

# STATUS OF THE SOFT X-RAY LASER (SXL) PROJECT AT THE MAX IV LABORATORY\*

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## Abstract

A Soft X-ray Laser project (the SXL) aiming to produce FEL radiation in the range of 1 to 5 nm is currently in a conceptual design phase and a report on the design is expected to be delivered by March 2021. The FEL will be driven by the existing 3 GeV linac at MAX IV laboratory, which also serves as injector for the two storage rings. The science case has been pushed by a large group of mainly Swedish users and consists of experiments ranging from AMO physics to condensed matter, chemistry and imaging in life science. In this contribution, we will present the current conceptual design of the accelerator and the FEL operation modes together with a general overview of the beamline and experimental station. In particular design options for the FEL will be discussed in conjunction with the features of the electron beam from the MAX IV linac and the connection with the proposed experiments.

## INTRODUCTION

The linear accelerator, which serves as injector for the two storage rings and the Short Pulse Facility (SPF) at the MAX IV laboratory in Sweden, can also drive a soft X-ray FEL with minor modifications. The SXL project has been proposed by Swedish users interested in exploiting FEL radiation in the range between 1 and 5 nm.

The linac will for the SXL project run at its maximum energy of 3 GeV with 100 Hz repetition rate and an upgraded photo cathode gun [1].

Several Swedish universities are engaged in this project: Stockholm university, Royal Institute of technology (KTH), Uppsala University and Lund University.

The project timeline sees now a three years period to work on a Conceptual Design Report (CDR) with final delivery in March 2021. The CDR work is divided in six work packages; Science Case, Accelerator, FEL, Insertion Devices, Beamline and Experimental Station.

## GENERAL LAYOUT

A schematic layout of the SXL is shown in Fig. 1. The 3 GeV linac is followed by the undulator modules (currently 3 m long, with 4.0 cm period). A long drift space, where

photon diagnostics will be placed and the power density allowed to drop until reaching the first mirror, will be followed by the monochromator. The experimental station will also include a laser for pump-probe experiments. Different options for the timing/synchronization system are now under discussion to make sure the best stability can be achieved with very short pulses. The data handling and collection will prove a challenge and is envisaged to be integrated into the existing capabilities and future capacity upgrades of MAX IV laboratory.

## THE SCIENCE CASE

Following a successful workshop in March 2016 where more than 100 Swedish (mostly but not only) users gathered in Stockholm to contribute to the science case [2] for the SXL, a set of representative experiments has been selected in the following categories: AMO, Condensed matter, chemistry and imaging in life science. The AMO experiments will explore processes from charge migration to charge transfer thanks to ultrashort pulses and the possibility to have two pulses with different colors in order to implement pump-probe schemes. For the chemistry applications the main focus is in understanding the dynamics of heterogeneous catalysis and probing transition states in surface reactions, and for these variable polarization is desired. In condensed matter the goal is to create new phases in quantum materials (like strontium titanate) with THz radiation and probe the emergent order with the SXL beam. Also experiments on coherence control in the attosecond frontier are foreseen, and they will require sub-fs pulses, besides the full control of the FEL polarization. Pumping with an HHG (High Harmonic Generation) source will also be beneficial. In Life Science the combination of THz or other pump lasers with the FEL radiation will allow to probe conformational changes in solution for the scattering experiments. Relatively long (50 fs) pulses with two colors will be required together with a split-and-delay line for dynamics between 100 fs and 10 ms.

## LINAC

The SXL will use the 3 GeV S-band linac currently serving the MAX IV 1.5 and 3 GeV storage rings and Short Pulse Facility (SPF). As of today a photo cathode gun and two bunch compressors provide 100 fs long pulses for the

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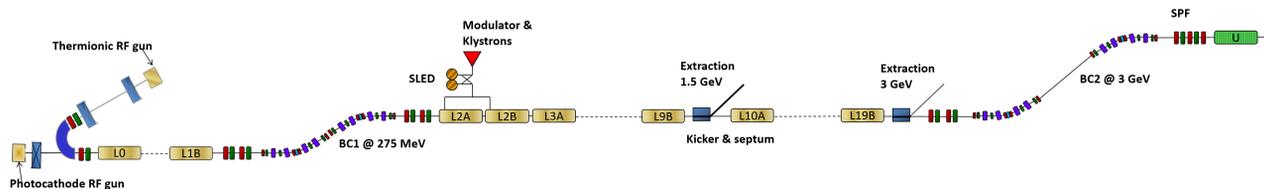


Figure 1: Schematic layout of the SXL at MAX IV (not-to-scale).

SPF with a normalised emittance below  $1 \mu\text{m}$ . The bunch compressors are two achromats placed at 250 and 3 GeV respectively. Together they can in simulations compress the electron pulse to a few fs without the double horn features of chicane compressors. The compressors are also able to passively linearize the longitudinal phase space, removing the need for a higher harmonic cavity. The compressors work with negative R56 and the energy chirp has a higher energy at the head of the pulse. While the final compression is at full energy a remaining energy chirp will be present in the beam. As the chirp is positive it provides some complexity to remove, as standard de-compressors will increase the chirp. An ongoing study is exploring different possibilities, including; reversing the R56 of the bunch compressors by additional optics, over compression and adding a traditional chicane compressors combined with a harmonic cavity and de-chirper.

### THE SXL BASELINE

Given the circumstances of being based on an existing and running linac, at present two main phases are foreseen for the SXL beamline, based on the linac operating with the current energy chirp or with the chirp removed.

Initially a baseline design has been defined using three linac modes. In phase 1 two modes using the chirped beam in a long pulse and a short pulse respectively, and in Phase 2 an un-chirped beam (Tab. 1). These modes were checked for consistency in time-independent SASE simulations and the followed up by time-dependent SASE simulations based on the defined parameter space. This information was then fed to the beamline and experimental stations design.

The simulations are now moving into full Start-to-end simulations of the system and analysis of advanced concepts for the SXL. Additional FEL modes are also added into the portfolio, such as a mode for higher flux, with 200-300 pC bunch.

Table 1: Basic Operation Modes of the MAX IV linac for the SXL

Phase	1	1	2
Linac mode	A	B	
Charge	100 pC	10 pC	100 pC
Bunch length (rms)	16 fs	2 fs	16 fs
Emittance (norm)	$0.5 \mu\text{m}$	$0.25 \mu\text{m}$	$0.5 \mu\text{m}$
Energy chirp	0.5 MeV/m	1 MeV/m	no chirp

### INSERTION DEVICES

The insertion devices for the SXL project will be designed to allow compactness, flexibility and polarisation control. A concept for an APPLE-X type undulator in a very compact frame has been elaborated [3]. The K-value adjustment is done by radial magnetic motion. The tuning range will cover 250-1000 eV ( $K=1.51-3.9$ ). A drawing of the undulator is shown in Fig. 2.

Initially 3 m long undulator sections with 0.75 m intrasections are envisaged, but studies of advanced concepts, such as HB-SASE, may point towards a shortening the undulator sections.

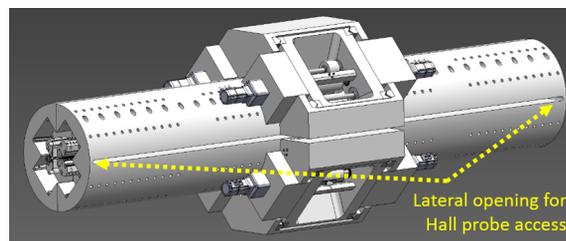


Figure 2: The compact APPLE-X type undulator for the SXL project.

### FEL

The FEL operation modes for SXL should accommodate different requirements from the science case in terms of spectral brightness, synchronization, coherence and power enhancement, very short pulses, two-color and two-pulses.

The current strategy is based on initially operating the SXL in SASE mode, which will cover a large set of requirements in the Science Case, and using the positively chirped electron pulses. This is complemented by linac modes with ultra strong compression, reaching the "few fs pulse" length range. To enhance the photon pulse flux tapering is anticipated. To reduce the bandwidth and increase the wavelength stability, and thus increase the throughput in the monochromator systems, HB-SASE type techniques [4] are being studied if possible to include already before phase 2. This concept incorporates short undulators and multiple chicanes which also open for as-pulse techniques [5]. While seeding most likely will require a non-chirped pulse it is investigated but not defined for the initial phase of the SXL. Alternatively seeding will, in addition to coherence enhancement, also provide improved timing and synchronization, which might be of high user interest. The system will thus be prepared

for external seeding, both ECHO and self-seeding. While an ECHO station [6] preceding the undulator chain also provides hardware for as-pulse generation, the self-seeding chicane is also a tool for two-pulse two-color operation.

How this is supposed to be implemented is shown in Fig. 3.

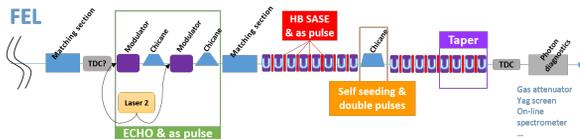


Figure 3: Implementing various FEL modes in the SXL.

### FEL Simulations

The baseline design has been simulated first in time-independent mode using Genesis 1.3 [7] using average parameters from the current linac followed by time dependent simulations allowing us to compile a table with baseline parameters for the FEL performance (Tab. 2) which also guided the second phase with start-to-end simulations. First time-dependent start-to-end simulations have been carried out (Fig. 4) with an electron beam that has been tracked in Astra [8] (for the pre-injector part) and Elegant [9] for the linac and bunch compressors [10]. In the following work focus will be put in enhanced modeling of the pre-injector, tolerances and stability and advanced concepts [11].

Table 2: Baseline FEL Performance in SASE Mode (time-dependent, parameter based, no taper)

Linac mode (Tab. 1)	1A	1B
Power (1/5 nm)	9/22 GW	10/18 GW
Saturation length (1/5 nm)	41/22 m	34/19 m
Pulse energy (1/5 nm)	0.18/0.49 mJ	0.03/0.04 mJ

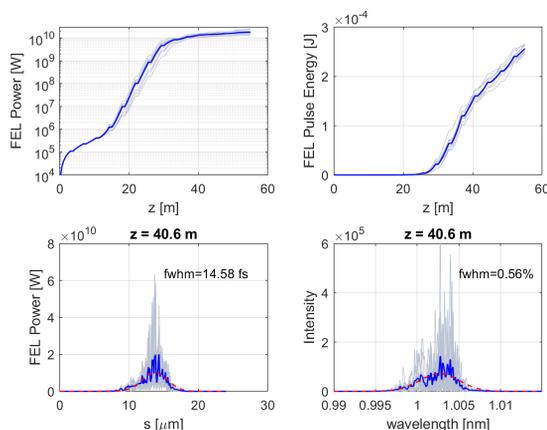


Figure 4: Start-to-end simulation in SASE mode at 1 nm (100 pC, no tapering, multiple shots & average).

## BEAMLINES AND EXPERIMENTAL STATIONS

Two beamlines are foreseen for the first phase of the SXL, a pink beamline and a monochromator beamline. Both beamlines will target the full photon energy range, 250-1000 eV, and share the same undulator line as radiation source. These two beamlines will allow most of the experiments put forward in the user case to be realized. The beamlines will define a substantial part of the length budget of the facility. By reducing the incidence angle on the first element to 0.5 deg this element can be placed closer than 40 m from the source also when operating in high-flux mode using tapering. While the monochromator beamline should operate at resolutions of 5000, the pink beamline will provide a resolution of 100.

The experimental stations should be flexible, allowing for sample changing systems and environment systems, which can also directly be used in complementary studies at the storage ring stations on the MAX IV 3 GeV and 1.5 GeV rings. Sample systems should be transportable within the building between the different photon sources. Currently two instruments are envisaged: one X-ray spectroscopy instrument for surface science, and one low density matter end station with a CCD and spectrometer.

The laser system is assumed to be a commercial solution and will be located near the end-station, it will be used for HHG and for low-harmonics/visible radiation.

Different options are under investigation for the synchronization, in particular the stability of the main drive line for the linac RF will be analysed if it is sufficient to reach sub 10 fs arrival jitter. Another option is exchanging the existing RF synchronisation system for an optical system, currently used in many other FEL facilities.

Initially optical synchronization of about 10 fs is required, while for the second phase 5 fs or better, while to reach 1 fs post-experiment methods will be needed.

## CONCLUSION

In this paper we presented the current status of the SXL project, which is in conceptual design phase. The performance of the linac, the undulator design and the beamline/experimental station concepts are described as well as the foreseen FEL operation modes. A glimpse of the science cases has been also presented. The work for the conceptual design report is supposed to deliver a document by March 2021.

## ACKNOWLEDGEMENTS

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