LCLS-II SCRF start-to-end simulations and global optimization as of September 2016

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Abstract

This technical note details the status of the LCLS-II global FEL optimizations and start-to-end simulations as of September 2016 and is intended to update the previous studies presented in LCLS-II TN-15-33. All FEL simulations use the electron beam distributions from the April 2016 IMPACT start-to-undulator release.

10/06/2021 Update:

- 1. Added authors Yuantao Ding and Heinz-Dieter Nuhn who helped evaluate the FEL performance from an electron beam having and energy of 4.5 GeV.
- 2. Added slides 28-30 detailing the 4.5 GeV electron beam energy driven FEL performance estimates.

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1 Introduction

The start-to-end modeling and optimization of the LCLS-II free-electron laser from the cathode through the undulator using high fidelity numerical particle simulations is crucial for evaluating the expected FEL performance. In addition, this modeling has been extremely useful in identifying, understanding, and mitigating a number of potential hazards that can adversely affect the FEL performance. The presentation slides detailing the LCLS-II global optimization procedure and results given to the LCLS-II accelerator physics group in September of 2016 act as a basis for this technical note and are included here. Comments specific to the slide content are included below.

2 Slide Content and Comments

- Slide 1: Title slide
 - The presentation was made by G. Marcus but includes a significant amount of work by J. Qiang. J. Qiang was responsible for evaluating the LCLS-II cathode to undulator performance. The electron beams produced through detailed optimizations were then handed off to G. Marcus for evaluation in the FEL. The FEL light was then evaluated after taper optimizations in support of the LCLS-II photon systems group.
- Slide 2: Outline
 - Three charge distributions spanning the LCLC-II operational parameter space were optimized and used to evaluate the FEL performance. The optimized charge distributions are reviewed along with the optimization procedure. Tables of parameters are given later.
 - An example is given illustrating how the FEL pulse is characterized both longitudinally and transversely for analysis by the photon systems group.
 - Global SASE performance tables are presented later.
- Slide 3: Multiobjective optimization of cathode-to-undulator performance for 20 pC charge (2)
 - Previously, optimization of the linac and compression settings in the presence of 3-D space charge (and other collective effects) was done by parameter scans and manual tuning.
 - Global optimization using stochastic, population-based evolutionary methods has recently become widespread in the accelerator community through the use of codes such as NSGA-II and SPEA-2.
 - Differential evolution is a population-based evolutionary algorithm developed to optimize real parameter, real valued functions that is easy to implement and

extend to multiple processors, and has been shown to be effective on a large range of classic optimization benchmark problems.

- Adapted to treat multiobjective optimization and integrated with the IMPACT suite using 2-level parallelization - allowing optimization of the linac, the injector, or cathode-to-undulator transport systems.
- This slide illustrates the control parameters and constraints used in the global optimization procedure.
- Slide 4: Multiobjective optimization of cathode-to-undulator performance for 20 pC charge (3)
 - This slide indicates, through the shift of the Pareto-optimal front to the left (green to red curve on right hand side figure), that the global optimization procedure for the chosen optimization parameters (current and energy spread) is better than optimizing the injector and linac independently.
- Slide 5: Cathode to undulator simulation: 100 pC, HXR (2)
 - This slide compares the results from optimizations in 2015 and 2016 for the nominal 100 pC charge electron beam.
 - Some changes include
 - * More compression in BC1 and less compression in BC2. This reduces current spikes due to longitudinal space charge.
 - * Optimization of the compensation chicanes in the doglegs. This reduces space-charge driven microbunching induced energy and density modulations along the longitudinal profile of the beam. 2015 results used non-optimal compensation chicane settings.
- Slide 6: Comparison of Oct. 2015 and July 2016 Solutions: 100 pC, HXR
 - This slide compares the projected emittance evolution and longitudinal profiles of the 100 pC electron beam between the 2015 and 2016 solutions.
 - The projected emittance is more well behaved in the 2016 solution.
 - More compression in BC1 and less compression in BC2 is illustrated in the electron beam longitudinal profile comparisons.
- Slide 7: Microbunching Dependence on Laser Heater Setting: 100 pC, SXR
 - This slide details the dependence of the energy and density modulations at the entrance to the SXR undulator from the microbunching instability on the laser heater settings.
 - The FEL performance shown later uses electron beams optimized with a laser heater setting of 7 keV.

- It may be possible to lower the laser heater settings (5 keV) to get better SASE performance, although self-seeding will still suffer from the modulations on the longitudinal profile.
- Slide 8: Summary of cathode-to-undulator simulation results
 - This slide includes a table detailing the electron beam properties important for FEL performance (current, energy spread, emittance) for the three charge distributions that span the LCLS-II parameter space.
- Slide 9: Tables of parameters (1) Machine settings (Linac) used in s2u IMPACT runs
 - This slide includes tables indicating linac and bunch compressor parameters used for the 2016 solution for both the 100 pC and 300 pC electron beams.
- Slide 10: Tables of parameters (2) Machine settings (Linac) used in s2u IMPACT runs
 - This slide includes tables indicating linac and bunch compressor parameters used for the 2016 solution for the 20 pC electron beam.
- Slide 11: 20 pC e-beam slice properties
 - This slide shows the detailed slice properties of the 20 pC electron beam tracked to the HXR undulator.
 - The longitudinal phase space in the core of the beam is relatively well behaved but still shows signatures of space charge driven microbunching instability induced energy modulations.
 - The peak current in the core is roughly 420 Ampere.
 - There is a slightly negative chirp (tail to head) along the core of the beam.
 - The normalized slice emittance in both transverse planes is well preserved from the injector.
 - The RMS slice energy spread in the core of the beam is roughly 400 keV.
- Slide 12: 100 pC e-beam slice properties
 - This slide shows the detailed slice properties of the 100 pC electron beam tracked to the HXR undulator.
 - The longitudinal phase space in the core of the beam is very well behaved with little signatures of space charge driven microbunching instability induced energy modulations.
 - The peak current in the core is roughly 700 Ampere.
 - The normalized slice emittance in both transverse planes is well preserved from the injector. The x plane shows only small growth.

- The RMS slice energy spread in the core of the beam is roughly 460 keV. The calculation of the energy spread near the head is corrupted by the filamentation seen in the LPS.
- Slide 13: 300 pC e-beam slice properties
 - This slide shows the detailed slice properties of the 300 pC electron beam tracked to the HXR undulator.
 - The longitudinal phase space in the core of the beam is extremely well behaved with little signatures of space charge driven microbunching instability induced energy modulations.
 - The peak current in the core is roughly 850 Ampere.
 - The normalized slice emittance in both transverse planes is well preserved from the injector.
 - The RMS slice energy spread in the core of the beam is roughly 360 keV.
- Slide 14:
 - SASE FEL performance example and full FEL characterization coming in the next slides.
- Slide 15: $Q = 300 \text{ pC}, E_{\gamma} = 250 \text{ eV}$ performance: gain curve and taper profile
 - Energy gain curve in the SXR undulator showing both the tapered (8.8 mJ) and un-tapered (2.7 mJ) performance.
 - Tapered and un-tapered undulator profile.
- Slide 16: $Q = 300 \text{ pC}, E_{\gamma} = 250 \text{ eV}$ performance: spectrum
 - Single shot tapered and un-tapered on-axis near-field spectrum at the end of the undulator.
 - The taper that optimizes the FEL pulse energy is often not the same taper that optimizes the peak spectral brightness, especially when looking only at the on-axis near-field.
- Slide 17: Calculating various quantities related to the transverse field size: transverse profile vs. s(t)
 - The FEL code GENESIS distributes the FEL field onto discrete time slices.
 - The transverse profile is discretized onto a transverse mesh.
 - The projected transverse profile (intensity) of the FEL pulse can be made by integrating over the temporal dimension.
- Slide 18: Calculating various quantities related to the transverse field size: projected intensity

- The size of the transverse profile can be analyzed by projecting the profile onto the horizontal and vertical planes.
- The size of the transverse profile can also be analyzed by taking slices through the peak of the distribution.
- Slide 19: Projected intensities using calculated quantities
 - Approximating the real field using the above mentioned quantities.
 - All representations are in qualitative agreement.
- Slide 20: $Q = 300 \text{ pC}, E_{\gamma} = 250 \text{ eV}$ performance: Effective source properties
 - The fields are forward and back propagated numerically using both the Fresnel and Spectral methods.
 - The effective source waist location, size, and divergence can be calculated.
- Slide 21: Full performance table: SXR
 - FEL performance table for the three charge distributions presented above across the SXR undulator tuning range.
 - The presented FEL properties include the pulse energy, length, bandwidth, peak power, average power (given listed repetition rate), waist location, transverse size, divergence, and degree of transverse coherence.
- Slide 22: Full performance table: HXR
 - FEL performance table for the three charge distributions presented above across the HXR undulator tuning range.
 - The presented FEL properties include the pulse energy, length, bandwidth, peak power, average power (given listed repetition rate), waist location, transverse size, divergence, and degree of transverse coherence.
- Slide 23: Performance (energy) relative to July 2015
 - Improvement in performance (with energy as the metric) of the 2016 optimization relative to the 2015 optimization.
- Slide 24: Summary
 - Self explanatory.
- Slide 25
 - Backup slides next.
- Slide 26: 100 pC LPS and RWW comparison

- Comparison of the longitudinal phase space and the resulting resistive wall wake-field in the undulator between the 2015 and 2016 optimizations for the 100 pC charge electron beam.
- Slide 27: 300 pC LPS and RWW comparison
 - Comparison of the longitudinal phase space and the resulting resistive wall wakefield in the undulator between the 2015 and 2016 optimizations for the 100 pC charge electron beam.

3 Presentation slides

LCLS-II Global FEL Performance



Outline

- 20, 100, and 300 pC e-beam distributions as of April 2016 (latest IMPACT release)
 - Brief review of injector, linac, and transport optimization
 - List of settings

• Example illustrating full FEL characterization

- 300 pC, SXR undulator, $E_{\gamma} = 250 \text{ eV}$
- Global SASE performance tables
- Summary

Multiobjective optimization of cathode-toundulator performance for 20 pC charge (2)



Multiobjective optimization of cathode-toundulator performance for 20 pC charge (3)



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Cathode to undulator simulation: 100 pC, HXR (2)



Comparison of Oct. 2015 and July 2016 Solutions: 100 pC, HXR



Microbunching Dependence on Laser Heater Setting: 100 pC, SXR



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Summary of cathode-to-undulator simulation results

Results are shown in each case for the July, 2016 settings. (Optimal CC settings)

IMPACT Studies	I_peak (A)	σ _E (keV)	Proj. ε_x / ε_y (mm-mrad)	Slice ε_x / ε_y (mm-mrad)	
20 pC	424	482	0.22 / 0.17	0.18 / 0.15	HXR
	429	494	0.29 / 0.18	0.17 / 0.16	SXR
100 0	714	562	0.54 / 0.45	0.48 / 0.38	HXR
100 pC	727	658	0.74 / 0.46	0.47 / 0.39	SXR
200 °C	956	499	1.22 / 1.05	0.48 / 0.62	HXR
500 pC	956	508	1.47 / 0.94	0.47 / 0.60	SXR

Tables of parameters (1)Machine settings (Linac) used in s2u IMPACT runs

100pC *HXR* &*SXR*

100 pC	Phase (deg)	Voltage (MV)	Grad (MV/m)	No. modls
L1	-13.25005	210.1863269	12.658862	2
HL	-147.988	63.40169152	11.455465	2
L2	-22.88456	1536.11502772	15.4192302	12
L3	0	2441.74385968	14.705856	20
	θ (rad)	R56 (m)	E (MeV)	
BC1	0.106335335	-0.05810644	250.42673	
BC2	0.0288582137	-0.017040778	1666.0272	

300pC

HXR &SXR

July 2016 settings

300 pC	Phase (deg)	Voltage (MV)	Grad (MV/m)	No. modls
L1	-11.7836	215.9457756	13.0057355	2
HL	-163.594	64.00000	11.563567	2
L2	-27.3891	1520.438381	15.261871	12
L3	0	2441.74385968	14.705856	20
	θ (rad)	R56 (m)	E (MeV)	
BC1	0.10279	-0.054315864	249.62109	
BC2	0.0542	-0.0600485698	1599.7260	

Note:

Impact-t was used for simulating the injector

Tables of parameters (2)Machine settings (Linac) used in s2u IMPACT runs

20pC HXR &SXR

20 pC	Phase (deg)	Voltage (MV)	Grad (MV/m)	No. modls
L1	-23.85274157	254.0452772	15.30034876	2
HL	-161.3758763	76.6953758043	13.85737781	2
L2	0.2691550759	1445.9112079	14.51378143	12
L3	0.0361324916	2655.5172025	15.99334567	20
	θ (rad)	R56 (m)	E (MeV)	
BC1	0.1002435924	-0.0516710032	259.90225	
BC2	0.01416892201	-0.0041092082	1705.7225	

July 2016 settings

Note:

Impact-t was used for simulating the injector

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20 pC e-beam slice properties



100 pC e-beam slice properties



300 pC e-beam slice properties





SASE FEL performance example: Q = 300 pC, E_{γ} = 250 eV, SXR undulator

Q = 300 pC, E_{γ} = 250 eV performance: gain curve and taper profile



Q = 300 pC, E_{y} = 250 eV performance: spectrum

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Calculating various quantities related to the transverse field size: transverse profile vs. s(t)





Calculating various quantities related to the transverse field size: projected intensity



x [m]

 $\times 10^{-3}$

Projected intensities using calculated quantities

 -3×10^{-3} -3 ×10⁻³ -3 ×10⁻³ **Projected RMS Projected FWHM** Real -2 -2 -2 -1 -1 -1 [m] 0 y [m] <u>م</u>[] م 1 2 2 2 3 3 3 -2 -2 0 2 0 2 -2 0 2 x [m] x [m] x [m] $\times 10^{-3}$ $\times 10^{-3}$ $\times 10^{-3}$ -3 ×10⁻³ $\times 10^{-3}$ Max RMS **Max FWHM** $\times 10^{-3}$ -3 3 -2 -2 2 -1 -1 y [n] v y [n] v v [] 1 -1 -2 2 2 3 3 -3 -2 -2 -2 2 0 2 0 0 2 x [m] x [m] x [m] $\times 10^{-3}$ $\times 10^{-3}$ $\times 10^{-3}$ $I \sim e^{-\frac{x^2}{2\sigma_x^2}}$ $\mathbf{2}$ \boldsymbol{y} $\frac{1}{2\sigma_y^2}$

Q = 300 pC, E_{γ} = 250 eV performance: Effective source properties

Calculate the previous quantities as the entire 3D field is forward and back propagated. Use this information to define the effective source properties as well as the pulse divergence.



Location of waist: z = -39.000000 m, Projection RMS z = -40.000000 m, Projection FWHM z = -40.000000 m, Max slice RMS z = -45.000000 m, Max slice FWHM z = -41.000000 m, Peak intensity Minimum of:

$$-\sigma_r = \sqrt{\sigma_x^2 + \sigma_y^2}$$

Full performance table: SXR

														•
											p: project	ted	JLAC	
					D	istanc	e fron	n en	d of undulato	ough peak				
					_									
	FWHM								Ca	alculated	using cut F	WHM value	es	
					\checkmark			\checkmark			\checkmark			
Q [pC]	Ε _γ [keV]	F [MHz]	E [µJ]	∆t _{FW} [fs]	ΔE _γ [eV]	P _{pk} [GW]	P _{avg} [W]	z₀ [m]	σ _{p,(c)} {x,y} [μm]	FWHM _{p,(c)} {x,y} [µm]	w₀ (x,y) [μm]	σ _{θ,p,(c)} {x,y} [µrad]	FWHM _{θ,p,(c)} {x,y} [µrad]	DTC
20	0.25	1.0	393	46	2.6	8	393	-32	{288, 278}, ({142,142})	{152,135}, ({114,97})	(96, 82)	{17.9,17.6}, ({14.5,14.3})	{26.8,26.9}, ({26.4,26.3})	0.29
20	0.75	1.0	266	35	2.1	7.5	266	-27	{100.1,93.8}, ({63.3,61.0})	{96.3,85.9} ({78.0,66.1}	, (66.2, ·) 56.1)	{6.9,6.8}, ({6.2,6.0})	{13.6,13.8}, ({14.5,14.2})	0.45
20	1.25	1.0	222	35	2.2	6.3	222	-22	{56.2,51.7}, ({40.7,38.6})	{74.1,63.9} ({71.5,61.0}	, (60.7, ·) 51.8)	{4.3,4.2}, ({4.2,3.9})	{9.8,10.0}, ({11.0,10.2})	0.59
100	0.25	0.3	2549	121	0.91	20.7	765	-37	{221.6,214.3}, ({121.7,118.6})	{166,165.7} ({133.4,131.8	y, (113.3, 3}) 111.9)	{13.3,12.8}, ({11.3,10.7})	{23.2,23.1}, ({25.6,24.0})	0.42
100	0.75	0.3	1635	112	2.4	14.4	491	-15	{94.5,83.6}, ({63.9,57.3})	{111.6,98.5] ({91.4,82.1}	}, (77.6, ·) 69.7)	{5.2,4.9}, ({4.8,4.4})	{10.4,10.3}, ({11.3,11.1})	0.57
100	1.25	0.3	1008	108	3.3	9.2	302	-15	{59,49.5}, ({43.7,36.6})	{78.9,65.2} ({73.3,60})	, (62.3, 51)	{3.9,3.6}, ({3.7,3.4})	{8.2,8.1}, ({8.2,8.1})	0.60
300	0.25	0.1	8801	251	1.0	34.5	880	-40	{162.0,150.7}, ({101.2,95.7})	{166.9,139.0 ({143.1,118.9)}, (121.5, 9}) 101.0)	{11.8,11.6}, ({10.7,10.1})	{24.0,23.2}, (26.1,23.6)	0.43
300	0.75	0.1	5699	234	2.1	24.1	570	-20	{84.3,76.3}, ({64.6,59.0})	{123.1,111.5 ({116.9,105.2	5}, (99.3, 2}) 89.3)	{4.7,4.5}, ({4.5,4.2})	{10.3,9.9}, ({11.2,10.7})	0.58
300	1.25	0.1	3386	223	2.7	15.0	339	-15	{58.0,51.7}, ({46.0,41.5})	{87.4,85.9} ({86.7,84.5}	, (73.6,) 71.8)	{3.2,3.1}, ({3.1,3.0})	{7.3,7.0}, ({7.9,7.6})	0.69
										γ]			

At the effective source location

Full performance table: HXR

Q [pC]	Ε _γ [keV]	F [MHz]	Ε [μJ]	∆t _{FW} [fs]	ΔE _γ [eV]	P _{pk} [GW]	P _{avg} [W]	z₀ [m]	σ _{p,(c)} {x,y} [μm]	FWHM _{p,(c)} {x,y} [μm]	w₀ (x,y) [µm]	σ _{θ,p,(c)} {x,y} [µrad]	FWHM _{θ,p,(c)} {x,y} [µrad]	DTC
20	1.5	1.0	251	31	3.3	7.8	251	-74	{65.2, 62.8}, ({49.1, 47.6})	{69.6, 67.2}, ({62.4, 59.7})	(53.0, 50.7)	{3.8,3.7}, ({3.6,3.5})	{7.9,8.1}, ({8.8,8.9})	0.58
20	3.25	1.0	191	30	5.3	6.2	191	-59	{45.2, 43.7}, ({34.8, 33.7})	{70, 62.6}, ({65.7,58.4})	(55.8, 49.6)	{2.0, 1.9}, ({1.8,1.7})	{4.0,4.1}, ({4.4,4.5})	0.61
20	5.0	1.0	37	28	4.3	1.3	37	-20	{28.8, 28.4}, ({23.5,23.7})	{49.9,48.0}, ({50.0,48.4})	(42.5, 41.1)	{1.5,1.5}, ({1.4,1.4})	{3.2,3.3}, ({3.6,3.6})	0.74
100	1.5	0.3	1731	108	3.9	15.8	519	-62	{70,67.2}, ({52.7,50})	{86.6,102.5}, ({84.2,98.6})	(71.5, 83.7)	{2.8,2.8}, ({2.5,2.4})	{5.5,5.6}, ({6.0,6.0})	0.64
100	3.25	0.3	617	104	5.8	5.9	185	-40	{46.4,45.9}, ({36.6,37.1})	{90.5,61.3}, ({90.3,60.1})	(76.7, 51.0)	{2.0,1.9}, ({1.6,1.5})	{3.3,3.3}, ({3.6,3.6})	0.70
100	5.0	0.3	6	60	2.0	0.075	1.8	-15	{62.1,64.1}, ({29.8,31.6})	{47.3,59.2}, ({46.5,60.4})	(39.5, 51.3)	{3.3,3.3}, ({2.0,2.0})	{3.8,3.0}, ({4.0,3.1})	0.61
300	1.5	0.1	4567	215	3.9	20.8	457	-64	{66.3,63.9}, ({49.2,47.5})	{92.1,85.8}, ({86.9,80.8})	(73.8, 68.6)	{2.7,2.7}, ({2.5,2.4})	{5.7,5.5}, ({6.2,6.0})	0.64
300	3.25	0.1	2064	206	8.1	9.9	206	-25	{44.0,44.0}, ({35.2,36.3})	{77.1,62.6}, ({72.0,58.2})	(61.1, 49.4	{1.4,1.5}, ({1.3,1.3})	{2.9,2.9}, ({3.1,3.1})	0.74
300	5.0	0.1	-	-	-	-	-	-	-	-	-	-	-	-

-SLAC

Performance (energy) relative to July 2015

		SXR		HXR				
	250eV	750eV	1.25keV	1.5keV	3.25keV	5keV		
20pC	47%	11%	32%	22%	30%	48%		
100pC	111%	105%	91%	52%	32%	-40%		
300pC	60%	48%	78%	93%	221%	N/A		

Summary

- **SLAC**
- Electron beam quality has been significantly improved through detailed optimization process
- These brighter and more longitudinally uniform beams produce more FEL radiation across the board
- Performance gains, using FEL pulse energy as the metric, can be as much as a factor of 2 over July 2015 optimizations
 - Implications for MCB? XTES?

Future work

- Evaluate self-seeding with new distributions
- Continue to update table as new IMPACT releases become available
- Characterize (parameterize) transverse intensity using an unconstrained nonlinear optimization on a bivariate distribution (fit a 2D Gaussian to the projected intensity instead of taking slices)



Backup

Full performance table: SXR @ 4 GeV



At the effective source location

Full performance table: HXR @ 4 GeV

Q [pC]	Ε _γ [keV]	F [MHz]	Ε [μJ]	∆t _{FW} [fs]	ΔE _γ [eV]	P _{pk} [GW]	P _{avg} [W]	z₀ [m]	σ _{p,(c)} {x,y} [μm]	FWHM _{p,(c)} {x,y} [μm]	w₀ (x,y) [µm]	σ _{θ,p,(c)} {x,y} [µrad]	FWHM _{θ,p,(c)} {x,y} [μrad]	DTC
20	1.5	1.0	251	31	3.3	7.8	251	-74	{65.2, 62.8}, ({49.1, 47.6})	{69.6, 67.2}, ({62.4, 59.7})	(53.0, 50.7)	{3.8,3.7}, ({3.6,3.5})	{7.9,8.1}, ({8.8,8.9})	0.58
20	3.25	1.0	191	30	5.3	6.2	191	-59	{45.2, 43.7}, ({34.8, 33.7})	{70, 62.6}, ({65.7,58.4})	(55.8, 49.6)	{2.0, 1.9}, ({1.8,1.7})	{4.0,4.1}, ({4.4,4.5})	0.61
20	5.0	1.0	37	28	4.3	1.3	37	-20	{28.8, 28.4}, ({23.5,23.7})	{49.9,48.0}, ({50.0,48.4})	(42.5, 41.1)	{1.5,1.5}, ({1.4,1.4})	{3.2,3.3}, ({3.6,3.6})	0.74
100	1.5	0.3	1731	108	3.9	15.8	519	-62	{70,67.2}, ({52.7,50})	{86.6,102.5}, ({84.2,98.6})	(71.5, 83.7)	{2.8,2.8}, ({2.5,2.4})	{5.5,5.6}, ({6.0,6.0})	0.64
100	3.25	0.3	617	104	5.8	5.9	185	-40	{46.4,45.9}, ({36.6,37.1})	{90.5,61.3}, ({90.3,60.1})	(76.7, 51.0)	{2.0,1.9}, ({1.6,1.5})	{3.3,3.3}, ({3.6,3.6})	0.70
100	5.0	0.3	6	60	2.0	0.075	1.8	-15	{62.1,64.1}, ({29.8,31.6})	{47.3,59.2}, ({46.5,60.4})	(39.5, 51.3)	{3.3,3.3}, ({2.0,2.0})	{3.8,3.0}, ({4.0,3.1})	0.61
300	1.5	0.1	4567	215	3.9	20.8	457	-64	{66.3,63.9}, ({49.2,47.5})	{92.1,85.8}, ({86.9,80.8})	(73.8, 68.6)	{2.7,2.7}, ({2.5,2.4})	{5.7,5.5}, ({6.2,6.0})	0.64
300	3.25	0.1	2064	206	8.1	9.9	206	-25	{44.0,44.0}, ({35.2,36.3})	{77.1,62.6}, ({72.0,58.2})	(61.1, 49.4	{1.4,1.5}, ({1.3,1.3})	{2.9,2.9}, ({3.1,3.1})	0.74
300	5.0	0.1	-	-	-	-	-	-	-	-	-	-	-	-

Estimation on FELs with 4.5 GeV beam



- There is potential that beam energy could be above 4 GeV based on the cavity measurement results, and higher energy is preferred especially for improving the hard x-ray FEL performance;
- Based on the 4-GeV FEL performance from start-end simulations, the FEL pulse energy with 4.5-GeV beam is estimated from theoretical formula with benchmarking with 4-GeV simulation results (Heinz-Dieter Nuhn);
- From the pulse energy with 4.5-GeV beam, we scale the FEL peak power and average power. The pulse duration, saturation point, and the FEL spot size are assumed to be the same as the 4-GeV simulated results. With these assumptions, we updated the tables in the next two slides.
- Since the saturation length would become shorter with a higher energy E-beam for the same photon energy, the effective source location would be shifted to upstream, and the downstream FEL beam size should be getting larger. So the estimation on the beam intensity/divergence in this way is conservative.

Full performance table: SXR @ 4.5 GeV

Scaled with calculated pulse energy Theoretical Calculation with 4.5 GeV Using the 4-GeV Start-end results FWHM_{p.(c)} W₀ Ε_γ [keV] F Ξ ∆t_{FW} ΔE_v P_{pk} P_{avg} $FWHM_{\theta,p,(c)} \{x,y\}$ Q $\sigma_{p,(c)} \{x,y\}$ $\sigma_{\theta,p,(c)} \{x,y\}$ z_0 DTC {x,y} [µm] (x,y) [pC] [MHz] [µJ] [fs] [eV] [GW] [W] [m] [µm] [µrad] [µrad] [µm] {288, 278}, {152,135}, (96. {17.9,17.6}, {26.8,26.9}, 0.25 482 -32 20 1.0 46 2.6 10 482 0.29 82) $(\{142, 142\})$ $(\{114, 97\})$ $(\{14.5, 14.3\})$ $(\{26.4, 26.3\})$ {100.1,93.8}, {96.3,85.9}, (66.2, {6.9,6.8}, {13.6,13.8}, -27 20 0.751.0 329 35 2.1 9 329 0.45 $(\{63.3, 61.0\})$ $(\{78.0, 66.1\})$ 56.1) $(\{6.2, 6.0\})$ $(\{14.5, 14.2\})$ {56.2,51.7}, (60.7, {4.3,4.2}, {74.1,63.9}, $\{9.8, 10.0\},\$ 1.25 2.2 20 1.0 280 35 8 280 -22 0.59 $(\{4.2, 3.9\})$ $(\{11.0, 10.2\})$ $(\{40.7, 38.6\})$ $(\{71.5, 61.0\})$ 51.8) (113.3, {13.3,12.8}, {221.6,214.3}, {166,165.7}. $\{23.2, 23.1\},\$ -37 100 0.25 0.266 3121 121 0.91 25.7 830 0.42 ({133.4,131.8}) $(\{11.3, 10.7\})$ $(\{25.6, 24.0\})$ $(\{121.7, 118.6\})$ 111.9) {94.5,83.6}, {111.6,98.5}, (77.6,{5.2,4.9}, {10.4,10.3}, 0.266 100 0.75 2009 112 2.4 17.9 534 -15 0.57 $(\{63.9, 57.3\})$ 69.7) $(\{4.8, 4.4\})$ $(\{11.3, 11.1\})$ $(\{91.4, 82.1\})$ {59,49.5}. {78.9,65.2}. (62.3, {3.9,3.6}, {8.2,8.1}, 0.266 100 1.25 1259 108 3.3 11.6 334 -15 0.60 51) $(\{43.7, 36.6\})$ $({73.3,60})$ $(\{3.7, 3.4\})$ $(\{8.2, 8.1\})$ {162.0,150.7}, (121.5,{11.8.11.6}. {24.0,23.2}, {166.9.139.0}. 300 0.25 0.088 9258 251 1.0 36.8 814 -40 0.43 $(\{101.2, 95.7\})$ $(\{143.1, 118.9\})$ 101.0) $(\{10.7, 10.1\})$ (26.1, 23.6){84.3,76.3}, {123.1,111.5}, (99.3, $\{4.7, 4.5\},\$ {10.3,9.9}, 300 0.088 0.75 6385 234 2.1 27.2 561 -20 0.58 $(\{4.5, 4.2\})$ $(\{11.2, 10.7\})$ $({64.6, 59.0})$ $(\{116.9, 105.2\})$ 89.3) {3.2,3.1}, {58.0,51.7}, {87.4,85.9}, (73.6, $\{7.3, 7.0\},\$ 300 1.25 0.088 3936 223 2.7 17.6 346 -15 0.69 $(\{86.7, 84.5\})$ $(\{3.1,3.0\})$ $(\{46.0, 41.5\})$ 71.8) $(\{7.9, 7.6\})$

At the effective source location

Full performance table: HXR @ 4.5 GeV

				Sca	aled w	ith calc	rulated	se enerav	1			SLAC		
				000					-	1				
Th	eoretic	cal Cal	culatio	n with	4.5 0	GeV				Using the 4	Start-end res	art-end results		
										/				
			\vee											
Q [pC]	Ε _γ [keV]	F [MHz]	E [µJ]	∆t _{FW} [fs]	ΔE _γ [eV]	P _{pk} [GW]	P _{avg} [W]	z₀ [m]	σ _{p,(c)} {x,y} [μm]	FWHM _{p,(c)} {x,y} [μm]	w₀ (x,y) [µm]	σ _{θ,p,(c)} {x,y} [µrad]	FWHM _{θ,p,(c)} {x,y} [µrad]	DTC
20	1.5	1.0	323	31	3.3	10.3	323	-74	{65.2, 62.8}, ({49.1, 47.6})	{69.6, 67.2}, ({62.4, 59.7})	(53.0, 50.7)	{3.8,3.7}, ({3.6,3.5})	{7.9,8.1}, ({8.8,8.9})	0.58
20	3.25	1.0	272	30	5.3	9.0	272	-59	{45.2, 43.7}, ({34.8, 33.7})	{70, 62.6}, ({65.7,58.4})	(55.8, 49.6)	{2.0, 1.9}, ({1.8,1.7})	{4.0,4.1}, ({4.4,4.5})	0.61
20	5.0	1.0	117	28	4.3	4.1	117	-20	{28.8, 28.4}, ({23.5,23.7})	{49.9,48.0}, ({50.0,48.4})	(42.5, 41.1)	{1.5,1.5}, ({1.4,1.4})	{3.2,3.3}, ({3.6,3.6})	0.74
100	1.5	0.266	2286	108	3.9	21.1	608	-62	{70,67.2}, ({52.7,50})	{86.6,102.5}, ({84.2,98.6})	(71.5, 83.7)	{2.8,2.8}, ({2.5,2.4})	{5.5,5.6}, ({6.0,6.0})	0.64
100	3.25	0.266	880	104	5.8	8.4	234	-40	{46.4,45.9}, ({36.6,37.1})	{90.5,61.3}, ({90.3,60.1})	(76.7, 51.0)	{2.0,1.9}, ({1.6,1.5})	{3.3,3.3}, ({3.6,3.6})	0.70
100	5.0	0.266	431	60	2.0	7.1	114	-15	{62.1,64.1}, ({29.8,31.6})	{47.3,59.2}, ({46.5,60.4})	(39.5, 51.3)	{3.3,3.3}, ({2.0,2.0})	{3.8,3.0}, ({4.0,3.1})	0.61
300	1.5	0.088	5425	215	3.9	25	477	-64	{66.3,63.9}, ({49.2,47.5})	{92.1,85.8}, ({86.9,80.8})	(73.8, 68.6)	{2.7,2.7}, ({2.5,2.4})	{5.7,5.5}, ({6.2,6.0})	0.64
300	3.25	0.088	2775	206	8.1	13.4	244	-25	{44.0,44.0}, ({35.2,36.3})	{77.1,62.6}, ({72.0,58.2})	(61.1, 49.4	{1.4,1.5}, ({1.3,1.3})	{2.9,2.9}, ({3.1,3.1})	0.74
300	5.0	0.088	1017	-	-	-	89	-	-	-	-	-	-	-

At the effective source location

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