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PROPOSED FEL SCHEMES AND THEIR PERFORMANCE FOR THE SOFT X-RAY FREE ELECTRON LASER (SXL) AT THE MAX IV LABORATORY

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Abstract

The existing MAX IV 3 GeV linac could drive, with minor improvements, a soft X-ray Free Electron Laser and the aim of the SXL project has been so far to deliver a conceptual design of such a facility in the 1—5 nm wavelength range. The project was initiated by a group of Swedish users of FEL radiation and 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). In this paper we will focus on the baseline FEL performance based on two different accelerator operation modes (medium and short pulses) and give some hints of future developments after the first phase of the project, such as two-pulses/two-colours and HB-SASE.

INTRODUCTION

The Science case for a Swedish Soft X-ray FEL was initially defined during and international workshop held in Stockholm in March 2016 with more than 100 participants [1]. The original idea was to take advantage of the existing 3 GeV linac at the MAX IV laboratory, which was from the conceptual phase thought to be a driver for a Free-electron laser, and "quickly" build a beamline in the Short Pulse Facility (SPF) [2] area. With the support of the Wallenberg foundation, some major universities in Sweden contributed, together with the MAX IV laboratory, to a conceptual design report (CDR) that was ready in March 2021 [3]. The CDR focuses on different aspects of 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.

A new workshop has been held in Stockholm in June 2022 to renew the Science Case.

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OVERVIEW OF THE SXL FEL

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) [4]. 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 [5]. 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 the SXL photon beam.

Table 1: Main SXL Parameters

Wavelength range	1 – 5nm
Photon energy	$\approx 0.25 - 1$ keV
Pulse duration	1 – 30 fs
Repetition rate	100 Hz
Energy per pulse	0.015 – 1.5 mJ
Peak brightness	10^{-33} Ph./s/mm^2/mrad^2/0.1%BW

The Existing Linac

The SXL will be driven by the 3 GeV S-band linac currently injecting into the MAX IV 1.5 and 3 GeV storage rings and the Short Pulse Facility (SPF). As of today, a photo cathode gun and two bunch compressors can provide 100 fs long pulses for the SPF with a normalised emittance below 1 µm. In the MAX IV linac the bunches are compressed using two double-achromat structures (BC1 and BC2), which provide also passive magnetic linearization. A detailed description of the MAX IV linac and its performance can be found elsewhere [6, 7]. The baseline FEL performance is based on two different accelerator operation modes: a high charge-medium pulse (1A) and a low charge-short pulse (1B). Both pulses display a residual energy chirp which it is not typical in other FELs, but at the same time a very high peak current can be achieved, which help the FEL process. More details about beam dynamics, collective effects and technical solutions that will be adopted can be found in the SXL CDR [3]. The layout of the MAX IV linac with the upgrades envisaged for SXL is shown in Fig. 1.

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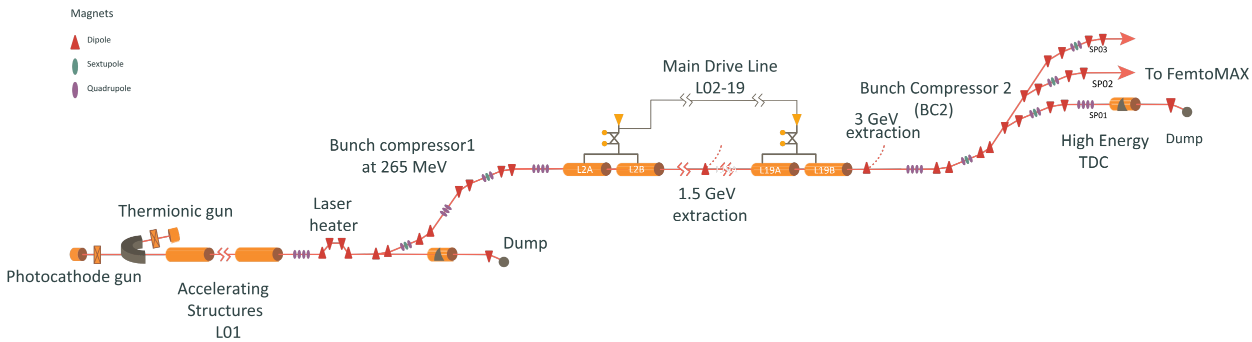

Figure 1: Layout of the MAX IV linac with the foreseen upgrades for SXL.

In particular, in the SP01 line (the lower beamline in the layout) the installation of a high-energy transverse deflecting cavity is currently underway and this device will soon allow a careful characterization of the longitudinal phase space of the electron beam from the linac [8].

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. 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 2.

Figure 2: View of the compact APPLE-X undulator.

In order to verify the feasibility of the design, a full-size prototype will be built in the framework of LEAPS-INNOV.

Table 2: 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	28 mm / 0.55
Magnetic length	2 m

BASIC FEL DESIGN AND ITS PERFORMANCE

The layout of the SXL undulator line consists of two sections of 10 undulators each (see Fig. 3). A big 5 m-long chicane is placed in between the two sections and this device will allow to delay the electron beam for two-pulse/two-colour operations or, if required, for "self-seeding". Full polarization control and tunability in the desired wavelength range will be guaranteed by the 2 m-long APPLE-X undulators (see previous section).

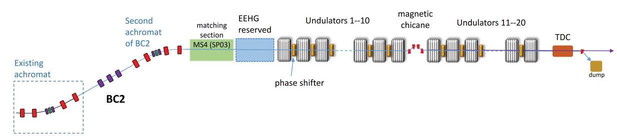

Figure 3: Detail of the FEL undulators line.

A distance of 1 m, is kept in between the undulators (intrasections) in order to to accommodate the required focusing magnets, some diagnostics and other elements needed for the vacuuum system. A FODO lattice is obtained with one quadrupole magnet in each intrasection with alternating focusing and after optimization an average value for the beta functions of 7 m has been chosen for the nominal case. The intra-undulator sections will be also equipped with compact but very strong delay chicanes which will have a threefold usage: as normal phase shifters; as delay lines for HBSASE; as shifting elements to translate the beam to orbits with different offsets.

As it can be seen from Fig. 3, some space is reserved in front of the undulators for accommodating a matching section, a de-chirper and the foreseen EEHG seeding setup.

On the opposite end of the undulator line, a transverse deflecting cavity will be installed to enable a full temporal diagnostics of the electron beam after lasing and to help tuning the performance of the FEL.

Phase 1 - SASE Mode

The phase 1 of SXL will rely on the SASE regime produced by the medium (1A) and the short (1B) electron bunches coming from the linac. In this section we will present the performance at 1 nm of the 1A and 1B pulses respectively in more detail and then refer to a table for the results obtained at 5 nm.

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With the 1A bunch, for the shortest wavelength (1 nm), an active length of 26 meters is sufficient to reach saturation, leaving about 14 m (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 1500 µJ at 5 nm, while the bandwidth remains about the same. The FEL power and the spectrum at 1 nm can be seen in Fig. 4.

For the short bunch (1B) we do not apply tapering to the undulators. The pulse length of the photon beam is slightly under 1 fs and the spectrum displays a relative small bandwidth (see Fig. 5 FEL power and spectrum at 1 nm).

In Table 3 we report a summary of the performance at 1 and 5 nm for the long pulse (1A) with and without tapering and for the short pulse (1B).

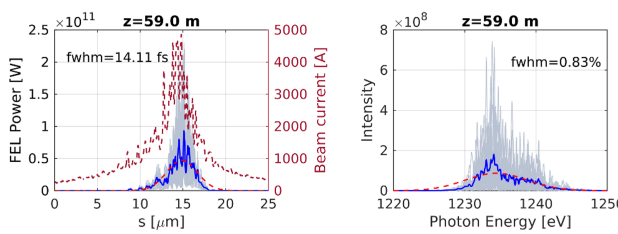

Figure 4: FEL power (left) and spectral intensity (right) obtained with the "long" pulse (1A).

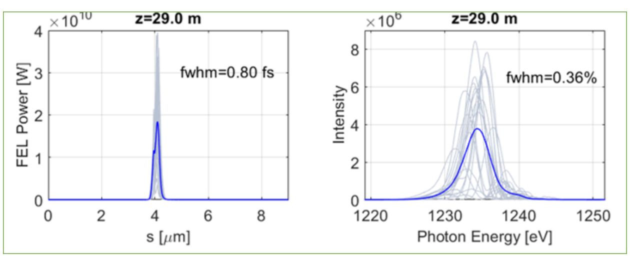

Figure 5: FEL power (left) and spectral intensity (right) obtained with the short pulse (1b).

PHASE 2 - MORE ADVANCED CONCEPTS

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 flattening the long phase space of the electron beam and at the moment we are studying the implementation of conventional de-chirpers combined with overcompression [9]. The de-chirped beam displays a long flat top region in the longitudinal phase space which is compatible with HB-SASE operations [10]. 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 [11]. FEL jitter studies have been performed with start-to-end simulations [12] with results indicating a very stable performance of the linac in terms of arrival time jitter and compression.

Two-Pulses/Two-Colours

Following the user demands, two colour-two pulses will also be a key feature of the SXL. Different concepts have been studied to target various time and colour separations. The most straightforward is the split-undulator scheme [13] which will allow to produce two pulses with different wavelengths and the strong chicane after the tenth undulator will ensure a variable delay between the two pulses spanning between 100 fs and 1 ps. Various wavelength combinations were studied both with the long (1A) and the short (1B) pulses, and simulations show that almost 1 keV could be reached also in this configuration. In Fig. 6 we report two examples of these results, one obtained with the long pulse (535 eV and 930 eV) and one with the short (310 eV and 248 eV).

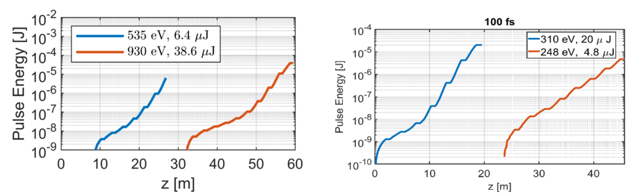

Figure 6: FEL pulse energy for the two colour option with the long bunch (left) and the short bunch (right).

In simulations we observed a variation of the properties of the second colour (pulse energy and bandwidth) depending on the delay applied by the big chicane. This effect has been observed also experimentally at European XFEL [14] (data not shown here).

Longer separation (>1 ps) between the two colours can be obtained accelerating two bunches in different RF buckets [15], with discrete steps of 330 ps. Optical methods (like an optical delay line at the experiment) could be used to make possible the "zero-delay" and the cross-over. Besides, steering the electron beam differently in the two undulator sections will produce photon beams with different pointing and this will help the separation and the manipulation of the two colours at the sample.

HBSASE

In order to get a stable central wavelength and a narrower spectrum, we considered HBSASE as some sort of seeding technique to be applied to the SXL. As it was already mentioned, the residual energy chirp present in the electron pulse at the end of the MAX IV linac cannot be removed by conventional de-chirpers, as it is the opposite. To overcome this problem, we studied the possibily to flip the sign of the chirp by overcompressing the electron pulse and then applying a two-plate wakefield de-chirper. The resulting pulse displays a flat longitudinal phase space with a long enough

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Table 3: Overview of the SXL FEL Performance for the Mildly Compressed Bunch (1A) and the Highly Compressed Bunch (1B)

	1A - standard		**1A - tapering**		**1B**	
	1 nm	5 nm	1 nm	5 nm	1 nm	5 nm
Pulse energy (μJ)	130	220	660	1500	15	20
Peak Power (GW)	14	36	50	56	15	12
Photons per pulse	6.6×10^{11}	5.5×10^{12}	3.3×10^{12}	3.8×10^{13}	7.6×10^{10}	5×10^{11}
Pulse duration (fs) [FWHM]	9.3	5.2	14	26	0.8	1.2
Bandwidth (%) [FWHM]	0.5	0.7	0.8	1.2	0.4	0.8
Brightness (Ph./s/mm^2/mrad^2/0.1%BW)	2.5×10^{33}	1×10^{33}	3.5×10^{33}	1×10^{32}	4×10^{33}	1.5×10^{32}

plateau. This electron beam has been used in HBSASE simulations [9] cross-check the overcompressing method and encouraging results show a narrowing of the spectrum and a good central wavelength stability.

CONCLUSIONS

In this paper we presented the main features of the FEL in the SXL project which has been from the beginning a user-driven initiative to capitalizes on the existing infrastructure to open research opportunities that are currently not possible at any other beamline at MAX IV. In particular we focused on the FEL schemes which will be introduced at different stages, starting with SASE and, thanks to the flexibility of the setup, continuing with two-pulses/two-colours and different "seeding" schemes. In general the design of SXL will provides competitive performance that can enable the experiments proposed in the science case. The SXL will produce very short pulses with very good stability. A wide range of pump options will be present from the begining and will used in combination with two-pulses/two-colours schemes with variable delays. The FEL design is flexible and will allow further development for example with seeding schemes (HBSASE, EEHG, self-seeding). If realized in short term SXL be an internationally competitive facility.

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