Intro


Gianluca Geloni


Svitozar Serkez


Takanori Tanikawa

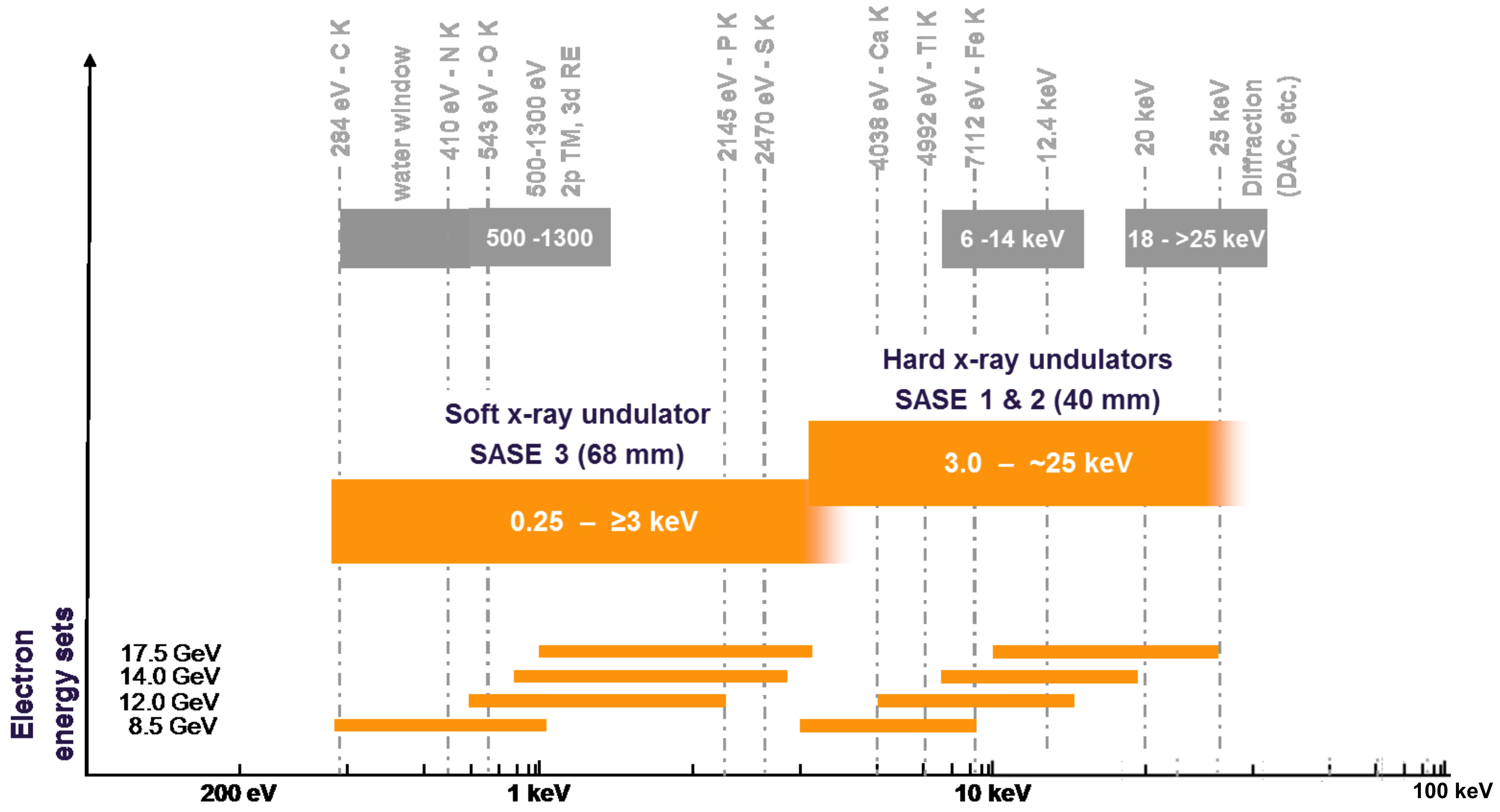

Sergey Tomin

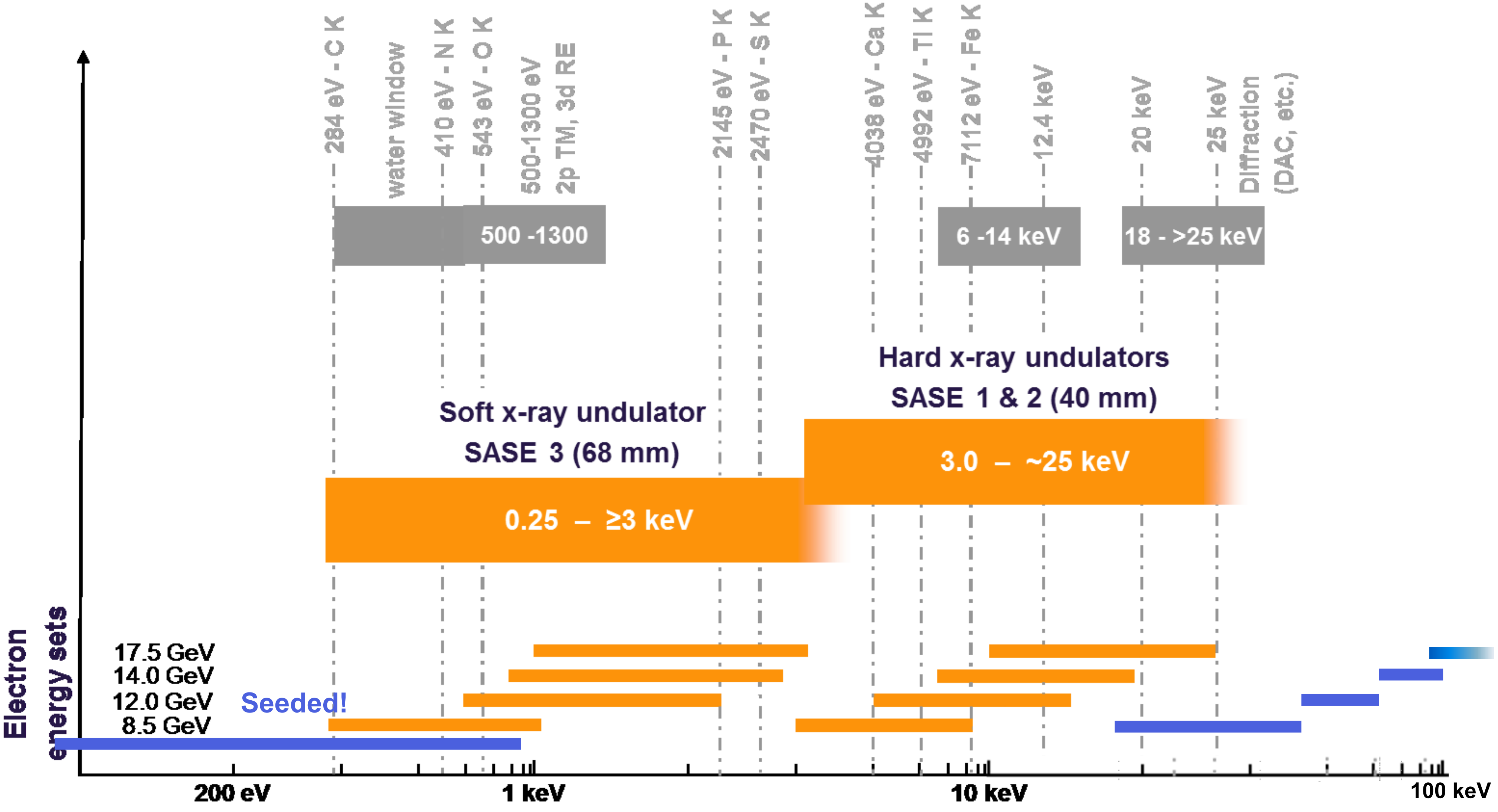
*"The **Simulation of Photon Fields** (SPF) Group devises and assesses novel advanced FEL schemes for improving the characteristics of the photon beams at the European XFEL."*

This Workshop: three talks from my group [with substantial contribution and support from **Sara Casalbuoni (KIT), Michael Gensch (HZDR), Suren Karabekyan (EuXFEL), Vitali Kocharyan (DESY), Shan Liu (DESY), Evgeni Saldin (DESY), Nikola Stojanovic (DESY), Patrik Vagovic (EuXFEL), and many others…**]

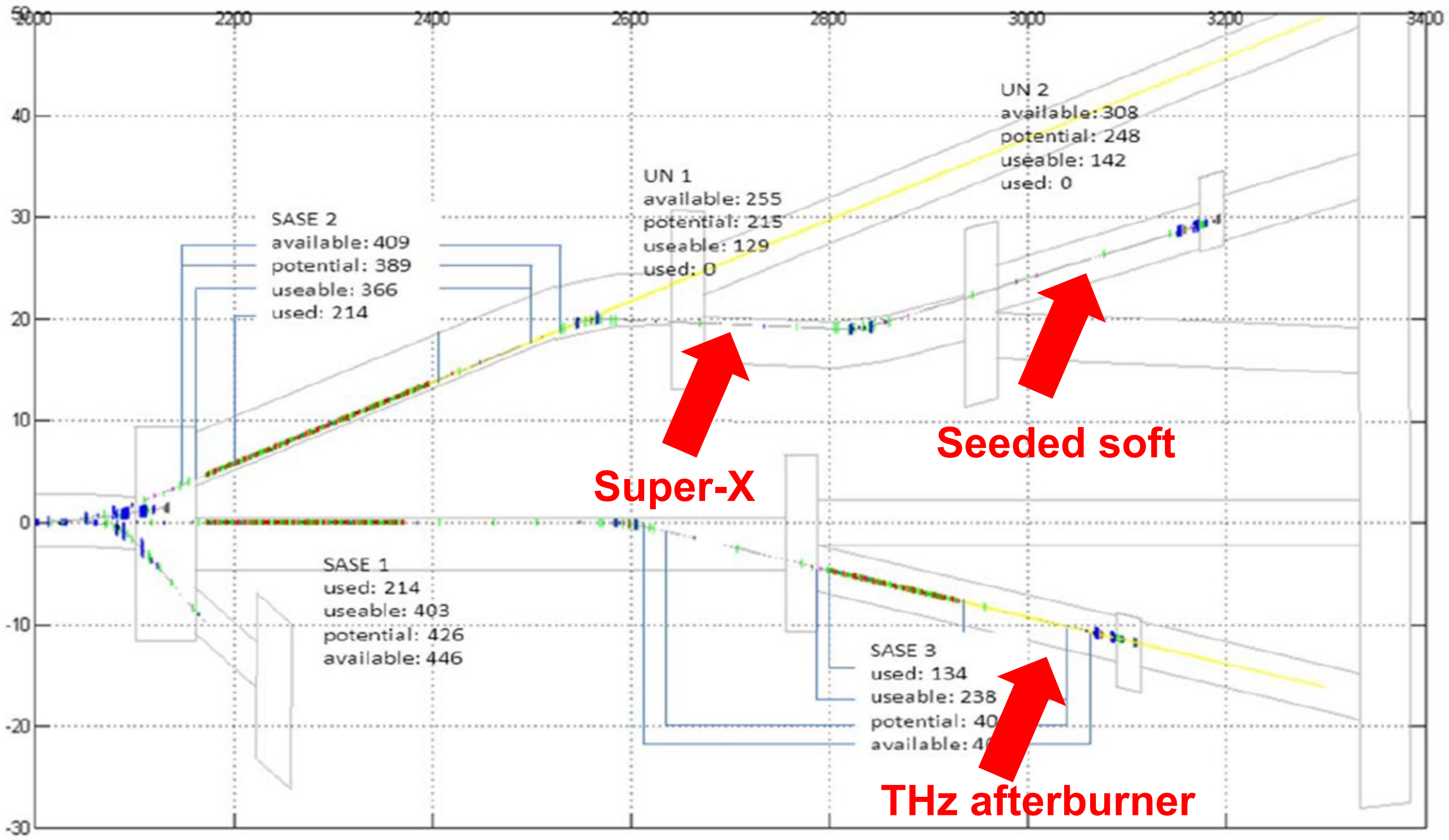
13:00 – 13:30	Svitozar Serkez, Gianluca Geloni (European XFEL) "Super-X: Simulations for the Super-Hard X-ray Generation with Short Period Undulators for the European XFEL"	**Now**
09:30 – 10:00	Takanori Tanikawa (European XFEL) "External Seeding Possibilities at the European XFEL (EEHG and HGHG) and THz Addition"	**Tomorrow**
13:30 – 14:00	Gianluca Geloni (European XFEL) "Self-seeding: Energy-Range Limits and Possibilities"	**Tomorrow**

There is a guiding idea linking these talks…


284 eV - C K
water window
410 eV - N K
543 eV - O K
500-1300 eV
2p TM, 3d RE
2145 eV - P K
2470 eV - S K
4038 eV - Ca K
4992 eV - Ti K
7112 eV - Fe K
12.4 keV
20 keV
25 keV
Diffraction
(DAC, etc.)
500 -1300
6 -14 keV
18 - >25 keV
Hard x-ray undulators
SASE 1 & 2 (40 mm)
3.0 – ~25 keV
Soft x-ray undulator
SASE 3 (68 mm)
0.25 – ≥3 keV
Electron energy sets
17.5 GeV
14.0 GeV
12.0 GeV
8.5 GeV
200 eV
1 keV
10 keV
100 keV



Plus THz Pump-probe possibilities between 3 THz and 40 THz



Fresh bunch needed…

- Many of the additions proposed require high-field and/or short period undulators
- One possibility: Superconducting Undulator Technology

Verbundprojekt FuE für
Erforschung der Materie an Großgeräten 2019-2022:
Supraleitende Undulatoren für die European XFEL

Vorhabenbeschreibung
Antragsteller:
Prof. Dr. Anke-Susanne Müller[1],
Prof. Dr.-Ing. Herbert De Gersem[2]

"Aim of this project is to explore the benefits of applying superconducting undulators to the European XFEL"

Proposed by KIT and TUD

Super-X: Simulations for super-hard X-ray generation with short period undulators for the European XFEL

Svitozar Serkez, Takanori Tanikawa, Sara Casalbuoni
Sergey Tomin, Suren Karabekyan, Gianluca Geloni

Outline

- Necessary assumptions
  - Electron beam
  - Space available
  - Undulator technology
- Analytical estimations
- Quantum fluctuations
- Comparison with harmonic lasing
- Period doubling
- CW operation
- Magnetic field tolerances
- Spread of SASE spectrum
- Radiation spatial coherence
- E-beam quality revisited
- 100keV numerical case study (incl. all detrimental effects)
- Conclusions

- *Analytical estimation and post-processing of numerical simulations done with OCELOT https://github.com/ocelot-collab/ocelot

E-beam assumptions

- I_{peak}=5kA
- E=17.5GeV
- dE = 1MeV (dγ = 1.9)
- Emittance=0.4 mm mrad

Summary

- Slice emittance in x/y plane, *µ*m

Position	500 pC, 5kA	500 pC, 10 kA	250 pC, 5 kA	100 pC, 5 kA
after injector booster	0.50	0.50	0.36	0.18
after collimator	0.57	0.57 / 0.75	0.40	0.24 / 0.30
after T1 arc (before SASE2)	0.57	0.57 / 0.75	0.40	0.24 / 0.30

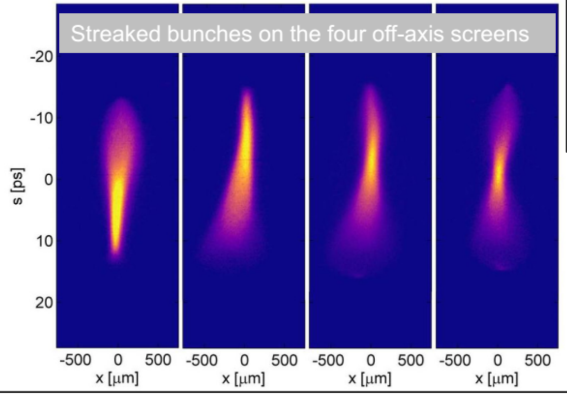
- Projected emittance in x/y plane, *µ*m

Position	500 pC, 5kA	500 pC, 10 kA	250 pC, 5 kA	100 pC, 5 kA
after injector booster	0.84	0.84	0.67	0.30
after collimator	1.15 / 1.21	1.10 / 2.93	0.80 / 1.37	0.30 / 0.82
after T1 arc (before SASE2)	1.35 / 1.16	2.64 / 2.52	1.34 / 1.26	0.83 / 0.73

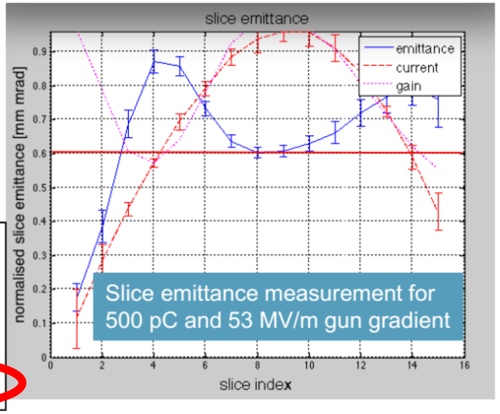
- In the simulations we have used the laser heater in the injector to provide 1 MeV slice energy spread after BC2

- **Talk by Igor Zagorodnov**

Slice Emittance Measurements



We are able to match single slices of the bunch. One matching iteration takes about 2 minutes including the magnet cycling.

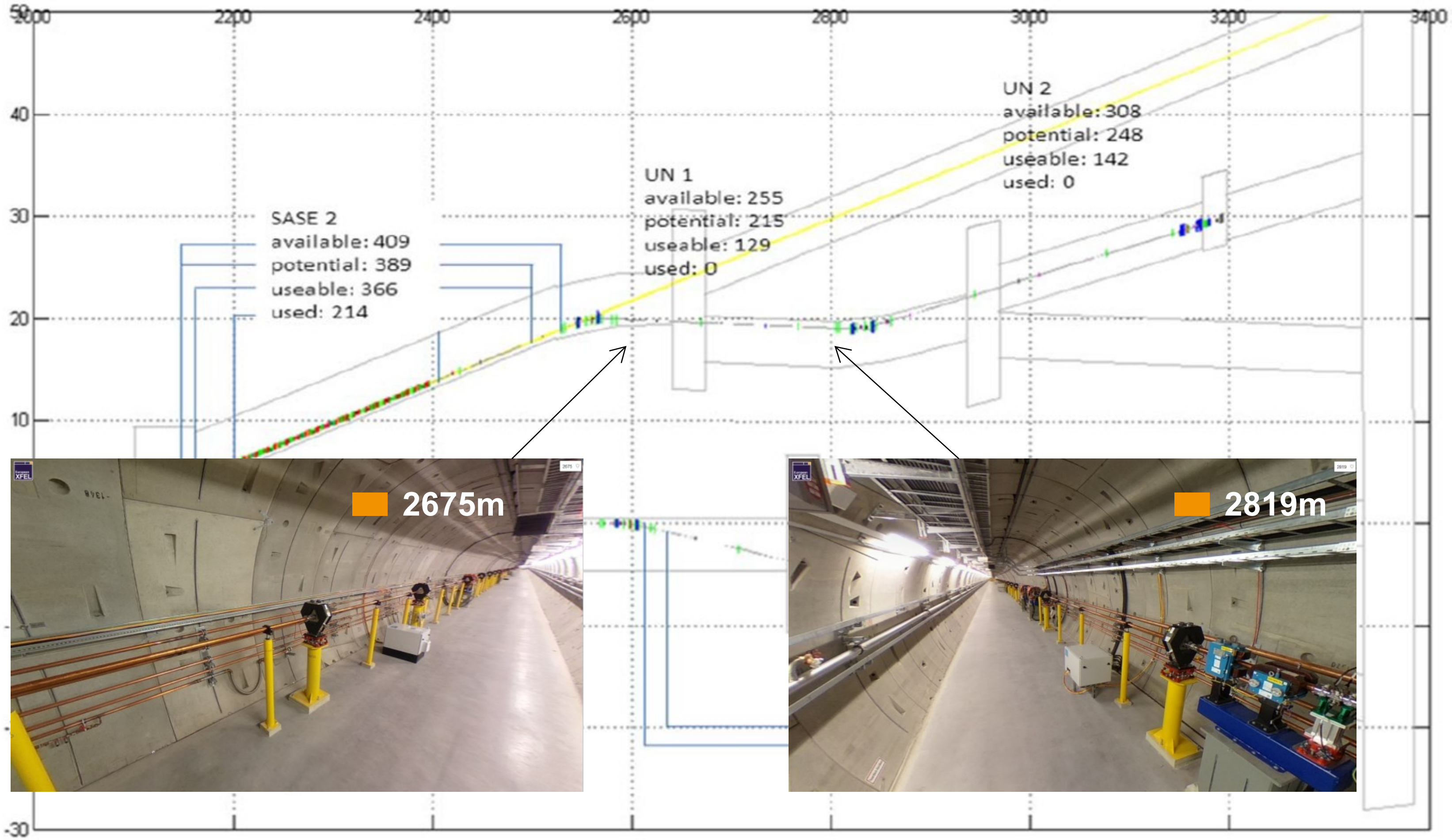


The smallest slice emittances achieved so far (four-screen method):
0.6 µm rad with 53 MV/m gun gradient (500 pC)
0.5 µm rad with 60 MV/m gun gradient (500 pC)
0.4 µm rad with 60 MV/m gun gradient (400 pC)

- **B. Beutner *European XFEL Injector Commissioning Results*, *talk* at International FEL Conference, Santa Fe (2017), slide of M.Scholz**

I.Zagorodnov, http://www.desy.de/fel-beam/s2e/xfel.html

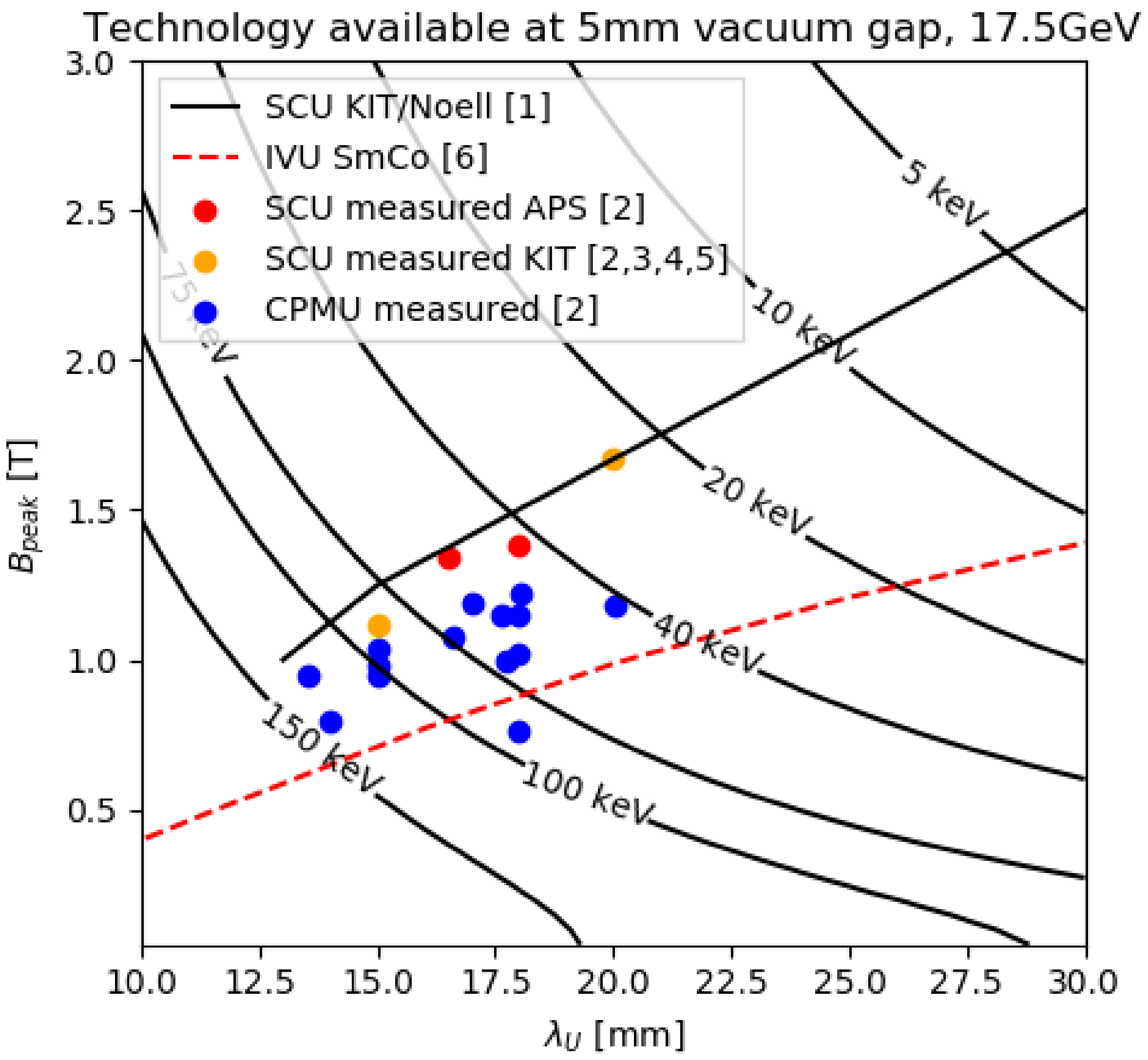
Tunnel location and length (XTD3/SASE4)



- Assume:
  - SASE2 open or bypassed
  - 150m undulator
  - 79% filling factor

Photos from http://xfelmd.desy.de/vtour/

Undulator technologies

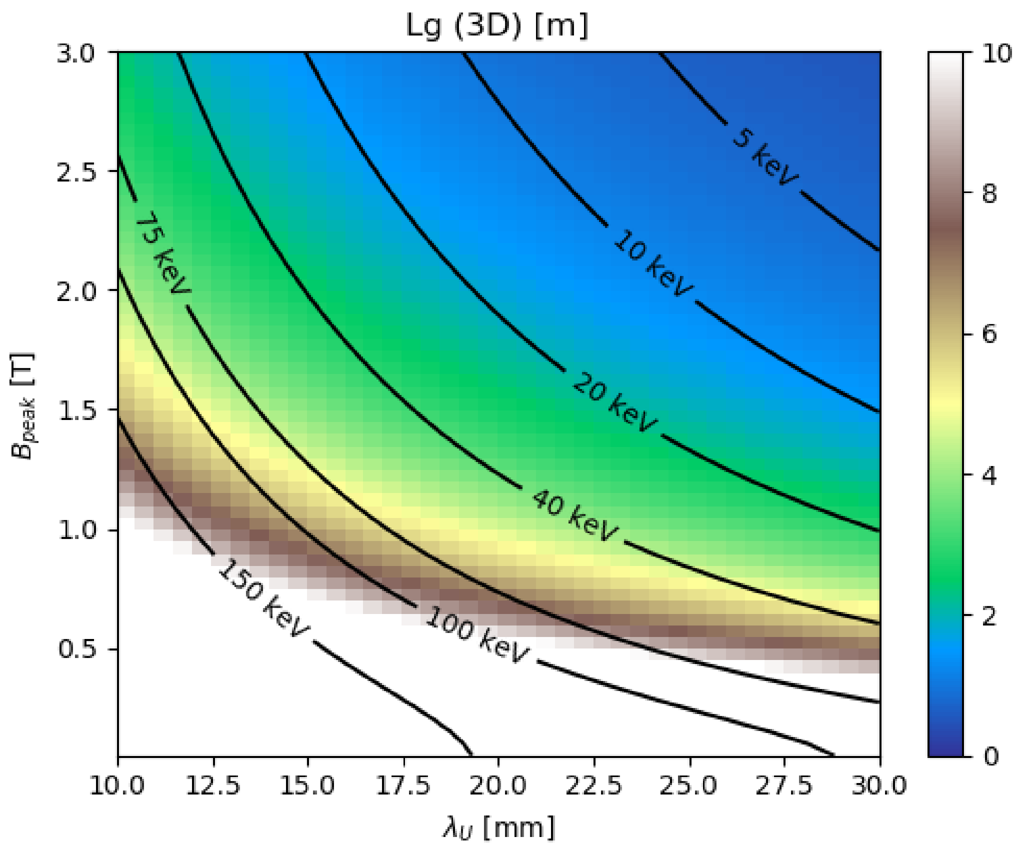


- [1] M. Turenne, C. Boffo, S. Casalbuoni, private communication
- [2] J. Bahrdt and E. Gluskin, “Cryogenic permanent magnet and superconducting undulators,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 907, no. March, pp. 149–168, Nov. 2018.
- [3] S. Casalbuoni, et. al., “Magnetic Field Measurements of Full-Scale Conduction-Cooled Superconducting-Undulator-Coils,” IEEE Trans. Appl. Supercond., vol. 28, no. 3, pp. 3–6, 2018.
- [4] S. Casalbuoni, et.al., “Characterization and long term operation of a novel superconducting undulator with 15 mm period length in a synchrotron light source,” Phys. Rev. Accel. Beams, vol. 19, no. 11, p. 110702, Nov. 2016.
- [5] S. Casalbuoni, et.al., “Superconducting Undulators: From Development towards a Commercial Product,” *Synchrotron Radiat. News*, vol. 31, no. 3, pp. 24–28, May 2018.
- [6] R. Dejus, M. Jaski, and S. H. Kim, “On-axis brilliance and power of in-vacuum undulators for the Advanced Photon Source.,” Argonne, IL (United States), Nov. 2009.

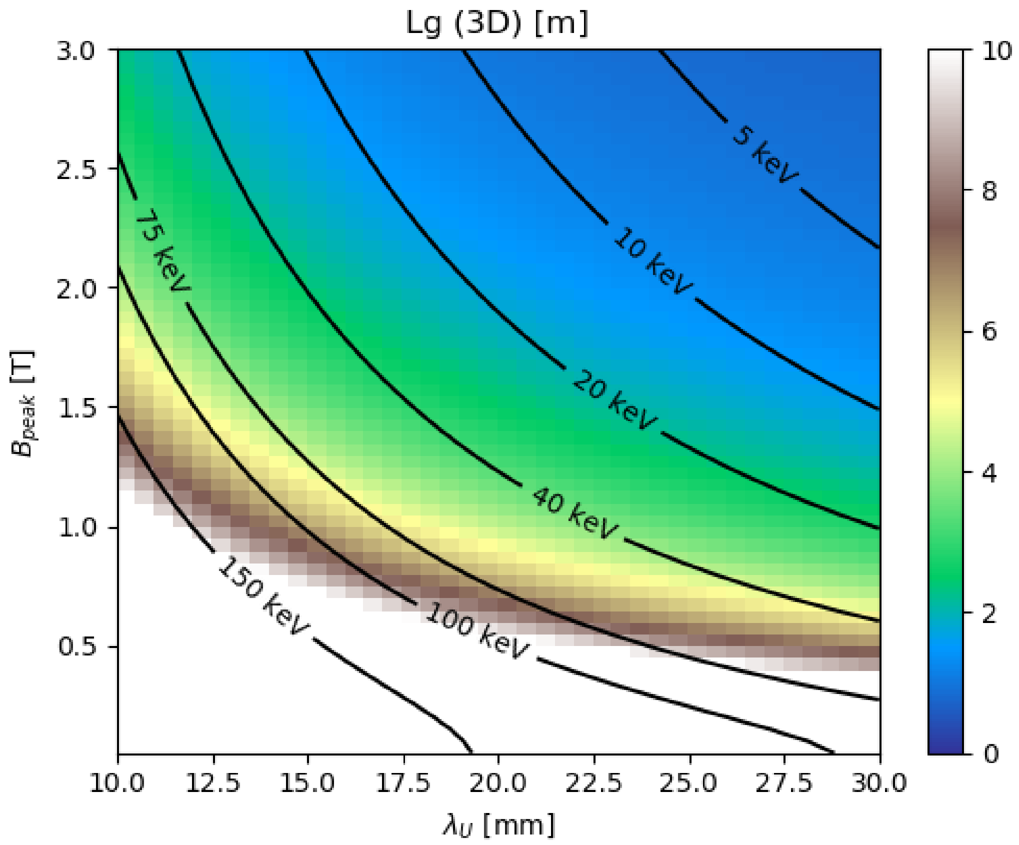
Methods to estimate FEL performance (3D gain length)

$$L_g^{3d} = L_g^{1d}(1+\delta)$$

■ Saldin, Schneydmiller, Yurkov



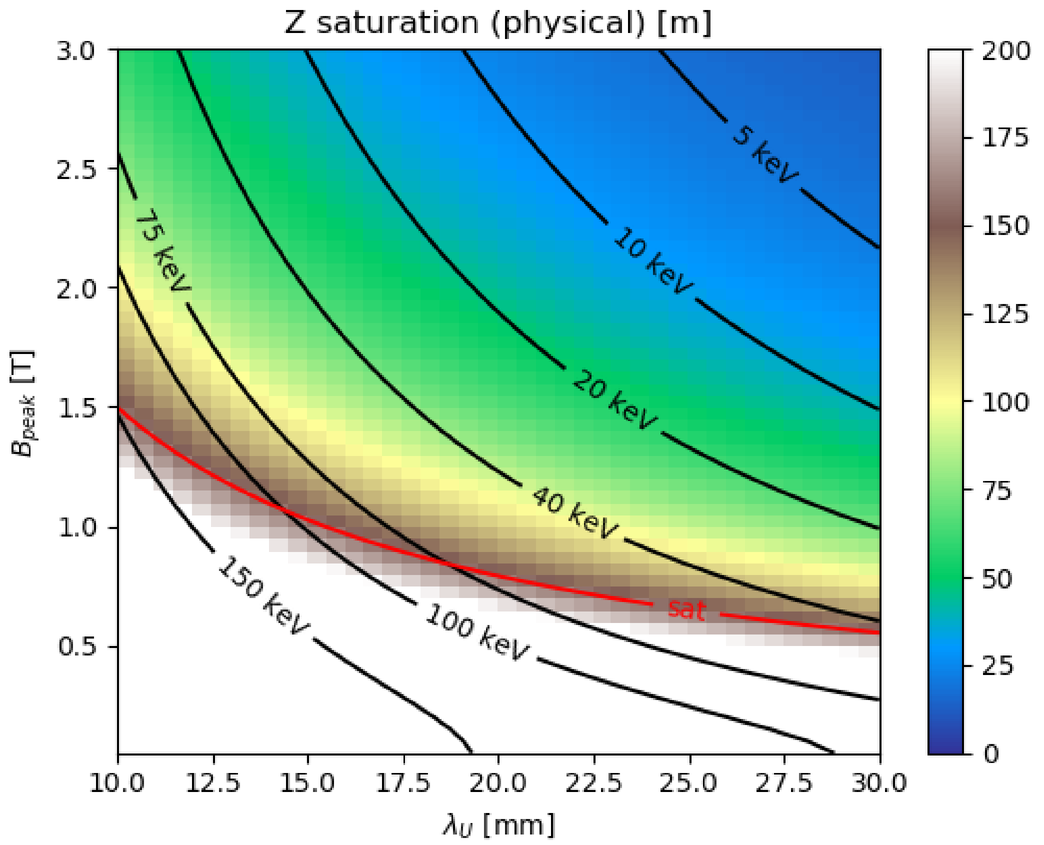
■ Xie

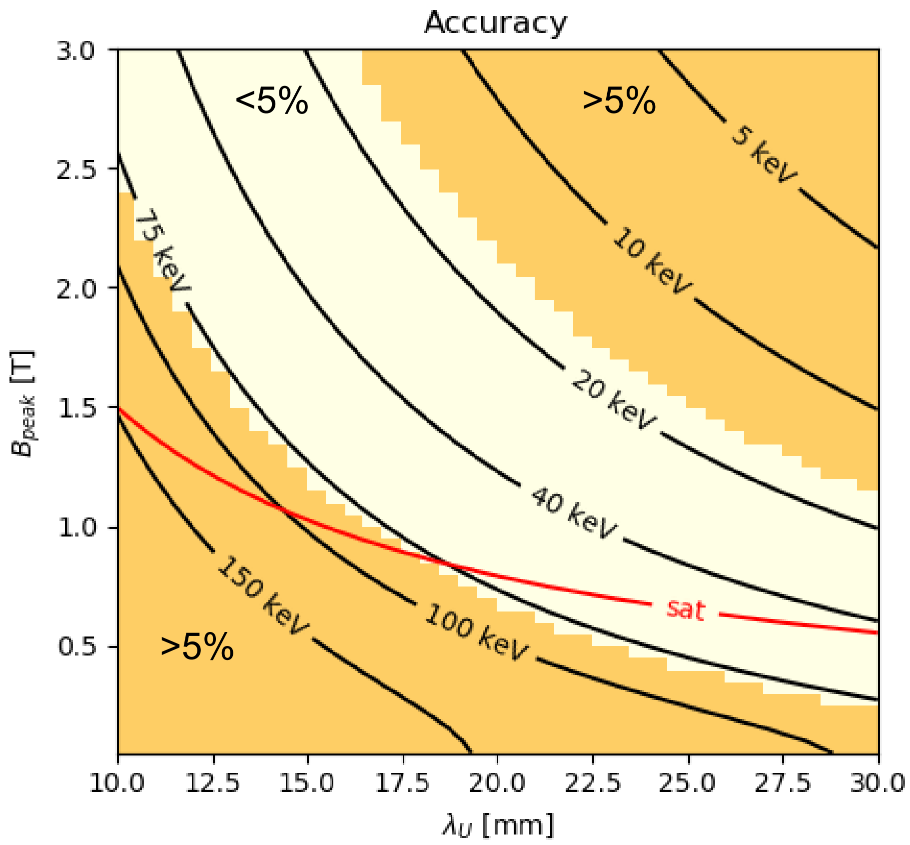


E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Design formulas for short-wavelength FELs," Opt. Commun., vol. 235, no. 4–6, pp. 415–420, May 2004.

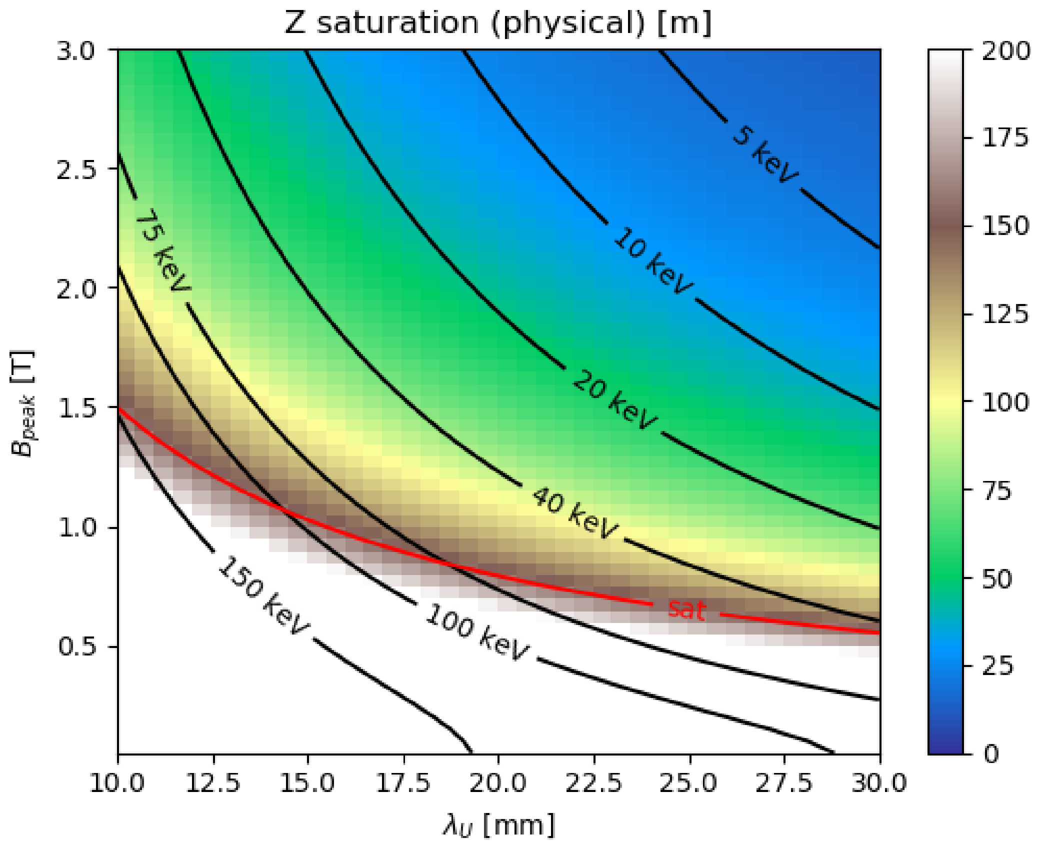
M. Xie, "Exact and variational solutions of 3D eigenmodes in high gain FELs," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 445, no. 1–3, pp. 59–66, 2000.

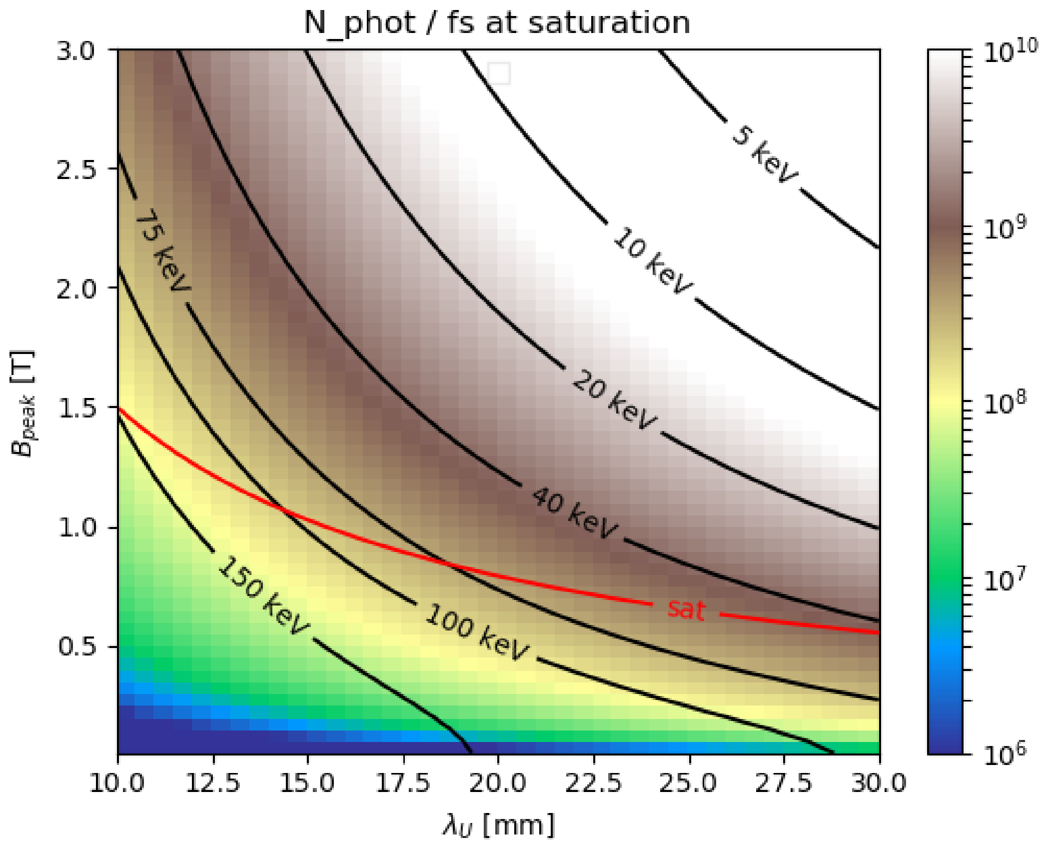
Saturation length and Accuracy



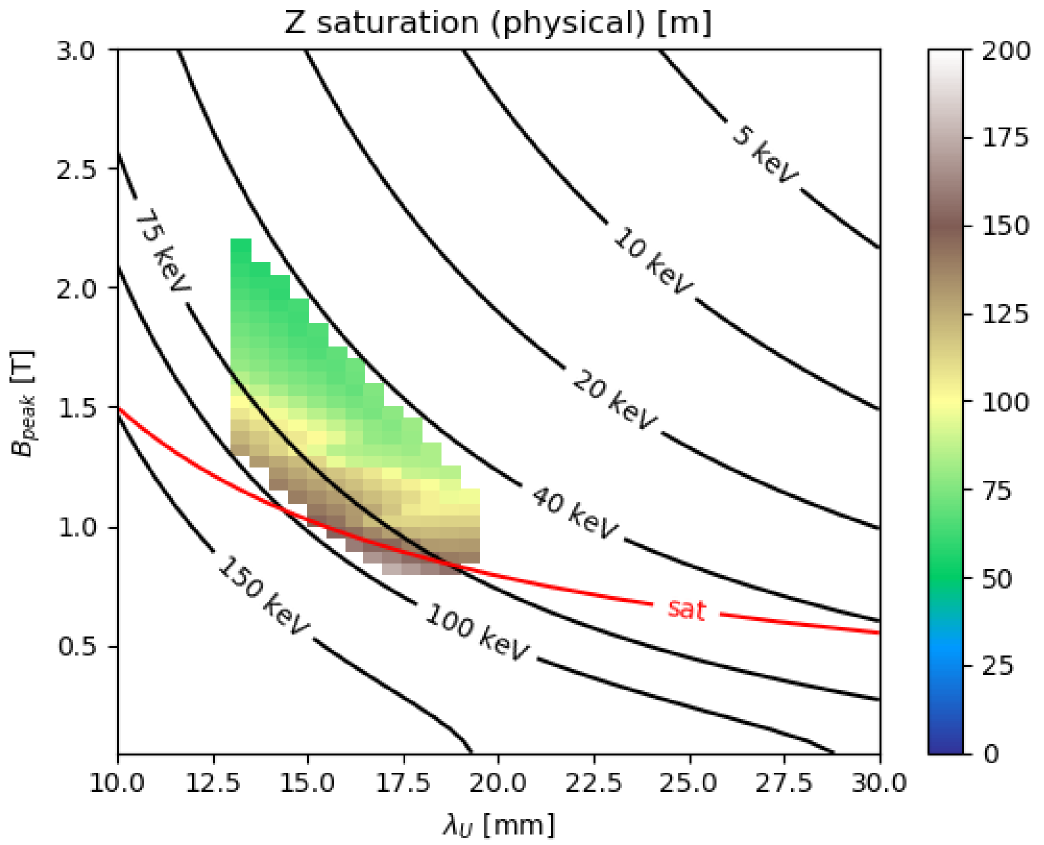


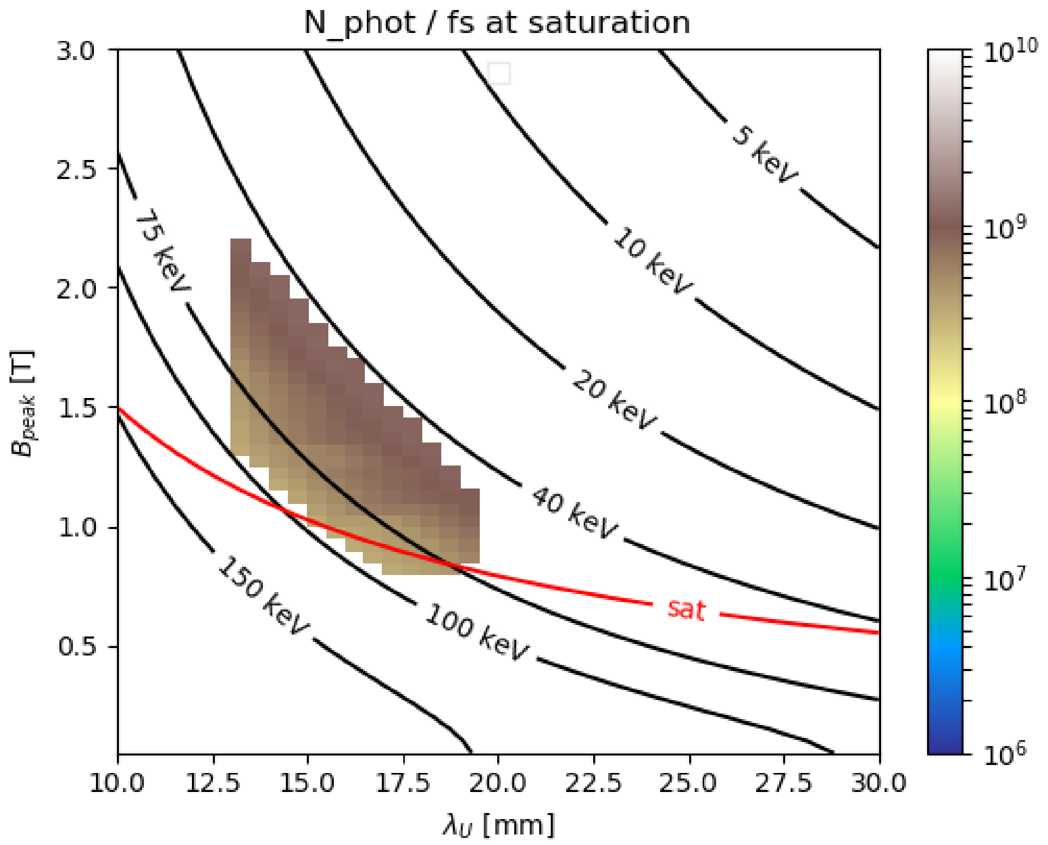
Saturation length and number of photons/femtosecond at saturation



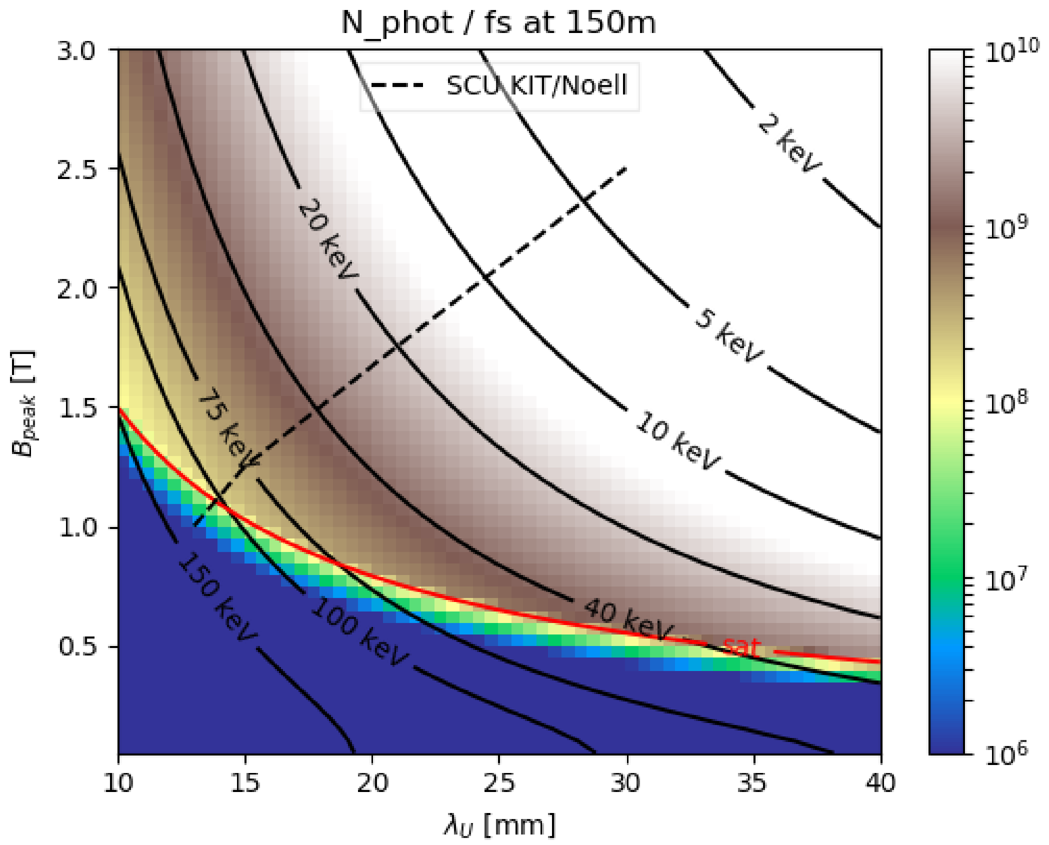


Results of numerical simulation (Genesis v2)



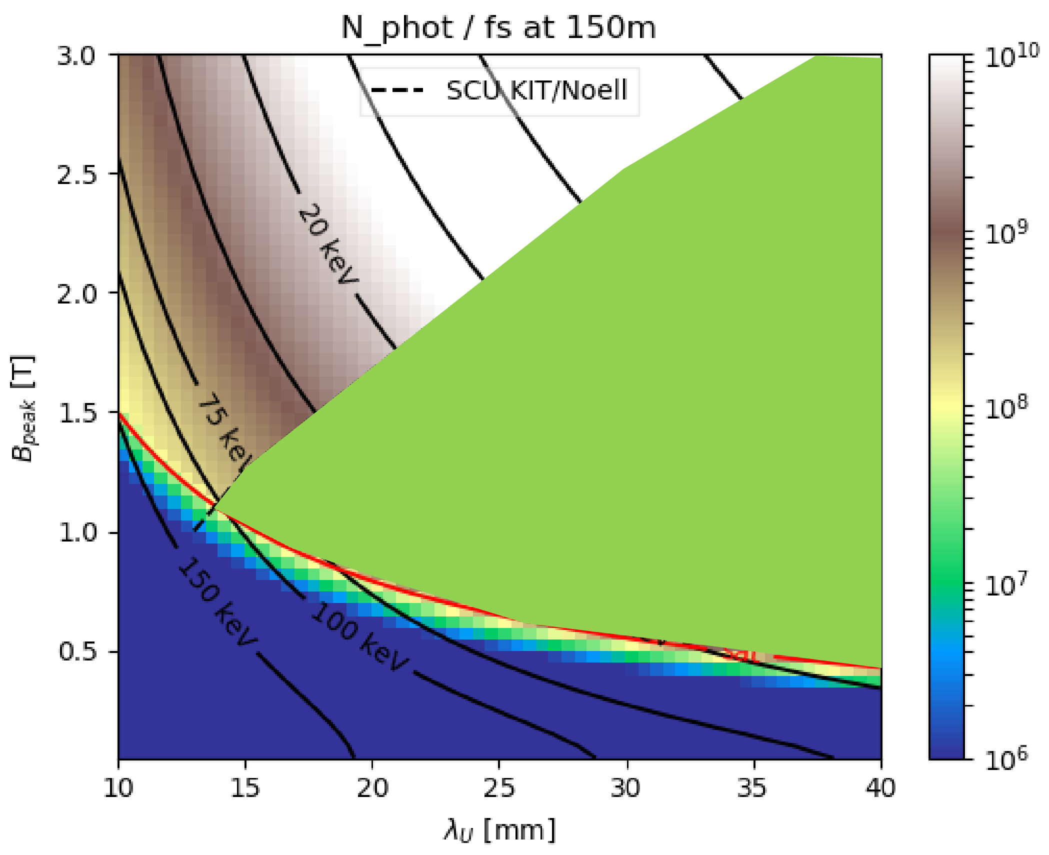


Estimated number of photons at the end of undulator



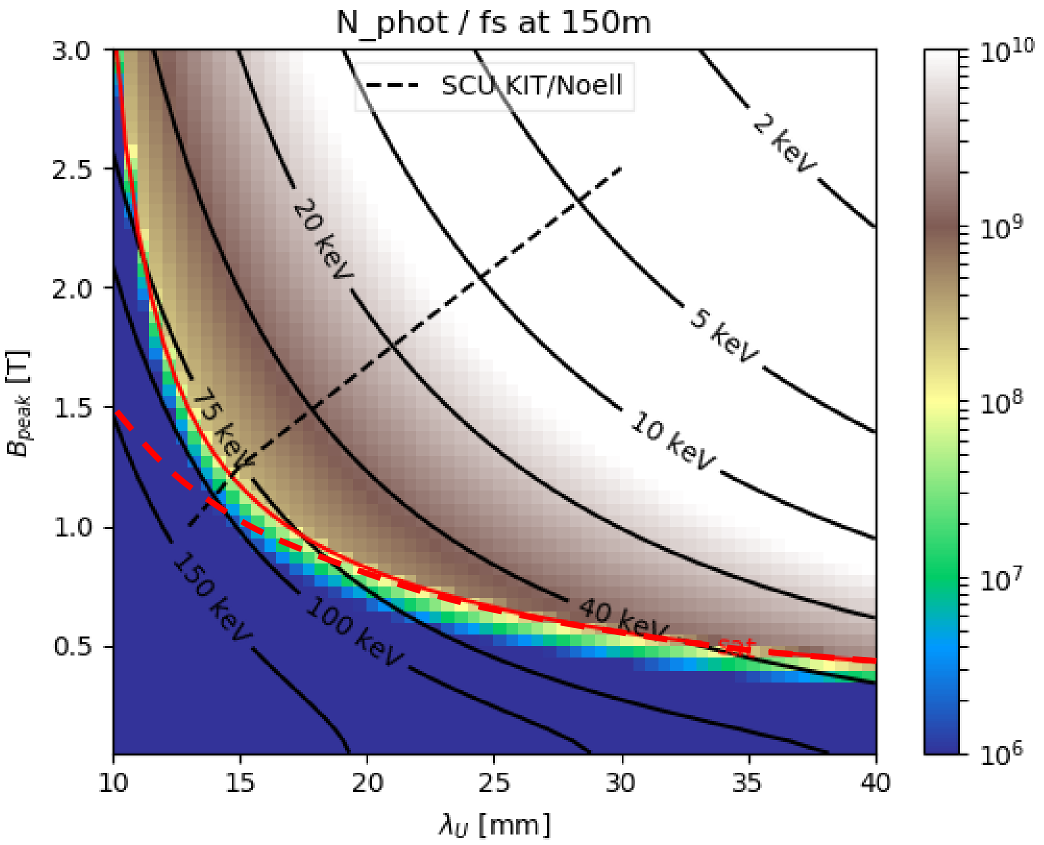
- Rough estimation, assuming
  no growth after- and exponential growth before saturation

Estimated number of photons at the end of undulator



- Rough estimation, assuming
  no growth after- and exponential growth before saturation
- Range of accessible photon energies

Effect of Quantum fluctuations at 17.5 GeV



$$\frac{d\sigma_\gamma^2}{dz} = \frac{14}{15} \lambda\!\!\!^{-}_c r_e \gamma^4 \kappa_w^3 K^2 F(K)$$

- FEL Gain at photon energies beyond 75keV is affected

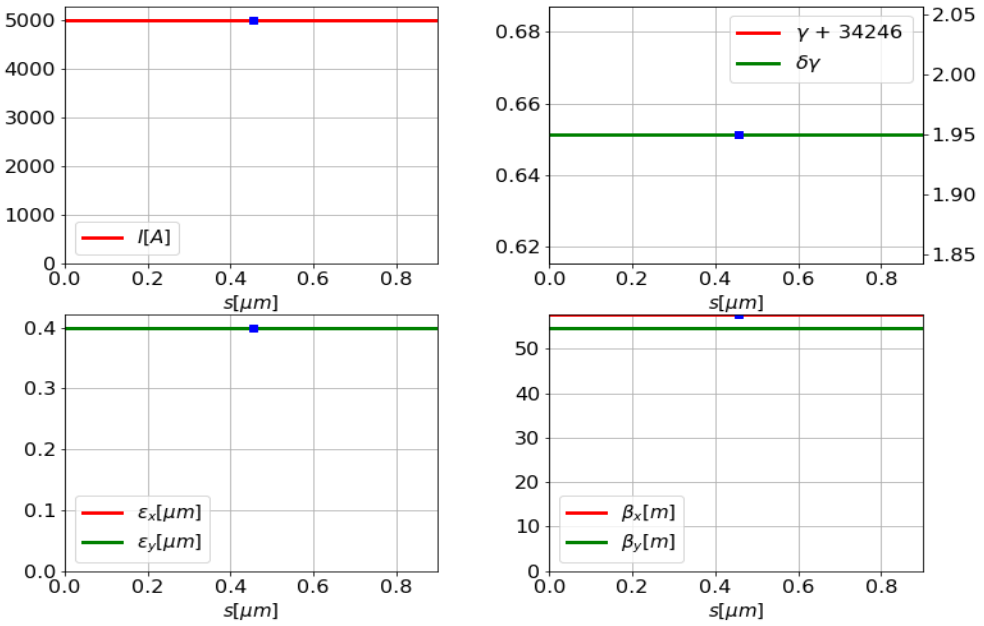
$$\delta_q = 5.5 \times 10^4 \left(\frac{I_A}{I}\right)^{3/2} \frac{\lambda\!\!\!^{-}_c r_e \epsilon_n^2}{\lambda_r^{11/4} \lambda_w^{5/4}} \frac{(1 + K^2)^{9/4} F(K)}{K A_{JJh}^3 h^{5/3}} \qquad \delta_{\text{eff}} = \frac{\delta + \delta_q}{1 - \delta_q},$$

[1] J. Rossbach, E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Fundamental limitations of an X-ray FEL operation due to quantum fluctuations of undulator radiation," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 393, no. 1–3, pp. 152–156, 1997.

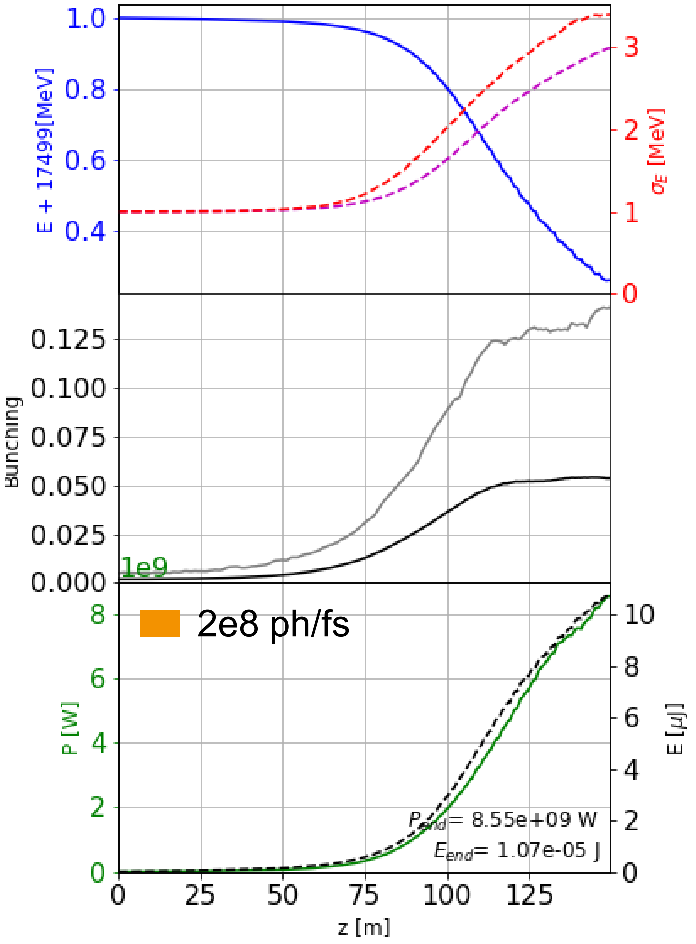
[2] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Design formulas for short-wavelength FELs," Opt. Commun., vol. 235, no. 4–6, pp. 415–420, May 2004.

Effect of Quantum fluctuations at 17.5 GeV, 100keV

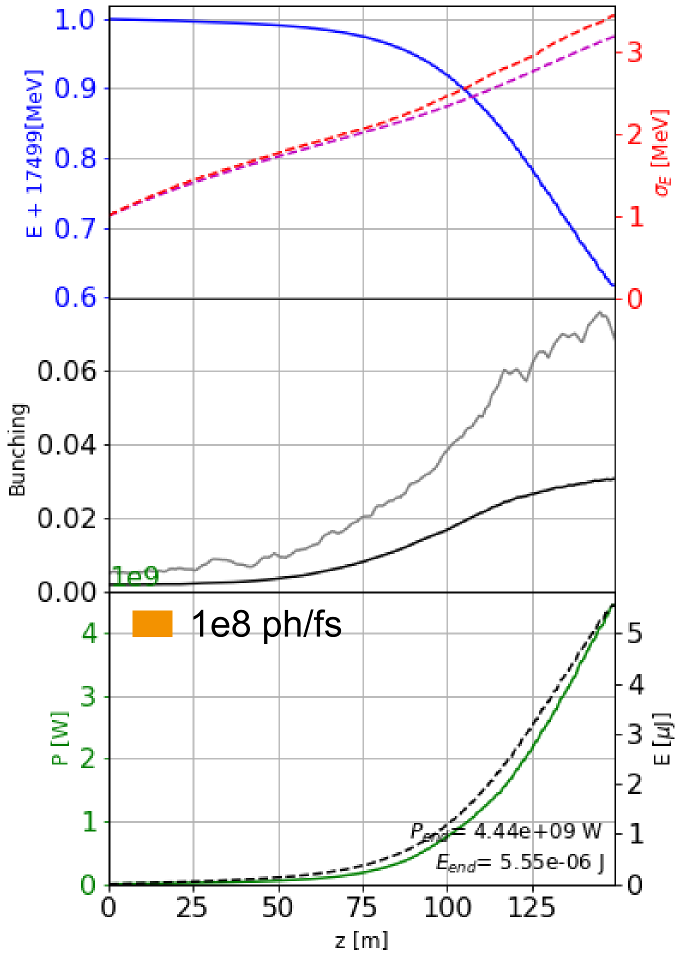
- Model beam



- no QF



- with QF



- Time-dependent Genesis simulation with model electron beam

Undulator period doubling

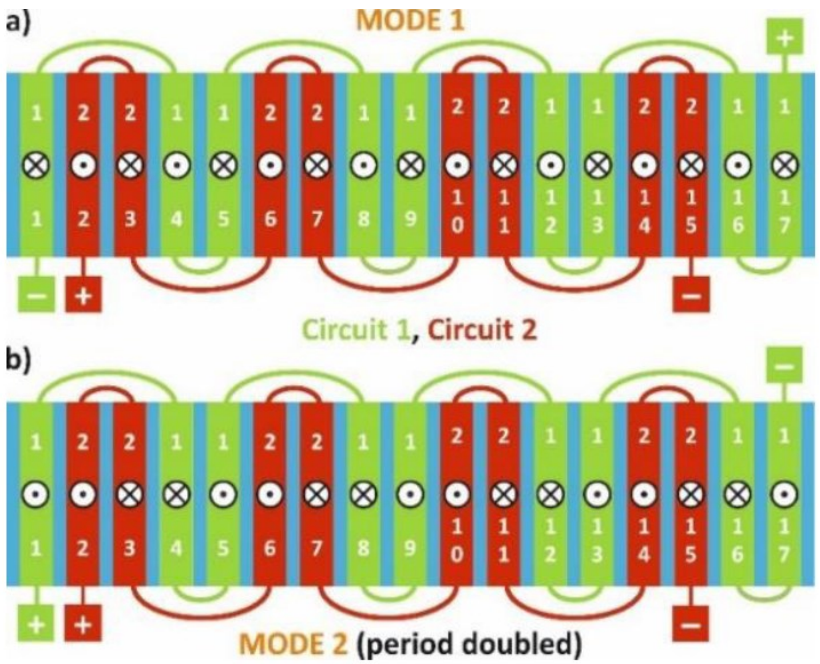


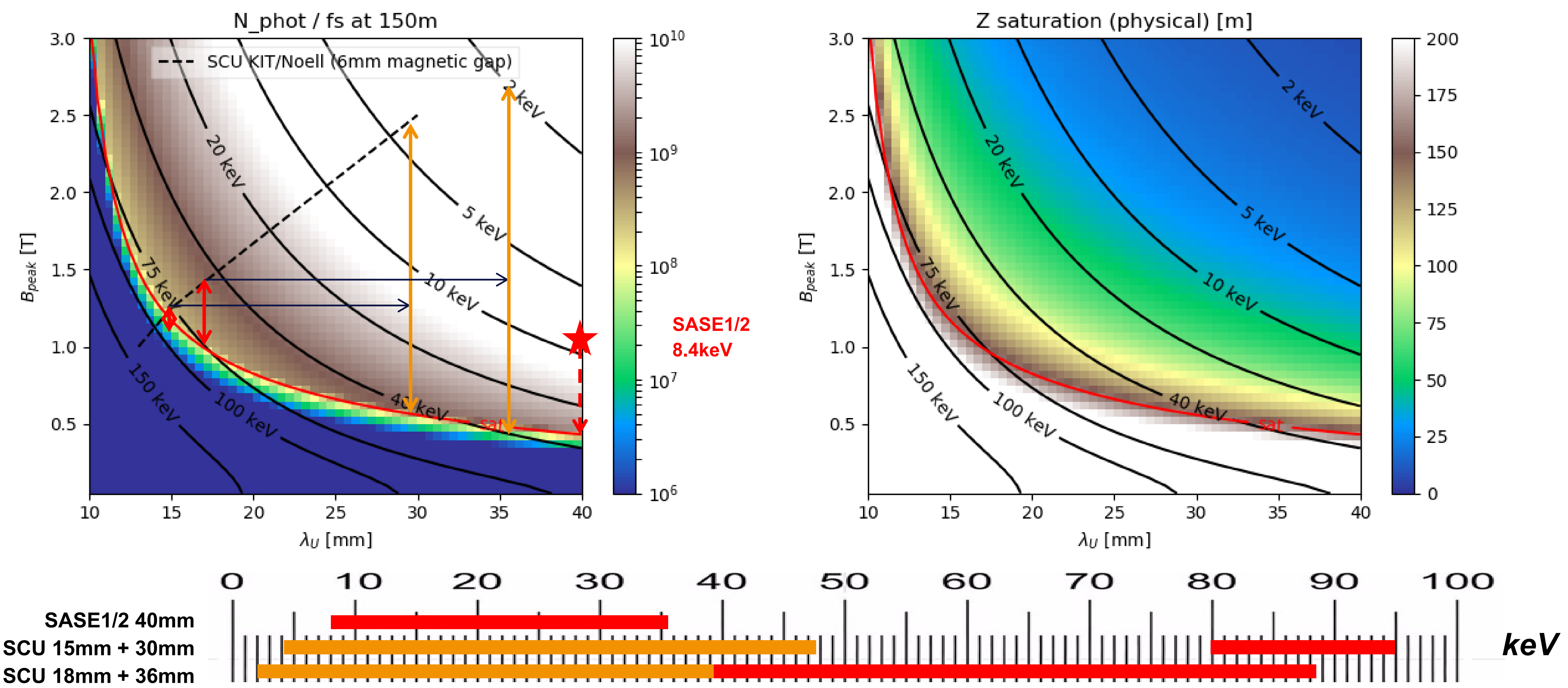
Figure 1: Sketch of period length doubling for superconducting undulators by changing the current direction in one subset of windings.

$$\lambda_r = \frac{\lambda_u[m] + (93 B_{rms}[T])^2 \lambda_u^3[m]}{2\gamma^2}$$

- Increasing undulator period allows to significantly reduce resonant photon energy

T. Holubek, S. Casalbuoni, S. Gerstl, N. Glamann, A. Grau, C. Meuter, and D. S. de Jauregui, “Design and Tests of Switchable Period Length Superconducting Undulator Coils,” in IPAC, 2018, pp. 4226–4228.

Undulator period doubling (17.5GeV)



CW operation (7.8 GeV)

$$\lambda_r = \frac{\lambda_u[m] + (93B_{rms}[T])^2\lambda_u^3[m]}{2\gamma^2}$$

TABLE VI. Beam energy and DF estimated for the upgraded XFEL accelerator.

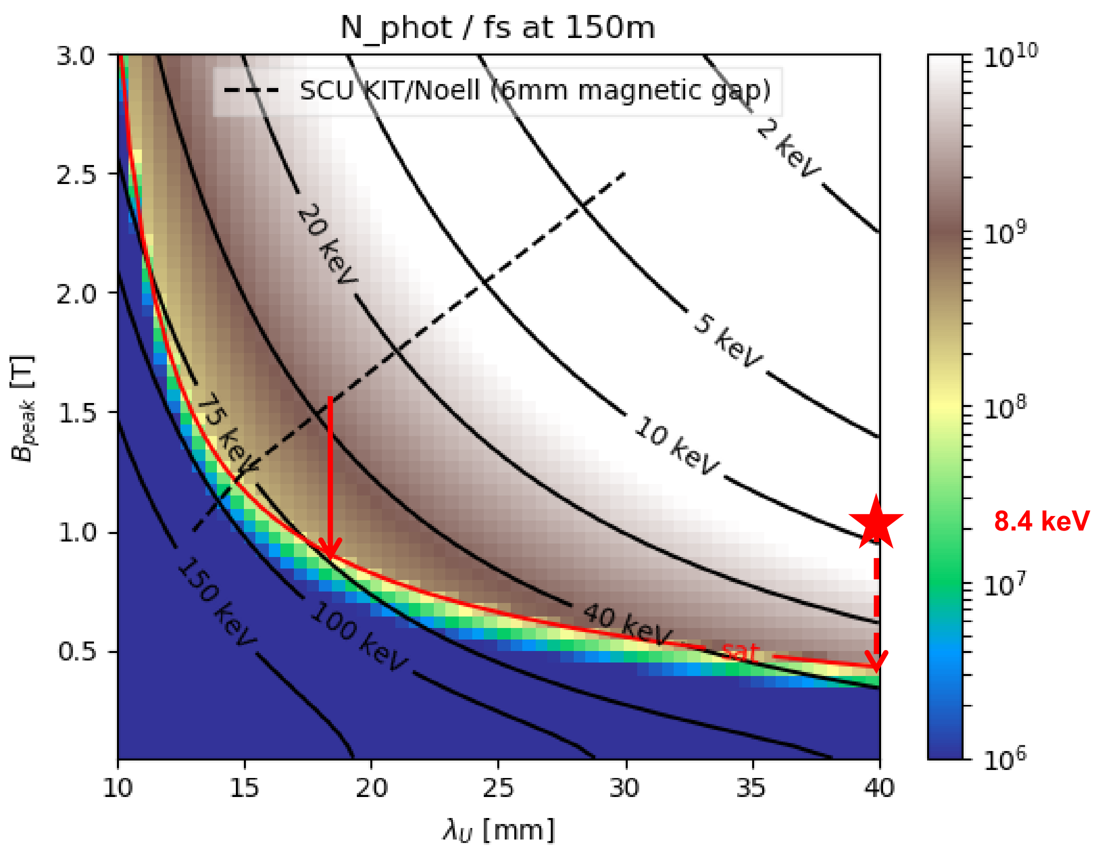
Operation mode	E_{beam} [GeV]	E_{acc} in ML [MV/m]	Beam-on DF [%]
sp (nominal)	19.8	23.4	0.6
cw	7.8	7.3	100
lp	10	10	53
lp	14	15	23

[1] J. Sekutowicz, V. Ayvazyan, M. Barlak, J. Branlard, W. Cichalewski, W. Grabowski, D. Kostin, J. Lorkiewicz, W. Merz, R. Nietubyc, R. Onken, A. Piotrowski, K. Przygoda, E. Schneidmiller, and M. Yurkov, "Research and development towards duty factor upgrade of the European X-Ray Free Electron Laser linac," Phys. Rev. Spec. Top. - Accel. Beams, vol. 18, no. 5, pp. 1–9, 2015.

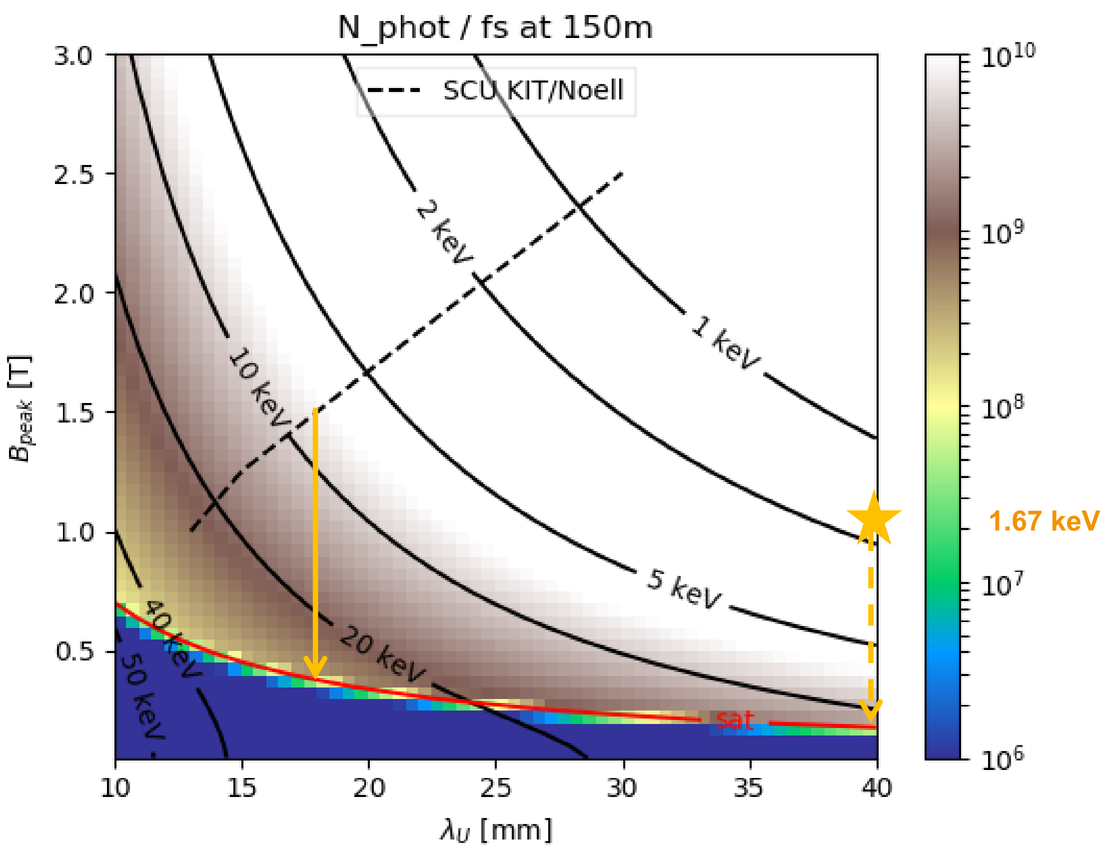
[2] R. Brinkmann, E. A. Schneidmiller, J. Sekutowicz, and M. V. Yurkov, "Prospects for CW and LP operation of the European XFEL in hard X-ray regime," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 768, pp. 20–25, Mar. 2014.

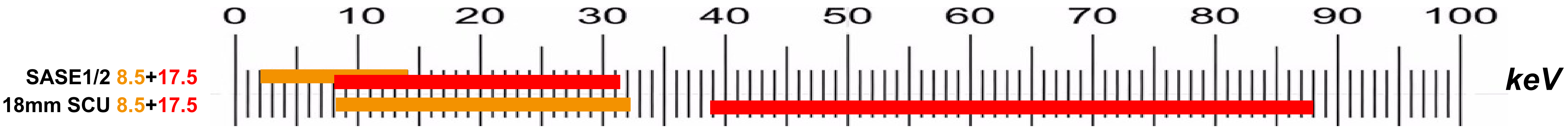
CW operation (7.8 GeV)

17.5 GeV



7.8 GeV





Comparison with harmonic lasing

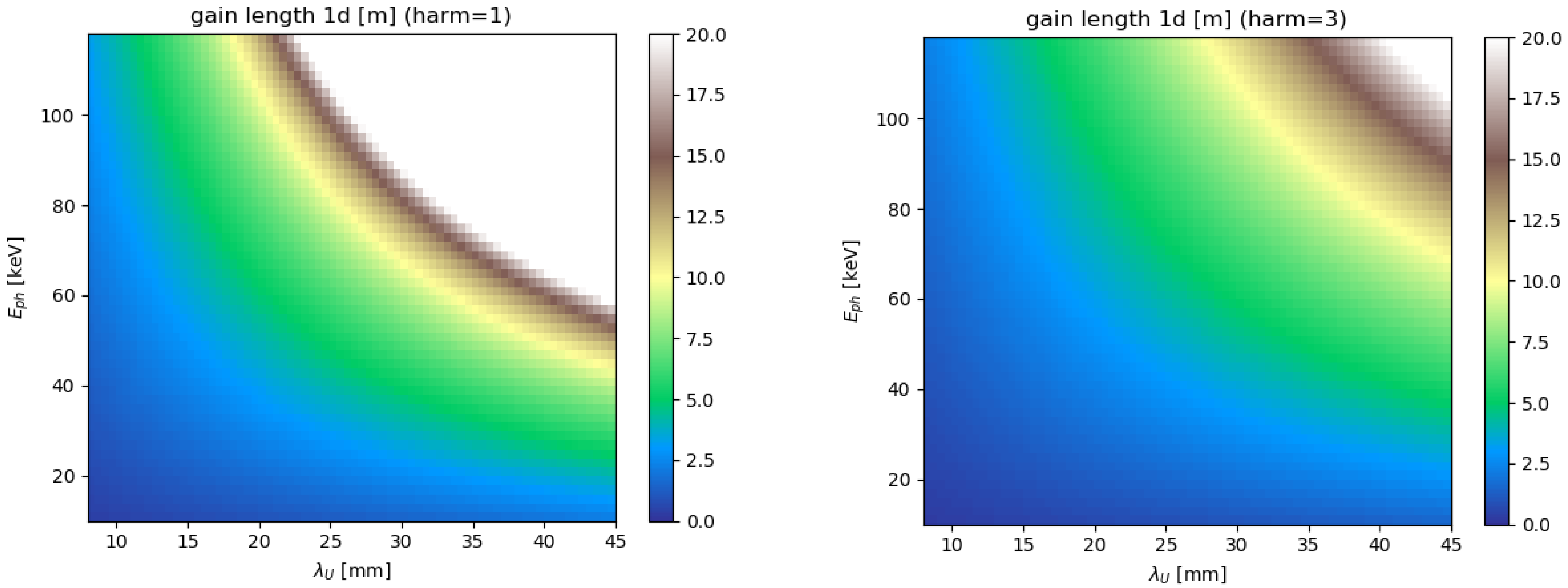
$$h\lambda_{wh}(1+K_h^2) = \lambda_{wSC}(1+K_{SC}^2)$$

$$L_{g0SC} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{wSC})^{5/6}}{\lambda_t^{2/3}} \frac{(1+K_{SC}^2)^{1/3}}{KA_{JJSC}}$$

$$L_{g0h} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{wh})^{5/6}}{\lambda_t^{2/3}} \frac{(1+K_h^2)^{1/3}}{h^{5/6}KA_{JJh}}$$

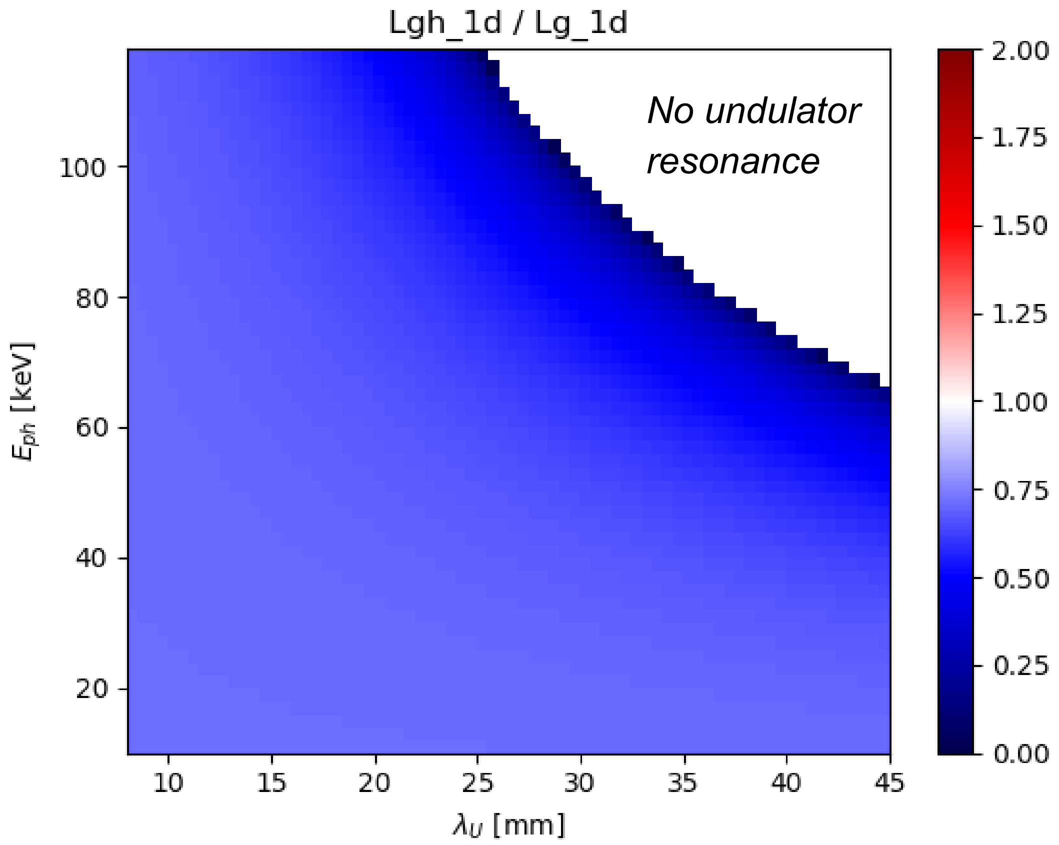
E. A. Schneidmiller and M. V. Yurkov, “Harmonic lasing in x-ray free electron lasers,” Phys. Rev. Spec. Top. - Accel. Beams, vol. 15, no. 8, p. 080702, Aug. 2012.

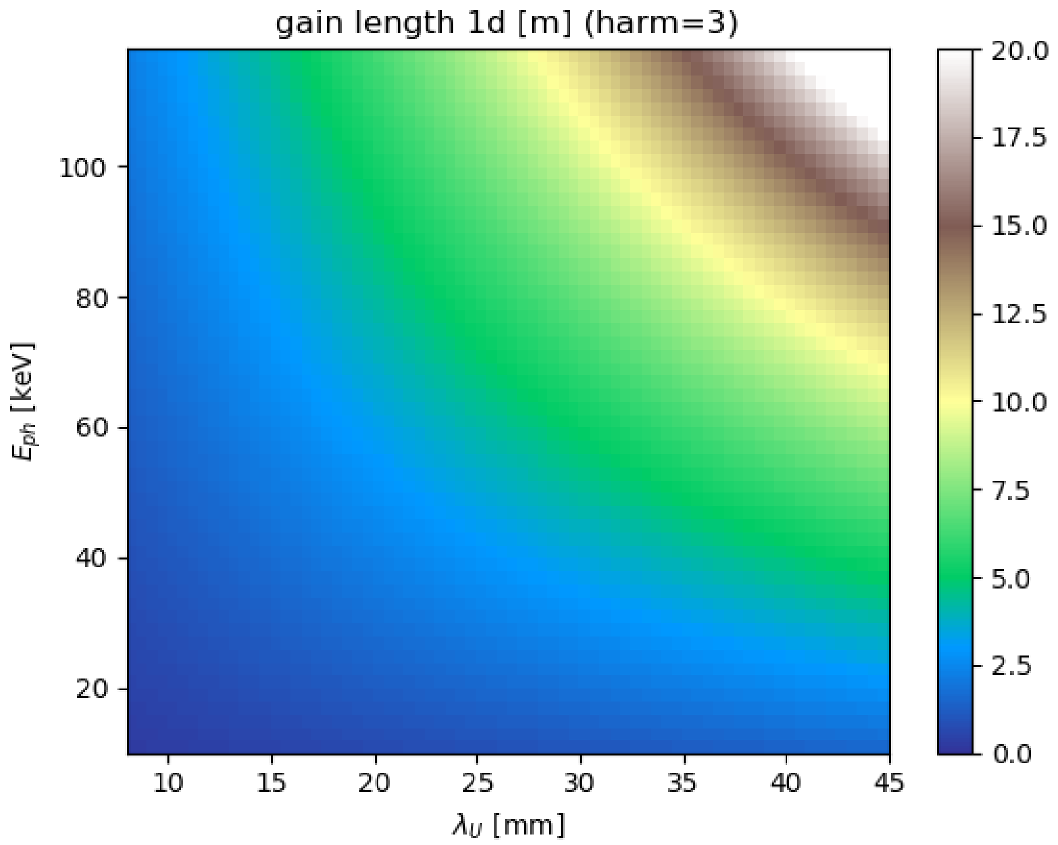
Comparison with harmonic lasing



- Harmonic lasing is superior for the same combination of λ_u and E_{photon}

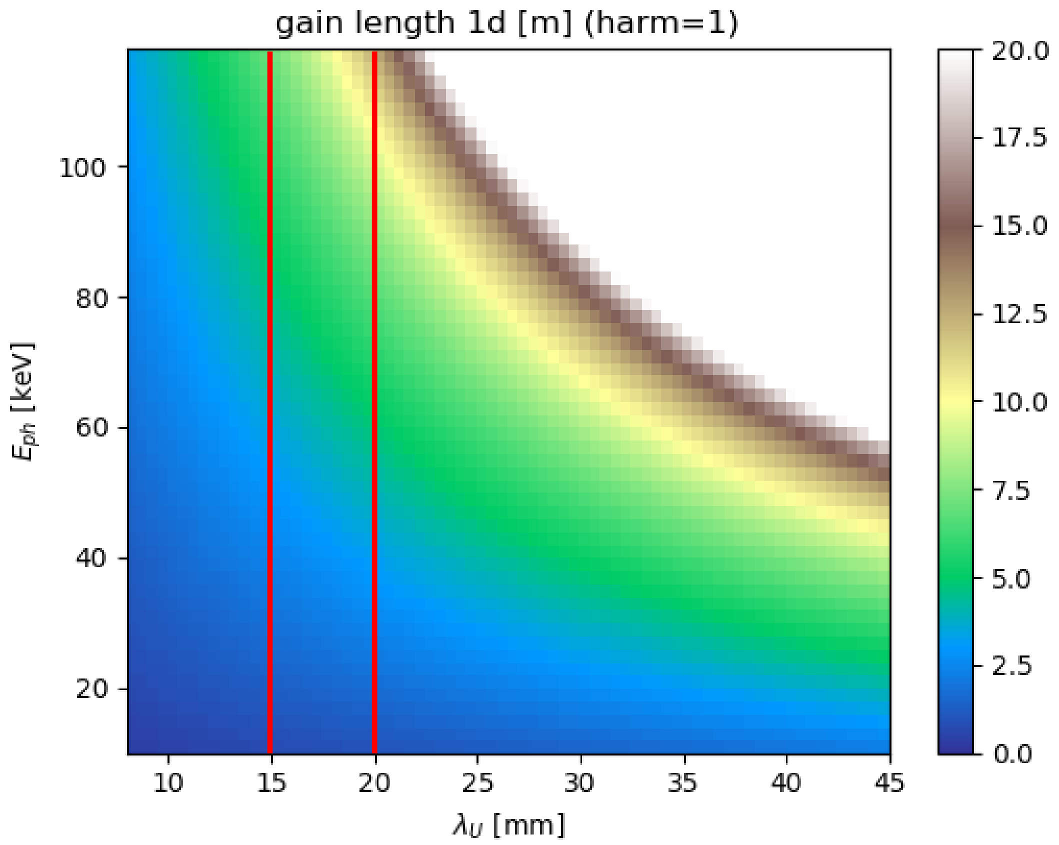
Comparison with harmonic lasing

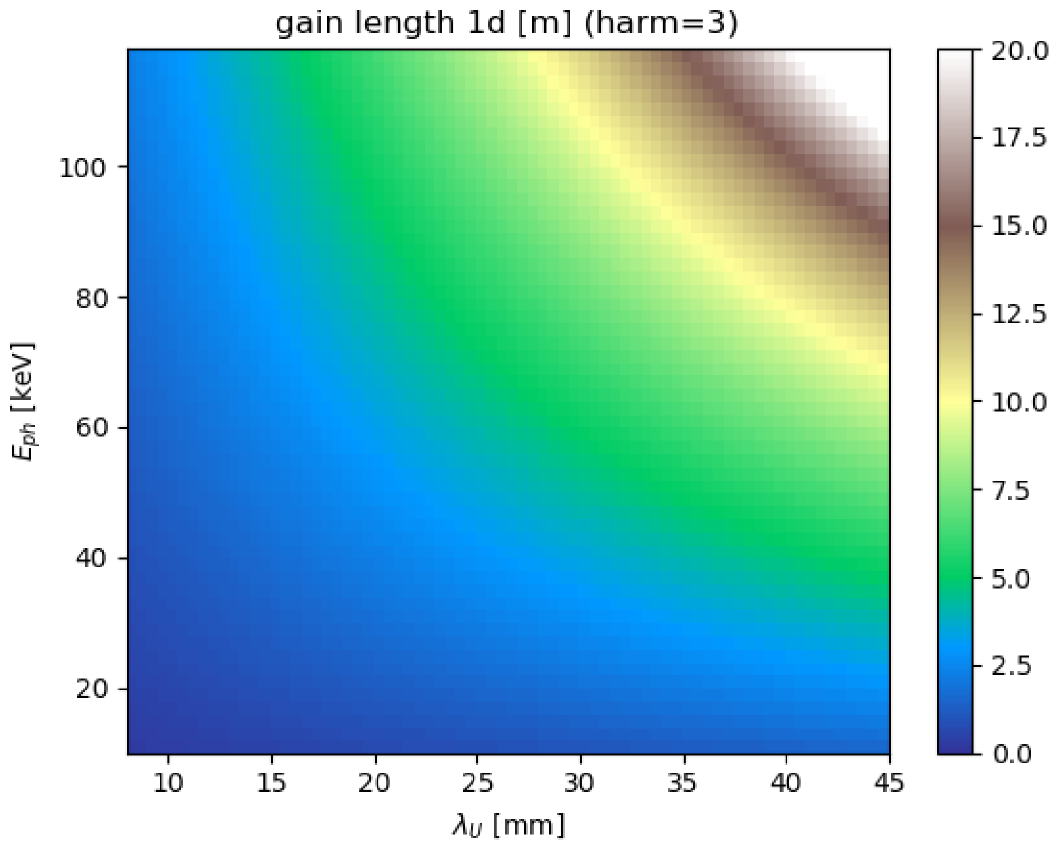




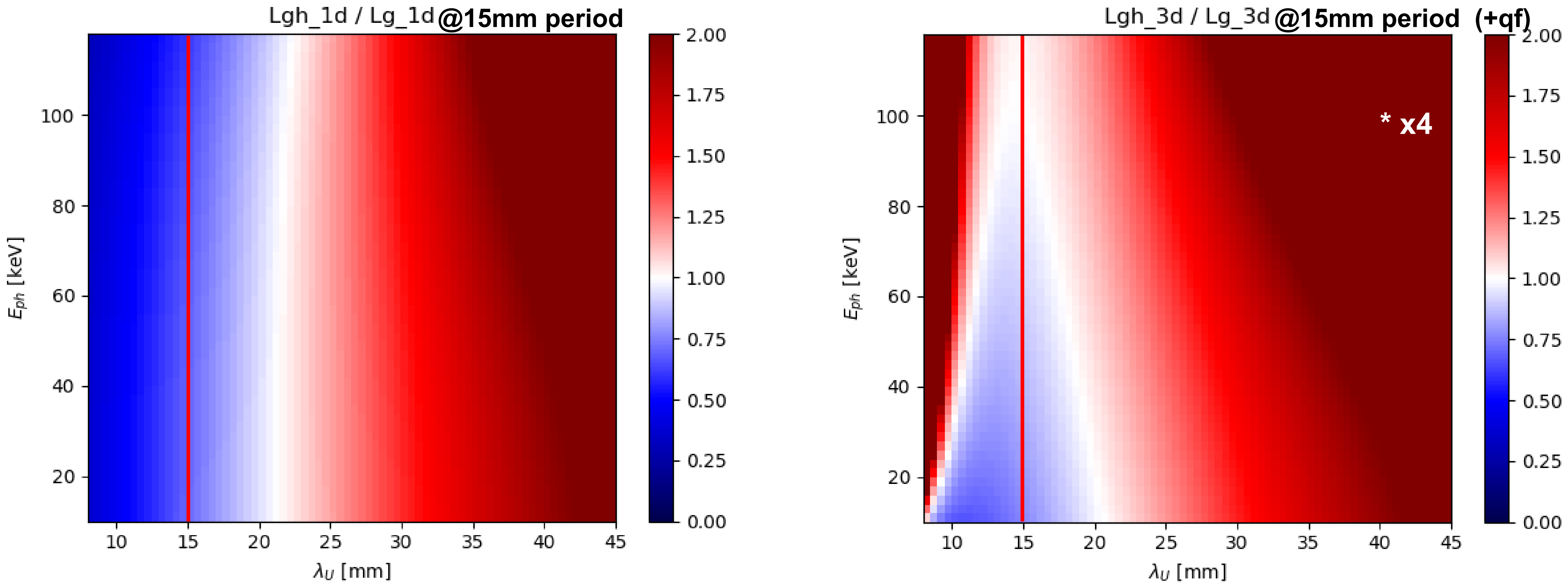
- Harmonic lasing is superior for the same combination of λ_u and E_{photon}

Comparison with harmonic lasing



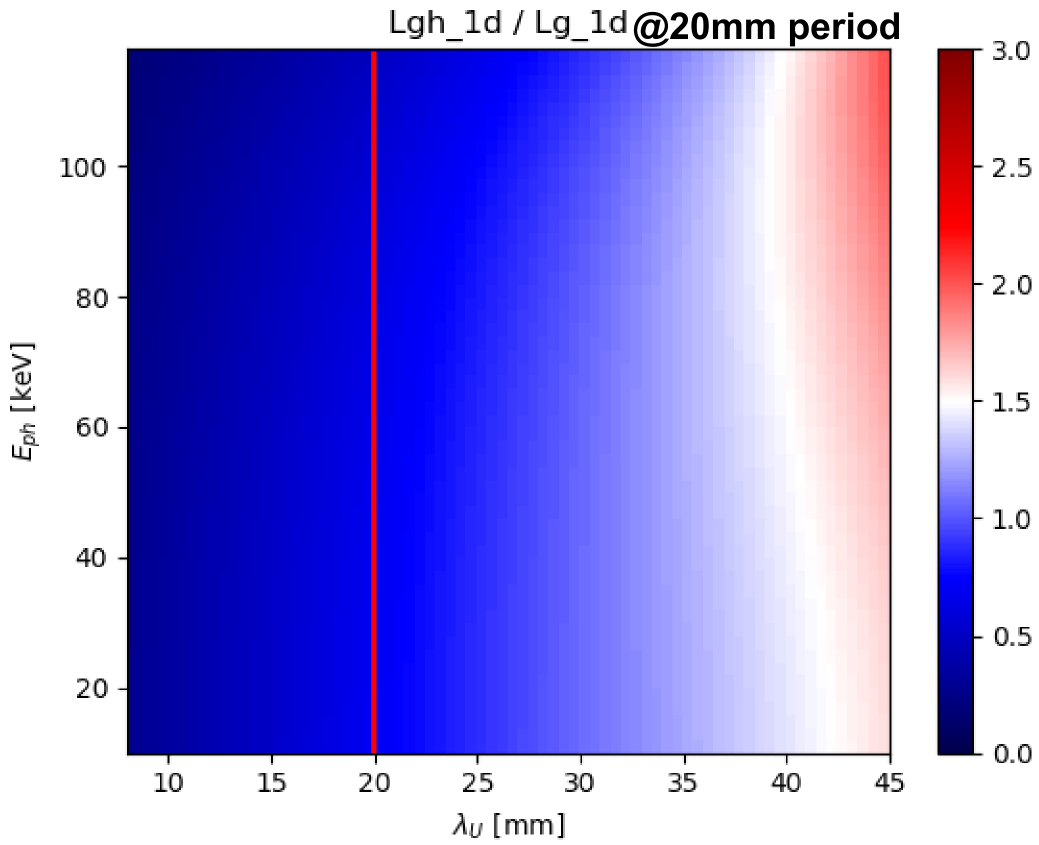


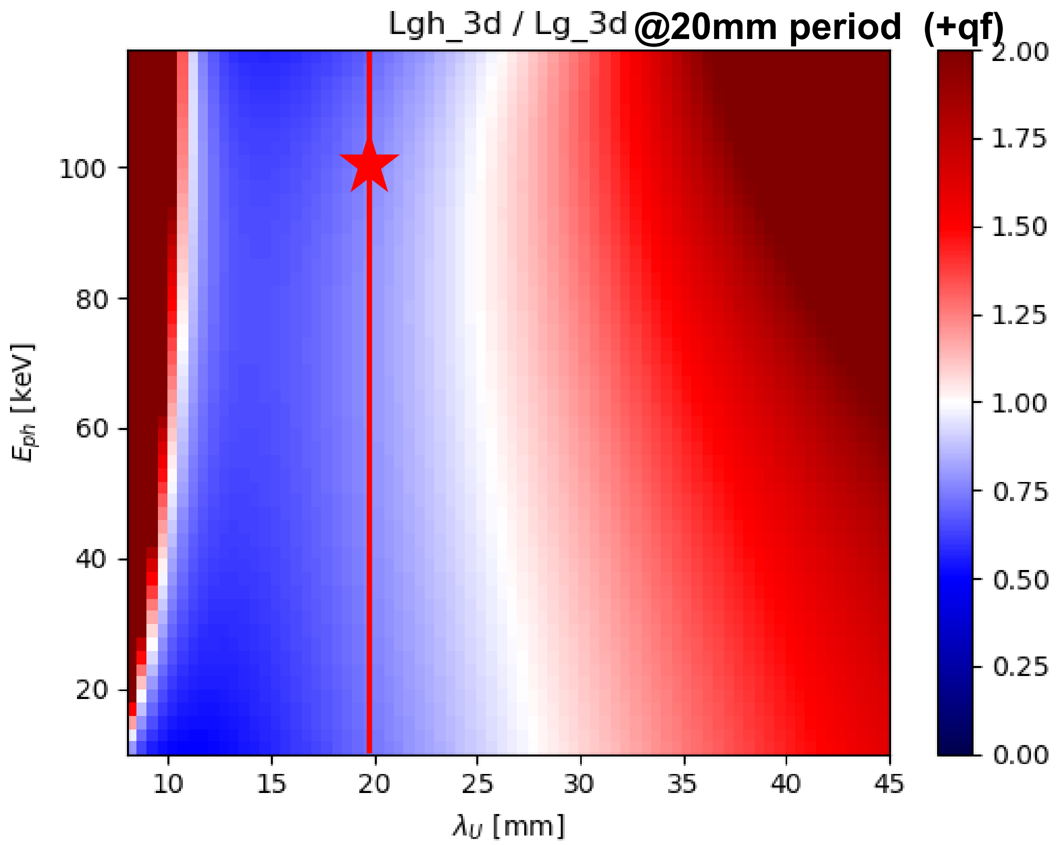
Comparison with harmonic lasing



■ Comparison with λ_u=15mm at fundamental

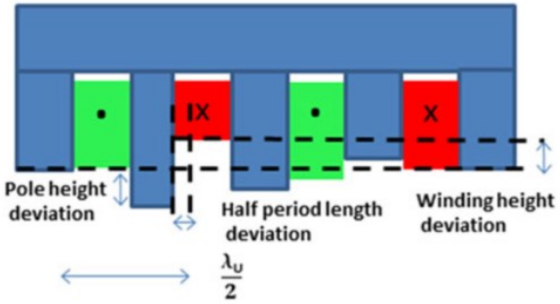
Comparison with harmonic lasing

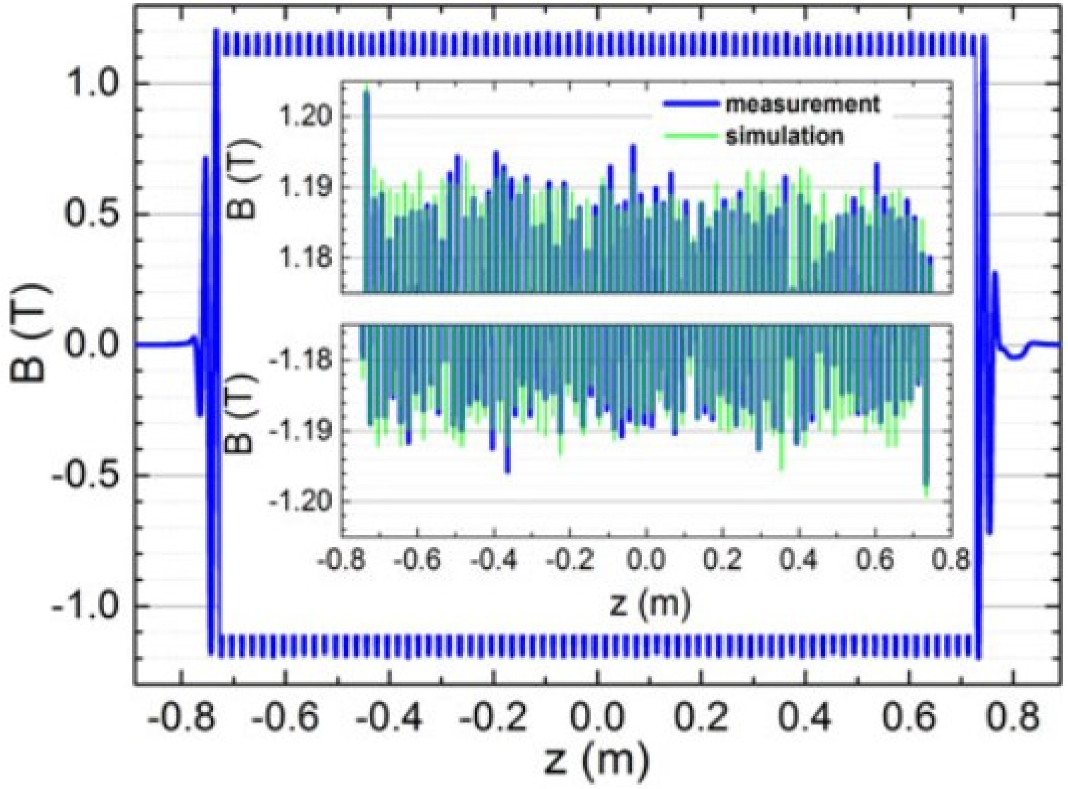




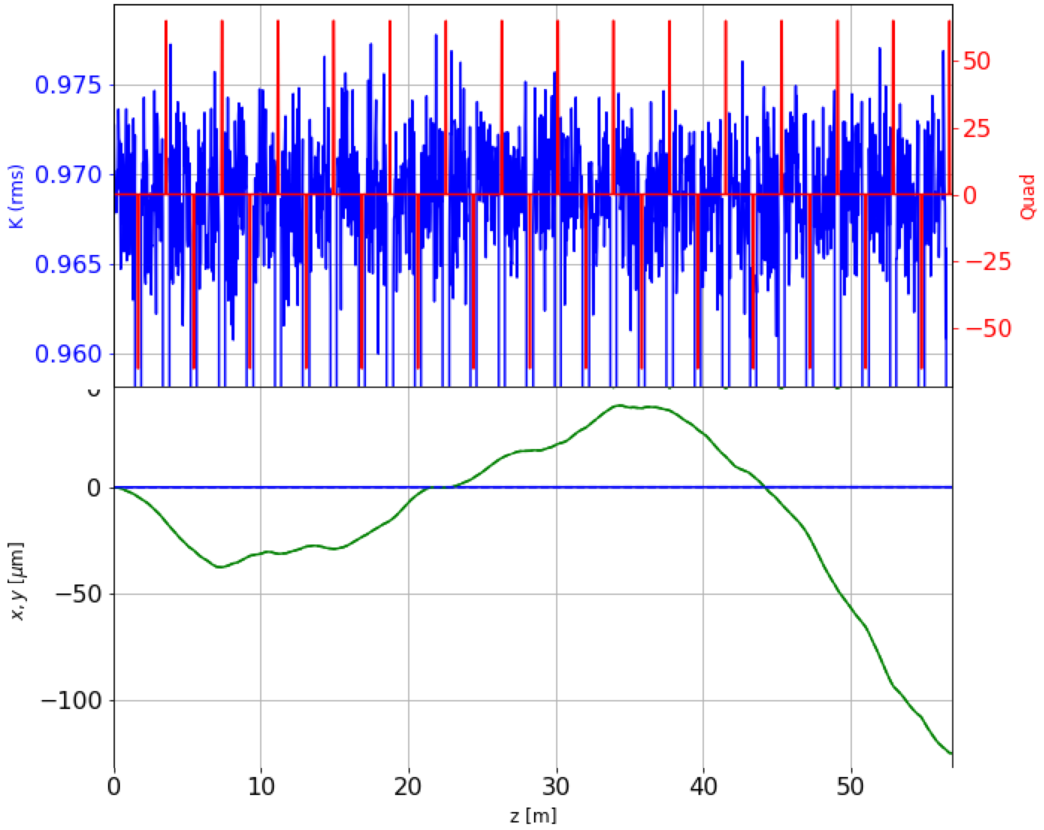
- Comparison with λ_u=20mm at fundamental

Effect of undulator field errors





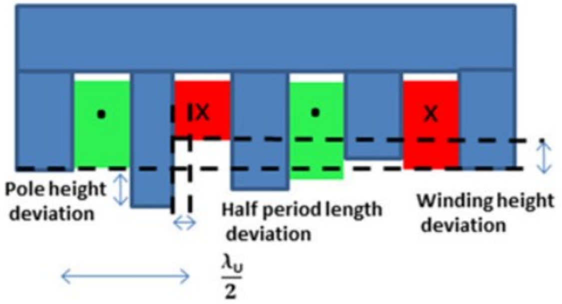
σ_K/K=0.3% period-wise field error (rms)

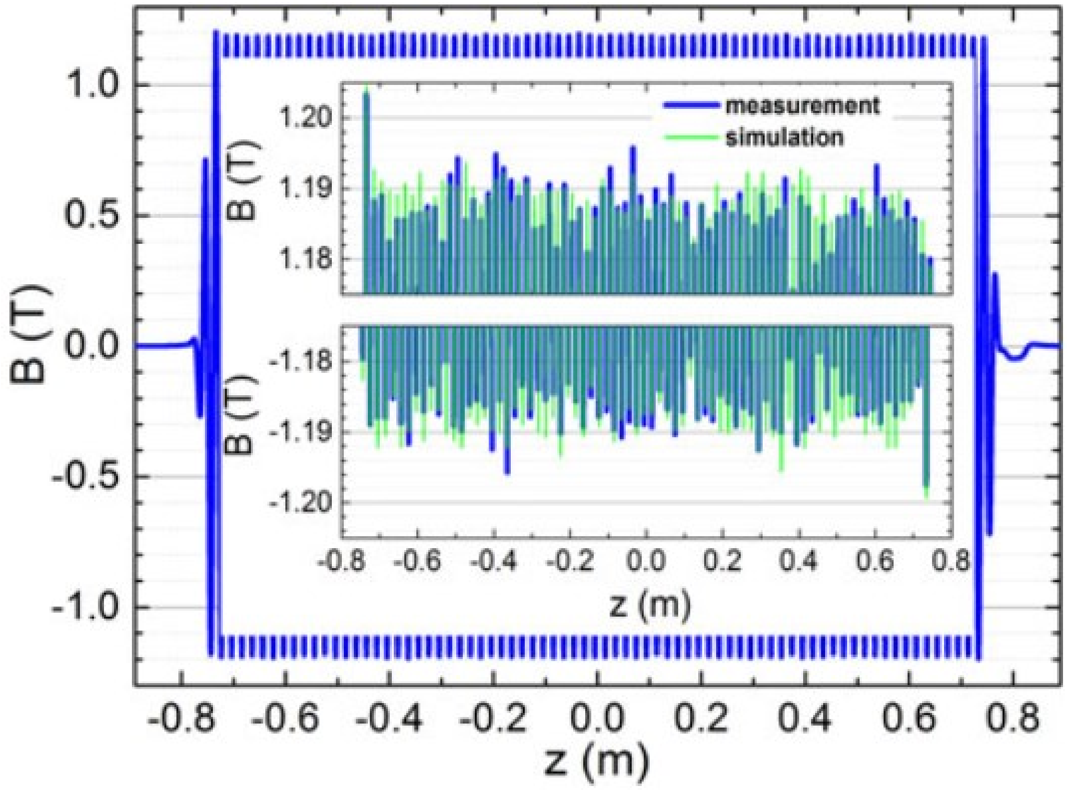


S. Casalbuoni, N. Glamann, A. Grau, T. Holubek, D. S. de Jauregui, C. Boffo, T. Gerhard, M. Turenne, and W. Walter, "Magnetic Field Measurements of Full-Scale Conduction-Cooled Superconducting-Undulator-Coils," IEEE Trans. Appl. Supercond., vol. 28, no. 3, pp. 1–4, Apr. 2018.

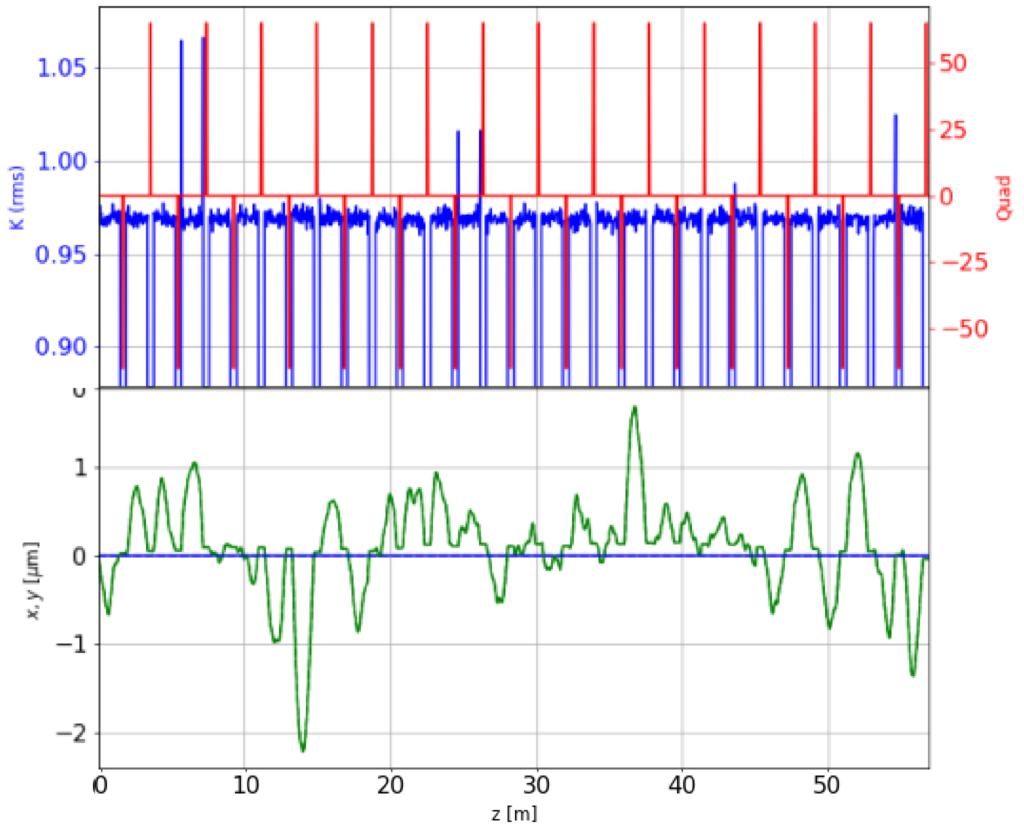
Y. Li, B. Faatz, and J. Pflueger, "Study of undulator tolerances for the European XFEL," 29th Int. Free Electron Laser Conf. FEL 2007, pp. 330–333, 2007.

Effect of undulator field errors





- σ_K/K=0.3% period-wise field error (rms)
- Corrected field integrals



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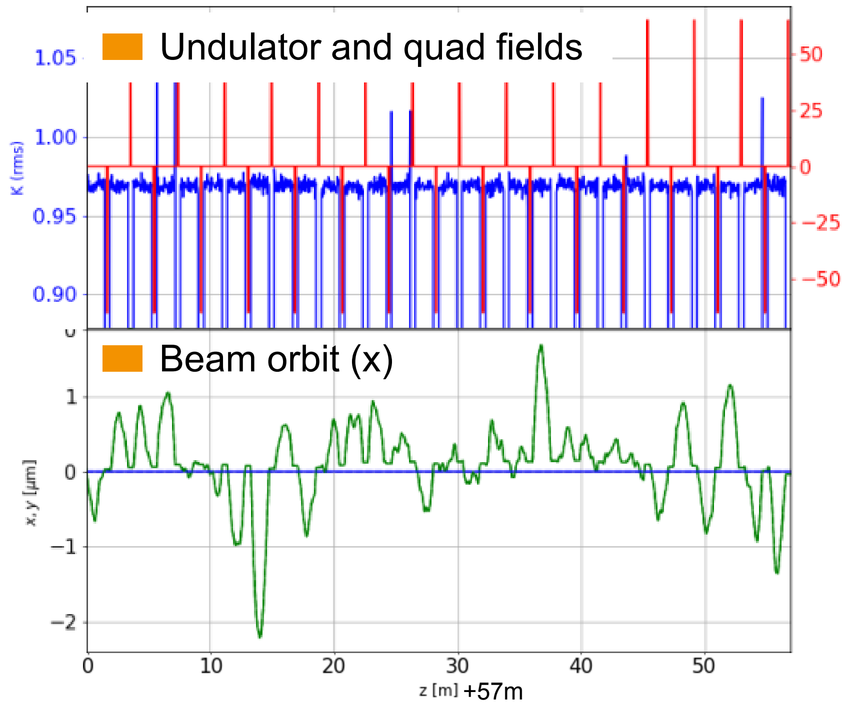
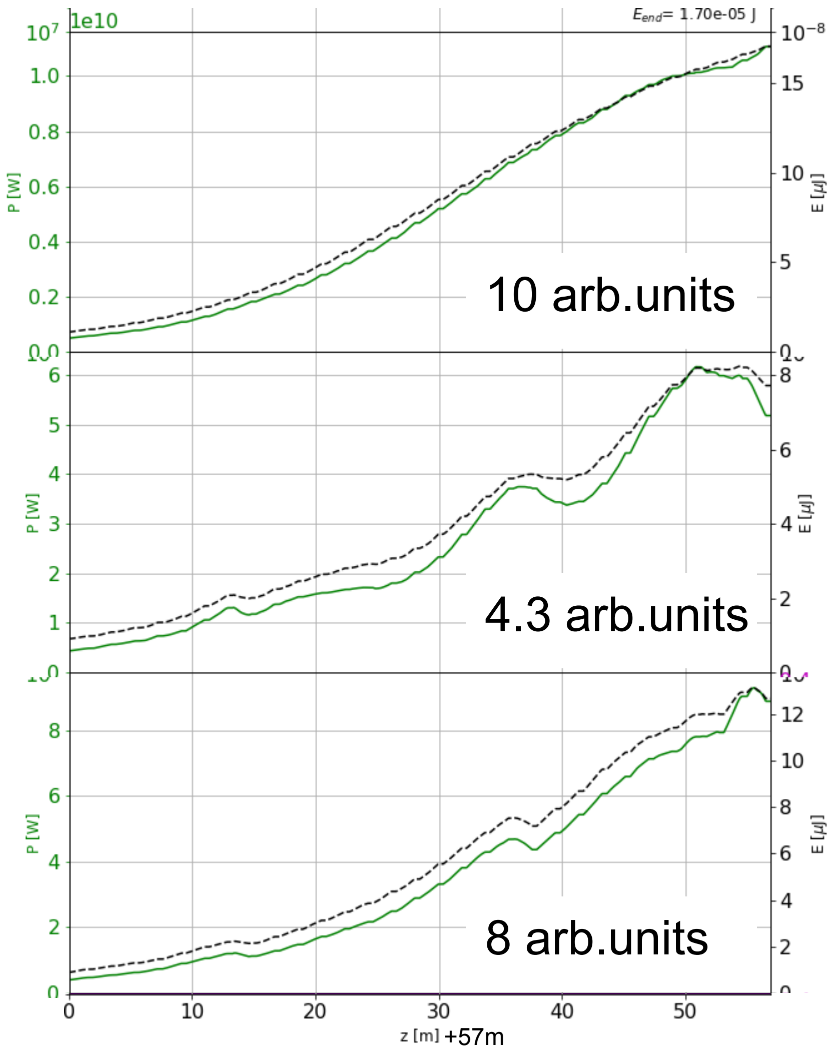
Y. Li, B. Faatz, and J. Pflueger, "Study of undulator tolerances for the European XFEL," 29th Int. Free Electron Laser Conf. FEL 2007, pp. 330–333, 2007.

Effect of undulator field errors

- 100keV = 0.12 Angstom

- 100keV, 15mm period
- Phase-shake effect
- Added path was calculated
  and compensated with phase shifter

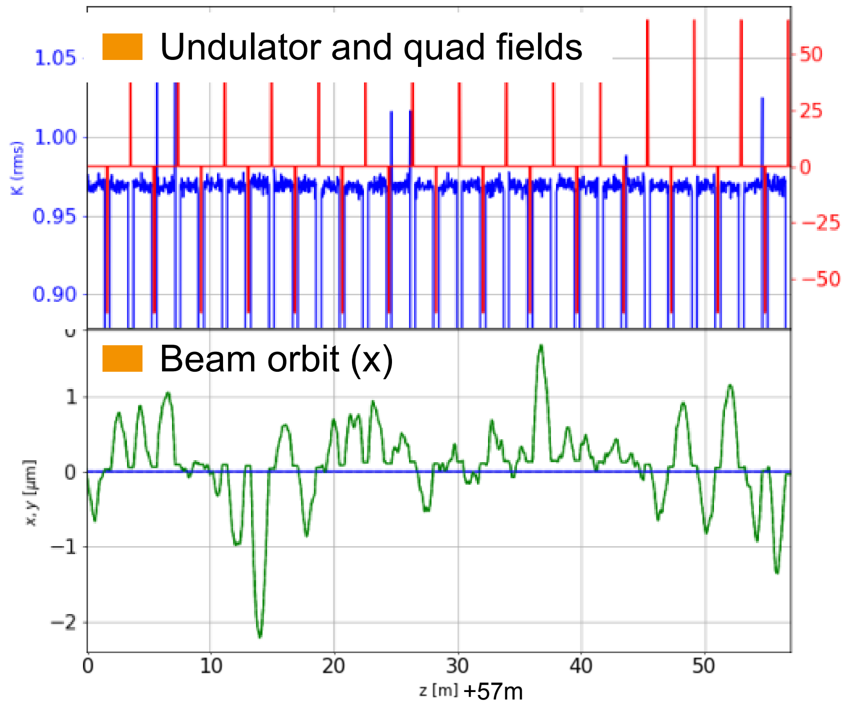




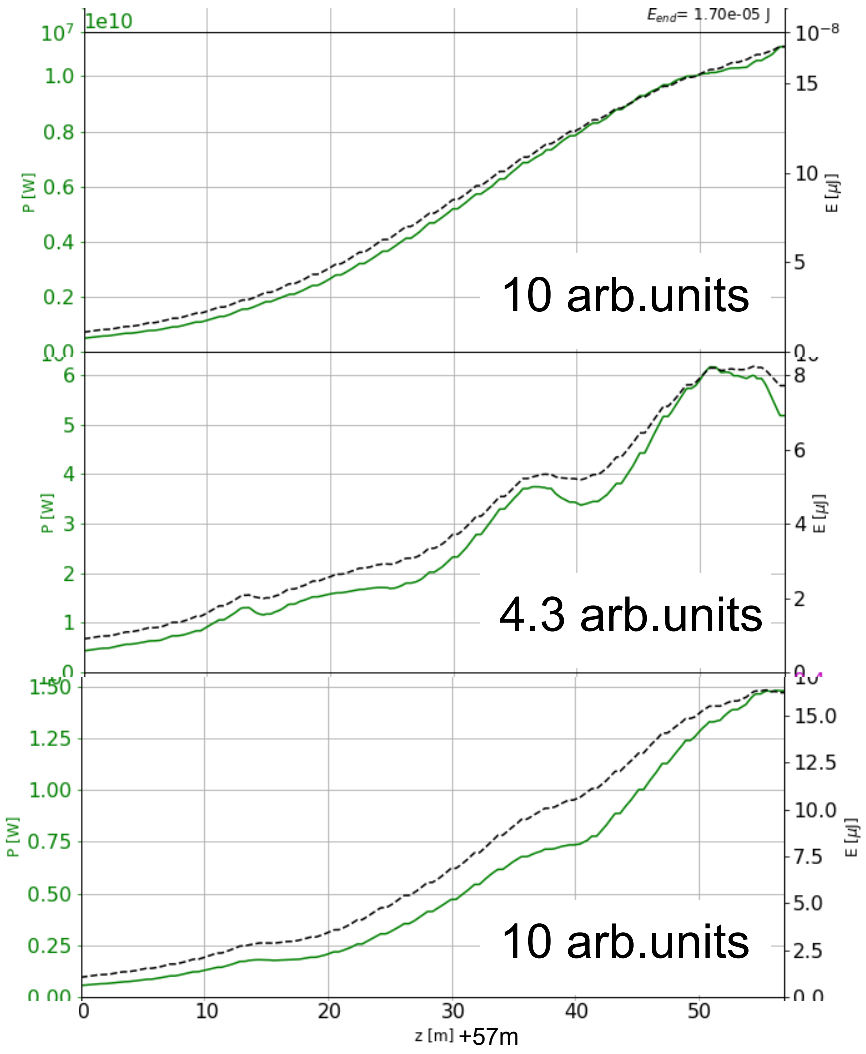
- No errors
- Corrected 1 and 2 field integrals
- Corrected 1 and 2 field integrals **and phase shifters**

Effect of undulator field errors

- 100keV, 15mm period
- Phase-shake effect
- Added path was calculated
  and compensated with phase shifter
- With 50% error magnitude effect negligible
  - Note: .15% errors > .01% rho

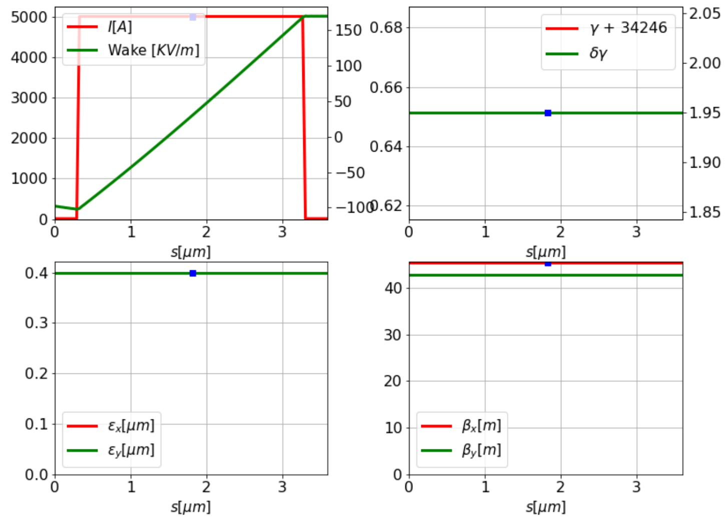


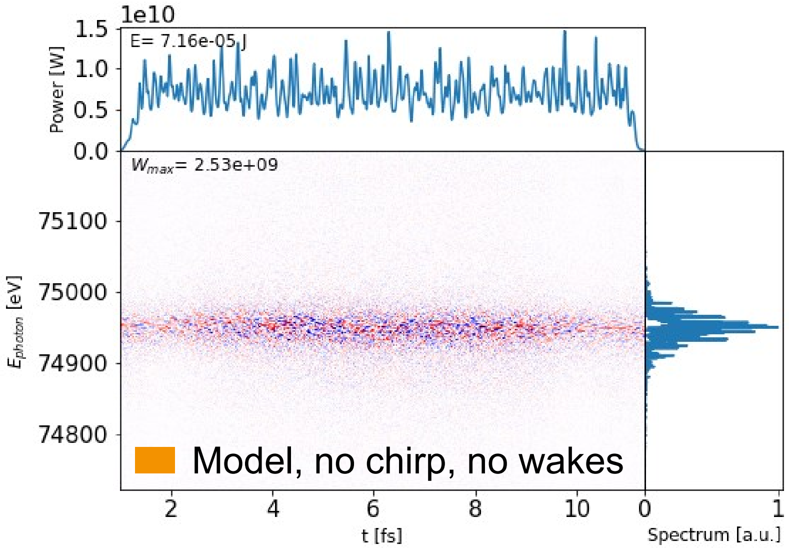
- 100keV = 0.12 Angstom

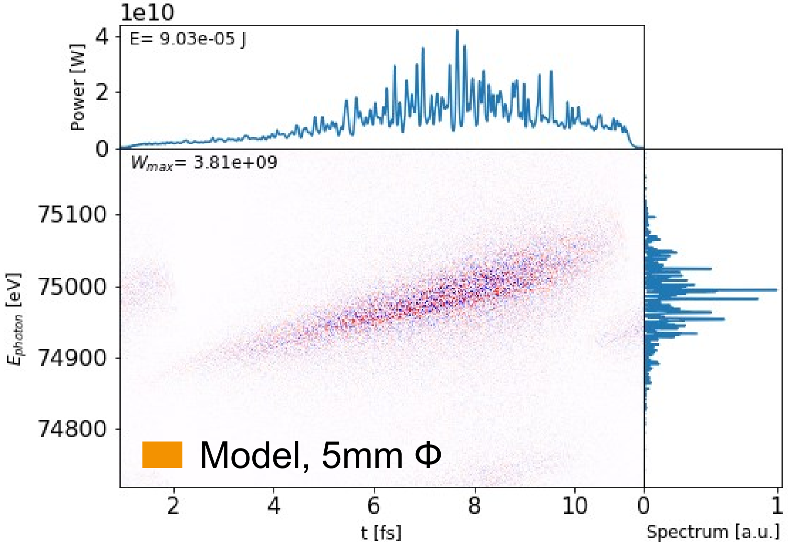


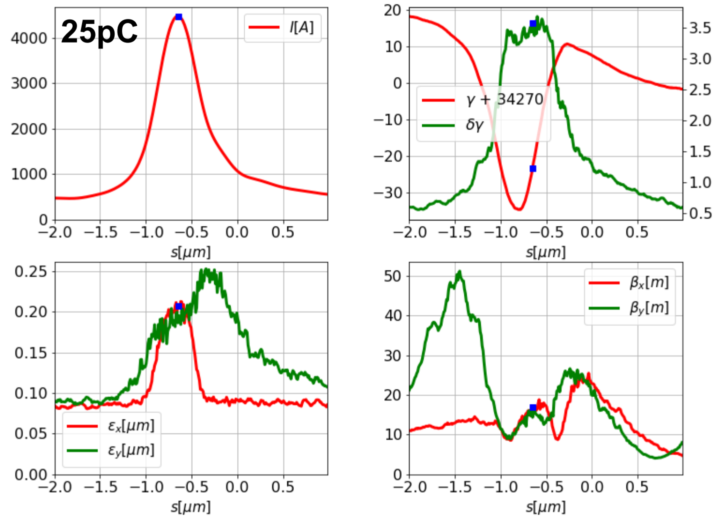
- No errors
- 0.3% error
- 0.15% error

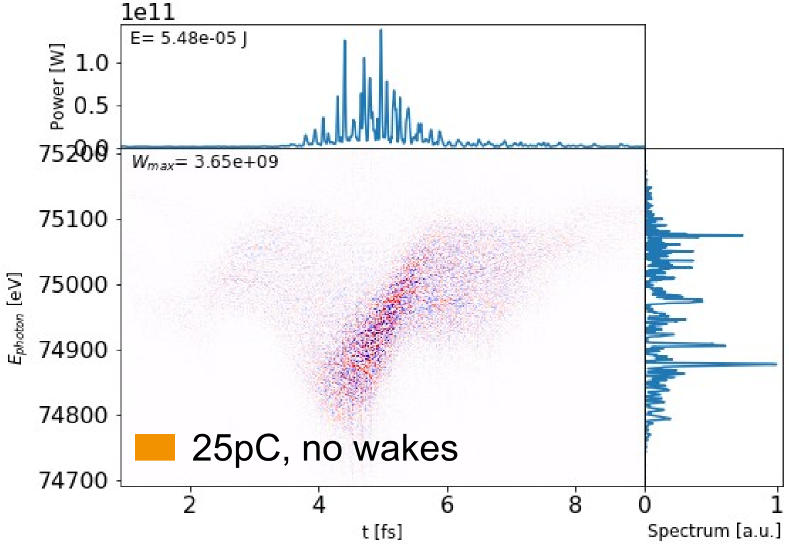
Spread of SASE spectrum (beam energy chirps & resistive wakefields)

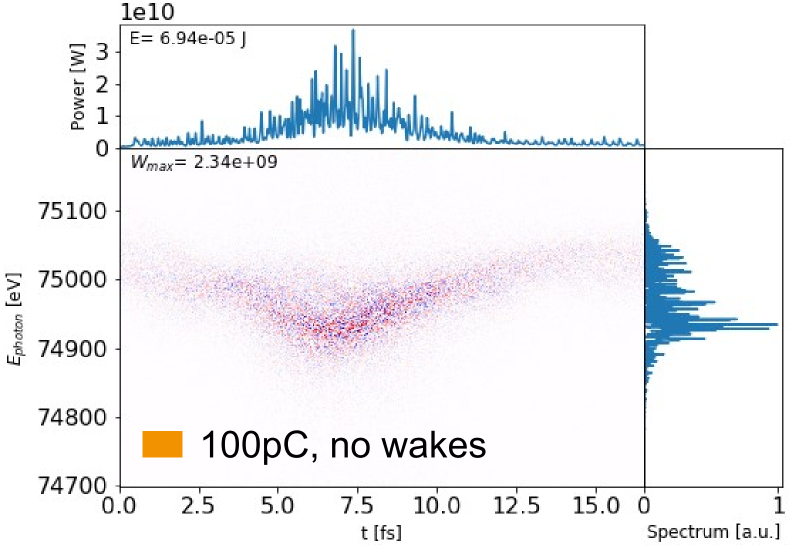












Transverse coherence (17mm period)

- Radiation fields simulated with Genesis (ε_{xy}=0.4urad, z=150m)

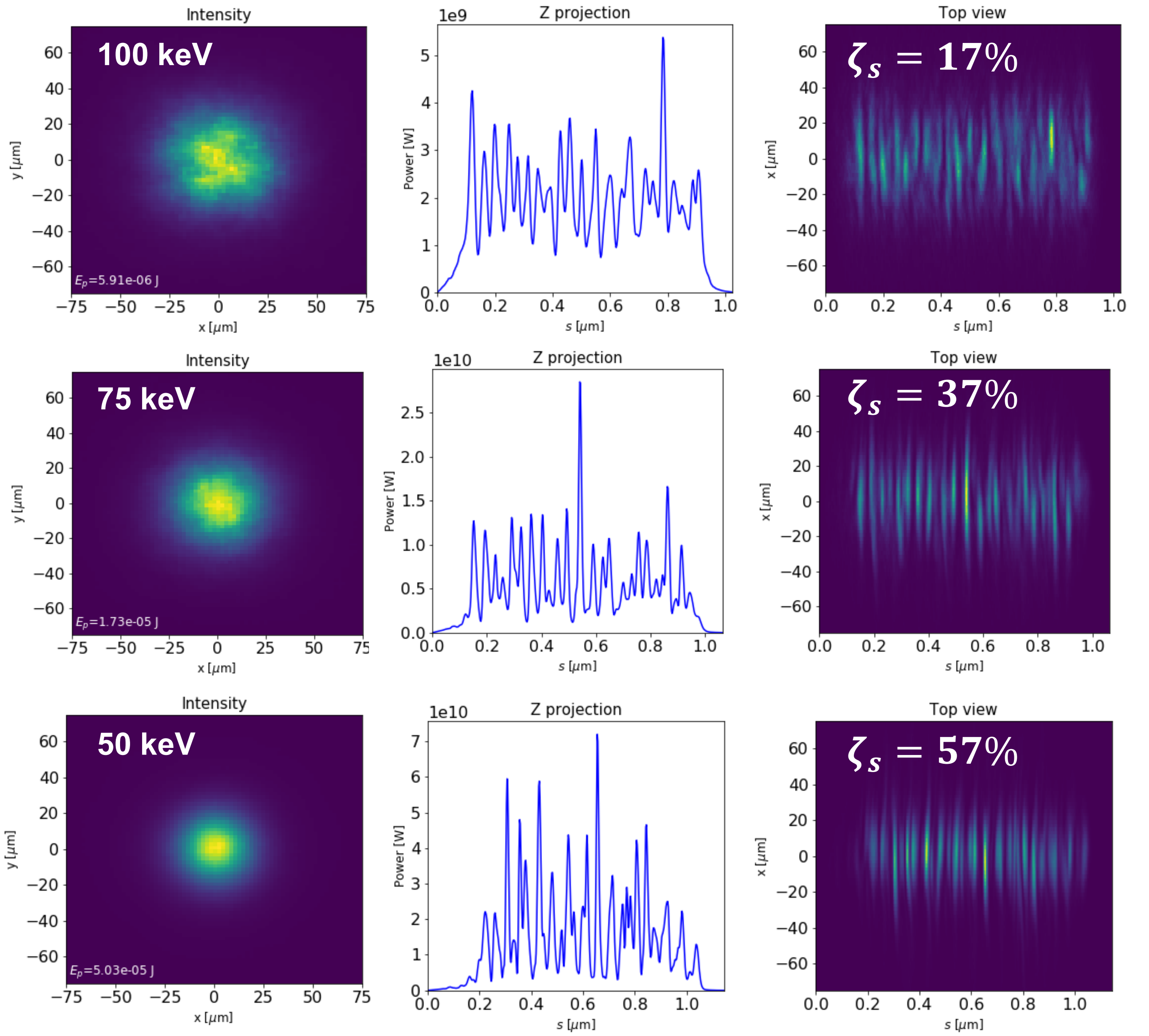
- $J(r_1, r_2, t) \equiv \langle E^*(r_1, t) E(r_2, t) \rangle$

  Mutual intensity function

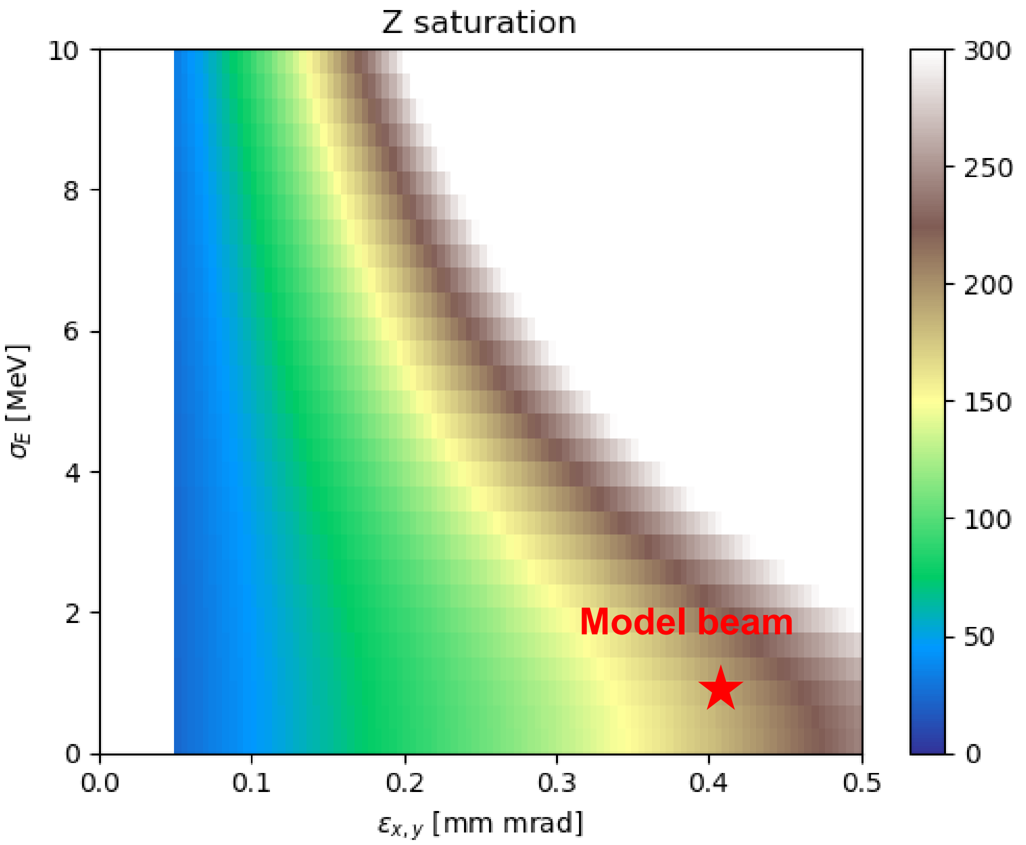
- $$\zeta_s = \frac{\int |J(r_1, r_2)|^2 dr_1 dr_2}{\left(\int I(r) dr\right)^2}$$

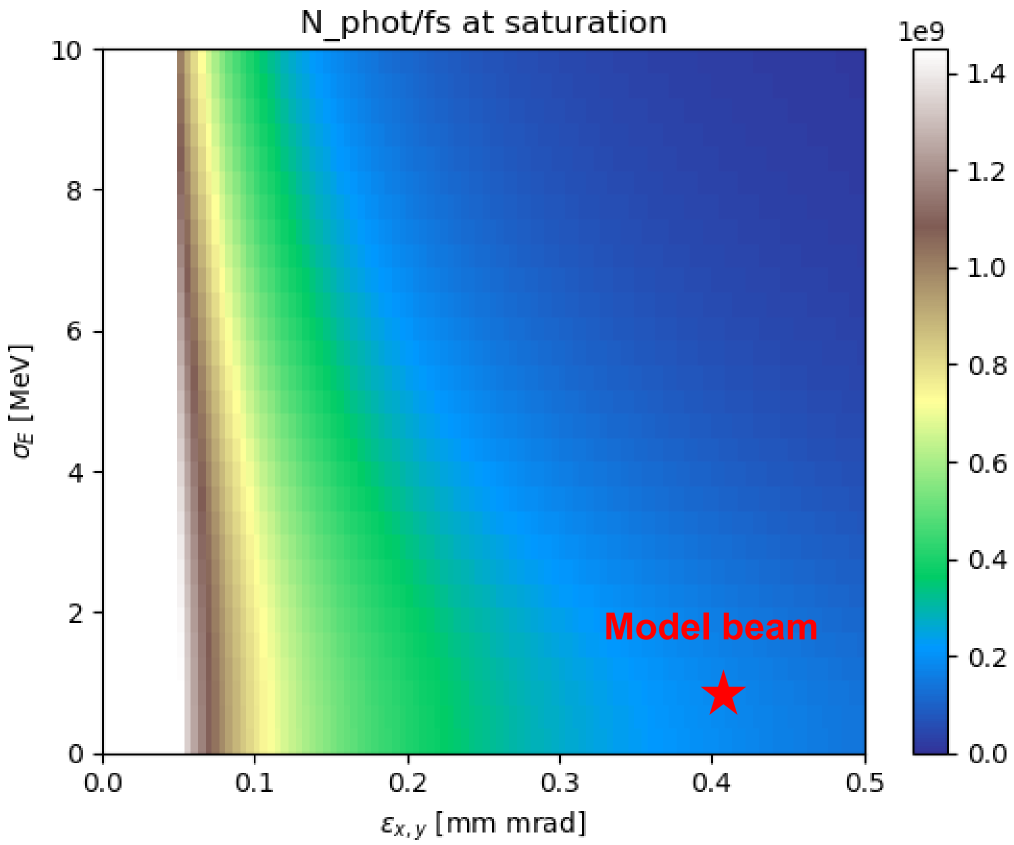
  Degree of spatial coherence

- Also depends on electron beam quality



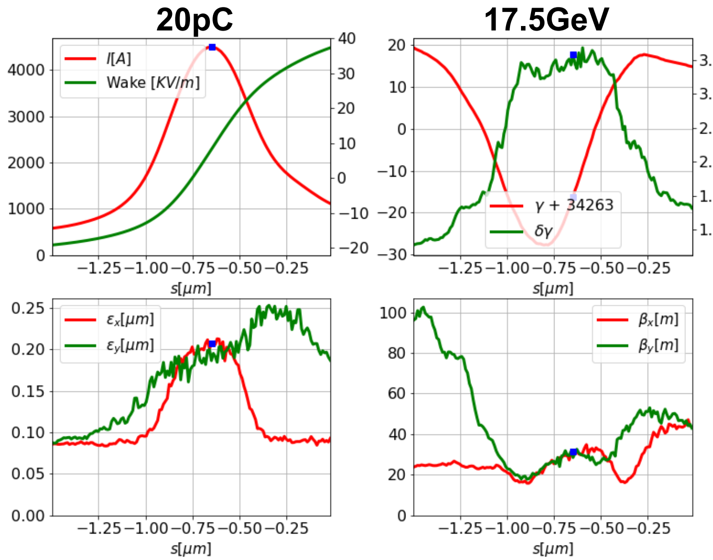
E-beam quality effect, 100keV, 15mm period

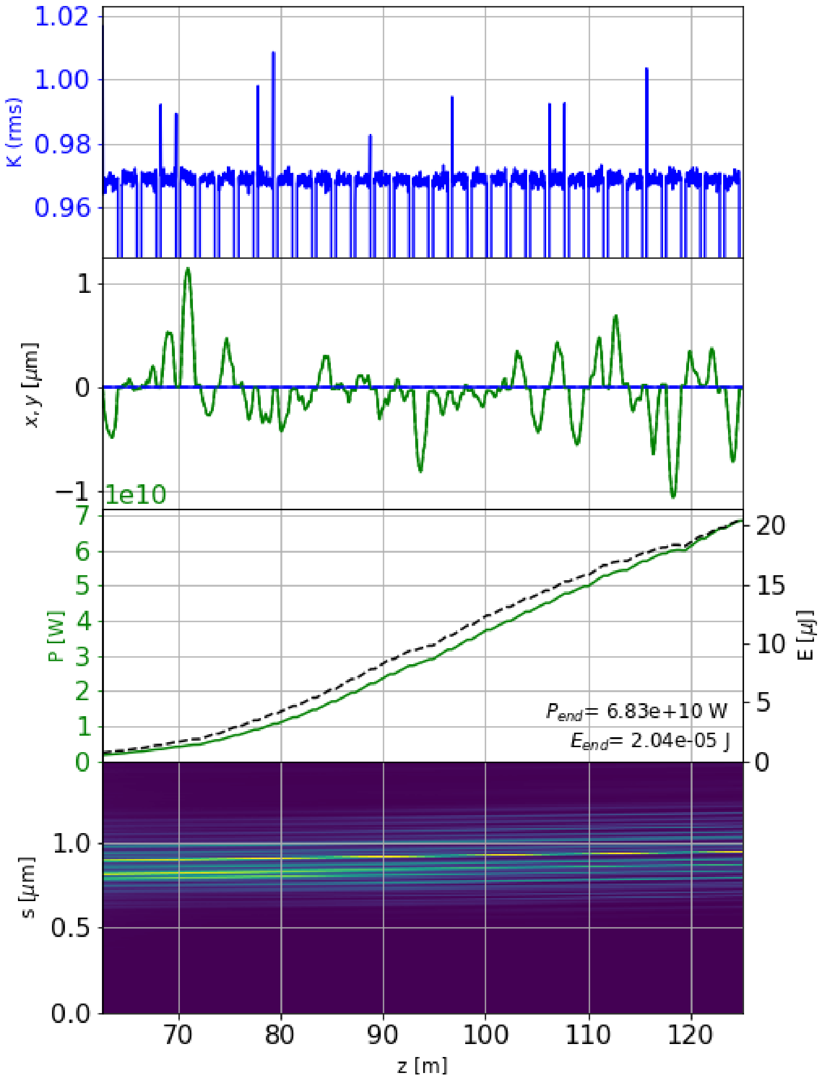


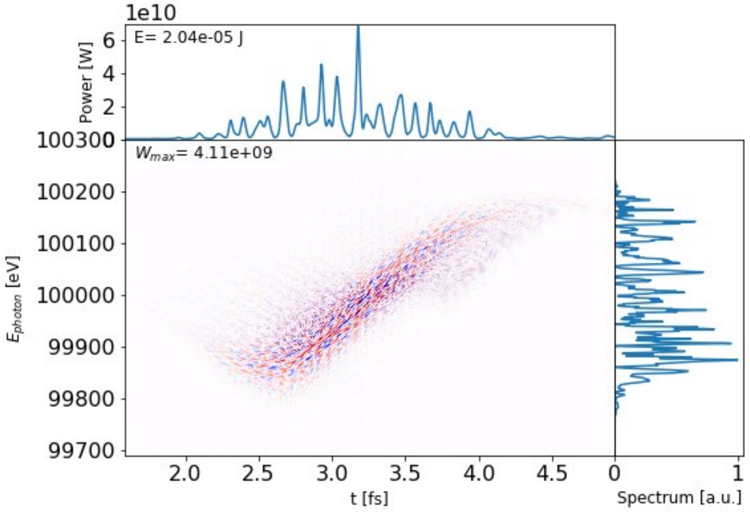


Emittance / 2 = Energy spread * 7

100keV S2E simulation:



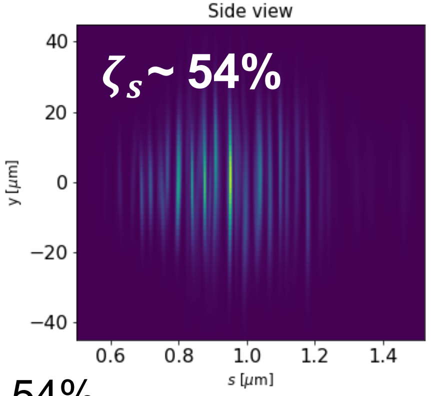




- Undulator:
  - 125m
  - 15mm period
  - σ_K/K=0.15% (1/2 of measured)
  - Wakefields for 5mm vacuum pipe
  - No post-saturation tapering

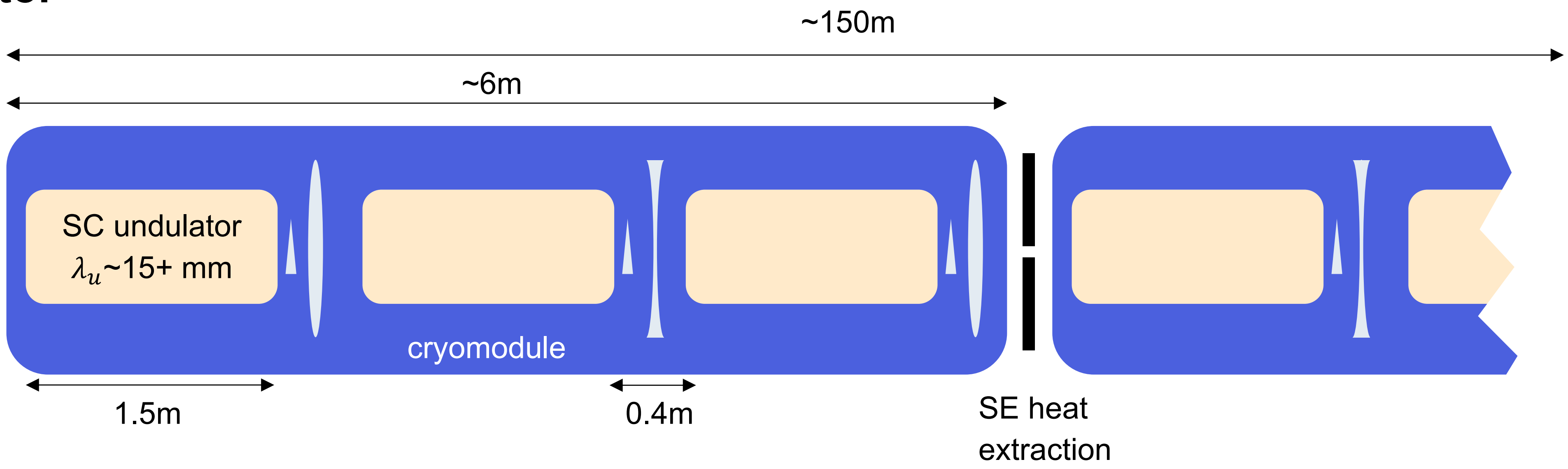
- E_{ph}=100keV
- $dE/E_{ph}=3*10^{-3}$

- $N_{ph}\sim10^9$
- $T_{fwhm}\sim$1.5fs
- Coherence: $\zeta_s\sim$ 54%



Summary 1: Undulator

- 25 cryomodules
- 79% filling factor



- SASE2 is best suited for SCU location
- Otherwise – SASE4 (provided SASE2 is open or bypassed)

Summary 2

- Our findings are based on two analytical approaches (SSY, Mxie) and two codes (Genesis, Simplex [T.Tanikawa])

- Potential detrimental effects on lasing:
  - E-beam quality is crucial (in particular: emittance < 0.4urad); it affects choice of the period
  - Quantum fluctuations important beyond 75keV at 17.5GeV
  - Undulator errors >> ρ can be compensated
  - Resistive wakefields and energy chirps in e-beam increase radiation bandwidth
  - Radiation coherence rapidly drops with photon energy and beam emittance

- At CW operation 18mm SCU complements SASE1/2 undulator photon energy range
- Period doubling is possible and allows one to significantly increase photon energy range at given e-beam energy
- SCU radiation damage (probably) smaller compared to IVU/CPMU
- Harmonic lasing becomes beneficial with 20mm SCU

- But the most important…

Reaching 100keV in EuXFEL is possible!

/10keV used to be Sci-fi/

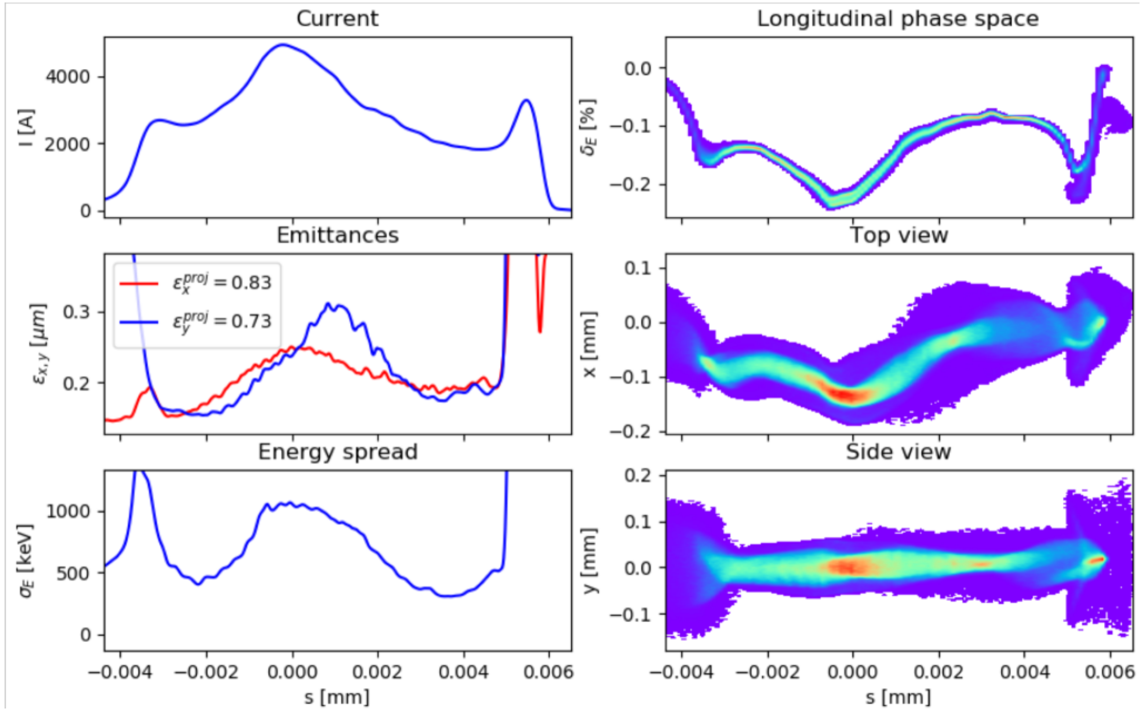
Thank you

E-beam

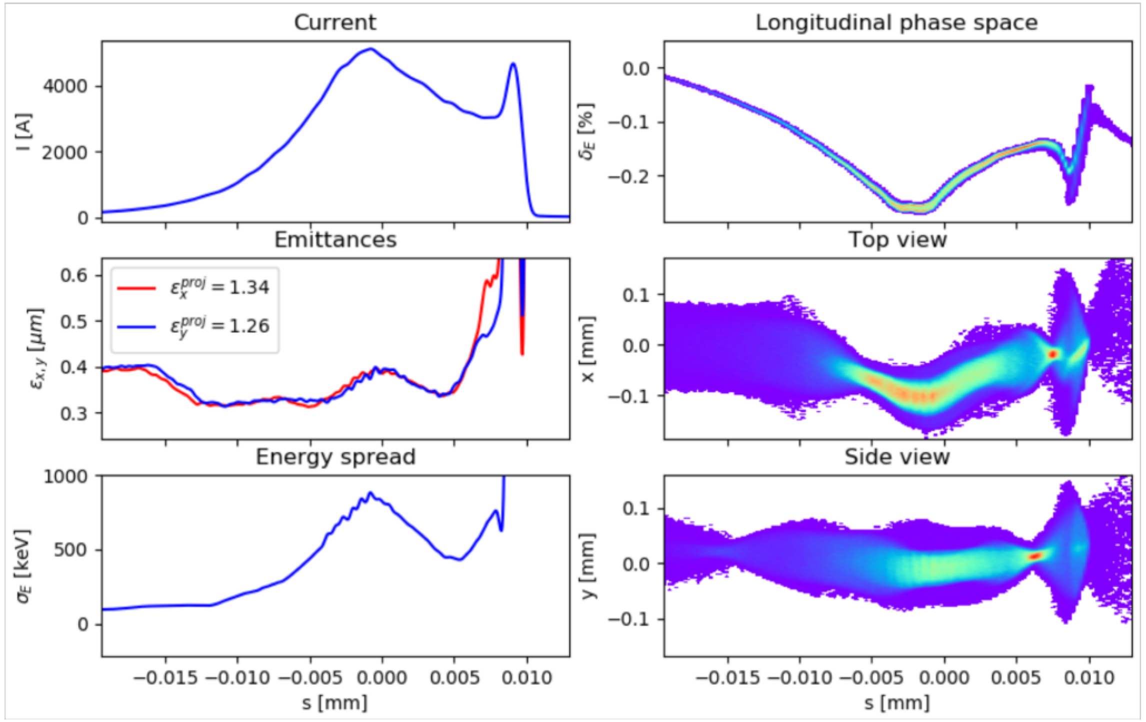
Beam Dynamics at the European XFEL up to SASE4/5

Igor Zagorodnov, 06.12.2018

- 100pC



- 250pC



Methods to estimate FEL performance (3D gain length)

- Saldin, Schneydmiller, Yurkov

$$L_g \simeq L_{g0}(1+\delta),$$

$$L_{g0} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_w)^{5/6}}{\lambda_h^{2/3}} \frac{(1+K^2)^{1/3}}{h^{5/6} K A_{JJh}},$$

$$\delta = 131 \frac{I_A}{I} \frac{\epsilon_n^{5/4}}{\lambda_h^{1/8} \lambda_w^{9/8}} \frac{h^{9/8} \sigma_\gamma^2}{(K A_{JJh})^2 (1+K^2)^{1/8}}$$

$$A_{JJh}(K) = J_{(h-1)/2}\left(\frac{hK^2}{2(1+K^2)}\right) - J_{(h+1)/2}\left(\frac{hK^2}{2(1+K^2)}\right)$$

E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Design formulas for short-wavelength FELs," Opt. Commun., vol. 235, no. 4–6, pp. 415–420, May 2004.

E. A. Schneidmiller and M. V. Yurkov, "Harmonic lasing in x-ray free electron lasers," *Phys. Rev. Spec. Top. - Accel. Beams*, vol. 15, no. 8, p. 080702, Aug. 2012.

- M.Xie

$$\frac{L_{1\mathrm{d}}}{L_\mathrm{g}} = \frac{1}{1+\Lambda}$$

$$L_{1\mathrm{d}} = 1/2\sqrt{3} k_\mathrm{w} \rho$$

$$\rho = \sqrt[3]{(I/I_\mathrm{A})(\lambda_\mathrm{w} a_\mathrm{w} f_B / 2\pi\sigma_x)^2 (1/2\gamma_0)^3}$$

$$\Lambda = a_1 \eta_\mathrm{d}^{a_2} + a_3 \eta_\varepsilon^{a_4} + a_5 \eta_\gamma^{a_6}$$
$$+ a_7 \eta_\varepsilon^{a_8} \eta_\gamma^{a_9} + a_{10} \eta_\mathrm{d}^{a_{11}} \eta_\gamma^{a_{12}} + a_{13} \eta_\mathrm{d}^{a_{14}} \eta_\varepsilon^{a_{15}}$$
$$+ a_{16} \eta_\mathrm{d}^{a_{17}} \eta_\varepsilon^{a_{18}} \eta_\gamma^{a_{19}}$$

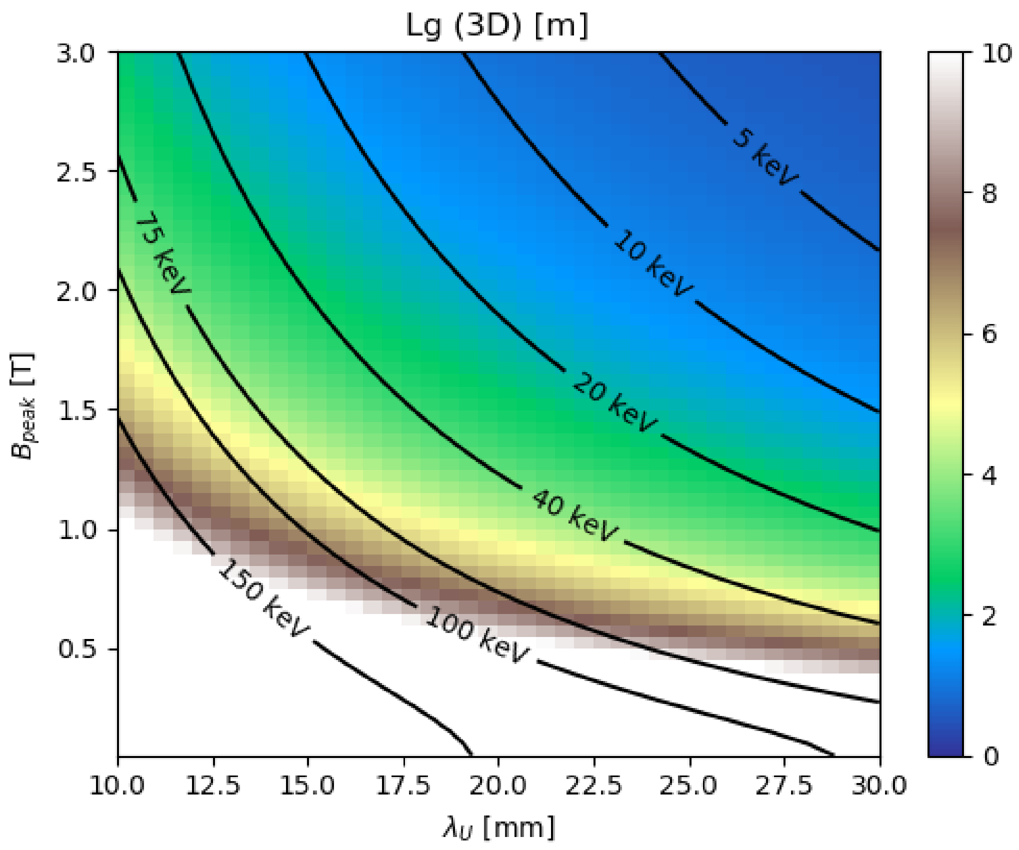
$$\eta_\mathrm{d} = 1/F_\mathrm{d}$$
$$\eta_\varepsilon = 4\pi(L_{1\mathrm{d}}/\lambda_\beta) k_r \varepsilon$$
$$\eta_\gamma = 4\pi(L_{1\mathrm{d}}/\lambda_\mathrm{w}) \sigma_\eta$$

M. Xie, "Exact and variational solutions of 3D eigenmodes in high gain FELs," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 445, no. 1–3, pp. 59–66, 2000.

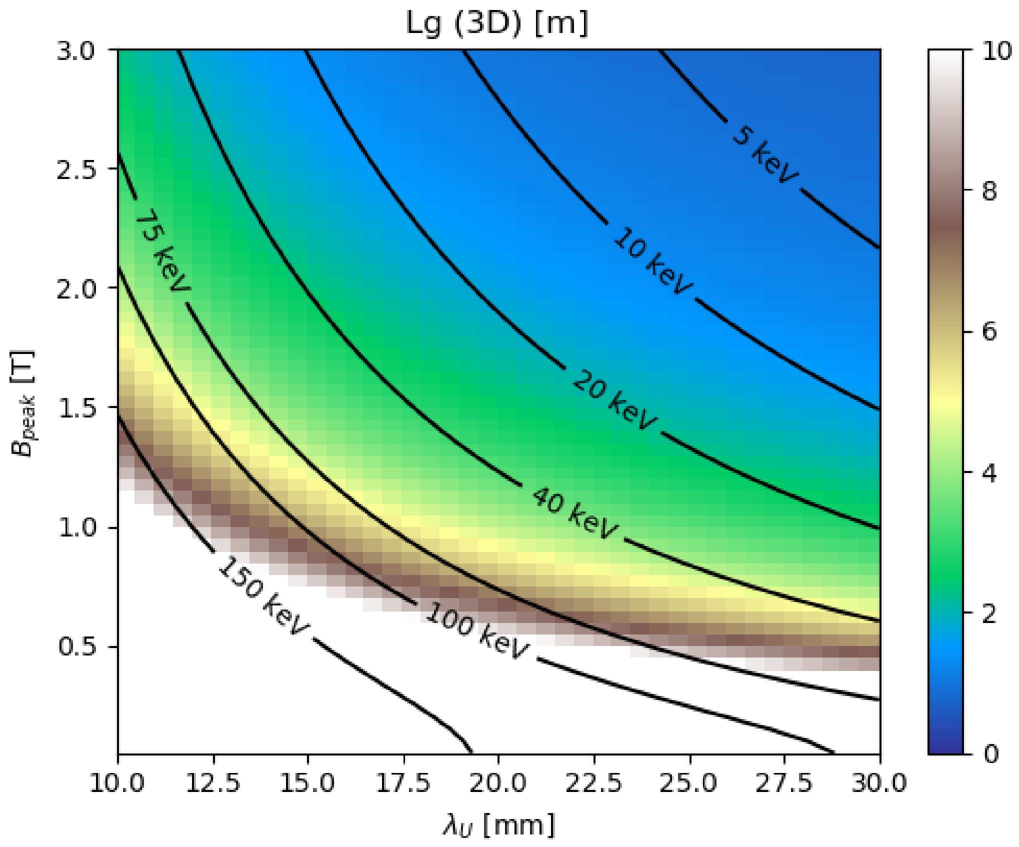
Methods to estimate FEL performance (3D gain length)

$$L_g^{3d} = L_g^{1d}(1+\delta)$$

Saldin, Schneydmiller, Yurkov



M.Xie



E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Design formulas for short-wavelength FELs," Opt. Commun., vol. 235, no. 4–6, pp. 415–420, May 2004.

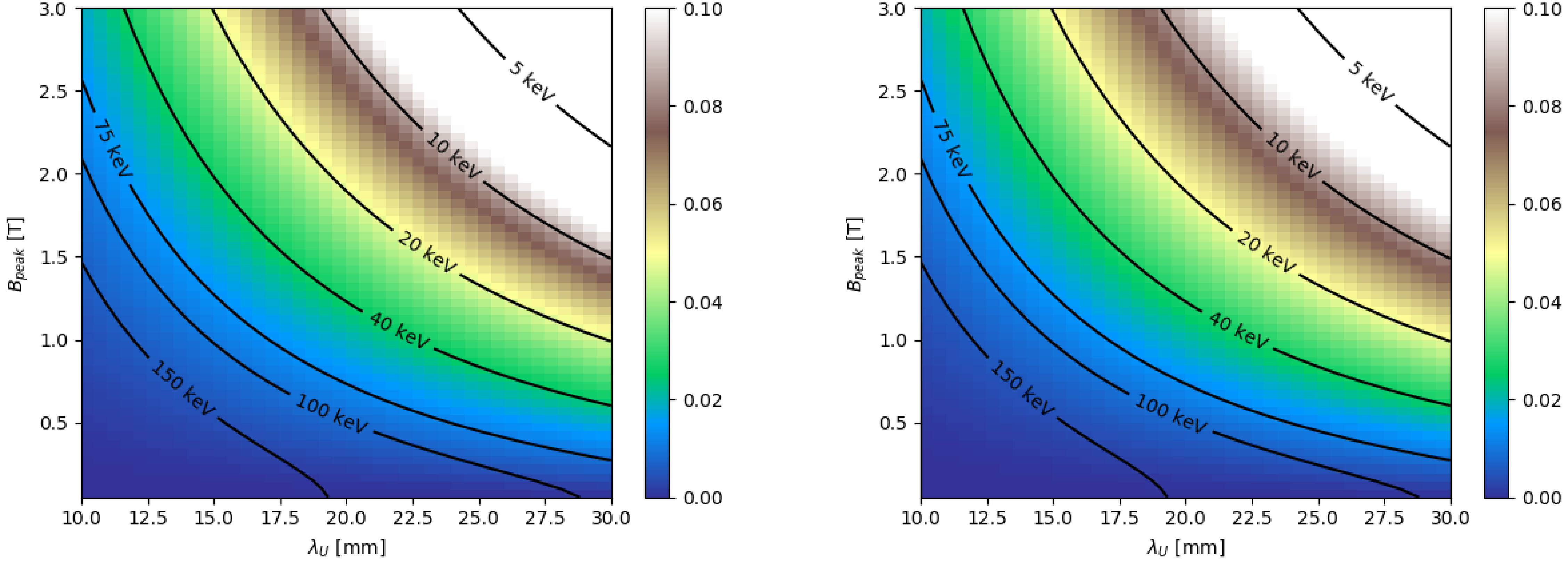
M. Xie, "Exact and variational solutions of 3D eigenmodes in high gain FELs," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 445, no. 1–3, pp. 59–66, 2000.

Methods to estimate FEL performance (~3D efficiency)

$$\frac{\lambda_u}{4\pi\sqrt{3}L_g^{3d}} * 100\%$$

Saldin, Schneydmiller, Yurkov

M.Xie



E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Design formulas for short-wavelength FELs," Opt. Commun., vol. 235, no. 4–6, pp. 415–420, May 2004.

M. Xie, "Exact and variational solutions of 3D eigenmodes in high gain FELs," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 445, no. 1–3, pp. 59–66, 2000.

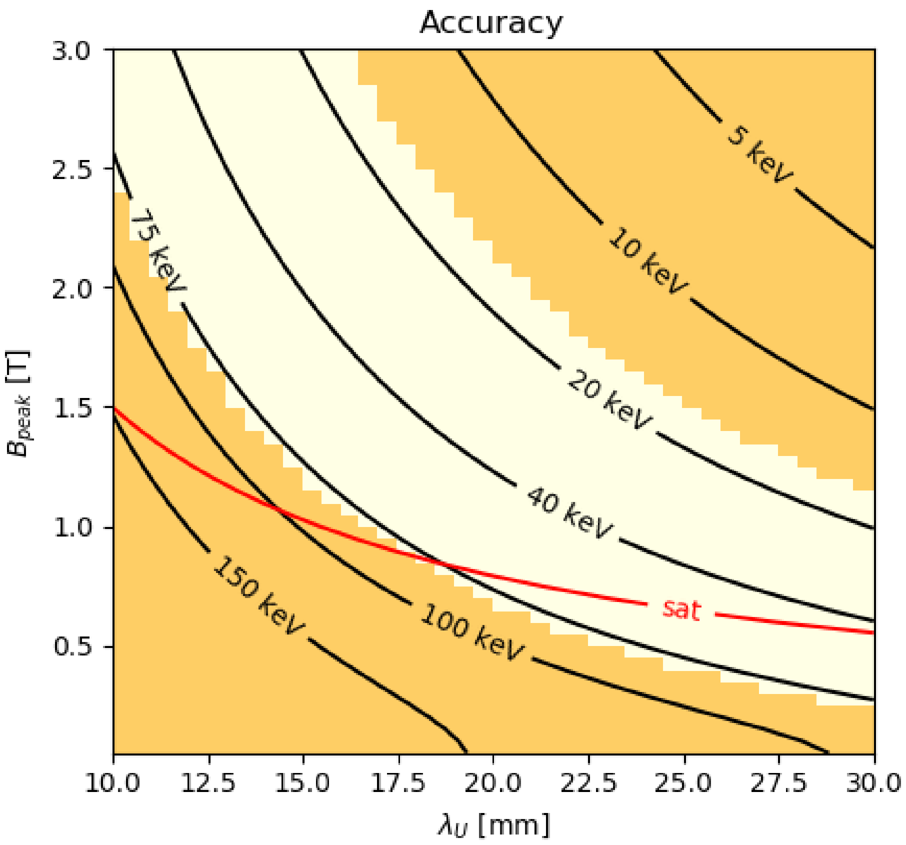
Accuracy

The formulas (3)–(5) provide an accuracy better than 5% in the range of parameters

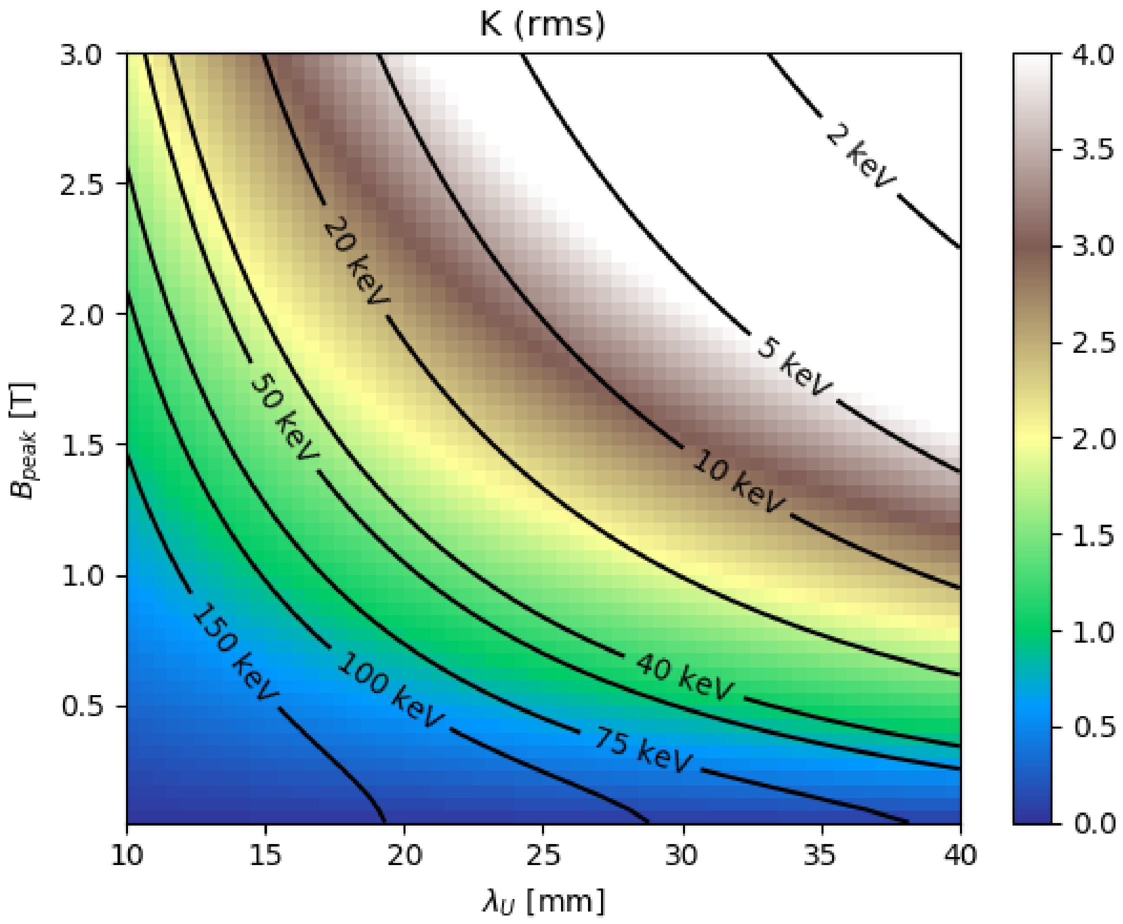
$$1 < \frac{2\pi\epsilon}{\lambda_h} < 5, \quad (6)$$

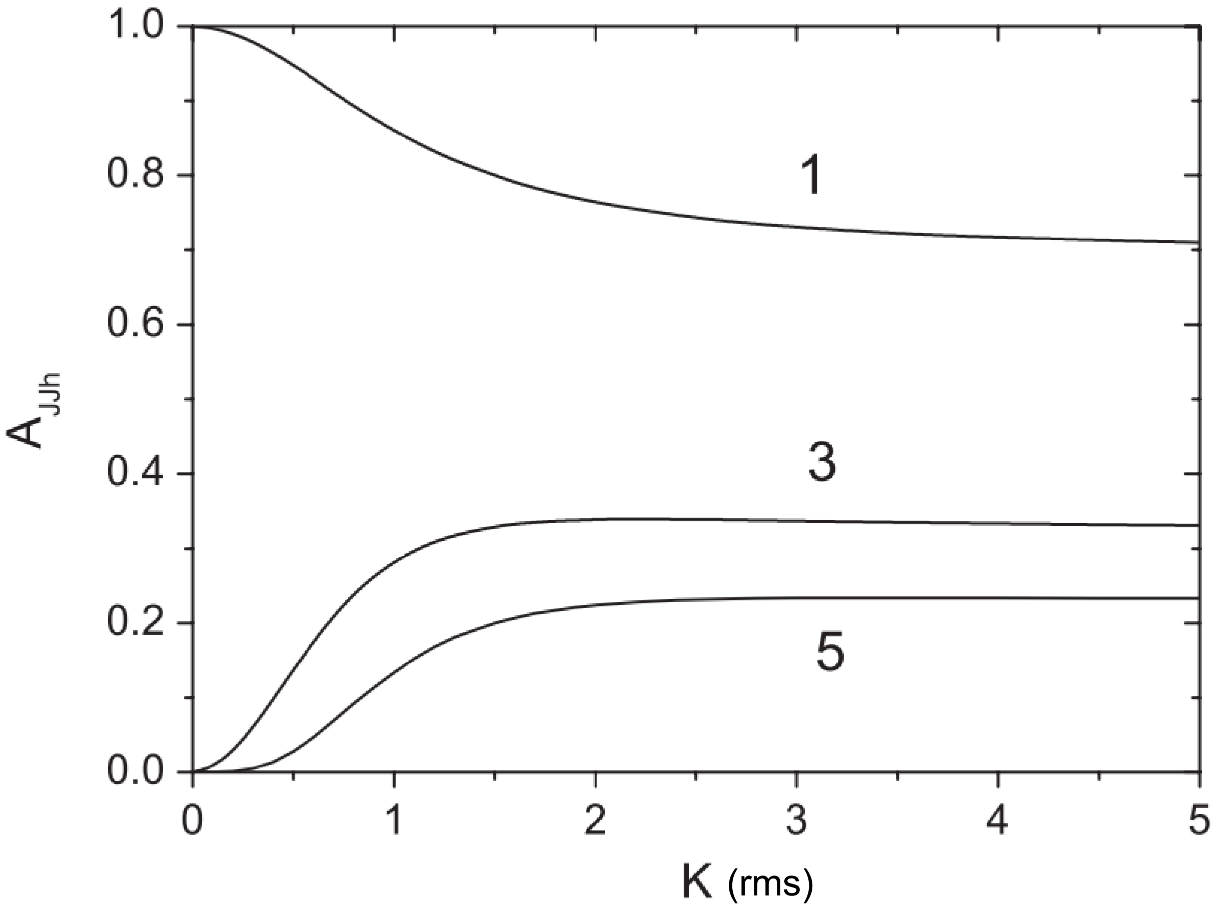
$$\delta < 2.5\left\{1 - \exp\left[-\frac{1}{2}\left(\frac{2\pi\epsilon}{\lambda_h}\right)^2\right]\right\}. \quad (7)$$

In fact, the formulas (3)–(5) can also be used well beyond this range, but the above-mentioned accuracy is not guaranteed.



E. A. Schneidmiller and M. V. Yurkov, “Harmonic lasing in x-ray free electron lasers,” *Phys. Rev. Spec. Top. - Accel. Beams*, vol. 15, no. 8, p. 080702, Aug. 2012.


K (rms)
B_{peak} [T]
λ_U [mm]
2 keV
5 keV
10 keV
20 keV
40 keV
50 keV
75 keV
100 keV
150 keV


A_{JJh}
K (rms)
1
3
5

Effect of beam energy chirps & resistive wakefields

- Wakefield calculated with OCELOT assuming:

- tube_radius=2.5e-3,
- tube_len=1,
- conductivity=3.66e+7,
- tau=7.1e-15,
- roughness=600e-9,
- d_oxid=5e-9

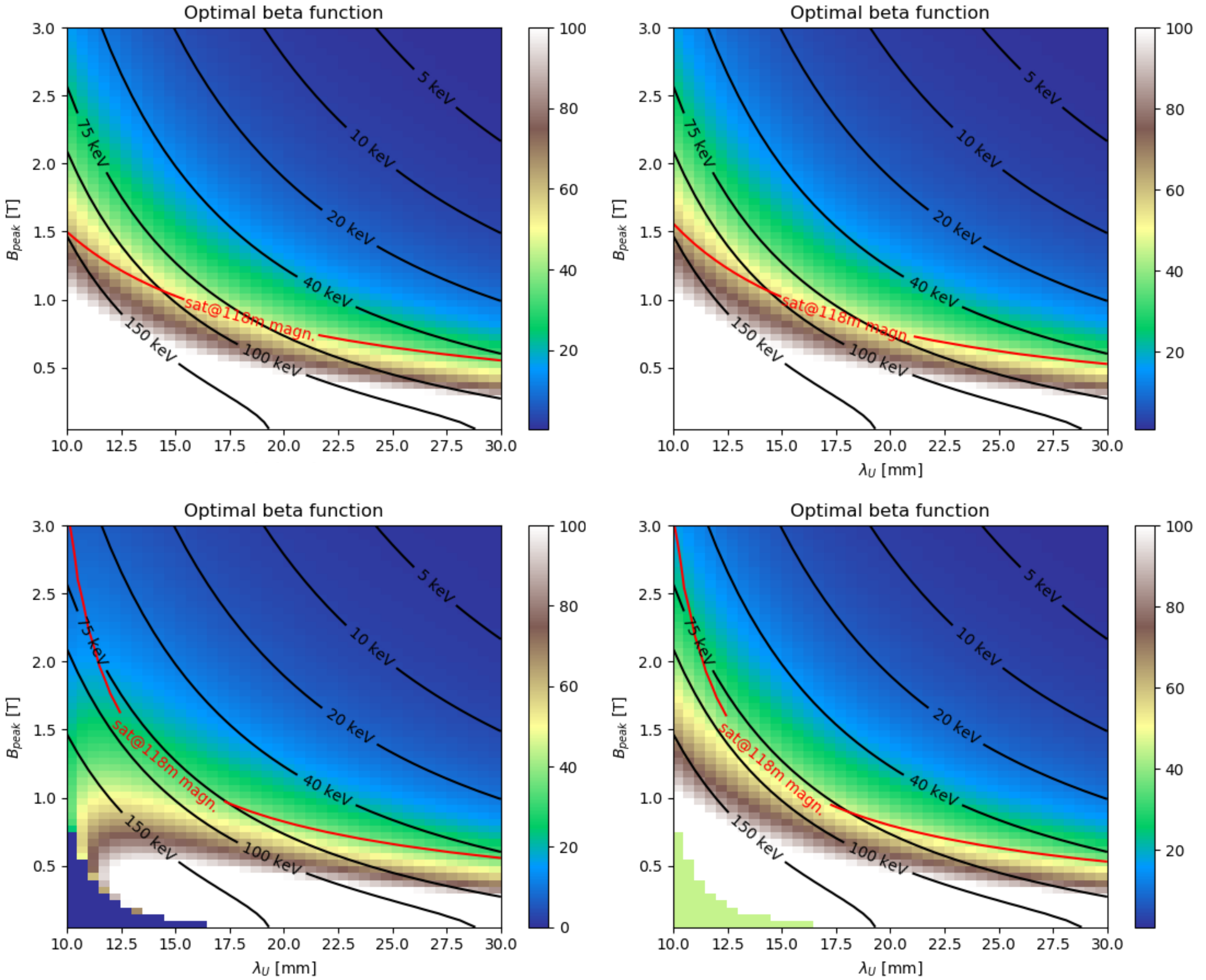
self.eloss = pipe_wake(self.s, self.I, tube_radius, tube_len, conductivity, tau, roughness, d_oxid)[1][1][::-1]

Optimal Beta Functions

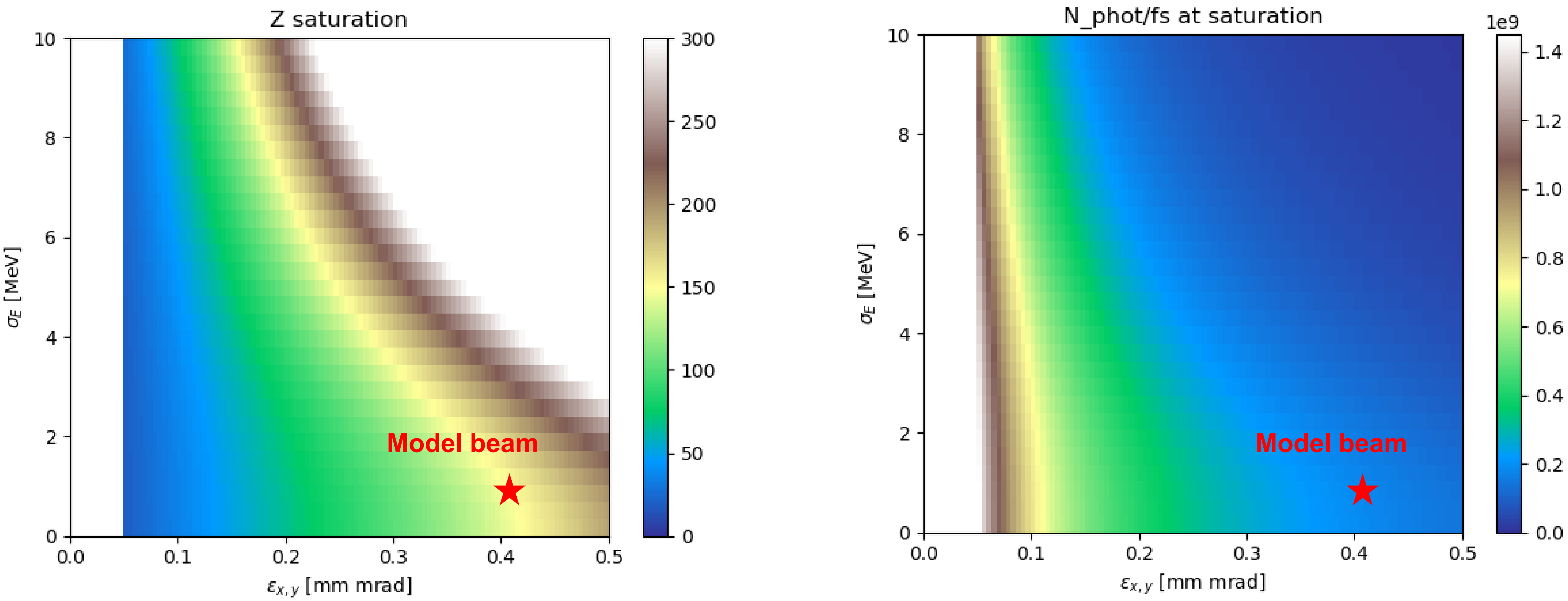
SSY **MXie**

QF off

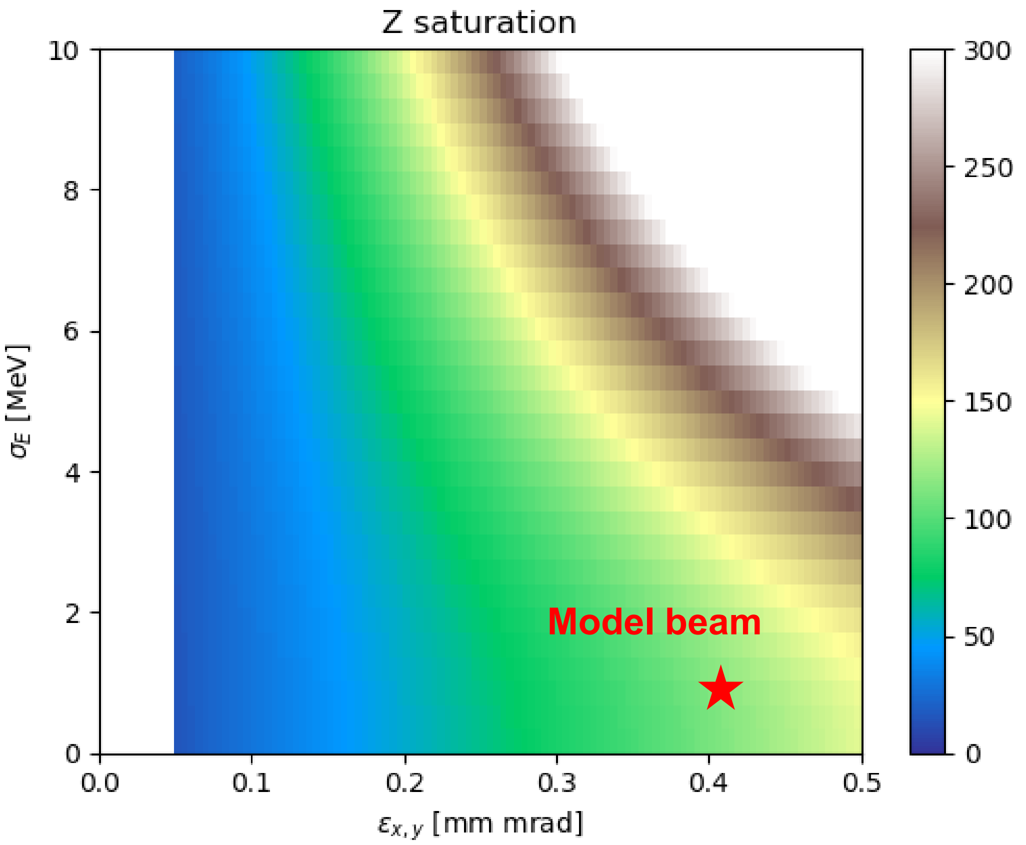
QF on

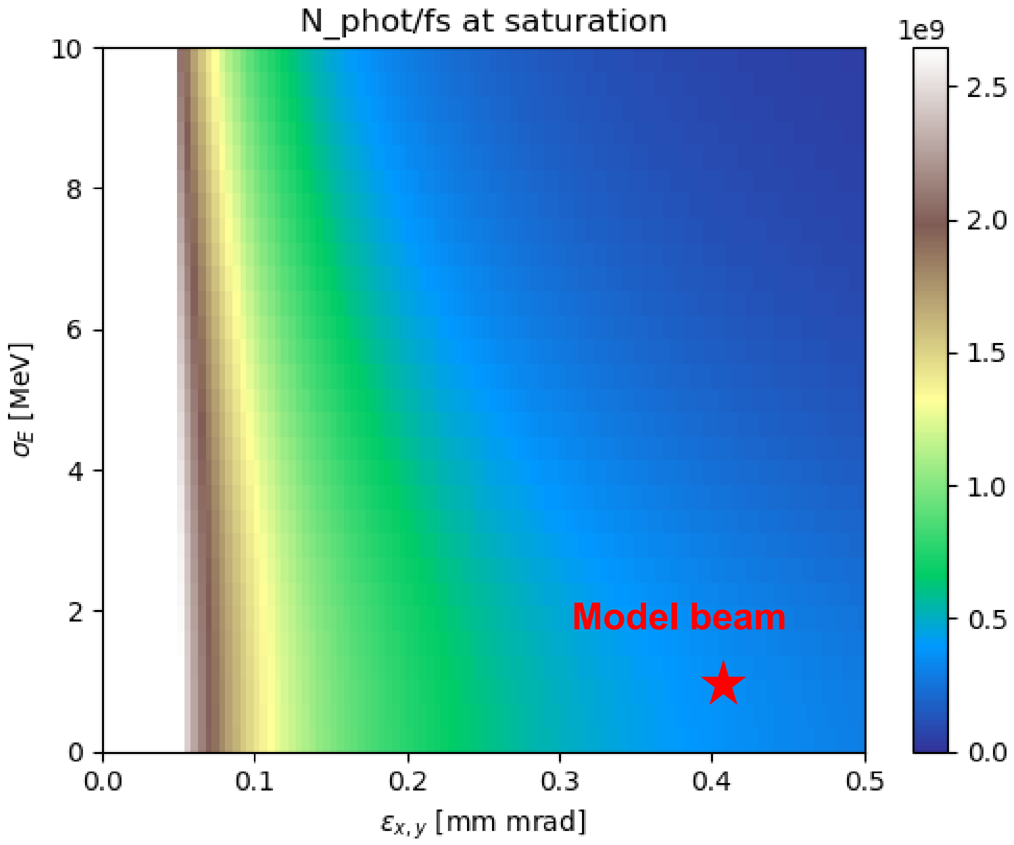


E-beam quality effect, 100keV, 15mm period

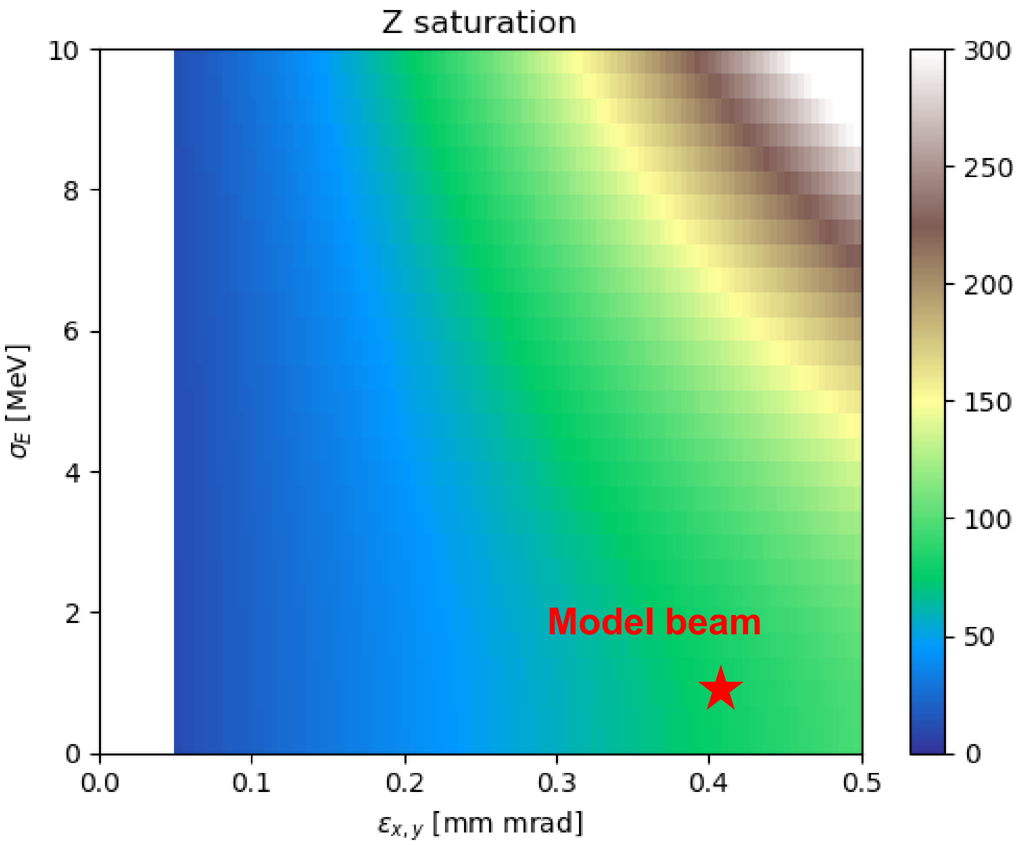


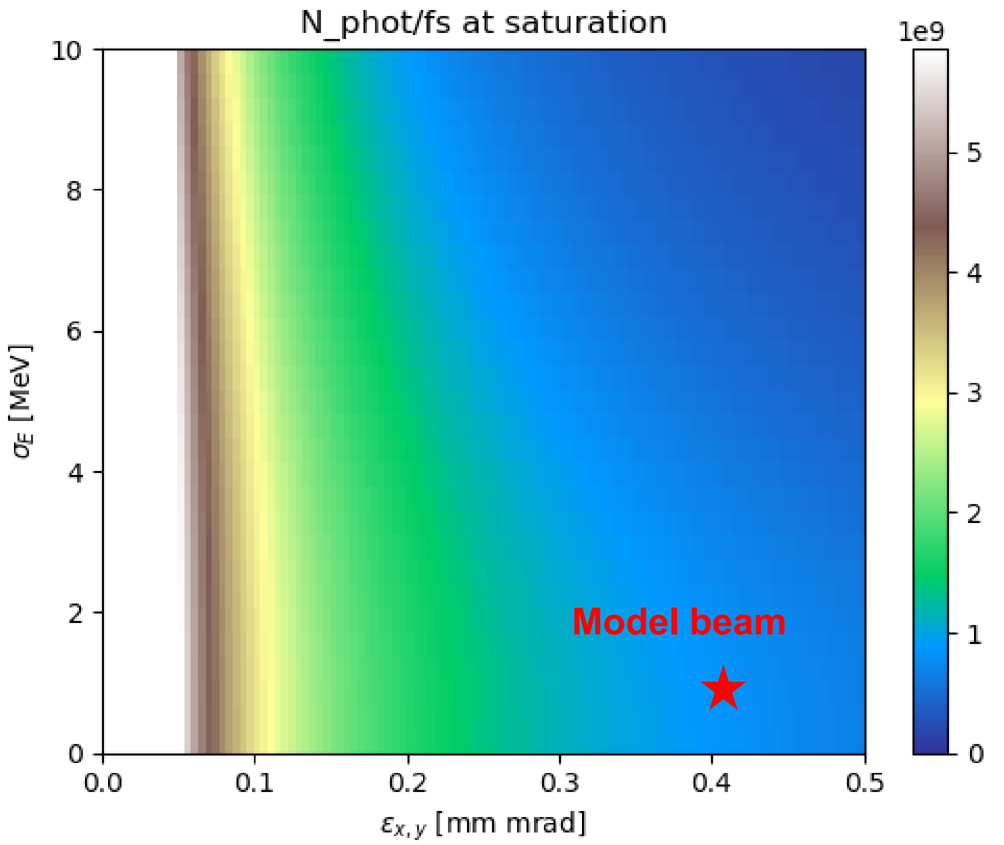
E-beam quality effect, 75keV, 17mm period



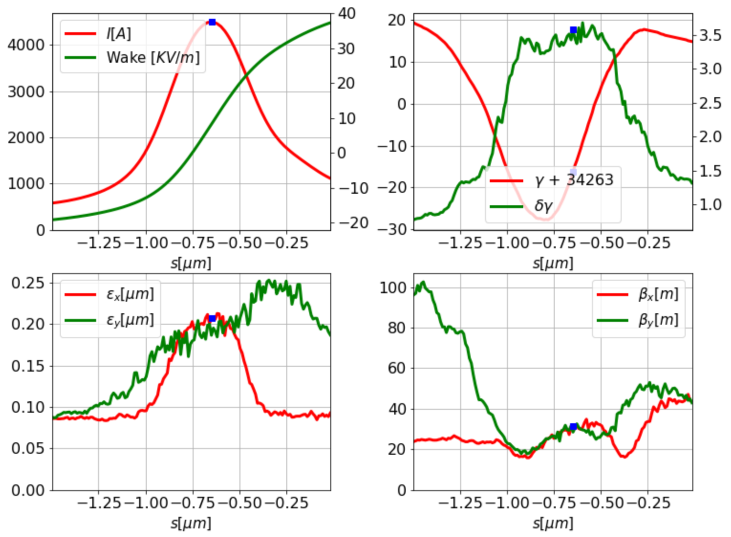


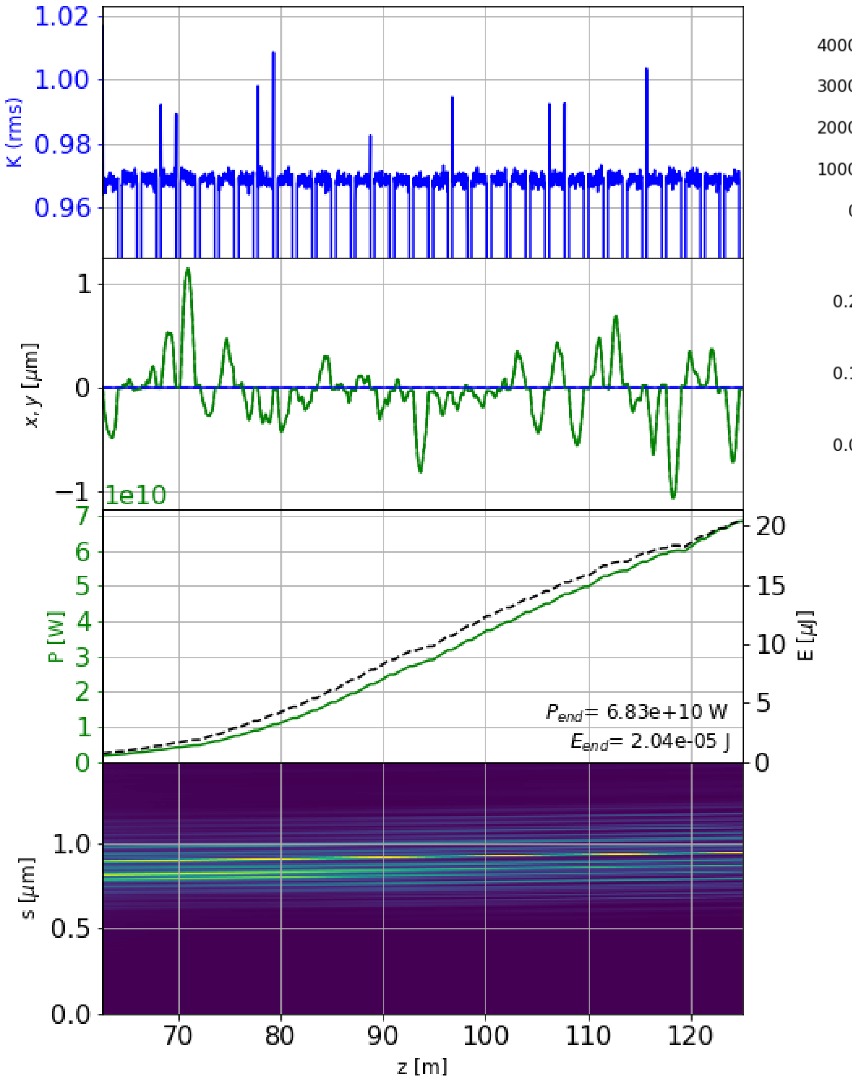
E-beam quality effect, 50keV, 18mm period

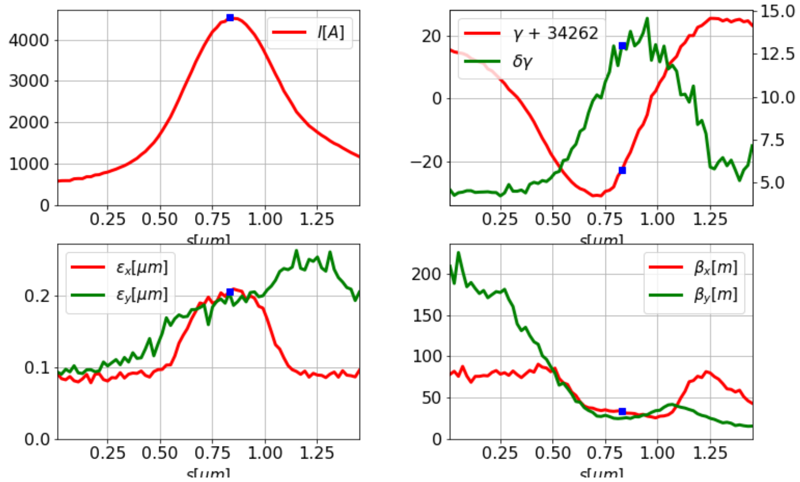


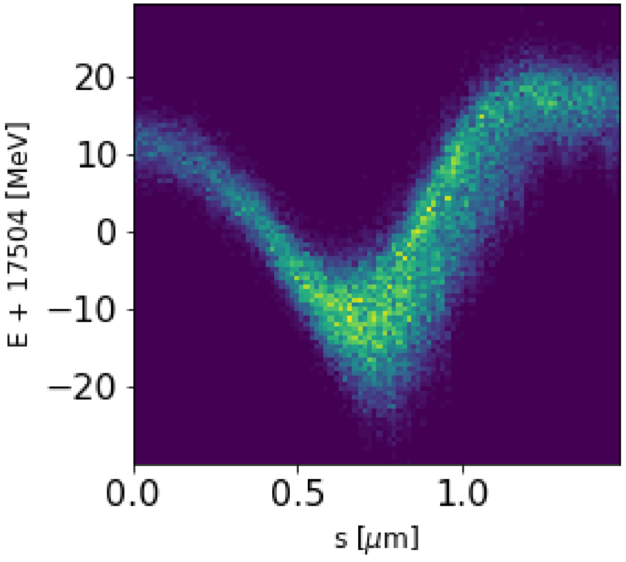


Beam after SASE4:









Optimistic scenario (SP mode, 19.8 GeV, 0.2mm*mrad beam)

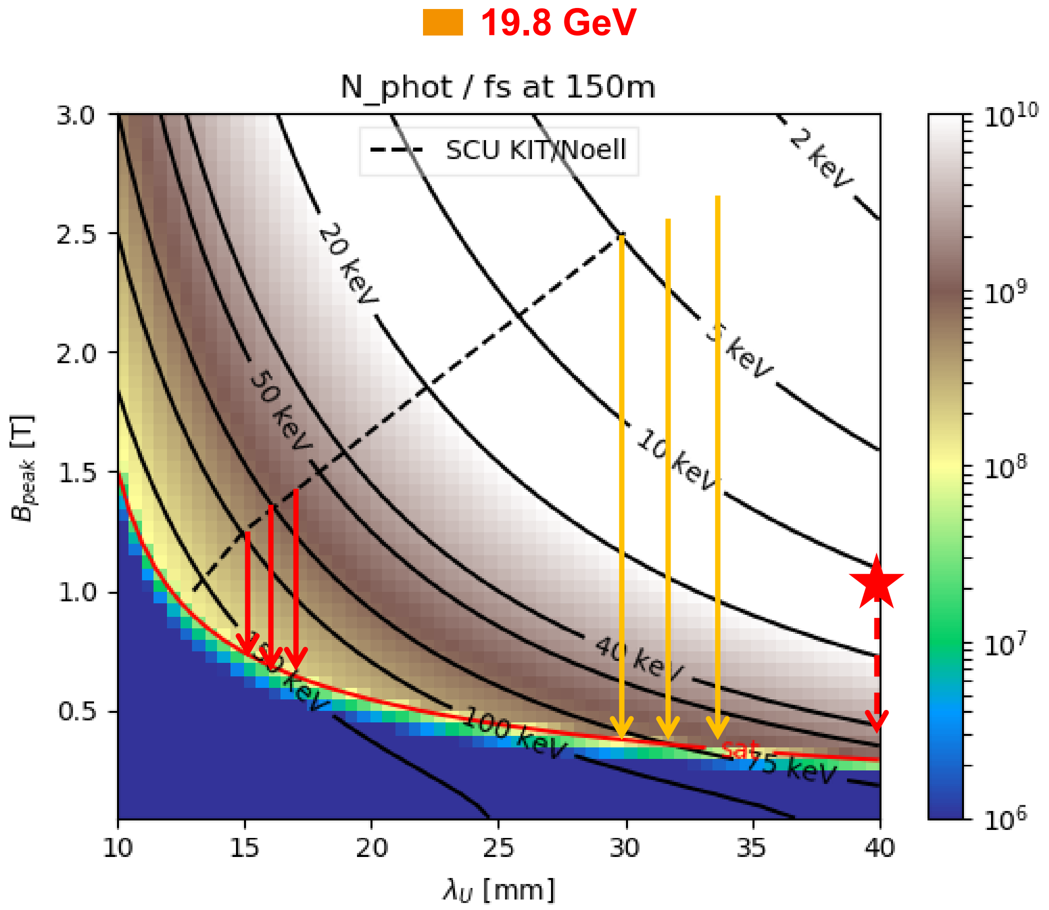
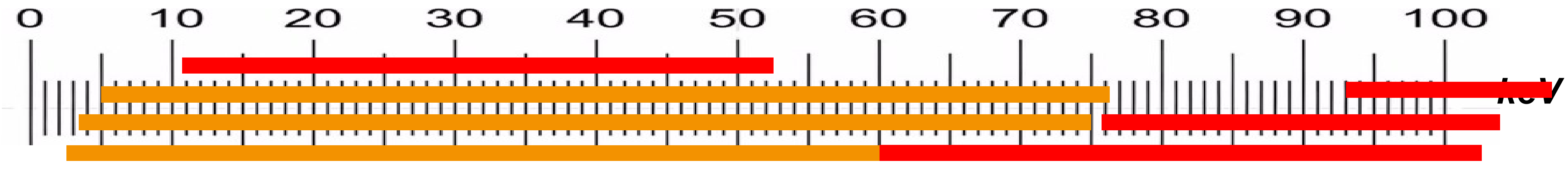


TABLE VI. Beam energy and DF estimated for the upgraded XFEL accelerator.

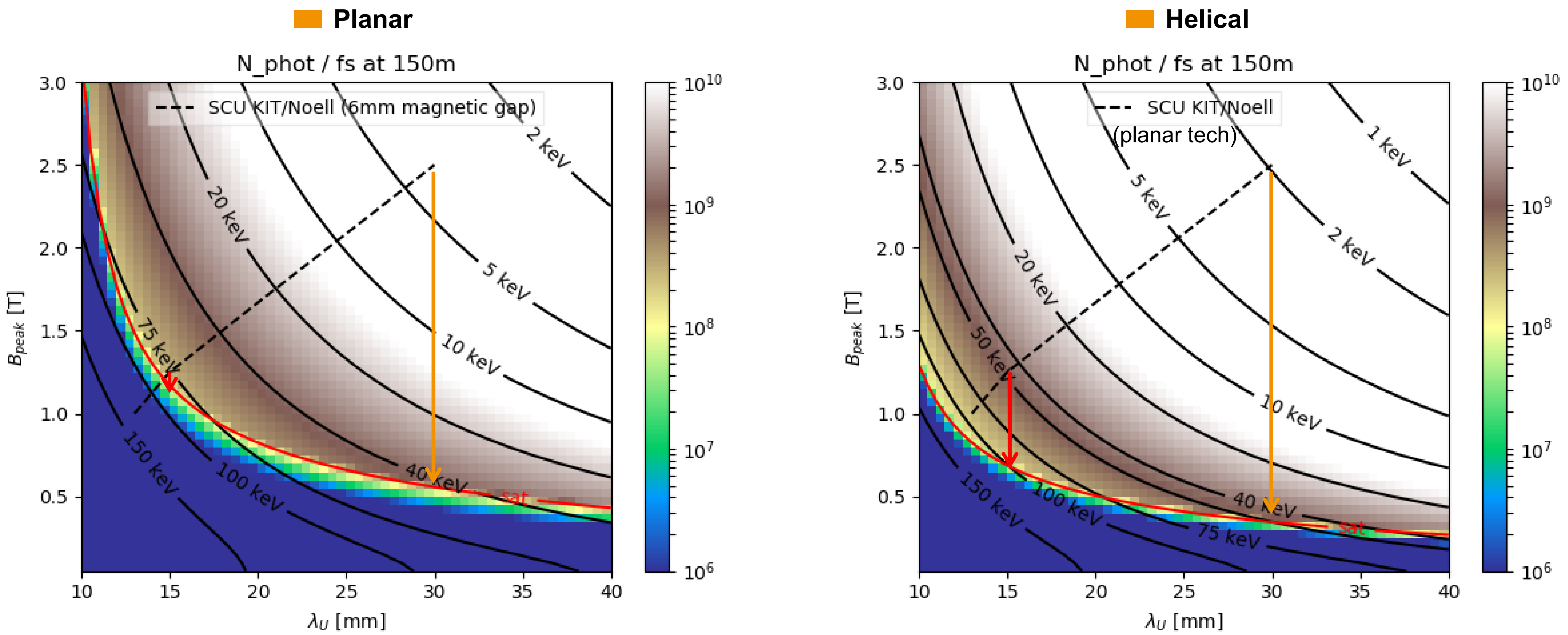
Operation mode	E_{beam} [GeV]	E_{acc} in ML [MV/m]	Beam-on DF [%]
sp (nominal)	19.8	23.4	0.6
cw	7.8	7.3	100
lp	10	10	53
lp	14	15	23

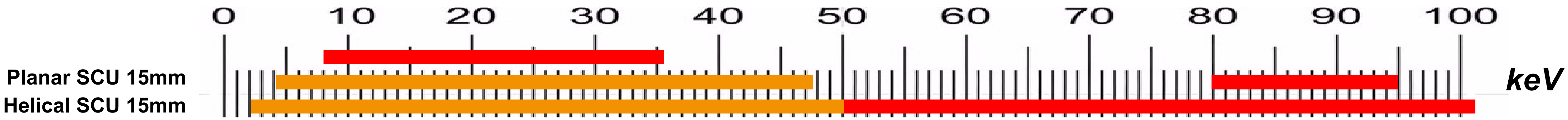
- At optimistic electron energy and emittance parameters one can expert to reach beyond 100keV

SASE1/2 40mm
SCU 15mm + 30mm
SCU 16mm + 32mm
SCU 17mm + 34mm



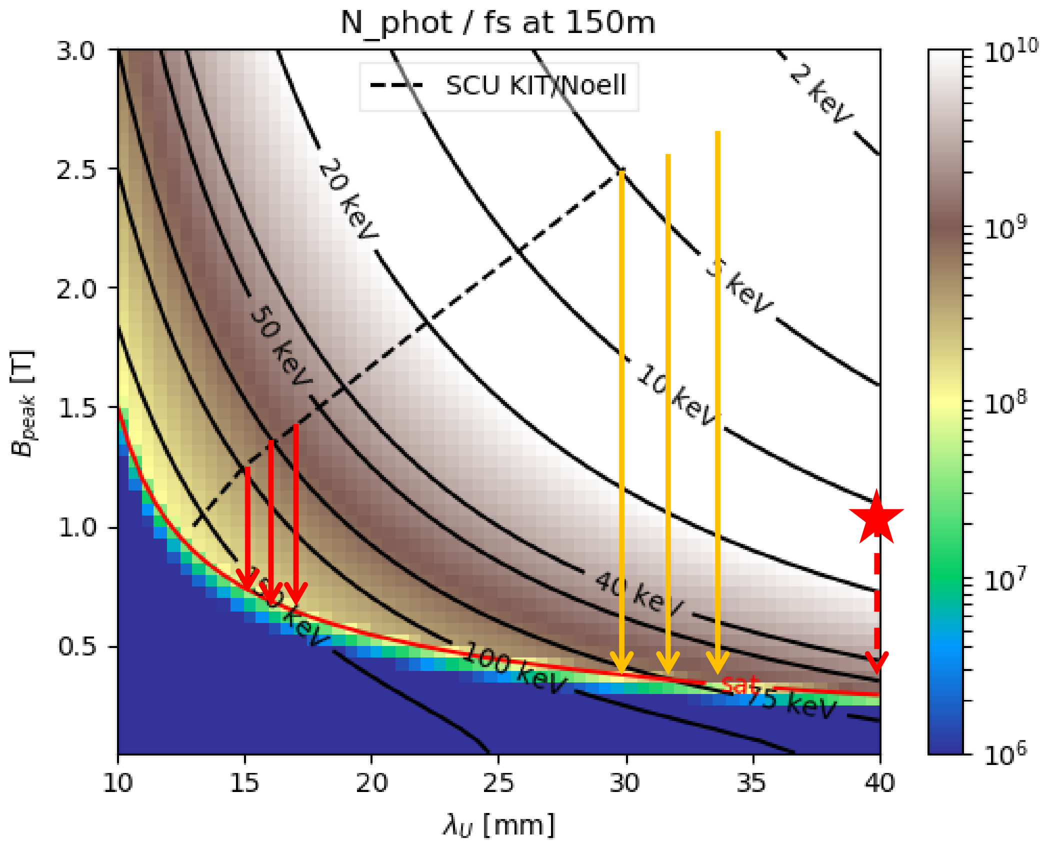
Planar vs Helical undulator





Optimistic scenario (SP mode, 19.8 GeV, 0.2mm*mrad beam)

19.8 GeV



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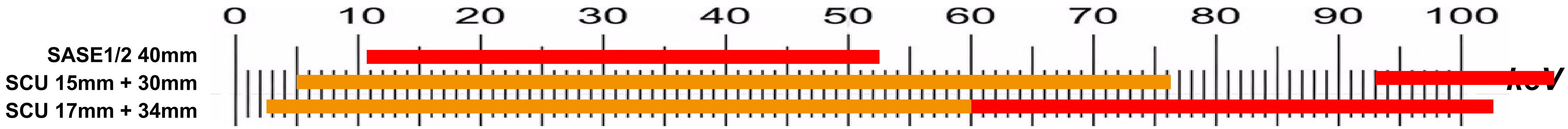
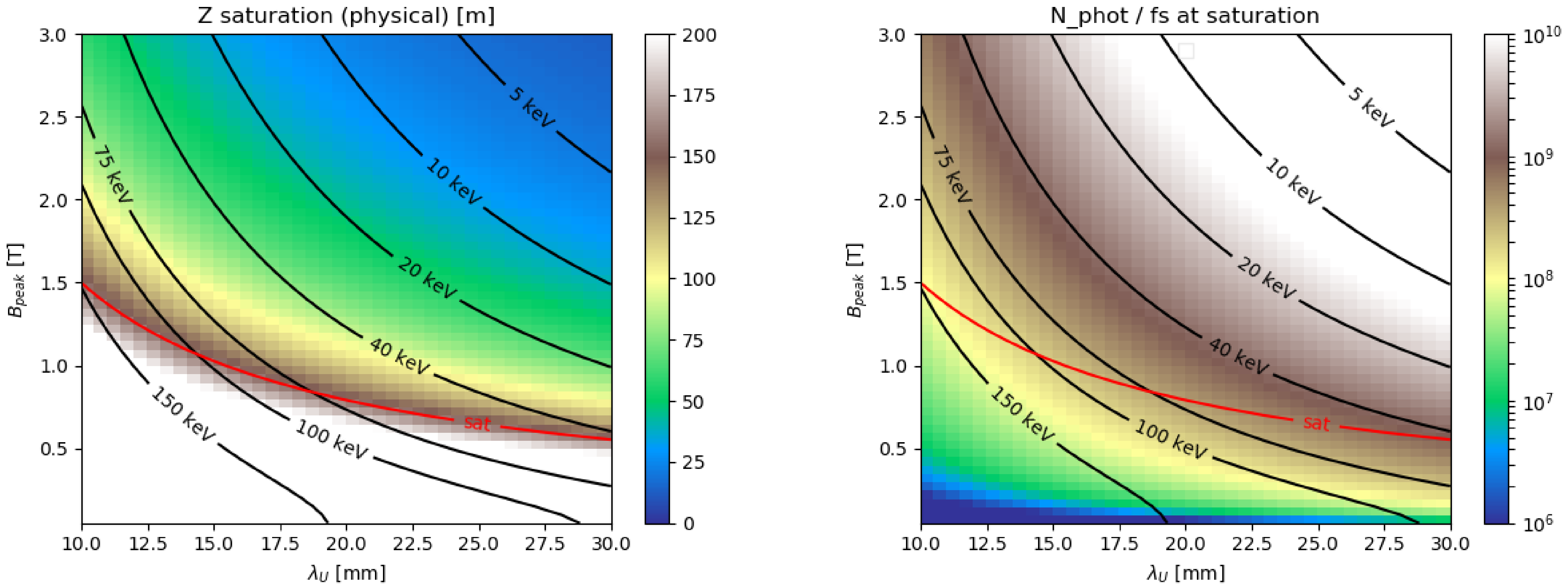


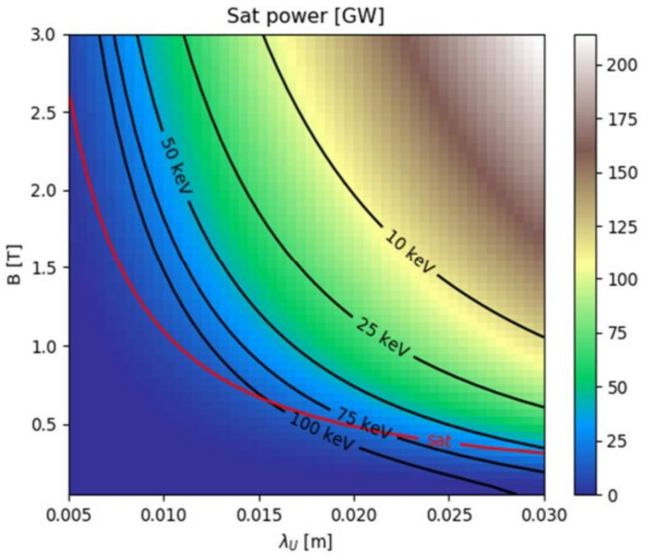
Saturation length and number of photons/femtosecond at saturation



Simplex vs Genesis

Good agreement

Ming Xie (SS) vs GENESIS

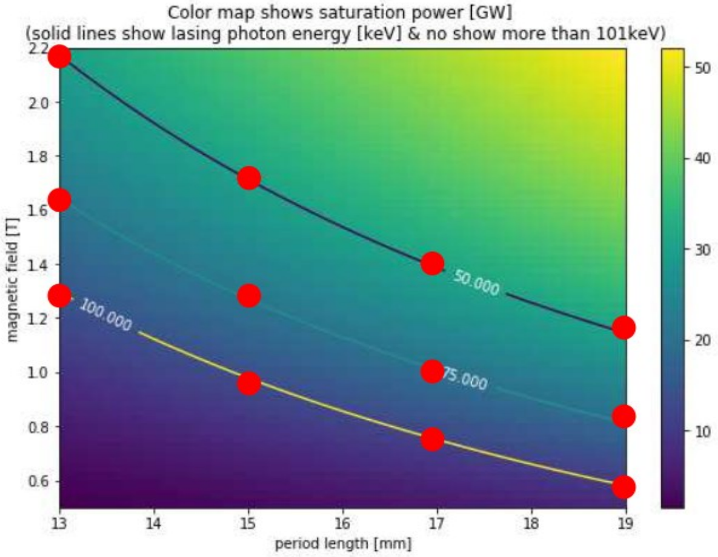


Peak saturation power simulated by GENESIS
(() indicates quantum effect considered)

Mag. Period \ Ph. Energy	50keV	75keV	100keV
13mm	28 GW (8)	17 GW (7)	16 GW (7)
15mm	27 GW (15)	18 GW (11)	13 GW (10)
17mm	27 GW (18)	18 GW (12)	Before satu.
19mm	28 GW (21)	Before satu.?	Before satu.

Ming Xie (TT) vs SIMPLEX

: simulation point



Peak saturation power simulated by SIMPLEX
(() indicates averaged power)

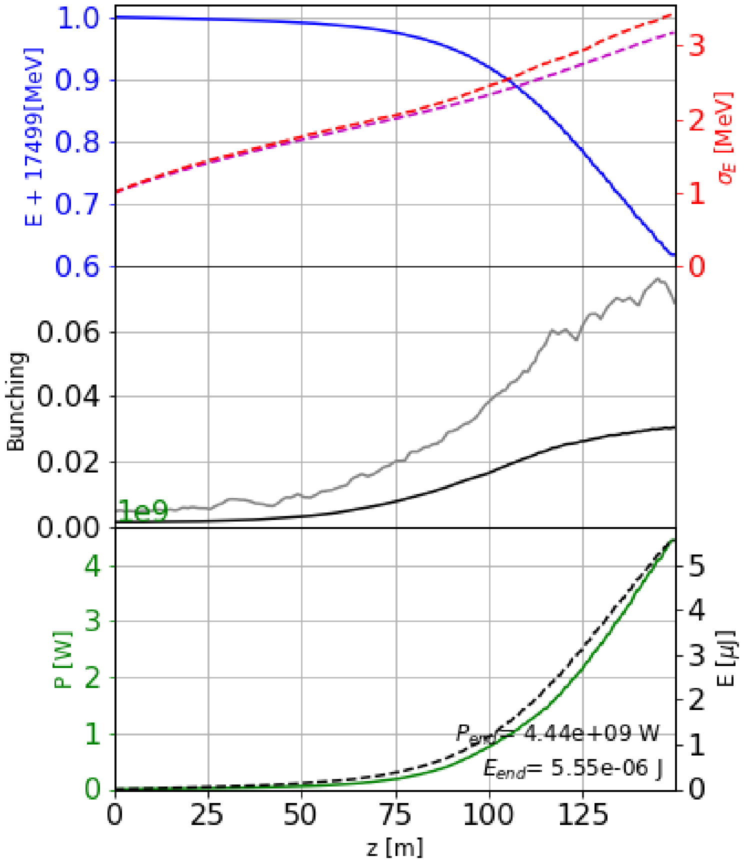
Mag. Period \ Ph. Energy	50keV	75keV	100keV
13mm	26 GW (11)	17 GW (8)	12 GW (4)
15mm	28 GW (11)	19 GW (8)	12 GW (5)
17mm	28 GW (11)	26 GW (7)	14 GW (4)
19mm	28 GW (10)	24 GW (7)	11 GW (3)

By Takanori Tanikawa

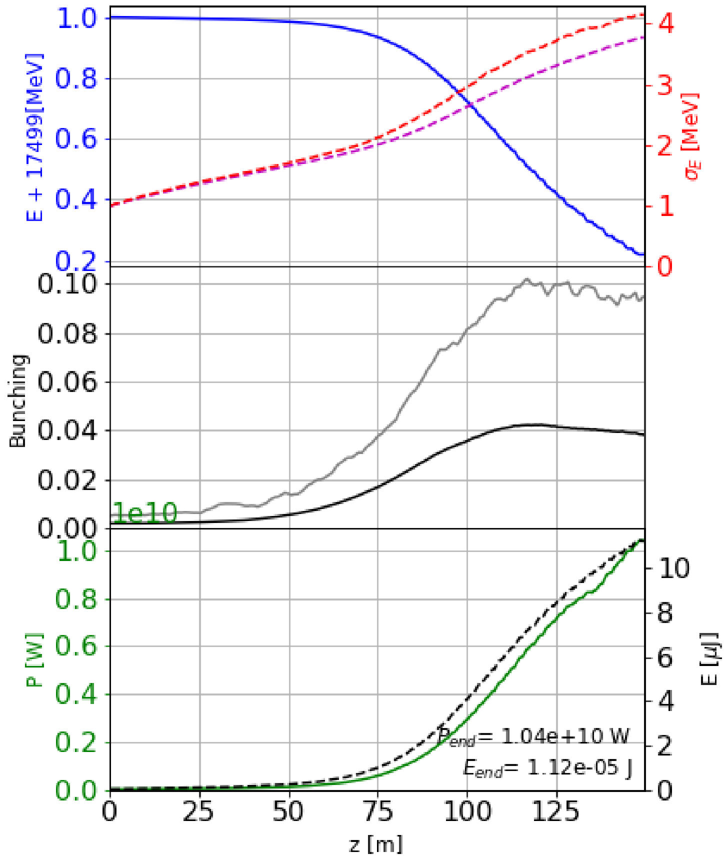
Planar vs Helical undulator: 100keV, 17.5 GeV, 15mm period, QF included

- $K_{rms} = 0.97$
- $Z_{sat}^{hel} / Z_{sat}^{pl} \sim (A_{jj}^{pl} / A_{jj}^{hel})^{2/3} \sim 0.9$

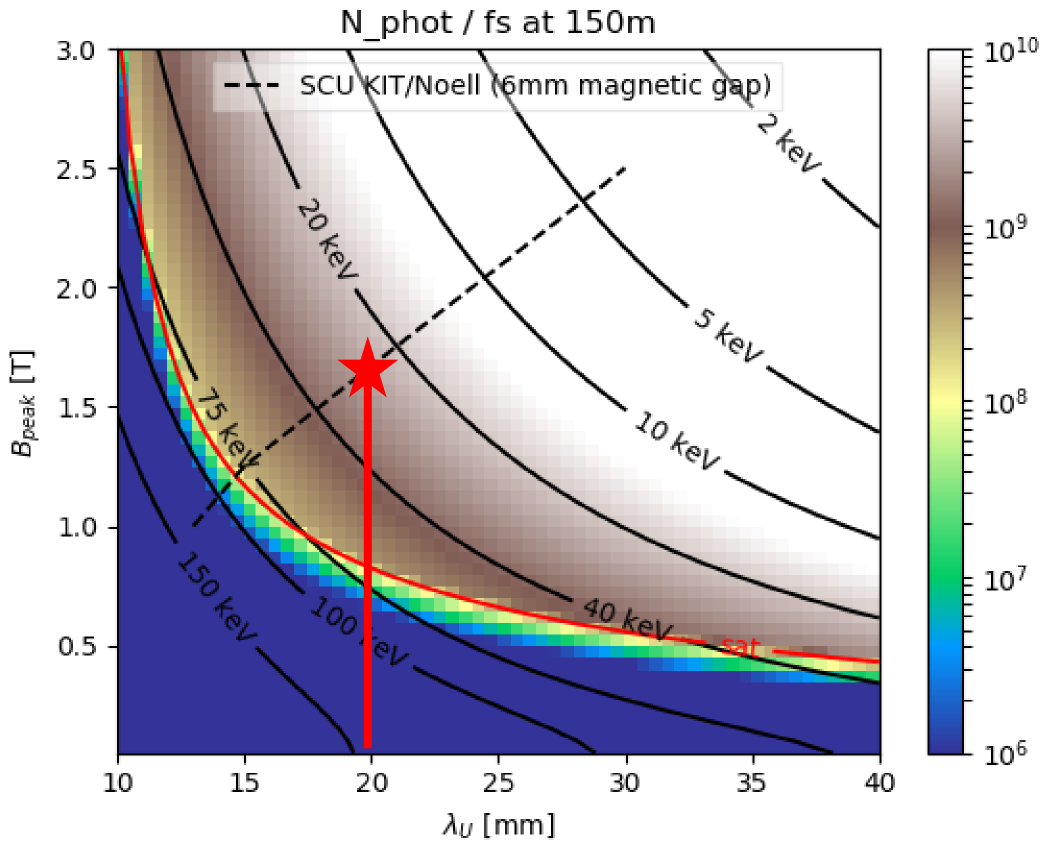
Planar



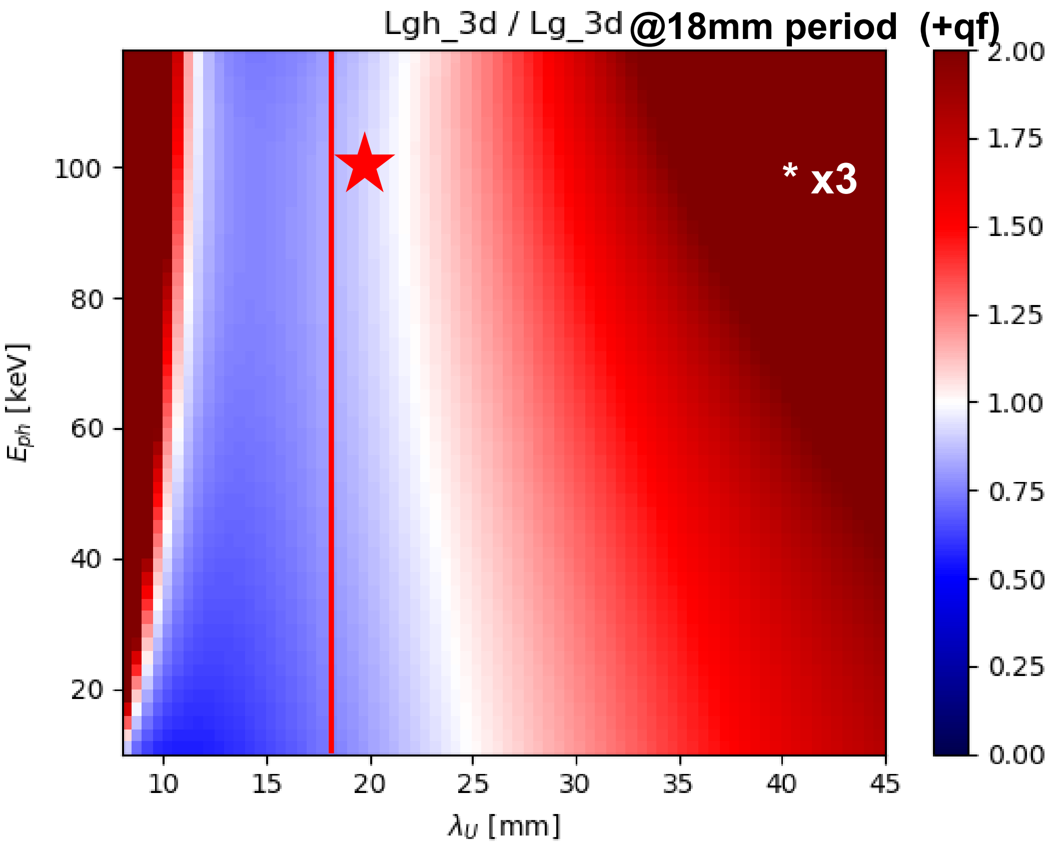
Helical



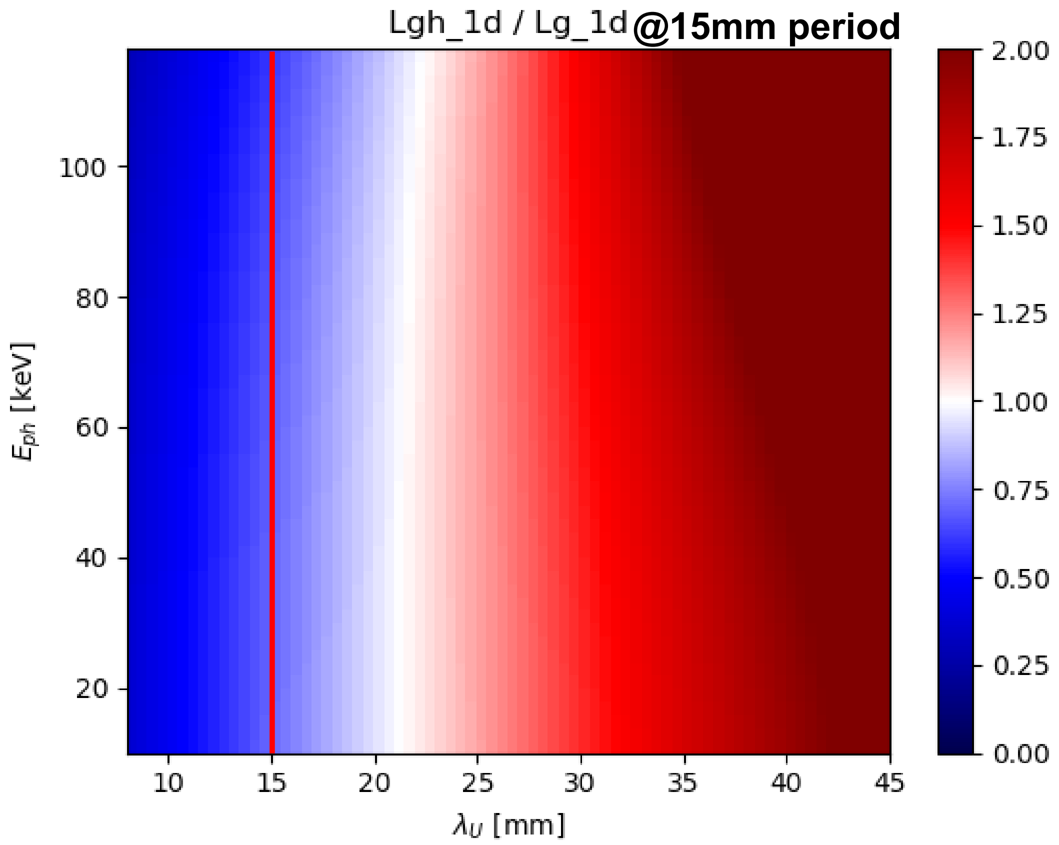
Comparison with harmonic lasing

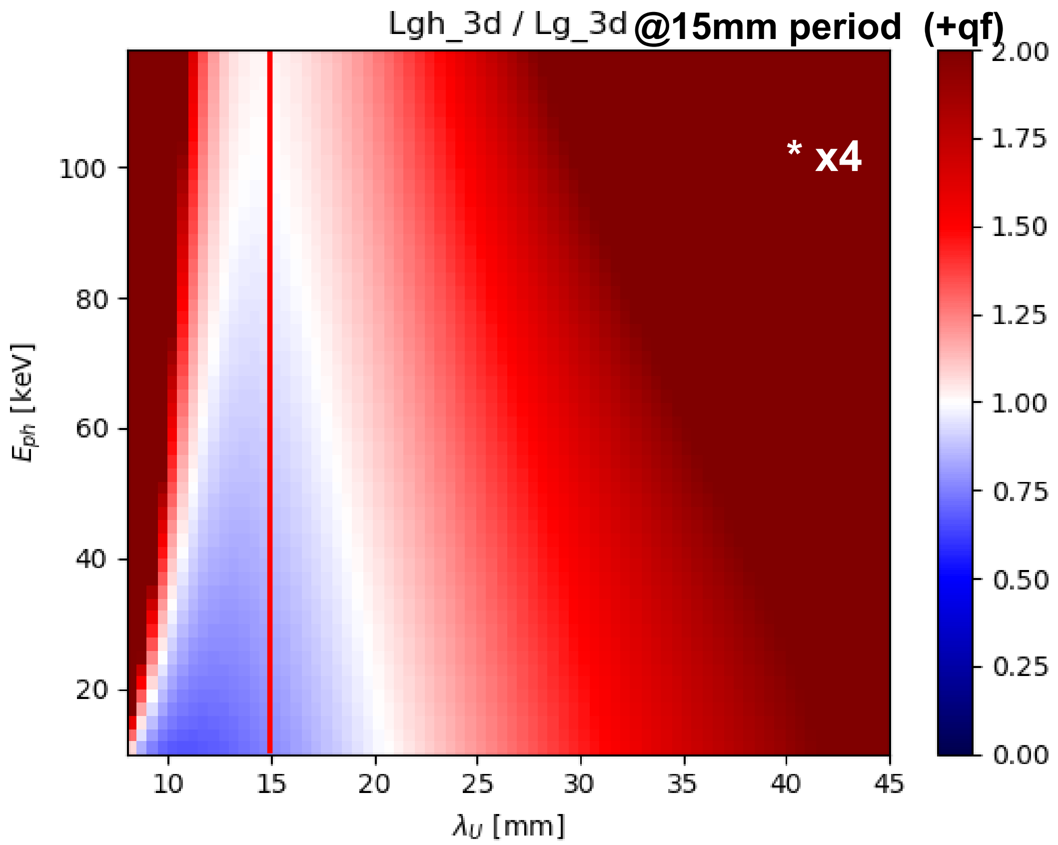


33*3=100

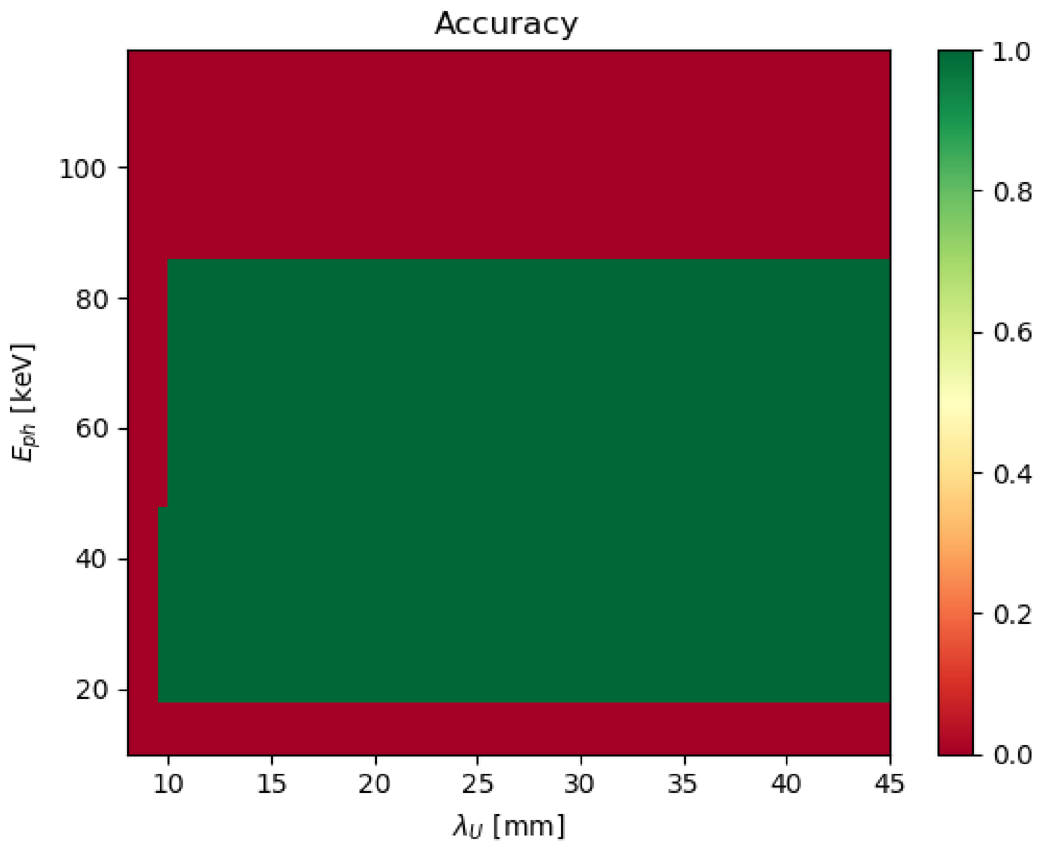


Comparison with harmonic lasing





Comparison with harmonic lasing



Phys. Rev. ST Accel. Beams **15,** 080702 (2012)

The formulas (3)–(5) provide an accuracy better than 5% in the range of parameters

$$1 < \frac{2\pi\epsilon}{\lambda_h} < 5, \quad (6)$$

$$\delta < 2.5\left\{1 - \exp\left[-\frac{1}{2}\left(\frac{2\pi\epsilon}{\lambda_h}\right)^2\right]\right\}. \quad (7)$$

In fact, the formulas (3)–(5) can also be used well beyond this range, but the above-mentioned accuracy is not guaranteed.

- SASE1/2 damage
  slides by Frederik Wolff-Fabris

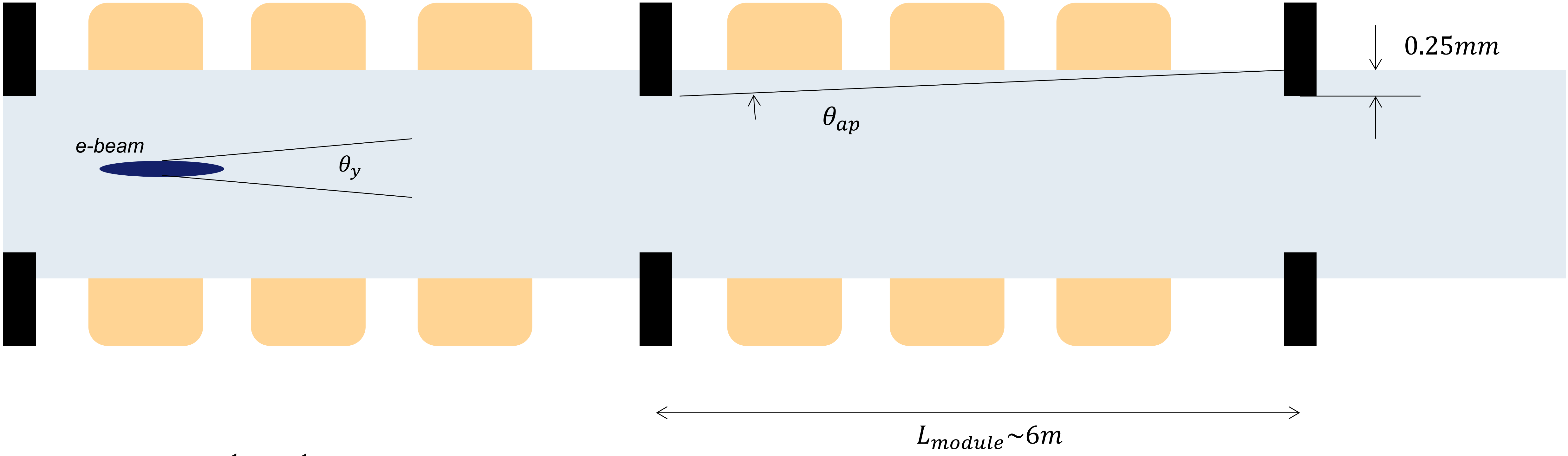
- Cell#27, 9.3keV

Using recent User Operation weeks

Using 1nC and not 0.25nC

Dose (Gy)	Charge (C)	Bunches	Time (weeks)	Time (weeks)	Time (weeks)
230	14.375	120	81	162-324	40.5-81
500	31.21	120	176	352-704	88-176
1000	62.42	120	352	704-1408	176-352
230	14.375	500	19.4	38.8-77.6	9.7-19.4
500	31.21	500	42.2	84.4-168.8	21.1-42.2
1000	62.42	500	84.4	168.8-337.6	42.2-84.4
230	14.375	1200	8.1	16.2-32.4	4.05-8.1
500	31.21	1200	17.6	35.2-70.4	8.8-17.6
1000	62.42	1200	35.2	70.4-140.8	17.6-35.2
230	14.375	2700	3.6	7.2-14.4	1.8-3.6
500	31.21	2700	7.8	15.6-30.2	3.9-7.8
1000	62.42	2700	15.6	31.2-62.4	7.8-15.6

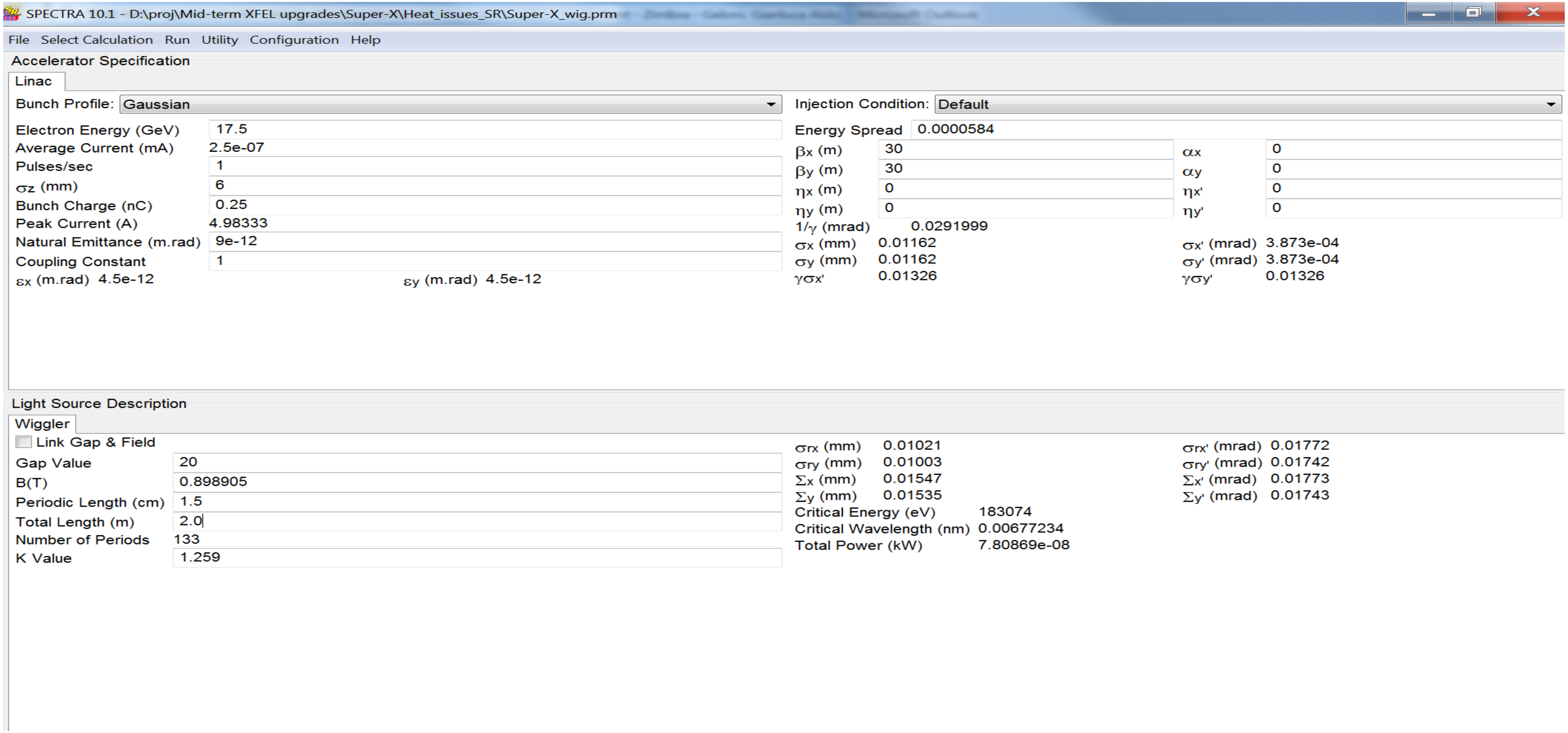
SR heating handled with apertures



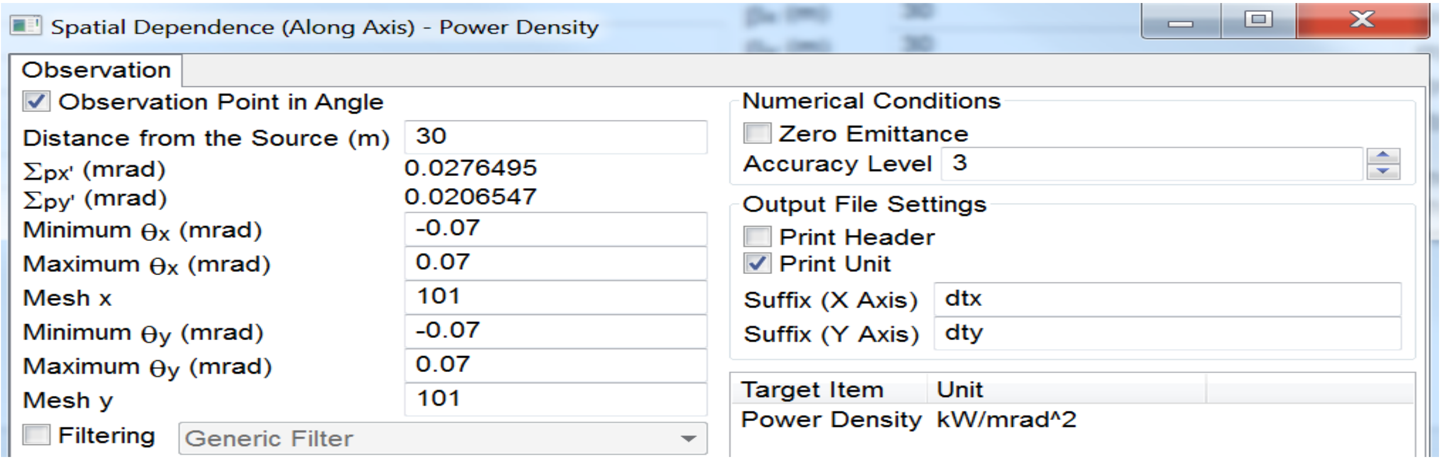
- $\theta_{rad}^{y} \sim \frac{1}{\gamma} = \frac{1}{35000} \sim 30\mu rad$
- $\theta_{rad}^{x} = K\theta_{rad}^{y}$

- $\theta_{ap}^{xy} = \frac{250\mu m}{6m} \sim 40\mu rad$

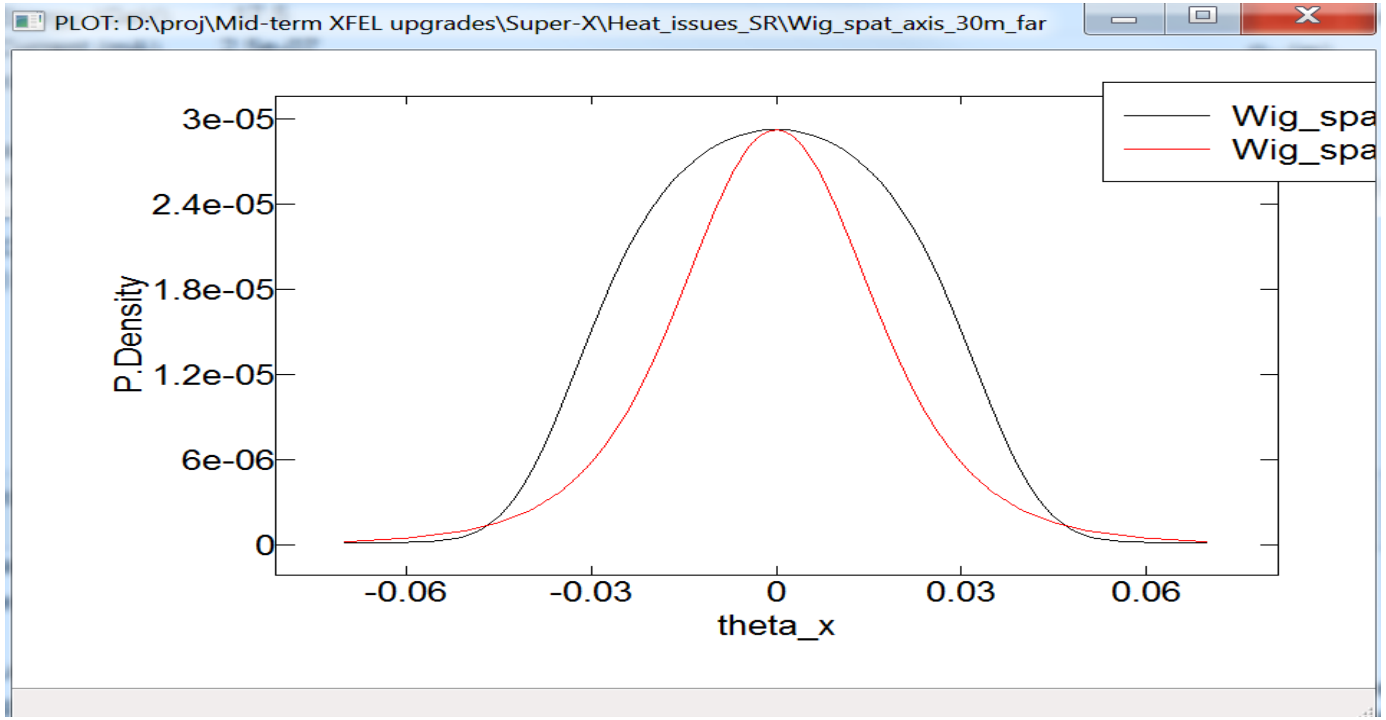
SPECTRA – Wiggler model



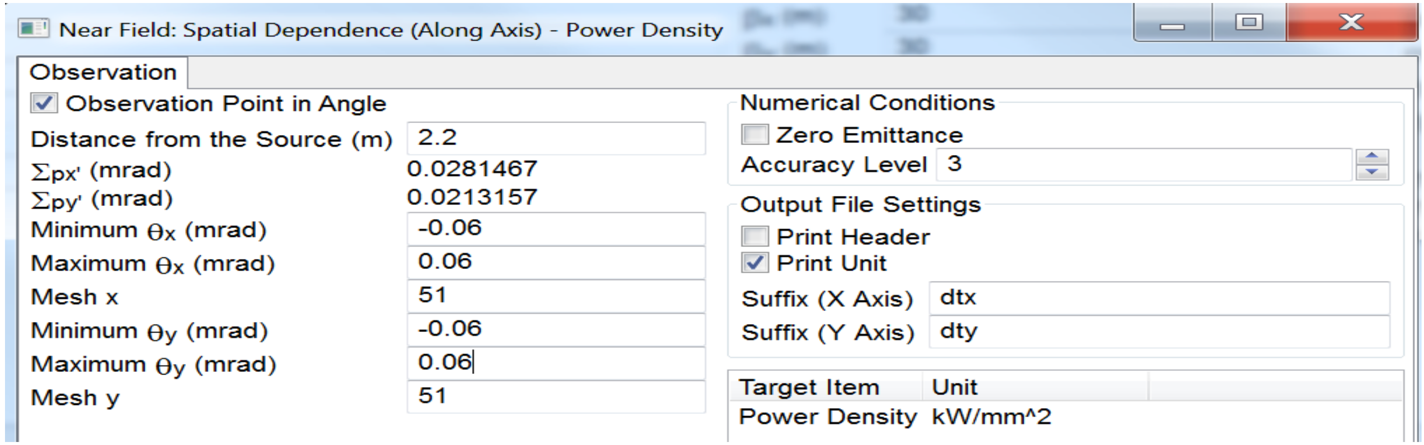
SPECTRA – Wiggler model – far zone calculation



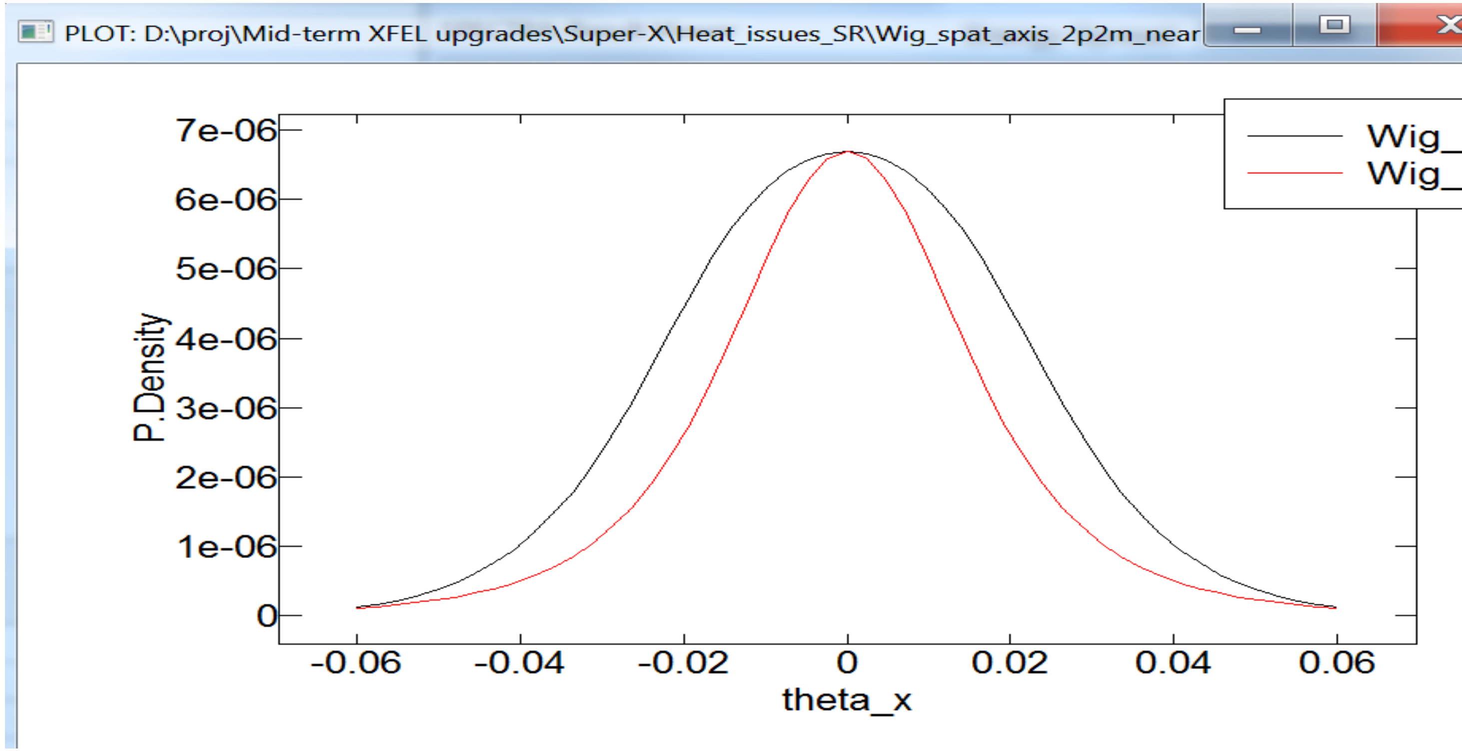
- R=Theta_x*Distance from source
- Source is in the MIDDLE of the ID



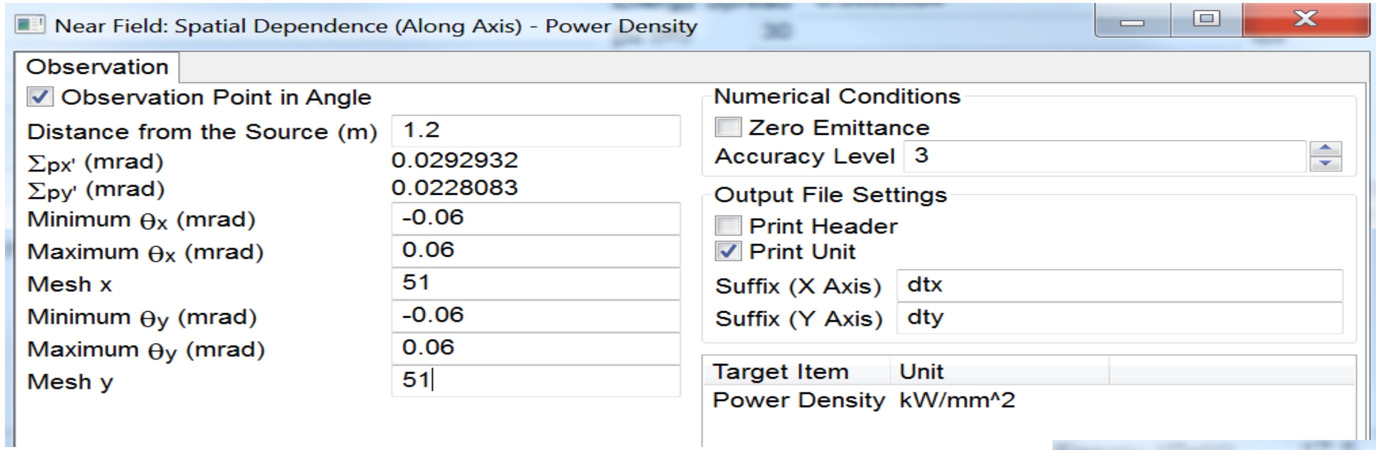
SPECTRA – Wiggler model – near zone calculation (2.2 m from source)

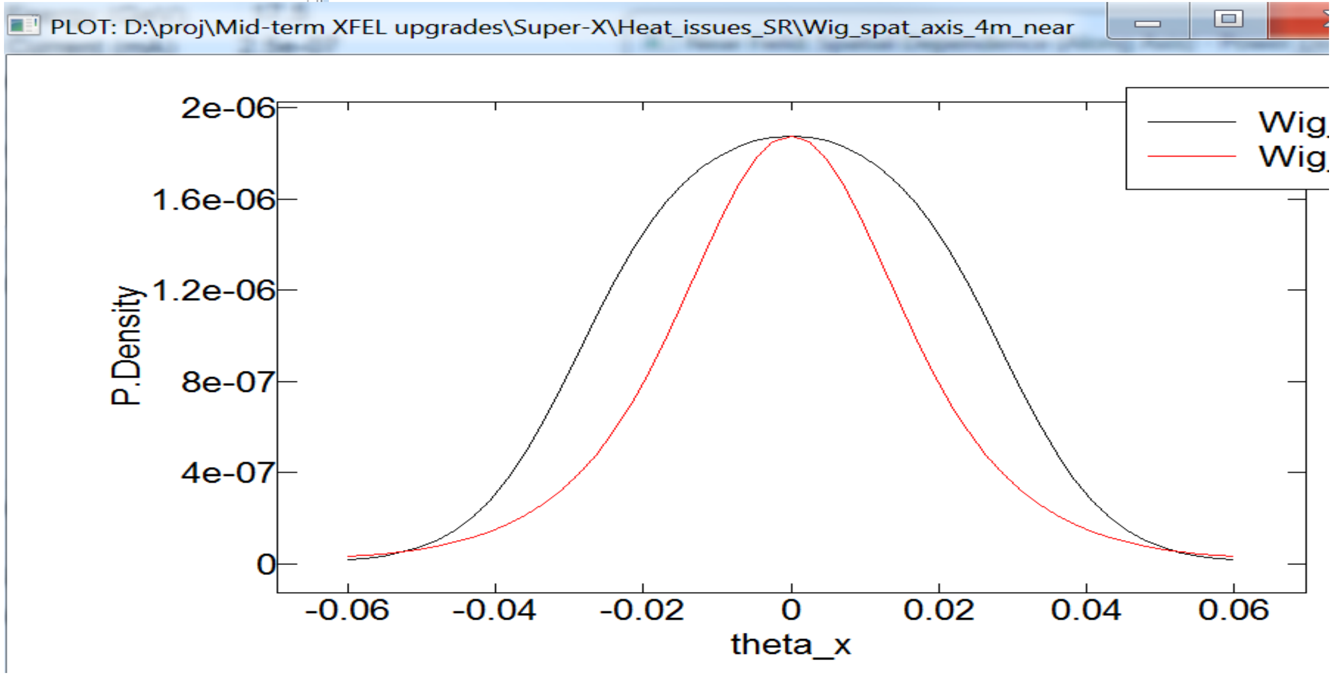


- R=Theta_x*Distance from source
- In kW/mm^2→ (2.2)^2=4.84 wrt previous



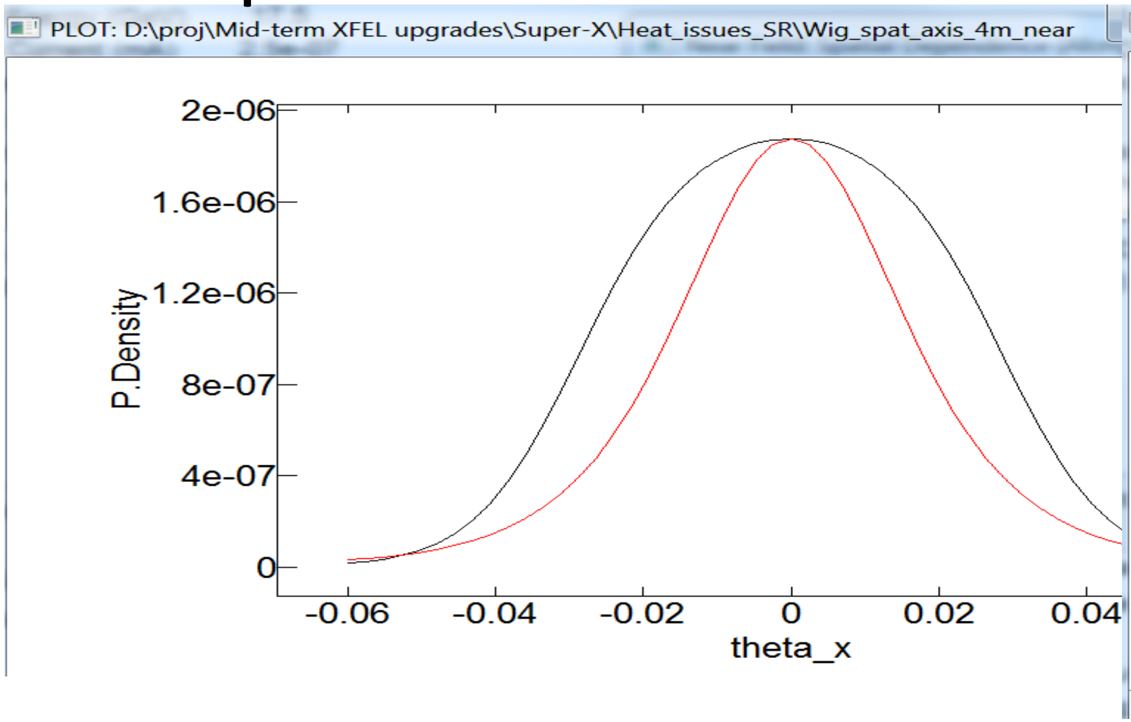
SPECTRA – Wiggler model – near zone calculation (4 m from source)

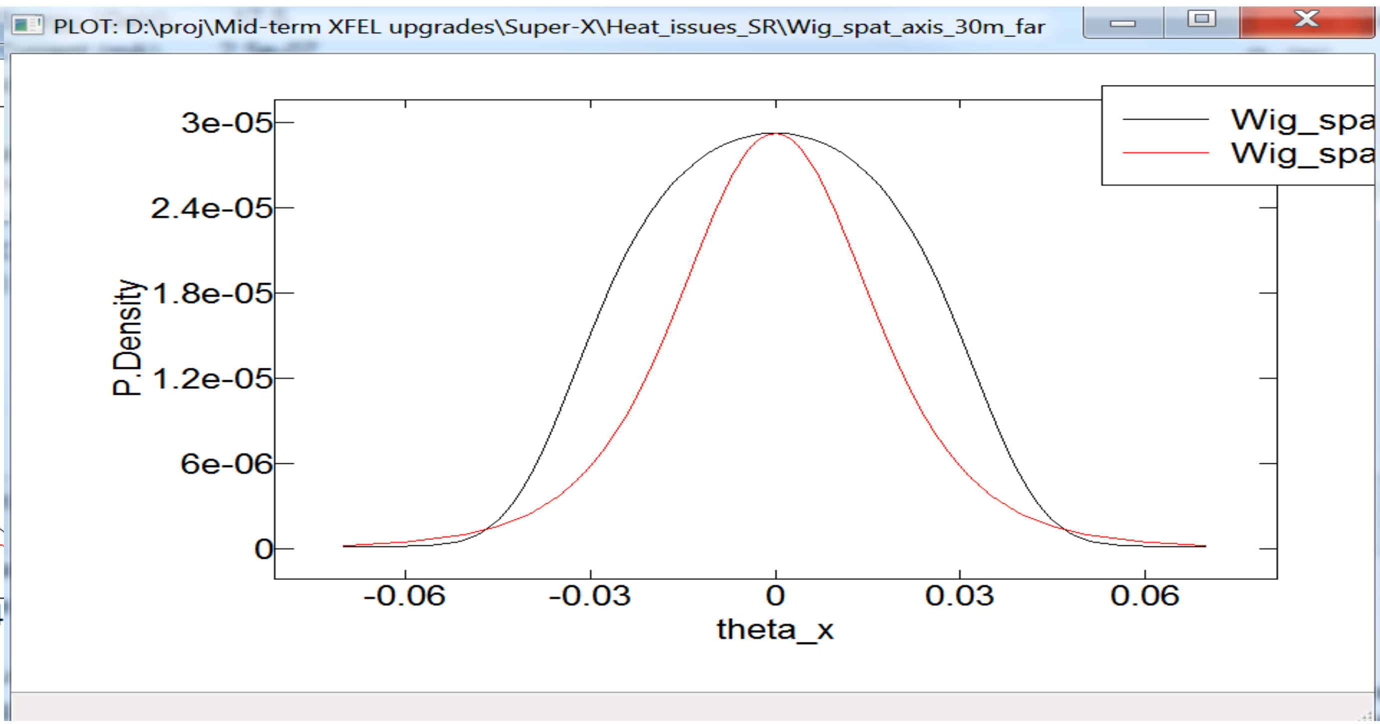




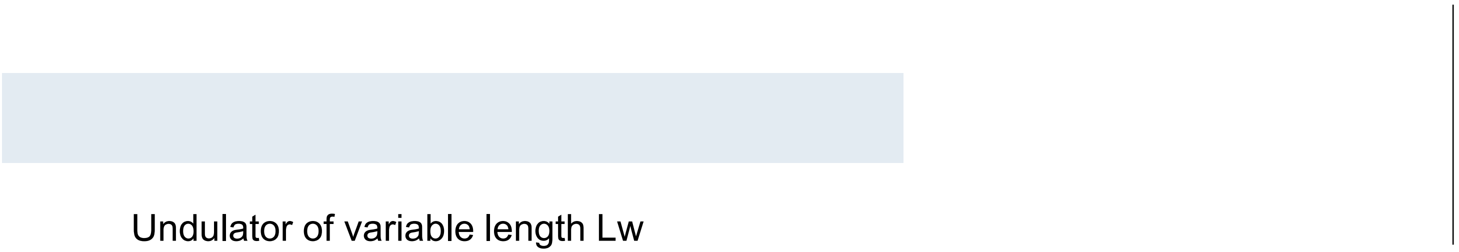
- R=Theta_x*Distance from source
- In kW/mm^2→ (4)^2=16 wrt previous

Receipt





- Since not too much difference after a couple of meters use the following model:



Undulator of variable length Lw

Observation position fixed at 5 m from the exit

SPECTRA – Undulator model

SPECTRA 10.1 - D:\proj\Mid-term XFEL upgrades\Super-X\Heat_issues_SR\Super-X_undu.prm

File Select Calculation Run Utility Configuration Help

Accelerator Specification

Linac

Bunch Profile: Gaussian
Injection Condition: Default

Electron Energy (GeV)	17.5	Energy Spread	0.0000584		
Average Current (mA)	2.5e-07	β_x (m)	30	α_x	0
Pulses/sec	1	β_y (m)	30	α_y	0
σ_z (mm)	6	η_x (m)	0	η_x'	0
Bunch Charge (nC)	0.25	η_y (m)	0	η_y'	0
Peak Current (A)	4.98333	$1/\gamma$ (mrad)	0.0291999		
Natural Emittance (m.rad)	9e-12	σ_x (mm)	0.01162	σ_x' (mrad)	3.873e-04
Coupling Constant	1	σ_y (mm)	0.01162	σ_y' (mrad)	3.873e-04
ε_x (m.rad) 4.5e-12	ε_y (m.rad) 4.5e-12	$\gamma\sigma_x'$	0.01326	$\gamma\sigma_y'$	0.01326

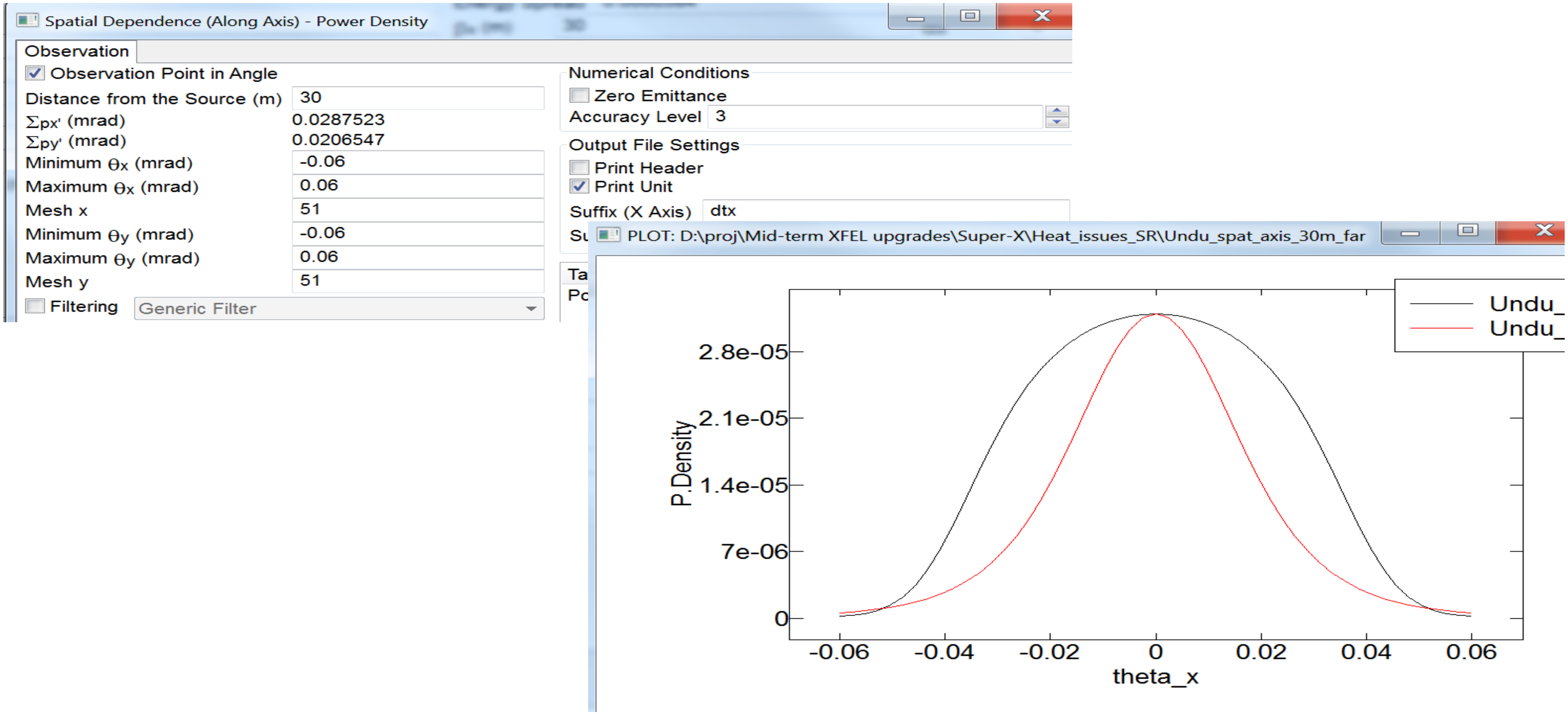
Light Source Description

Linear Undulator

- [ ] Link Gap & Field
- [ ] Segmented Undulator
- [ ] Special Magnet Setup

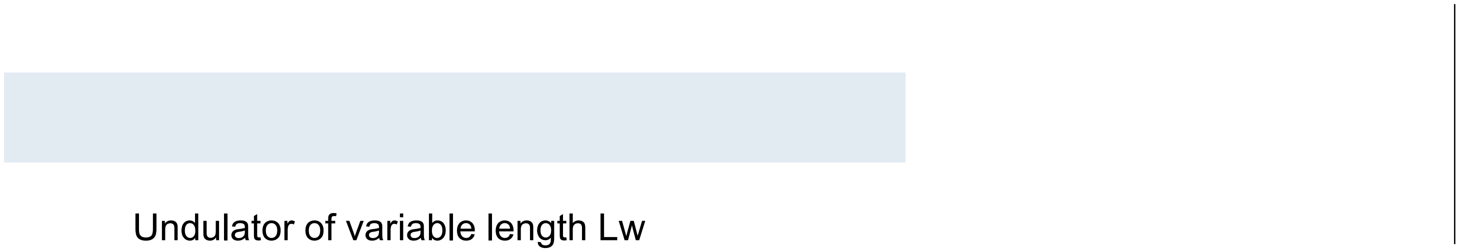
		σ_r (mm)	5.597e-04	σ_r' (mrad)	1.763e-03
		Σ_x (mm)	0.01163	Σ_x' (mrad)	1.805e-03
		Σ_y (mm)	0.01163	Σ_y' (mrad)	1.805e-03
Gap Value	20	λ_{1st}(nm)	0.012396		
B(T)	0.978157	ε_{1st}(peak:eV)	100005		
Periodic Length (cm)	1.5	ε_{3rd}(peak:eV)	300008		
Total Length (m)	2.0	$Flux_{1st}$	1.72445e+06		
Number of Periods	133	$Brilliance_{1st}$	9.91211e+13		
K Value	1.37	Peak Brilliance	1.97581e+24		
ε_{1st}(eV)	100020	Bose Degeneracy	0.00156919		
		Total Power (kW)	9.2463e-08		

SPECTRA – Undulator model – far-zone calculation

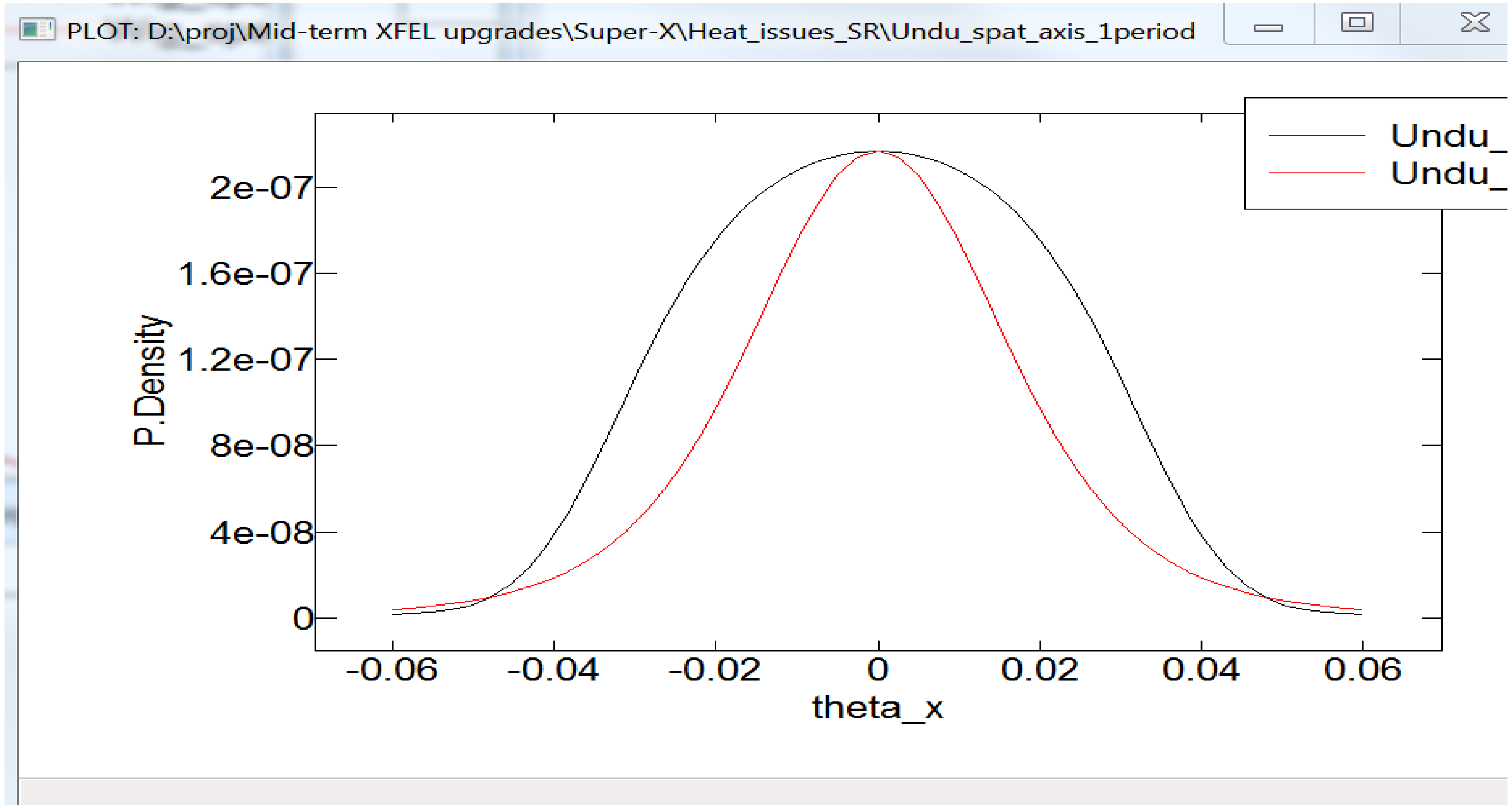


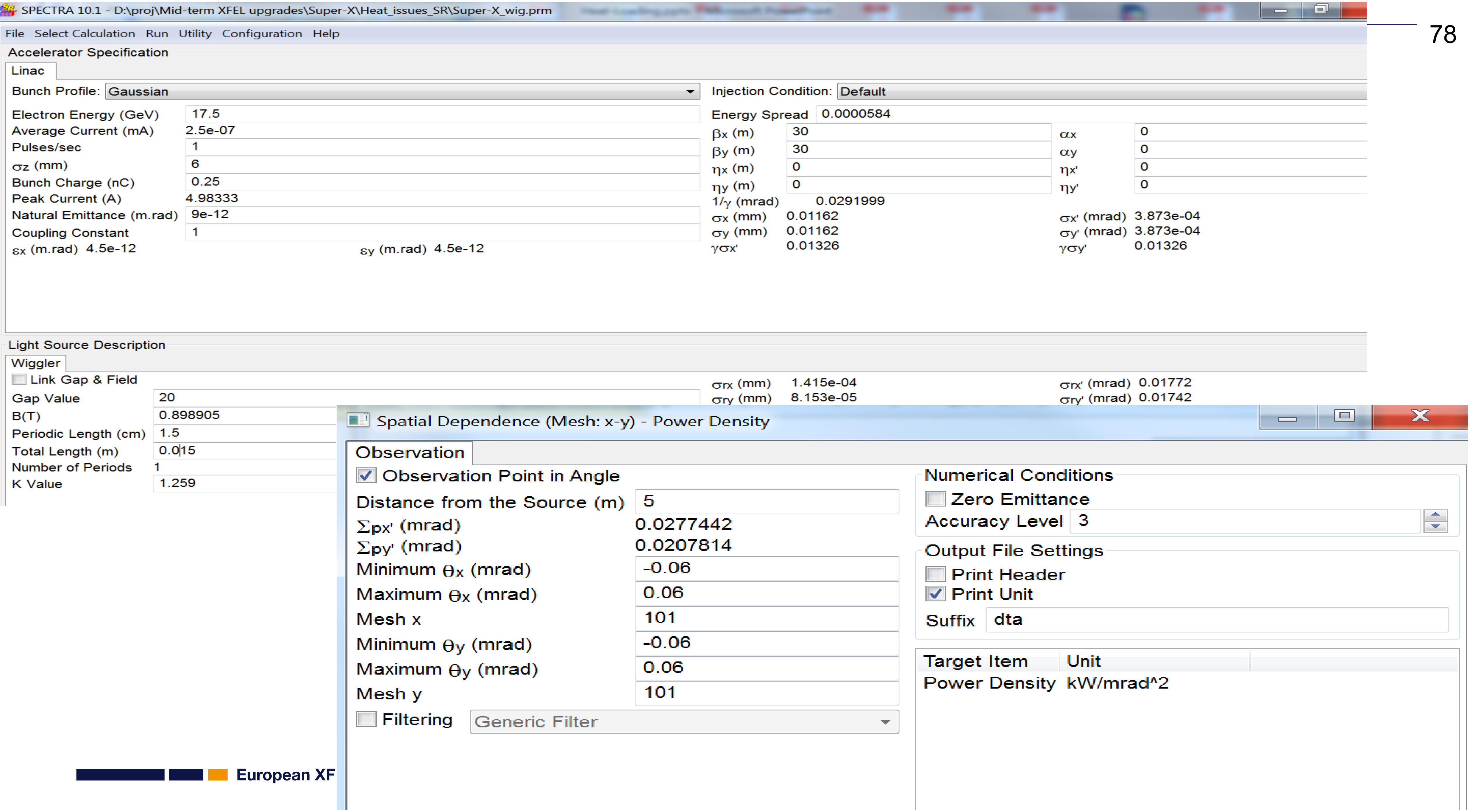
Therefore:

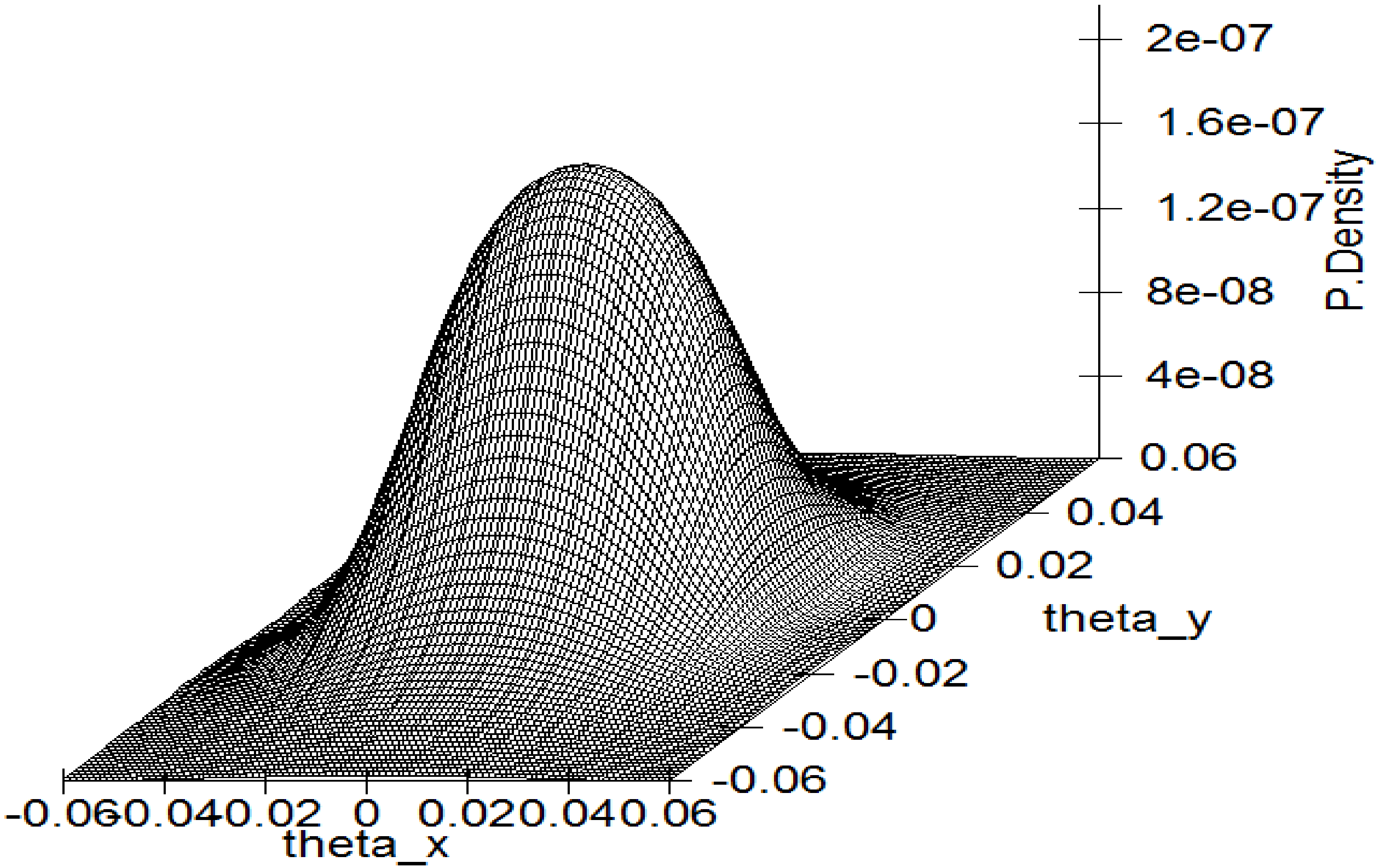
- No big difference between undulator and wiggler model
- Far zone starts to be ok for a distance a few time the ID length
- Use wiggler model, far zone
- Assume e.g. 5m from the exit of a wiggler of variable length
- Study as a function of the wiggler length



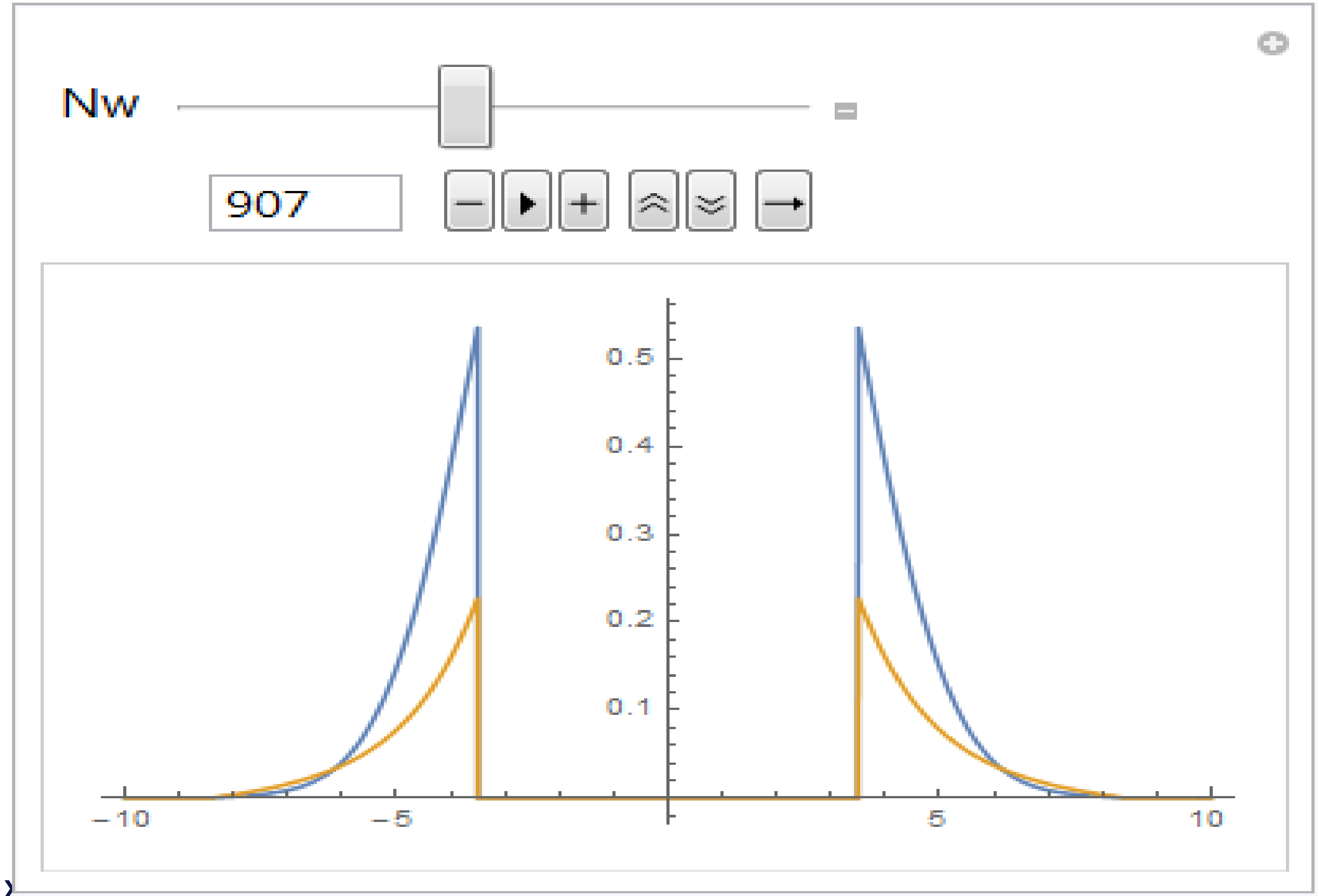
Selecting 1 period just divides the full flux by #periods




SPECTRA 10.1 - D:\proj\Mid-term XFEL upgrades\Super-X\Heat_issues_SR\Super-X_wig.prm
File Select Calculation Run Utility Configuration Help
Accelerator Specification
Linac
Bunch Profile: Gaussian
Injection Condition: Default
Electron Energy (GeV) 17.5
Average Current (mA) 2.5e-07
Pulses/sec 1
σz (mm) 6
Bunch Charge (nC) 0.25
Peak Current (A) 4.98333
Natural Emittance (m.rad) 9e-12
Coupling Constant 1
εx (m.rad) 4.5e-12
εy (m.rad) 4.5e-12
Energy Spread 0.0000584
βx (m) 30
βy (m) 30
ηx (m) 0
ηy (m) 0
1/γ (mrad) 0.0291999
σx (mm) 0.01162
σy (mm) 0.01162
γσx' 0.01326
αx 0
αy 0
ηx' 0
ηy' 0
σx' (mrad) 3.873e-04
σy' (mrad) 3.873e-04
γσy' 0.01326
Light Source Description
Wiggler
Link Gap & Field
Gap Value 20
B(T) 0.898905
Periodic Length (cm) 1.5
Total Length (m) 0.015
Number of Periods 1
K Value 1.259
σrx (mm) 1.415e-04
σry (mm) 8.153e-05
σrx' (mrad) 0.01772
σry' (mrad) 0.01742
Spatial Dependence (Mesh: x-y) - Power Density
Observation
Observation Point in Angle
Distance from the Source (m) 5
Σpx' (mrad) 0.0277442
Σpy' (mrad) 0.0207814
Minimum θx (mrad) -0.06
Maximum θx (mrad) 0.06
Mesh x 101
Minimum θy (mrad) -0.06
Maximum θy (mrad) 0.06
Mesh y 101
Filtering
Generic Filter
Numerical Conditions
Zero Emittance
Accuracy Level 3
Output File Settings
Print Header
Print Unit
Suffix dta
Target Item
Unit
Power Density
kW/mrad^2


2e-07
1.6e-07
1.2e-07
8e-08
4e-08
P.Density
0.06
0.04
0.02
0
theta_y
-0.02
-0.04
-0.06
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
theta_x

Example after about 907 periods (see Analysis.nb)



Harmonic Lasing Basic Fitting Formulas

Harmonic Lasing Basic Fitting Formulas

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 080702 (2012)

Harmonic lasing in x-ray free electron lasers

E. A. Schneidmiller* and M. V. Yurkov

$$L_g \simeq L_{g0}(1 + \delta)$$ Field gain length

$$L_{g0} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_w)^{5/6}}{\lambda_h^{2/3}} \frac{(1 + K^2)^{1/3}}{h^{5/6} K A_{JJh}}$$

$$\delta = 131 \frac{I_A}{I} \frac{\epsilon_n^{5/4}}{\lambda_h^{1/8} \lambda_w^{9/8}} \frac{h^{9/8} \sigma_\gamma^2}{(K A_{JJh})^2 (1 + K^2)^{1/8}}$$

$$A_{JJh}(K) = J_{(h-1)/2}\left(\frac{hK^2}{2(1 + K^2)}\right) - J_{(h+1)/2}\left(\frac{hK^2}{2(1 + K^2)}\right)$$

$$\beta_{\mathrm{opt}} \simeq 11.2\left(\frac{I_A}{I}\right)^{1/2} \frac{\epsilon_n^{3/2} \lambda_w^{1/2}}{\lambda_h h^{1/2} K A_{JJh}} (1 + 8\delta)^{-1/3}$$

$$L_g(\beta) \simeq L_g(\beta_{\mathrm{opt}})\left[1 + \frac{(\beta - \beta_{\mathrm{opt}})^2 (1 + 8\delta)}{4\beta_{\mathrm{opt}}^2}\right]^{1/6} \quad \text{for } \beta > \beta_{\mathrm{opt}}.$$

$$2\pi\frac{\epsilon}{\lambda} > 1$$

Harmonic Lasing vs. SCU

Target Wavelength $$\lambda_t = \lambda_w \frac{1 + K^2}{2\gamma^2}$$

$\lambda_t = \lambda_h$ **fixed**

γ **fixed**

λ_w **variable**

$K\ (rms)$ **variable**

→ $$\lambda_w(1 + K^2) = \text{constant}$$

- Note the difference with the "retuning" case, where the period is fixed too (see PRSTAB 15, 080702 Appendix A)

Therefore

$$\lambda_{wh}(1 + K_h^2) = \lambda_{wSC}(1 + K_{SC}^2)$$

Index "h" → Harmonic lasing
Index "SC" → Superconducting Undulator

Harmonic Lasing vs. SCU

$$\lambda_{wh}(1 + K_h^2) = \lambda_{wSC}(1 + K_{SC}^2)$$

$$L_{g0SC} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{wSC})^{5/6}}{\lambda_t^{2/3}} \frac{(1 + K_{SC}^2)^{1/3}}{KA_{JJSC}}$$

$$L_{g0h} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{wh})^{5/6}}{\lambda_t^{2/3}} \frac{(1 + K_h^2)^{1/3}}{h^{5/6}KA_{JJh}}$$

$$\frac{L_{g0h}}{L_{g0SC}} = \frac{\lambda_{wh}^{1/2} K_{SC} A_{JJSC}}{h^{5/6} K_h A_{JJh} \lambda_{wSC}^{1/2}}$$

Harmonic Lasing vs. SCU

Get the K for SC and HL case

$$\mathrm{Ksc} = \frac{\sqrt{2\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{usc}}}{\sqrt{\lambda\mathrm{usc}}}; \quad \mathrm{Kh} = \frac{\sqrt{2\,h\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{uh}}}{\sqrt{\lambda\mathrm{uh}}};$$

Use the above expressions with

$$\frac{L_{g0h}}{L_{g0SC}} = \frac{\lambda_{wh}^{1/2} K_{SC} A_{JJSC}}{h^{5/6} K_h A_{JJh} \lambda_{wSC}^{1/2}}$$

$$\mathrm{FullSimplify}\left[h^{-5/6}\,\frac{\lambda\mathrm{uh}^{1/2}\,\mathrm{Ksc}}{\lambda\mathrm{usc}^{1/2}\,\mathrm{Kh}}\,\frac{\left(\mathrm{BesselJ}\left[0,\ \mathrm{Ksc}^2/(2+2\,\mathrm{Ksc}^2)\right] - \mathrm{BesselJ}\left[1,\ \mathrm{Ksc}^2/(2+2\,\mathrm{Ksc}^2)\right]\right)}{\left(\mathrm{BesselJ}\left[(h-1)/2,\ h\,\mathrm{Kh}^2/(2+2\,\mathrm{Kh}^2)\right] - \mathrm{BesselJ}\left[(h+1)/2,\ h\,\mathrm{Kh}^2/(2+2\,\mathrm{Kh}^2)\right]\right)}\right]$$

$$\frac{\lambda\mathrm{uh}\,\sqrt{2\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{usc}}\,\left(\mathrm{BesselJ}\left[0,\ \frac{1}{2} - \frac{\lambda\mathrm{usc}}{4\,\gamma^2\,\lambda\mathrm{target}}\right] - \mathrm{BesselJ}\left[1,\ \frac{1}{2} - \frac{\lambda\mathrm{usc}}{4\,\gamma^2\,\lambda\mathrm{target}}\right]\right)}{h^{5/6}\,\sqrt{2\,h\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{uh}}\,\lambda\mathrm{usc}\,\left(\mathrm{BesselJ}\left[\frac{1}{2}(-1+h),\ \frac{h}{2} - \frac{\lambda\mathrm{uh}}{4\,\gamma^2\,\lambda\mathrm{target}}\right] - \mathrm{BesselJ}\left[\frac{1+h}{2},\ \frac{h}{2} - \frac{\lambda\mathrm{uh}}{4\,\gamma^2\,\lambda\mathrm{target}}\right]\right)}$$

Set the gain length ratio [redacted]

$$\mathrm{L0HdivL0SC}[h\_,\ \lambda\mathrm{target}\_,\ \lambda\mathrm{uh}\_,\ \lambda\mathrm{usc}\_] =$$

$$\frac{\lambda\mathrm{uh}\,\sqrt{2\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{usc}}\,\left(\mathrm{BesselJ}\left[0,\ \frac{1}{2} - \frac{\lambda\mathrm{usc}}{4\,\gamma^2\,\lambda\mathrm{target}}\right] - \mathrm{BesselJ}\left[1,\ \frac{1}{2} - \frac{\lambda\mathrm{usc}}{4\,\gamma^2\,\lambda\mathrm{target}}\right]\right)}{h^{5/6}\,\sqrt{2\,h\,\gamma^2\,\lambda\mathrm{target} - \lambda\mathrm{uh}}\,\lambda\mathrm{usc}\,\left(\mathrm{BesselJ}\left[\frac{1}{2}(-1+h),\ \frac{h}{2} - \frac{\lambda\mathrm{uh}}{4\,\gamma^2\,\lambda\mathrm{target}}\right] - \mathrm{BesselJ}\left[\frac{1+h}{2},\ \frac{h}{2} - \frac{\lambda\mathrm{uh}}{4\,\gamma^2\,\lambda\mathrm{target}}\right]\right)}$$

Harmonic Lasing vs. SCU

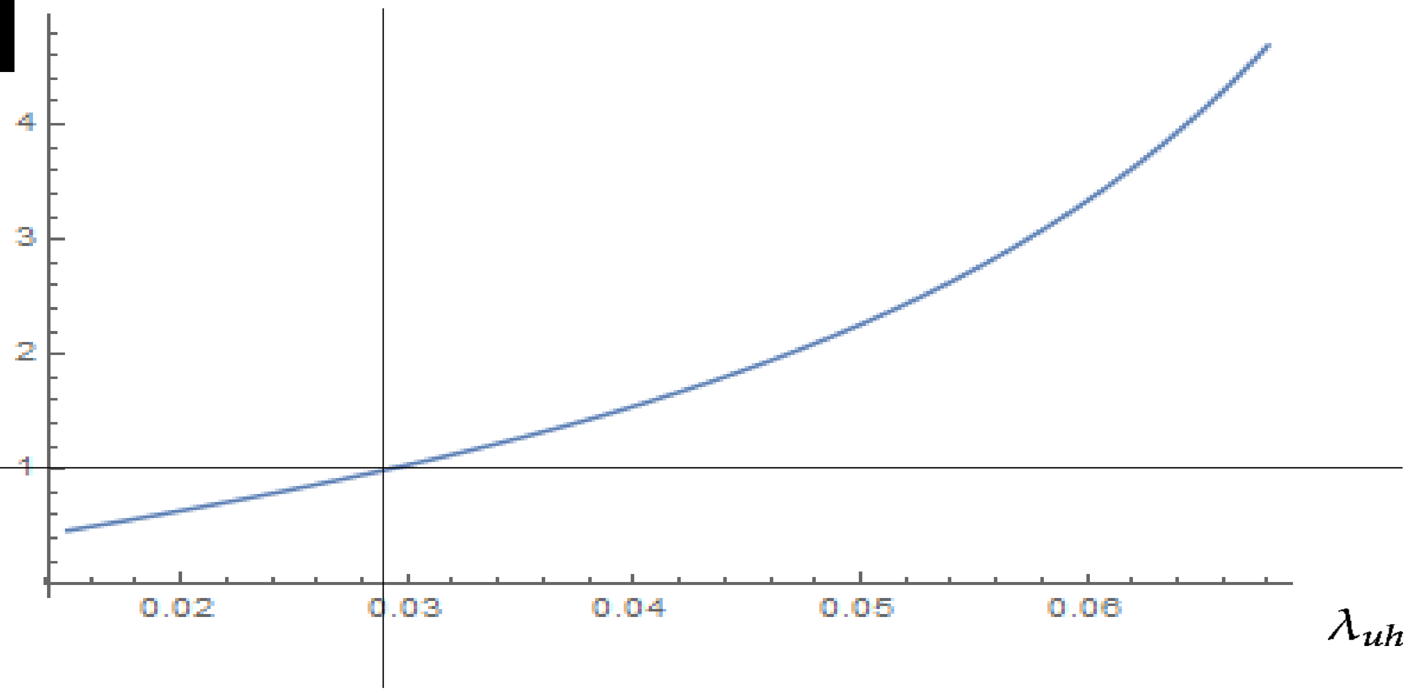
So we indicated with `LOHdivLOSC[h_, λtarget_, λuh_, λusc_]` the ratio [redacted]

Now set

`λtarget = 0.0155 * 10^-9`   `γ = 17500 / 0.511`   `h = 3`

`λusc = 0.015`   15mm period SCU!

[redacted]



Harmonic Lasing has longer gain-length

for undulator periods > 30mm

Energy-spread modifications
make the situation worse for HL

Harmonic Lasing vs. SCU

Energy-spread modifications make the situation much worse for HL

$$L_g \simeq L_{g0}(1 + \delta) \qquad \delta = 131 \frac{I_A}{I} \frac{\epsilon_n^{5/4}}{\lambda_h^{1/8} \lambda_w^{9/8}} \frac{h^{9/8} \sigma_\gamma^2}{(K A_{JJh})^2 (1 + K^2)^{1/8}}$$

```
In[1]:= δ[ϵ_, λu_, h_, σγ_, Ku_, AJJh_] =
131 * IA / Ip * en ^ (5 / 4) / (λtarget ^ (1 / 8) * λuh ^ (9 / 8)) h ^ (9 / 8) σγ ^ 2 / ((Ku AJJh) ^ 2 (1 + Ku ^ 2) ^ (1 / 8))
```

$$\text{Out[1]=} \quad \frac{131\, h^{9/8}\, IA\, en^{5/4}\, \sigma\gamma^2}{AJJh^2\, Ip\, Ku^2\, \left(1 + Ku^2\right)^{1/8}\, \lambda target^{1/8}\, \lambda uh^{9/8}}$$

$\gamma = 17\,500 / 0.511 \qquad \lambda target = 0.0155 * 10^{-9} \qquad en = 0.3 * 10 \wedge (-6)$

$IA = 17\,000;\ Ip = 5000;\ h = 3;\ \sigma\gamma = 2.;\ Ku = \dfrac{\sqrt{2\, h\, \gamma^2\, \lambda target - \lambda uh}}{\sqrt{\lambda uh}};$

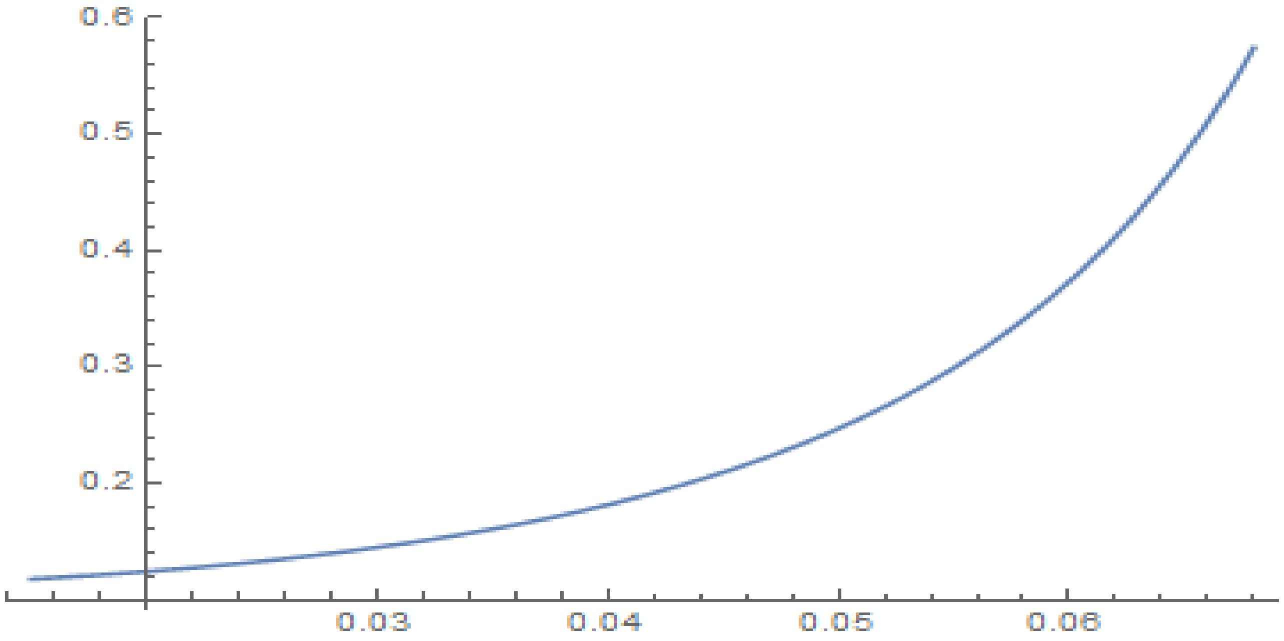
$AJJh = BesselJ\left[(h - 1)/2,\ h\, Ku^2 \big/ \left(2 + 2\, Ku^2\right)\right] - BesselJ\left[(h + 1)/2,\ h\, Ku^2 \big/ \left(2 + 2\, Ku^2\right)\right];$

Harmonic Lasing vs. SCU

Energy-spread modifications make the situation much worse for HL

```
In[10]:= h = 3
Out[10]= 3

In[11]:= Plot[δ[εn, λuh, h, σγ, Ku, AJJh], {λuh, 0.015, 0.068}]
Out[11]=
```



Harmonic Lasing vs. SCU

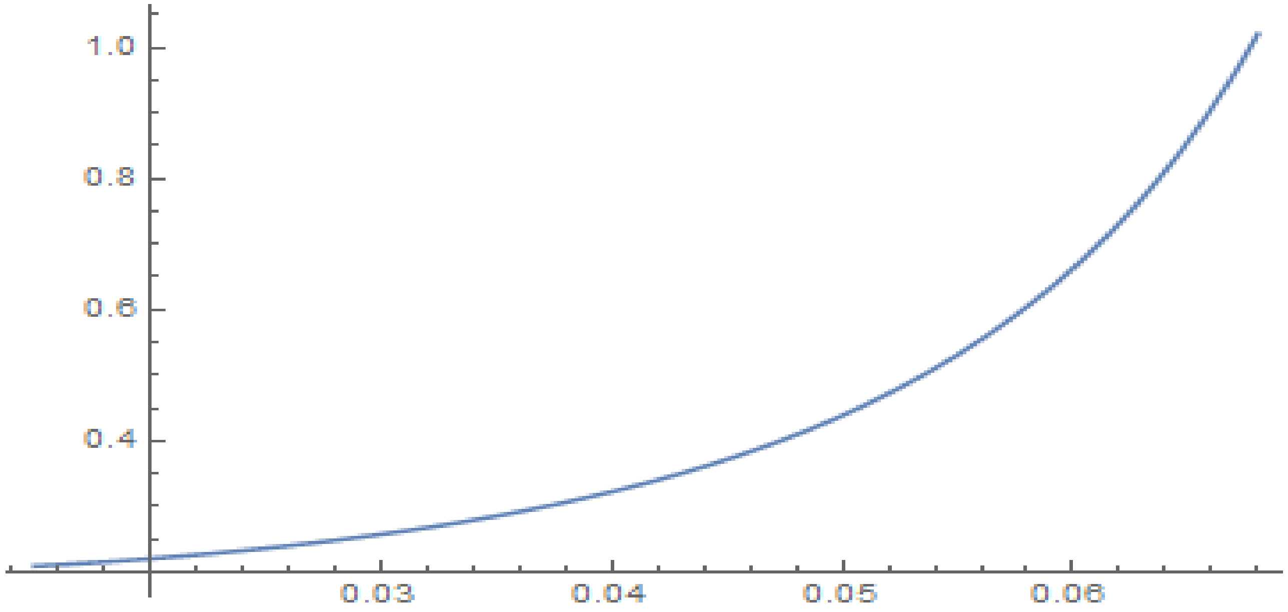
Energy-spread modifications make the situation much worse for HL

```
In[12]:= h = 5

Out[12]= 5

In[13]:= Plot[δ[εn, λuh, h, σγ, Ku, AJJh], {λuh, 0.015, 0.068}]
```

Out[13]=



Harmonic Lasing vs. SCU

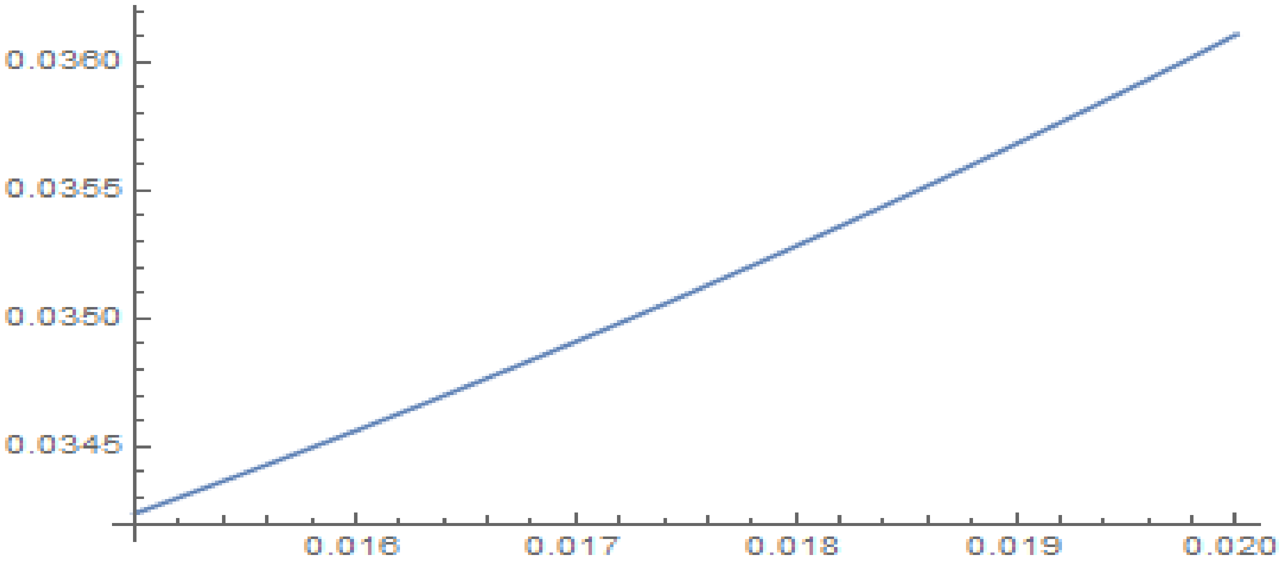
Energy-spread modifications make the situation much worse for HL

```
In[15]:= h = 1

Out[15]= 1

In[16]:= Plot[δ[εn, λuh, h, σγ, Ku, AJJh], {λuh, 0.015, 0.02}]
```

Out[16]=



No large influence for the case of SCU!

Harmonic Lasing Seeding vs. SCU

HLSS → Use part (A) of the undulator tuned directly at λ_t, part (B) tuned at a sub-harmonic
Conceptually the same as pSASE

Two different undulator periods are used for the two undulator parts

Then assume part (A) is the same as in the SCU case
And
Part (B) is like in the harmonic lasing case

Assume a fraction 0<f<1 of the total length is (A) tuned directly at λ_t as SCU

The total gain length can be then written (assuming perfect suppression of the sub-harmonic fundamental in (B) as

$$L_g = fL_{gSC} + (1-f)L_{gh} > L_{gSC} \quad \text{for } L_{gh} > L_{gSC}$$

Usually part (A) is shorter than (B), so f < 0.5 tipically

Conclusions

Harmonic Lasing

Unless a short-period undulator is used, gain length is longer than for an optimized SCU

Example:

Case 40mm vs. SCU with 15mm: $L_{g0h} = 1.55 L_{g0SC}$

Energy spread (1MeV rms)

$$L_{gSC} \simeq L_{g0SC}$$

$$h = 3: \quad L_{gh} \simeq 1.18 L_{g0h} \longrightarrow L_{gh} \simeq 1.83 L_{gSC}$$

$$h = 5: \quad L_{gh} \simeq 1.32 L_{g0h} \longrightarrow L_{gh} \simeq 2 L_{gSC}$$

HLSS

Is also longer as $L_g = f L_{gSC} + (1-f) L_{gh} > L_{gSC}$ for $\mathrm{L_{gh}} > \mathrm{L_{gSC}}$ a small part

Important notes:

→ All this assuming perfect suppression of the fundamental in HL (or HLSS), worse in reality

→ The extra “budget” due to SCU can be used e.g. for tapering

→ Moreover: HL or HLSS are better with short periods. And SCUs produce large magnetic field

So they are best for tuning at sub-harmonic of the fundamental. One could install SCUs as baseline and still employ HL and HLSS to increase the spectral brightness, this time with a better gain length (energy spread effect still there, but short period)