Determination of X-ray beam divergence and longitudinal X-ray source position for LCLS II

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Technical Note

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SASE FEL process is caused by micro-bunching of electron beam with a period equal to the resonant wavelength. During the amplification process the photon field is bound to the electron distribution due to optical guiding. However, after passing the saturation point the optical guiding becomes less effective and the photon beam begins starts to diverge [1]. Therefore the effective source position is expected to be located between the saturation point and the undulator's exit. Saturation point can be estimated with 10%-20% accuracy as $L_s \cong 20L_g$ where L_g is the power gain length [2]. The power gain length can determined from the linear theory of the XFEL [2][3]. Here we are using the formulas from the work [2].

In the presence of the undulator's taper the analytical derivation of the source location is very difficult because of the nonlinear character of the amplification process. Therefore we have calculated the source position numerically and performed several start to end simulation for LCLS I using the Genesis code. We have found that the following empirical formula describes reasonably, with accuracy of few meters, the longitudinal source location z_s.

$$z_s \approx -\sqrt{\left(\frac{2}{3}(L_u - 1.1 \cdot L_s)\right)^2 + z0^2} \qquad (1)$$

Here, the z_s position is calculated with respect to the end of the undulator, L_u is the undulator length and *z0* is an additional source shift which is originated from the curvature of the wavefront. The z0 distance is in order of the Rayleigh length which was determined from an apparent photon beam waist size [3].

We have assumed that the empirical formula (1) also holds true for the LCLS II case and we have calculated the longitudinal SXR and HXR source position for the input parameters presented in table 1 and table 2.

Parameter	Symbol	Value	Unit
Energy	E	4.0	GeV
Peak current	I	1.0	kA
Emittance	ϵ_n	4.5×10^{-7}	m-rad
Energy spread	σ_E	500	keV
Beta function	<β>	12 (13)	m

Table 1. Electron beam parameters for SC liniac.

Parameter	Value SXR (HXR)	Unit
Type	Hybrid PM, planar	-
Full gap height	Variable	-
Period	39 (26)	mm
Segment length	3.4	m
Break length	1.0	m
# segments	21 (32)	-
Total length	96 (149)	m

Table 2. Undulator parameters.

For the case of the Cu linac the beam peak current I_p was scaled with photon energy as $I_p = 2000\left(E_{ph}\right)^{2/5}$ [A], where E_{ph} is photon energy expressed in keV.

Source positions for the SXR, HRX and Cu linac cases are presented in Fig. 1.

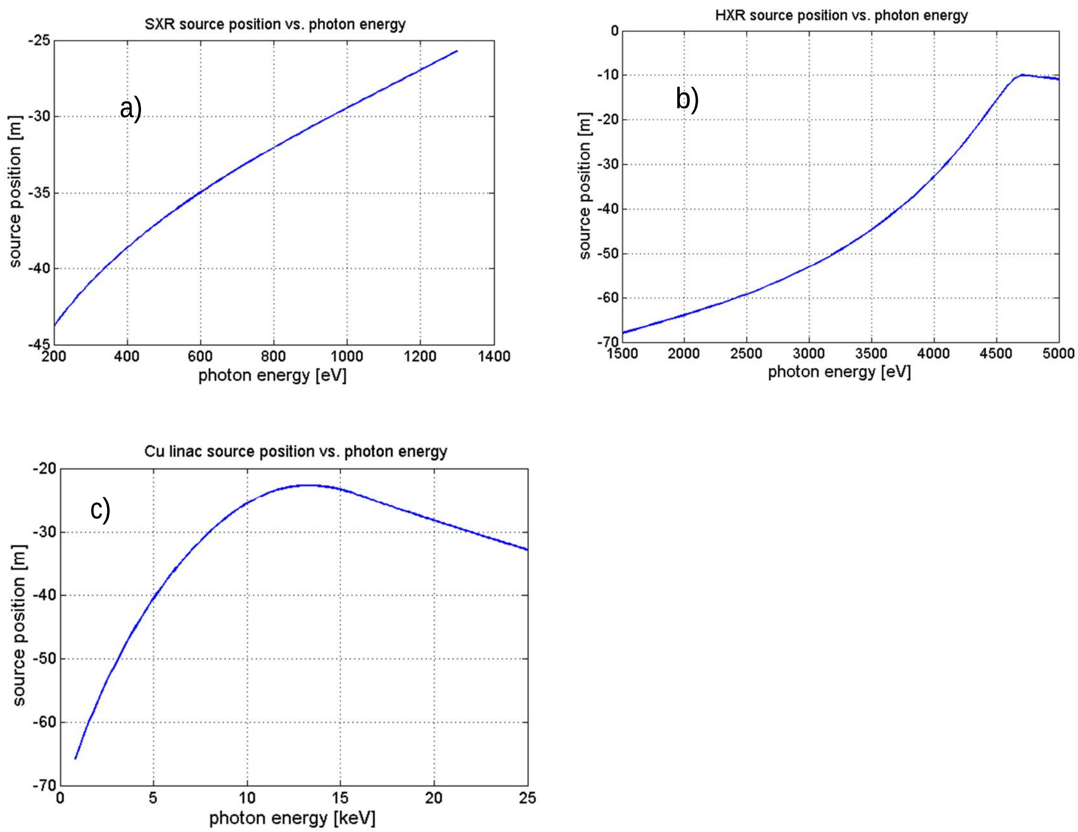

Fig. 1 Longitudinal source positions for a) SXR, b) HRX and c) Cu linac cases.

The photon beam divergence was calculated according to the theory presented in [4] as: $\theta_{rms} = 2k/\sigma_{ph}$

where k is the wave vector of the radiation, $\sigma_{ph} = \sqrt{\sigma_e \sigma_D}$, $\sigma_D = \sqrt{\lambda L_{1D} / 4\pi}$, L_{1D} is the FEL power gain length, and σ_e is the electron rms beam size. The above divergence formula has been compared with the divergence calculated from start to end simulations, performed for LCLS I. We have found that the agreement was very reasonable (see Fig. 2).

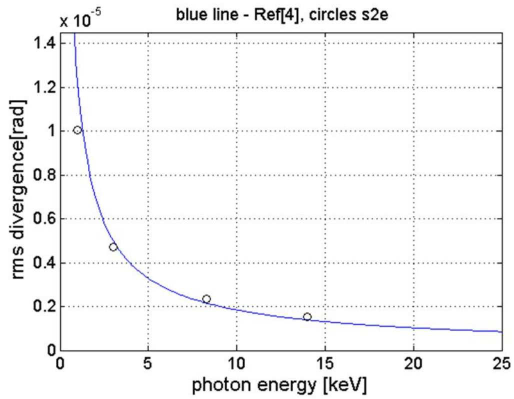

Fig.2. Comparison between the divergence calculated according to the formula from Ref. [4] (blue line) and the divergence derived from start to end simulations (circles)

Calculated FWHM beam divergences for SXR, HXR and Cu-linac case are presented in Fig. 3.

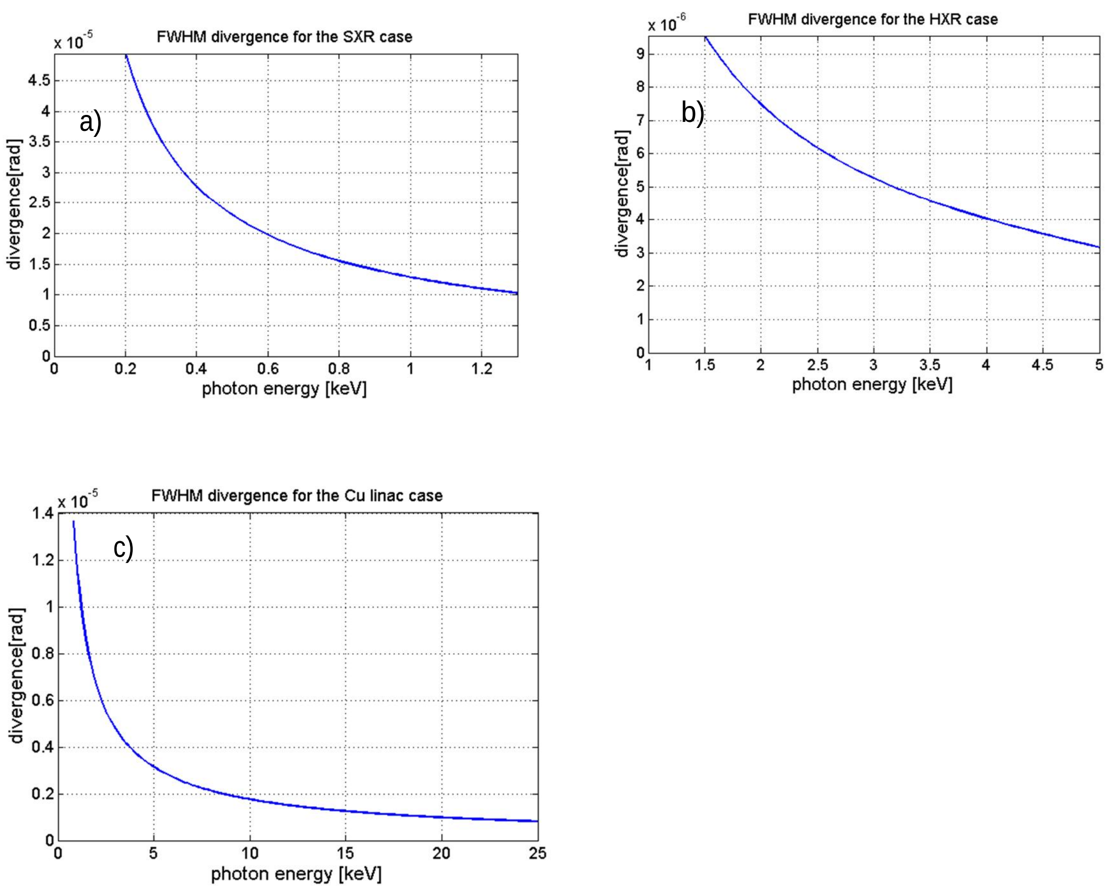

Fig. 2 FWHM beam divergence for a) SXR, b) HRX and c) Cu linac cases.

Literature

1. E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, “The Physics of Free Electron Lasers”, Springer, Berlin, 1999
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3. M. Xie, Nucl. Instrum. and Methods **A 445** (2000)59
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Appendix

The divergences and source locations can be fitted with power and polynomial functions that are presented below. The photon energy is denoted by the variable x and should be expressed in keV units. The divergence is expressed in radians and the location in meters. The location is given with respect to the end of the undulator.

FWHM beam divergences for SXR case:

$$\mathbf{y = 1.28531E\text{-}05x^{-8.37861E\text{-}01}}$$

FWHM beam divergences for HXR case

$$\mathbf{y = 1.37652E\text{-}05x^{-8.88487E\text{-}01}}$$

FWHM beam divergences for Cu-linac case

$$\mathbf{y = 1.18385E\text{-}05x^{-8.29988E\text{-}01}}$$

Longitudinal source positions for the SXR case:

$$\mathbf{y = -6.86582E{+}00x^4 + 2.88017E{+}01x^3 - 4.61806E{+}01x^2 + 4.61743E{+}01x - 5.13787E{+}01}$$

Longitudinal source positions for the HRX case:

in the photon energy range 1keV – 4.6 keV

$$\mathbf{y = 1.24313E\text{-}01x^4 - 5.61271E\text{-}02x^3 - 1.52348E{+}00x^2 + 1.14013E{+}01x - 8.21218E{+}01}$$

in the photon energy range 4.7 keV - 5 keV

$$\mathbf{y = 7.31650E{+}00x^3 - 1.08819E{+}02x^2 + 5.36246E{+}02x - 8.86193E{+}02}$$

Longitudinal source positions for Cu linac case

$$\mathbf{y = -3.695930E\text{-}06x^6 + 2.787051E\text{-}04x^5 - 7.848709E\text{-}03x^4 + 1.088181E\text{-}01x^3 - 1.057413E{+}00x^2 + 9.881049E{+}00x - 7.310326E{+}01}$$

The table below lists the beam parameters for the minimum and the maximum energy for the SXR, HXR and Cu-linac cases.

	Photon energy [keV]	FWHM divergence [rad]	Source location [m]
SXR	0.2	4.93959E-05	-43.818066
	1.3	1.02914E-05	-25.703405
HXR	1	1.34312E-05	-72.223633
	5	3.16747E-06	-10.863085
Cu-linac	0.8	1.36724E-05	-65.79836
	25	8.14659E-07	-32.843963