COHERENCE PROPERTIES OF THE LCLS X-RAY BEAM*

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Abstract

Self-amplifying spontaneous radiation free-electron lasers, such as the LCLS or the European X-FEL, rely on the incoherent, spontaneous radiation as the seed for the amplifying process. Though this method overcomes the need for an external seed source one drawback is the incoherence of the effective seed signal. The FEL process allows for a natural growth of the coherence because the radiation phase information is spread out within the bunch due to slippage and diffraction of the radiation field. However, at short wavelengths this spreading is not sufficient to achieve complete coherence. In this presentation we report on the results of numerical simulations of the LCLS X-ray FEL. From the obtained radiation field distribution the coherence properties are extracted to help to characterize the FEL as a light source.

INTRODUCTION

Self-Amplified Spontaneous Emission Free-Electron Lasers (SASE FEL) [1] allow to overcome the restriction in wavelength imposed by existing seeding sources and to explore new wavelength regimes. A particular interest is in the Ångstrom wavelength regime which opens entire new classes of experiments such the 3D imaging of individual molecules or the analysis of chemical reaction on the femtosecond scale. Supported by the successful demonstration of SASE FELs at wavelength down to 14 nm [2], several X-ray FELs are currently under construction such as the Linac Coherent Light Source (LCLS) [3] or the European X-FEL [4].

The drawback of any SASE FEL is that it uses the spontaneous undulator radiation as its seed signal, which is intrinsically broadband and incoherent. Though the FEL process increases the longitudinal and transverse coherence by slippage and diffraction over the length of the undulator it never reaches the coherence level of a seeded FEL amplifier. In particular at short wavelength diffraction – the main method to the build-up transverse coherence – is ineffective and under certain circumstances the FEL can reach saturation before obtaining transverse coherence [5].

For the design of the optical transport line and diagnostic as well as proposed experiments it is of importance to characterize the radiation properties of the SASE FEL as a light source in advance. For that simulations were conducted and the results are presented here. The work was done in context of the LCLS (Tab.1 list the main parameters of LCLS). The main radiation properties have been presented elsewhere [6] and this presentation focusses solely on the stability of the spot size at the detector locations and the degree of coherence of the FEL signal.

Table 1: LCLS Design Parameters

Beam Energy	13.4 GeV
Beam Current	3.4 kV
Undulator Period	3 cm
Undulator Parameter	3.5
Undulator Length	130 m
Radiation Wavelength	1.5 Å

SPOT SIZE STABILITY

Start-end simulations have shown that the expected electron beam parameters are not full agreement with the design parameters. Often the slice emittance is better (about 0.9 mm·mrad) than the design parameter value but the electron slice is either misaligned or mismatch to the focussing lattice of the LCLS undulator. All these parameters have an impact on the FEL radiation spot distribution at the detector station. It is difficult to quantize the impact of the various effects from the start-end simulation alone. For that we used the LCLS design case as reference and varied only one parameter at a time.

Beam Offset

Injecting the electron beam with an offset will cause a wider FEL spot size at the detector location and a shift in is centroid position. The reference case yields an RMS spot size of 110 μm in both planes. Overall the dependence is rather weak and the spot size does not grow by more than 10 % for an initial offset of 25 μm, which is also the maximum offset to allow for saturation within the 130 m long undulator, based on the electron beam design parameters. The FEL size in the perpendicular plane exhibit also a growth but it is rather weak (less then 3%) and comes from the degraded FEL amplification due to the centroid oscillation. There is also a shift in the centroid position of the FEL radiation which is roughly three times larger then the initial electron beam offset.

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Mismatch

A mismatch of the electron beam size to the focusing lattice of the undulator causes an oscillation of the electron beam envelope along the undulator. With respect to the FEL gain the impact of a mismatch is rather weak and becomes only noticeable for extreme parameters. However it can alter the FEL spot size significantly. The results for different electron beam radius as compared to the optimum (matched) beam radius is shown in Fig. 1. While the FEL still reach saturation the spot size radius can be increased by up to 100 %.

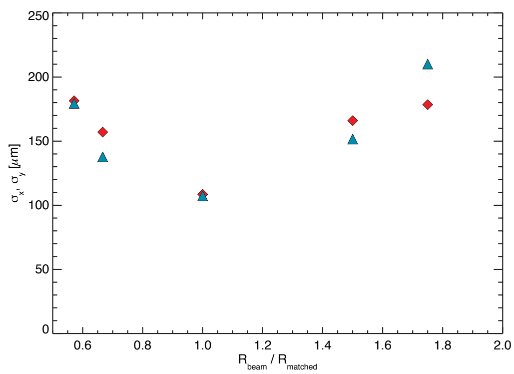

Figure 1: Dependence of the FEL spot size at the detector location on the mismatch of the electron, expressed by the beam radius as compared to the matched beam radius. Diamond and triangle markers refer to the size in the x- and y-plane, respectively.

Emittance

For the case of LCLS the emittance has a strong impact on the FEL performance and defines the size of the matched electron beam and therefore the diffraction. Simulations show that for the design value of 1.2 mm·mrad the spot size of the FEL pulse at the detector location is the smallest. For lower values of the emittance the size grows due to the enhanced diffraction, though the dependence is rather weak (less then 2% for an emittance of 0.9 mm·mrad). For values above the design values the FEL interaction is weakened. The reduced gain guiding allows for more radiation field to escape resulting in a larger spot size. The size increases by less than 10% for an emittance value of 1.5 mm·mrad.

Comparison with Start-end Results

Start-end simulations for LCLS are based on an electron beam which parameters varies along the bunch, including mismatch, offset and varying emittance values for the different electron slices. As shown above mismatch has the strongest impact, which is significantly present in the electron beam. However the simulated spot size is 235 μm in the x-plane and 200 μm in the y-plane, which is more than it can be explained by mismatch of the electron beam slices alone nor with the contribution of a smaller slice emittance and a beam slice offset. Two contribution, which are hard to quantify, are wakefields and the explicit detail of the electron beam profile. The undulator wakefield detune parts of the electron beam faster than they can reach saturation. The gain guiding is strongly suppressed, yielding a stronger divergent background signal, which increases the FEL spot size, when integrated over the bunch. The other contribution comes directly from the transverse beam profile. At saturation the electron slice is almost fully bunched but gain guiding of the fundamental mode vanish. Instead the beam emits coherently and can couple to higher modes when the distribution deviates from a Gaussian.

COHERENCE

Coherence is a statistical property of a radiation source and refers to how much you can extrapolate the radiation phase information in time and space for any given measurement. Mathematically it is expressed by the mutual coherence function [9]:

$$\Gamma_{12}(\tau) = \left\langle \vec{E}(\vec{r}_1, t)\vec{E}(\vec{r}_2, t+\tau)\right\rangle \quad . \tag{1}$$

While the temporal coherence function is easy to define ($\Gamma_{11}(\tau)$) any experiment which relies on spatial coherence (e.g. diffraction on a grating) will always include some temporal information due to the difference in the path length to the detector. For sake of simplicity we assume that the signal $\vec{E}(\vec{r}, t)$ is quasi-monochromatic so that the time delay due to the path length difference from $\vec{r}_1$ and $\vec{r}_2$ falls within the temporal coherence of the signal and thus the time dependence in the mutual coherence function can be neglected. The mutual coherence function becomes then the mutual intensity $J_{12} \equiv \Gamma_{12}(0)$. In analogy to the temporal coherence function, the mutual intensity function is normalized as

$$\mu_{12} = \frac{J_{12}}{\sqrt{J_{11}J_{22}}} \tag{2}$$

to yield values between zero and one. It is referred to also as the complex coherence factor. A zero value refers to no correlation in phase between the observed field at the two postions $\vec{r}_1$ and $\vec{r}_2$ while a value of one means that the phase remains constant over time.

The complex coherence factor compares two fixed points in the transverse plane. If we allow both points to be free parameter μ_{12} would yield a four dimensional distribution. For sake of simplicity we restrict one point to be on the undulator axis. In analogy to the temporal coherence time [10] the coherence area is defined as

$$A_c = \int \mu_{12} dA \tag{3}$$

and reflects the size of a usable target area for experiments, relying on coherence, without the need to enforce coherence (e.g. with a pin hole). The optimum case would be when the coherence area is much larger than the actual spot size. Note that for a fully coherent signal the coherence area is infinite.

The entire field information of a time-dependent simulation for the LCLS design case was saved and used to evaluate the mutual intensity function and complex coherence factor. The coherence area, as defined in Eq. 3, is 0.071 mm^2, about five times larger than the spot size Σ. This indicates sufficient transverse coherence over the entire spot-size and that the FEL pulse can be used for diffraction experiments without the requirement to enhance coherence by a pin hole aperture. The growth in the transverse coherence can be seen in Fig. 2 which is a monotonically increasing function along the undulator. On the other hand the radiation diffracts faster than the build up in the coherence area within the first tens of meter. However, at around 70 m gain guiding is dominant and the spotsize remains constant till saturation where the spot grows again due to diffraction. At around 60 m, the coherence area becomes larger than the spot size though it does not necessarily indicate good transverse coherence. For that the ratio between A_c and Σ must be much larger than one.

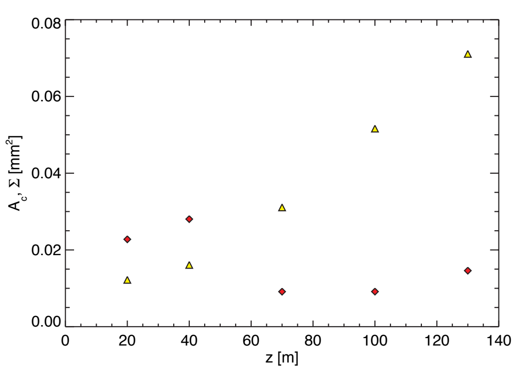

Figure 2: Evolution of the coherence area A_c and spotsize Σ (triangle and diamond shape, respectively) along the undulator.

For LCLS the FEL pulse has to propagate at least 115 m till it reaches the first user station. The coherence area is further increase and in the case of the LCLS design case the value becomes 0.32 mm^2 while the spot size is 0.044 mm^2. The reason is that noise consists typically of higher modes which diffracts stronger than the FEL pulse itself, clearing up the signal at the detector location. This becomes more apparent in the case of the start-end simulation where the electron beam slices are not aligned and matched to the focusing lattice (see previous section). The complex coherence factor is shown in Fig. 3 and the resulting coherence area is 0.27 mm^2 while the spotsize is 0.057 mm^2. The ratio indicates that the coherence is still sufficient.

CONCLUSION

Simulations have been conducted to study the radiation properties of the LCLS pulse, namely the stability in the

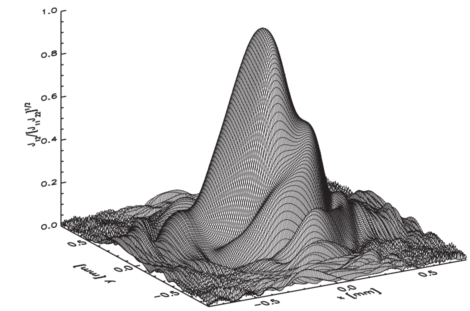

Figure 3: Complex coherence factor for LCLS for the start-end simulation, evaluated 115 m downstream of the undulator exit.

beam size at the detector location and the degree of coherence. A mismatch of the electron beam has the strongest impact to widen the spot size at the detector location, confirmed by start-end simulation that most part of the electron beam is matched locally. However, additional effects contributes, including the effect of the electron beam profile at saturation, which are difficult to model and mostly fall back on the approximation by a Gaussian profile. The build-up of transverse coherence during the FEL amplification process is sufficient to spread throughout the entire bunch. For the LCLS case The effective coherence area, within which the field amplitude and phase have a significant correlation to each other, is about 5 times larger than the spot size when evaluated at the first experimental location 115 m downstream the undulator.

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