SIMULATION STUDIES FOR AN X-RAY FEL BASED ON AN EXTENSION OF THE MAX IV LINAC

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Abstract

It is well known that the few X-ray FELs around the world are severely overbooked by users. Having a medium energy linac, such as the one now being installed at the MAX IV laboratory, it becomes natural to think about slightly increasing the electron energy to drive an X-ray FEL. This development is now included in the long term strategic plan for the MAX IV laboratory. We will present the current FEL studies based on an extension of the MAX IV linac to 5 GeV to reach the Ångstrom region. The injector for the MAX IV accelerator complex is also equipped with a photocathode gun, capable of producing low emittance electron beam. The bunch compression and linearization of the beam is taken care by two double achromats. The basic FEL layout would consist of short period undulators with tapering for extracting all the power from the electron beam. Self-seeding is considered as an option for increasing the spectral and intensity stability.

BACKGROUND

The MAX IV facility [1], successor of the MAX-lab accelerators at Lund University, Sweden, was already in the initial plans around year 2000 drawn with the idea that the facility could be extended with a FEL in a later stage. Since then the X-ray FELs LCLS [2] and SACLA [3] have been put into operation as well as the UV machines FLASH [4] and Fermi [5]. The European XFEL [6], the SwissFEL [7] and the PAL-XFEL [8] are currently being constructed, indicating the development of the photon science scene worldwide. The MAX IV facility is right now being constructed with the installation of the linac structures (up to 3 GeV), waveguides and magnetic systems almost completed (August 2013) [9]. Swedish users are heavily involved in experiments and the development of experiments in the LCLS and the Euro XFEL projects, as well as the UV FELs FLASH and FERMI [10]. In December 2011 a group of Swedish scientists started the discussions to join forces with the aim of producing a scientific case for X-ray lasers in Sweden [11]. Different concepts have been presented to the MAX IV Laboratory scientific advisory committee which later recommended that an X-ray FEL based on an extended linac (up to 5-6 GeV) should be investigated. The MAX IV laboratory strategy includes a plan for an extension of the facility with an X-ray FEL starting by a conceptual design in near future, followed by a technical design and a tentative operation in 2021. No funding is at the moment available. Figure 1 gives an impression about the different activities connected to the MAX IV FEL.

As a baseline case for the conceptual design a 5 GeV linac and an FEL at 3 Å has been chosen both in Self Amplified Spontaneous Emission (SASE) and seeded mode. Initially the study includes self-seeding by a crystal monochromator and tapering, to increase the extracted power. The goal is a transform limited pulse < 100 fs, > 10 GW peak power, 100 Hz rep rate, 3 Å. The concept will later be complemented by studies including: short pulse operation (< 10 fs), peak power optimization (multi 100 GW), tuning range (1-7 Å), self seeding at > 4 Å, a soft X-ray system based on lower electron energy and beam spreader for several end stations. The MAX IV linac consists of a warm S-band system able to provide > 3 GeV, two bunch compressors [12] able to compress to < 100 fs, two injectors (one thermionic RF gun and one low emittance photo cathode gun). It will provide pulses both for injection into the two storage rings and drive a SPF (Short Pulse Facility) providing spontaneous undulator radiation in 100 fs pulses [13].

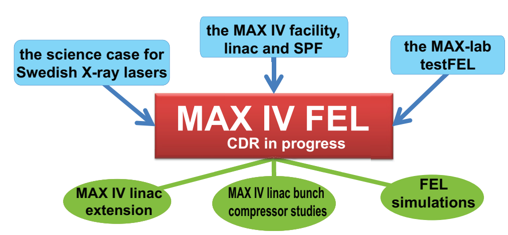

Figure 1: Cartoon showing the current work around the MAX IV FEL.

LAYOUT OF THE X-RAY FEL

The general layout of the MAX IV FEL is shown in Fig. 2. The energy of MAX IV linac will be extended from 3 GeV to about 5 GeV using the same kind of accelerating structures as the main linac [9]. The design of the second bunch compressor allows to use it also as beam spreader. After the accelerating structures, a matching section will allows to prepare the electron beam before entering the undulator chain.

The Injector

The injector consists of an RF gun and an S-band linac structure accelerating up to 100 MeV. The MAX IV FEL will take advantage of the photocathode gun which is foreseen for the SPF. This gun is design to deliver beam with

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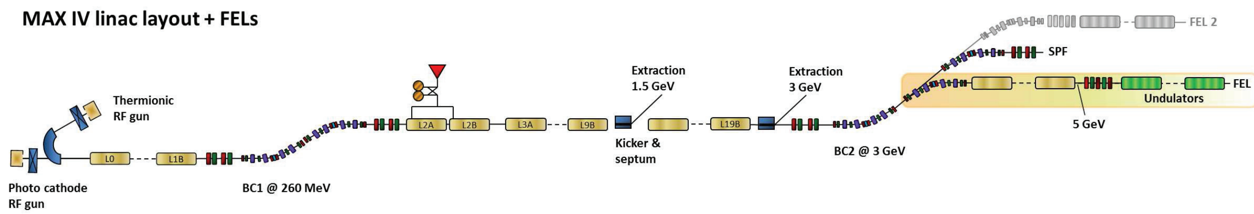

Figure 2: Schematic view of the MAX IV linac with the extension to 5 GeV and the FEL undulators.

0.5 mm mrad normalized emittance for 100 pC charge and 7 ps pulse length. The performance could be improved reducing the charge to 75 pC and re-optimizing the gun-to-linac distance, solenoid compensation and the RF phase. Astra [14] simulations show a 40% reduction on the emittance.

The Linac

The MAX IV linac will provide the beam for the two storage rings and the SPF, so it is designed to switch frequently between different operation modes and even different electron guns. The main change for the FEL will be the extension of 26 S-band accelerating structures of the same type as in the first part of the linac. The final energy of the beam before entering the FEL undulators will be about 5 GeV. The bunch compressors are double achromats and provide also linearization of the longitudinal phase space without the need of an harmonic cavity. Besides the second bunch compressor at 3 GeV is used as beam spreader. The electron beam parameters used in the following FEL simulations have been obtained through particle tracking in Elegant [15], starting from the non-optimized injector file. This means that there is room for improvement the performance of the linac. Compressing the beam to about 30 fs FWHM the peak current reaches 3 kA, with a slice emittance of 0.4 mm mrad and slice energy spread of 2×10^{-4}. Transverse wakefields effects have been evaluated [16] and they have a negligible effect on the emittance.

The Undulators

An extension of the presently built tunnel will accommodate the undulator section after the extension of the linac. As the target wavelength chosen for this FEL is in the Ångstrom region, in-vacuum undulator technology allows to reach such high magnetic field with short period length. In this preparatory phase we took into account undulators with 18 mm period, similar to the ones chosen for the SPF but the length of each section is reduced to 3 m, in order to focus the beam placing quadrupoles in the intra-section, which will be about 1 m long. The basic lattice used for the following simulations has a doublet arrangement, but the optics has not been yet optimized for the FEL performance. That will be done in the following months.

FEL CONCEPTS

With the extension of the MAX IV linac to 5 GeV, the electron beam parameters will be good enough to drive an FEL based on the SASE process. But the full coherence of the radiation would be a need for some users. The basic strategy to improve the SASE performance resides on the combination of self-seeding [17] and undulator tapering [18]. The advantage of self-seeding has been experimentally demonstrated at LCLS [19] and it is a clear path for improving the brilliance of a SASE FEL. The combination with tapering allows to extract the maximum power from the electron beam and convert it to photon flux. That is the ultimate goal for delivering to users the most brilliant and powerful source. The self-seeding can be also applied in the soft-X-ray region, where there is still a lack of powerful source to use for direct seeding or cascade.

Self-seeding

Self-seeding for MAX IV FEL is achieved by breaking the SASE process when the FEL is still in the linear regime, filtering the photon pulse with a crystal monochromator while the electron beam passes through a magnetic chicane and finally recombining the photon beam with the electron beam and let them interact in the undulators. As described in [17], after filtering out a narrow-bandwidth signal in the frequency domain, trailing pulses will result in the time domain, although with reduced amplitude. One of these trailing pulses is then used as seed in the second stage of the FEL (see Fig. 3).

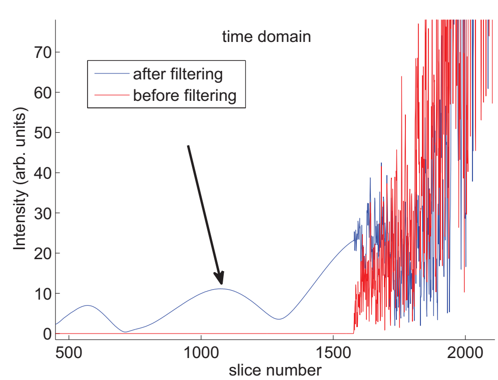

Figure 3: Trailing pulse appearing in the time domain after the filtering.

For the first part, the linear regime, 6 undulators are

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enough to generate the needed power. After filtering, the radiation has to be still few (1-2) orders of magnitude bigger than the shot-noise. At the same time, the induced energy spread in the first undulator chain should be small, such that in the second stage the electron beam can still lase. The role of the magnetic chicane is not only to delay the electron beam, which has to meet the trailing pulse at the beginning of the second stage, but also to erase the microbunching. Even a weak chicane (R_{56} few tens of μ m) can do the job if the resonance wavelength is below ten nm.

Numerical implementation of self-seeding The filtering of the spectrum is performed, similarly to [17] in the frequency domain by multiplication of the filter–vector and field–vector. A complex electric field is read in time domain for each transverse pixel from a GENESIS 1.3 [20] field file. This complex field is padded with enough zeros in time domain so that the frequency spacing of the field–vector is at least as small as frequency spacing of the filter–vector. The filter–vector is calculated using XOP 2.3 [21] code for diamond crystal oriented so that the absorption peaks at the central wavelength of the field-vector. The imaginary part of the filter–vector is calculated using the Kramers–Kronig relations. The function *hilbert* in MATLAB is used for this purpose. Interpolation of the filter–vector to the frequencies of the field-vector is performed before the multiplication. In case the frequency span of the filter–vector is smaller than the frequency span of the field–vector the filter–vector is extrapolated (this is typically just an extension that contains pure transmission). After the multiplication in frequency domain the inverse transform is performed to return to the time domain. In time domain a time-trailing segment at a certain time position is clipped. This trailing part, by design of the self–seeding, contains dominantly the frequencies contained by the field–vector where absorption of the filter peaked. The whole process is repeated for each transverse pixel from the field file separately until all the pixels are processed and a new filtered field–file is created. Figure 4 explains the procedure in pictorial way.

Tapering

In order to increase the peak radiation power, undulator tapering will be introduced in the MAX IV FEL. In a tapered undulator, the undulator parameter a_u decreases with distance z along the undulator, so as to maintain the resonance condition

$$\gamma_r = \sqrt{\frac{\lambda_u}{2\lambda}(1 + a_u^2)}, \qquad (1)$$

where γ_r is the resonance Lorentz factor, λ is the radiation wavelength and λ_u is the undulator period length. By maintaining the resonance condition beyond the initial saturation of the radiation power, it is possible to extract more of the electron beam's energy and convert it into photon flux. While tapering can be done by a continuous decrease in a_u, it can also be done in a stepwise fashion. A study by

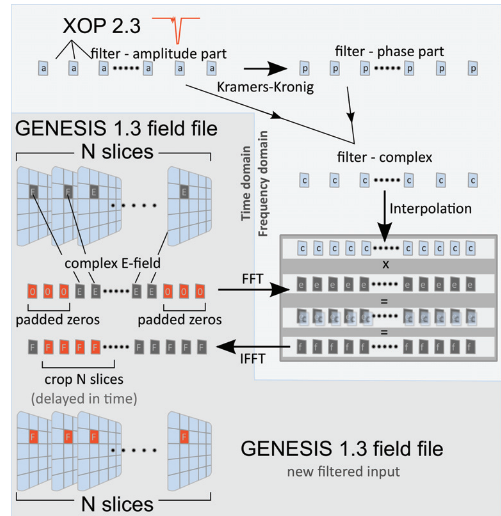

Figure 4: Cartoon explaining the filtering procedure.

Nguyen and Freund [22] shows that a series of uniform undulators with decreasing a_u can give essentially the same performance as comparable undulators with continuously decreasing a_u. Uniform undulators have a few advantages over undulators with continuously changing gap size. They are relatively easy to build and optimize. Also, each undulator can be adjusted independently from the others during operation.

Following the footsteps of [22], we perform a study on stepwise tapering with the simulation code GENESIS 1.3. In our simulation, we set up a series of uniform undulators. Each of them is 3 meters long. In between the undulators there are 1-meter sections. The essence of our study is to scan over different values for a_u, and thereby maximizing the peak radiation power at the exit of each undulator as a function of a_u. The result shows that with a_u = 1.4765 the exponential growth starts the earliest (in the 8th undulator, data not shown). The decrease in a_u beyond the 8th undulator is almost linear, with a gradient of 0.0015 per meter (see Fig. 5).

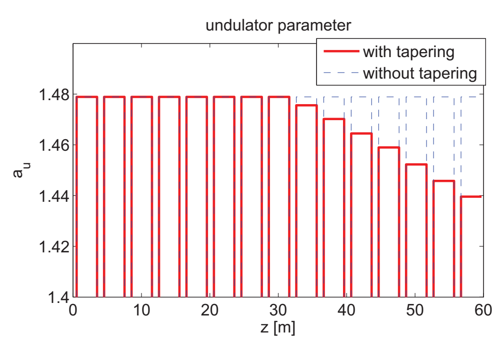

Figure 5: Tapered and untapered profile of the undulator strength.

Figure 6 shows the corresponding radiation power as a function of the distance z. It is evident that the tapering

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leads to an increase of the final radiation power with respect to the untapered configuration. However the optimization is still in progress and we hope to find better results increasing the trapping of electrons.

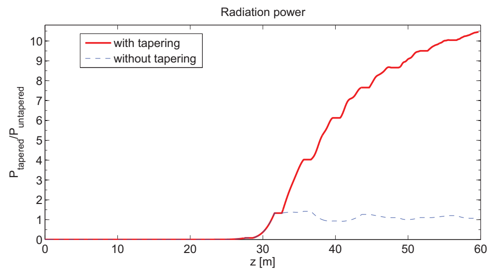

Figure 6: Radiation power obtained using the tapered profile (red) and the untapered undulators (blue).

Additional Soft X-ray FEL Branch

The hard X-ray FEL could be complemented with a soft X-ray FEL using the low energy part of the linac. In fact 3 GeV energy is more than enough to drive the FEL process around the water-window region (few nm). Different configurations can be foreseen for this second branch of the facility: direct seeding, seeded cascade, cascade with HHG.

CONCLUSIONS

Due to the low emittance of the linac, the MAX IV facility (presently under construction in Lund) is basically designed to accommodate also an FEL. As the goal is to build an hard X-ray machine, the linac energy should be extended to about 5 GeV. We started investigations on different FEL schemes for reaching GW power level and the most promising is the combination of self-seeding and undulator tapering. A soft X-ray FEL could be also foreseen and different kind of seeding techniques can be implemented in that case.

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