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PARALLEL OPERATION OF SASE1 AND SASE3 AT THE EUROPEAN XFEL

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Abstract

At the European XFEL a hard X-Ray SASE FEL (SASE1) and a soft X-Ray SASE FEL (SASE3) share in series the same electron beamline. This configuration couples the operation conditions for both undulators and their subsequent user experiments in terms of SASE intensity and background. We report on our experience in parallel operation and discuss the solutions that enable the operation of both undulators as independently as possible.

INTRODUCTION

The European XFEL is in operation since 2017. It is based on superconducting accelerator technology and serves three undulator beamlines simultaneously [1]. The three beamlines are named as SASE1, SASE2 and SASE3. SASE1 and SASE2 are hard X-Ray beamlines (3-25 keV) and SASE3 is a soft X-Ray beamline (0.25-3 keV). The first lasing of SASE1 beamline was achieved in May 2017 [2], followed by the first lasing of SASE3 in February 2018 and the first lasing of SASE2 in May 2018 [3]. After that the three beamlines are operated in parallel [4, 5].

The layout of the three beamlines is shown in Fig. 1. One can see that SASE1 and SASE3 are located in series in the same electron beamline. This configuration couples the operation conditions for both undulators and their subsequent user experiments in terms of SASE intensity and background.

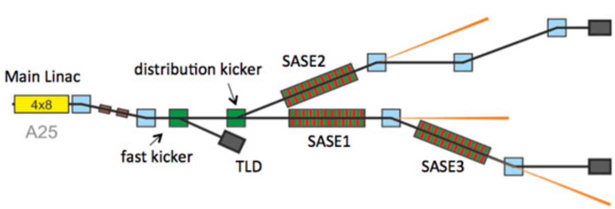

Figure 1: Layout of the three undulator beamlines at the European XFEL starts from the last cryomodule of the main linac.

Coupling Between SASE1 and SASE3 Beamlines

Two different techniques, an afterburner and "fresh bunch", are used to operate SASE1-SASE3 beamline. Spent electron from SASE1 is used to generate radiation in SASE3 in the afterburner configuration [1]. FEL process in SASE1 induces energy spread in the electron beam which is proportional to the radiation pulse energy. As a result, SASE3 and SASE1 performance are coupled such that increase of the radiation pulse energy in SASE1 leads to degradation of SASE3 output. The calculated minimum operational wavelength of SASE3 versus operating wavelength of SASE1 is shown in Fig. 2 (left) (for 14 GeV and 250 pC electron beam case) [6]. Operation of SASE3 in saturation is only possible for the wavelengths above the curves[1]. However, FEL efficiency visibly falls down as it is illustrated with measured pulse energy coupling between SASE1 and SASE3 shown in Fig. 2 (right). Electron energy is 14 GeV and bunch charge is 250 pC in this experiment. SASE1 and SASE3 operate at the wavelength of 0.13 nm and 1.4 nm, respectively.

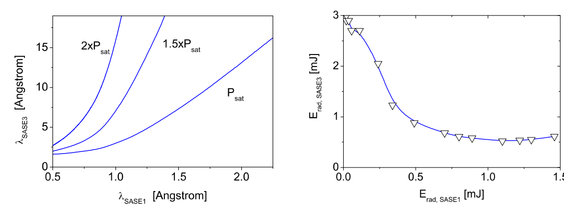

Figure 2: Calculated wavelength coupling (left) and measured pulse energy coupling (right) between SASE1 and SASE3 beamlines when operating SASE3 as a succession of SASE1 for 14 GeV and 250 pC electron beam case.

Mitigate Coupling with Betatron Switcher

In order to mitigate the coupling between SASE1 and SASE3, the betatron switcher technique (also called "fresh bunch" technique) was introduced [7, 8]. Using the fast kicker (4.5 MHz) in front of SASE1 [9], one can give a kick to the SASE3 bunches and generate a betatron oscillation for these bunches in SASE1. This kick is then compensated by a corrector (or a quadrupole kick) in front of SASE3, which also generates a betatron oscillation for the SASE1 bunches in the SASE3 beamline.

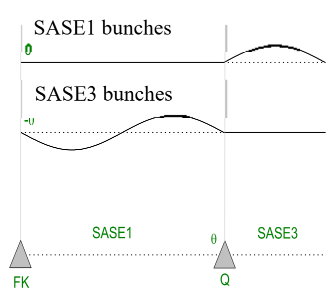

Figure 3: Betatron switcher used to suppress SASE3 bunches lasing in SASE1 and SASE1 bunches lasing in SASE3.

In this way, lasing of SASE3 bunches in SASE1 beamline and SASE1 bunches in SASE3 beamline are suppressed. The scheme of this technique is shown in Fig. 3. Dedicated simulations to study the performance of this

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scheme are presented in [10]. In the following, we will present the experimental performance of the betatron switcher.

PERFORMANCE OF BETATRON SWITCHER

The betatron switcher was demonstrated at the European XFEL in May 2018. Figure 4 shows an example of the SASE pulse energy output from the XGM monitor [11] during the operation with the betatron switcher mode. In this example, the first 50 bunches are SASE1 bunches and the last 5 bunches are SASE3 bunches. In Fig. 4 (bottom) one can see the calculated suppression factor[2]: lasing of SASE3 bunches in SASE1 beamline is supressed by around factor 200 and lasing of SASE1 bunches in SASE3 beamline is suppressed by around factor 100. The suppression of SASE3 bunches in the SASE1 beamline is more effective, because the hard X-ray beamline is more sensitive to the orbit distortion than the soft X-ray beamline.

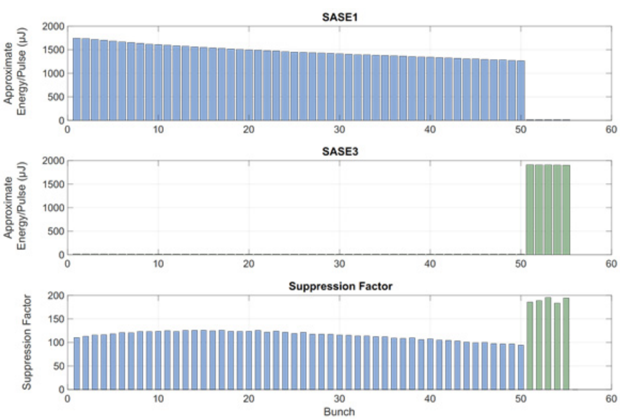

Figure 4: SASE pulse energy in SASE1 (top) and SASE3 beamline (middle) and suppression factor (bottom) as a function of bunch number.

Residual Lasing

Since the vacuum chamber in the undulator section is relatively small, the maximum kick (i.e. the maximum oscillation amplitude) that can be generated is limited by the beam losses in both beamlines. Meanwhile, SASE1 beamline is more sensitive to beam losses than SASE3 beamline, because it has more undulator cells and it operates with smaller undulator gaps.

Due to the limited oscillation amplitude, SASE1 bunches can still reach the same saturation level as SASE3 bunches, although the saturation length is much longer. Therefore, residual lasing of SASE1 bunches in SASE3 can still be observed by the SASE3 users. The background level from the residual lasing of SASE1 bunches highly depends on the ratio of number of bunches between SASE1 and SASE3 and the operation photon energy in the SASE3 beamline. Typically the background varies from 1% to 10% of the total pulse energy.

An additional fast kicker is installed in front of the SASE3 beamline during 2019 summer shutdown, which will help to increase the amplitude of betatron oscillations for SASE1 bunches in SASE3 beamline (without changing the oscillation amplitude in SASE1 beamline)[3].

Further Techniques to Suppress Residual Lasing

There are several ways to suppress residual lasing in combination with the betatron switcher.

Since the saturation length of the kicked SASE1 bunches are much longer than the SASE3 bunches, one can open the undulator cells beyond the saturation point of SASE3 bunches. Besides, one can also add aggressive quadratic taper starting from the saturation of SASE3 bunches.

Another way is to use different compression settings by applying different RF flat tops for SASE1 and SASE3 bunches. Adding stronger compression for SASE3 bunches result in larger peak currents, which consequently leads to shorter gain lengths for SASE3 bunches.

OTHER TYPES OF BACKGROUND OBSERVED IN SASE3

Except for residual lasing, the SASE3 users have also observed other types of backgrounds. The backgrounds range from optical to XUV. The backgrounds in these ranges can affect the photon detectors and damage the user samples when x-ray beam is focused for single shot imaging experiments.

Optical Background

Background in the optical light range has been observed on a YAG screen in the SQS instrument and wavefront sensor. By using an Al filter one can reduce the background on the imager. However, when the ratio of SASE1/SASE3 bunches is increased, imagers can not be used even with Al filters (see Fig. 5).

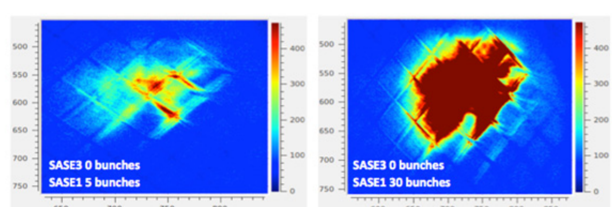

Figure 5: Optical background observed on a YAG screen in the SQS instrument with an Al filter inserted upstream in the beamline for the operation with 5 (left) and 30 (right) SASE1 bunches. The quadratic pattern that is visible stems from a grid structure imprinted on the YAG screen.

XUV Background

Background in the XUV range (few tens of eV) has

[2] One should keep in mind that due to the limited dynamic range of the XGM monitor, the actual suppression factors should be higher than the values shown here.

[3] However, the maximum oscillation amplitude is still limited to 2 mm both by the kicker strength (with 14 GeV electron beam) and for safety reasons.

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been verified by introducing small amounts of nitrogen in the gas absorber, as well as by inserting thin diamond filters, which remove some contributions. However attenuation strongly depends on the photon energy. Background in this range can ionize the samples, which affect especially the electron and ion spectroscopy experiments.

One example of the ionization of atomic beam by the background from SASE1 bunches is shown in Fig. 6. This effect is observed even when the SASE3 undulators are open as shown in Fig. 6 (right).

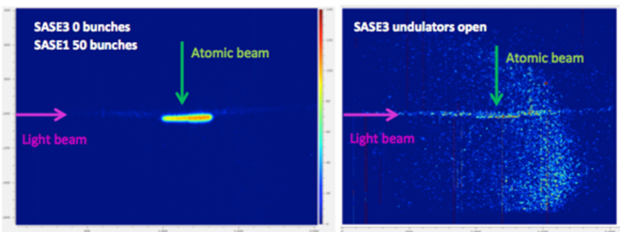

Figure 6: XUV background observed on velocity map imaging (VMI) spectrometer at the SQS instrument.

Optical Afterburner Effect

The background from optical to XUV range can be explained by the optical afterburner effect reported in [12]. Energy modulations, induced by SASE process on the scale of coherence time, can be converted into density modulations (in the range from VUV to FIR, depending on the configurations) in a dispersive element (can be chicane, arc or simply dump dipole), then the modulated beam radiates (can be CSR, edge radiation or a dedicated undulator) in the corresponding wavelength range (from VUV to FIR) [13].

Since there is a significant momentum compaction factor (R56=110 um) in the arc between SASE1 and SASE3, the density modulations induced by the arc can radiate in different ways as mentioned above. The background observed when the SASE3 undulators were open (see Fig. 6 (right)) is most probably due to edge radiation as explained in [14]. One can control the modulation scale by changing R56 and cancel this effect by either modify the arc or install a chicane (behind or in front of the arc).

On the other hand, this effect can be used for SASE1 pulse duration measurements or for SASE3 pump-probe experiments. Such measurements have already been demonstrated at FLASH [15].

FLEXIBLE OPERATION MODES

To help coping with the background issues, different operation modes were introduced together with the operation of the betatron switcher.

Typical 10 Hz Mode

The typical operation mode at the European XFEL delivers bunches to all SASEs within a train at 10 Hz repetition rate (see Fig. 7 (top)) and the SASE1 and SASE3 bunches are in sequence. This mode works for experiments exploiting pulse-resolved large-area detectors, and detectors for electron and ion Time of Flight (ToF) spectroscopy. However, the slower detectors[4] cannot seperate the SASE1 background from the SASE3 bunches and may record corrupted data. In addition fixed experimental targets are constantly exposed to the SASE1 background, which can cause sample heating or even damage the samples in single shot diffraction experiments.

[4] The slow detector has better transverse resolution than the fast detector and it is needed for some experiments.

5 Hz Mode

5 Hz mode (see Fig. 7 (middle)) is used to separate the SASE1 and SASE3 bunches into two sequential trains. In this way, one can work with the slow detectors with the help of a train picker (optical chopper), which enables full separation of the two SASEs, and the SASE1 background can be stopped before reaching the samples at SASE3 instruments. Therefore, this mode is needed for single shot imaging, pulson-demand experiments and radiation sensitive samples.

Interleaved Mode

Since not all the experiments require high repetition rates, interleaved mode (see Fig. 7 (bottom)) with SASE1 and SASE3 within a train is a good option for lower repetition rate (below 2.25 MHz) experiments. In this mode, both experiments can benefit from the long pulse window and double their data rate.

Other Modes

Besides the above-mentioned modes, the bunch pattern server and the timing system also allow different combinations of modes, and the users can define their own bunch pattern and repetition rate according to their needs [5].

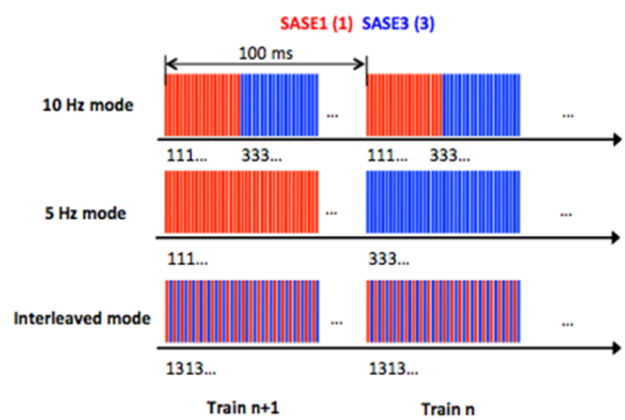

Figure 7: Example of operation modes for parallel operation of SASE1 and SASE3. SASE1 bunches are marked in red and SASE3 bunches are in blue.

SUMMARY AND FUTURE PLANS

In this paper we first presented the coupling between SASE1 and SASE3 operation, when they use the same electron beam. Decoupling has been achieved using the betatron switcher technique, which suppresses lasing of SASE3 bunches in SASE1 beamline and vice versa by generating betatron oscillations for different bunches. We

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showed that residual lasing of SASE1 bunches in SASE3 can still be observed due to the limited oscillation amplitude in the present setup. Different ways to further suppress the residual lasing were introduced including the use of different undulator configurations in SASE3 and the use of different compression setting for SASE1 and SASE3 bunches.

Except for the residual lasing, background from optical to XUV range was also observed. This can be explained by the optical afterburner effect and might be cancelled by modifying the arc between SASE1 and SASE3 beamline.

In the end, we introduced different operation modes, which we established in the parallel operation of SASE1 and SASE3 and explained how we can adapt these modes to different user requirements.

The experience we have learned in the parallel operation of SASE1 and SASE3 will help us to design the future undulator beamlines. Design studies for the two empty tunnels SASE4 and SASE5 downstream of SASE2 (see Fig. 1) are ongoing [16-18]. Besides, R&D towards doubling FEL beamlines with a 2nd fan is also in progress.

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