THE MAX IV INJECTOR AS A SOFT X-RAY FEL DRIVER*

N. Cutic, M. Eriksson, F. Lindau, S. Thorin, S. Werin, MAX-lab, Lund University, Sweden.

Abstract

The MAX IV facility [1] consisting of a 3 GeV ultra low emittance storage ring and a full energy linac injector is funded and under construction. The injector linac [2] is designed to not only perform storage ring injection but also drive a Short Pulse Facility generating spontaneous incoherent photon pulses in the keV range with pulse lengths below 100 fs in the first phase of the project.

We here sketch a possible future development of the facility.

This source will, with minor modifications, be able to drive a Free Electron Laser down into the soft X-ray region and with an extended energy a full X-ray FEL at 1-2 Å.

The key feature of the system is the availability of a 3-3.5 GeV linac, a low emittance photo cathode RF-gun and two bunch compressors including sextupoles for linearization. By extracting pulses of 0.1-0.2 nC charge, normalized emittances below 1 mm mRad and peak currents above 3 kA can be achieved. Such pulses are very well suited for a FEL facility.

INTRODUCTION

The MAX IV injector is "prepared" to operate as a driver for a Free Electron Laser already from the first planning phase. In the initial phase this will be utilized in the Short Pulse Facility (SPF) to generate 100 fs incoherent spontaneous undulator radiation pulses in the keV photon energy range.

Table 1: The Basic Electron Beam Parameters of the MAX IV injector.

Charge	100 pC
Emittance, normalized	<1 mm mRad
Energy	3.5 GeV
Energy spread, relative	<1e-4 RMS
Repetition rate	100 Hz

The trends regarding FELs can be noted as:

- Low emittance is the key. It is favorable to reduce charge to decrease the emittance. This also opens up for lower electron beam energies to reach the same photon energy.
- Seeding. Most FEL designs regard stability and coherence as an issue and are considering seeding of different kinds at wavelengths above 1 nm.

The MAX IV FEL ideas are regarded as Phase 2 of the project. A few sample roads have been studied (figure 2) and are discussed below.

A more standard FEL in the nm wavelength range is possible to build with modest investments and in principle possible to fit into the available space of the SPF hall, with one experimental station. The scientific case in this range is similar to FERMI@Elettra [3] with a focus on ultra fast coherent imaging, nano spectroscopy, cluster and femtosecond dynamics.

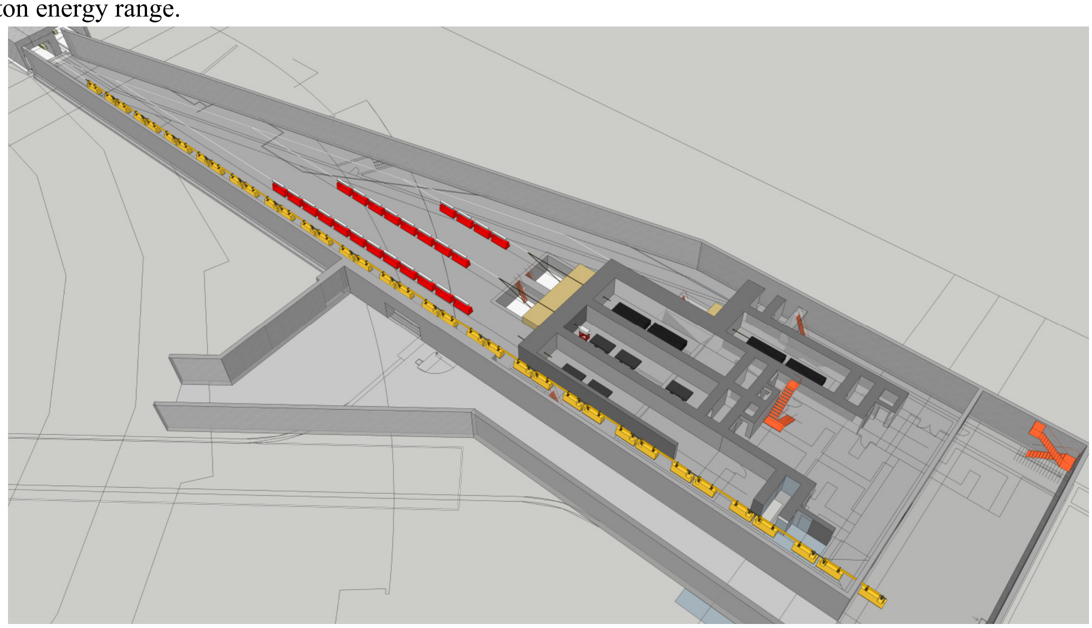

Figure 1: Layout of the MAX IV SPFbuilding with the sketched examples of a 20-30 m FEL undulator on the second branch and a 1.8-2 GeVS-band linac on the first branch.

*This work has been partially supported by the EU Commission in the sixth framework program, Contract no. MEST-CT-2005-020356 and the Swedish Research Council

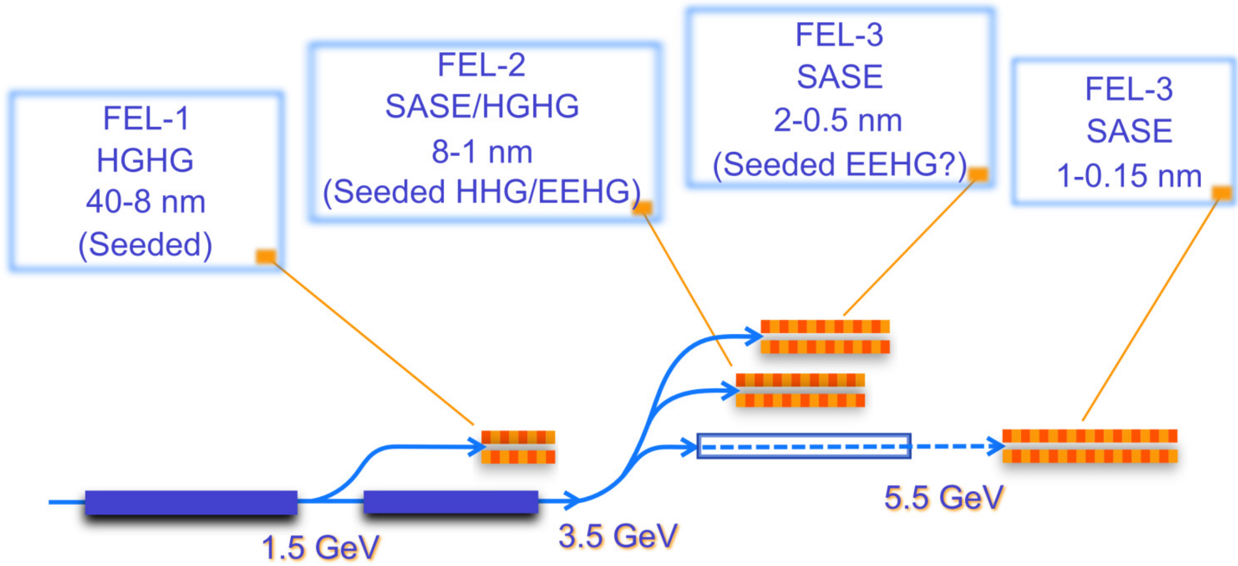

Figure 2: The four possible basic paths for a FEL on MAX IV.

Extending the wavelength range down below 1 nm opens the requirement of either shorter period undulators (~20 mm) or increasing the electron energy. The undulators will need to have a length of 20-30 m and the SPF hall is on the limit of being enough. Increasing the electron energy for this operating range is probably not possible to defend regarding costs-to-performance. (see branch 2 in figure 1).

The basic parameters of the MAX IV injector are of such a quality that an FEL operating at a few Ångströms is possible with increased electron energy. By extending the linac with 2 GeV the final energy will be 5.5 GeV (see branch 1 in figure 1). This source will have a similar wavelength range as the XFEL [4] and the Swiss FEL at PSI [5]. In addition to the extra linac, undulators of 40 m magnetic length (with a 20 mm period) are needed. Also the beam dump and the beamline optics require more space. An extension could be achieved with the linac type of the initial MAX IV injector, S-band structure. Twenty sections of 6 m (120 m in total) would thus be needed. A more preferred choice would be to install C-band structures, which would reduce the necessary length. We are in any case talking about an installation of a few hundred meters (including the SPF building). This is a major investment and is clearly, at earliest, a phase 2 of the MAX IV project.

FOUR EXAMPLES OF FREE ELECTRON LASERS ON THE MAX IV

The MAX IV injector will, as mentioned, be well suited to drive a FEL in the wavelength range down into the Ångström region, but in the initial design not to the "few Ångström" region. To reach 1-2 Å a higher electron energy is necessary.

Below are four sketch-designs for FELs on the MAX IV (see also figure 2). They address four different wavelength ranges, four degrees of complexity and different approaches to seeding/stability and also possible project times. All parameters are to be considered as tentative especially regarding wavelength ranges, which can be combined differently.

All FELs considered here provide a saturating power around 10 GW in the fundamental and losing roughly one order of magnitude per jump to the subsequent odd harmonic (1-to-3, 3-to-5…).

Table 2: FEL-1 Parameters for Seeded Mode (example)

Seeding wavelength	37.5	Nm
Seeding energy	100	pJ
Seeding pulse length	30	fs
Electron energy	1500	MeV
Undulator period	5	cm
K	5	
I peak	3400	A
Energy spread	0.02	%
Emittance (norm)	0.4	mm mRad

FEL-1: Seeded VUV FEL

This FEL utilizes undulators with ~5 cm period and would cover a spectral range 8-40 nm, similar to FLASH or FERMI. This is to regard as the most straightforward system to implement. It could be operated in the SASE mode, but would probably benefit from being seeded. Seeding at these wavelengths can be done by HHG (High Harmonic Generation) [6], a high power laser is focused into a gas jet and harmonics are produced with a plateau in the emission for harmonics 10-30 which corresponds to the range 100-30 nm. A collaboration within the Lund

Laser Center is already in place for this kind of laser seeding.

The FEL will also emit on harmonics of the seed. This can be enhanced by a different arrangement of the undulators. The basic parameters of this system are given in table 1 and a simulation of the performance, done in PERSEO [7] in figure 3.

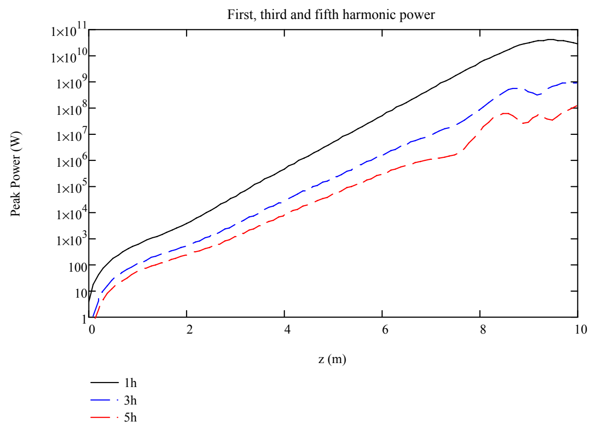

Figure 3: FEL power in FEL-1 along the undulator (fundamental and harmonic 3 &5) (calculated in PERSEO)

FEL-2: VUV-XUV FEL

The FEL-2 shows a concept where the complete linac energy is utilised, but the undulators still have several cm period (table 3 and figure 4). The example in the table operates with the first harmonic at 5.5 nm, which is currently beyond the wavelength of laser seeding (using HHG). To achieve stability by seeding other concepts are necessary to adapt. Either seed at slightly longer wavelength and optimize emission to harmonics, cascading of HGHG stages [8] or, if possible, Echo Enhanced Harmonic Generation (EEHG) [9].

Table 3: FEL-2 Parameters in SASE Mode (example).

First harmonic	5.5	nm
Electron energy	3500	MeV
Undulator period	6	cm
K	4	
I peak	3400	A
Energy spread	0.02	%
Emittance (norm)	0.4	mm mRad

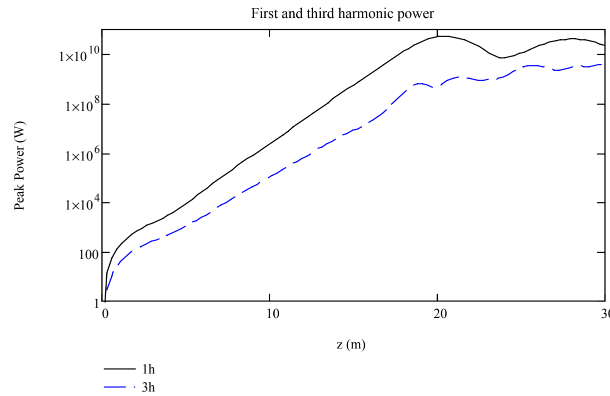

Figure 4: FEL power in FEL-2 along the undulator (calculated in PERSEO)

FEL-3: Soft X-ray FEL

This example is the most aggressive design with the original electron energy of the MAX IV injector. The undulators are more technically advanced with 20 mm period and 30 m in length. In SASE mode it is possible to reach a few Ångströms in wavelength, but the gain is significantly weaker and the undulators are longer. In this range no immediate solution for seeding is available, though EEHG might be a way to follow. (see table 4 and figure 5)

Table 4: FEL-3 Parameters in SASE Mode (example).

First harmonic	0.43	nm
Electron energy	3500	MeV
Undulator period	2	cm
K	1.5	
I peak	3400	A
Energy spread	0.02	%
Emittance (norm)	0.4	mm mRad

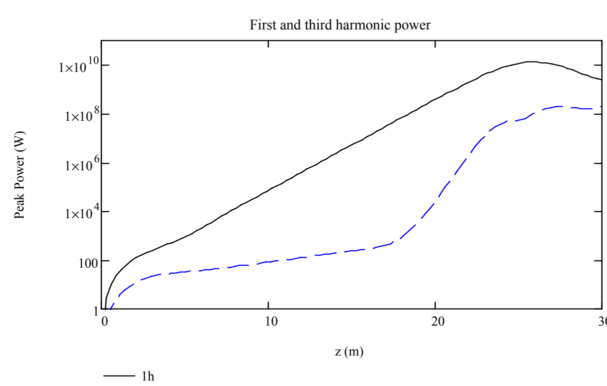

Figure 5: FEL power in FEL-3 along the undulator (calculated in PERSEO).

FEL-4: Soft X-ray FEL

In what can be seen as the ultimate design for the MAX IV injector the linac is extended by 2 GeV up to 5.5 GeV (see branch 1 in figure 1 and figure 2) which provides a state of the art FEL driver, well comparable to the XFELs at PSI and Spring-8. Basic simulations show that it is possible to reach 1-2 Ångström (figure 6), but it should be remembered that this is probably an ultimate performance, and more evaluations have to be done to assure the feasibility. In the power simulation below the third harmonic has a pronounced step wise growth, which could be interpreted as sensitivity to electron beam parameters.

The undulator system is demanding (20 mm period, with 40-50 m of undulator structure). The linac will need an additional 120 m (20 sections of 6 m, S-band), driven by 10 klystrons and SLED systems. Preferrably a C-band system should be used to make the system more compact. The beam distribution systems and the beam dump will also require longer space together with the beamline following the FEL. In total the system will cover a few hundred meters, including the SPF hall.

Seeding is not seen as an option in this range at the moment.

Table 5: FEL-4 Parameters

First harmonic	0.176	nm
Electron energy	5500	MeV
Undulator period	2	cm
K	1.5	
I peak	3400	A
Energy spread	0.02	%
Emittance (norm)	0.4	mm mRad

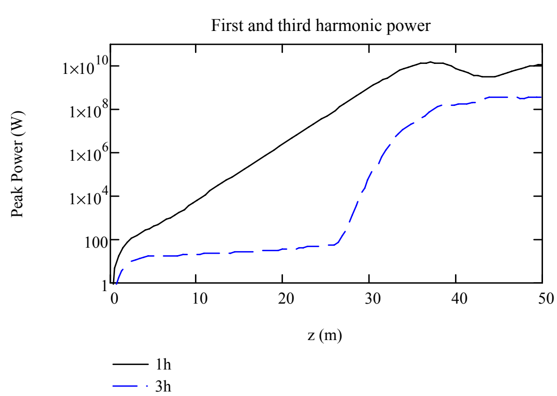

Figure 6: FEL power in FEL-4 along the undulator (calculated in PERSEO)

SUMMARY

The conclusion is that it is possible to immediately complement or replace part of the SPF with a FEL operating in the 100-10 nm wavelength (12-120 eV) range. The additional cost would basically consist of 10 m of undulators and electron beam diagnostics for a SASE FEL. A seeded HGHG FEL, which is a more likely choice in this range, would add a seeding system, synchronization and chicane.

A more interesting scenario, both from a user and accelerator perspective, is to approach an FEL design aiming at 1 nm range (FEL-2 or FEL-3 below). Both scenarios are on the limit to fit into the SPF hall. The undulators are longer and the development effort bigger. If this is Phase 2 of the MAX IV project it is timely to start soon, to be able to take a decision close to the time of start of operation in MAX IV phase 1.

The last option of an extension of the linac up to 5.5 GeV and a 1-2 Å FEL is an aggressive approach for which the budget is significant (money, personnel effort, building and land). On the other hand the scientific case for this kind of FEL is most likely stronger. If this is chosen as an option it is possible to aim for a project start in 4 years (in time with the MAX IV phase 1 start-up).

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