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HIGHLIGHTS FROM THE CONCEPTUAL DESIGN REPORT OF THE SOFT X-RAY LASER AT MAX IV

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Abstract

The SXL (Soft X-ray Laser) project developed a conceptual design for a soft X-ray Free Electron Laser (FEL) in the 1–5 nm wavelength range, driven by the existing MAX IV 3 GeV linac. In this contribution we will focus on the FEL operation modes developed for the first phase of the project based on two different linac modes. The design work was supported by the Knut and Alice Wallenberg foundation and by several Swedish universities and organizations (Stockholm, Uppsala, KTH Royal Institute of Technology, Stockholm-Uppsala FEL center, MAX IV laboratory and Lund University).

INTRODUCTION

In 2016 an international workshop with more than 100 participants defined the initial user case for a Swedish Soft X-ray FEL that could be driven by the existing linac at the MAX IV laboratory [1]. In 2018 the work with a conceptual design started and is now available at the MAX IV website [2]. During this time the work has focused on the different aspects revolving around the SXL as a FEL user facility (science, experimental stations, beamline, undulators, linac driver, electron gun source, timing and synchronization). These matters were investigated from a conceptual point of view in order to satisfy the needs of the user case and design a competitive and up-to-date machine. While initially limiting the scope we kept in mind possible future upgrades and different modes of operations.

OVERVIEW OF THE SXL PROJECT

SXL (Soft X-ray laser) will cover a wavelength range from 1 to 5 nm with rather short pulse duration (from tens of femtoseconds down to a few femtoseconds, in the first phase) [3] . This source can accommodate the user requirements for a large variety of experiments in four main areas: AMO physics, condensed matter, Chemistry and Life Science [4]. The underlying idea in the conceptual design phase has been to keep the machine flexible for future expansions and enhancing some typical features like the embedded broad spectrum of pump sources. Table 1 summarizes the main parameters of SXL.

Table 1: Main SXL Parameters

Wavelength range	1 to 5 nm
Electron beam energy	3 GeV
Bunch charge	10 to 100 pC
Photon pulse duration (FWHM)	0.8 to 26 fs
Energy per pulse	0.015 to 1.5 mJ
Maximum repetition rate	100 Hz

During the initial user workshop in 2016, it emerged that a FEL source in the soft X-ray range would satisfy a vast range of Swedish research groups and therefore the existing MAX IV linac would be the perfect candidate as driver. The injector system at the MAX IV has been conceived from the beginning to be able to drive also an FEL, besides injecting into the two storage rings and the short-pulse facility [5]. The proximity to the MAX IV storage rings will also provide the perfect environment for collaborations and sharing of resources.

Main Features of Sxl and the Baseline

- Full polarization control;
- Extensive range of pump lasers from IR to XUV;
- two-pulse/two-color capabilities, with delays from few fs to tens of ns;
- Ultra-short pulses;
- Possibility of future expansion: EEHG, HB-SASE, self-seeding, hard X-rays.

The SXL will come in two phases, where the first phase will satisfy the bulk of the user requirements in SASE mode with full polarisation control, two-pulse/two-color operation, enhanced power through tapering and short pulses below 10 femtoseconds. In a second phase, more advanced concepts are envisaged: ultra-short pulses (few tens of as), coherence enhancement and seeding.

THE DRIVING BEAM

In the 3 GeV MAX IV linac the bunches generated by a photo-cathode gun are compressed using two double-achromat structures (BC1 and BC2), which provide also

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passive magnetic linearization. A detailed description of the MAX IV linac and its perfromance can be found elsewhere [6, 7]. Two main modes, or ”typical pulses”, have been studied during the SXL CDR work: a high charge-long pulse (1A) and a low charge-short pulse (1B). Both pulses displays a residual energy chirp, as can be seen in Fig. 1, which it is not typical in other FELs, but at the same time a very high peak current, i.e., a very short pulse, can be reached. More details about beam dynamics, collective effects and technical solutions that will be adopted can be found in the CDR [2].

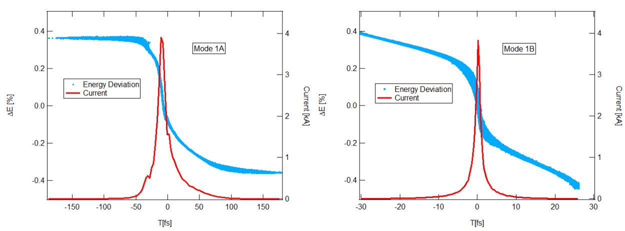

Figure 1: Longitudinal phase space. The high charge-long bunch mode (left) and low charge-short bunch mode (right).

FEL DESIGN

The layout of the SXL undulator line is illustrated in Fig. 2. Two sections of 10 undulators each are separated by a 5-m-long strong chicane which will allow to delay the electron beam for two-pulse/two-color operations. The 2 m-long APPLE-X undulators will allow full polarization control and tunability in the desired wavelength range (see following section). The intra-undulator sections will be equipped with a combined phase shifter and delay chicane, a quadrupole to generate a FODO lattice, diagnostics and the vacuum system. In front of the undulators a matching section is followed by space reserved to install de-chirpers and EEHG seeding. At the end of the undulator chain, a transverse deflecting system will enable full temporal diagnostics of the electron beam.

The FEL will start in SASE mode with the long bunch 1A (high charge - mildly compressed) , then the optical-klystron effect and undulator tapering will be implemented to enhance the pulse energy. In a following stage, the short bunch 1B (low charge - strongly compressed) will be utilized and the split undulator technique to produce two color/two pulses will be tested first with the long and then with the short bunch.

Performance in Sase Mode with Tapering

For the shortest wavelength (1 nm) an active length of 26 meters is sufficient to reach saturation, leaving about 14 meters (7 modules) of undulator available for post-saturation tapering. In our simulations, a quartic (fourth order) taper profile has been optimized to maximize the output pulse energy, which increases to about 700 μJ at 1 nm and 1 500 μJ at 5 nm, while the bandwidth remains about the same. The evolution of the FEL power and energy along the undulator as well as the spectrum at 1 nm can be seen in Fig. 3. In Table 2 we report both the performance at 1 and 5 nm for the long pulse (1A).

Table 2: FEL Performance for the ”Long” Bunch (1A)

	1A with tapering	
	1 nm	5 nm
Pulse energy (μJ)	660	1500
Peak Power (GW)	50	56
Photons per pulse	$3.3{\times}10^{12}$	$3.8{\times}10^{13}$
Pulse duration (fs) [FWHM]	14	26
Bandwidth (%) [FWHM]	0.8	1.2

Two-pulses/Two-colors Operations

In order to meet the users’ wishes for two pulses (with the same or different colors), we plan to use the so-called ”split-undulator” [8] technique and two electron pulses in adjacent RF buckets [9].

In the split-undulator, the strong chicane between the two undulator sections will allow to tune the delay from +10 fs to +1 ps. An optical system at the end-station will take care of the ”cross over”, i.e., overlap the pulses with zero delay and even switch the order of the pulses. The generation of the two photon pulses will be coupled because the same electron bunch will produce both and this will limit the wavelength tuning range. Moreover the FEL pulse energies will be coupled to time and wavelength separation. Simulations for the split undulator case have been performed using both the long and the short bunch for several combinations of delays and wavelength separations of interest from the potential experiments, with separation from a few eV to a few hundred eV. The output pulse energies for the two pulses are comparable and span from a few to a few hundred μJ.

For longer time separations, we will use two electrons pulses accelerated in successive RF buckets. The time interval will come in multiples of the RF frequency at n×333 ps up to a maximum of about 50 ns between the two pulses. While the tunability will be limited [10], from the FEL point of view these pulses can be regarded as more or less independent and with similar performance.

UNDULATORS

The proposed undulators for SXL are a compact type of APPLE X, with a structure composed of four permanent magnet blocks with triangular shape, Fig. 4. They are disposed radially at equal distance around the electron beam axis. This symmetric structure allows to achieve, at the same gap, the same energy range at all polarizations. Tuning the polarization can be obtained shifting two magnets sub-girders longitudinally. By moving the magnet arrays radially, i.e., adjusting the magnetic gap, it is possible to change the resonant wavelength. The main parameters of the APPLE X undulator are shown in Table 3. In order to verify the feasibility of the design, a prototype will be built in the framework of a LEAPS pilot program.

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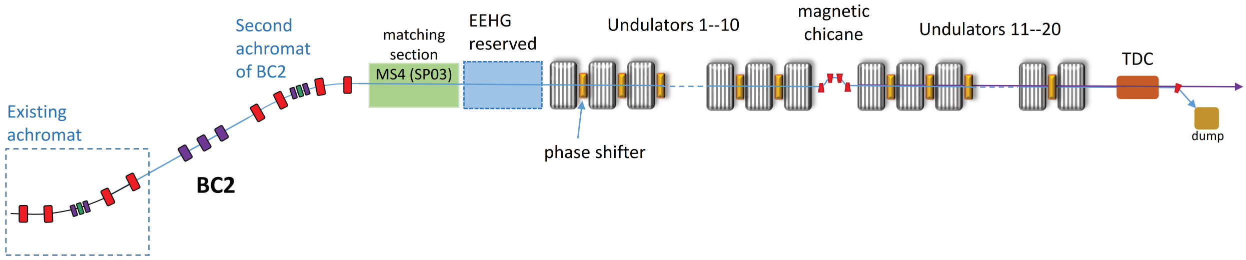

Figure 2: Layout of the SXL FEL line from the end of the last bunch compressor (BC2).

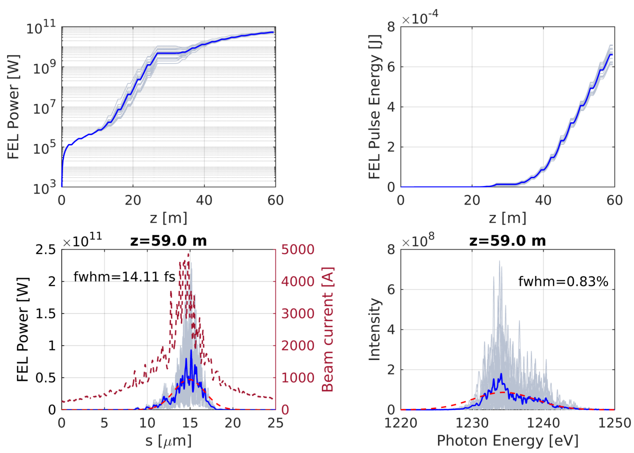

Figure 3: FEL performance at 1 nm for the 1A pulse.

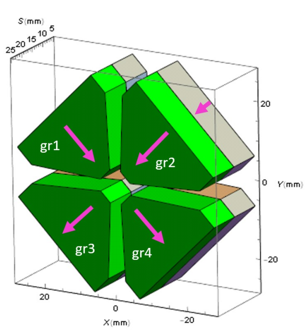

Figure 4: Half period structure of the APPLE X undulator at minimum gap with magnetization orientation for the four sub-girders.

Table 3: APPLE X Undulator Parameters

Magnet material	SmCo
Period length	40 mm
Magnetic gap range	8 to 17.3 mm
required effective K range	3.9 to 1.2
Max. gap / min eff. K	28mm / 0.55
Magnetic length	2 m

ADVANCED MODES OF OPERATION

As previously mentioned, in the second phase of the project more advanced concepts will be employed in order to improve the features of SXL. In particular, from indications in the science case, three areas have been chosen: ultra-short pulses, coherence enhancement and seeding for improving the stability. We believe that some of the advanced schemes will be facilitated by "de-chirping" the electron beam and at the moment we are studying the implementation of conventional de-chirpers combined with overcompression. The de-chirped beam displays a long flat top region in the longitudinal phase space which is compatible with HB-SASE operations [11]. Echo Enabled Harmonic Generation (EEHG) has been studied in a defined wavelength range (3 to 5 nm) and encouraging results have been obtained even with the chirped beam. More details are presented in [12]. FEL jitter studies have been performed with start-to-end simulations [13] with results indicating a very stable performance of the linac in terms of arrival time jitter and compression.

CONCLUSIONS

In this paper we presented the main features of the SXL project from the accelerator/FEL perspective. The design of SXL provides competitive performance that can enable the experiments proposed in the science case. The SXL will produce very short pulses with very good stability and a wide range of pump options will be used in combination with two-pulses/two-colors schemes with variable delays. The FEL design is flexible and will allow further development.

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