# TOWARDS AN X-RAY FEL AT THE MAX IV LABORATORY

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*Abstract*

The design of the 3 GeV linac for the MAX IV facility was done to provide the ability to host a future FEL in the hard X-ray as well as in the soft X-ray range. The linear accelerator, with its two bunch compressors, is now under commissioning. Through the years increasing details for the actual FEL have been discussed and presented. In parallel a steering group for the science case for a Swedish FEL has worked and engaged a large number of Swedish user groups. These two paths are now converging into a joint project to develop the concept of an FEL at MAX IV.

We will report on the paths to FEL performance based on the 3 GeV injector, FEL design considerations, the scientific preparation of the project, the linac commissioning and the strategy and priorities.

## INTRODUCTION

The MAX IV Laboratory is in a strong phase of development with the completely new MAX IV facility which includes two ultra low emittance storage rings (3 and 1.5 GeV) [1] (Fig. 1). These rings are to be injected from a full energy (3 GeV) linac. The linac will from the start also drive the Short Pulse Facility (SPF) with the FemtoMAX beamline [2] for experiments using short (<100 fs) incoherent X-ray pulses. Currently the linac system is completely installed and under commissioning while the storage ring building is being finalized and magnet delivery has commenced.

From the very start of the MAX IV design around year 2000, it was envisaged that the future development would most likely be in the field of Free Electron Lasers. Thus the facility is prepared to be expanded into an X-ray FEL.

In the strategy of the MAX IV laboratory for the period 2013-2026 the two main goals after completing the MAX IV storage rings are a) the build-up of all 25 experimental stations at the storage rings and b) a FEL. Thus the work has been initialized both on the scientific applications of a FEL and the design of such a source. The first assumed opportunity to apply for funding is after the inauguration of the MAX IV facility (June 21st, 2016).

## A FEL AT THE MAX IV LABORATORY

The design of a FEL at the MAX IV Laboratory has so far been driven by accelerator considerations. To realize the project the input from the scientific community in Sweden is being collected, leading to a science case for a FEL in Sweden (see below).

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Figure 1: The MAX IV Facility in June 2014 with the Area for FEL Expansion to the Left. (photo P. Nordeng)

The 3 GeV linac at the MAX IV will be the base for a FEL project. It is in its base line design equipped with a photo cathode RF-gun [3], emittance compensating injection and two bunch compressors [4]. The performance is more or less on the level of a soft FEL driver, while expansion towards a hard X-ray FEL is well prepared. We foresee an expansion of the linac by approximately 3 GeV, total 6 GeV, following the second bunch compressor to reach a photon energy of about 9 keV (1.3 Å). The relatively low final electron energy indicates a FEL design with a low normalized emittance which is basically achieved by low charge, < 100 pC, operation.

### *General Layout*

The general layout of the proposed facility is found in Fig. 2, where the necessary expansion is marked by the yellow field. Two FELs share the photon energy range 1.2-9 keV (1.3-10Å) and 0.25-1.2 keV (10-50 Å) respectively. Table 1 summarizes the "Start-of-design" parameters for the FEL which represent a picture of the possible machine performance and a first match to the user requirements. We believe that the final design will come close to these performances but a full design analysis is not done yet, and we expect additional user input.

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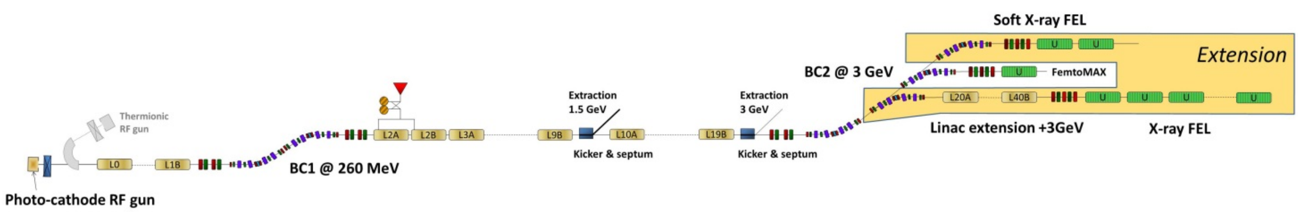


Figure 2: Overview of the MAX IV linac and the possible FEL. (White background: constructed and under commissioning. Yellow background: FEL extension.)

### *Hard X-ray FEL*

The most demanding branch line for the MAX FEL will be the one reaching 9 keV/1.3Å. With an electron energy around 6 GeV meeting the emittance requirements means retaining a low normalized emittance. This can be done by reducing the accelerated charge. To keep the gain length short the peak current has to be high. Meeting the user requirement of $10^{12}$ photons/pulse makes the design demanding and tapering is considered. Simulations of the injector [5] show that the peak current can be reached and combining proper seeding with tapering of the undulators we believe to meet the requirements.

The hard X-ray FEL will benefit from seeding based on the HXRSS, crystal based self-seeding, as operated at the LCLS [6] and SACLA [7]. We foresee difficulties in providing seeding in the complete photon energy range, especially between roughly 1 and 2.5 keV.

The undulators should reach 16 mm period and a K value between 1.5 and 2.1. An initial choice is in-vacuum devices, which are already under construction for the FemtoMAX beamline at MAX IV. As the operating gap has to be reduced below 5 mm in certain energy ranges, we will closely investigate the wake field effects, and thus also look for alternative insertion devices, such as the super conducting undulator technology developed for LCLS-II [8].

### *Soft X-ray FEL*

A soft X-ray FEL can be built as a branch line in parallel to the linac extension. The maximum energy of the existing injector is 3 GeV which is more than adequate. A further consideration is the position of the second bunch compressor, which in this case is at full energy. Other concepts will be studied, such as adding a traditional chicane compressor at an earlier point in the lattice.

The undulators for the soft X-ray system are more relaxed with a 22.5 mm period and K=2.5. This can be achieved by in-vacuum devices at larger gaps, which simplifies the design. Here helical devices will be needed for the final radiation section.

There is a user demand for seeding and we believe that soft X-ray self seeding using a monochromator [9] will cover the upper part of the energy range, while laser seeding (HHG laser source or EEHG) could prove beneficial in the lower energy range, as well as helping time stamp/synchronization.

### *Simulations and Considerations*

Modelling of the complete system is now being set-up and as first data from the pre-injector commissioning is coming in, this will be added to the model.

**Seeding** will be included into the modelling, but the tools for the different methods (HXRSS, SXRSS, HHG) are being developed [10].

**Tapering** is studied [11] to be able to reach to photon flux requirements. A modified algorithm is promising but still the length requirement is significant and would be a cost driver.

**Wake fields** and CSR effects act differently on the beam as the double achromat bunch compressors [4] operate on a different RF slope compared to chicane compressors. With low charge operation the compression needs to be hard to reach peak current able to drive the hard X-ray FEL, which further complicates the design. To this the effect of low gap in-vacuum undulators has to be added.

**Injector tests** have already started on the photo cathode gun in the gun test stand and with the first electrons in the pre-injector. As the system is commissioned data will be extracted and the system tuned to find optimum operating conditions and issues that need improvement for FEL operation up to 9 keV.

A key investigation is to explore the longitudinal phase space to assure that the peak current and energy spread can be reached while controlling the emittance growth. The MAX IV linac lacks this kind of diagnostics and thus a transverse deflecting system will be investigated.

## THE MAX IV INJECTOR

### *Linac, Guns and BC*

The pre-injector is built around two RF guns, one thermionic for storage ring injection and on one photo cathode for short pulse-low emittance operation. The thermionic gun [12] is similar to the guns developed at MAX-lab for injection of MAX I-III [13] and also operated as photo cathode gun for the MAX-lab FEL test facility [14]. The photo cathode gun is of a similar type as the system for Fermi@ELETTRA [15].

The linac is an S-band system (3 GHz) driven in pairs with one klystron and a SLED system per two structures. The operating energy is 3 GeV with a maximum energy of 3.5-3.7 GeV. The maximum repetition rate is 100 Hz, though in principle higher repetition rates can be achieved by short circuiting the SLED system, shortening the RF pulse and thus reducing the final energy. The linac will inject the two storage rings in top-up mode which is assumed to require short (≈ second) interruptions every 2-5 minutes. With the double RF-gun system and the ability to change RF power and phase pulse-by-pulse both compression and final energy can be tuned separately for the two modes. A small limitation is that the optics has to be retained, but simulations show that this is feasible especially as the second bunch compressor is positioned after the extraction to the rings. Combining higher rep rates (>100 Hz) for FEL and top-up still needs to be investigated. Low field X-band structures could here become a solution.

The two bunch compressors (at 0.25 and 3 GeV) are double achromats with fixed first order momentum compaction but tuneable second order momentum compaction. Thus they can also passively linearize the longitudinal phase space. The compression is adjusted by the preceding linac phase.

### *FemtoMAX and SPF*

The first station at the MAX IV facility is the FemtoMAX beamline in the Short Pulse Facility (SPF). The SPF will take compressed (<100 fs) electron pulses directly from the linac. The FemtoMAX will utilise incoherent undulator radiation based on these pulses to cover the range 1-8 keV with pulses of up to $10^7$ photons/pulse. This station will not only be very special on the MAX IV, but also many of the techniques and operation modes for a FEL will be developed and tested here.

### *Commissioning of the Linac*

The complete linac system has been installed during 2013-2014 and is now under commissioning. The two electron guns have previously been operated in a gun test stand and the gun laser system has been tested at the FEL test-facility at MAX-lab. First electrons have now been accelerated through the pre-injector on-site and the main linac is under RF power.

## SWEDISH FEL SCIENCE

To date, Sweden has been very well represented at current FEL facilities.

Swedish groups made notable contributions to the science cases at LCLS and the European XFEL, and were also among the first users of FLASH and LCLS.

In addition, the Swedish user community has been very successful in obtaining beamtime at LCLS, and there are several Swedish in-kind contributions to both the preparatory and construction phases for the European XFEL.

In 2012 the work on a science case for a Swedish FEL was initiated by the formation of a steering committee at a meeting at the Swedish research council (VR) between representatives from the main Swedish Universities [16]. Since then, several workshops have been organized to identify future possibilities and to collect input from the Swedish user community. To date, more than 40 proposals from Swedish scientists have been collected, making up a preliminary science case ranging from fundamental studies of femtosecond dynamics and non-linear spectroscopy of atoms and molecules, via clusters and nanosystems, to investigations of biomolecular systems and artificial photosynthesis.

The work with the Swedish science case is now continuing with the extraction of required FEL parameters from the received proposals, the identification and conceptual design of the needed end-stations, as well as the integration of these requirements into the FEL design.

Table2: FEL Parameters ("Start-of-design") Yellow Fields Met in the Existing Linac Design

| | FEL 1 | FEL 2 |
|---|---|---|
| **Accelerator** | | |
| Energy | ≈ 6 GeV | 2-3 GeV |
| Rep rate | 100 Hz | 100 Hz |
| Linac | S-band | S-band |
| Bunch compressors | 0.250 & 3 GeV | 0.25 GeV |
| | | |
| **Electron beam** | | |
| Peak current | 2-3 kA | |
| Charge | 20-150 pC | |
| Beta function | 7.5 m | |
| Emittance, norm | 0.25-0.4 mmRad | |
| Pulse length | 10 - 100 fs | 10 - 100 fs |
| | | |
| **FEL undulator** | | |
| Undulator period | 16 mm | 22.5 |
| Undulator K | 1.5-2.1 | 1.5-2.5 |
| Type | In-vac | (In-vac) |
| | | |
| **FEL performance** | | |
| Wavelength | 1.3-10 Å | 10-50 Å |
| Energy | 1.2-9 keV | 0.2-1.2 keV |
| Flux | $10^{12}$ ph/pulse | |

## CONCLUSION/SUMMARY

For many years Swedish scientists have expressed need for an FEL. The recent work combining a scientific case with the appropriate accelerator design is pushing such a Swedish FEL closer to becoming a real option. With the MAX IV linac a firm platform to start an FEL project is

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now at hand. It is clear that a multi station FEL in both the hard and soft X-ray is feasible.

Funding for studying the design, analysing the MAX IV injector in FEL mode and continued focusing of the scientific case is now being sought. The aim is to have a complete design ready by the time of the MAX IV storage rings start-up (June 2016), after which funding for the complete project can be sought.

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