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START-TO-END SIMULATIONS FOR THE SOFT X-RAY FEL AT THE MAX IV LABORATORY

W. Qin*, F. Curbis, M. Pop, S. Werin, Lund University and MAX IV Laboratory, Lund, Sweden
J. Andersson, L. Isaksson, M. Kotur, E. Mansten, S. Thorin, MAX IV Laboratory, Lund, Sweden

Abstract

A Soft X-ray FEL (the SXL) using the existing 3 GeV linac at the MAX IV Laboratory is currently in the design phase. In this contribution, start-to-end simulations, including the photo-injector simulations using ASTRA, the linac simulations using ELEGANT and the FEL simulations using GENESIS, are presented for 100 pC and 10 pC operation modes. The features of the electron beam from the MAX IV linac and their impact on the FEL performance are discussed.

INTRODUCTION

A Soft X-ray FEL (the SXL) [1] at the MAX IV Laboratory is currently in conceptual design phase. The SXL utilizes the existing 100 Hz, 3 GeV linac [2] and the photocathode injector [3,4] at MAX IV to generate high brightness electron beams to drive radiation ranging from 1 nm to 5 nm. Considering the features of the 3 GeV beam from the existing linac, phase I of the SXL would be mostly operating in SASE mode using beam parameters that do not require major modification of the existing linac. With improvement of the beam quality, especially removal of the beam chirp, more advanced schemes are foreseen in phase II.

The layout of the SXL FEL is sketched in Figure 1. There are two injectors, one based on a thermionic RF gun to produce beams for the 1.5 GeV and 3 GeV ring injection, the other based on a photocathode RF gun to produce high brightness beams for the Short Pulse Facility (SPF) [5] and the SXL. After the injector, the electron beam is accelerated in the S-band linac and compressed by two double-achromat bunch compressors. The 3 GeV electron beam is then matched and sent into the undulator line, which consists of 3 m long, 40 mm period, APPLE-X undulator modules. The overall undulator line length is not fully defined yet. Empty sections before the main undulator and in the middle of the undulator are reserved for possible advanced schemes such as external seeding or self-seeding. Small chicanes could be added in the undulator break sections to delay the electron beam for possible coherence improvement schemes and high power schemes. The X-ray pulses are transported through the photon diagnostic section and then to the experimental stations.

In this paper, we present start-to-end particle tracking results from the photocathode gun to the end of the undulator line. The particle tracking is conducted in three stages. The injector is simulated with ASTRA [6] from the cathode to approximately 100 MeV. At the end of the first linac, ELEGANT [7] is used to model the downstream acceleration to 3 GeV and two-stage bunch compressions, including wakefields and CSR effect. The ELEGANT output distribution is sent into GENESIS [8] to simulate the generation of FEL pulses. 2M macro-particles are used in the simulations. Simulation details for the three stages are described in the following sections.

INJECTOR SIMULATION

The designed SXL injector is optimized based on the currently operating 10 Hz MAX IV injector, consisting of a 1.6 cell S-band BNL/SLAC type RF gun with a copper cathode, an emittance compensation solenoid, a 5.2 m long S-band linac, a drive laser system and relevant diagnostics. Standard operation of the designed injector generates 100 pC electron beam with 100 Hz repetition rate. Another operation mode aims at generating 10 pC electron beams with lower emittance and shorter pulse duration. To generate 100 pC charge, a 263 nm laser pulse with plateau temporal distribution and cut-gaussian transverse distribution is illuminated on the copper cathode, with 7.6 ps temporal duration and 0.24 mm transverse rms size. The maximum field is 100 MV/m and the gun phase is 25 degrees. Figure 2 shows the electron beam slice parameters and longitudinal phase space at the injector exit for the 100 pC case. An electron beam with about 18 A current, 6 ps FWHM duration and slice emittance lower than 0.4 μm is obtained. By adjusting the laser diameter and gun settings, a 10 pC electron beam with 11 A current, 1 ps FWHM duration and 0.2 μm slice emittance is obtained.

Further optimization of the gun and injector setup is ongoing. More parameters are included and advanced algorithm like MOGA is deployed in the optimization procedure. Comparing ASTRA results with full space charge code Impact-T [9] is also ongoing. A gun test stand has been setup at MAX IV as a useful platform to test the performance of the SXL gun.

LINAC SIMULATION

The MAX IV linac consists of 39 normal conducting S-band accelerating sections. Bunch compression is accomplished with two double-achromat type bunch compressors at 260 MeV and 3 GeV. The bunch compressors have positive R56 and positive T566, thus linearizing the longitudinal phase space without the help of a prior harmonic cavity. The linearization effect can also be tweaked using sextupoles in the bunch compressors. The second bunch compressor is also used as a beam distributor for the SPF and a diagnostic beamline. Figure 3 shows the electron beam slice parameters and longitudinal phase space at the exit of the linac for the 100 pC case. After the two-stage compression, the

* weilun.qin@sljus.lu.se

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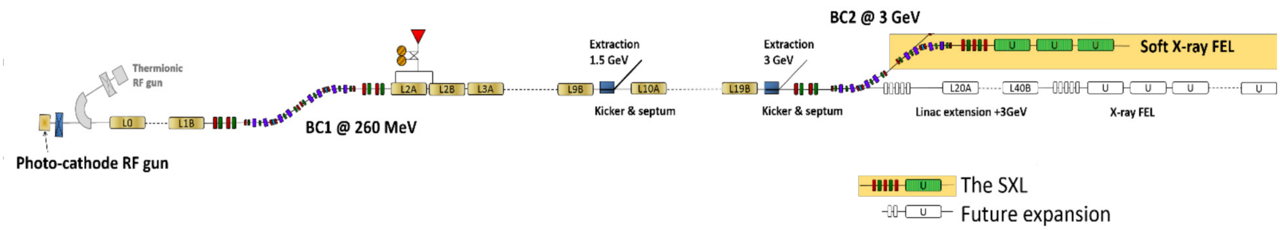

Figure 1: Layout of the SXL FEL.

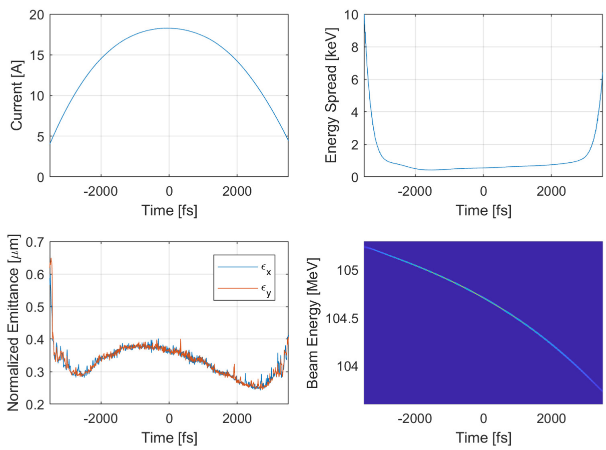

Figure 2: Electron beam slice parameters and longitudinal phase space at the injector exit (before BC1) for 100 pC charge. Bunch head is to the left.

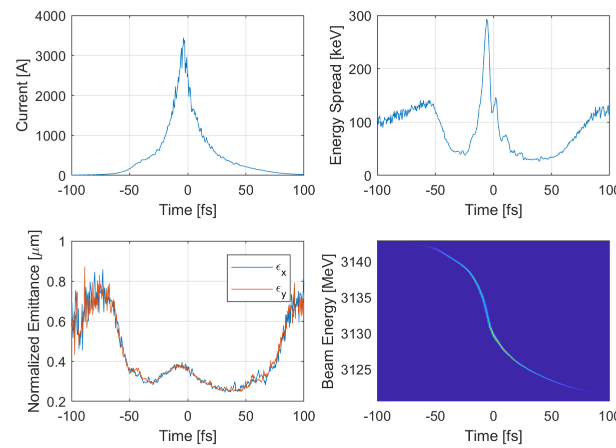

Figure 3: Electron beam slice parameters and longitudinal phase space at the linac exit (after BC2) for 100 pC charge. Bunch head is to the left.

electron beam is compressed to about 15 fs FWHM with a 3.5 kA narrow current peak. The slice energy spread is about 0.3 MeV. The slice emittance is well preserved in the acceleration and compression. A residual energy chirp is presented in the longitudinal phase space, with about 0.5 MeV/fs in the core part. Figure 4 shows the electron beam slice parameters and longitudinal phase space at the exit of the linac for the 10 pC case. The slice emittance in this case is increased to about 0.4 μm in x plane while it is kept below 0.3 μm in y plane. The residual chirp in the longitudinal phase space is increased to about 1 MeV/fs.

Removing the residual positive chirp as shown in Figure 3 with the current setup of the linac is not easy to realize. There are considerations of configuring the second bunch compressor to zero R56 or negative R56 with additional magnets. Overcompressing the beam and cancelling the residual chirp using wakefields is another possible configuration, while initial simulations show that this might require an increase in bunch charge to provide enough wakefields. Initial simulations on the jitter and tolerance of the linac are ongoing.

FEL SIMULATION

The simulation parameters for the high charge mode (1A) and low charge mode (1B) of the SXL are shown in Table

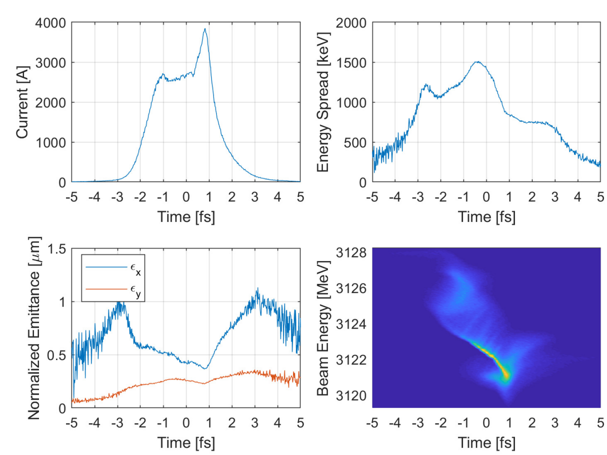

Figure 4: Electron beam slice parameters and longitudinal phase space at the linac exit (after BC2) for 10 pC charge. Bunch head is to the left.

1. The APPLE-X type undulator allows for full polarization control while the simulations here are for linear polarized light. The undulator module is 3 m long with 40 mm period. The undulator strength K can be tuned between 1.2 and 3.9 to generate radiation from 1 nm and 5 nm at a fixed 3 GeV beam energy.

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Table 1: SXL FEL Simulation Parameters

Parameters	1A	1B	Unit
Q_b	100	10	pC
E_b	3	3	GeV
$\sigma_{E,slice}$	0.3	1.5	MeV
dE/dt	0.5	1	MeV/fs
$\varepsilon_{n,slice}$	0.35/0.35	0.4/0.25	μm
I_{pk}	3.5	3.5	kA
λ_u	40	40	mm
K	1.2-3.9	1.2-3.9	
L_{module}	3	3	m
L_{break}	0.76	0.76	m
<β>	8	8	m
λ_s	1-5	1-5	nm

After BC2, the electron beam distribution from ELEGANT is matched and sent into GENESIS for FEL simulation. Twenty GENESIS runs with different random numbers are conducted for each case. Figure 5 and 6 show the GENESIS simulation results for both high charge (1A) and low charge (1B) at 1 nm. For the 100 pC case, maximum average bunching is reached after 11 modules, producing FEL pulses with 160 μJ pulse energy and 15 fs duration. Due to the residual beam chirp, the FEL bandwidth is broadened to about 0.6%. For the 10 pC case, owing to the lower slice emittance, the FEL saturates after 8 modules. The 10 pC electron beam has about 3 fs FWHM duration, while the FEL output has 0.8 fs FWHM duration. This is because the radiation from the high current peak in the bunch tail is dominating in the FEL process and slips ahead to the bunch head. Since the electron beam duration is comparable to the slippage length, the temporal profile is almost one single spike, providing good longitudinal coherence. Although the beam chirp in the 10 pC case is higher than that in the 100 pC case, the FEL bandwidth is even narrower due to the short electron pulse duration. It is worth mentioning that, for both of the two cases, the chromatic effects in the linac are not fully optimized, causing increase of projected emittance. With further optimization of the chromatic effects, the FEL pulse energy can be further improved.

In the FEL simulation in this paper, undulator wakefields and taper are not yet included. Wakefields from the undulator vacuum chamber will further introduce an energy chirp in the beam phase space and an average energy loss to the beam. The wake induced energy chirp is relatively small compared with the residual chirp in the beam, thus has no significant impact on the FEL performance. The average energy loss can be compensated by an linear undulator taper. Post-saturation taper can further increase the pulse energy, especially for longer wavelengths.

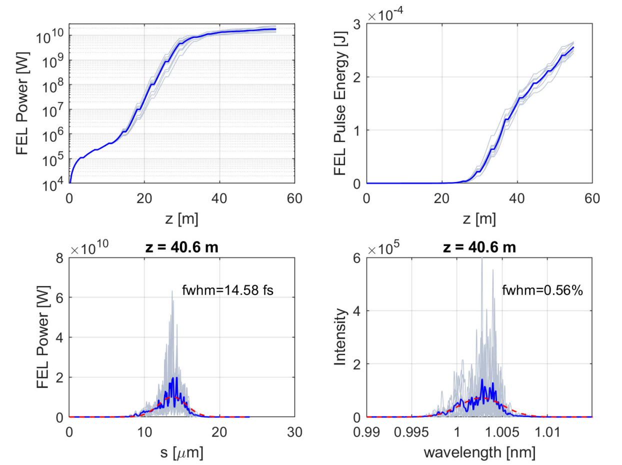

Figure 5: GENESIS simulation results for the 100 pC case (1A) at 1 nm. Each grey line corresponds to one shot simulation and the blue line corresponds to the average of all the 20 shots.

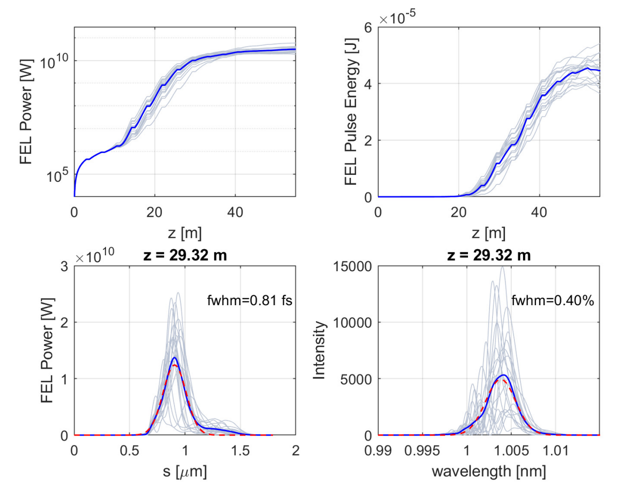

Figure 6: GENESIS simulation results for the 10 pC case (1B) at 1 nm. Each grey line corresponds to one shot simulation and the blue line corresponds to the average of all the 20 shots.

SUMMARY

In this paper, we have presented start-to-end simulation results for the SXL FEL. Using the photocathode injector and the 3 GeV linac at MAX IV, high brightness electron beams are generated and used to produce FEL pulses ranging from 1 nm to 5 nm. Large positive energy chirp is presented in the electron beam longitudinal phase space. For baseline SASE operation, simulation results show that the chirped beam is sufficient to drive an FEL with good performance. FEL pulses with a few femtosecond or even subfemtosecond pulse duration can be generated. Simulations including undulator wakefields and tapering are ongoing.

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