EXTENSION OF THE MAX IV LINAC FOR A FREE ELECTRON LASER IN THE X-RAY REGION

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Abstract

The 3 GeV linac for the MAX IV laboratory is currently under construction in Lund (Sweden). As full energy injector for the MAX IV rings, a thermionic gun will be used to create electrons. However a photocathode gun planned for a short pulse facility will deliver small emittance and ultra-short electron bunches that will be suitable to also drive a Free-Electron Laser. Moreover extending the linac energy with 1 or 2 GeV will give the opportunity to get closer to 1 Å radiation with much more flexibility and better performances. Given these opportunities at the MAX IV laboratory, a free electron laser is envisaged in the long term perspective of the facility. In this study we investigate the case of a 5 GeV machine which can produce radiation in the X-ray region. The FEL design will benefit from the implementation of self-seeding, to enhance stability of the central wavelength and spectral bandwidth. Tapering along variable gap undulators will help to extract the maximum photon flux and increase the brilliance of the source. Among others, this kind of machine would be suitable for time resolved experiments and imaging.

INTRODUCTION AND BACKGROUND

Nowadays there are only few operational Free Electron Lasers (FELs) around the world and the user community needs much more beamtime than can be provided. The MAX IV laboratory is building a synchrotron facility in Lund (Sweden) [1] where the main injector is a 3 GeV linear accelerator, equipped with both a thermionic gun and a photocathode electron gun and two self-linearizing bunch compressors. The role of such a linac in the MAX IV project is as injector for the two rings and also as driver for a short pulse facility (SPF) [2]. Since the combination of the photocathode gun with the linac can provide a beam with relatively small emittance, the natural extension of this project is to include a Free Electron Laser. Given the demands from the scientific community, we have assumed that the most useful wavelength range would be in the Ångstrom region. For this project an extension of the linac energy is envisaged as well as a careful tweak of the gun and other linac components. Of course one could directly make use of the 3 GeV beam and build a much smaller and less performing FEL. The two ideas have been presented at the Scientific Advisory Committee of the MAX IV laboratory and they strongly advised to build a “long” FEL instead of a “quick” FEL. In the strategic plan for MAX IV laboratory it is now foreseen an X ray FEL based on the linac. A sketch of the current MAX IV linac with the layout of the extension for the FEL is shown in Fig. 1.

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THE ELECTRON GUN

The injector to be used for the MAX IV FEL is based on the system currently being built for the MAX IV linac [1]. This is a photo cathode RF gun system with an S-band linac accelerating up to 100 MeV. From this point the beam will be carried by two more linac sections up to 250 MeV where the first bunch compressor is located (see below). The simulations of the linac and FEL system in this work are based on the same injector pulses as defined for the Short Pulse Facility (SPF) [2] of the MAX IV project. The SPF is not a FEL and thus not very sensitive to emittance. The design anyway shows a normalized emittance below 0.5 mm mRad for a pulse of 7 ps length and 100 pC charge [3]. This is basically enough also to drive a FEL, but not completely optimized. The simulations have been revisited and it can be shown that the system perform well at even lower emittances. In addition the linac model has been changed to comply with the ramped field of the TW structures used in the MAX IV linac. The field has been approximated to a linearly ramped field, which is closer to reality. The consequence is mainly that the initial cells in the linac have a significantly lower field than in the even-linear case. This influences mainly the focusing, but also has consequences for housing pulses with strong space charge [4] which is still to be fully investigated. Optimization using the code HOMDYN [4] indicates that a lower emittance would be possible and simulations in ASTRA [5] confirms the result (Fig 2). By including the revised linac model, reducing the charge from 100 to 75 pC and re-optimizing the gun-to-linac distance, solenoid compensation and the RF phase a 40 % reduction of the emittance can be obtained. This shows the potential of the MAX IV injector system. From Fig. 2 it is also clearly seen the reduced focusing strength of the ramped linac. Further optimizations will be done to match a full start-to-end simulation.

LINAC EXTENSION

The MAX IV linac has been designed to be flexible enough for handling both injection and top-up for the storage rings, and to produce high brightness pulses for a Short Pulse Facility (SPF). The SPF uses the 3 GeV high brightness beam to produce short spontaneous X-ray pulses. The linac is also fully prepared to handle the high demands for an FEL driver. An addition of 26 accelerating structures of same type as in the main linac will allow the beam to reach

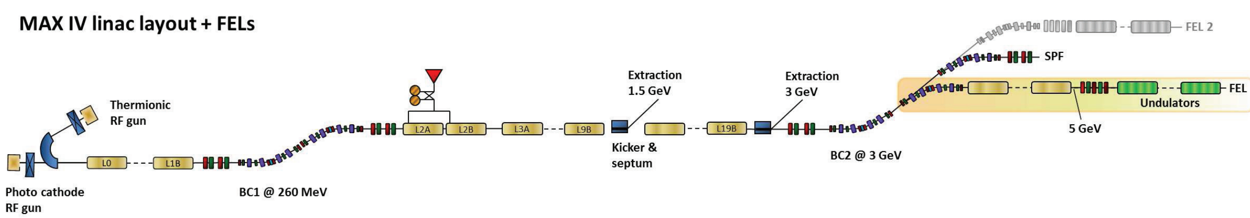

Figure 1: Layout of the MAX IV linac with the extension to 5 GeV and the FEL undulators.

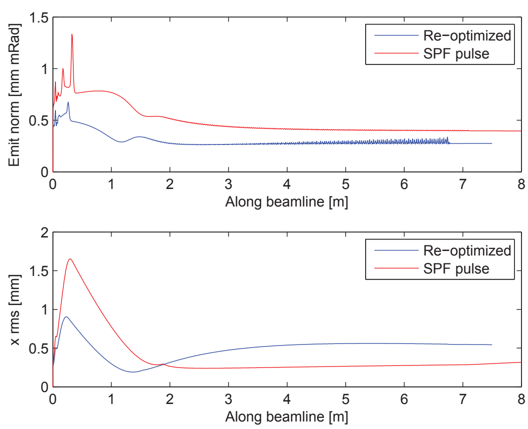

Figure 2: The emittance (top) and the beam size (below) for the SPF optimization (red) and the low emittance, ramped linac field case (blue).

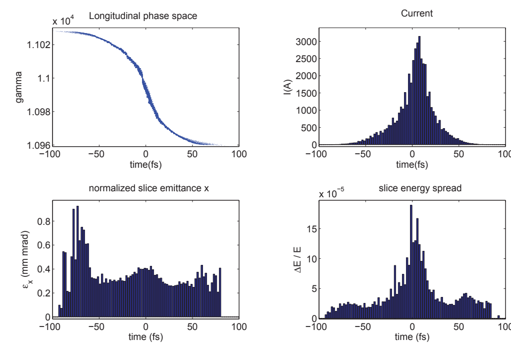

Figure 3: Longitudinal phase space (upper-left), current (upper-right), normalized emittance (lower-left) and energy spread (lower-right) of 100k particles tracked through the extended linac.

an energy of about 5 GeV at the entrance of the FEL undulator section. The second bunch compressor in the MAX IV linac is located at 3 GeV, and is used both for compression and as a beam spreader (see Fig. 1). The FEL extension would follow right after the first bunch compressor exit line. The magnetic double achromats used as bunch compressors in the MAX IV injector has a positive R56 unlike the commonly used magnetic chicane which has a negative R56. The electrons are therefore accelerated on the falling slope of the RF voltage. The linac uses the natural non linearity of the achromats together with a weak sextupole in the center of the achromat to linearize longitudinal phase space [6]. Particle tracking simulation throughout the entire linac, including the extension, was performed with elegant [7]. At compression around 30 fs FWHM and with a beam peak current of 3 kA one can preserve the slice emittance at 0.4 mm mrad and keep the slice energy spread reasonably low at 2×10^{-4}, see fig. 3. Optimization of the linac for the reduced emittance case in Fig. 2 has not yet been done.

The effect from the transverse wakefields has been evaluated [8] to ensure that the linac satisfies the emittance requirement which is a crucial condition for an FEL driver. In the study, it was found that these wakefields exhibit a negligible effect on the beam quality. Moreover, in an ongoing project [9] we investigate how the longitudinal wakefields will influence the beam in the MAX IV linac compression scheme.

Table 1: Electron beam parameters at the beginning of the undulator section.

Energy	5 GeV
Bunch length	30 fs
Normalized (hor.) emittance	0.4 mm mrad
Relative energy spread	2×10^{-4}
Peak current	3 kA

FEL DESIGN

Given the electron beam parameters from the extended linac (see Table 1), we chose to start with simulation of an FEL based on Self Amplified Spontaneous Emission (SASE). The undulator strength should be quite big, in order to ensure emission in the Ångstrom region. With the current technology, this can be achieved with in-vacuum permanent magnet undulators with relatively short period (18 mm). The selected length for each undulator section is 3 m and the distance between each section is about 1 m. In each intra-section two quadrupoles are arranged as a doublet are assuring to limit the divergence of the beam. Figure 4 shows the first preliminary results from time-dependent simulations performed using GENESIS 1.3 [10].

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We believe that there is a lot of room for improving the FEL performance and reducing the saturation length by implementing the optimal injector pulses and consequently re-optimizing the linac. In the next steps we will also study the sensitivity to emittance, energy spread and peak current and refine the focusing.

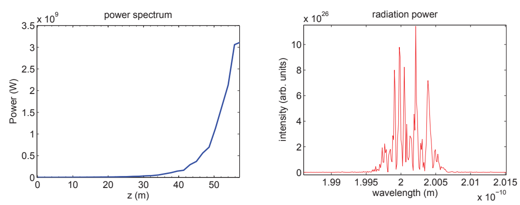

Figure 4: Power along the FEL (left) and wavelength spectrum of the FEL pulse (right).

In order to improve the spectral characteristics of the radiation, modeling is ongoing for applying the "self-seeding". The principle is to use the filtered radiation produced in a first section of undulators running in exponential regime as the seed in a further chain of undulators [11]. To enhance the performance of the FEL, self-seeding will be used in combination with tapered undulators. With tapering, the undulator strength decreases to take into account for the energy loss of the electron beam and maintain the resonance condition. We performed a preliminary study with 12 undulators of 3 m each. In the 1-m sections between undulators, the same lattice as in the time-dependent simulations is used. We examined a simple tapering profile, wherein the undulator parameter decreases in three discrete steps. Tapering starts in 10th undulator. Figure 5 shows the radiation power as a function of the distance for both uniform undulators (blue) and tapered undulators (red). In the former case, the radiation power becomes saturated in the 10th undulator. But in the latter case, the radiation power continues to grow. At about 48 m, the radiation power is 1.36×10^9 W for uniform undulators and 1.28×10^{10} W for tapered undulators. This preliminary study shows that the introduction of tapering can potentially increase the power extracted from the electron beam and the number of photons per pulse by one order of magnitude. Beyond this proceeding, our next step is to explore more advanced tapering strategies and to find out the optimum mode of tapering for the MAX IV free-electron laser.

CONCLUSIONS

In this paper we presented a preliminary design for an X-ray FEL based on the MAX IV linac. The energy of the machine has to be increased to 5 GeV in order to achieve the Ångstrom region with wide margins with respect to machine fluctuations. The FEL driver relies on a photocathode gun able to produce very small emittance bunches. The linac and bunch compressor design is such that the electron beam is not spoiled during acceleration and compression. The basic concept for the FEL is Self Amplified Spontaneous Emission but we are starting modeling self-seeding in combination with tapered undulators. This will increase the extracted power and improve the spectral stability of the FEL radiation. A further expansion of the facility may include a soft X-ray FEL using the electron beam at 1.5–3 GeV. This will complement the hard X-ray FEL.

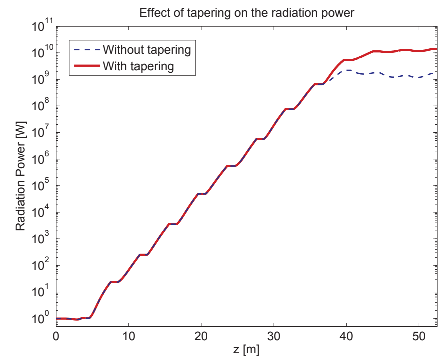

Figure 5: Radiation power as a function of undulator distance for both uniform undulators (blue) and tapered undulators (red).

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