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TWO COLORS AT THE SASE3 LINE OF THE EUROPEAN XFEL: PROJECT SCOPE AND FIRST MEASUREMENTS

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Abstract

The European XFEL is a high-repetition rate facility that generates high-power SASE radiation pulses in three beamlines. A joint upgrade project, with Finnish universities, to equip the SASE3 beamline with a chicane has been recently approved to generate two SASE pulses with different photon energies and temporal separation. In this work we report the status of the project, its expected performance, and recent experimental results. Additionally, we discuss methods to diagnose the properties of the generated radiation.

INTRODUCTION AND PROJECT SCOPE

Funding has been recently granted by the Academy of Finland, with co-funding by the European XFEL, for constructing a device at the SASE3 undulator of the European XFEL. This will add two-color capability with tunable delay, and enable pump-probe experiments at the SASE3 endstations. A similar scheme is already enabled at SASE2, owing to the presence of the Hard X-ray Self-Seeding chicanes. The proposed setup relies on the simplest method available at date for generating two closely separated pulses of different colors at XFELs as suggested in [1] and experimentally proven in [2, 3]. The scheme is illustrated in Fig. 1, where the baseline SASE3 soft X-ray undulator is split into two independently radiating parts, *U1* and *U2*, by a magnetic chicane. The chicane introduces a tunable delay and washes out the electron microbunching from *U1*, which is important if the color separation, in energy, is smaller than the FEL amplification bandwidth. One must ensure that the electron beam quality at the entrance of *U2* is still good enough to sustain the FEL process, which limits the power that can be extracted below the saturation level. The photon energy separation between the two pulses can theoretically span across the entire range made available by the undulator system. In the case of SASE3 at the electron energy of 8.5 GeV, this range roughly spans between 240 eV and 1 keV. At 14 GeV – between 650 eV and 2.9 keV. For 17.5 GeV – between 1.02 keV and 3 keV. However, the impact of the FEL process on the electron beam quality depends on the photon energy, so that the first pulse to be produced should be at the highest energy.

A dedicated chicane will allow for a maximum delay of about 2.3 ps, see [4]. The minimum delay between pump and probe radiation pulses is not zero. The electron beam is naturally overtaken by the radiation emitted in *U1*, as it moves slower than the speed of light in *U2*. The delay between pump and probe FEL pulses is thus larger than zero even when chicane is switched off and is in the order of 1 µm (3fs).

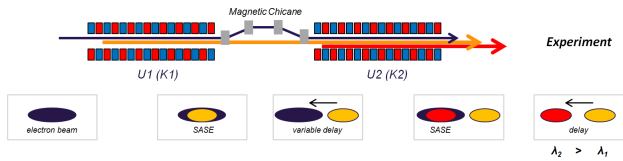

Figure 1: Simplest 2-color scheme relying on a single magnetic chicane.

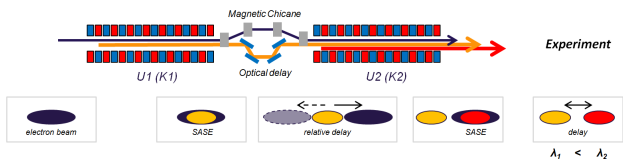

Figure 2: Solving the zero-crossing problem by implementing an optical delay line.

Optical Chicane and Possible Further Upgrades

The magnetic chicane can only increase the delay between the FEL pulses, and its construction and commissioning constitutes only the first phase of the two-color project at SASE3. In fact, in order to enable a zero-delay and even a negative one, two possible solutions can be considered. The first, which constitutes the second phase of the project, consists in the introduction of an optical delay line to retard the radiation emitted in the first undulator with respect to the electron beam and, therefore, to compensate or overcompensate the radiation slippage, Fig. 2. A more detailed concept for the chicane with an optical delay line was developed in [4], see Fig. 3. It will allow for a negative delay of up to 100 fs, thus enabling zero-crossing and subsequent scan until 2.3 ps. Further investigation on the actual implementation of the scheme is being conducted.

An alternative solution can be found in electron beam manipulations enabling fresh slice lasing, which may be achieved by means of a “dechirper module”, or other techniques inducing a kick in part of the electron beam [5]. In this way, the trajectory of electrons vary as a function of the

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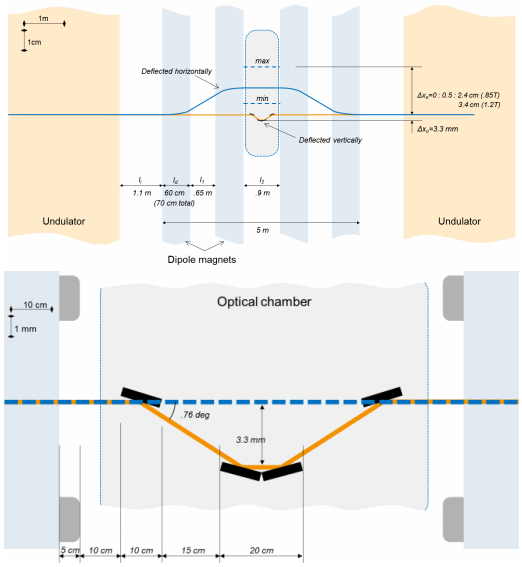

Figure 3: Concept of chicane and optical delay line.

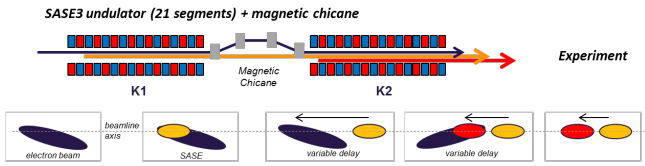

Figure 4: Solving the zero-crossing problem by implementing a fresh slice technique.

longitudinal position in the beam. One can obtain that in *U1* the electron beam emits radiation from a short lasing window at the tail, while in *U2* the lasing window is located in the head of the beam. If the distance between the two lasing windows is larger than the expected radiation slippage, both positive and negative pump-probe delays will be achievable, see Fig. 4.

SIMULATIONS

Simulations were performed for the baseline case in Fig. 1 as well as for the fresh bunch option. For the baseline case, we assumed a nominal 20 pC electron bunch from start-to-end electron simulations (4.5 kA current, normalized emittance ϵ_n = 0.2 mm mrad, 1.3 MeV rms energy spread [6]), see [7], which gives the shortest radiation pulse duration. The electron energy was 8.5 GeV, which allows reaching the lowest photon energy (250 eV). *U1* was set to lase at 630 eV, with 5 active segments, and *U2* was set to lase at 250 eV with 7 active segments. The output at the exit of *U1* and *U2*, respectively, is shown in Fig. 5. The simulated mean energy per pulse is 50 µJ for *U1* at 630 eV, corresponding to 5×10^{11} photons per pulse, and 70 µJ for *U2*, corresponding to 1.5×10^{12} photons per pulse.

The presence of two separate sources, inside *U1* and *U2*, complicates the focusing at the sample. However, it was shown in [7] that KB mirrors can be tuned to image a virtual

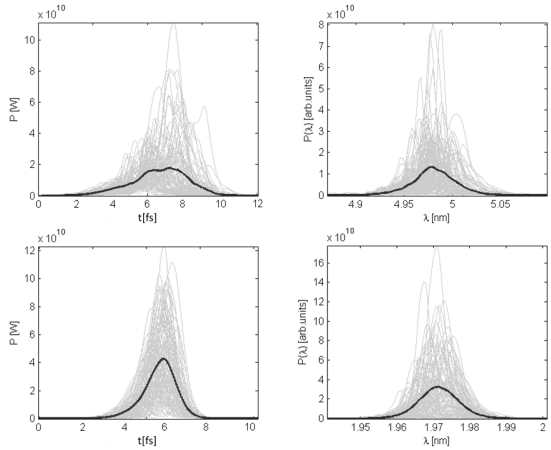

Figure 5: Simulated temporal duration and spectra at the exit of *U1* and *U2*, according to the setup in Fig. 1. Grey lines refer to single shots, black lines are the ensemble average.

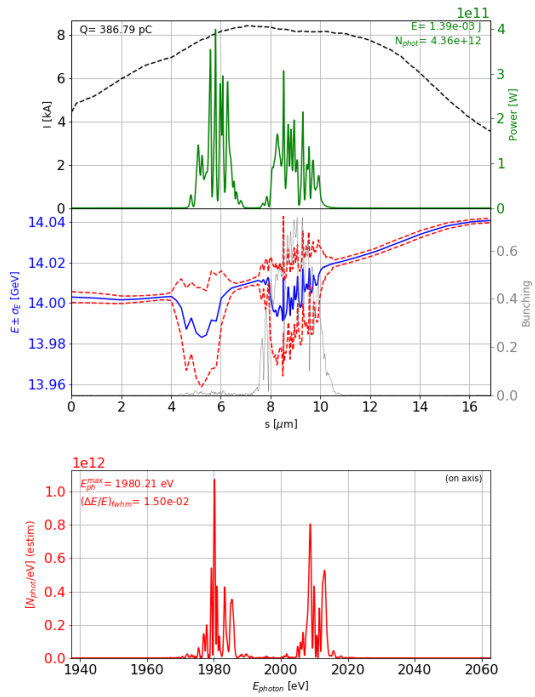

Figure 6: Simulated temporal duration (top) and spectrum (bottom) at the exit of the setup in Fig. 4. Grey lines refer to single shots, black lines are the ensemble average. The electron beam deterioration within the lasing windows is evident from the middle plot.

source in between the two, leading to a fluence in the order of 10^{18} ph/cm^2 per pulse on the sample.

Simulations for the fresh-slice option were run, instead, with a 500 pC start-to-end nominal bunch (5 kA current, normalized emittance ϵ_n = 0.45 mm mrad, 0.5 MeV rms energy spread [6]), in order to ensure enough length to accommodate two separate lasing windows. In this case, both pulses evolve up to saturation, see Fig. 6.

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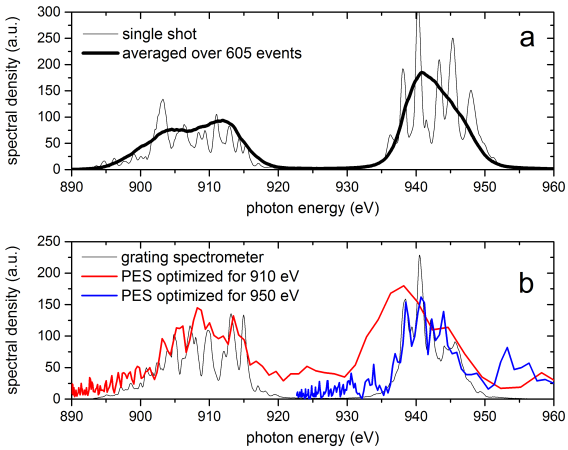

Figure 7: Experimental demonstration of two-color lasing: (a) single shot (thin line) and averaged over 605 events (thick line) spectral distribution measured with grating spectrometer; (b) single shot spectra measured with grating spectrometer (black line), with PES optimized for 910 eV (red line) and with PES optimized for 950 eV (blue line).

FIRST MEASUREMENTS AND DIAGNOSTICS

First tests on the expected performance of the system in Fig. 1 have been performed at the European XFEL without the chicane, which is expected to be installed in 2020. The SASE3 undulators were divided into two parts consisting of 9 segments for *U1* and 11 segments for *U2*, and tuned to different photon energies, ranging from about 700 eV to about 1 keV, and selected in such a way that the two spectra did not overlap. The electron beam energy and charge were 14 GeV, and 250 pC respectively. Typical pulse energies were above the 350 µJ-range for each of the two colors.

Figure 7a shows the spectrum for the case of 950 eV emitted in *U1* and 910 eV emitted in *U2* with average pulse energy about 600 µJ in each color, thin and thick lines correspond to single shot spectrum and the ensemble average of 605 events respectively. The spectra were measured using grating soft X-ray spectrometer which comprises the SASE3 monochromator beamline [8] operating in spectrometer mode [9]. The grating spectrometer, although providing high resolution up to $5 \cdot 10^3$ and thus allowing to characterize spectrum with high accuracy, is an invasive device with a limited spectral window which does not allow to detect two pulses simultaneously in case they are largely separated in photon energy.

To provide non-invasive shot-to-shot diagnostics in multi-bunch mode in terms of each color intensity and spectrum, the gas-based Time-Of-Flight(TOF) Photo-Electron Spectrometer (PES) [10] can be used during user experiments. The PES device consists of 16 eTOF drift-tubes, located around the interaction region with a target gas and partitioned into four groups (one per quadrant) with independent control of the retardation voltage. The latter allows to independently optimize their photon energy resolution. When FEL operates in single color mode, each PES can be cross-calibrated in terms of pulse energy to the X-ray Gas Monitor (XGM) device [11]. The XGM, being capable to measure absolute intensity, is not capable to distinguish the photon energies, so that PES is to be used as a diagnostic tool for two-color experiments. To achieve higher detection precision, for each color we add the signal from several PES detectors. We found the XGM/PES pulse energy correlation coefficient to be 0.93 from which we estimate a pulse energy error of 7%. The single shot PES spectra acquired during 2-color operation are presented in Fig. 7b. The red curve shows the output of PES quadrant optimized for 910 eV, and the blue curve – of optimized for 950 eV. Although the optimized PES resolution is too low to resolve SASE spectrum structure, it is capable of providing the bandwidth estimation for each photon energy.

SCIENTIFIC RELEVANCE

The two-color operation mode enables a large number of scientific applications based on a pump-probe excitation scheme of molecules, doped clusters or nanoparticles with two individually controllable X-ray pulses. As an example, one can enable atomic site-specific excitation or ionization in molecules at the SQS scientific instrument of the European XFEL [12]. This is achieved by tuning the pump wavelength to match the energy of a specific resonant excitation from an atomic core or inner-valence orbital, or by choosing an energy just above the binding energy of a certain atomic orbital. A typical case where such site-selectivity is applicable would be organic compounds containing heavy element(s), sulphur or phosphorus atoms. The probe can then be tuned independently to react with another atomic site in the molecule or, for example, to enhance its sensitivity to the presence of a particular fragment or isomer created as the result of the pump pulse. Furthermore, the variable time delay between the pump and the probe allows real-time insight into the dynamics of the pump-induced processes, such as the relatively slow nuclear rearrangement and dissociation, or the faster electronic motion. As an example, the case of chloroiodoethane was presented in [7], where the charge transfer from the chlorine to iodine atomic site can be monitored by a suitable choice of the two wavelengths.

CONCLUSION

We reported on the status of the European XFEL two-color project at SASE3. We discussed different implementations, from the simplest setup just based on the installation a single magnetic chicane, to more advanced allowing for delay zero-crossing. We also presented simulations for different cases and preliminary measurements of temporally superimposed two-color pulses without the chicane.

ACKNOWLEDGEMENTS

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