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GENERATING TRAINS OF ATTOSECOND PULSES WITH A FREE-ELECTRON LASER

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Abstract

Recently, a Hard X-ray Self-Seeding setup was commissioned at PAL XFEL. Its main purpose is to actively increase the temporal coherence of FEL radiation. We report another application of this setup, namely - to generate trains of short sub-femtosecond pulses with linked phases. We discuss the preliminary results of both experiment and corresponding simulations as well as indirect diagnostics of the radiation properties.

INTRODUCTION

Hard X-ray Self-Seeding (HXRSS) based on a single chrystal monochromator [1–4] allows for an increased spectral density and longitudinal coherence at hard X-ray SASE FELs through active spectral filtering. It was originally proposed to use a single Bragg or Laue reflection from a thin diamond to generate a series of trailing maxima following SASE pulse. The electron beam is delayed to temporally overlap with one of these maxima, which is then amplified in a downstream undulator up to saturation and beyond. Later it was proposed to use two crystals [5], or several reflections of a single crystal simultaneously [6, 7], to generate a seed that contains more than one frequency within the FEL amplification bandwidth. Then, the final FEL section amplifies such multi-frequency seed radiation and due to non-linear intermodulation yields satellites – "beat waves" – observable at saturation [8].

One easy way to understand the emergence of satellite frequencies is to consider the amplification process of two spectral lines in the time domain. Combination of two overlapped seed beams with frequencies different by $\Delta\omega$ yields sinusoidal "beating" of the resulting seed power in the time domain at that difference frequency. Upon amplification of this seed to saturation, the now-increased radiation slippage distorts the shape of that sinusoidal modulation. Such distortion manifests itself in the frequency domain via the emergence of the additional equidistant "satellites". The resulting train of short pulses will allow studies of ultrafast phenomena [9–11].

SELF-SEEDING WITH "PHANTOM LINES"

PAL-XFEL at Pohang accelerator laboratory is the world's third hard X-ray free-electron laser facility starting its user

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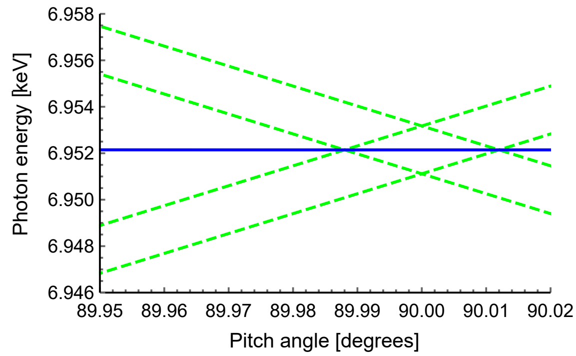

Figure 1: Seeding lines for Bragg reflections from diamond with photon energy versus crystal pitch angle for [004] reflection and four reflections from the [022] family assuming 0.012° yaw angle.

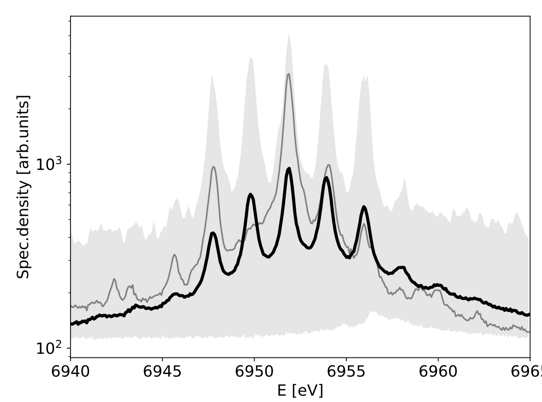

Figure 2: Radiation power spectrum as a function of photon energy for the case of seeding with 5 equidistant reflections. Also we can already see non-linear effects as additional maxima on both sides. Black line depicts the ensemble average over the ensemble of 10000 events, dark grey line shows a single-shot spectrum, light grey band represents the range of maximum and minimum values in the ensemble.

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service operation in June 2017, and since then it has proven to be one of the most stable XFEL with a FEL timing jitter of 18 fs and a mJ-class hard X-ray FEL up to 14.4 keV [12, 13]. And a HXRSS for PAL-XFEL was successfully commissioned in 2018 to be able to provide users with a high spectral intensity FEL three times more than SASE [14].

The self-seeding operation mode was established using the diamond crystal with (001) lattice orientation. The FEL was tuned to generate SASE with photon energy around 6952 eV, that corresponds to a [004] Bragg reflection at 90° pitch angle.

If the crystal is not perfectly aligned, four additional reflections appear around the [004] line, namely [022], [0-22], [202] and [-202]. Tuning the crystal pitch and yaw angles, to approximately 89.965° and 0.012° respectively, see Figure 1, allowed us to arrange the reflection lines at equal separation of $\hbar\Delta\omega = 2$ eV. Upon FEL amplification, four satellite "beat waves" with the same spacing were observed, as presented on Figure 2.

Therefore, FEL radiation pulses with 9 discrete equidistant frequency components were generated, 4 of which do not have a crystallographic origin.

The spectral properties of the emitted radiation were measured with a single-shot spectrometer installed at the beamline which is equipped with Si(111), Si(220), and Si(333) crystals [14].

OPTIMISING FOR TRAINS OF SHORT PULSES

Seeding simultaneously at n discrete equidistant frequencies yields, depending on the combination of crystal reflections, up to n^2 times higher peak power of the seed. Nevertheless, the temporal structure of such combined seed depends on phase differences between those frequencies and can be quite complex, see Figure 3.

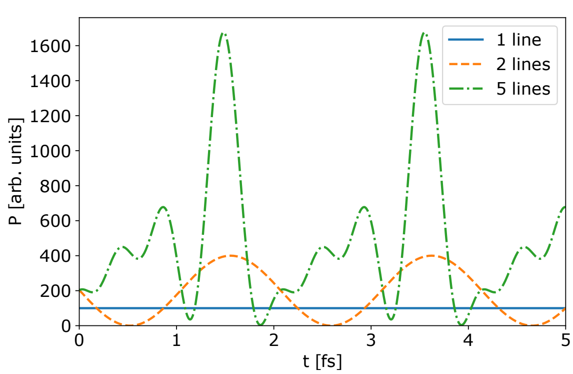

Figure 3: Illustration of the power distribution along the seed for the different number of the contributing resonance lines, separated by 2 eV, each providing radiation with random phases and equal intensities.

The seed is effectively generated via bandpass-filtering the SASE radiation spectrum. The latter is stochastic, therefore the intensity and phase of each transmitted frequency component vary randomly shot-to-shot.

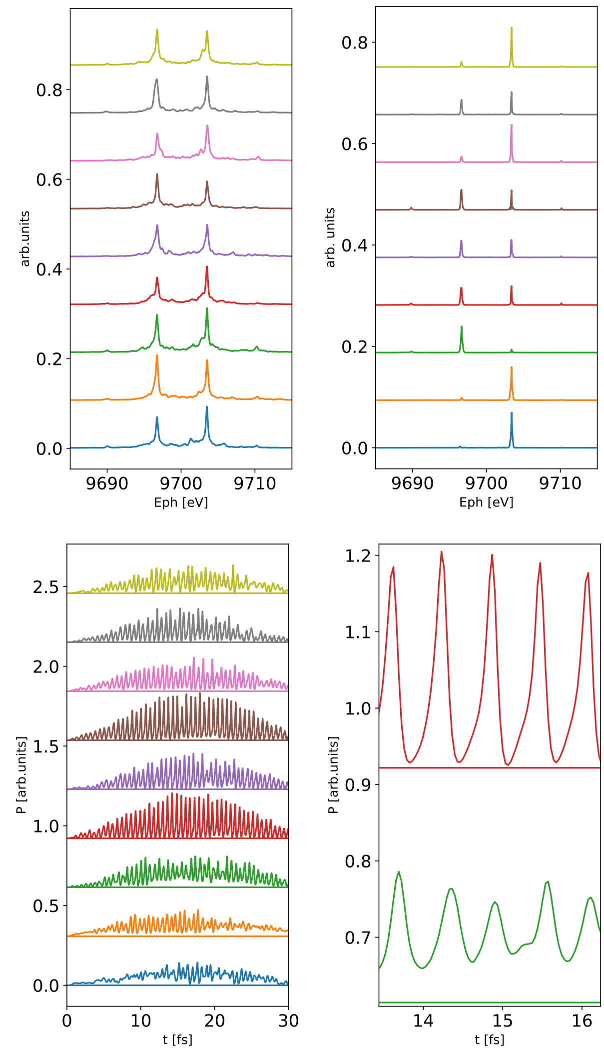

Figure 4: Measured FEL spectra (top left subplot with filtered subset representing best 1% of events in terms of peaks ratio and pulse energy) and simulated spectra (top right plot) with corresponding power profiles (bottom left plot). The bottom right plot depicts an enlarged part of the left plot, illustrating events with good and poor contrast.

If only two seed frequencies are chosen, the phase difference between them determines the temporal shift of the sinusoidally modulated seed- and, consequently, the amplified pulse. The phase of such modulation may, in principal, be measured, by examining the optical replica from the spent electron beam before reaching saturation [15]. The maximum contrast of the modulated seed is achieved when the intensities of both seed components are comparable. Such condition can be diagnosed using a non-invasive online spectrometer with subsequent filtering of the undesired events.

Such seed radiation with sinusoidally modulated power can be considered as a comb of pulses with durations equal to their temporal separation. The emergence of the satellite peaks in the spectrum at saturation would indicate a decrease of their duration.

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This scenario was studied experimentally and numerically: the 9700 eV SASE radiation was filtered using [-115] and [1-15] forward Bragg reflections, separated by 6.76 eV and consecutively amplified beyond saturation. On Figure 4 we present the acquired single-shot FEL spectra with emerging satellites as well as the simulation results in both time and frequency domains using Genesis numerical code [16] and Ocelot package [17]. Simulation results indicate that trains of the 180 as-long pulses (FWHM value) with 610 as separation can be generated.

Separation between the seeding frequencies ΔE allows one to control the temporal separation of the pulses in the trains: Δt [fs] $\simeq 4.135/\Delta E$ [eV].

The proposed method to generate trains of attosecond pulses has the relaxed hardware requirements compared to the method proposed in [10], especially for the facilities that have already installed a HXRSS monochromator setup. Nevertheless, both methods may potentially be combined to achieve the best results.

CONCLUSIONS

We proposed a cost-effective method to generate a series of ultrashort pulses with a Hard X-ray Self-Seeded FEL and demonstrated it at PAL XFEL.

The seed radiation is produced using two adjacent crystal reflections. The seed radiation, modulated in time, is amplified beyond saturation. The emergence of the satellite frequencies indicates that the duration of the resulting pulses within the train decreases. The expected duration of a single pulse in such train is in order of 200 attoseconds.

The usage of only two reflections allows to discriminate the events with a poor contrast in the time domain by examining the single-shot FEL spectra. Otherwise, FEL pulses containing up to 9 discrete equidistant frequencies can be delivered.

REFERENCES

[1] G. Geloni, V. Kocharyan and E. Saldin "A novel self-seeding scheme for hard X-ray FELs", *J. Mod. Opt.*, vol. 58, no. 16, pp. 1391–1403, 2011; https://doi.org/10.1080/09500340.2011.586473

[2] J. Amann *et al.*, "Demonstration of self-seeding in a hard-X-ray free-electron laser", *Nat. Photonics*, vol. 6, pp. 693–698, 2012; https://doi.org/10.1038/nphoton.2012.180

[3] Yu. Shvyd'ko, R. Lindberg, "Spatiotemporal response of crystals in x-ray Bragg diffraction", *Phys. Rev. Spec. Top. Accel Beams*, vol. 15, no. 10, p. 100702, 2012; https://doi.org/10.1103/PhysRevSTAB.15.100702

[4] R. R. Lindberg, and Yu. V. Shvyd'ko, "Time dependence of Bragg forward scattering and self-seeding of hard x-ray free-electron lasers", *Phys. Rev. Spec. Top. Accel Beams*, vol. 15. no. 5, p. 050706, 2012; https://doi.org/10.1103/PhysRevSTAB.15.050706

[5] G. Geloni, V. Kocharyan and E. Saldin, "Generation of doublet spectral lines at self-seeded X-ray FELs", *Opt. Commun.*, vol. 284. no. 13, pp. 3348–3356, 2011; https://doi.org/10.1016/j.optcom.2011.02.082

[6] F.-J. Decker *et al.*, "Two-color self-seeding and scanning the energy of seeded beams at LCLS" in Proc. 35th Int. Free-Electron Laser Conf. (FEL'13), New York, NY, USA, Aug. 2013, paper WEPSO09, pp. 514-–517.

[7] A. A. Lutman *et al.*, "Demonstration of Single-Crystal Self-Seeded Two-Color X-Ray Free-Electron Lasers", *Phys. Rev. Lett.*, vol. 113, p. 254801, December 2014. https://doi.org/10.1103/PhysRevLett.113.254801

[8] H. P. Freund, and P. G. O'Shea, "Two-Color Operation in High-Gain Free-Electron Lasers", *Phys. Rev. Lett.*, vol. 84, no. 13, pp. 2861–2864, 2000; https://doi.org/10.1103/PhysRevLett.84.2861

[9] A. Zholents, "Attosecond X-Ray Pulses from Free-Electron Lasers", *Laser Phys.*, vol. 15, no. 6, p. 855, 2005.

[10] N. R. Thompson and B. W. J. McNeil, "Mode Locking in a Free-Electron Laser Amplifier", *Phys. Rev. Lett.*, vol. 100, no. 20, p. 203901, 2008.

[11] S. Serkez *et al.*, "Overview of options for generating high-brightness attosecond x-ray pulses at free-electron lasers and applications at the European XFEL", *J. Opt.*, vol. 20, no. 2, p. 024005, 2018.

[12] H.-S. Kang *et al.*, "Hard X-ray free-electron laser with femtosecond scale timing jitter", *Nat. Photon.*, vol. 11, no. 11, pp. 708–713, 2017.

[13] H.-S. Kang *et al.*, "FEL performance achieved at PAL-XFEL using a three-chicane bunch compression scheme", *J. Synchrotron Rad.*, vol. 26, no. 4, pp. 1127-1138, 2019.

[14] C.-K. Min *et al.*, "Hard X-ray self-seeding commissioning at PAL-XFEL", *J. Synchrotron Rad.*, vol. 26, no. 4, pp. 1101-1109, 2019.

[15] E. L. Saldin, E. A. Schneidmiller, M. V. & Yurkov, "Optical afterburner for an x-ray free electron laser as a tool for pump-probe experiments", *Phys. Rev. Spec. Top. Accel Beams*, vol. 13, no. 3, p. 030701, 2010; https://doi.org/10.1103/PhysRevSTAB.13.030701

[16] S. Reiche,"GENESIS 1.3: A fully 3D time-dependent FEL simulation code", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, no. 1, pp. 243–248, 1999; https://doi.org/10.1016/S0168-9002(99)00114-X

[17] OCELOT: a versatile computational tool for light sources, 2016–present; https://github.com/ocelot-collab/ocelot