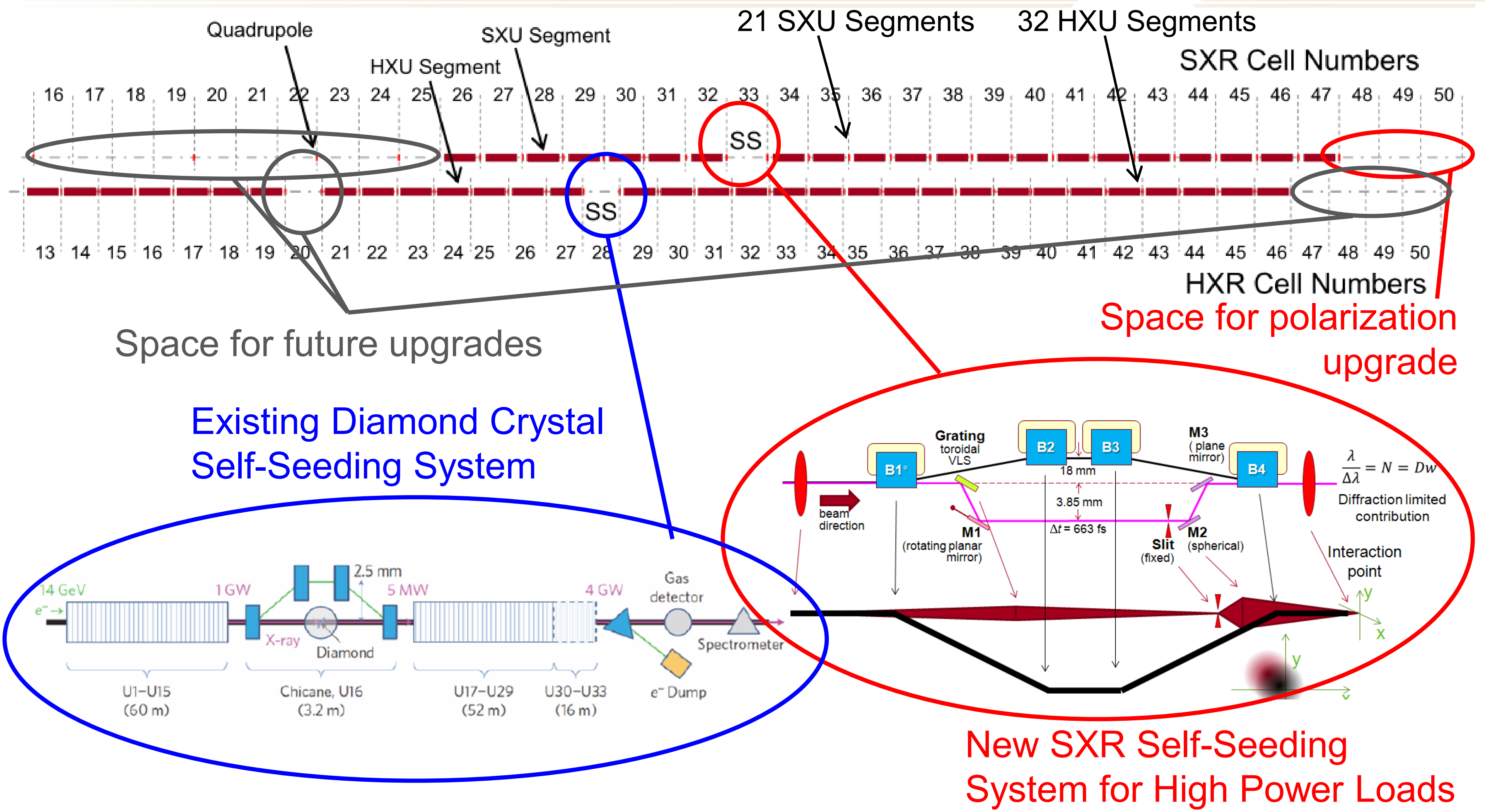
Variable gap undulators used in LCLS-II to provide greater wavelength tuning flexibility: standard vertical gap for SXR and a horizontal gap Vertically Polarized Undulator for HXR.





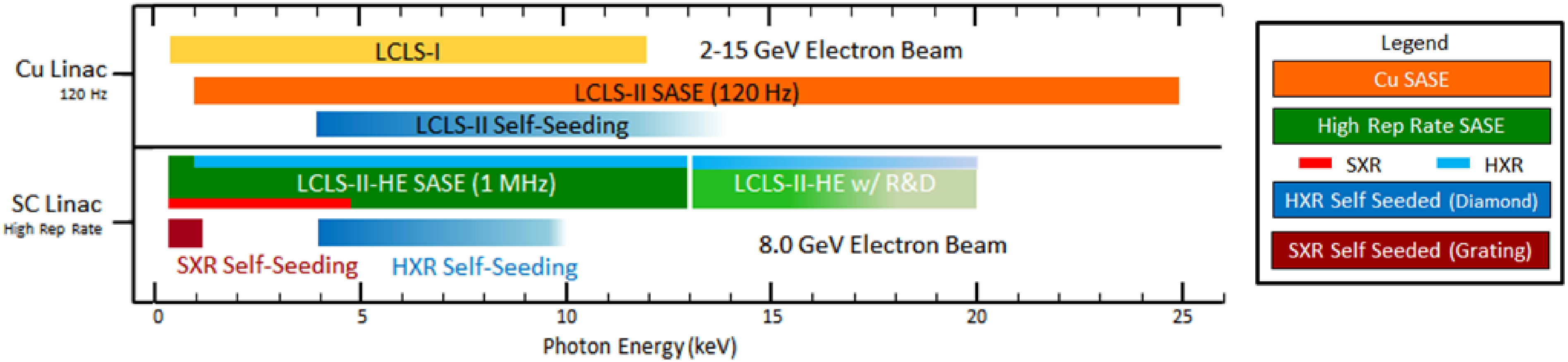
LCLS-II Undulator Layout

Replace Existing LCLS Undulator with HXR and add SXR



LCLS-II-HE Goals

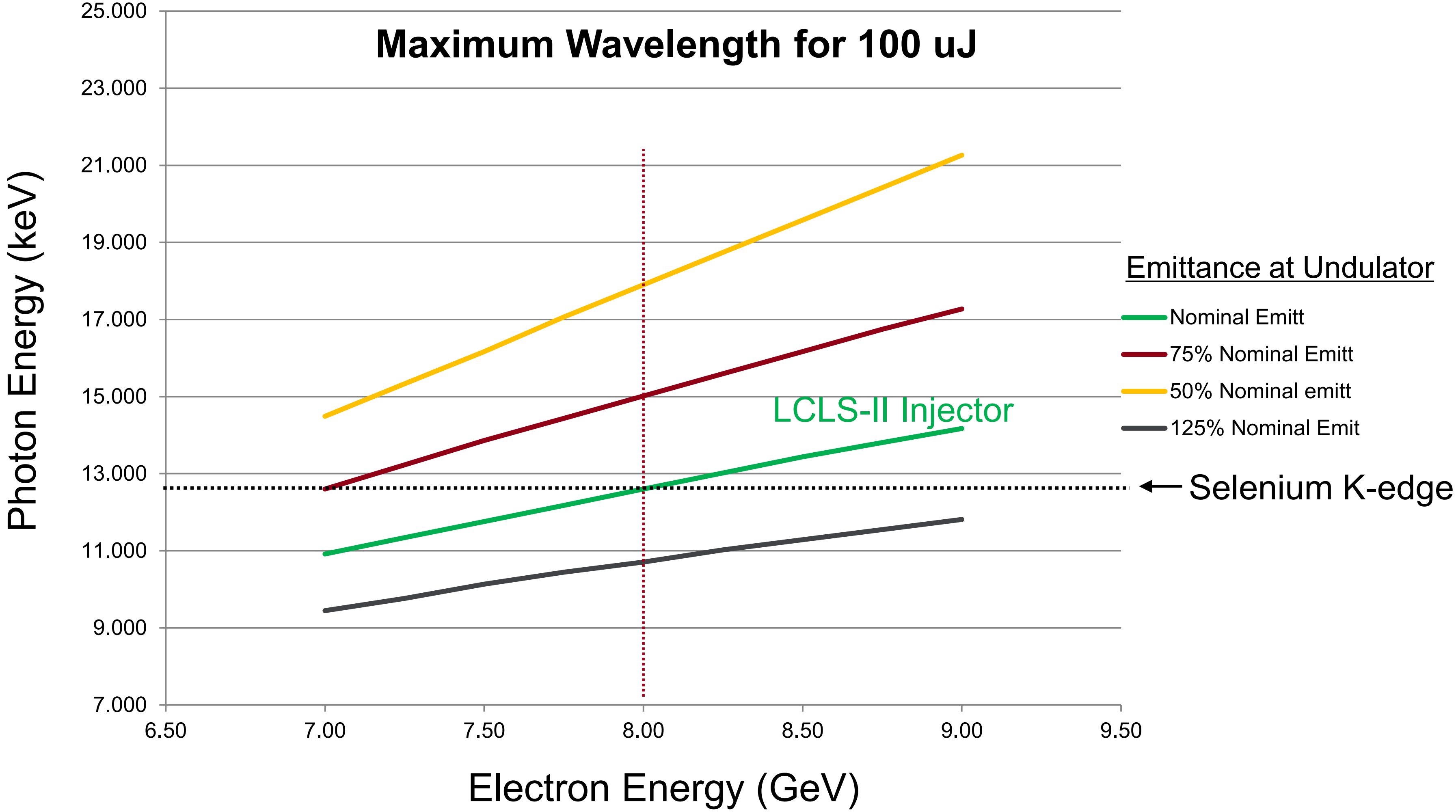
Build on LCLS-II Performance Goals



1. Hard X-rays at 1 – 13 keV with the possibility of approaching 20 keV
2. Soft X-rays at 0.2 – 1.3 keV or 1 – 5 keV *at the same time* as the production of hard X-rays
3. Hard X-ray (as well as soft X-ray) self-seeding at MHz-rates
4. The hard X-ray beamlines and instruments will be upgraded to maximize the science from the MHz-rate high energy FEL beams
5. Hard X-ray experimental hall (FEH) will be modified to incorporate an additional experimental instrument
6. The performance of LCLS and LCLS-II operational modes and techniques will not be negatively impacted by the LCLS-II-HE upgrade

Analytic Estimates of Minimum Beam Energy

LCLS-II Injector → 8 GeV Minimum for 12.8 keV



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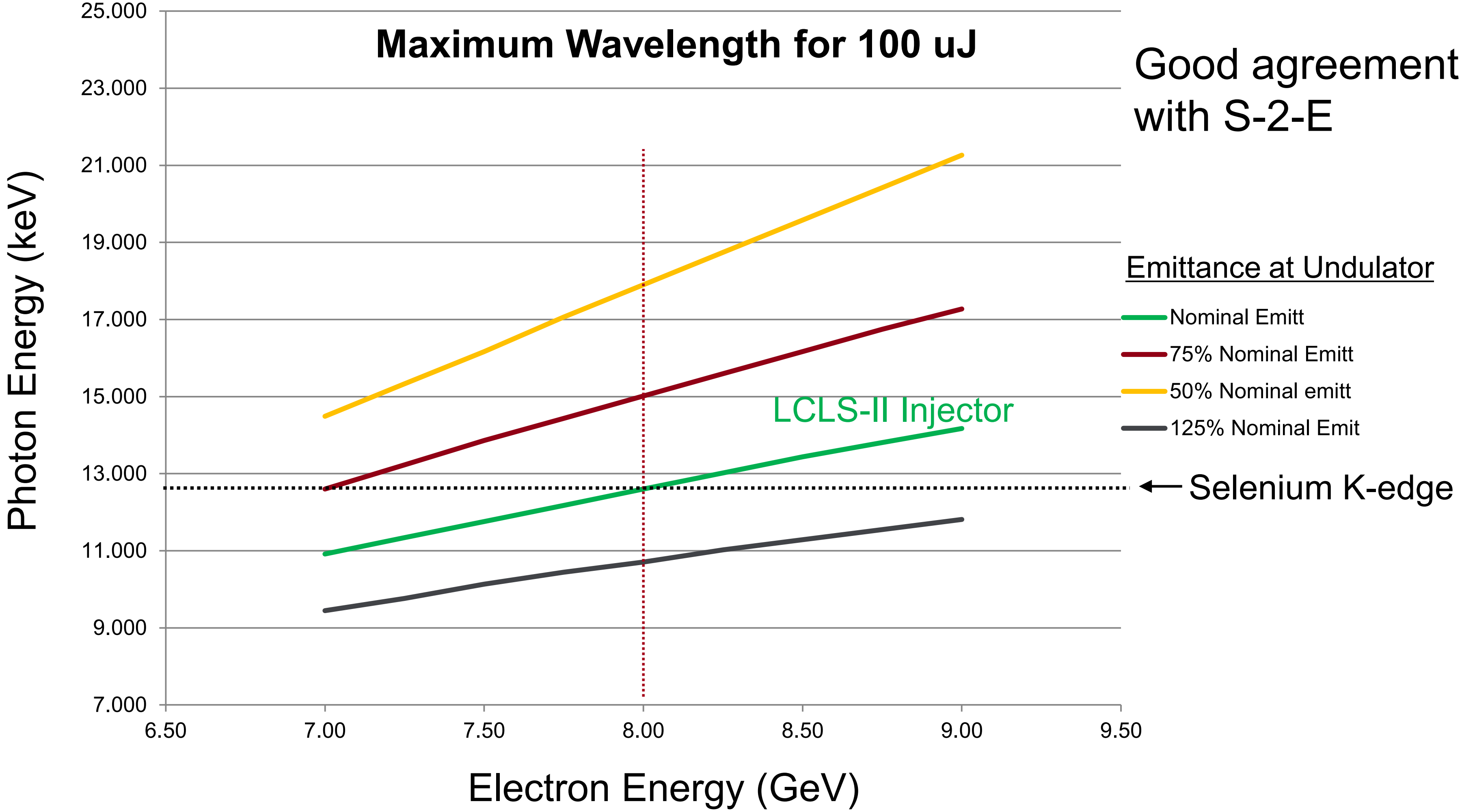

Good agreement with S-2-E

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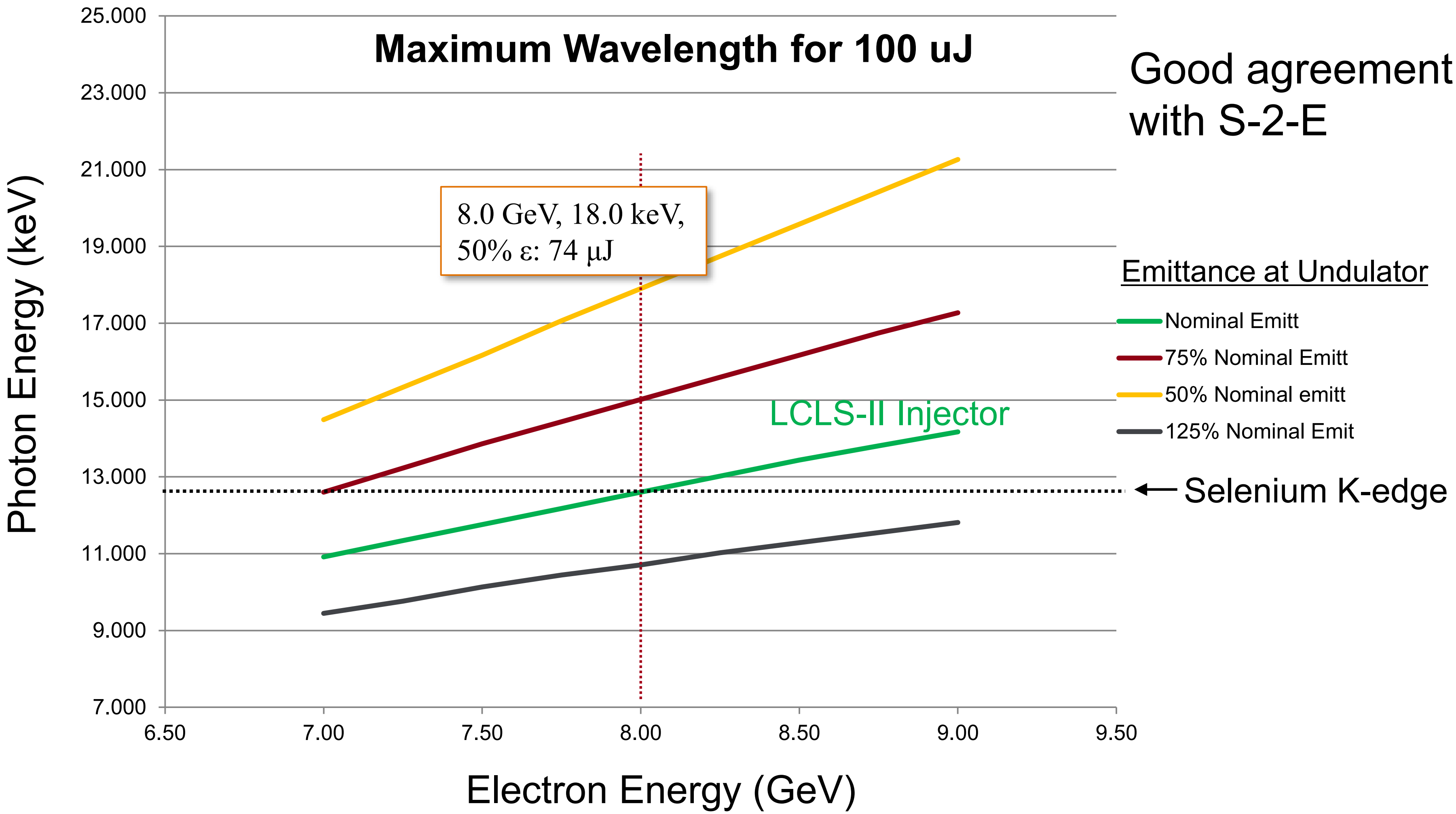

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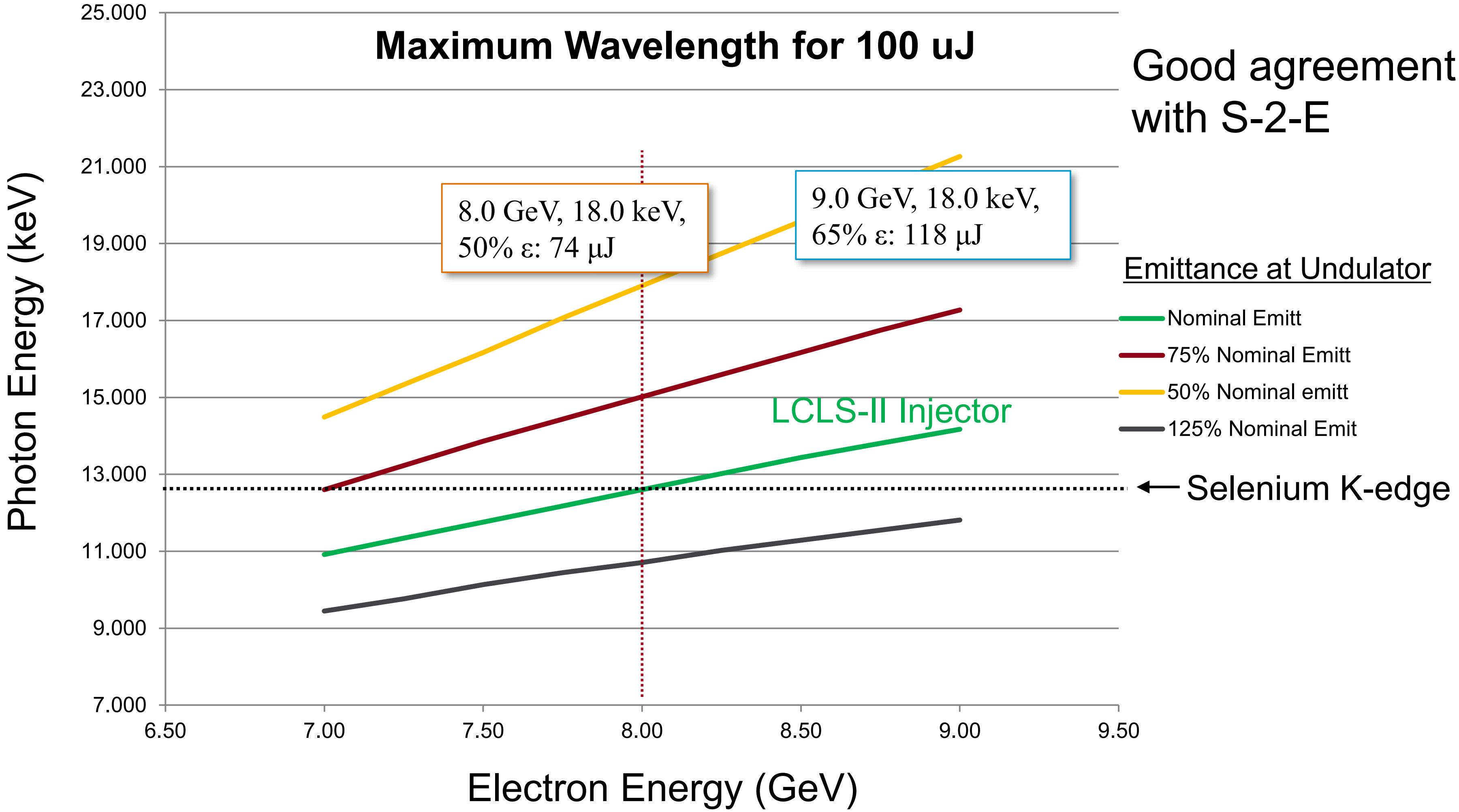

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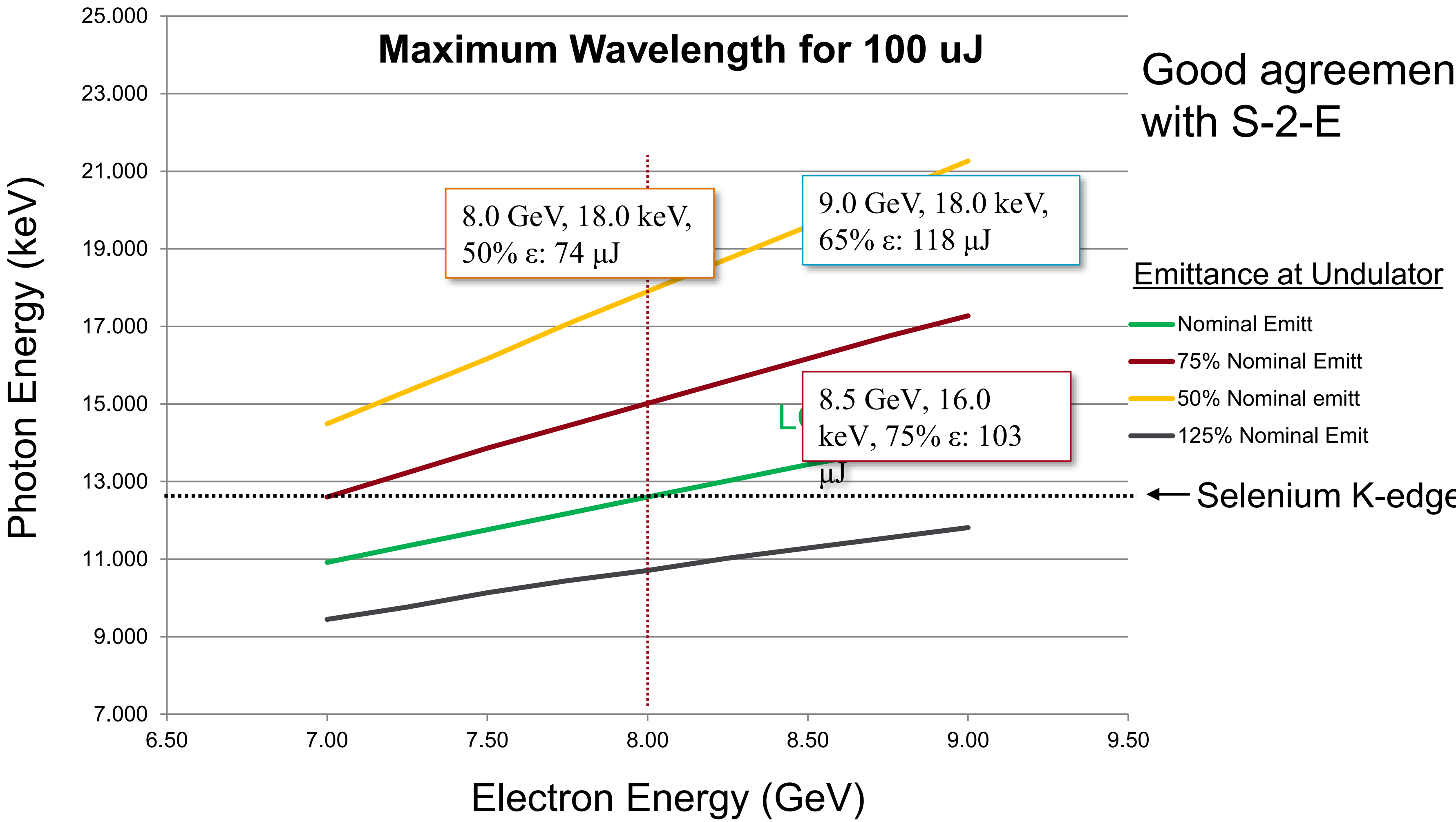

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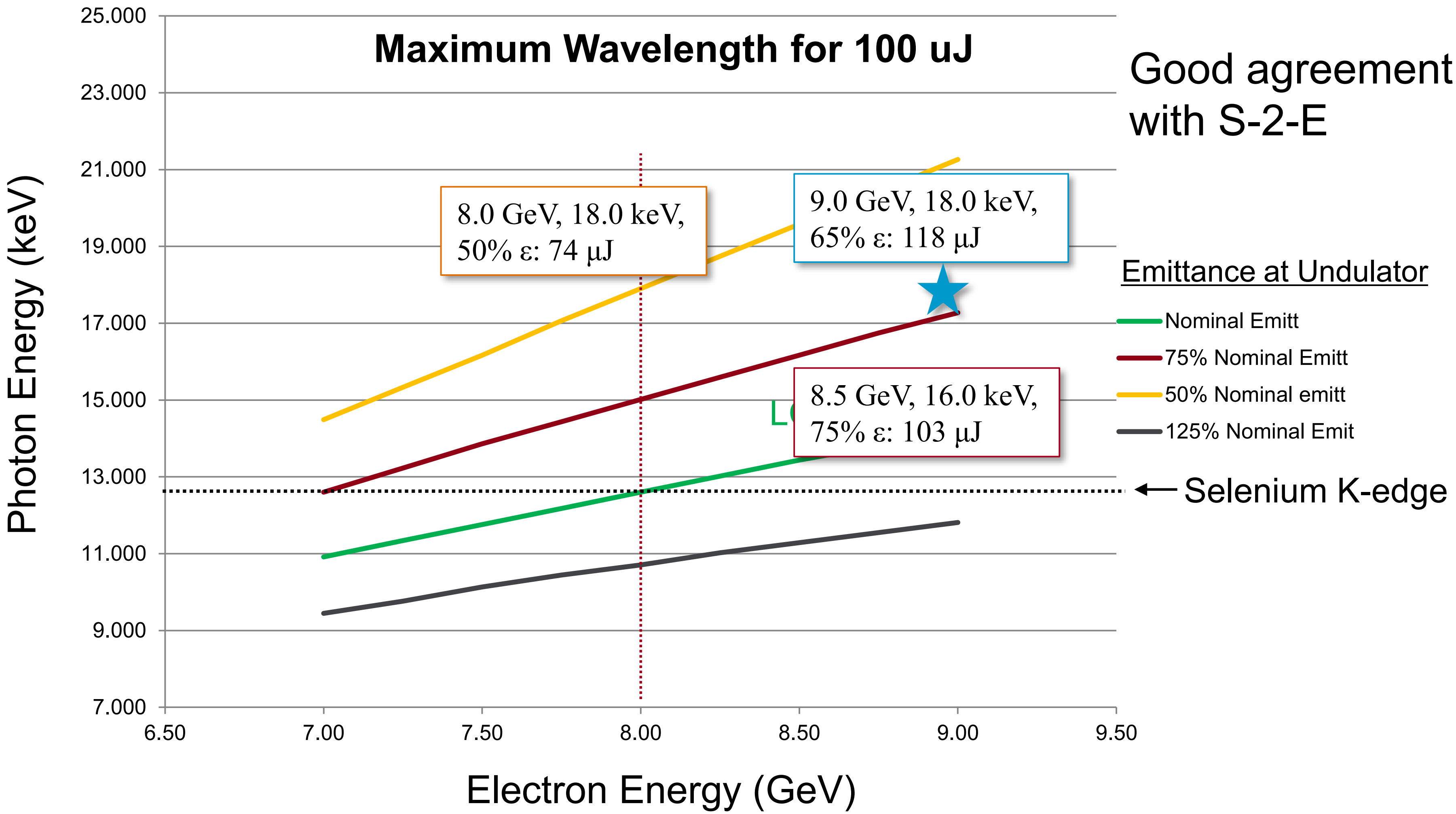

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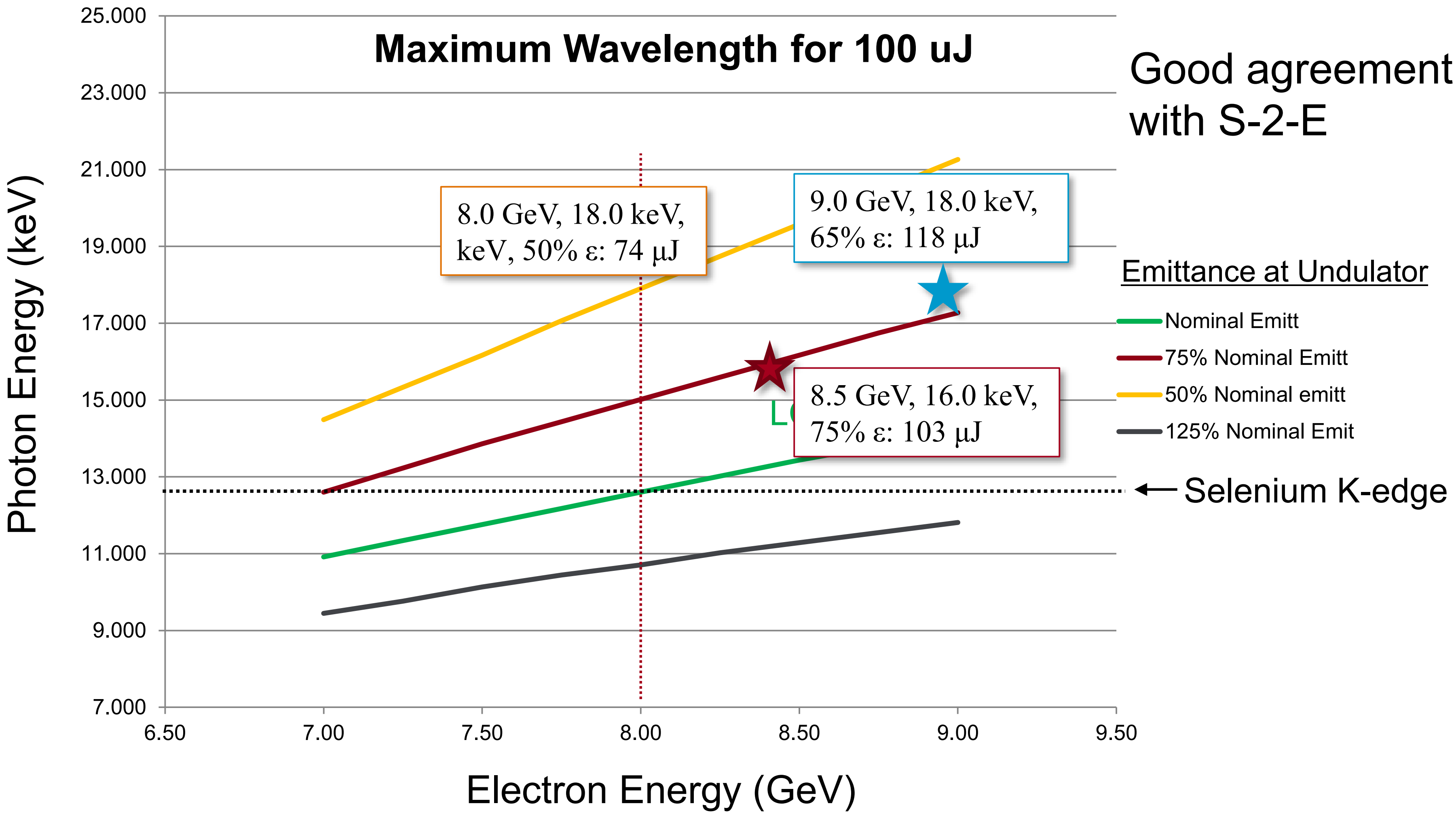

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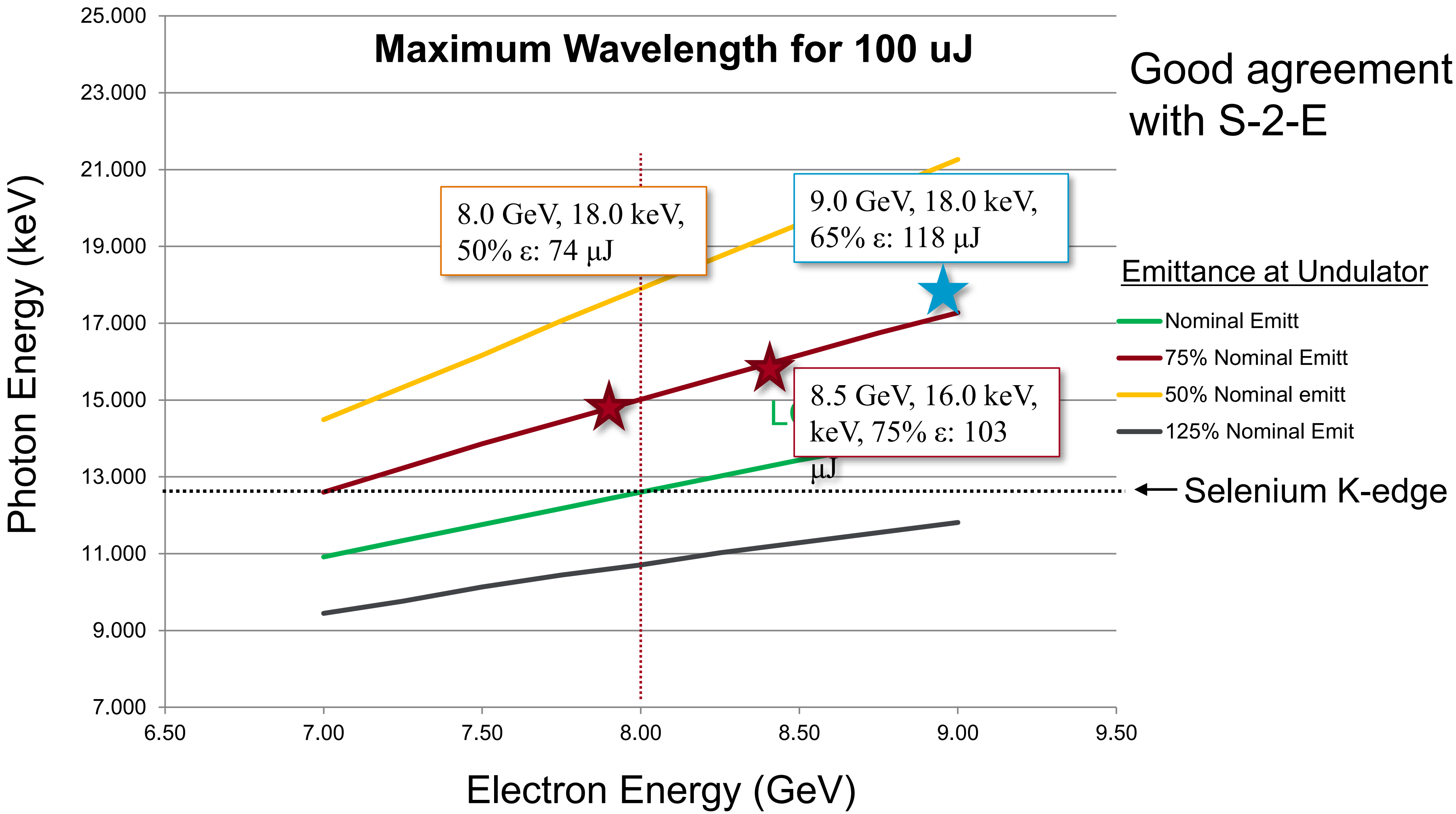

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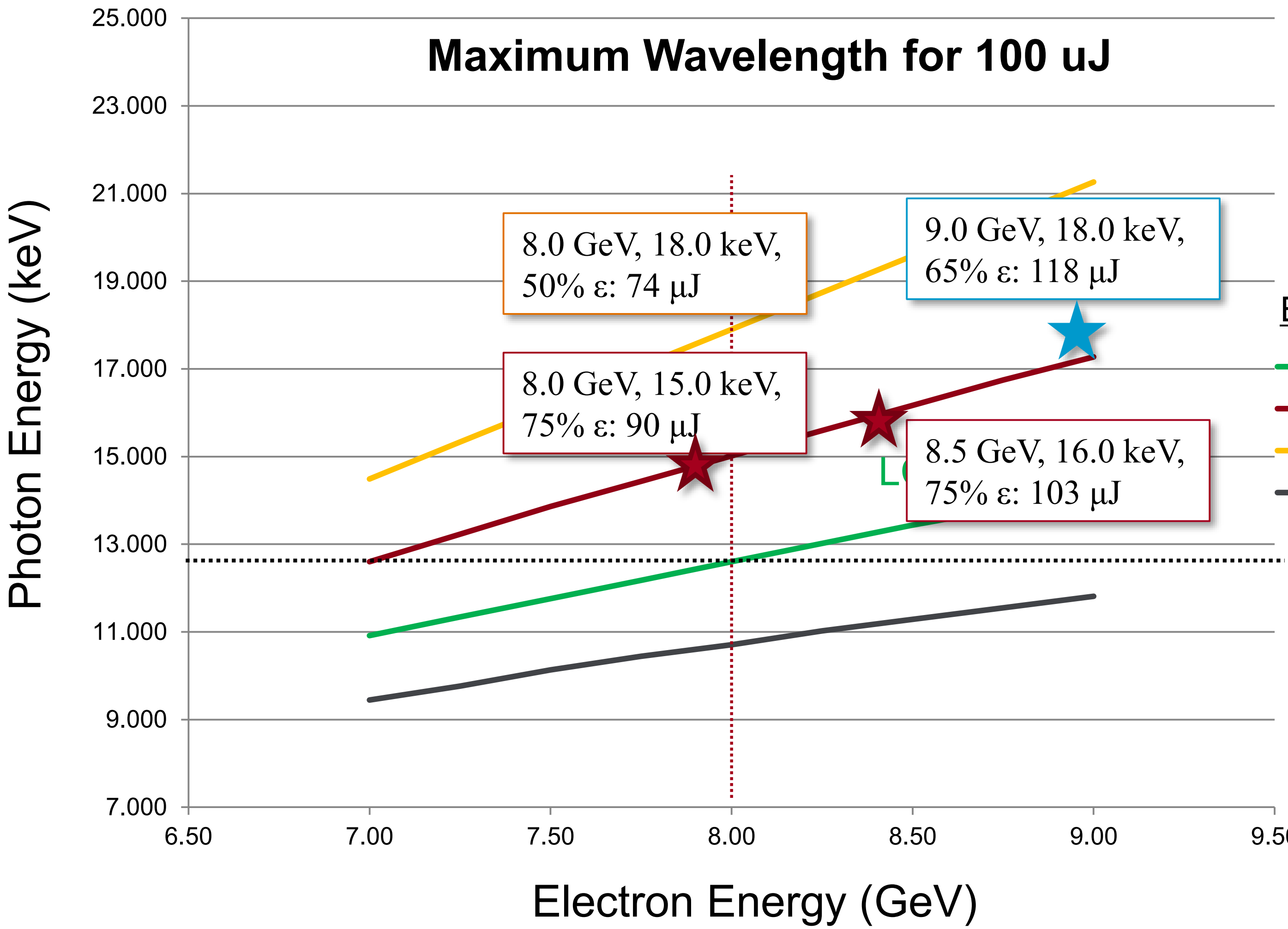

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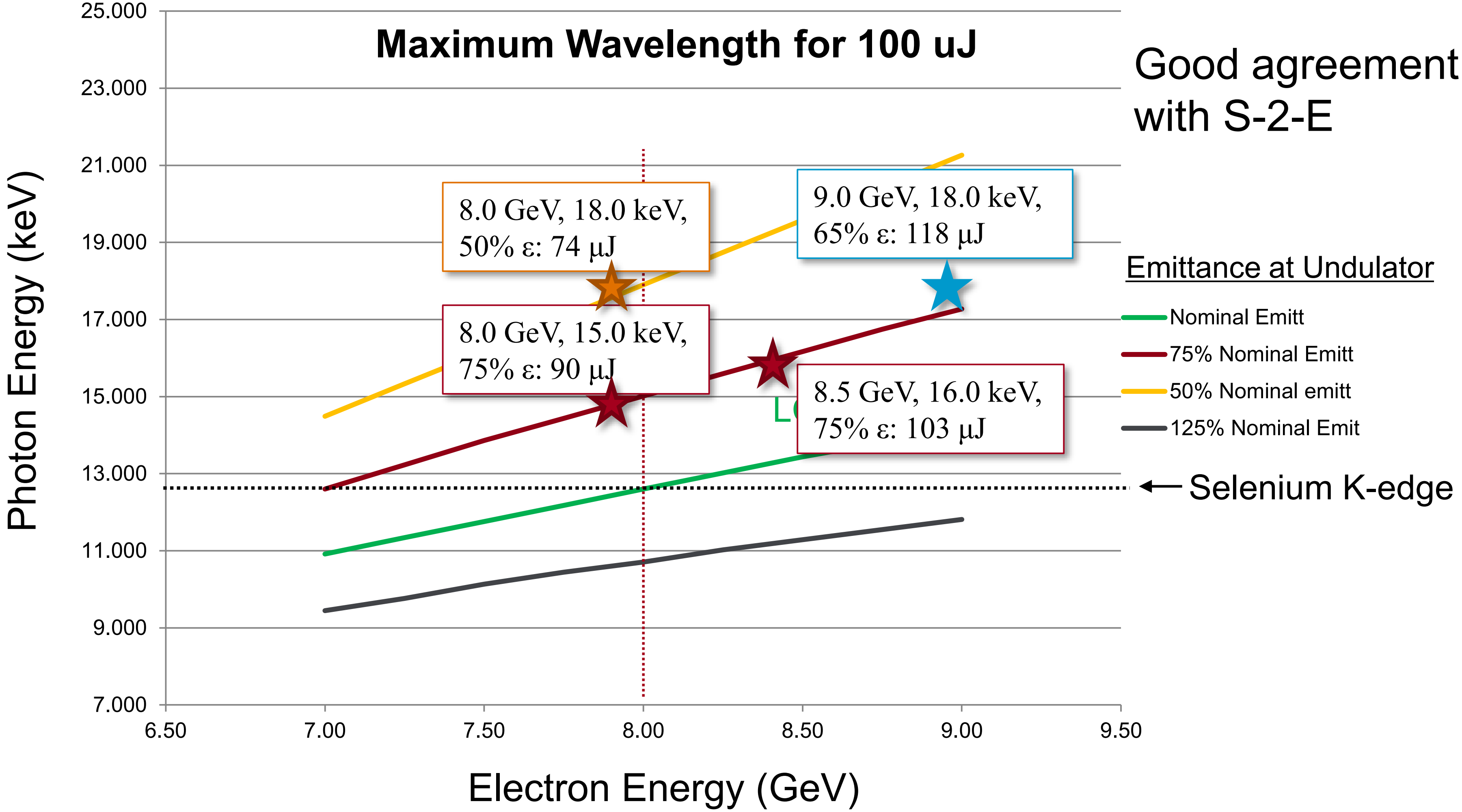

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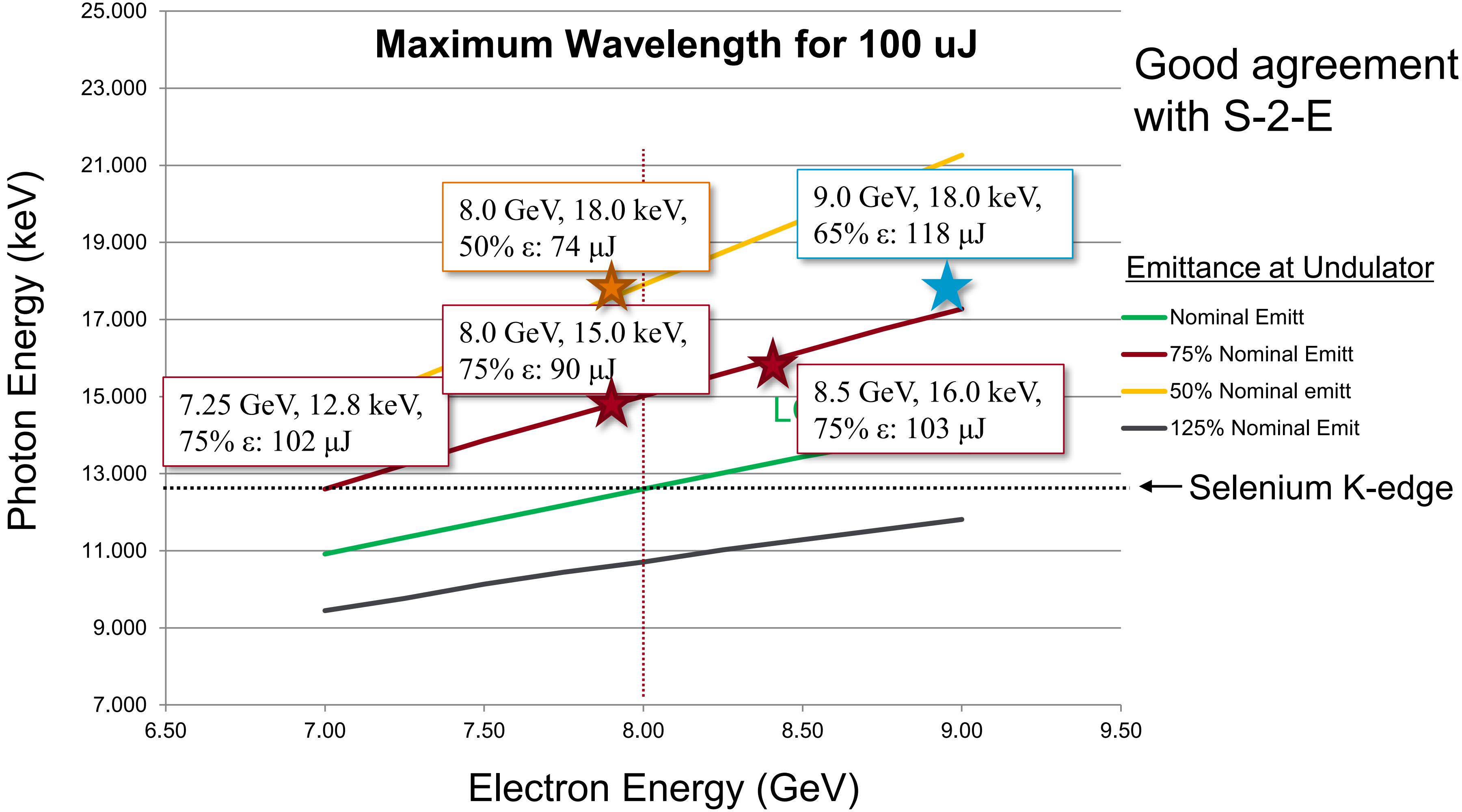

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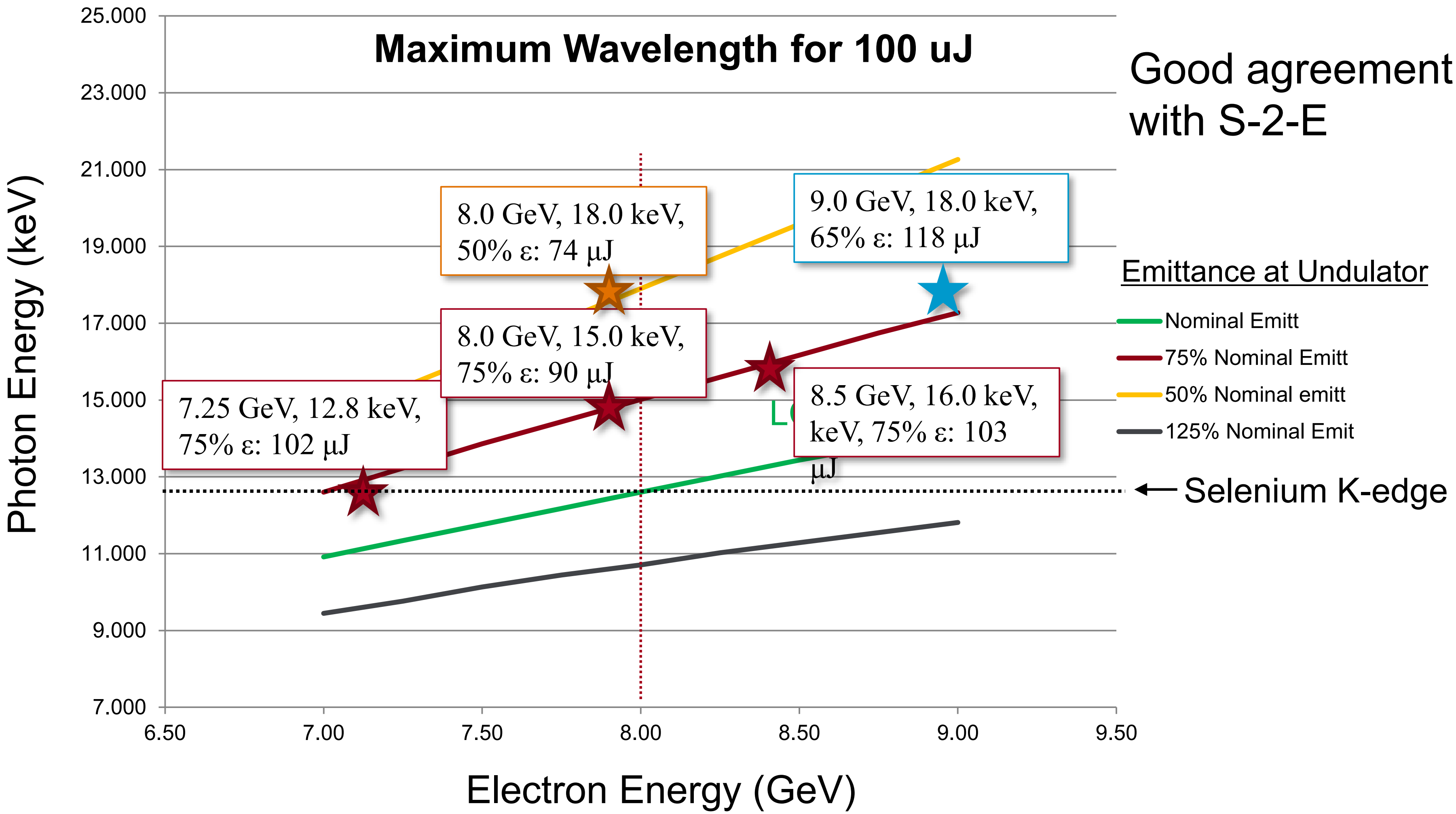

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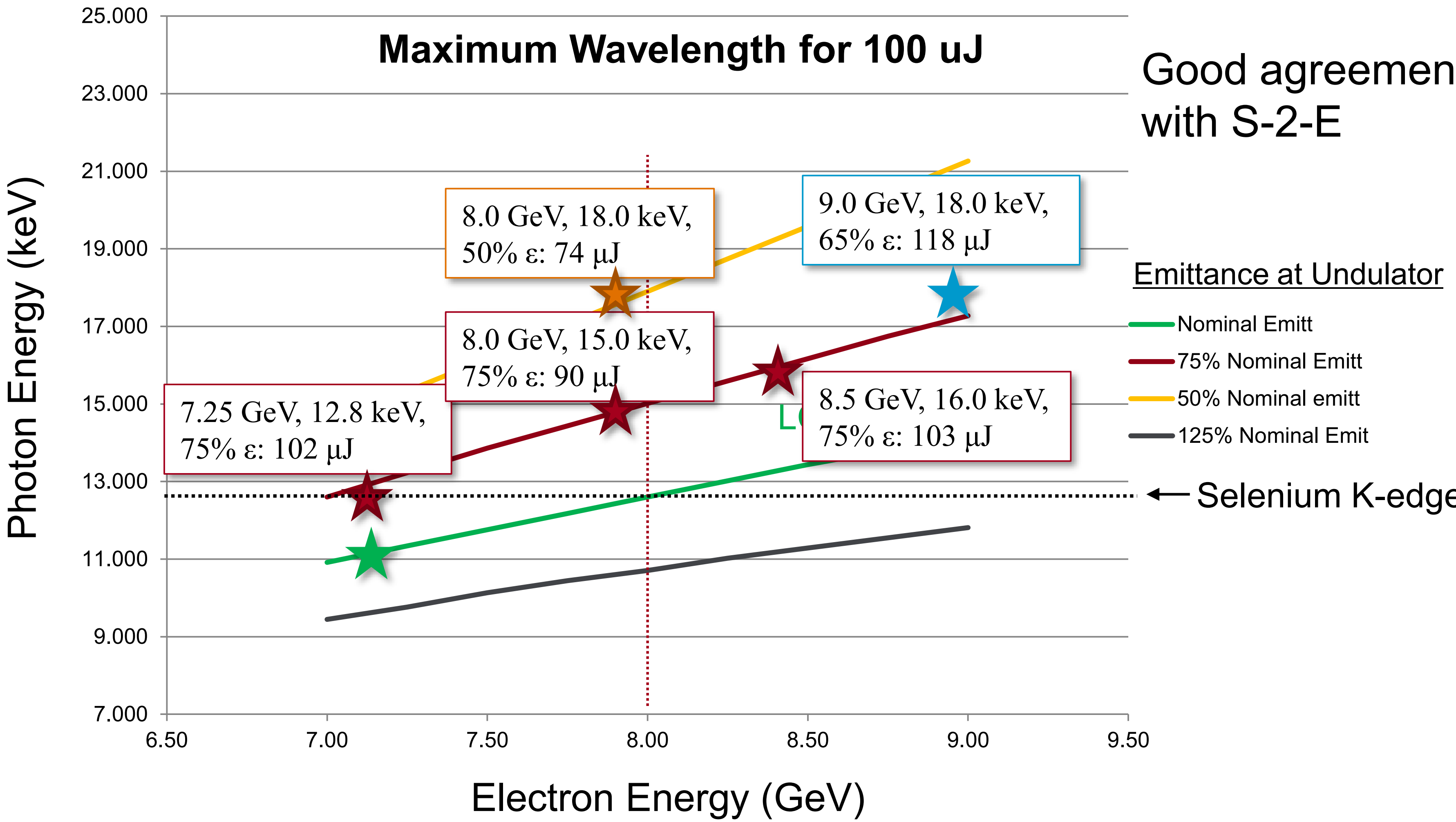

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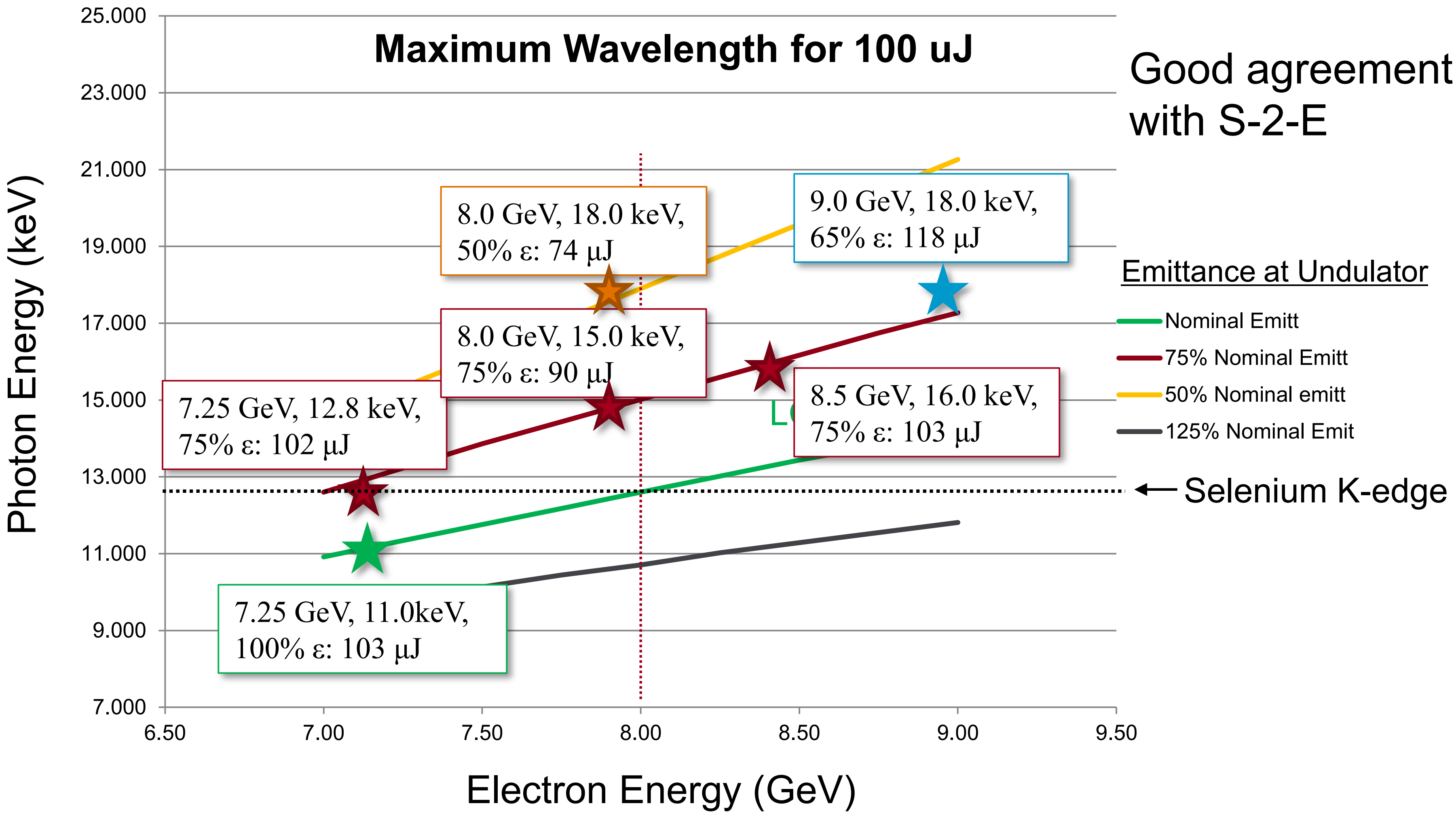

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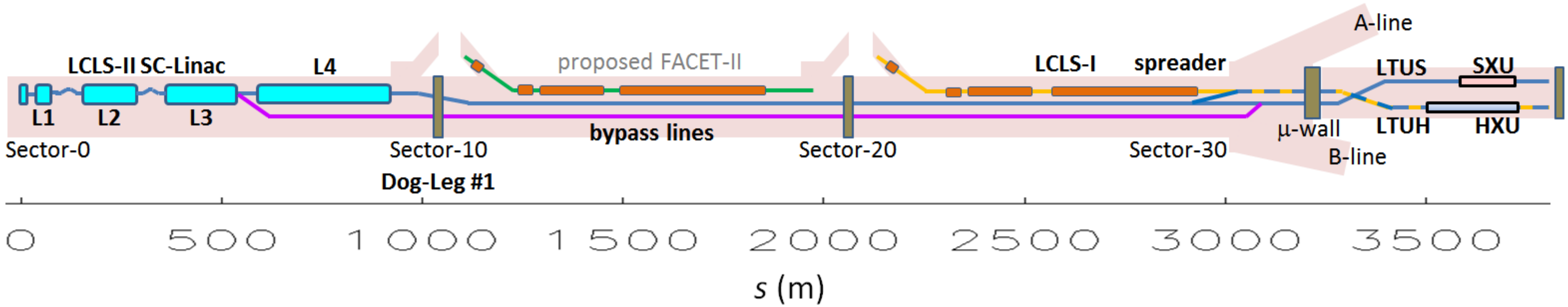
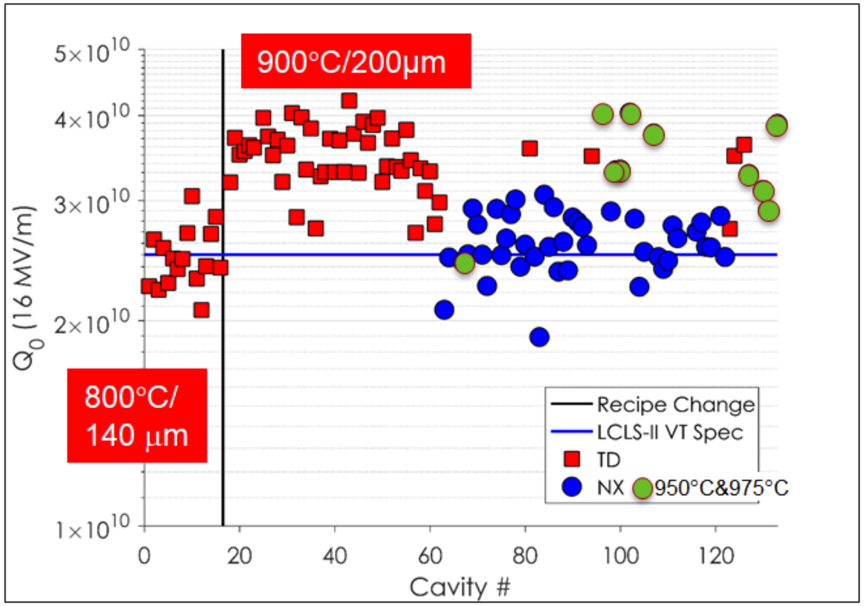
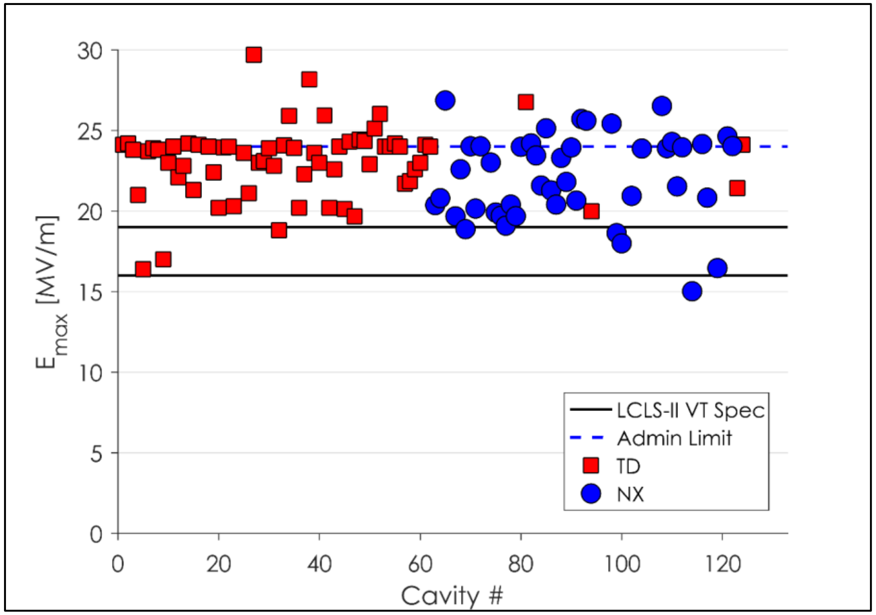
LCLS-II-HE Accelerator Configuration



- Add linac section L4 and increase gradient to reach 8 GeV
- Extract 3-4 GeV beam to maintain soft X-ray program
- Keep Sector-10 access clear for access and maintenance
  - Fit 20 new cryomodules before S10 access including LE extraction
- Utilize LCLS-II injector and bunch compressor configuration
  - No layout changes upstream of L3
- Add 2nd HXR Self-seeding for high rate operation

LCLS-II Cavity Performance



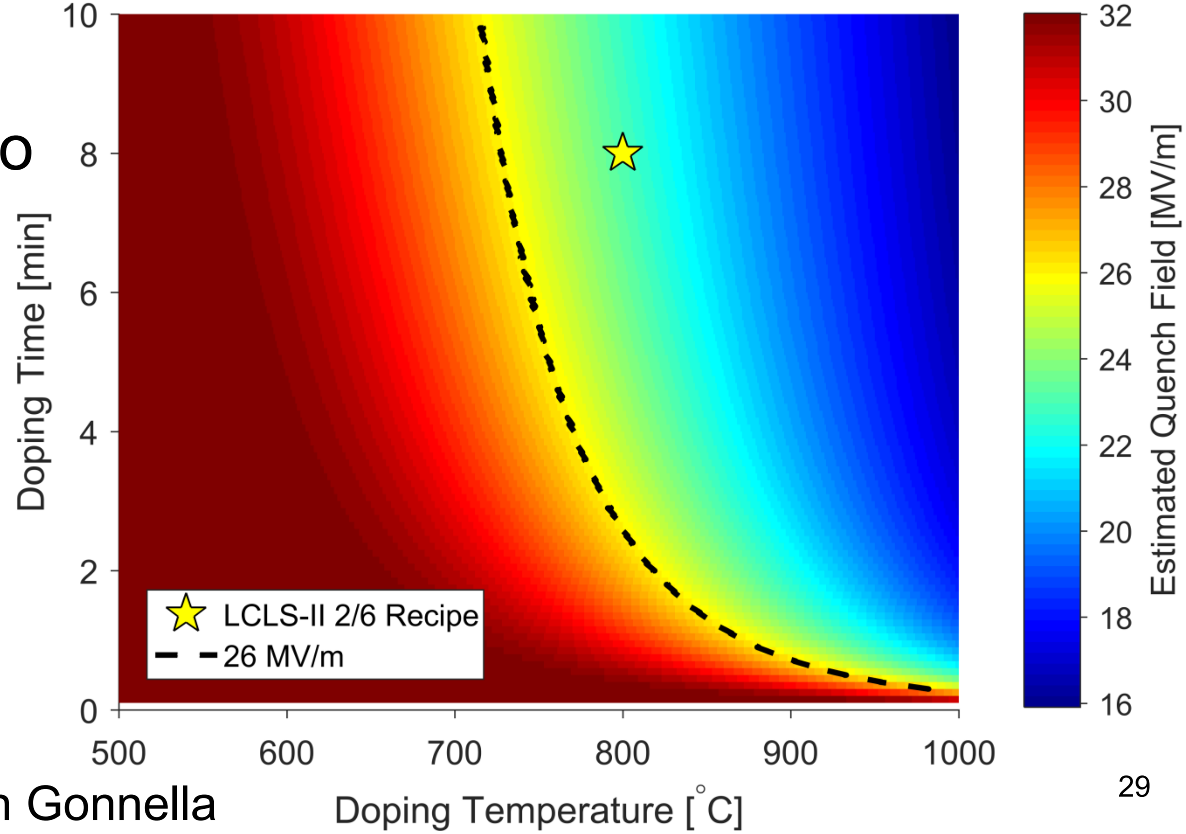


- RI/TD cavities in VT have average Q_0 of 3.4 x 10^{10} with ave. gradient ~23 MV/m (including 24 MV/m admin. testing limit)
- Working on translation into CM but others have seen ~15% gradient reduction, i.e. >19 MV/m, consistent with 1st LCLS-II CM
- More knowledge with ~20 CM tests within the next year

Improving LCLS-II Cavity Gradient

Q_0 consistently exceeds $3x10^{10}$ with many cavities being much higher ($3.4x10^{10}$ average) BUT more than 50% of cavities quench at or below 24 MV/m in VT (LCLS-II-HE spec is 24.5 MV/m)

→ Tweak N_2 doping to trade Q_0 for gradient



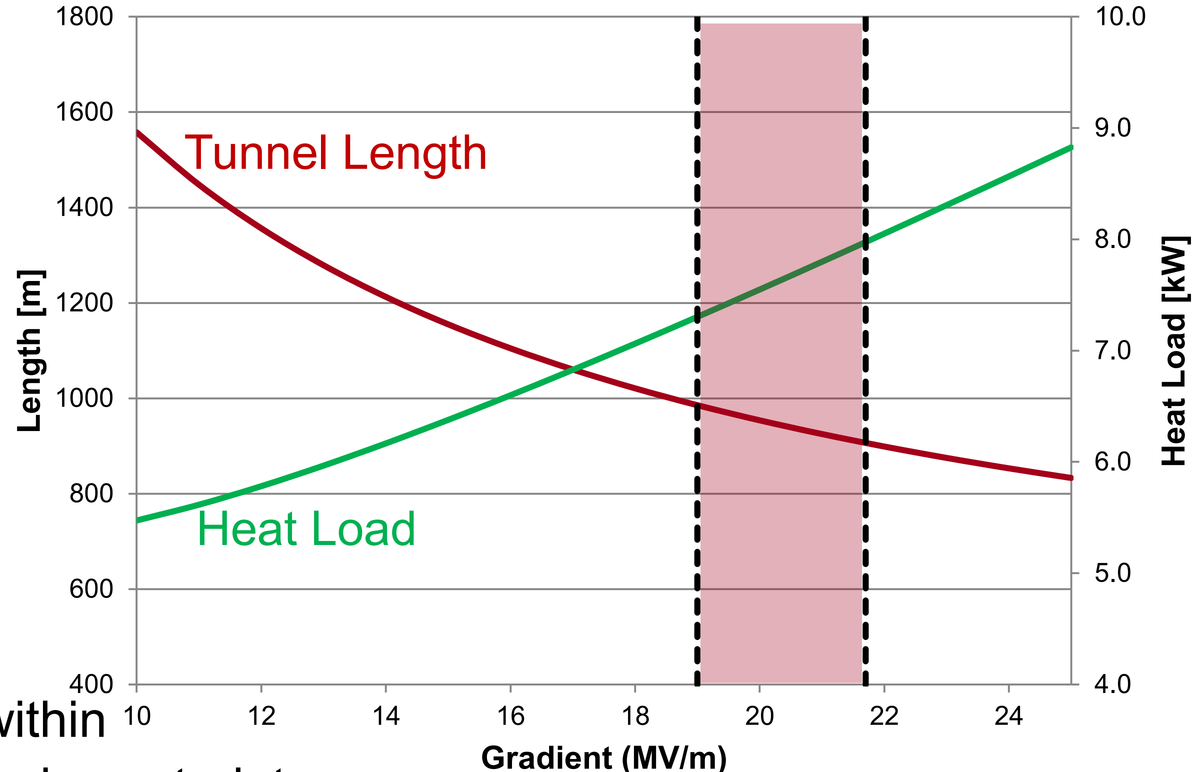
Achieving 8 GeV with LCLS-II Infrastructure

1 km linac tunnel and 8 kW 2K cooling

LCLS-II cavity Q_0's are exceeding 2.7×10^{10} goal
→ Extra cryo-cooling

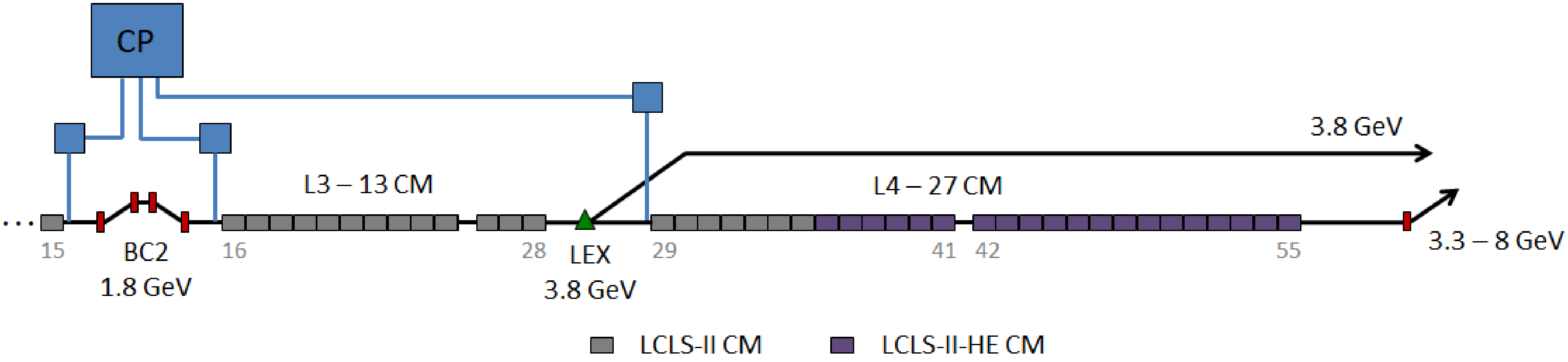
LCLS-II cleared ~1km of the SLAC tunnel but uses ~700 meters
→ Extra tunnel

An average gradient of 19 MV/m ~ 22 MV/m fits within cleared tunnel with cryoload constraints



Heat load is minimized at ~8 MV/m with 2+ km linac length but extra length will significantly increase cost

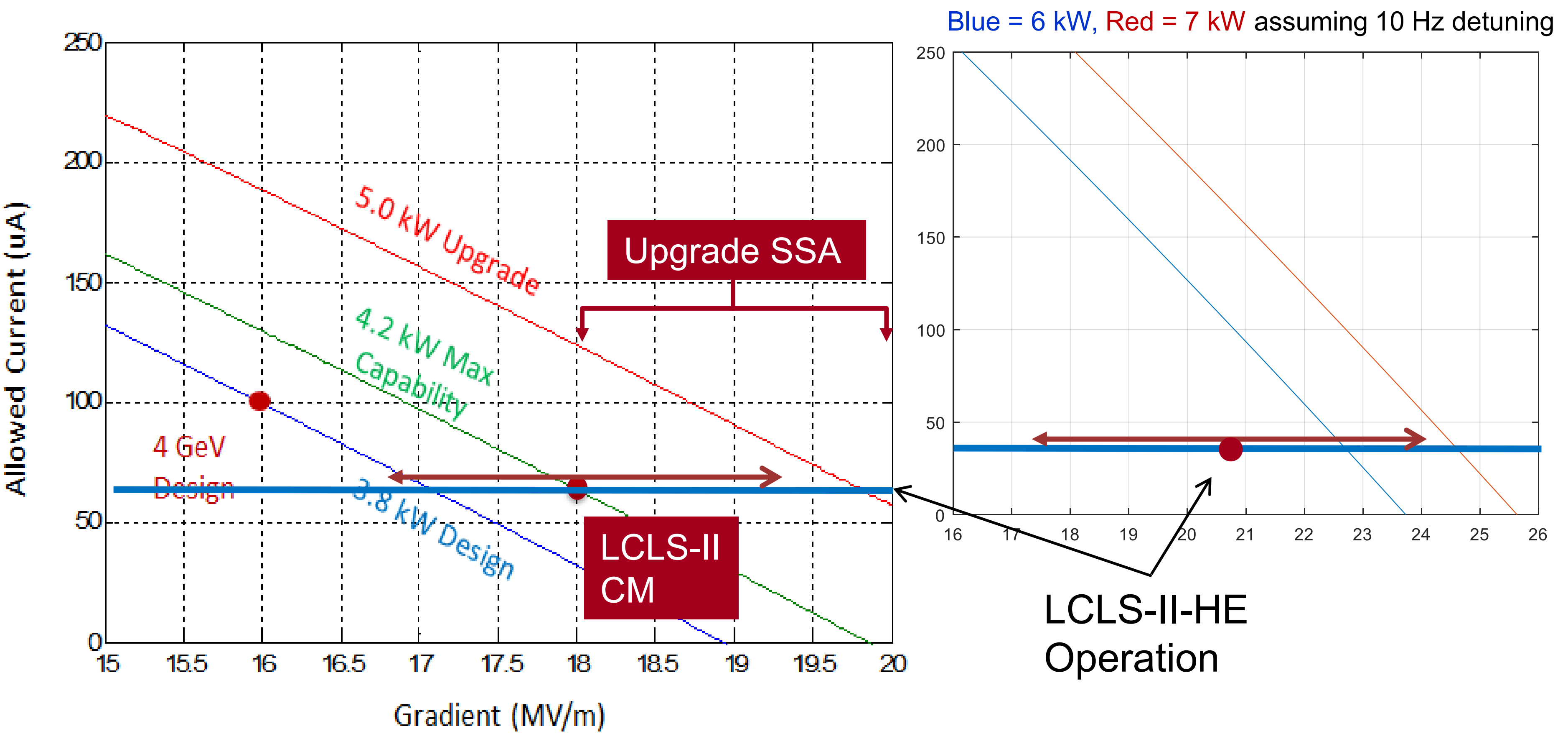
LCLS-II SRF Linac Modifications for LCLS-II-HE



- No layout changes up through middle of L3
- Move 7 LCLS-II CM from L3 40-meter downstream to create break for Low Energy Extraction (LEX) break
- Extract 3.8 GeV beam to 2nd bypass line in ~40-m space
- Add 20 new LCLS-II-HE CM in L4
- Use CP1 to cool L0 – L3 and CP2 to cool L4

LCLS-II-HE RF Power Upgrades

- Upgrade ~100 SSAs to 5 kW for operation at 18 MV/m ave.
- Install 160 new 7 kW SSAs for HE cryomodules at 20.8 MV/m



Gradient and Field Emission Risk Mitigation

Believe that LCLS-II gradient of 18 MV/m is likely reasonable but LCLS-II-HE gradient of 21 MV/m has risk – *will know more in a year*

1. Trade gradient in the LCLS-II-HE cryomodules for the LCLS-II cryomodules → small increase in cost due to additional RF source upgrades

2. The HXU period shortened to ~22 mm allowing for a *lower final beam energy* and an average gradient of 18 MV/m → reduces long wavelength performance

3. The injector emittance and linac brightness could be improved allowing for *lower final beam energy* and 18 MV/m

4. The SRF linac at 18 MV/m could be lengthened by 3 or more cryomodules → most costly (~20M$) but maintains capability

LCLS-II High Energy Upgrade

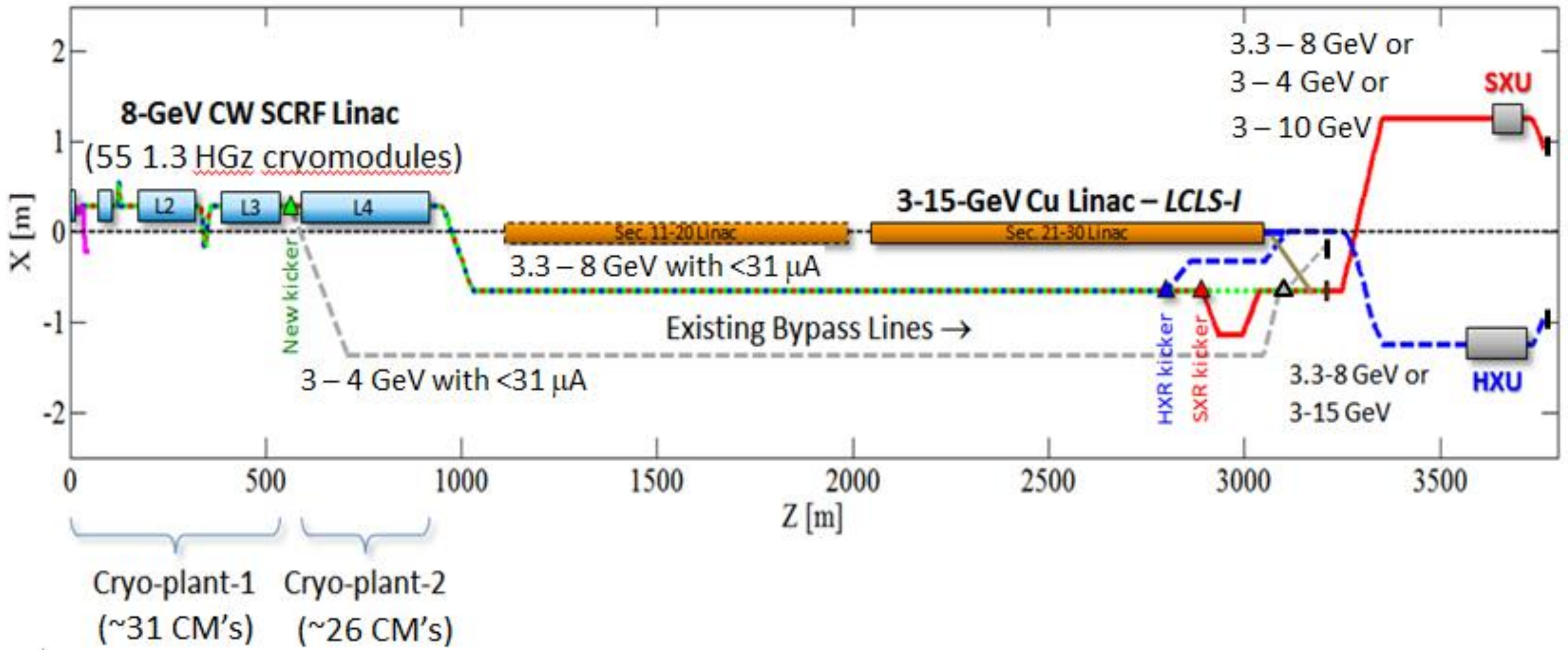
LCLS-II extension to go from 5 keV → 12.8 keV or more

Left space in the LCLS-II for additional cryomodules

→ Add 20 additional cryomodules and 2nd bypass

Three independent sources: CuRF 2-15 GeV, 120 Hz;

LCLS-II: 3-4 GeV, 31 μA; LCLS-II-HE: 3-8 GeV, 31 μA



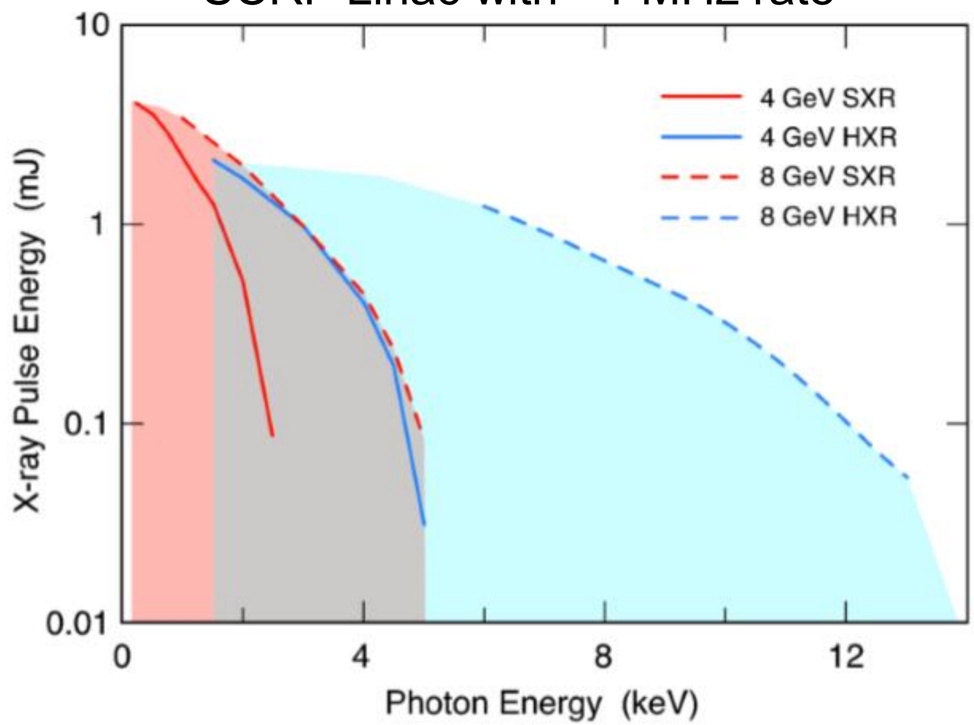
LCLS-II/LCLS-II-HE Accelerator Parameters

SCRF-Linac Parameters	LCLS-II	LCLS-II-HE	Unit
Final electron energy	3.3 - 4.0	3.3 - 8.0	GeV
Electron energy at L3/L4 extraction point	-	3.3 - 4.0	GeV
Electron Bunch Charge	0.01 – 0.30	0.01 – 0.30	nC
Max. bunch repetition rate	929	929	kHz
Average electron beam power in L2-L4	<0.25	<0.25	MW
Average electron power in BSY	<0.25	<0.375	MW
Max. avg. electron current in L0-L3	62	62	μA
Max. avg. electron current in L4	--	31	μA
Max. avg. electron current in Low Energy Extraction line	--	31	μA
Total Number of 1.3-GHz Cryomodules	35	55	-
Total Number of 3.9-GHz Cryomodules	2	2	-
Installed 1.3 GHz RF Voltage	4.65	8.64	GeV
Active SCRF accelerator length	296	462	m
1.3 GHz Cryomodules in L0, L1, L2, L3	1, 2, 12, 20	1, 2, 12, 13	-
1.3 GHz Cryomodules in L4	--	27	-
RF Overhead (spare cavities)	6.1	4.1	%
Mean RF Gradient in powered cavities: L0-L1	< 16.0	< 16.0	MV/m
Mean RF Gradient in powered cavities: L2-L3	< 16.0	18.0	MV/m
Mean RF Gradient in powered LCLS-II cavities: L4	--	18.0	MV/m
Mean RF Gradient in powered LCLS-II-HE cavities: L4	--	20.8	MV/m
Installed 2K cryo-capability	8.0	8.0	kW
Expected heat load at max energy: L0-L3	3.7	3.5	kW
Expected heat load at max energy: L4	-	3.8	kW

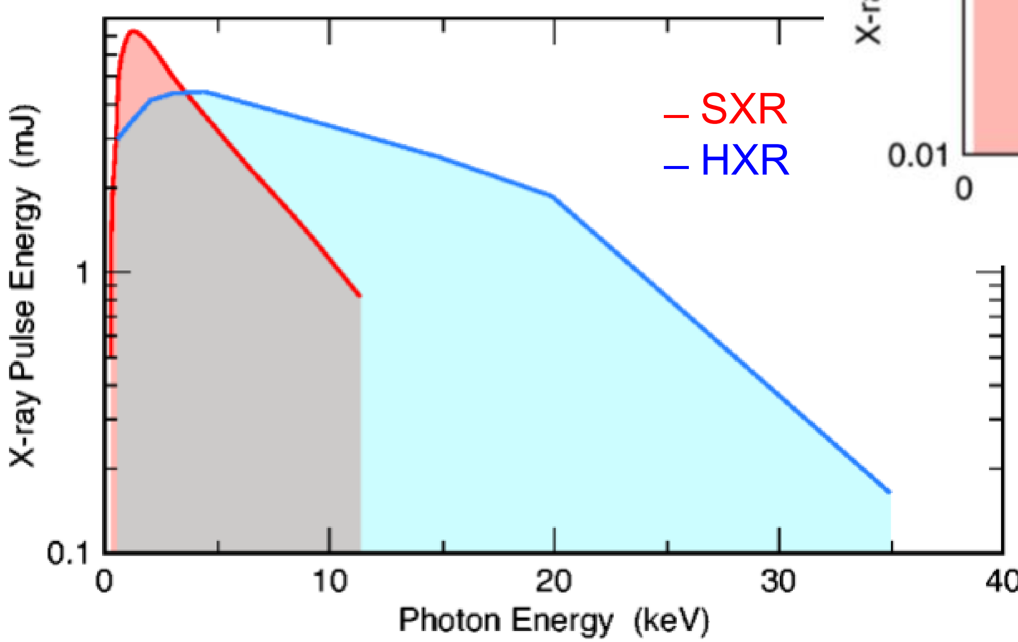
LCLS-II-HE X-ray Performance

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

SCRF Linac with ~1 MHz rate



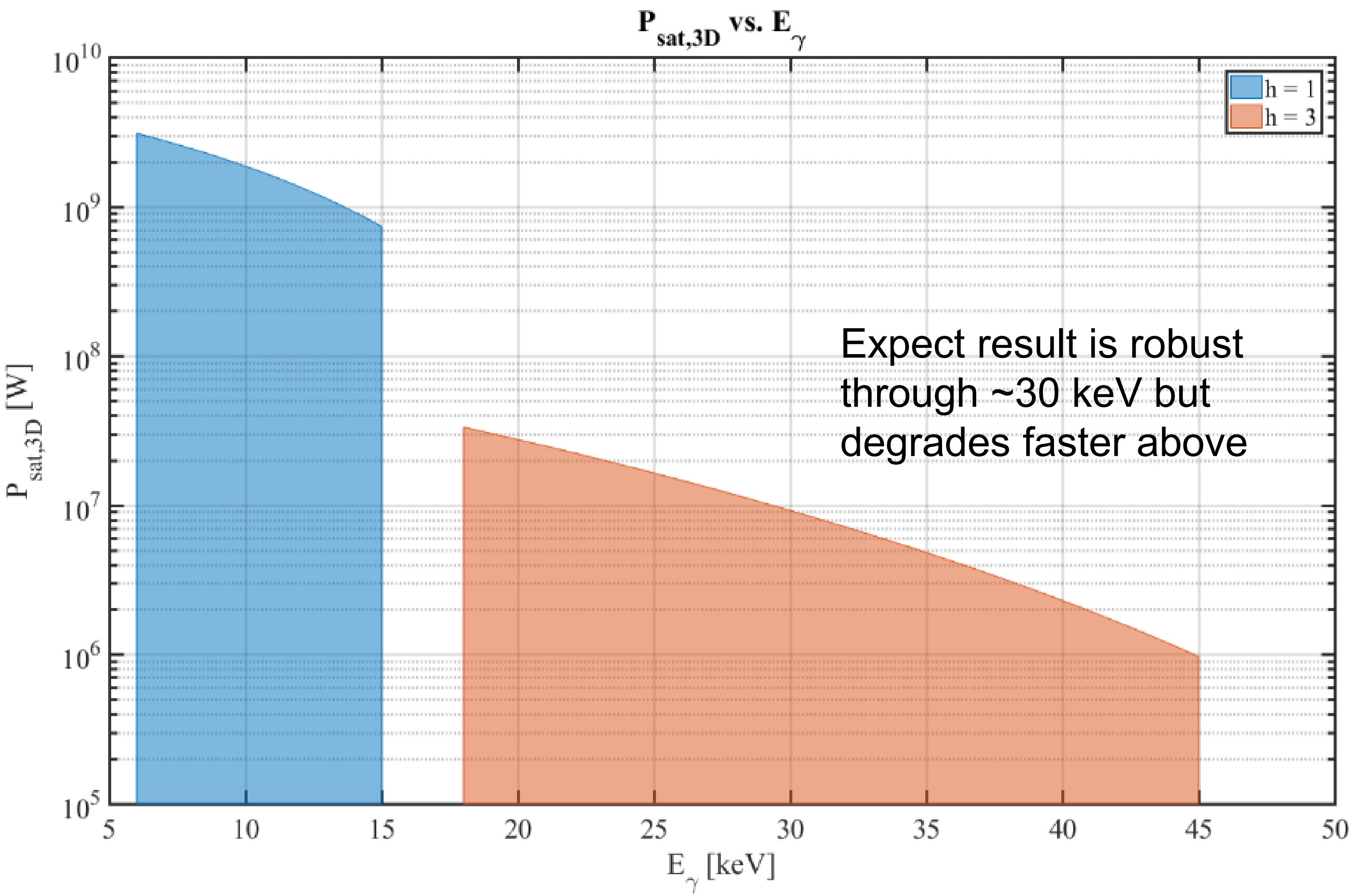
CuRF Linac with 120 Hz rate



Undulators will also produce %-level 3rd harmonic radiation out to ~30 keV

Analytic Estimate of Power at the 3rd Harmonic

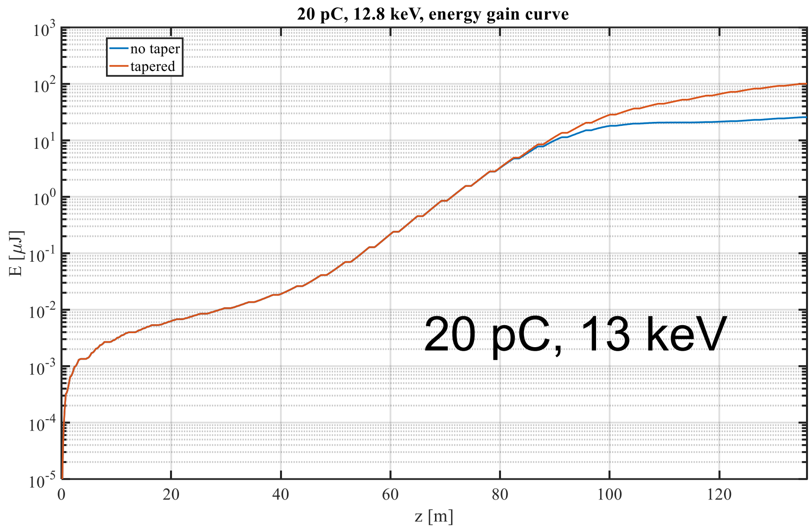
Without post-saturation taper

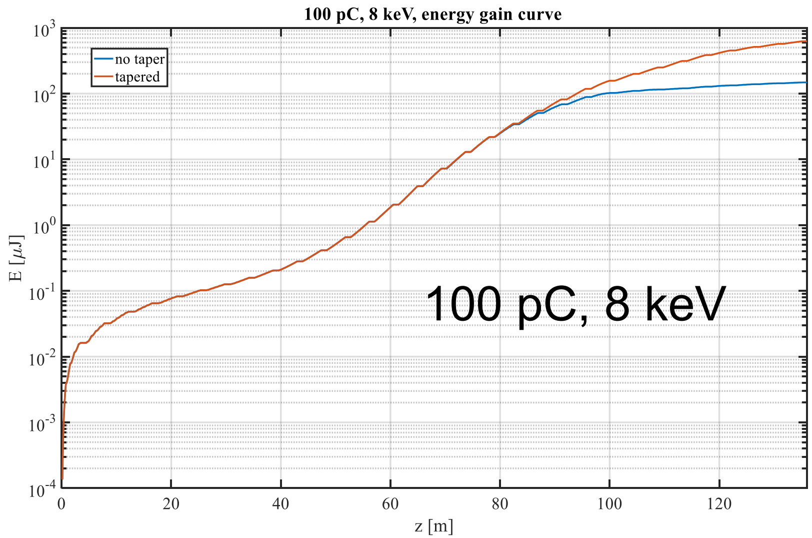


Start-2-End Simulation Results

Examples at 8 and 13 keV

Fundamental Energy	8 keV	13 keV	Units
Maximum Repetition Rate	929 (300)	929 (300)	kHz
FW Pulse Duration	30 (105)	30 (102)	fs
Total energy/pulse	235 (625)	108 (57)	µJ
Source point relative to end of undulator	25 (19)	24 (21)	m
First Harmonic			
Photons per FEL pulse	0.18 (0.49)	0.05 (0.028)	10^{12}
Relative FWHM Bandwidth	0.05 (0.09)	0.06(0.1)	%
FWHM Source Size	36 (37)	26 (22)	μm
FWHM Source Divergence	2.4 (2.0)	1.8 (1.8)	μrad
Third Harmonic			
Photons per FEL pulse	0.15 (0.29)	0.016 (0.005)	10^{10}
Relative FWHM Bandwidth	0.05 (0.09)	0.06 (0.1)	%
FWHM Source Size	<36 (<37)	<26 (<22)	μm
FWHM Source Divergence	<2.4 (<2.0)	<1.8 (<1.8)	μrad





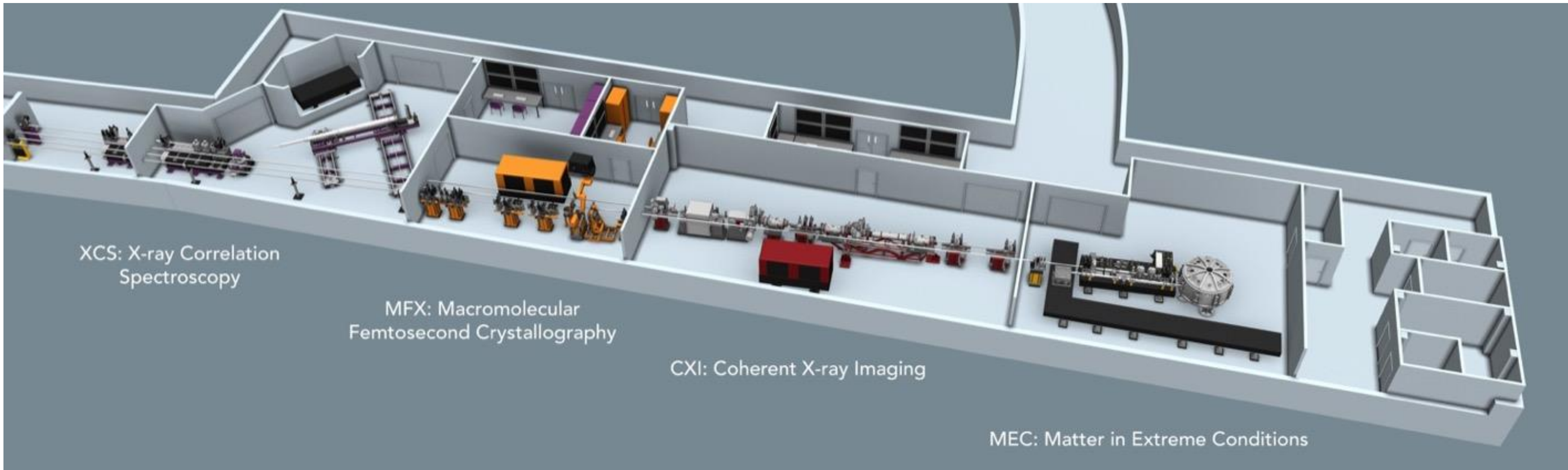
LCLS-II-HE Operating Modes

Spreader kickers allow flexible bunch patterns to SXR and HXR

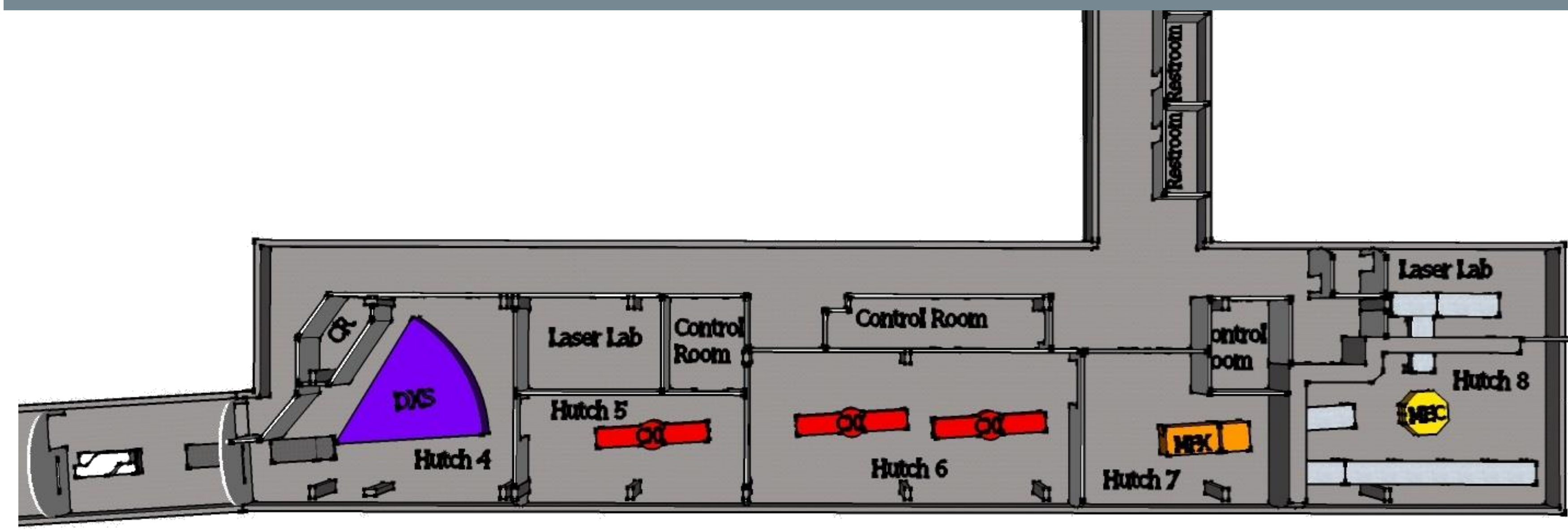
SXR choices	HXR SC-Linac options	or	HXR Cu-Linac options
3.8 GeV **< 31 μA e-** **SC-Linac** (< 1 MHz) **0.1-1.3 keV with >> 20 W**			
3-8 GeV **< 31 μA e-** **SC-Linac** (< 1 MHz) **0.2-5 keV with >> 20 W**	**3-8 GeV** **< 31 μA e-** **SC-Linac** (< 1 MHz) **1-13 keV with >20 W**	or	**3-15 GeV** (3-10 GeV if CuRF→SXR) (≤ 120Hz) **1-25 keV with mJ pulses**
3-10 GeV **Cu-Linac** (≤ 120Hz) **0.1-10 keV with mJ pulses**			

Reconfigure LCLS X-ray hutches for LCLS-II-HE

Current



LCLS-II-HE



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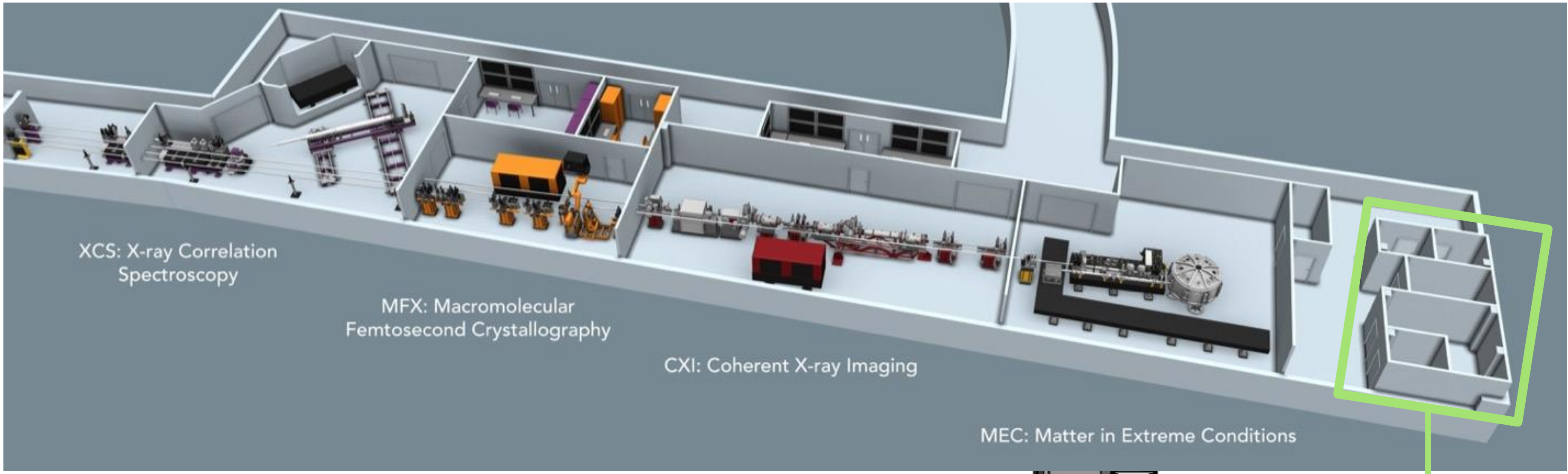
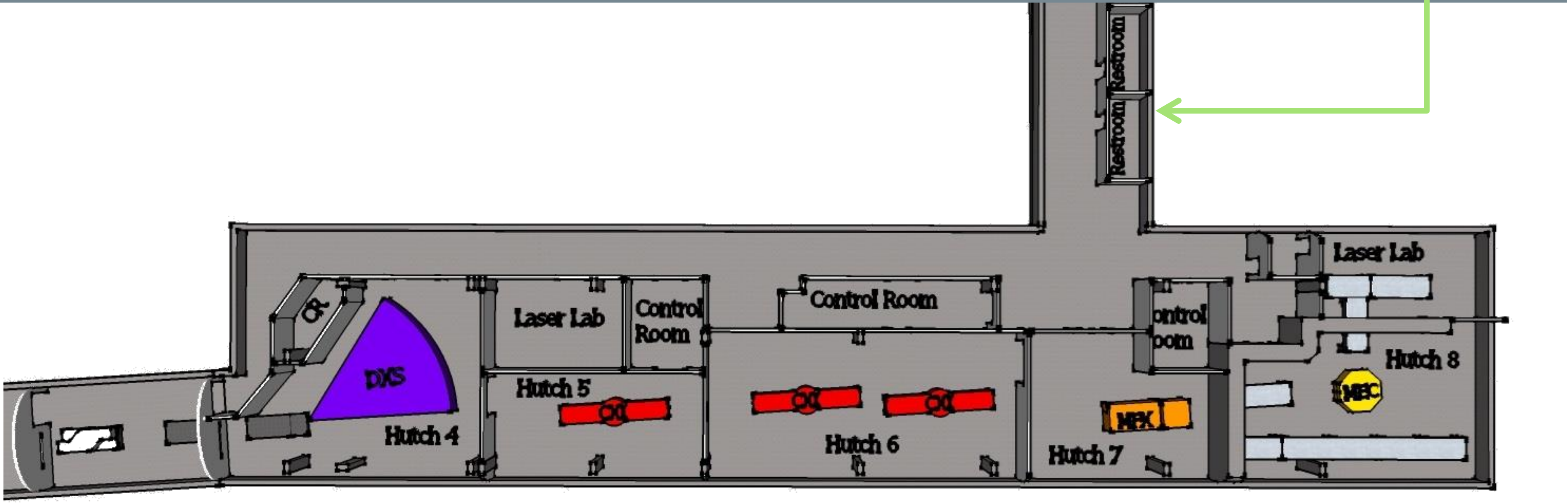


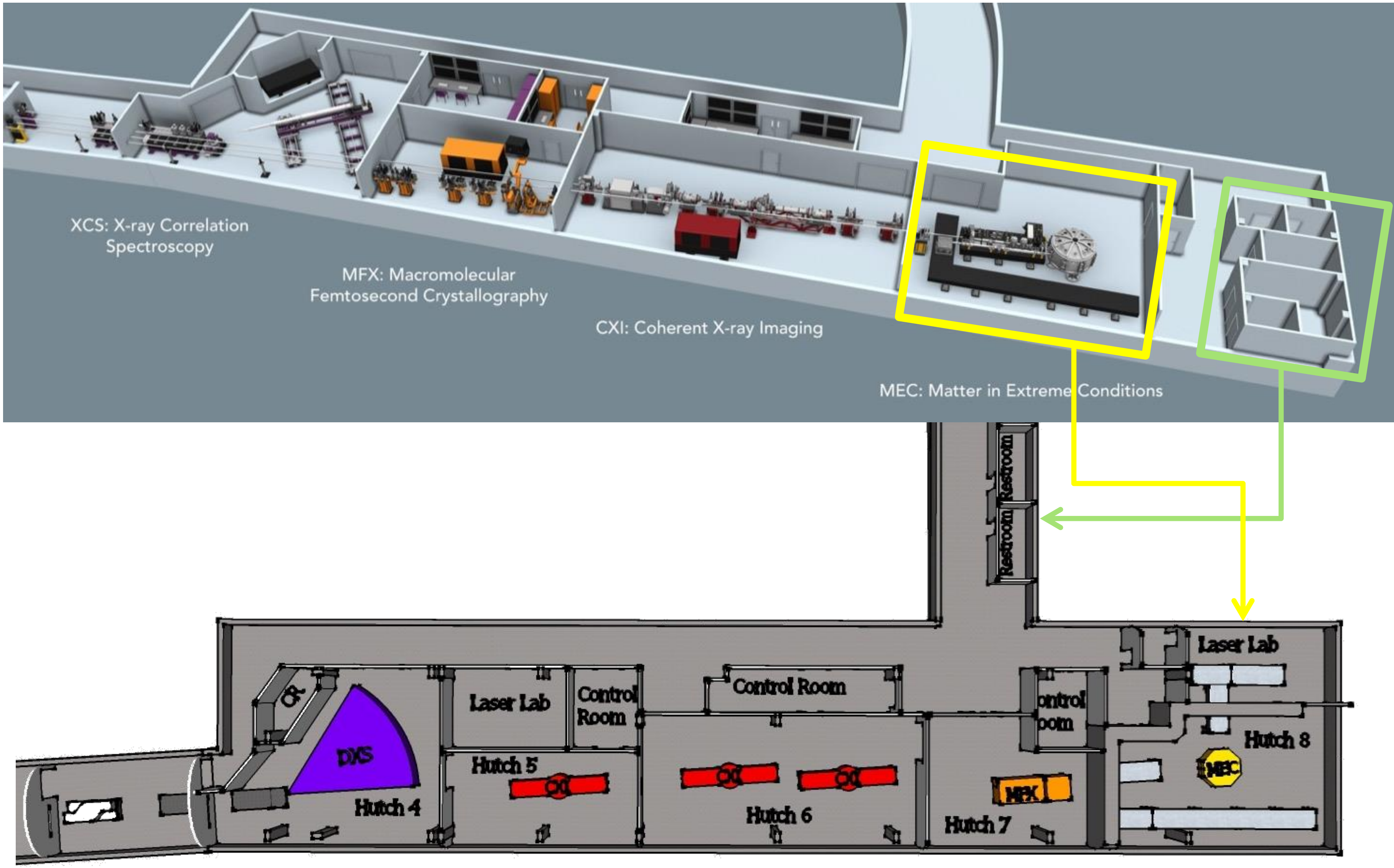
LCLS-II-HE



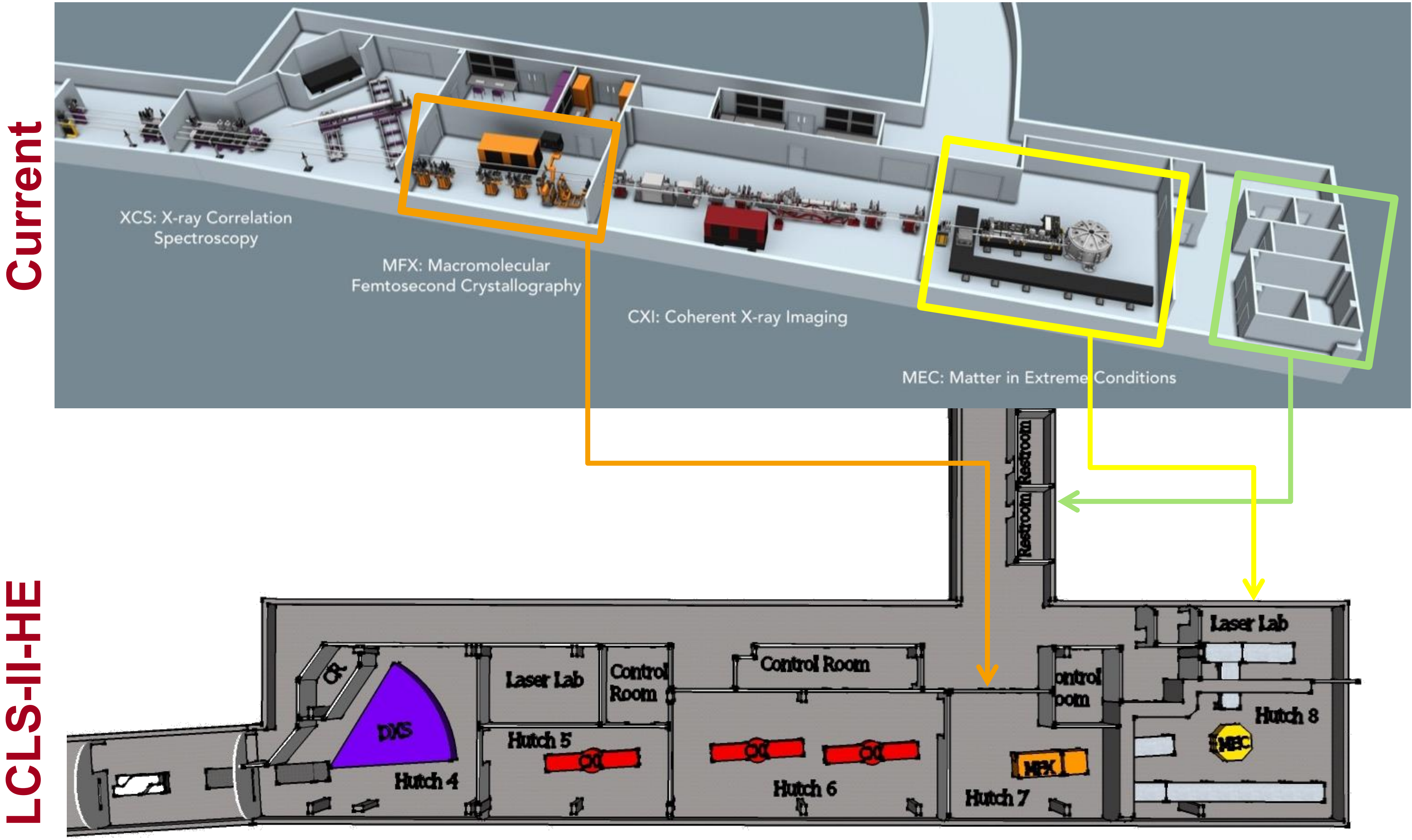
Reconfigure LCLS X-ray hutches for LCLS-II-HE

Current

LCLS-II-HE



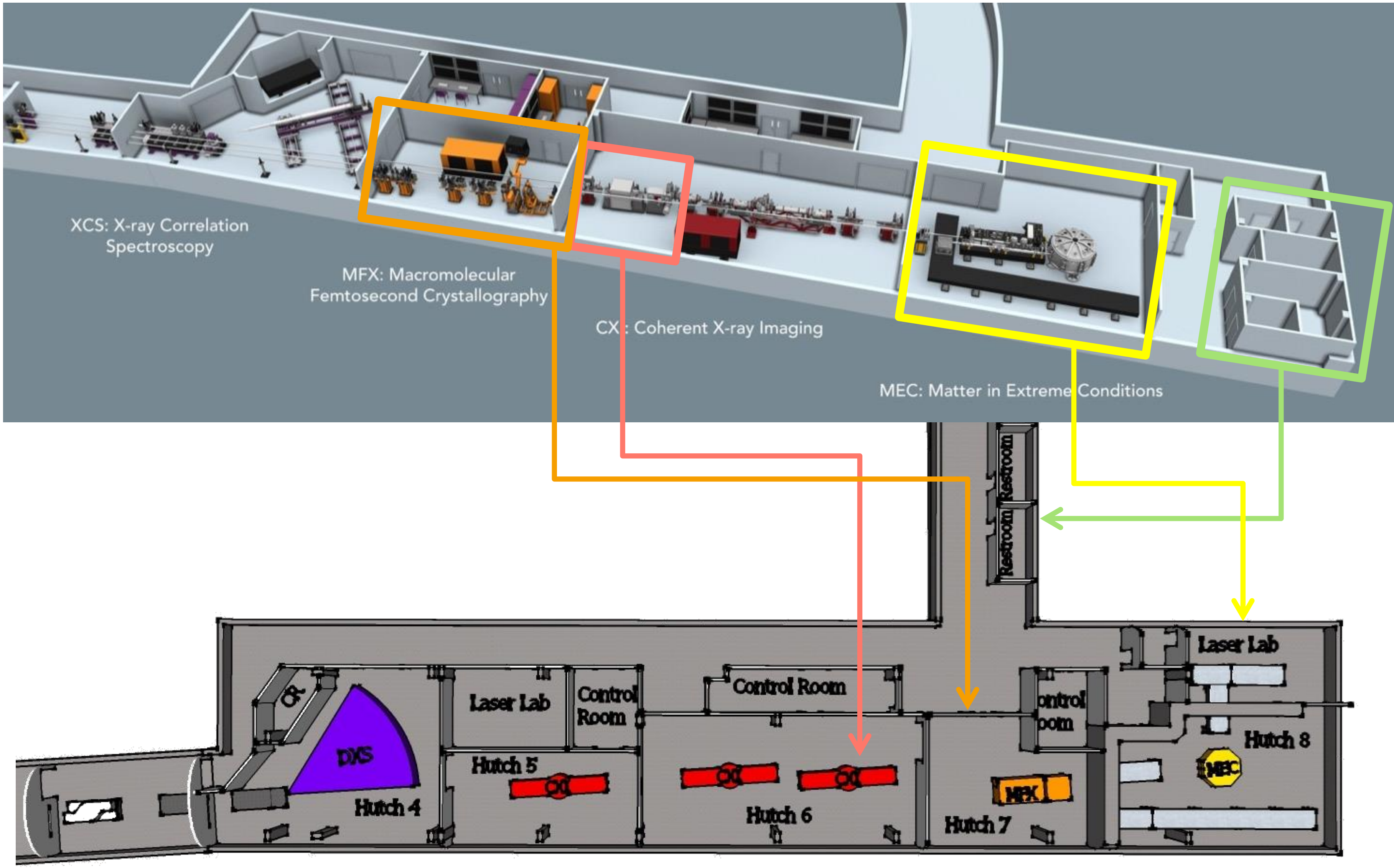
Reconfigure LCLS X-ray hutches for LCLS-II-HE



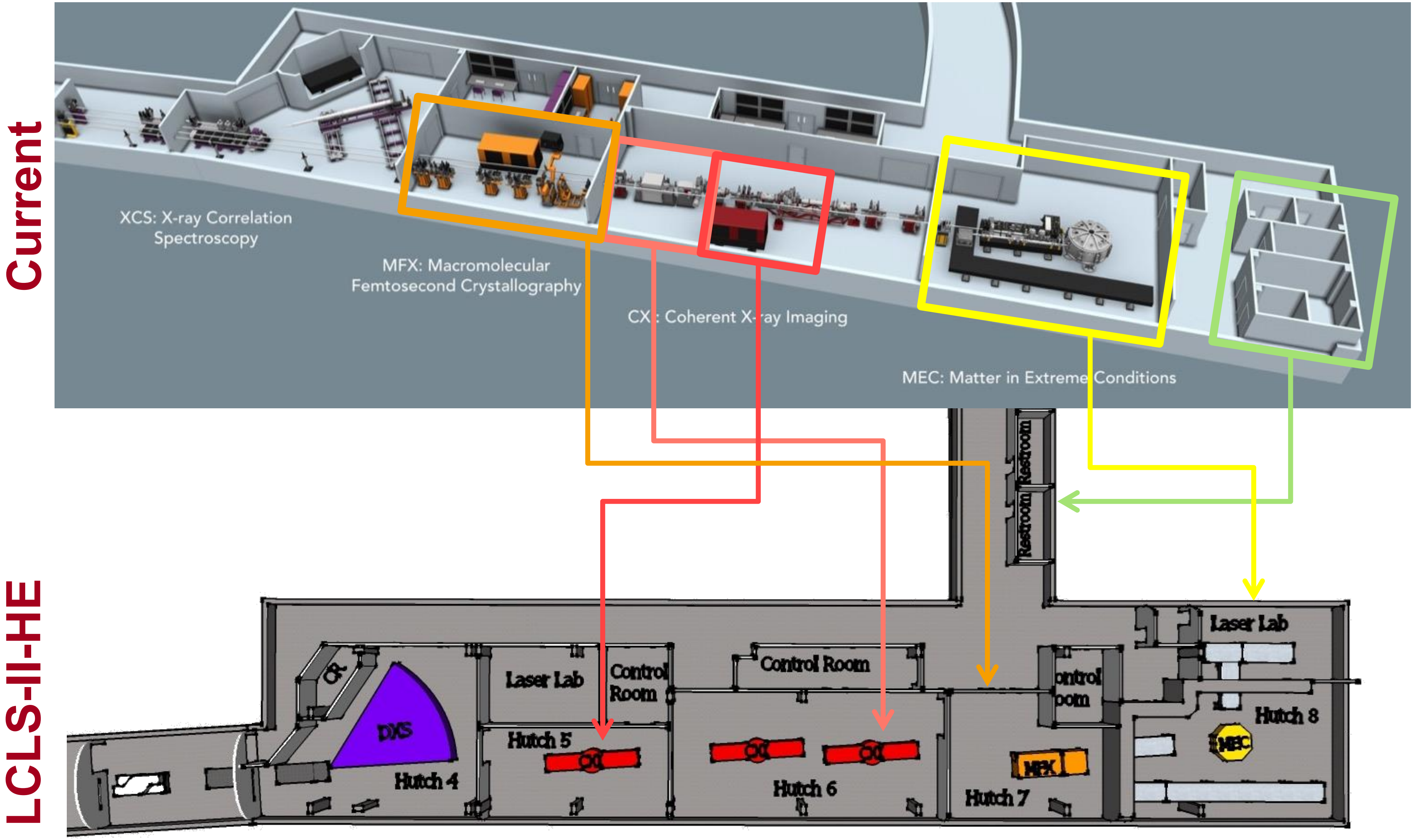
Reconfigure LCLS X-ray hutches for LCLS-II-HE

Current

LCLS-II-HE



Reconfigure LCLS X-ray hutches for LCLS-II-HE



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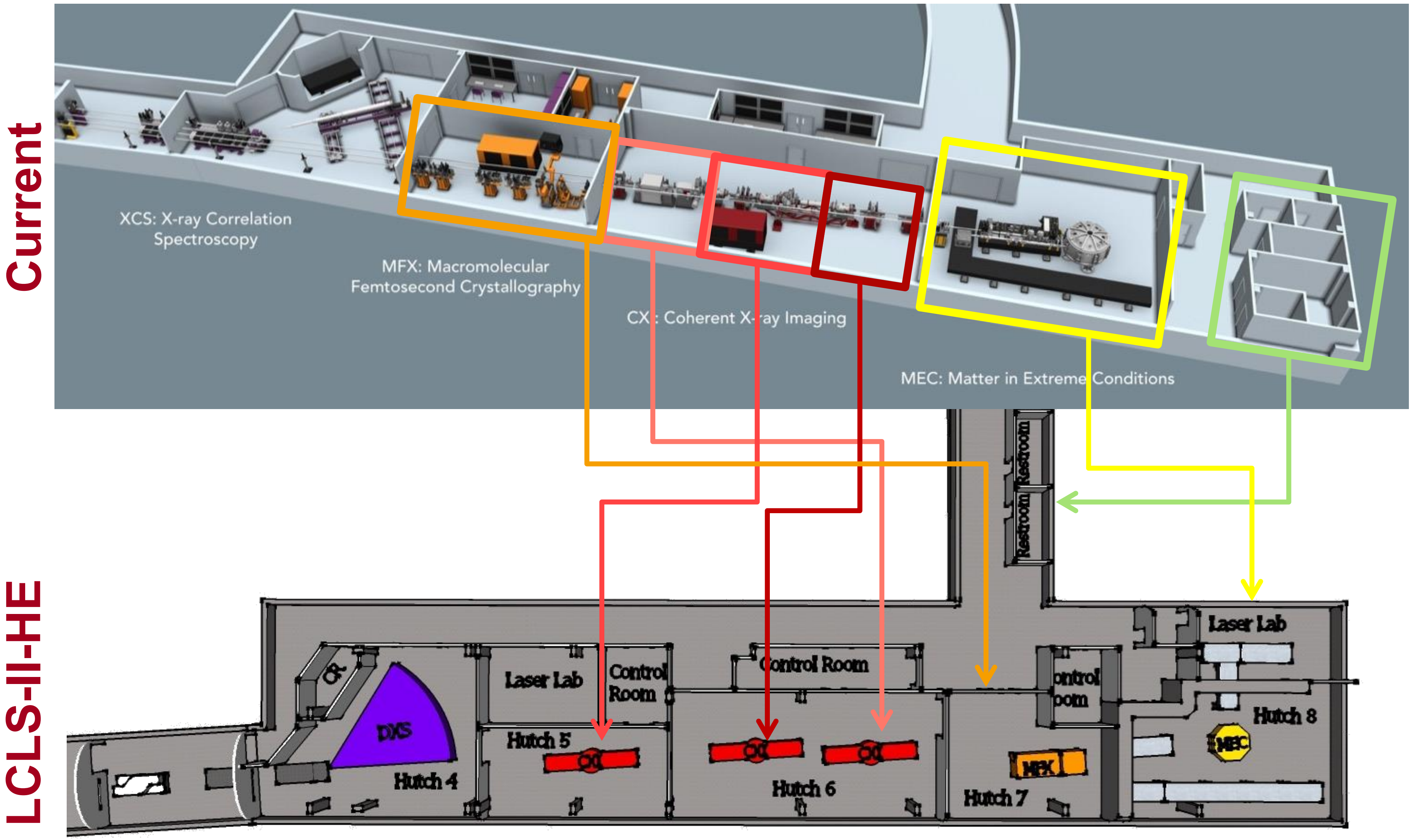
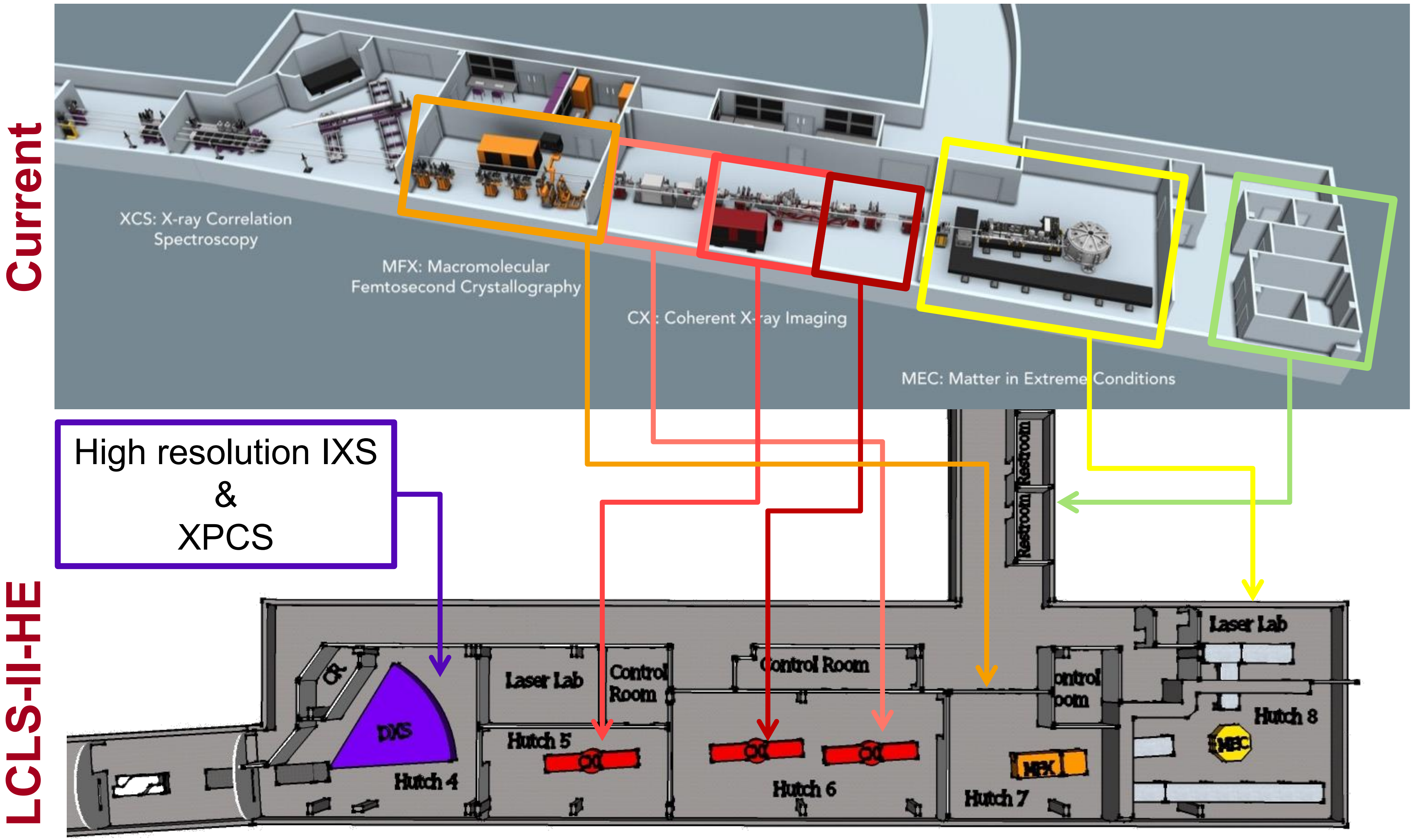
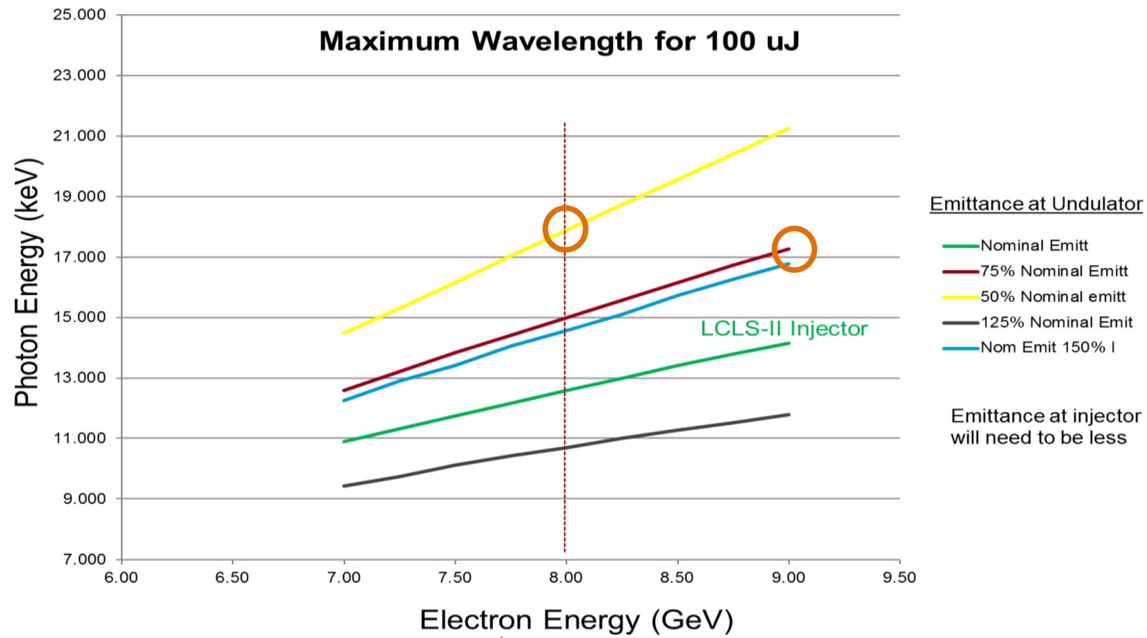


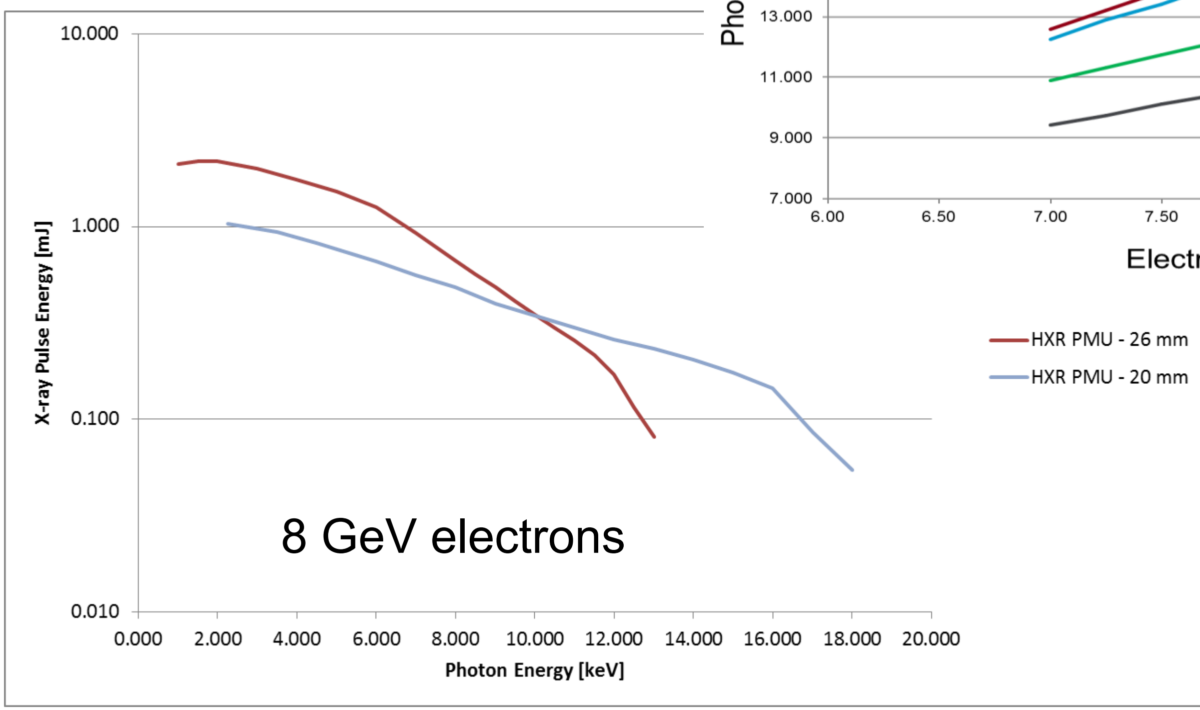
Reconfigure LCLS X-ray hutches for LCLS-II-HE



Photon Energy Upgrade Options

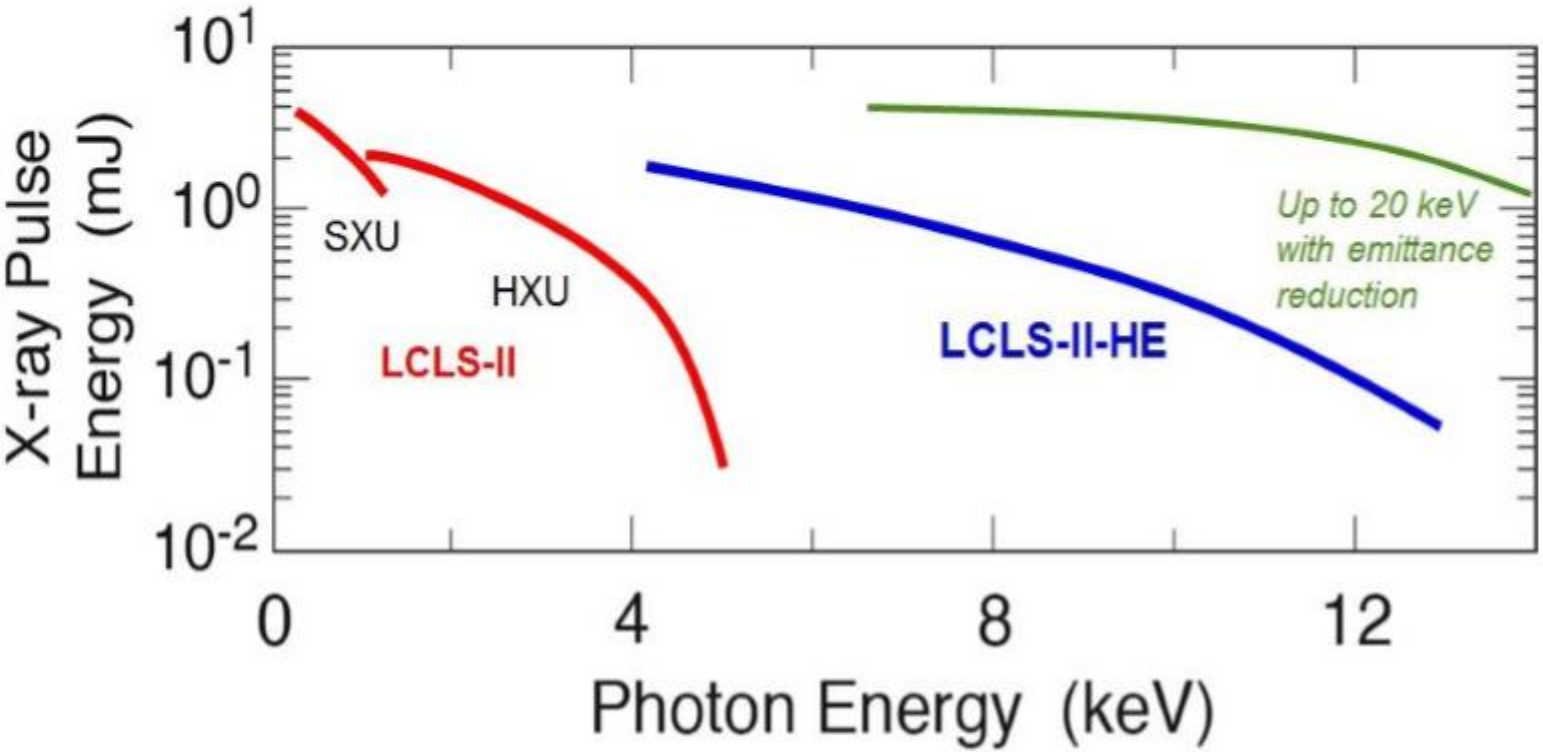
Reduced emittance, higher peak current, and/or higher energy can enable 17 ~ 18 keV. Shorter undulator period can do similar.





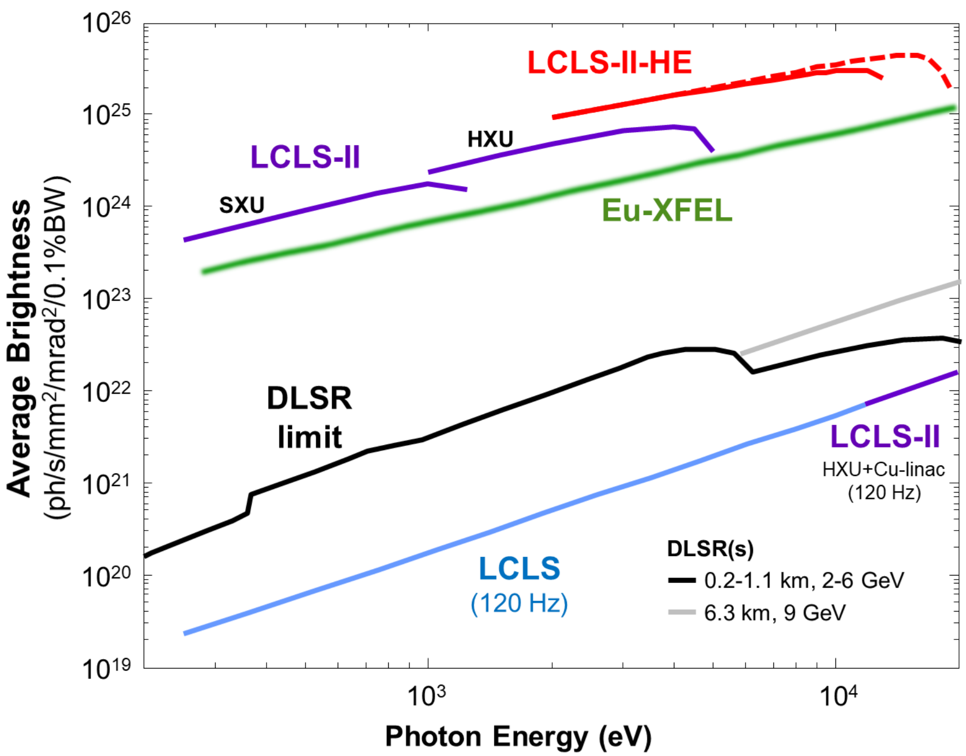
LCLS-II-HE X-ray Pulse Energy

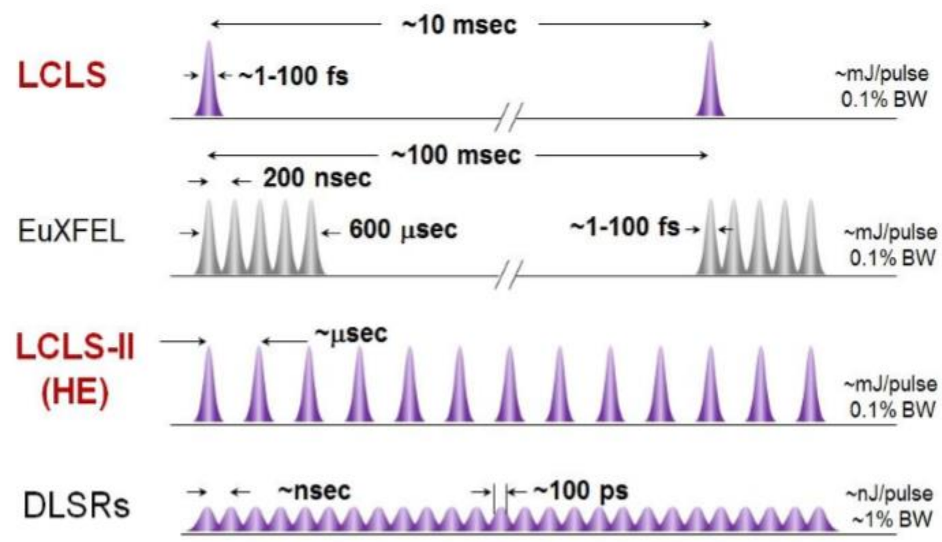
Expected performance, including post-saturation taper, with improved injector is illustrated in green



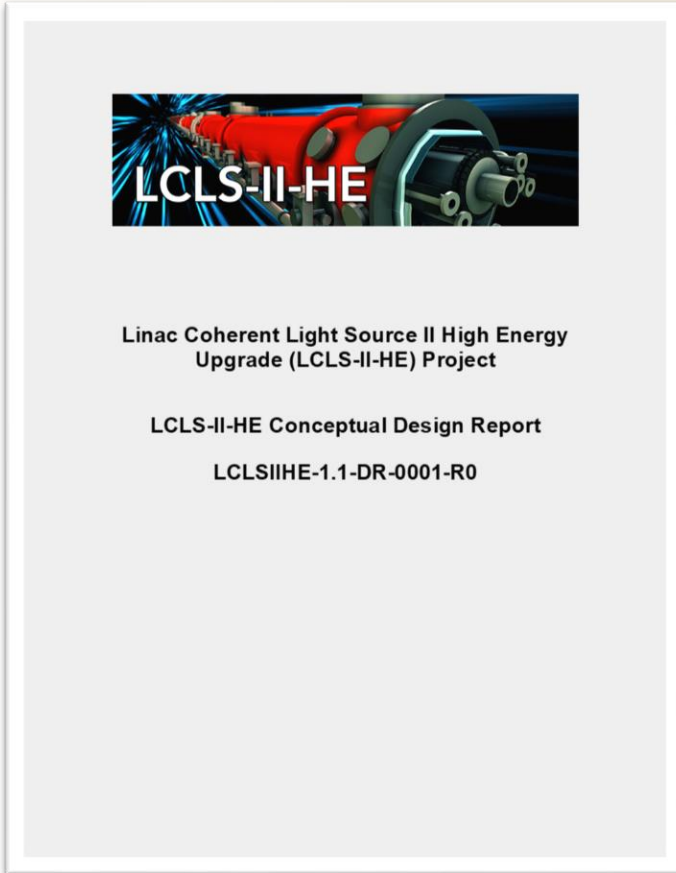
LCLS-II-HE Brightness

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





LCLS-II-HE Conceptual Design Report


LCLS-II-HE

Linac Coherent Light Source II High Energy Upgrade (LCLS-II-HE) Project

LCLS-II-HE Conceptual Design Report

LCLSIIHE-1.1-DR-0001-R0

Chapter	Title
	Preface
	Introduction
1	Project Summary, Background, & Mission Need
2	Scientific Opportunities
3	Project Overview
4	Accelerator Parameters & FEL Performance
5	LCLS-II-HE FEL Layout
6	SRF Linac Systems
7	Electron Transport
8	Photon Transport and Diagnostics
9	Experimental Instruments
10	Controls and Safety Systems
11	Data Systems
12	Infrastructure and Facilities
13	Radialogical Considerations
14	Environment, Safety, Health
15	Upgrade Opportunities
App. A	LCLS-II-HE Key Parameters

>30 SLAC staff members contributed to the CDR.

https://slacspace.slac.stanford.edu/sites/reviews/lclsiihe/cdr_ch/LCLS-II-HE CDR Sept 24.pdf

External CDR Review – Oct. 27, 2017

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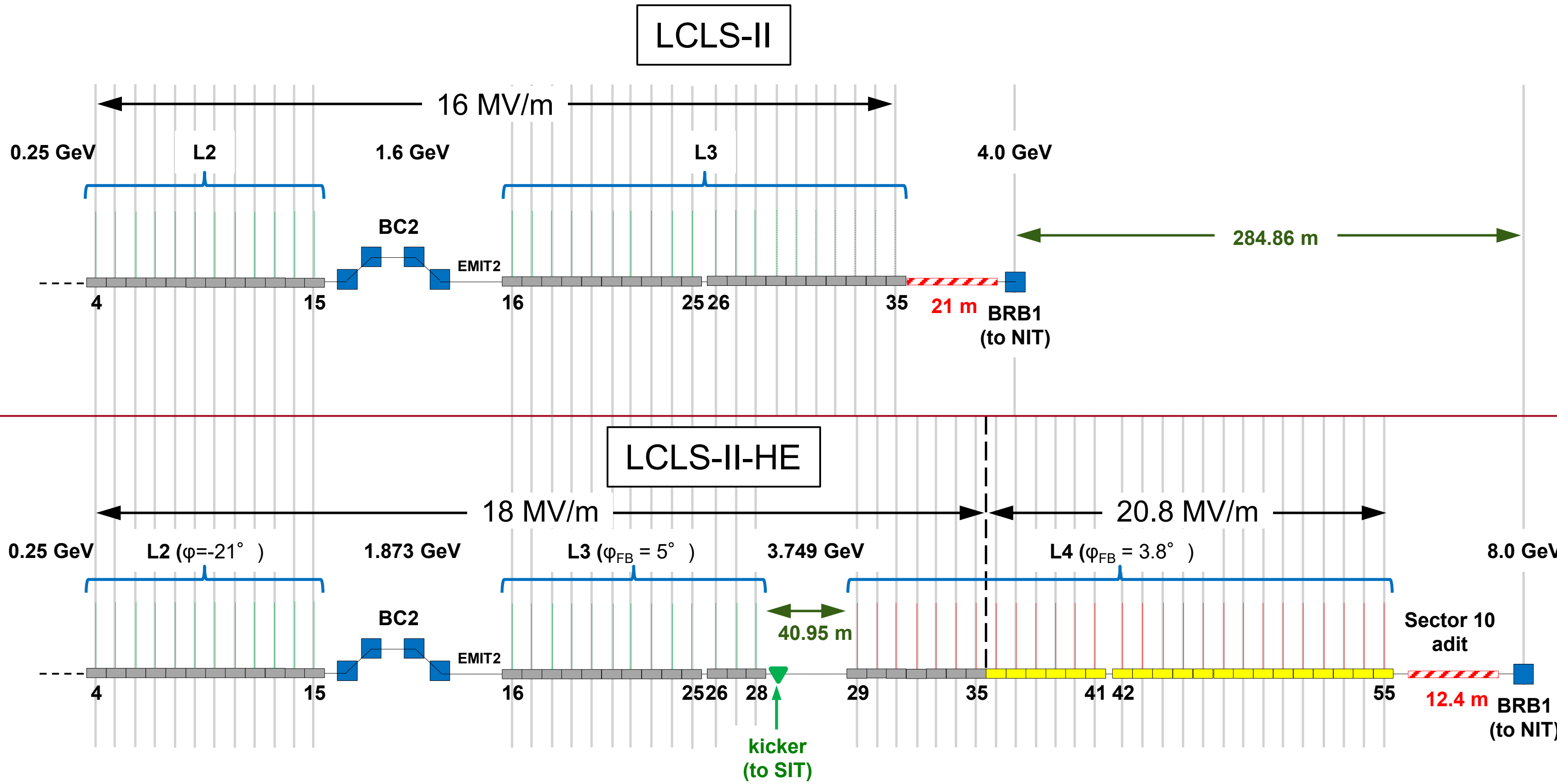
Summary

- 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

Evolution of superconducting linac layouts



LCLS-II waveguide run designs:
- solid green = no change for HE
- dashed green = will not be used for HE
- red = new design required for HE

accelerating gradients:
- 18.0 MV/m includes 3% overhead
- 20.8 MV/m includes 6% overhead

note: not to scale