THE SOFT X-RAY LASER PROJECT AT MAX IV

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Abstract

A Soft X-ray Laser (SXL) beamline utilising FEL technology is being designed for the Short Pulse Facility (SPF) at the MAX IV Laboratory. A conceptual design study has been started following on the scientific case already prepared in collaboration between several Swedish Universities and driven by a strong (Swedish) user demand.

The baseline goal of the SXL beamline is to generate intense and short pulses in the range 1-5 nm (0.2-1 keV). The system is building on the MAX IV linac system, already today providing 100 fs 3 GeV and pulses compressed to 100 fs for other applications within the SPF. As a special feature we foresee a variety of pump-probe capabilities.

INTRODUCTION

The Short Pulse Facility (SPF) at the MAX IV laboratory is designed to utilize compressed electron pulses directly from the S-band linear accelerator at energies up to 3 GeV. In this facility (fig. 1) there is at the moment one beamline, FemtoMAX, but there are available “slots” for another 2-3 stations or experiments. Ideas for both a hard X-ray free electron laser extension and a station for plasma wake field acceleration [1] have been put forward. The most elaborated idea was put forward by a Swedish user consortium, detailed during a workshop in Stockholm in 2016 [2] gathering more than 100 participants. This is an advanced beamline in the soft X-ray range which will provide coherent pulses at high peak power in the range from 0.2-1 keV. To achieve the necessary requirements the accelerator will drive a free electron laser (FEL), the Soft X-ray Laser (SXL).

The SXL will enable ground breaking scientific discoveries and understanding in many important fields such as atomic and molecular science, chemistry, condensed matter physics, and life science. These opportunities are created by the intense, ultrashort and coherent soft X-ray pulses generated by the SXL together with unique pumping options, detection schemes and imaging possibilities. A specific asset of the soft X-ray spectral region is that it provides access to many important absorption edges (e.g. C, N, O, and 3d transition metals) and thus permits the use of powerful spectroscopic and coherent techniques in a time-resolved manner. In combination with pump pulses covering the full spectral range from THz to soft X-rays, not accessible at any existing FEL, and with potential for attosecond temporal resolution, new exciting pump-probe studies can be performed which addresses several meaningful scientific questions.

Scientifically and technically the SXL will complement the FemtoMAX beamline which can reach far higher photon energies in intense, short, partially coherent pulses.

The SXL project is a collaboration among many research groups in Sweden with experience in both science at FELs and groups with experience of accelerators. Partners come from the MAX IV laboratory, the Stockholm-Uppsala FEL center, Uppsala University, Lund University, Stockholm University and the Royal Institute of Technology. The scientific interest of the SXL project though, spreads over all Swedish universities.

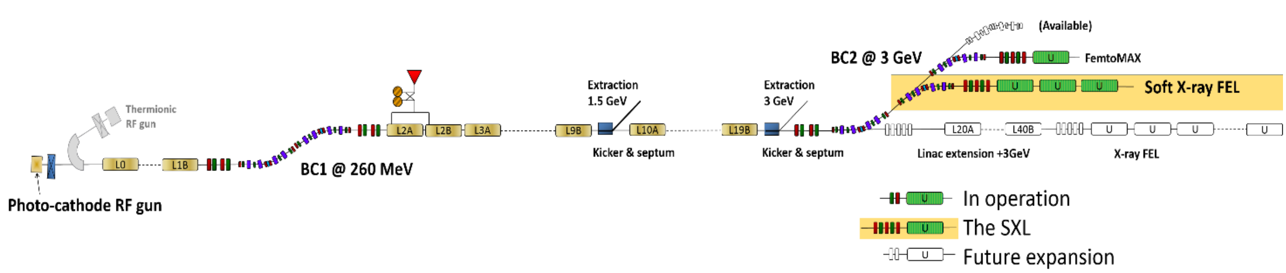

Figure 1: The MAX IV linear accelerator.

A Conceptual Design Study has been initiated and will mainly focus on the design of the FEL itself and the assurance of the performance of the MAX IV linear accelerator as FEL driver. In addition the beamlines and experimental stations will be defined, while the scientific case is basically in place [3]. The conceptual design should be ready after two years and provide the base for an application of funding of the full project. This is adjusted into the overall

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timeplan for expansion of experimental facilities at the MAX IV Laboratory.

The strategy of the MAX IV Laboratory in an even longer perspective also includes an expansion with a hard X-ray FEL based on an extended energy of the linear accelerator. However the funding situation in a near perspective is not believed to be strong enough, and thus the SXL project will provide the first step from which competence and experience towards a full X-ray FEL can be realized beyond 5 years.

THE FREE ELECTRON LASER

The SXL beamline at MAX IV will provide high power pulses, with pulse lengths below 100 fs in the 0.25-1 keV photon energy range. This basic idea has been presented previously [4], but with input from the Swedish user community the focus of what has become the SXL project has been updated.

The most important input on the SXL design is the discussion on seeding. Seeding can provide wavelength and power stability but is not fully available in the actual wavelength range today [5]. The available technology is self-seeding where a shorter FEL ends before saturation and the optical pulse is passed through a monochromator and re-injected onto the electron beam as a seed pulse. This method is still not easy to operate for users and thus the conclusion is to start in SASE mode and when seeding is developed further include this in a second phase.

The scientific questions in the present wavelength range will benefit strongly from a two pulses and two colour scheme. This is regarded as fundamental, and should, if possible, be part of the first phase and fully implemented in a second phase.

Short photon pulses are of interest, but initially most science will satisfy with pulses >10 fs. In a second phase the SXL should approach single fs pulses and possibly into the as-region. Schemes for generating few femtosecond pulses and shorter are currently being developed [6, 7, 8] and can be made available for the SXL.

The SXL should be flexible enough that seeding schemes and ultrashort pulse operation modes can be implemented in a second phase.

Special emphasis should be put on providing a set of multiple pump sources for which the integration and concepts should be developed. While visible and VUV lasers are already available in the FemtoMAX beamline, the implementation of soft X-ray and THz systems has to be addressed. In a first phase both a THz source and a UV-laser are required. Later this should be complemented with soft X-ray HHG lasers and possibly also a THz undulator or even a THz FEL. Pump-probe operation also sets the requirements for timing and synchronization which has to be integrated in the design.

The undulator technology for the SXL is still an open question (see tab. 1). The user input is clear in that full polarization control is necessary. This probably removes the option of utilising only compact short period (below 20 mm) undulators, which would provide the most compact system. Compactness is otherwise a key feature as the SXL is to be fitted within the existing buildings or with a limited extension. As the linac at MAX IV also is used for top-up into the storage rings, it might turn out a feature if the energy could remain unchanged. Thus a rather long period (35-40 mm) undulator could be considered (compare SwissFEL [9]), which would cover the wavelength range in a limited energy span. It is also important to note that the undulators will be an (the) important cost driver.

Table 1: Two Sets of Tentative Parameters for the SXL Based on Different Undulator Concepts (Values given by analytical approximation.)

Undulator type	Planar in-vacuum		APPLE II/III	
Period (mm)	18		36	
Wavelength (nm)	1	5	1	5
Photon energy (keV)	1.24	0.25	1.24	0.25
e-Energy (GeV)	3	1.35	3	2.6
K	2.38	2.38	1.35	3.5
L-saturation (m)	18	11	29	15
Photon power (peak)	some GW			

ε_{norm} (mm mRad)	0.4
$\overline{Beta}$(m)	10
$\hat{I}$ (A)	1400
Q (nC)	100
σ_t(fs)	30
$\Delta E/E$	1e-4

THE MAX IV LINEAR ACCELERATOR

The MAX IV linear accelerator [10] is used for both full-energy injection and top-up to two storage rings, and as a high brightness driver for a Short Pulse Facility (SPF) [11]. The linac was already in the initial plans around year 2000 drawn with the idea that it should be able to handle the high demands of a Free Electron Laser, such as short pulses, high peak current, low emittance and high beam stability (tab. 2).

During spring and early fall of 2016 a pre-study concluded that the MAX IV linac design gives a performance that is within the assumed requirements for SXL. The initial measurements on the linac show no indications for the specifications not being possible to achieve. However, in order to reach the design goals, a couple of developments are foreseen and some upgrades and changes may be needed in areas like gun, diagnostics, laser, optics and bunch compressors. Many of these developments are already expected and prepared for, and none of them would be impossible to achieve within the current MAX IV linac design.

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Table 2: MAX IV Linac Parameters

Energy	3 GeV
Energy spread	<0.05% + chirp
RF Frequency	3 GHz
Rep. rate	1-100 Hz
Bunch length	10-500 fs
Charge per bunch	20-200 pC
Normalised emittance	<1 μm

INFRASTRUCTURE

A compact solution may fit into the SPF building. There are two main alternatives for its placement. The FemtoMAX beamline already occupies the second branchline position and an easy solution is to place the SXL at the adjacent first branchline (fig. 2). This would require the smallest adaptions of the building but on the other hand it allows only for a short SXL system with a basic SASE FEL operation using planar undulators. A second option is to put the SXL in the tunnel called the "future klystron gallery". This provides a longer available length for the undulators and more space for the experimental stations, and thus more flexibility. Even more flexible alternatives are created by extending the SPF building.

The space needed for the SXL will be investigated during the design study.

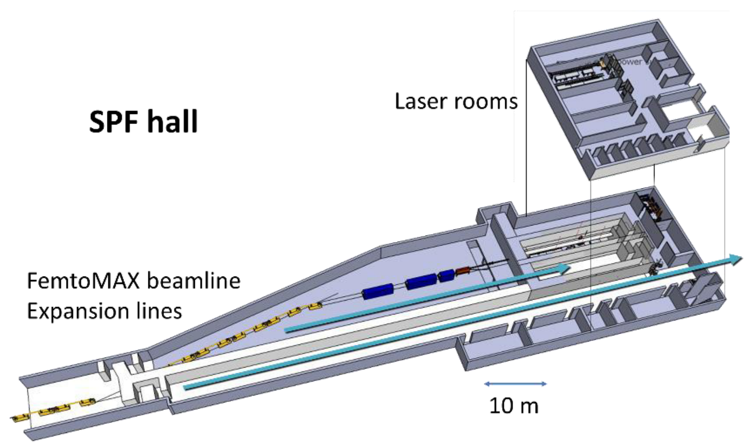

Figure 2: The existing SPF hall, the installed second bunch compressor and the FemtoMAX beamline. Blue arrows indicate tentative locations of the SXL.

SUMMARY

A Soft X-ray Laser beamline for the MAX IV Laboratory has been proposed by the Swedish user community. The SXL will be a flexible source in the energy range 0.25 to 1 keV with unique capabilities for pump-probe experiments and proper detection schemes. We anticipate that it will be a powerful tool for time-resolved studies in chemistry, condensed matter physics, atomic and molecular physics and life sciences.

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