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ADVANCED CONCEPTS IN THE DESIGN FOR THE SOFT X-RAY FEL AT MAX IV

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Abstract

A Soft X-ray FEL (the SXL) is currently being designed at the MAX IV Laboratory. In the work to adapt the FEL to the scientific cases several advanced options are being studied for coherence enhancement, generation of short pulses and two-color pulses. We will discuss the current status and initial results of the schemes studied, especially regarding the FEL performance with the features of the MAX IV linac, including a positive energy chirp.

INTRODUCTION

A Soft X-ray FEL (the SXL) [1] at the MAX IV Laboratory is currently in conceptual design phase. Phase I of the SXL will be based on realistic chirped electron beam from the existing 3 GeV linac [2]. The baseline is SASE FEL operating with 100 pC and 10 pC charge. To meet the increasing demand of various features of the FEL pulses, such as ultra-short pulses, two-color pulses, coherence improvement as well as high flux pulses, advanced FEL schemes need to be employed. The SXL is based on 3 m long, 40 mm period APPLE-X undulator with strength K tuning range from 1.2 to 3.9. The length of the whole undulator line is not yet fully defined but should be enough to bring the shortest wavelength to saturation. To allow possible implementation of advanced schemes, a few sections are reserved, as sketched in Figure 1. Prior to the undulator line, one section is reserved for modulator and chicane modules for external seeding methods such as the Echo-Enabled Harmonic Generation (EEHG) [3,4], or attosecond pulse generation methods such as the XLEAP [5]. In the middle of the undulator line one section is reserved for split undulator based two-color FEL pulse generation as well as monochromator based self-seeding [6]. Space for small delay chicanes in each undulator break section is reserved for schemes such as high-brightness SASE [7] and high power short pulse generation. In this paper we present preliminary advanced concepts for the design of the SXL as well as example simulations for the schemes that are relatively straightforward to implement. FEL simulations are conducted using 3D FEL code GENESIS [8].

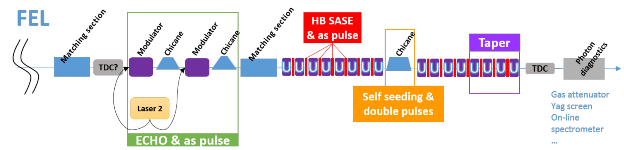

Figure 1: Schematic layout showing the implementation of various FEL schemes.

SHORT PULSE GENERATION

Ultra-short pulse is crucial for probing ultra-fast dynamics as it defines the resolution in time. Typical operation of FELs provides pulses with a few tens of femtosecond duration, close to the length of the electron beam. While for ultra-fast applications, FEL pulses down to a few femtosecond or even subfemtosecond are required. To generate ultra-short FEL pulses, common methods are selecting an ultra-short region of the electron beam to lase or shortening the electron beam itself. To select an ultra-short region, one can use a slotted foil [9] or a modulation laser [10] in the laser heater section, one can also enhance the beam current of a local region using a few-cycle laser [11], another method is transversely tilting the electron beam [12] to create good interaction region in the beam. One way to shorten the electron beam is to start with lower bunch charge, which produces a shorter beam with lower emittance from the beginning and allows higher compression factor [13]. Selecting an ultra-short region usually requires additional hardware, while low charge method is straightforward to implement, despite it produces less pulse energy. In the current design of the SXL, the low charge method is considered as a standard way to produce ultra-short pulses and thus one of the two baseline operation modes.

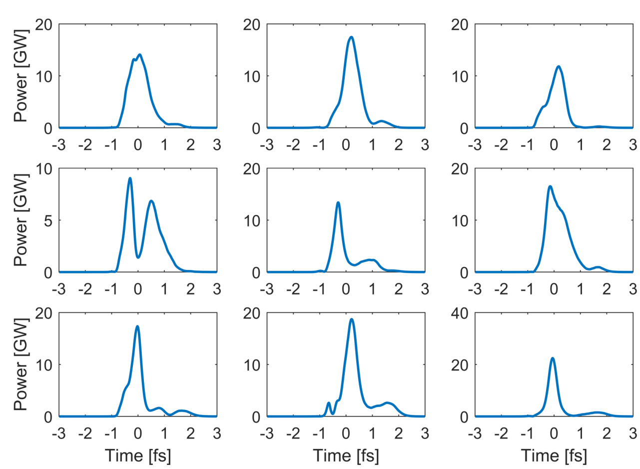

Figure 2: 9-shot simulated temporal profiles for the 10 pC mode of the SXL. The resonant wavelength is 1 nm.

Start-to-end simulations have been conducted for the low charge operation mode of the SXL. Beam parameters and phase space before the undulator can be found in Ref. [14]. The 10 pC electron beam is compressed to about 3.5 kA after two double-achromat compressions. Figure 2 shows

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9-shot FEL temporal distributions for the low charge case at 1 nm. Ultra-short FEL pulses with an average (over 20 shots) of 0.8 fs FWHM duration, 15 μJ pulse energy is obtained. Since the bunch length is comparable to the slippage length, almost one single spike is generated, giving good longitudinal coherence.

For low charge operation at longer wavelength such as 5 nm, the FEL pulse slips out of the electron bunch quickly, causing the FEL to saturate. Figure 3 shows the power growth along the undulator for 5 nm radiation, which saturates around 20 m. The inset plot shows the temporal profile around power saturation position. The averaged temporal profile over 20 shots gives about 1.5 fs FWHM duration, corresponding to about 80 μJ average pulse energy.

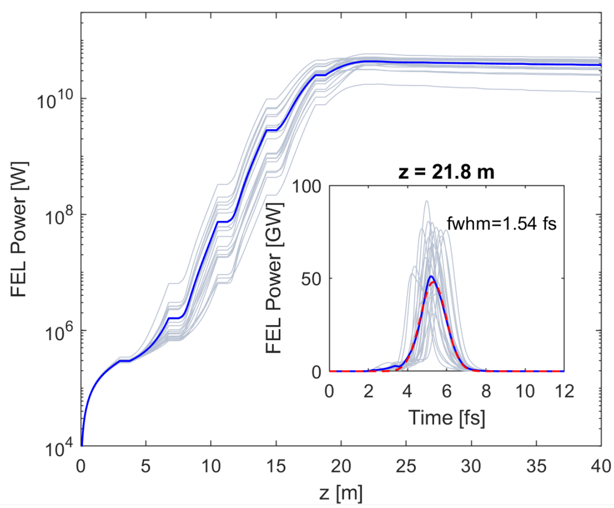

Figure 3: Simulated power growth along the undulator for 5 nm radiation. The inset plot shows corresponding temporal profile around saturation.

TWO-COLOR PULSE GENERATION

Two-color two-pulse FEL provides the ability to do X-ray pump X-ray probe experiments with natural synchronization. According to the resonant condition, generating two-color FEL requires either two distinct beam energies, two undulator K values or two undulator periods. Various methods have been proven the capability to produce two-color FEL pulses. The split undulator method [15] splits the undulator line into two sections with two distinct K values. The wavelength separation of the two FEL pulses can be varied over a large range with the help of gap tunable undulators. A magnet chicane is placed between the two sections to tune the delay between the two pulses. This method is highly flexible in wavelength separation and delay control but lacks efficiency since the beam quality is reduced in the first section due to the lasing process. Fresh-slice technique [16] has been developed to improve the efficiency of the split undulator method. Twin bunch method [17], which generates two electron bunches from the injector and accelerates them to different energies, is highly efficient since it requires only half of the undulator length compared with the split undulator method. However, the twin bunch method is limited in tunability due to the correlation between the energy separation and delay of the two electron bunches. Among the scientific applications of two color pulses, large wavelength separation has drawn increasing interest in the user community. Generation of such pulses favors the split undulator method owing to its flexibility in wavelength separation.

For the SXL, both the split undulator method and the twin bunch method are considered. There has already been some experiments at MAX IV about generating twin bunches from the injector. While the twin bunch method requires start-to-end simulations to figure out what wavelength separation range it can cover, the split undulator method has more flexibility and defines the longest undulator length given a pair of target wavelengths. Here, in this paper, we show a widely separated two-color FEL example aiming at 250 eV and 500 eV. The electron beam is assumed to be 100 pC, 3 GeV without energy chirp, other parameters are 2.5 kA peak current, 0.5 μm normalized emittance and 0.3 MeV energy spread. The first undulator section consists of 7 undulator modules, tuned to 500 eV (K=2.56). The second undulator section consists of 8 undulator modules, tuned to 250 eV (K=3.9). A chicane section is assumed to control the delay between the two colors and smear out the microbunching from the first undulator section. The delay between the two pulses is assumed to be 50 fs in this simulation. Figure 4 shows GENESIS simulated pulse energy growth along the undulator. Both pulses are close to saturation and produce above 100 μJ pulse energy. The saturation length for the second color is longer than a fresh electron beam due to the increased energy spread from the FEL process in the first section.

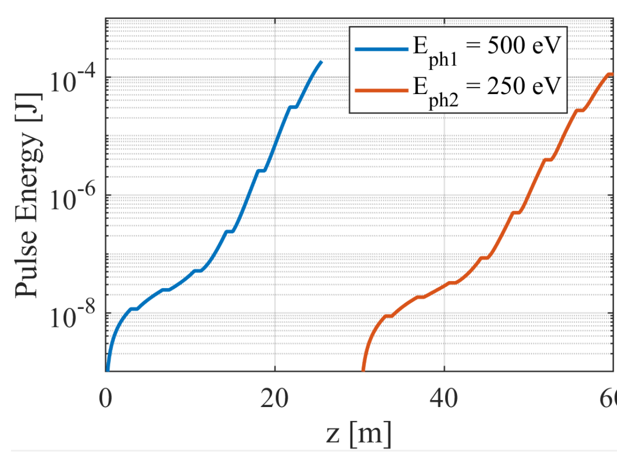

Figure 4: Pulse energy growth along the undulator for two-color generation at 500 eV and 250 eV.

Like the SASE FEL case, an energy chirp would broaden the spectrum while almost not affect the saturation length. The positive energy chirp would even slightly increase the saturation pulse energy due to detuning effect. With the split undulator method, it may not be able to let both pulses saturate with a given length of undulator line in the case

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where higher photon energies are required. For higher photon energy with small wavelength separation, the twin bunch method would be appropriate. Another possible way to improve the efficiency of the split undulator method and bring both pulses to saturate could be using the beam chirp to create a transverse tilt in the beam and enable the fresh-slice technique.

HIGH-BRIGHTNESS SASE

Since SASE FEL starts from shot noise of the electron beam and the FEL pulse only slips over a small fraction of the whole electron beam, the FEL pulse has spiky temporal profile and spectrum, giving poor longitudinal coherence. There are numerous ways to improve the longitudinal coherence. With recent progress in external seeding, the HGHG or the EEHG method may reach the long wavelength end of the SXL operation range. Soft X-ray self-seeding based on monochromator can cover the full operation range but has limitation on undulator length needed and stability. Another way to improve the longitudinal coherence is the high-brightness SASE scheme which introduces extra delays between the FEL pulse and the electron beam, thus increasing the coherence length. The delays can be introduced via small magnet chicanes in the undulator break sections.

For the SXL, the delay chicanes could be placed in the 0.76 m long break sections, providing delays up to a few femtosecond. Since the R56 of the small chicanes are not zero, the electron beam also experiences an extra rotation in longitudinal phase space. In initial theory of the high-brightness SASE, no R56 is included and the amount of chicane delays are gradually increasing with the position. R56 from small chicanes would cause the electron beam to overbunch quickly in the exponential growth stage of FEL and limit the saturation pulse energy. As is pointed out in Ref. [18], undulator module length also affects the narrowest bandwidth that high-brightness SASE can achieve. Shorter undulator module is favorable since it allows to apply the delay more frequently.

In this paper, we show preliminary simulation results of the high-brightness SASE for the SXL. The electron beam is assumed to be the same unchirped beam as the two-color case. The delay sequence is assumed to be a decreasing geometric sequence. GENESIS version 4 is used to scan the first delay and the ratio between two consecutive delays. Figure 5 shows temporal profiles and spectra for SASE with 3 m undulator (top row), high-brightness SASE with 3 m undulator (middle row) and high-brightness SASE with 2 m undulator (bottom row). The SASE case is plotted at 40 m, while the other two are plotted at 30 m. Due to the optical klystron effect from the delay chicanes, the bunching process in the high brightness scheme is accelerated and the FEL saturates faster than the SASE case. It can be seen that with 3 m long undulator, the averaged bandwidth is reduced to about half of the SASE case, while with 2 m long undulator, the averaged bandwidth can be further reduced to 4×10^{-4}, giving 6 times bandwidth reduce. It should be noted that a large energy chirp would significantly affect the effect of the high-brightness SASE scheme. As in Ref. [14], start-to-end simulations show, the SASE spectrum is twice large compared with the unchirped case. Studies using the chirped start-to-end electron beam in the high-brightness scheme are ongoing.

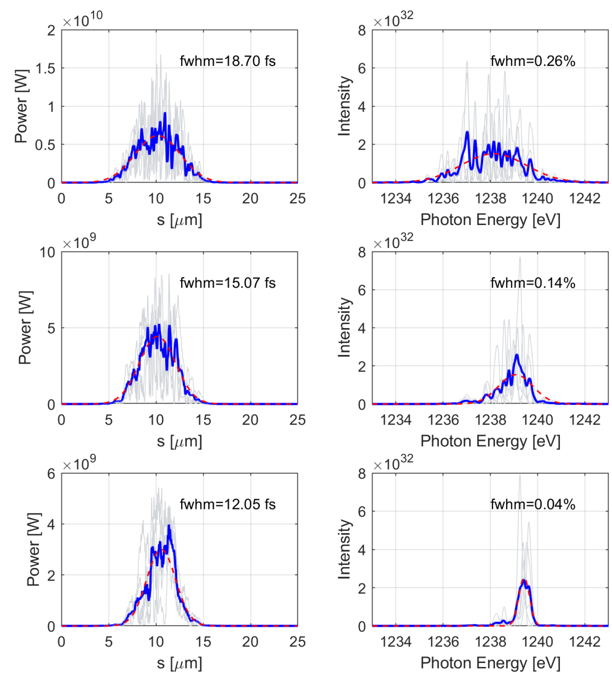

Figure 5: Temporal profiles and spectra for SASE with 3 m undulator (top row), high-brightness SASE with 3 m undulator (middle row) and high-brightness SASE with 2 m undulator (bottom row). The simulation is based on unchirped electron beam. Five GENESIS runs are conducted for each case and the blue line indicates the average over the five shots.

CONCLUSION

We have presented a few advanced concepts in the design of the SXL, along with preliminary simulations using chirped start-to-end simulated 3 GeV beam or ideal unchirped beam. Low charge operation for short pulse generation as well as two-color two-pulse generation using split undulator method can accommodate to the chirped beam. Both the energy chirp and undulator module length are limiting the performance of the high-brightness SASE scheme. More detailed studies are ongoing to characterize the chirp influence on the advanced schemes. Studies on other schemes, like XLEAP, twin bunch, self-seeding and external seeding, are also ongoing.

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