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INVESTIGATION OF THE COHERENCE PROPERTIES OF THE RADIATION AT FLASH

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Abstract

We present the results of the studies of coherence properties of the radiation from FLASH. General overview of the parameter space is performed including peak current, emittance, and external focusing. The results of our studies show that present configuration of FLASH free electron laser is not optimal for providing ultimate quality of the output radiation. We find that the physical origin of the problem is mode degeneration. The way for improving quality of the radiation is proposed.

INTRODUCTION

After an energy upgrade the soft X-ray FEL FLASH at DESY covers a spectral range between approximately 45 nm and 4.2 nm wavelength [1, 2]. With the present undulator (period 2.73 cm, peak field 0.486 T) the minimum wavelength of 4.2 nm is determined by the maximum electron beam energy of approximately 1.25 GeV. Many user's experiments rely on coherent properties of the radiation, both temporal and spatial.

At the initial stage of amplification coherence properties are poor, and radiation consists of large number of transverse and longitudinal modes [3]. The fundamental mode (having maximum gain) dominates over higher modes when undulator length progresses. Total undulator length to saturation is finite, and is in the range from 9 to 11 field gain lengths (hard x-ray to visible SASE FELs) [4, 6, 7]. Degree of transverse coherence is high when relative separation of increments between fundamental and higher modes is more than 20%. In this case degree of transverse coherence asymptotically approaches to unity in the amplification process, and can reach values above 90% in the end of the high gain linear regime [5, 8]. Further development of amplification process in the nonlinear stage leads to visible degradation of the spatial and temporal coherence [4, 6, 7]. Separation of the increments of the beam radiation modes strongly depends on the value of diffraction parameter, and is more pronouncing for stronger focused electron beams [9]. Increase of the energy spread and emittance also leads to better separation of the increments of the beam radiation modes.

In the present experimental situation many parameters of the electron beam at FLASH depend on practical tuning of the machine. Analysis of measurements and numerical simulations shows that depending on tuning of the machine emittance may change from about 1 to about 1.5 mm-mrad. Tuning at small charges may allow to reach smaller values of the emittance down to 0.5 mm-mrad. Peak current may change in the range from 1 kA to 2 kA depending on the tuning of the beam formation system. One (more or less) fixed parameter is average focusing beta function in the undulator which has average value about 10 meters. We performed thorough analysis of described parameter space with special attention devoted to the coherence properties of the radiation. Our conclusion is that spatial coherence of the radiation at FLASH suffers significantly from not sufficient suppression of the higher azimuthal radiation modes. This happens due to the large value of the diffraction parameter. Our analysis shows that operation with stronger beam focusing, lower emittances and lower peak current will allow to operate FLASH with ultimate quality of the radiation in terms of the degree of transverse coherence exceeding 90%.

For illustration we have chosen specific wavelength of 8 nm. The main reason for this is that this wavelength has been used by several user groups (see, e.g. [10, 11]). Thus, results, presented here, can be used directly for analysis of obtained results and planning future measurements.

SIMULATION RESULTS

Simulations have been performed with three-dimensional, time-dependent FEL simulation code [12]. Simulations of the statistical properties have been performed for the case of a long bunch with uniform axial profile of the beam current. Simulations cover the range of practical interest for emittances from 0.5 mm-mrad to 1.5 mm-mrad, and the range of peak currents from 1 to 2 kA. Radiation wavelength of 8 nm is chosen for detailed analysis.

We present in Figure 1 evolution along the undulator of the radiation power in the fundamental harmonic. Higher values of the peak current and smaller emittances would allow to reach higher radiation powers. Bottom plot in Fig. 1 presents an overview of the degree of transverse coherence in the complete parameter space. Brief view on these plots tells us that the degree of transverse coherence is visibly lower than ultimate value 95%. The reason for reduction of the spatial coherence is in the feature which is called mode degeneration. This physical phenomena takes place at large values of the diffraction parameter [9]. Figure2 shows contribution of higher azimuthal modes to the total power for specific example of emittance 1 mm-mrad and peak current 1.5 kA . Contribution of the first azimuthal modes falls down in the high gain linear regime, but to the value of 12% only, and then starts to grow in the nonlinear regime, and reaches the value of 16% at the undulator end. This results in the degree of transverse coherence of only 50%.

The feature of poor transverse coherence is reflected in the field distributions. Upper plot in Fig. 3 shows typical intensity distribution over single slice. We see that transverse intensity pattern has rather complicated shape due to inter-

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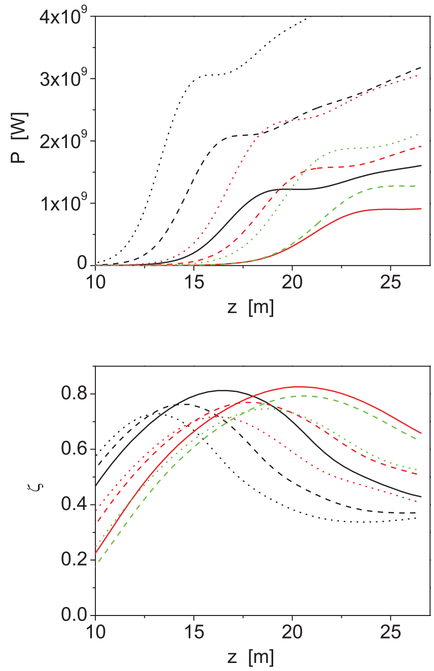

Figure 1: Evolution along undulator of the radiation power (top plot) and of the degree of transverse coherence of the radiation (bottom plot). Radiation wavelength is 8 nm. Color codes (black, red and green) refer to different emittance ϵ_n = 0.5, 1, and 1.5 mm-mrad. Line styles (solid, dash, and dot) refer to different values of peak current 1 kA, 1.5 kA, and 2 kA.

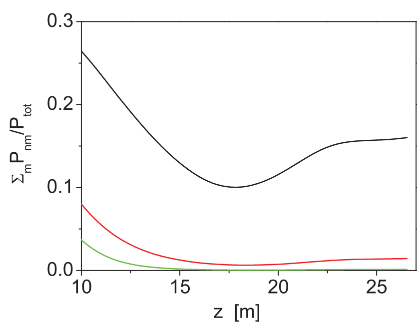

Figure 2: Partial contribution of the higher azimuthal modes of the fundamental harmonic to the total radiation power. Peak current is 1.5 kA, rms normalized emittance is 1 mm-mrad. Black, red, and green curves refer to the modes with $n = \pm 1$, $n = \pm 2$, and $n = \pm 3$, respectively.

ference of fields of statistically independent modes. Shape of the intensity distributions changes on a scale of coherence length. Bottom plot in Fig. 3 shows intensity profile of a typical single photon pulse with 50 fs duration (or, about ten coherence lengths). Cross at this plot shows the center of gravity of the radiation intensity averaged over many pulses. We see that the center of gravity of single shot is visibly shifted off axis. Spot shape of a short radiation pulse changes from pulse to pulse. Position of the pulse

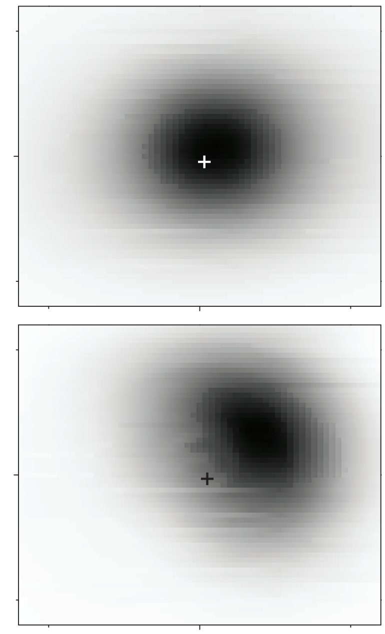

Figure 3: Profiles of the radiation at the 1st harmonic at the exit of undulator. Peak current is 1.5 kA, rms normalized emittance is 1 mm-mrad. Top: typical intensity distribution over single slice. Bottom: typical single shot with average energy in the radiation pulse of 100 microjoules (radiation pulse length 50 fs). Crosses on the plots show center of gravity of radiation intensity averaged over many pulses.

also jumps from shot to shot which is frequently referred as bad pointing stability. However, in our case bad pointing stability has fundamental origin in poor transverse coherence, but not in unstable operation of the accelerator systems. It is our practical experience from FLASH that an effect of poor pointing stability becomes more pronouncing for shorter pulses. This effect will also take place for X-ray FELs with large value of the geometrical emittance to the radiation wavelength operating in a short pulse mode [4, 6, 7].

DISCUSSION

Simulations presented in this paper trace nearly complete range of parameter space of FLASH in terms of emittance and peak current. Detailed illustration is presented for specific wavelength of 8 nm. We found that the radiation has relatively poor transverse coherence. This happens because FLASH FEL operates in the parameter space when different radiation modes have close values of the gain. In other words, and effect of mode degeneration takes place. Figure of merit here is the diffraction parameter presenting the ratio of the electron beam size to the diffraction expansion of the radiation on a scale of the field gain length [9]. Power of the effect becomes stronger at the increase of the electron beam size. In the parameter space of FLASH diffraction parameter is in the range between 10 and 20. According to earlier studies ([9], Chapter 5), gain of the first azimuthal mode TEM_{01} approaches to the gain of the ground TEM_{00} mode.

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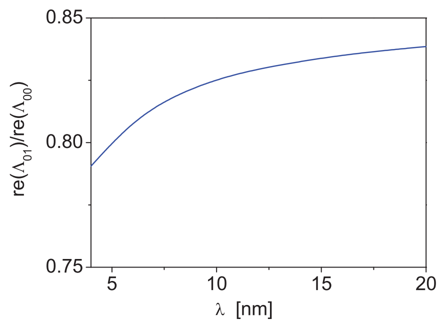

Figure 4: Ratio of the field gain of the first azimuthal mode TEM_{01} to the gain of the ground FEL mode TEM_{00} versus radiation wavelength. Peak current is 1.5 kA, rms normalized emittance is 1 mm-mrad. Focusing beta function is 10 m.

Quality of the electron beam is high (small longitudinal velocity spread due to emittance and energy spread) which is not sufficient to suppress the gain of the higher modes. The plot in Fig. 4 traces the ratio of the field gain of the first azimuthal mode TEM_{01} to the gain of the ground FEL mode TEM_{00} versus radiation wavelength. We see that situation with mode selection is unfavorable in the whole wavelength range of FLASH. Ratio is nearly constant which means that detailed results for 8 nm wavelength can be referred to the whole parameter space.

Reasonable question arises: what can we do for improving situation with transverse coherence at FLASH? A straightforward way to avoid mode degeneration effect is to reduce electron beam size. Currently FLASH operates with average focusing function of 10 meters. Hardware allows to organize stronger focusing with average focusing beta function down to 5 meters. This action would allow more strong separation of the modes. Another hint would be operation at smaller peak currents and lower emittances, say 1 kA and 0.5 mm-mrad. Our simulations show that with both actions we can easily reach ultimate degree of the transverse coherence of the radiation exceeding 90%.

We can also use another mechanism for suppression of the effect of the mode degeneration. In fact, increase of the energy spread in the electron beam leads to stronger suppression of higher beam radiation modes [9]. Increase of the energy spread can be done with laser heater [13]. Increase of the rms energy spread to the value of 0.8 MeV in terms of mode separation is equivalent to the reduction of the beta function from 10 to 5 meters. However, the price for this improvement is significant reduction of the gain of the fundamental mode and of the FEL power, while reduction of the beta function improves these important FEL parameters.

In view of results obtained we conclude that FLASH (and FLASH2) should be operated with stronger focusing of the electron beam to provide good spatial coherence of the radiation. Future developments (like design of a new undulator for FLASH) should also take into account this problem and provide relevant technical solutions for keeping small size of the electron beam in the undulator.

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REFERENCES

[1] S. Schreiber et al., Proc. of FEL 2012 Conference, http://accelconf.web.cern.ch/AccelConf/FEL2012/papers/mopd01.pdf

[2] M. Vogt et al., Proc. IPAC 2013 Conference, http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/tupea004.pdf.

[3] G. Moore, Opt. Commun. 52(1984)46.

[4] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. 281(2008)1179.

[5] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. 281(2008)4727.

[6] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, New J. Phys. 12 (2010) 035010, doi: 10.1088/1367-2630/12/3/035010.

[7] E.A. Schneidmiller, and M.V. Yurkov, Proc. FEL 2012 Conference, http://accelconf.web.cern.ch/AccelConf/FEL2012/papers/mopd08.pdf.

[8] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. **186**(2000)185.

[9] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, "The Physics of Free Electron Lasers" (Springer-Verlag, Berlin, 1999).

[10] C. Gutt et al., Phys. Rev. B 79, 212406 (2009).

[11] A.P. Mancuso et al., Phys. Rev. Lett. 102, 035502 (2009).

[12] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Nucl. Instrum. and Methods **A 429**(1999)233.

[13] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Nucl. Instrum. and Methods A 528(2004)355.