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STATUS OF THE HARD X-RAY SELF-SEEDING SETUP AT THE EUROPEAN XFEL

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Abstract

A Hard X-Ray Self-Seeding (HXRSS) setup will be soon commissioned at the European XFEL. It relies on a two-chicanes scheme to deal, in particular, with the high pulse repetition rate of the facility. In this contribution we review the physics choices made at the design stage and the expected performance of the setup. We will also focus on the description of the hardware installations made at the SASE2 line of the European XFEL.

INTRODUCTION AND SETUP

Single crystal monochromator Hard X-ray Self-Seeding (HXRSS) [1, 2] allows for an increased spectral density and longitudinal coherence at hard X-ray SASE FELs by means of active spectral filtering. This capability is now being enabled at the European XFEL, where the compatibility with the high-repetition rate in burst mode is important and heat-loading of the crystals needs to be dealt with. This issue can be mitigated with the introduction of a two-chicane HXRSS setup, Fig. 1. As shown in [3], and reviewed here, a two-chicane solution allows for an increased Signal-to-Noise Ratio (SNR), the signal being the seeded FEL pulse, and the noise being, in this case, the underlying shot-noise amplification. The natural exploitation of this increased ratio is for decreasing the crystals heat loading, while keeping the seed signal large enough for the setup to work. One should consider that there are two sources of heat-load on the crystals: one is related to radiation around the undulator resonant frequency (both SASE and seeded signals), which tends to heat-up the crystal as illustrated in Fig. 2, while the second one is related to the broadband spontaneous emission. One always needs to confront with the spontaneous radiation (SR) heat-load, which is always present and is nearly independent of the fundamental tune. However, a higher SNR of the 2-stage self-seeding can be used to decrease the FEL power level needed at the crystal position, and therefore the crystal heat-load caused by FEL radiation. Since the heat-load due to both FEL and SR heavily depends on the wavelength, the relative importance of the two contributions also depends on the wavelength.

In this paper we will first discuss simulation results relying on start-to-end simulations of the electron beam that drives the FEL process. We stress that a comparison between the simulated electron beam properties and those achieved in reality is important. First, to precisely foresee the actual performance of the HXRSS setup at the European XFEL and, second, to optimize performance by changing the electron beam properties. This, however, will require an ad-hoc experimental measurements campaign and is beyond the scope of this work.

Furter on, based on simulations we will show the nominal performance of the HXRSS setup designed for the European XFEL, which is expected to operate from below 5 keV (theoretically down to 3 keV, with probable limitations due to heat-loading) up to 14.4 keV (and above, if one considers the option of tuning part of the radiator to a harmonic of the fundamental [4]). Finally, we will discuss the hardware implementation of the setup at the European XFEL.

SIMULATIONS

We first consider an upper target for seeding of a photon energy of 14.4 keV, to be generated at the SASE2 undulator at the European XFEL. SASE2 consists of 35 segments of 5 m magnetic length each, with a period of 40 mm, and we assume a 100 pC beam optimized for seeding, as described in [3]. The 14.4 keV energy point is the most demanding in terms of electron beam quality and necessary undulator length, and its analysis allows to optimize the chicane

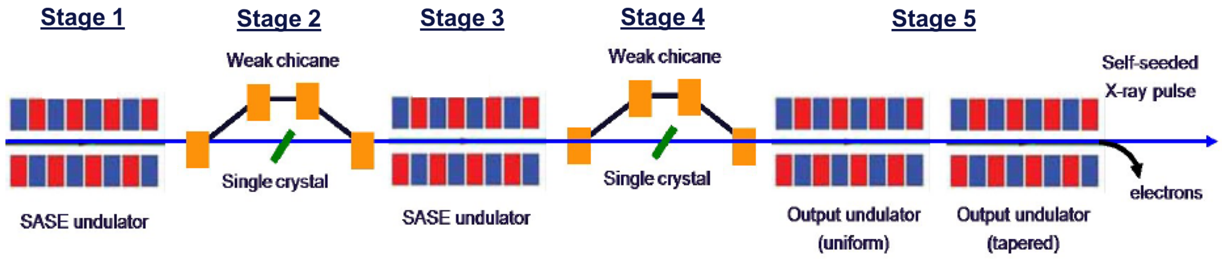

Figure 1: Sketch of the two-chicane HXRSS at the European XFEL.

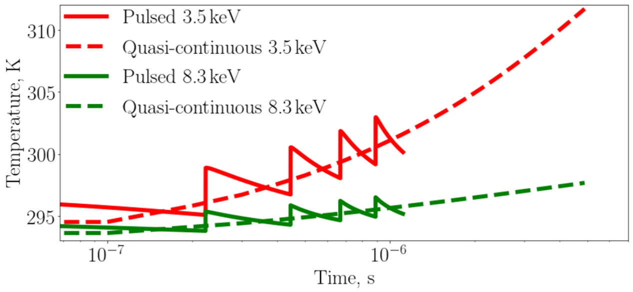

Figure 2: Calculations of peak temperatures at 3.5 keV for the case of 3 µJ FEL incident power level, using impulsive heating model and treating each pulse in the train individually. Dashed lines correspond to the quasi-continuous case.

placement in the overall setup. We proceeded by optimizing the output of a double-chicane HXRSS setup at saturation in the case when the two undulator stages preceeding the magnetic chicanes are formed by 7 undulator segments (we call this case "7+7"), by 8 undulator segments (we call this case "8+8") and by 9 undulator segments (we call this case "9+9"). For these simulations we used 100 µm thick diamond crystals and a symmetric C400 reflection. In Fig. 3 we plot the radiation power and the averaged spectral density at the exit of the self-seeding setup at saturation, i.e. after the two seeding chicanes followed by 10 undulator segments for the three cases "7 + 7", "8 + 8" and "9 + 9". All plots refer to an ensemble average over 10 events. The "7 + 7" option is characterized by the highest radiation power, and in the "8 + 8" and "9 + 9" scenarios, the pre-pulses from the third stage are large compared to the final twice-filtered pulse. Moreover, looking at the spatially-averaged spectral density one sees that the maximum value is comparable in all cases. The conclusion from this analysis is that the "7 + 7" case is the best performing one: by increasing the length of the first undulator part the signal can be increased at the expenses of a larger incident power on the crystal, and of a larger impact on the electron beam quality. As we increase the length of the setups from 7 + 7 to 9 + 9 the SNR increases but the electron beam quality deteriorates, and the output flux decreases (while a large pre-pulse appears). An analysis of detrimental effects due to energy spread and emittance beyond the nominal level [3] shows that the 7 + 7 setup should perform within about 80% of the nominal level for emittance increases up to 40% (from a nominal value below 0.4 mm mrad) and energy spread increase of about 500% (from a nominal value of about 2 MeV). In order to account for deviations from the nominal FEL performance, we suggested to add one extra segment in each undulator part, and to configure the double-chicane HXRSS setup at the European XFEL as in the "8+8" configuration, at least during the commissioning period.

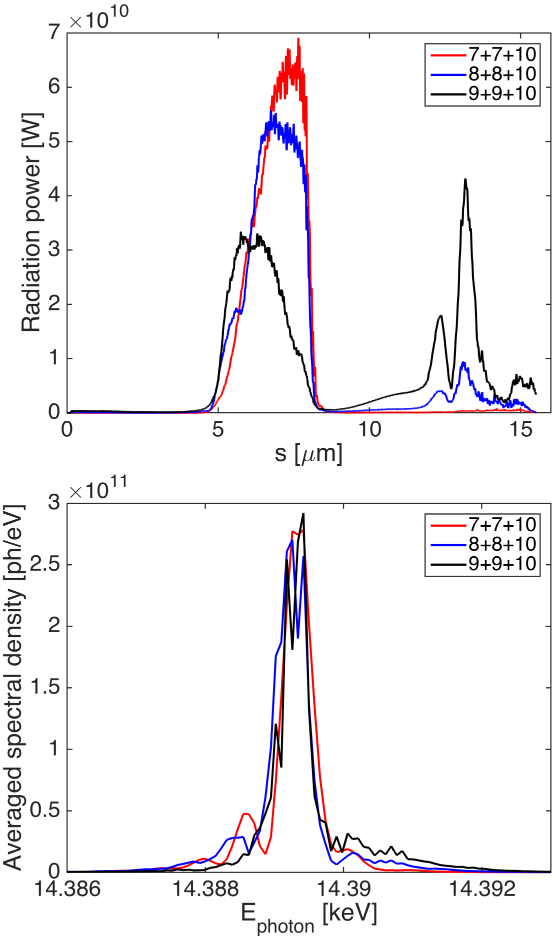

Figure 3: Radiation power (upper plot) and averaged spectral density (lower plot) at saturation after 10 undulators, for different configurations "7 + 7", "8 + 8" and "9 + 9". All plots are the results of an ensemble average over 10 events.

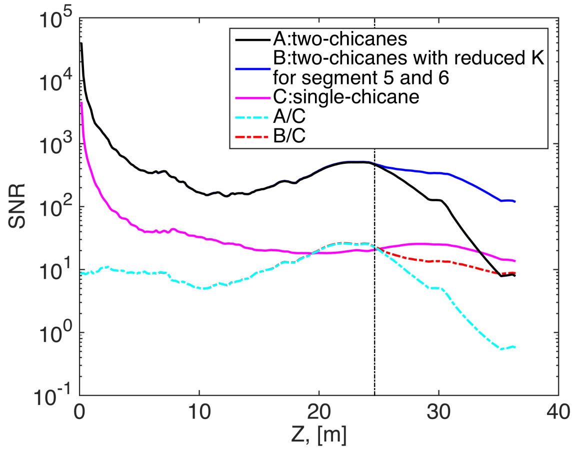

Figure 4: Signal-to-noise ratio at low photon energy (3.5 keV) for a 4 + 4 two-chicane setup, compared to the case of a single-chicane setup, with and without retuning of the undulator parameter. The vertical line indicates the point where K is changed, see text.

Analysis of a low photon-energy point around 3.5 keV [3] showed that a 4 + 4 setup is best at these energies, and may yield an estimated spectral flux of $6 \cdot 10^{10}$ ph/eV per pulse around saturation, corresponding to a peak power of about 50 GW. Studying the low photon-energy point also allowed us to compare the evolution of the SNR of the two-chicane setup to that of a one-chicane setup, see Fig. 4, where the

SNR is calculated out of an ensemble of ten pulses. Curve (A) corresponds to the two-chicane case and curve (C) to the single-chicane setup. The ratio (A/C) along the final undulator is also shown. The SNR ratio (A/C) remains almost constant (about a factor 10) up to saturation. Note that the large values around 10^4 for the (A) curve at the beginning of the amplification process in Fig. 4 are due to a numerical effect: at the beginning of the radiator, when one starts from shot noise, there is no radiation at the very beginning of the amplification process. Finally, after saturation, the SNR ratio (A/C) drops due to the fact that the single-chicane setup saturates further downstream compared to the two-chicane setup, due to the lower seed level. One can, of course, change the value of the K undulator parameter in the two-chicane setup to keep up with the change of electron energy (B). Even a simple reduction of the value of K (without an optimized tapering profile, whose study is outside of the scope of this contribution) is enough to keep the SNR almost constant beyond the saturation point, see Fig. 14 (B and B/C), see [3] for more details.

HARDWARE INSTALLATION

The chicane design, based on H-type magnets, allows for a maximum delay of about 450 fs up to an energy of 11 GeV, and of about 180 fs for 17.5 GeV, Fig. 5, in order to provide the possibility for multi-color experiments with tunable delay, owing to the variable-gap undulators of the European XFEL. The power supply allows for steps of about 0.1 fs, thus enabling the possibility of autocorrelation measurements. The two chicanes were installed in the SASE2 tunnel during the 2018/2019 winter shutdown.

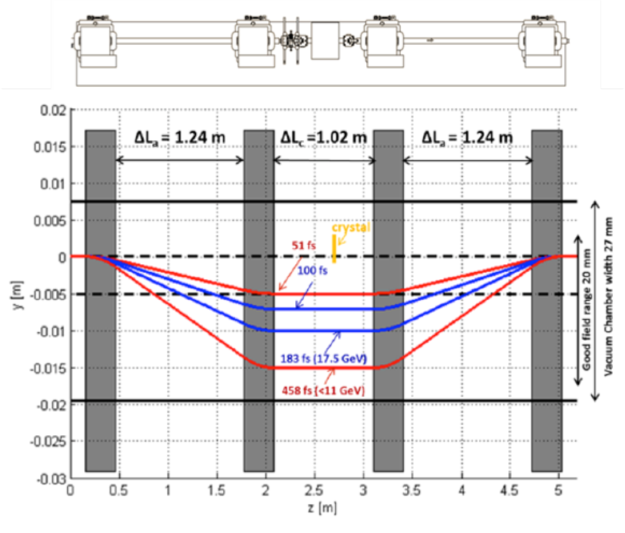

Figure 5: Sketch of the self-seeding chicane.

The vacuum chamber is sketched in Fig. 6, right. It is equipped with two windows, one at 45 degrees and one at 90 degrees with respect to the horizontal plane, in order, respectively, to observe the crystal and -via a YAG screen- to detect various crystal reflections. A monochromator consists of a flange with a main goniometer stage for pitching the crystal, as well as X, Y and tip-tilt stages to insert the crystal and controlling the roll[1] angle Fig. 6, left. A crystal holder with two slots, Fig. 7 is mounted on the crystal positioning system. C100 and C111 cut crystals are currently lodged in the slots of both monochromators.

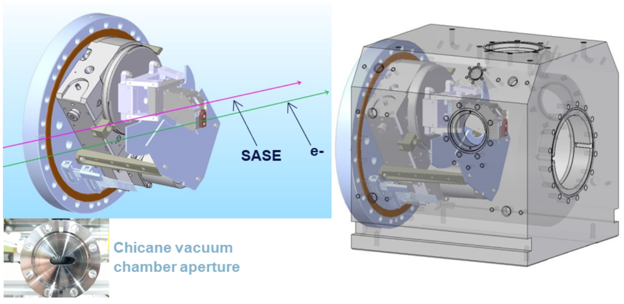

Figure 6: Monochromator flange and vacuum chamber.

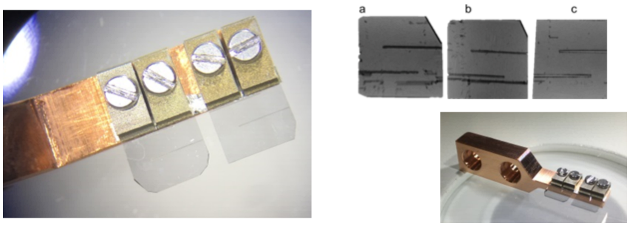

Figure 7: Crystal holder with two slots and several diamond crystals.

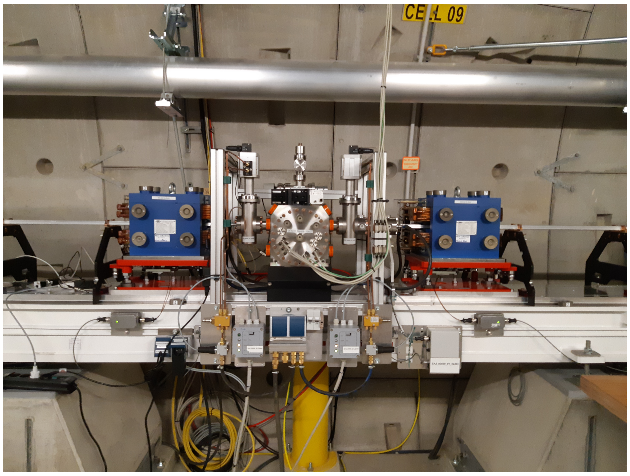

Figure 8: One of the two setups installed in the SASE2 tunnel. The beam direction is from right to left.

The monochromators were installed in Summer 2019. One of the two chicanes setup is pictured in Fig. 8.

CONCLUSIONS

A Hard X-Ray Self-Seeding (HXRSS) setup has been installed and will soon be commissioned at the European XFEL. The availability of high repetition rate X-ray pulses poses novel challenges in the setup development, compared to the choices made at other facilities, mainly crystal heat-loading and radiation-damage issues. However, high-repetition rate is expected to allow for unprecedented output

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[1] Also called yaw e.g. at the LCLS, due to a different naming convention.

characteristics. From simulations, a two-chicane HXRSS setup, installed in a "8+8" configuration, was found to be optimal for the European XFEL. In this paper we discussed design and choices peculiar to the European XFEL, and we reviewed the hardware installations currently in place. Commissioning of the setup, where the HIREX spectrometer [5] will help finding the seeded signal, is expected to take place in Autumn 2019.

REFERENCES

[1] G. Geloni, V. Kocharyan, and E. Saldin, "A novel self-seeding scheme for hard X-ray FELs", *J. Mod. Opt.*, vol. 58, pp. 1391, Jun. 2011. `doi:10.1080/09500340.2011.586473`

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

[3] S. Liu *et al.*, "Preparing for high-repetition rate hard x-ray self-seeding at the European X-ray Free Electron Laser: Challenges and opportunities", *Phys. Rev. Accel. Beams*, vol. 22, pp. 060704, Jun. 2019. `doi:10.1103/PhysRevAccelBeams.22.060704`

[4] G. Geloni, V. Kocharyan, and E. Saldin, "Extension of self-seeding to hard X-rays >10 keV as a way to increase user access at the European XFEL", DESY 11-224, 2011. `arxiv:1111.5766`

[5] N.G. Kujala *et al.*, "The High Resolution Hard X-Ray Single Shot Spectrometer (HIREX Spectrometer) Installation and Commissioning in SASE2 Beamline of the European XFEL", presented at the FEL'19, Hamburg, Germany, Aug. 2019, paper WEP074, this conference.