# Prospects for a Free Electron Laser at the FemtoMAX Beamline

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# Abstract

A Free Electron Laser (FEL), is a device that generates extremely coherent and brilliant radiation using electrons accelerated to relativistic velocities in a particle accelerator. The process utilises similar equipment to what is used at a synchrotron source like MAX IV, but in addition there is an interaction between the relativistic electron beam and the generated radiation to achieve an exponential growth in radiation intensity. The produced radiation can potentially be several orders of magnitude more brilliant than what is possible at a synchrotron source like MAX IV, which also produces brilliant and coherent radiation in the form of X-rays. This is mainly done in the two storage rings at the facility, but also at a beamline called FemtoMAX. FemtoMAX lies in the Short Pulse Facility (SPF), and is connected directly to the linear accelerator (linac), that also injects electrons into the storage rings.

When MAX IV was built, there was an idea that the linac could also be used to drive an FEL. The prospective FEL at FemtoMAX would be a so-called Self-Amplified Spontaneous Emission (SASE) FEL, similar to other major FELs like European XFEL or LCLS. In such FELs, the radiation is generated with a single pass of electrons through undulators which make the electrons emit radiation. FemtoMAX also generates radiation with an undulator driven by electrons from a linac, but what makes the difference to an FEL is that in the latter the wavelength and electron energy are tuned so that the electrons will emit radiation coherently, which causes a self-amplifying effect, and an exponential growth in radiation intensity. This exponential growth is characterised by a distance over which the intensity increases by a factor of $e$, the gain length, which depends on a number of parameters of the electron beam. Most importantly for this thesis, it decreases with decreasing electron energy. At the 3 GeV electron energy where FemtoMAX currently operates, the exponential growth requires a considerably longer undulator length than what is available at FemtoMAX. Lowering the energy of the linac would shorten the gain length, and could make the exponential growth long enough to generate FEL radiation. By simulating the FEL process using parameters from FemtoMAX, the prospective FEL at FemtoMAX was investigated. The results show that by lowering the electron energy to 2 GeV or lower, there is a significant lasing and exponential growth of the radiation. At 1.6 GeV, there is even saturation of the FEL process. The conclusion is that there is a real possibility to implement such an FEL at FemtoMAX, provided the energy of the linac can be lowered.

## Abbreviations and acronyms

- Genesis - GENESIS 1.3
- FEL - Free Electron Laser
- linac - Linear Accelerator
- SPF - Short Pulse Facility
- SASE - Self-Amplified Spontaneous Emission
- ID - Insertion Device
- EM - Electromagnetic
- HHG - High-order Harmonic Generation
- HGHG - High-Gain Harmonic Generation
- UV - Ultraviolet
- VUV - Vacuum Ultraviolet
- BPM - Beam Position Monitor

# Contents

# 1 Introduction

The MAX IV facility in Lund, Sweden, is the first fourth generation synchrotron light source in the world, representing a large increase in many important parameters of the generated synchrotron radiation compared to previous sources. As with all fields of research however, there are continual efforts to improve the measurement techniques so that new discoveries can be made. In the field of light sources such as MAX IV, this is achieved by producing light with improved performance in certain radiation properties. The most important such properties are the intensity, coherence, and pulse length.

Storage rings, like the ones at MAX IV, transport relativistic electrons in a circle, where the electrons emit photons, so-called synchrotron radiation, when bent in their orbit by the bending magnets keeping them in orbit. For most modern storage rings however, this radiation is not used for measurements. Instead, one uses so-called *insertion devices* (IDs). One common type is the *undulator*, which is a periodic array of magnets which causes electrons to travel in a sinusoidal path through it, emitting photons as they turn. This allows the produced radiation to be improved in all properties mentioned above, compared to early generation storage rings which just used the synchrotron radiation from the bending magnets in the ring. Another type of light source which categorically improves these properties is the so-called Free Electron Laser (FEL). In principle, it operates very similarly to a modern storage ring light source, also using undulators to generate the radiation. There are even FELs which are built using existing storage rings [8]. Even though the technological requirements are quite similar, FELs are capable of producing radiation which is several orders of magnitude brighter than storage ring sources. In addition, they have superior coherence properties, and are also capable of generating far shorter pulses. Bearing this in mind, one might question why storage ring sources are used at all. The reason is of course that there are several difficulties in creating an FEL. Furthermore, they are more limited in how they can provide radiation to several experiments. MAX IV can provide synchrotron radiation to more than a dozen beamlines simultaneously, something which would be challenging to match with an FEL. Consequently, the two types of sources have their respective strengths and weaknesses and are as such best used complementing each other. The slightly different types of X-ray radiation could be used for many things, for example measurements of proteins, new types of electronics, and even archaeological finds.

Considering this, one can see why an FEL at MAX IV would be useful. With all the improvements it could provide compared to the storage ring source, it would complement the existing facility nicely. Building an FEL at MAX IV is a project which has been discussed for some time [10], but it has not yet become reality. The suggestion was to build the FEL at the end of the linear accelerator of the facility, which is currently injecting electrons into the two storage rings, as well as driving the FemtoMAX beamline at the so-called Short Pulse Facility (SPF), shown in Figure 1. The proposed FEL in this thesis would utilise the existing FemtoMAX beamline in another operation mode, which would enable the creation of FEL radiation. This means that one could use the same undulators which are already in place at FemtoMAX, instead of constructing a separate beamline for the FEL. As already mentioned, the linac is used both to top up the storage rings at MAX IV, and to run experiments at the FemtoMAX beamline. Since the two storage rings need to be topped up with 1.5 and 3 GeV electron bunches respectively, the electrons reaching FemtoMAX are accelerated to the full 3 GeV. As it turns out, this causes some problems when considering implementing an FEL at FemtoMAX, as will be discussed later.

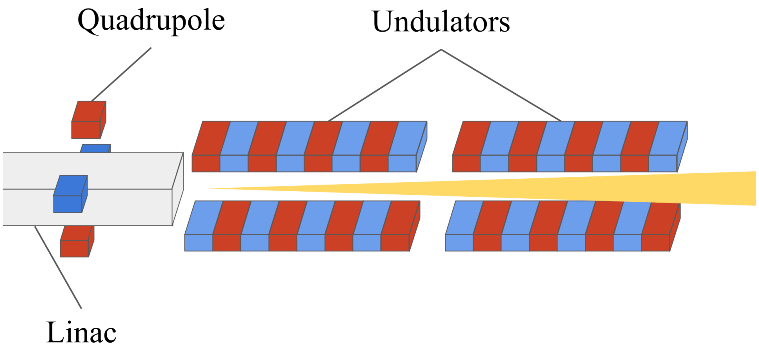

Figure 1: A schematic view of the FemtoMAX beamline, which is identical to what it would look like for the proposed FEL. The linac accelerates an electron beam to relativistic energy. The beam then passes through a matching section of quadrupole magnets, the last of which is shown in the schematic. These adjust the optics of the electron beam, which then enters the undulators. The synchrotron radiation is emitted when the electrons are forced to turn in a sinusoidal path through the undulator.

As mentioned before, the process for creating FEL radiation is quite similar to what is done at storage rings and FemtoMAX, and one can use the same undulators for the proposed FEL. Of course, some tweaking of the existing setup is needed to get FEL radiation. Most importantly, the length of the existing undulators is limited, which means that the FEL process only has a certain length to fully develop. The FEL process develops exponentially, where an increase of a factor of $e$ requires a length called a *gain length*. Ideally, the undulator length in an FEL is around 18-20 gain lengths, which is the so-called *saturation length*. In an FEL, the gain length shortens with decreasing electron energy. At 3 GeV electron energy, the saturation length exceeds the length of the existing undulators. This means that to get an FEL which produces the desired radiation intensity, one would need to lower the energy of the linac. However, this will conflict with the injection of 3 GeV electrons to the storage ring at MAX IV. Lowering the energy of the linac is difficult, and so ideally the energy should be as close to the 3 GeV required by the storage ring as possible. Herein lies one of the difficulties of implementing an FEL at the FemtoMAX beamline.

## 1.1 Motivation

Implementing an FEL at the FemtoMAX beamline is a project which could provide intense radiation in an interesting wavelength regime, with coherence properties currently not attainable at MAX IV. FELs are currently a very active research topic, due to their potential improvements compared to other radiation sources. They can improve important properties like brilliance and coherence, providing almost fully coherent radiation with several orders of magnitude greater brilliance than storage rings [6]. Furthermore, the pulses can be very short, like what the current FemtoMAX beamline can produce. An FEL would enable new types of experiments at MAX IV utilising the short pulses, as well as the improved coherence and brilliance. What makes this project particularly interesting is that the current FemtoMAX beamline in principle has everything needed to operate as an FEL. This means that one could potentially achieve the above mentioned improvements without any major investment, provided it is possible to shorten the saturation length enough get a significant gain from the FEL process. In order to investigate this possibility, the FEL-simulation program GENESIS 1.3 (Genesis) [14] is used to simulate the operation of the FemtoMAX beamline as an FEL, using realistic parameters for the facility. By varying the parameters of the undulators and the electron beam within the limits set by the facility, and analysing the resulting radiation, it will be seen whether the exponential gain of the FEL process can be obtained at FemtoMAX. Based on a more comprehensive analysis, the feasibility of implementing an FEL at the FemtoMAX facility will be evaluated. Not all parameters of the linac and FemtoMAX are known precisely however, so the results of the simulations are subject to large uncertainties. Therefore, the goal of the thesis is showing that exponential gain is possible at FemtoMAX.

# 2 Theory

## 2.1 Accelerator-based radiation sources

For a measurement made with radiation from an accelerator based radiation source, the quality of the result is in large part determined by the number of photons per pulse. There are other factors which also impact the quality of the radiation, like the size and angular spread. FELs generally achieve small beam sizes and angular divergences, since the FEL process requires a high density of electrons in the transverse plane, with a low angular divergence, which consequently means that the light inherits these properties. Therefore, comparing the number of photons per pulse is customary when comparing results to other FELs, and that is what is done in this thesis. Beyond the number of photons per pulse of the radiation, there are several other properties which FELs improve. The most important ones are the pulse length, and the coherence. If the pulse length is short, it also means that processes taking place over shorter time-scales can be captured. The pulse length at FemtoMAX is however already very short, around 100 fs [3], so the pulse length will not be discussed further in this thesis.

There are two different types of coherence, which impact measurements in different ways. There is temporal coherence, which is a measure of how monochromatic a wave is. In turn, this is related to the spectral coherence, which describes how uniform the spectrum of radiation is. For spontaneous (non-FEL) undulator radiation, the temporal and spectral coherence are quite low, with a significant increase when moving to an FEL. This is because of the mechanism of the FEL where it amplifies wavelengths around a certain resonant wavelength, as will be described later. For FELs which use external seed lasers to start the FEL process, so called seeded FELs, the temporal coherence is almost maximised, producing essentially monochromatic radiation. The other type of coherence is transverse coherence, which describes the phase relationship between different waves in the radiation in the plane perpendicular to the undulator direction. Maximum transverse coherence is reached when all waves are in phase. Transverse coherence is considerably improved in FELs compared to undulator radiation. In fact, it is almost maximised in FELs near saturation [5]. Both these properties are useful in experiments in different ways, and can enable experiments which would not be possible using a storage ring.

## 2.2 The FEL process

### 2.2.1 Undulator radiation

FEL radiation is produced in undulators, like those already used at MAX IV, both as IDs in the storage ring, and at the FemtoMAX beamline located at the end of the linac. As mentioned before, undulators bend the electron beam so that it emits radiation. In an undulator, magnets are placed pair-wise, above and below the electron beam, with opposite polarity. These pairs are positioned periodically, with alternating polarity, along the longitudinal axis of the beam, as shown in Figure 1. The alternating magnetic field causes the electron to wiggle through the undulator. In each turn, when they are bent by the magnetic field, they will emit synchrotron radiation. In general however, the phase of the electrons with the EM wave would change over time since they travel with different speeds. Since the EM wave is moving slightly faster than the relativistic electron beam, it can only remain in a constant phase relationship with the beam if it slips an integer number of wavelengths for every undulator period. This means that at every turn in the undulator, the phase between the EM wave and the electron beam is the same, and the interaction between the two can continue over the entire undulator. The radiation emitted at each turn of the undulator by a single electron will be in phase with the radiation emitted by the same electron in all other turns, but not with the other electrons. The wavelength which fulfills this condition is called the *resonant wavelength*. It depends on the energy of the electrons, as well as the magnetic field strength and period of the magnets, $\lambda_u$, in the undulator. Normally however, one does not refer to the field strength, $B$, inside the undulator, but the $K$-parameter,

$$K = \frac{eB\lambda_u}{2\pi m_e c}, \tag{1}$$

where the remaining factors are constants, the elementary charge, $e$, the electron mass, $m_e$, and the speed of light in vacuum, $c$. From this, the resonant wavelength of the FEL process can be expressed as

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) [6], \tag{2}$$

where $\gamma = \frac{E}{m_e c^2}$ is the electron energy, $E$, divided by the electron rest energy. This is the resonant wavelength for radiation straight ahead from the undulator, i.e. on axis. For radiation off axis however, there is a correction term. For the discussion in this thesis, the above form will suffice.

### 2.2.2 Microbunching

When the electron beam interacts with the electromagnetic (EM) radiation at the resonant wavelength, the electrons will exchange energy according to $W = e\vec{E} \cdot \vec{v}$, in the transverse direction of the E-field of the EM wave. This interaction causes the electrons to either gain or lose energy. This means that the electrons which gain energy are bent less by the magnetic field, and thus travel a shorter distance, and vice versa. Thus, the electrons will move relative to each other in phase, eventually gathering at distances of one wavelength of the EM wave, the desired *microbunching* [6, 19]. This can also be seen in the phase space of energy vs phase for the particles, as seen in Figure 2. In this case, the electrons which are behind in phase are gaining energy from the EM wave, moving upwards in phase space, but also forward since they move faster (because they travel a shorter distance). This creates a clockwise rotation of the phase space, since the particles ahead in phase instead lose energy and move slower. This process builds up gradually over the undulator, and after some time there is a large concentration of electrons at the same phase compared to the EM wave, as seen in b) in Figure 2. The electrons do not stop here, however. The clockwise motion continues, since the electrons either have higher or lower energy than the resonant energy needed to stay at constant phase with the EM wave. This is shown in c) in Figure 2, and this stage is called *saturation*. That is when the exponential energy growth through the undulator stops. Consequently, for operations of an FEL, it is desirable to just reach saturation at the very end of the undulator. That way, one does not need to build unnecessary undulators.

This microbunching is what makes the difference to the undulator radiation described above. The radiation emitted by the microbunches at the resonant wavelength will interfere constructively, unlike that at other wavelengths. For a regular undulator, since the electrons are more or less randomly distributed in the bunch, the EM waves from the electrons will interfere both constructively and destructively. This means that for an FEL, the radiation power grows considerably more than for a regular undulator, once significant microbunching is achieved. This also explains the coherence properties of FEL radiation. As mentioned above, the interaction between the electrons and the electric field causes the electrons and field to exchange energy. If the electrons were spread out across the phase space, an equal number of them would give energy to the field, as those that take energy. Then there would be no net gain for the field from this interaction. This is however not the case in an FEL, because of the behaviour of the microbunching. As seen in Figure 2, the electrons do not bunch at zero phase compared to the EM wave, but ahead of it. This is referred to as the slippage of the FEL bucket, and means that the large number of electrons in the microbunches will lose energy to the EM wave. Since these outnumber the electrons which gain energy, there is a net loss of energy to the wave which will increase as the strength of the field growths along the undulator, leading to an exponential growth of the radiation power [6]. This section describes the operation of a so-called high-gain FEL, as the prospective one at FemtoMAX, and so does not apply to other types of FELs.

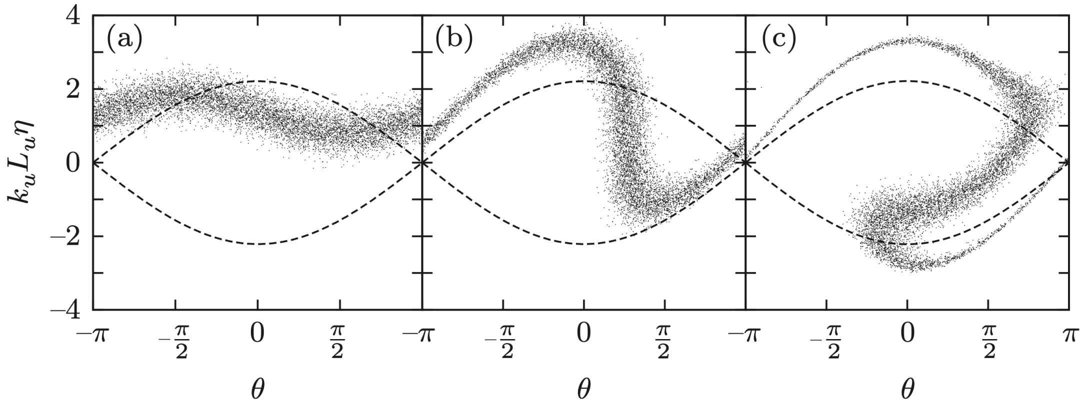

Figure 2: The phase space distribution of the electrons in the beam in the beginning, (a), middle, (b), and end, (c), of an undulator which reaches FEL saturation. This shows the microbunching of the beam in (b), where many electrons are bunched at a specific phase. The energy deviation from resonant energy, $\eta$, is shown in units of $k_u L_u$ on the y-axis, where $k_u = \frac{2\pi}{\lambda_u}$ and $L_u$ is the longitudinal length of the undulator. The phase difference from the EM wave is shown on the x-axis. Taken from [8].

### 2.2.3 Exponential growth and Pierce parameter

The rate of the exponential growth explained above is characterised by the gain length, $L_G$, which is the length of undulator required to increase the power of the radiation by a factor of $e$. To reach saturation in an FEL, an undulator length of around $18 - 20$ gain lengths is required, the so-called *saturation length* [5, 6].

The gain length can be expressed using the so called Pierce parameter,

$$\rho = \left( \frac{1}{16} \frac{I_e}{I_A} \frac{K^2 [JJ]^2}{\gamma^3 \sigma_x^2 k_u^2} \right) [6], \tag{3}$$

where $k_u = \frac{2\pi}{\lambda_u}$, $I_e$ is the peak current of the electron beam, $I_A = \frac{ec}{r_e} \approx 17$ kA is the Alfvén current, and $\sigma_x$ is the transverse RMS size of the electron beam. The factor $[JJ] = [J_0(\xi) - J_1(\xi)]$ is the Bessel function factor, where $\xi = K^2/(4 + 2K^2)$ in this case. Using the Pierce parameter, the gain length can be expressed as

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho} [6]. \tag{4}$$

Using this, the impact of certain parameters on the behaviour of the FEL can be qualitatively analysed. Considering the fact that the undulator length at FemtoMAX is limited, and shorter than most comparable FELs in operation today, a shorter gain length is generally desirable. Ideally, the FEL process should just reach saturation by the end of the undulator. Since the gain length is inversely proportional to the Pierce parameter, and the pierce parameter in turn is proportional to the peak current, and inversely proportional to the electron energy to the third power, $\gamma^3$, we can see that increasing the peak current or decreasing the energy should shorten the gain length. In the case of the electron energy, this effect would be quite considerable as well, since the dependence is to the third power. Lowering the electron energy thus has several effects, since lowering the energy also affects the wavelength of the radiation according to Equation 2.

### 2.2.4 Emittance and betatron functions

One further aspect which affects the power of the resulting FEL radiation is how focused the electron beam is. If the beam is very concentrated, it will interact more with the EM wave, and therefore the gain length will be shortened [13]. Considering this, one might think that the optimal setting would be to focus the beam as much as possible. That is however not the case, because the beam is not only characterised by its size, but also its divergence, $x'$ and $y'$. When the beam is focused so that the beam size decreases, the divergence necessarily increases to compensate. The relation between these two quantities is the emittance, $\epsilon$. In a phase space with transverse position $x$ on one axis, and the corresponding divergence, $x'$ on the other, every electron in the beam would be located on an ellipse around the origin. The area of this ellipse, which in simplified terms can be described as the product of the transverse size and divergence, is the emittance. Under the reasonable assumption of conservative forces, emittance is constant for an electron beam, and of course a smaller emittance means that the beam can be more focused without diverging. Therefore, achieving a small emittance is one of the main goals when designing new sources.

The emittance of the beam is constant along the undulator, but it turns out that the size cannot be constant. The size of the beam will oscillate throughout the undulator, and the relation is given by a so-called betatron (or beta) function:

$$\sigma = \sqrt{\epsilon\beta(s)}\,[19], \tag{5}$$

where $s$ is the longitudinal coordinate along the undulator, and $\sigma$ is the size of the beam. Since $\epsilon$ is taken to be constant, the oscillation of the beta functions corresponds to the oscillation of the transverse size of the beam. Furthermore, the inverse of the beta function is proportional to the divergence of the beam, meaning that whenever the beam size, and consequently the beta function, is small, the divergence will be large. Therefore, the beam size will increase again, until the divergence becomes small. This is what causes the oscillations of the beam size.

The beta functions initial values can be controlled by the matching section of quadrupole magnets at the end of the linac, just before the undulators, which allows for selecting values which give an even and focused beam. The only way to control the functions is through magnets, typically by quadrupole magnets, which can focus or de-focus the beam. A planar undulator, like the one at FemtoMAX, also has a focusing effect in the vertical $y$-plane, and a negligible one in the horizontal $x$-plane. This becomes especially apparent at lower electron energies, where the focusing will have a larger impact [13]. Controlling the beta functions is important, because as mentioned above, having a more focused beam gives a shorter gain length due to stronger interaction with the radiation. Because of the increasing divergence of the beam however, there is an ideal degree of focusing in the beta functions. The theoretical optimum for the average value of the beta function can be found either numerically, or by simulation. In the cases where the focusing is too great, many electrons will disappear because of the large divergence, which of course reduces the final power of the FEL radiation. On the other hand, too large beta function averages means that very few electrons in the bunch are able to interact with the EM wave, which also reduces the final power [7].

## 2.3 Comparison to other FELs

The potential advantages of FELs to storage rings are many, such as potentially increasing the power by many orders of magnitude, improving the coherence, and also shortening the pulse lengths, enabling measurements of shorter timescales. In order to properly compare different radiation sources however, using a quantity such as power can be misleading, since it only represents one quality of the radiation. Aspects such as the transverse size and angular divergence of the beam are examples of other important qualities. However, when dealing with FELs, these quantities are very similar between different machines, and therefore it is common to simply compare the number of photons per pulse. This gives slightly more information than the power, since it also takes the wavelength of the radiation into account, and of course the length of the pulse. The number of photons per pulse at some major FELs are given in Table 1.

Table 1: The number of photons per pulse for some major FELs. Note that FLASH operates in the soft X-ray to UV range, whereas the other two sources operate in the X-ray range, capable of producing hard X-rays [1].

| FEL | Photons per pulse |
|---|---|
| European XFEL, Germany | $10^{12}$ |
| FLASH, Germany | $3 \cdot 10^{13}$ |
| LCLS I, USA | $10^{13}$ |
| SwissFEL, Switzerland | $3.6 \cdot 10^{10}$ |

One of the main motivations behind FELs is that the resonant wavelength can be almost freely chosen using the relation 2. As long as enough energy can be provided to the electrons, and a long enough undulator can be built based on the saturation length of the FEL. The electrons will spontaneously emit synchrotron radiation at the resonant wavelength, which can be chosen to be somewhere in the X-ray regime. In fact, this is where many FELs operate, such as the European XFEL. This is an interesting wavelength regime to use for measurements, but it is not attainable in a traditional laser. Methods like High-Order Harmonic Generation (HHG) used to shorten wavelengths of a traditional laser can only reach the ultraviolet (UV) or vacuum ultra-violet (VUV) part of the electromagnetic spectrum [9]. Therefore, it is highly interesting to use FELs in the X-ray regime.

There are several types of FELs. The one discussed here is called a Self-Amplified Spontaneous Emission (SASE) FEL, which is a so-called high-gain FEL, where the electron beam only makes one pass through the FEL. The FEL then amplifies the shotnoise generated by the electrons in the beginning of the undulator, resulting in a spectrum with relatively low spectral coherence. The spectrum generally contains a number of peaks in a narrow region around the resonant wavelength, rather than a single Gaussian around this wavelength. Low-gain FELs are typically undulators placed in storage rings, where the gain for each pass of the electron beam is very small, but the radiation is reflected so that the beam and radiation interact many times, allowing lasing to be achieved. Beyond SASE FELs, there is another type of high-gain FEL. This is called *seeded* FEL, and operates similarly to a SASE FEL, except that an external laser pulse at the resonant wavelength of the FEL is overlapped in space and time with the electrons. Consequently, the microbunching will immediately start at the wavelength of the seed, and the FEL will amplify this signal, instead of amplifying the spontaneous synchrotron radiation from the electrons. This considerably improves the temporal and spectral coherence of the radiation, but the wavelength range is limited by that of the seed laser. Certain schemes have been devised which allow the wavelength to be lowered slightly, like High-Gain Harmonic Generation, but none have yet reached the X-ray wavelengths possible with a SASE [8]. Similarly, the low-gain storage ring based FELs are limited in the wavelengths they can reach by requiring mirrors which reflect in the desired wavelength. This is very difficult in the X-ray regime [4].

## 3 Method

In order to determine whether it is feasible to implement an FEL at FemtoMAX, simulations based on the linac and equipment at FemtoMAX were used. The simulations were done in a simulation program called GENESIS 1.3, version 4.5.1 [14]. This software simulates the electron bunch travelling through a pre-defined *lattice*, and returns several parameters of the resulting FEL radiation and the bunch itself. The *lattice* is the combination of elements such as undulators, quadrupoles and other elements at the end of the linac. At FemtoMAX, there is a matching section with five quadrupoles, which control the optics of the electron beam, followed by two five-meter long undulators. These have a gap of one meter between them, which contains a Beam Position Monitor (BPM) and a phase shifter. Only this eleven meter long section of undulators was included in the simulations. The BPM does not impact neither the electron beam nor the EM wave, so it was entirely neglected. The undulators at FemtoMAX have a period of $\lambda_u = 1.5$ cm, which means that the total number of undulator periods over the 10 meters of undulator length is quite large. The parameters of the linac and FemtoMAX are listed in Table 2. These values were used as input parameters for Genesis. A Gaussian electron beam was generated by Genesis using realistic parameters from FemtoMAX. This does not represent the exact shape of the electron beam from the linac, but is a decent first approximation. In order to agree with the values for bunch charge, $Q$ and peak current, $I_e$, the standard deviation, $\sigma$, of the bunch had to be calculated for the simulations, using the relation:

$$\sigma = \frac{Q}{\sqrt{2\pi} I_e} c. \tag{6}$$

Furthermore, since the basis of the FEL process is the synchrotron radiation spontaneously generated when the electron beam enters the undulator, the so-called *steady-state* simulations required an initial field corresponding to this so-called *shotnoise* radiation. For so-called *time-dependent* simulations however, Genesis computed this shotnoise itself. The strength of the shotnoise varies with the electron energy, and was therefore adjusted accordingly for each simulation.

As mentioned previously, a large challenge in implementing an FEL at FemtoMAX is that the 3 GeV electron bunches normally provided by the linac would cause the saturation length of the FEL process to be too long compared to the length of undulators at FemtoMAX. In order to investigate this, simulations were run for different electron energies, and the resulting FEL radiation was analysed. For these runs, the energy was increased in increments of 0.2 GeV from 1 GeV to 3 GeV. This means that the gamma factor, $\gamma$, for the energy and the resonant wavelength were changed in the input file according to Equation 2. The undulator parameter, $K$, was kept constant at $K = 2.1$, and consequently, the wavelength varied for the different energies according to Equation 2. This of course means that comparing the resulting radiation from simulations with different energies is slightly misleading. However, since the point is only to consider whether an FEL is feasible, such simulations still provide interesting information. Performing several simulations while changing a single parameter of the input is called a *scan*, and this is what the majority of the simulations are. Beyond scanning the energy, the peak current was also scanned over a range from 1 kA to 4 kA. Since the charge of the bunch generated by the electron gun at the beginning of the linac is constant, changing the peak current corresponds to compressing the bunch to different degrees. In practice this is done using two magnetic bunch compressors in the linac. Furthermore, scans of the energy spread and the emittance of the beam were also performed.

These scans were all made in so-called *steady-state* simulations in Genesis, where only the central slice of the electron bunch is simulated. For these simulations, a different shotnoise power for each electron energy was required by Genesis, which was found by using the program SIMPLEX [17]. These simulations give a good qualitative understanding of the process, but neglect certain effects between different slices of the electron bunch. Therefore, a few simulations of the FEL were also made using the *time-dependent* mode of Genesis, where the entire bunch is simulated. These simulations take considerably longer (around 1000 times longer) than the steady-state ones, and were therefore only done for the most interesting settings for the FEL. To shorten the computation time, simulations were run in the MAX IV cluster. A time window for the simulation was selected to fit slightly more than one standard deviation of the bunch in each direction. For both steady-state and time-dependent simulations, 8192 particles per slice were simulated over a transverse grid with $151 \times 151$ grid spaces with a length of $10^{-3}$ m. The other settings were kept the same as for the steady-state simulations which were interesting to study more properly. Example settings for a steady-state run at 1.6 GeV electron energy is included in the appendix. One input in the settings is the seed number, which starts the random generation used for the electron distribution in time-dependent simulations. In order to counteract this random effect, several simulations were made with different seed number for the most interesting settings.

## 3.1 FemtoMAX

FemtoMAX is the beamline at the short-pulse facility at MAX IV. It is directly connected to the linac and utilises two undulators with a large number of periods to create very short X-ray pulses for investigating phenomena on the femtosecond time-scale [11]. The properties of the electron beam from the linac, as well as those of the undulator, are listed in Table 2. As a consequence of FemtoMAX directly using the electron beam from the linac at MAX IV, it can only operate whenever the linac is not used for injecting into the two storage rings at MAX IV. This means that FemtoMAX is operational a majority of the time, but it also has to integrate well with the operation of the storage rings. Consequently, FemtoMAX uses the same 3 GeV electron energy as is used when injecting into the 3 GeV storage ring, as seen in Figure 3. Since changing the energy of the linac is not easy, there would be difficulties if FemtoMAX were to operate at another electron energy than 3 GeV, which of course would be desirable for a prospective FEL.

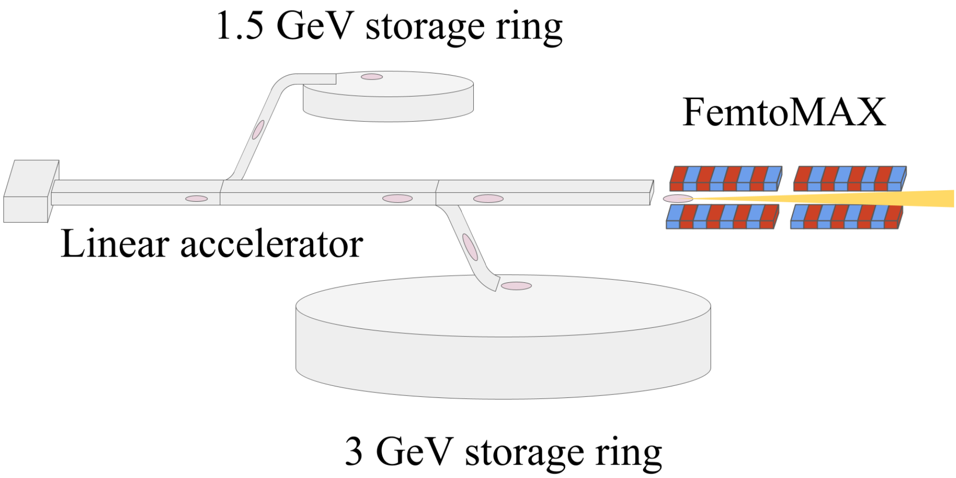

Figure 3: A schematic showing how the linac at MAX IV feeds both the storage rings and FemtoMAX with electron bunches. In actual operations, this does not happen simultaneously, but injection to the rings take place at a regular interval. At all other times, FemtoMAX receives electron bunches.

Table 2: The relevant properties of the linac and FemtoMAX undulators, based on [3, 12].

| Linac | |
|---|---|
| Emittance | $\geq 0.4$ mm·mrad |
| Energy spread $\Delta\gamma/\gamma$ | $5 \cdot 10^{-4}$ |
| Bunch charge | 100 pC |
| Peak current | 4 kA |
| Energy | $\leq 3$ GeV |
| **Undulator** | |
| K-parameter | 0.9–2.7 |
| Period length | 1.5 cm |
| Total length | $2 \times 5$ m |

Between the undulators at FemtoMAX, there are no quadrupoles for focusing the electron beam. Consequently, the beta functions of the beam cannot be controlled after this point. This means that the only possibility to adjust the size of the electron beam is by adjusting the initial optical properties called *initial twiss parameters*. These are the initial value of the beta functions mentioned above, and a value $\alpha$ for the divergence of the electron beam. This is implicitly done by the matching section at FemtoMAX, but is not included in the simulations. The choice of the initial twiss parameters was done to get as optimal beta functions as possible, with average values of around 10 m and a reasonable shape, as seen in Figure 4. As mentioned in the Theory section, there is an optimal average beta function value for a given set of settings. When selecting the values for this simulation, the values were based on finding the optimum using another simulation with a so-called FODO-lattice, with a focusing quadrupole before the first undulator, and a defocusing one between the two undulators. This allowed for controlling the beta functions to a much larger extent, and by having the other parts of the simulation be identical to the others, the optimal value was found to be for a beta function average of 10 m. This was done by simulations in another program, SIMPLEX [17].

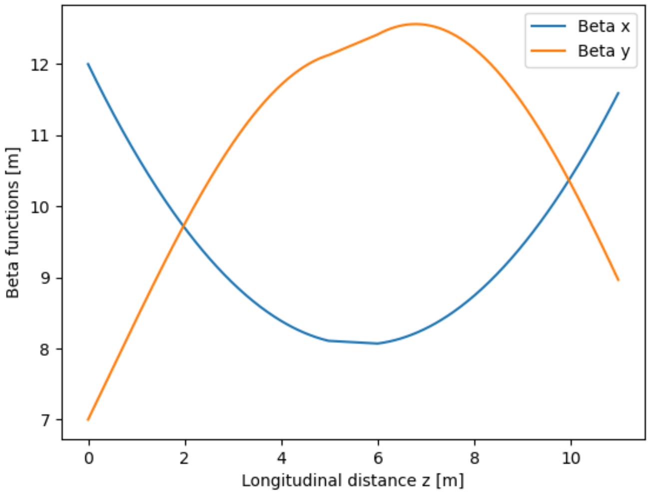

Figure 4: The beta functions along the length of the undulators for an electron beam at 2 GeV electron energy.

### 3.2 Genesis 1.3

Genesis 1.3 was developed out of a need to improve existing simulation codes for FELs in several regards [15]. It is mainly designed to deal with single pass, high-gain FELs, such as the one being investigated in this thesis. The code operates by dividing the electron beam and radiation field into several slices (in time-dependent simulations). For each slice, the code simulates the interaction between the radiation field and the electrons, as well as the effect from the undulator. To simulate the development of the beam and the field, it integrates their respective equations of motion. By alternating between integrating the motion of the beam and the field, the interaction between the two is included in the development. Because the field slips ahead of the electron beam for every turn in the undulator, the interaction of each electron slice is with the radiation from another slice in the beam. The change in the radiation which results from this interaction is then what is used in the interaction with yet another electron slice in the next time step, and so on.

## 4 Results

In order to assess the feasibility of an FEL at FemtoMAX, the results from the scans mentioned above are very interesting. Not only do they show whether or not it is possible to generate FEL radiation intense enough to be useful, but they also give an indication about when the process reaches saturation in different cases. When scanning the peak current of the electron beam, six simulations, from 1 kA to 4 kA, were made. The other parameters were chosen to be an electron energy of 2 GeV, with a beta function average of 10 m in each direction. The $K$-parameter was chosen as $K = 2.1$, which gave a wavelength of 1.6 nm. The emittance and energy spread were chosen according to Table 2, i.e. an emittance of the design value 0.4 mm·mrad, and an energy spread of $5 \cdot 10^{-4}$ of the 2 GeV electron energy. The resulting maximum power from the scans are plotted in Figure 5. An exponentially increasing trend with peak current is observed.

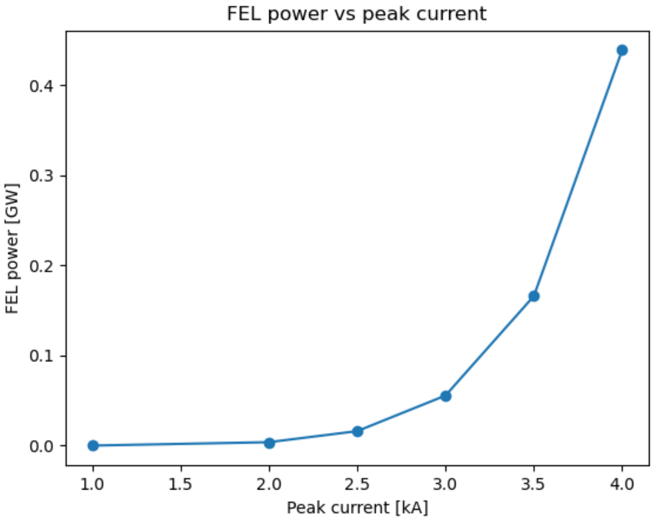

Figure 5: The maximum simulated power of the FEL radiation at different peak currents for the electron beam, at electron energy 2 GeV.

A scan was also performed over the electron energy, from 1 GeV to 3 GeV in intervals of 0.2 GeV. The emittance and energy spread were taken as in Table 2. The $K$-parameter was kept constant for these simulations, which consequently means that the wavelength changed with the energy, according to Equation 2. This means that the wavelengths are in a range from 0.7 nm for 3 GeV, to 6.3 nm for 1 GeV. The maximum power for the simulation at each energy are plotted in Figure 6. It is interesting to note that for the lower energies, saturation was observed in the gain curve from the simulations. The gain curves for a few selected energies are shown in Figure 7. Here, the gain curve clearly reaches saturation for the simulation at 1.4 GeV electron energy. For 1.6 GeV, the gain curve is also approaching saturation, but for higher energies there is no sign of saturation. For lower energies, the saturation of course becomes even more pronounced, as expected. This is also seen in the plateau in Figure 6 for energies below 1.6 GeV. Lowering the electron energies as low as 1 GeV is however not reasonable, so these results are not very interesting, apart from that they show clear saturation. Furthermore, the beta function in the $y$-direction changed considerably between the different runs. For 2 GeV, it was the same as in Figure 4, but for lower energies it decreased noticeably, and likewise it increased significantly for higher energies. The average beta function in $y$ ranged from 5.1 m for 1 GeV electron energy, to 16.4 m for 3 GeV.

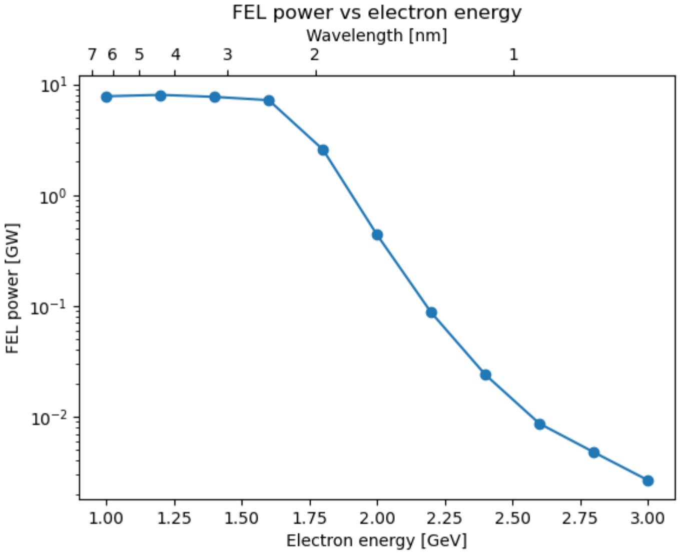

Figure 6: The maximum simulated power of the FEL radiation at different electron energies. The secondary x-axis shows the wavelength corresponding to each electron energy, according to Equation 2 and the chosen parameters.

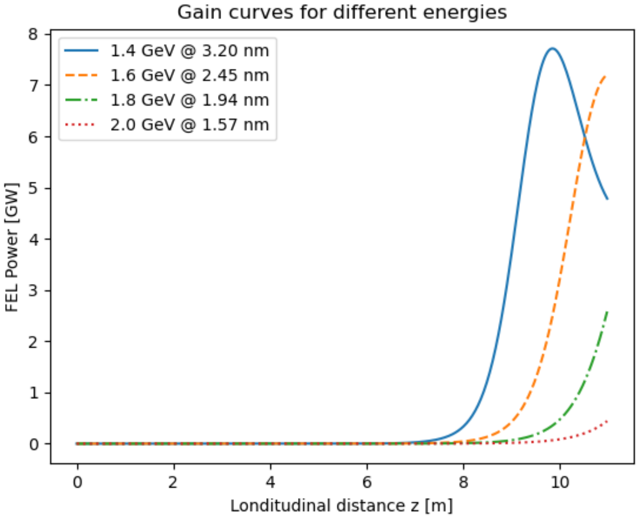

Figure 7: A selection of simulated gain curves at different electron energies, and consequently different wavelengths.

In order to quantify the impact of the emittance and the energy spread in the electron beam, simple scans of these parameters were taken as well. The settings were the same as for the 1.6 GeV simulation above, except that the emittance and energy spread, respectively, were varied from their value in Table 2. Six different values for the emittance were taken, and only three for the energy spread. The maximum power of the FEL radiation are plotted in Figures 8 and 9. For the emittance, a nearly linear decrease is seen around the design value of 0.4 mm·mrad. For the energy spread, there was only a slight increase in power when halving the energy spread from 0.82 MeV, i.e. a relative energy spread of $\Delta E/E = 5 \cdot 10^{-4}$, to 0.41 MeV. When doubling the energy spread to 1.6 MeV, there was a large decrease in FEL power, to 0.33 GW.

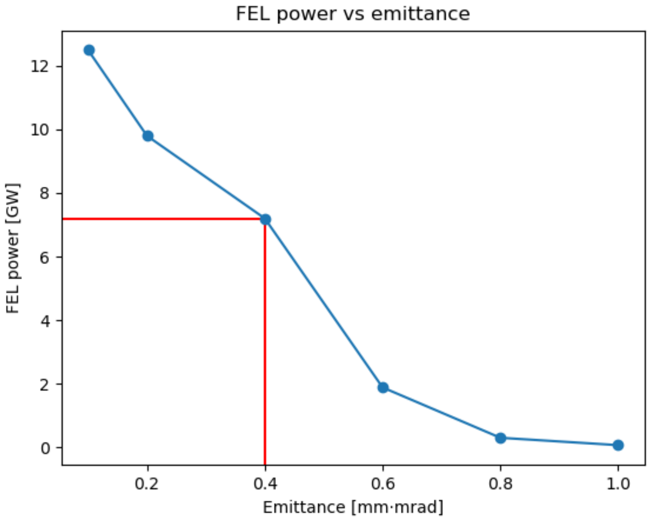

Figure 8: The maximum simulated power of the FEL radiation at 1.6 GeV electron energy at different emittance values for the electron beam. The red lines indicate the design value from Table 2 used in the other scans.

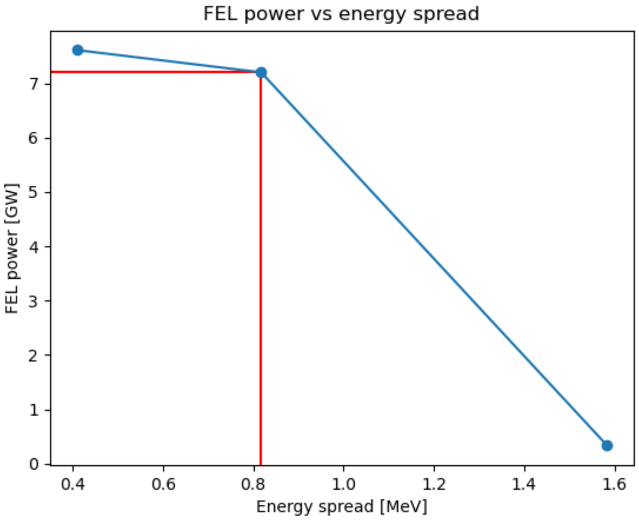

Figure 9: The maximum simulated power of the FEL radiation at 1.6 GeV electron energy at different energy spread values for the electron beam. The red lines indicate the design value from Table 2 used in the other scans.

The previous scans were all made in steady-state simulations, with the wavelength set to the resonant wavelength according to Equation 2. However, the optimal choice of wavelength is slightly higher than this resonant wavelength due to the slippage of the FEL bucket [19]. Therefore, the wavelength was changed to find the optimum choice for the steady-state simulations, which was at an increase to 2.4558 nm from 2.4518 nm, i.e. an increase of 0.004 nm. This optimisation is not necessary time-dependent simulations, which include a spectrum of wavelengths. The steady-state result was compared with a simulation made in time-dependent mode, since steady-state simulations do not provide as accurate results as a time-dependent simulation. Therefore, a few select time-dependent simulations were also made at interesting settings. Besides giving more accurate results in the simulations, time-dependent simulations also give information about the spectrum of the radiation. In Figure 10, we see the gain curve of a time-dependent simulation with the same settings as the 1.6 GeV simulation in steady-state above. The steady-state one reached a maximum FEL power of 10.8 GW, whereas this time-dependent simulation reached a maximum of 10.6 GW, with both showing signs of saturation. The same comparison was done for other selected energies, as well as for changes in emittance and energy spread, showing similar results. However, the time-dependent results showed some variation in the maximum FEL power, which is due to the randomised power distribution from the seed number in the input file. Therefore, eight additional time-dependent runs were made, with different seed numbers, at the settings for 1.6 GeV electron energy, and the average FEL power from these simulations was found to be 10.5 GW, which is slightly lower than the FEL power for the steady-state simulation.

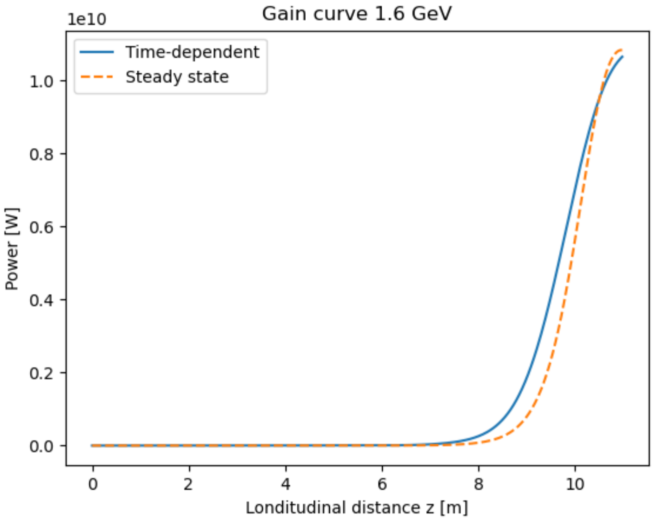

Figure 10: Gain curve for a time-dependent and a steady-state simulation for electron energy 1.6 GeV, with the same settings.

The time-dependent simulations did not only serve as comparison to the steady-state simulations, but also gave the spectrum of the radiation. The spectrum from the same simulation at 1.6 GeV discussed above is shown in Figure 11. The spectrum is very uneven, as is expected for a SASE spectrum, and spread out over a range of roughly 4 eV, corresponding in this case to a range from 2.445 nm to 2.465 nm. The exact shape of a SASE spectrum cannot be calculated before a run or simulation, but depends on the characteristics of the distribution of the electrons at the start of the undulator. Genesis calculates this distribution based on a seed, a number which helps determine the random parameters for the simulation. This means that the shape of the spectrum will be identical for different simulations if the seed is not changed. In order to compensate for this, eight different simulations were made with identical settings to the one for 1.6 GeV, except that the seed was changed to different randomised value for each run. These spectra were then added together, and a Gaussian fitted to the resulting spectrum. This could then be used to find both the photon energy at the peak of the spectrum, as well as the spectral bandwidth. These were found to be 504.9 eV, corresponding to a wavelength of 2.456 nm, and $\Delta E/E = 1.65 \cdot 10^{-3}$ using the $\sigma$-value from the Gaussian fit, respectively. The summed spectrum used for this analysis is found in Figure 12. This one resembles a Gaussian more than the one from a single simulation, Figure 11, but it is still quite uneven. Since only eight spectra were used, the statistics are not very good, which is the reason for this.

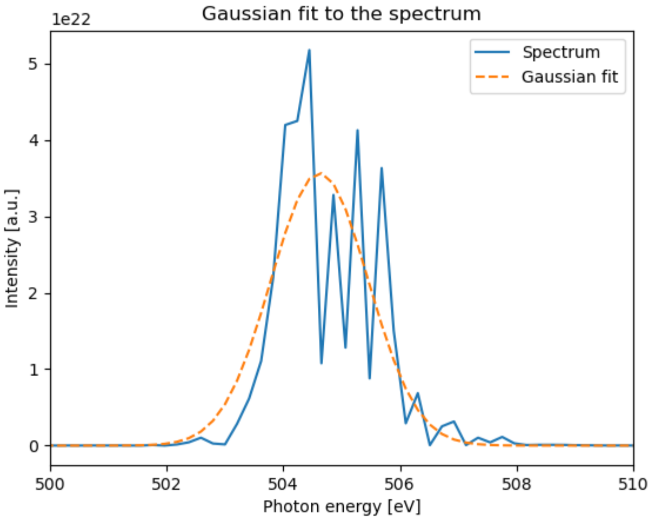

Figure 11: Spectrum for a time-dependent simulation for electron energy 1.6 GeV, with the same settings as the corresponding steady-state one shown in Figure 7. A Gaussian fit to the spectrum is also shown. The limits of the spectrum correspond to a wavelengths of 2.480 and 2.431 nm, respectively.

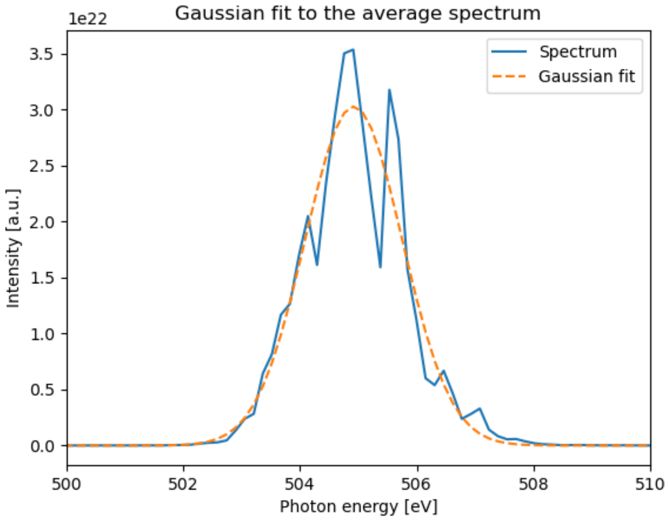

Figure 12: The average spectrum from eight different time-dependent simulations at 1.6 GeV electron energy with different seeds. A Gaussian is fitted to the spectrum.

## 4.1 Analysis

In order to analyse the results from the simulations, a Python code was written which could read the HDF5 files produced by Genesis. To find the FEL power, slightly different methods had to be used for steady-state simulations and time-dependent ones. In the first case, the array with the values of power of the field could be used as they were, but for the time-dependent simulations, the output was a 2-dimensional array with the power of each slice of the simulation over the entire length of the undulator. Since the power differs considerably in the different slices, but is expected to approximately follow a Gaussian distribution about the centre of the electron beam, a Gaussian fit over the slices was made. The maximum value of this Gaussian fit was used as the FEL power in the results above. An example of how the power was distributed over the slices, as well as the corresponding Gaussian fit, is shown in Figure 13.

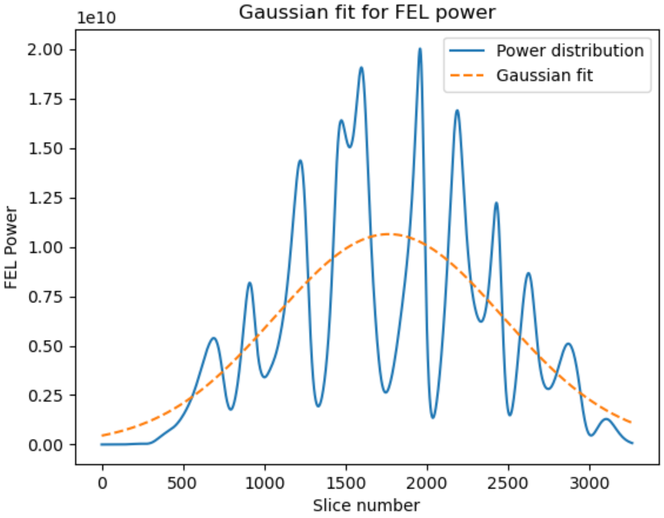

Figure 13: The FEL power for each slice of a time-dependent simulation at 1.6 GeV electron energy at the end of the undulator, with a Gaussian fit to the power distribution.

In order to compare the simulated FEL radiation to other FELs, the number of photons per pulse was calculated. This was done by using the peak photon energy of the spectrum, as identified above. By integrating the power distribution, as seen in Figure 13, over the slices, the total energy in the pulse could be found. To find the time corresponding to each slice, the total length of the simulated time window was divided by the number of slices. The total energy found from the integration was divided by the energy of a photon at the energy of the peak to find the number of photons. This of course ignores the energy spread of the photons. This was however very small, as found below, and so has no significant impact. The resulting number of photons per pulse at different energies is shown in Table 3

Table 3: The number of photons per pulse from the time-dependent simulations of the FEL at different electron energies.

| Electron energy [GeV] | Photons per pulse |
|---|---|
| 1.6 | $1.7 \cdot 10^{12}$ |
| 1.8 | $8.6 \cdot 10^{11}$ |
| 2.0 | $2.4 \cdot 10^{11}$ |

# 5 Discussion

## 5.1 Discussion of results

The behaviour of the simulations largely agree with theoretical expectations, with a few exceptions which will be discussed later. In fact, in many regards, the results indicate a performance which would be comparable with many major FELs. Although the simulations are made with realistic parameters from the linac, some choices of parameters are optimistic in nature. Therefore, the best results achieved in the simulations are not going to be found in practice, as will be discussed in detail for those cases.

### 5.1.1 Electron energy

By analysing the scan of the energy, finding the optimal electron energy to reach saturation at a certain wavelength can be done. However, this energy would be different than the injection energy for the rings, which would create difficulties for the operation of the facility. This is an additional topic that lies beyond the scope of this thesis. Therefore, there will be no conclusion made in this thesis which includes all aspects of the issue. However, it is worth considering that the larger the energy difference is, the greater the difficulty will be in combining the operations of the rings and the FEL. From the scan in Figure 6, it is clear to see that decreasing the energy below 1.6 GeV has little value, since it only leads to marginal increases in FEL power. This is however of course only true for the ideal settings in the simulation, with a peak current of 4 kA, an emittance of 0.4 mm·mrad, and an energy spread of $\Delta E/E = 5 \cdot 10^{-4}$. At these settings, saturation of the FEL process begins by the end of the undulators. Changing any of the other settings so that the gain length increases will mean that a reduced energy could in fact be useful to reach the same point of saturation as in this case. However, this case is not really interesting to discuss further, since those energies would be too low to combine with the other operations. 1.6 GeV is an optimistic, but possible choice of energy.

When looking at the actual FEL power at this electron energy, the value of 10.8 GW in steady state simulations, and the slightly lower average 10.5 GW in time-dependent simulations, is very good. As discussed previously though, the power itself is not a good measure for comparison of different sources, and so the number of photons was used. The results for the number of photons from Table 3 can be compared to those from other facilities, a selection of which are shown in Table 1. Seeing that the existing, dedicated FEL facilities like European XFEL have values very close to what is achieved in the simulation for 1.6 GeV electron energy at FemtoMAX, is a very promising result. Uncertainties in these results imply that the actual performance will not be on this level, but it is not unreasonable to achieve a performance not far from a smaller FEL like SwissFEL. Worth considering is that the length of undulator is comparatively very short, European XFEL has an undulator length of over 100 m [16], and the results nonetheless show a promising performance for the proposed FEL at FemtoMAX. The deciding differences explaining this are the shorter undulator period at FemtoMAX, and the longer wavelength radiation it would produce. Most importantly, it is seen that the suggested premise of decreasing the gain length by decreasing the electron energy made it possible to get FEL gain, and even reach saturation. Comparing also with MAX IV, the produced radiation has useful coherence properties which the radiation from FemtoMAX or the storage rings does not. Therefore, there is room for moving to greater electron energies with less photons per pulse and still providing interesting radiation. Being further from saturation does however mean that some coherence is lost, so one must proceed with caution when doing this.

Another consequence of this operation mode with low electron energy is longer wavelengths than European XFEL and LCLS. Depending on the choice of experiment, different wavelengths are desired. What can be deduced from the results here is that at the produced X-rays are in the soft X-ray range, and thus cannot compete with European XFEL or LCLS in terms of photon energies. The interesting regime will be around 1 to 5 nm, based on what electron energies gave a considerable exponential growth. By varying the $K$ parameter, the wavelength can be adjusted over a decently large interval. Since $0.9 < K < 2.7$ at FemtoMAX, as seen in Table 2, the wavelength range for 1.6 GeV electron energy is 1.07 nm to 3.55 nm. Based on Equation 4 and its dependence on $K$, the gain length and thus the power would also change because of this change. For large changes in

$K$, the gain would be significantly impacted, but for smaller tuning of the wavelength, the effect should not be too large.

### 5.1.2 Other electron beam parameters

The simulated dependence of FEL power on the peak current of the electron beam, as seen in Figure 5, behaves much as one would expect. For these scans, the wavelength was not optimised. The qualitative conclusions are however still valid. From the inversely linear dependence of gain length on peak current from Equations 3 and 4, a linear increase in peak current is expected to lead to a linear decrease in gain length. As long as the FEL process is far from saturation, this would in turn result in an exponential increase in FEL power. As seen in Figure 10, the FEL reached saturation at energies around 10 GW, which is far above any of the points in the scan for peak current. It would still be far from saturation if the wavelength was optimised. An exponential increase in FEL power with peak current of course means that it is very important to have the peak current be as large as possible. It might actually be possible to increase the peak current beyond 4 kA in the linac, as this has been shown in simulations [12]. However, it is difficult to measure the exact peak current of the linac, and thus the maximum achievable peak current is not known. Therefore, this potentially conservative value of 4 kA was chosen as maximum. If the peak current would increase further, considering the exponential increase seen in Figure 5, the FEL power could be considerably improved in the cases where it does not reach saturation. More importantly, though, it would enable the FEL to reach saturation at higher electron energies, and consequently shorter wavelengths. This would broaden the wavelength range in which the FEL could operate. Furthermore, since it is difficult to lower the energy of the linac, there is some unknown lower limit for the electron energy at which the FEL could operate. Consequently, being able to reach saturation at higher electron energies would make it easier to realise the FEL at FemtoMAX. The choice of 4 kA is however a reasonable maximum value, so one cannot reasonably expect much larger values of the peak current.

Scans were also performed for emittance and energy spread. As the results in Figures 8 and 9 show, any increase from the design values for the linac gives a noticeable change in FEL power. In both cases however, the significant gain from the FEL process remains when the respective values are increased, and though the final result is less competitive, it does not fundamentally change the conclusion from the results. Nonetheless, the results clearly show that these parameters are very important for the proper function of an FEL. Changing the energy spread to twice its design value gave a decrease of around a factor 20, which shows a very large sensibility. However, this energy spread is achievable with the current linac, so it is reasonable to expect the result from the simulation with the design value to be accurate. For the emittance however, the design value of 0.4 mm·mrad has been achieved in simulations [18], but not yet measured. Therefore, the design value used in these simulations is optimistic, but not unrealistic. A more realistic value for the facility currently would be around 1.0 mm·mrad, with potential to go lower in the future. In the simulations, this gave an FEL power a factor ten smaller than for 0.4 mm·mrad. This is a clear decrease, but the exponential gain is still present. The actual power may differ depending on how one can optimise different parameters, and the simulations are not perfectly accurate in terms of final power. However, showing that there is an exponential gain means that it is possible to convert FemtoMAX into an FEL, which is the main goal of this thesis.

Furthermore, it is worth considering that the scans of emittance and energy spread were taken at 1.6 GeV, and that saturation was present at the design values of these parameters. Consequently, decreasing these values simply served to give saturation earlier, without considerably increasing the power. For the energy spread, the gain process shifted around a meter compared to the design value, reaching total saturation before 11 m, but without increasing the power significantly. Had the scan been taken at a higher electron energy, this decrease in energy spread would have increased the FEL power considerably more. For the emittance, the scan shows a considerable increase in power with decreasing emittance, as expected, but this could actually have been even greater if the process was not close to saturation.

### 5.1.3 Time-dependent results

In the analysis of the spectra and power distributions from time-dependent simulations, a Gaussian fit was made to extract values such as the peak wavelength, spectral bandwidth and FEL power. As a consequence of the SASE process, specifically the random shotnoise generated at the start of the undulator, individual distributions are not very similar to a Gaussian. This problem is further accentuated by having run simulations with relatively few particles, which limits the resolution of these distributions. Using a Gaussian fit is a reasonable assumption, as can be seen in the average spectrum in Figure 12, which resembled a Gaussian more. If it would have been possible to make a considerably larger number of simulations, the results would have been slightly more accurate. This would have made the comparison with steady-state simulations slightly more accurate as well.

### 5.1.4 Spectrum

Looking at the spectrum of the radiation, like in Figure 11, one can see that it is very uneven. The consequence of the uneven spectrum is that it represents a reduction in the quality of the photon beam. When performing experiments with accelerator-based light sources, having a well-defined wavelength can be crucial for certain experiments, and regardless of whether the wavelength is of imperative importance to the specific experiment, the results will be less clear and more difficult to analyse if the radiation wavelength is not well-defined. This uneven spectrum is inherent to the SASE process. Using the seeding process described in the Theory section, a Gaussian-like spectrum with a more well-defined wavelength can be achieved. The minimum wavelength is however limited by the wavelength of the seed radiation, and so even with schemes such as HGHG, the soft X-ray wavelengths produced in these simulations are not attainable.

Another important aspect of the spectrum of the radiation, which is also very important in measurements, is the bandwidth. Having a narrow bandwidth corresponds to having most photons in a narrow band of energy around the central wavelength. In some cases, this can be of more experimental importance than having a large temporal coherence, especially if the bandwidth is narrow enough. The relative bandwidth from these simulations at 1.6 GeV was found to be $\Delta E/E = 1.65 \cdot 10^{-3}$ at a photon energy of 504.9 eV, corresponding to a bandwidth of 833 meV. Compared to other accelerator based X-ray sources, this is quite good. The European XFEL has a FWHM relative bandwidth around $2 \cdot 10^{-3}$ for its lowest photon energies [2]. This is larger than the simulated value not only in that it uses FWHM instead of the fitted $\sigma$ from the Gaussian distribution as in this report, corresponding to a factor of $2\sqrt{2\ln(2)}$, but also in a considerably larger bandwidth in eV, since the photon energy there is greater than 2 keV. Since the European XFEL also operates according to the SASE principle, this is the most fair comparison to the prospective FEL at FemtoMAX, and it is clear that it is definitely competitive. Of course, the difference in photon energy makes the comparison slightly unfair. The result does show that the bandwidth is not an area where the simulated FEL has any considerable drawbacks compared to existing FELs.

## 5.2 Sources of error and uncertainties

The sources of error can be divided into two categories, those resulting from uncertainties with the capabilities of the MAX IV linac, for instance what the actual values of the electron beam emittance, peak current, and energy spread are. The second category is the group of errors and uncertainties in the simulation in Genesis. When dealing with the experimental values from the SPF facility, realistic values from the facility have been chosen. As will be discussed later though, some of these values are not accurately known at the time of writing.

The simulation of the FEL starts with the undulators, and does not include the matching section. An assumption was therefore made, that the matching section could provide the initial twiss parameters used in the simulation. This might not be the case, which would introduce an error. Furthermore, the choice of beta functions was based in the optimal values found in Simplex simulations. Because of the undulator focusing in the vertical plane, the beta functions changed for different electron energies. This means that for extreme values around 1 and 3 GeV, the vertical beta function average was far away from the optimum. This will have changed the FEL power slightly at these energies. The most interesting simulations, which are around 2 GeV, are however all close to the optimal beta value. The longitudinal shape of the electron beam was assumed to be a Gaussian, which does not agree perfectly with the actual shape. This idealisation is however a reasonable assumption, and should not differ much from the real longitudinal profile.

The number of electrons in the simulation differs from the actual number. An actual electron beam has a very large number of electrons, $6.24 \cdot 10^8$ for a bunch charge of 100 pC. For the simulation however, a considerably smaller number of electrons are simulated. The simulation had 8192 particles per slice, resulting in a total number on the order of $10^7$ particles, depending on the number of slices. This is enough to simulate the microbunching of the electron beam, and will give a decent result. It is however reasonable to expect that there are some effects which are missed in the simulation when fewer particles are simulated. Particularly, the detail in the spectrum and power distribution of the beam is reduced. The power should however not be considerably affected [15].

## 6 Conclusions and outlook

A potential FEL at the end of the linac at MAX IV is a possibility planned for since the construction of MAX IV, but has never become reality. Instead of building a separate FEL, the existing FemtoMAX beamline could be converted to an FEL. By decreasing the electron energy from the linac, very intense FEL radiation could be generated in an interesting soft X-ray wavelength regime by the undulators currently at FemtoMAX. This, and the associated exponential gain has been shown by simulations in Genesis. Since the FEL would use the same undulators currently installed at FemtoMAX, the two operation modes could implemented alternatively, depending on the measurement. The changes needed to switch to an FEL are adjusting the matching section to get an appropriate electron beam and lowering the electron energy.

The change in energy is however not easy to achieve. In fact, it is beyond the scope of this thesis to discuss this problem. At 3 GeV electron energy, the limitation of the undulator length would mean that the FEL process would not go on for long enough to get any of the advantages of an FEL in terms of coherence or exponential growth of the intensity. However, if it is possible to lower the energy to 2 GeV, or maybe even further, the FEL process has time to get close to, or even reach, saturation, achieving a large exponential growth in power. At what was found to be the optimal electron energy, 1.6 GeV, the simulated radiation is close to some of the leading FELs in the world, like European XFEL and LCLS, in terms of several key characteristics, such as the number of photons per pulse and the bandwidth of the radiation. Even at slightly higher electron energies, the results are comparable to other FELs, which have been constructed specifically to be FELs, like SwissFEL. These comparisons are promising for the possibility of an FEL at FemtoMAX. If the hurdle of lowering the energy of the linac is overcome, the possible FEL could be able to produce very intense radiation in the soft X-ray regime. Although it could not compete with the likes of European XFEL in terms of wavelength, this is still an interesting regime, with shorter wavelengths than what is achievable with seeded FELs or traditional lasers.

Some of the uncertainties of these results could be mitigated if one were to investigate this topic further. Primarily the errors and uncertainties related to the simulation could be improved significantly if time was taken to perform more simulations across the entire parameter space. Parameters such as the number of particles and other similar aspects of the simulation could also be optimised, but this would not drastically change the results. Improving all these parameters to the ideal values would result in simulations which would take considerably longer to run than the ones used in this thesis. Considering that each scan of a parameter would require a large number of simulations for each value of the parameter, in order to get a decent Gaussian fit to the power and spectrum, this would be an very large amount of work.

Something which would require less work, but still give some more interesting information from the simulations, would be performing the same scans at different choices of other parameters. It might especially be interesting to investigate the emittance and energy spread at higher electron energies, where the process would not reach saturation. Similarly, investigating the peak current at lower electron energies, where the process gets close to saturation, would also be interesting. To get a full grasp of the parameter space, this should be done for all possible combinations of values of course, to see if e.g. changing peak current and emittance simultaneously has the effect on the gain curve one might expect based on the separate scans. Furthermore, investigating the choice of $K$-parameter would also be interesting, especially in combination with other parameters. For this thesis, the impact of this parameter was calculated using theoretical equations, but it would be interesting to investigate it in simulations as well.

To be certain of how an FEL at FemtoMAX would behave, the most important investigation is to find certain values for the parameters of the electron beam. By measuring the beam, one could get up to date values for the emittance, bunch charge, peak current and energy spread. If these were known, a set of simulations with different seeds, using the most realistic parameters possible could be made. Such simulations, using the known parameters of the linac and which had been optimised as described above, would give trustworthy results about what one could expect from an FEL at FemtoMAX. One important aspect of the experimental considerations would be to analyse the matching section at the end of the linac, to make sure it could produce the desired beta functions.

If one would want to improve the performance of the FEL, this is also an area where one could relatively easily do so. By including a quadrupole between the two undulators, the beta functions could be controlled much more accurately, giving averages closer to the optimum. This would improve the gain of the FEL across all electron energies, and particularly for those high and low energies where the beta functions are not well-behaved.

The key questions remaining for the prospective FEL are primarily the lowering of the electron energy, which will not be discussed further, and the emittance of the electron beam from the linac. For emittance values close to the design value of 0.4 mm·mrad, there is considerable gain. It is likely that such a value can be achieved, but that will be difficult. Therefore, this might be a limitation which prevents the gain from reaching the levels of a useful FEL. Apart from this question though, the results from the simulations give a positive outlook. In fact, it might be possible to increase the peak current beyond the maximum value used in the simulations, which could counter the effects of the lower emittance somewhat. If the electron energy could be lowered further than 1.6 GeV, the same effect could be achieved. Of course, this would lengthen the wavelength of the radiation, but there is some room for adjusting this with the $K$-parameter.

In conclusion, it has been shown from simulations that an FEL with considerable exponential growth at FemtoMAX is possible. The performed simulations showed that at an electron energy of 1.6 GeV, corresponding to a wavelength of 2.5 nm, the process even reaches saturation, with considerable gain also for higher electron energies. This shows great promise for the possibility of such an FEL.

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# References

[1] M. Altarelli. X-ray FEL Science: The International Perspective. `https://www.clf.stfc.ac.uk/Pages/Altarelli_London_2019_s.pdf`, July 2019.

[2] A.P. Mancuso et.al. Scientific Instrument Single Particles, Clusters, and Biomolecules (SPB). Technical report, European XFEL, 2013.

[3] H. Enquist, A. Jurgilaitis, A. Jarnac, Å. U. J. Bengtsson, M. Burza, F. Curbis, C. Disch, J. C. Ekström, M. Harb, L. Isaksson, M. Kotur, D. Kroon, F. Lindau, E. Mansten, J. Nygaard, A. I. H. Persson, V. T. Pham, M. Rissi, S. Thorin, C.-M. Tu, E. Wallén, X. Wang, S. Werin, and J. Larsson. FemtoMAX – an X-ray beamline for structural dynamics at the short-pulse facility of MAX IV. *Journal of Synchrotron Radiation*, 25(2):570–579, Mar 2018.

[4] Hansen, Jordis. Feasibility Study of X-ray Free Electron Lasers in Fourth Generation Storage Rings, 2023. Bachelor thesis.

[5] Z. Huang. Brightness and Coherence of Synchrotron Radiation and FELs. In *4th International Particle Accelerator Conference*, page MOYCB101, 2013.

[6] Z. Huang and K.-J. Kim. Review of x-ray free-electron laser theory. *Phys. Rev. ST Accel. Beams*, 10:034801, Mar 2007.

[7] Q.-K. Jia, D.-H. He, S.-K. Lu, S.-C. Zhang, Y. Cao, Z.-M. Dai, Z.-T. Zhao, C. Yun, and Q.-G. Zhou. Design of undulator for the Shanghai DUV-FEL. In *26th International Free Electron Laser Conference and 11th FEL User Workshop (FEL 04)*, page 495, 8 2004.

[8] K.-J. Kim, Z. Huang, and R. Lindberg. *Synchrotron Radiation and Free-Electron Lasers: Principles of Coherent X-Ray Generation.* Cambridge University Press, 2017.

[9] A. L'Huillier and P. Balcou. High-order harmonic generation in rare gases with a 1-ps 1053-nm laser. *Phys. Rev. Lett.*, 70:774–777, Feb 1993.

[10] N. Martensson and M. Eriksson. The saga of max iv, the first multi-bend achromat synchrotron light source. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 907:97–104, 2018. Advances in Instrumentation and Experimental Methods (Special Issue in Honour of Kai Siegbahn).

[11] Femtomax. `https://www.maxiv.lu.se/beamlines-accelerators/beamlines/femtomax/`, June 2023.

[12] W. Qin, F. Curbis, J. Andersson, V. Goryashko, L. Isaksson, B. Kyle, F. Lindau, E. Mansten, M. Pop, P. Salén, H. Tarawneh, P. F. Tavares, S. Thorin, A. Vorozhtsov, and S. Werin. The FEL in the SXL project at MAX IV. *Journal of Synchrotron Radiation*, 28(3):707–717, May 2021.

[13] M. Quattromini, M. Artioli, E. Di Palma, A. Petralia, and L. Giannessi. Focusing properties of linear undulators. *Phys. Rev. ST Accel. Beams*, 15:080704, Aug 2012.

[14] S. Reiche. Genesis 1.3: a fully 3d time-dependent fel simulation code. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 429(1):243–248, 1999.

[15] S. Reiche. *Numerical studies for a single pass high gain free electron laser.* PhD thesis, Hamburg U., 2000.

[16] E. Schneidmiller and M. Yurkov. Reverse Undulator Tapering for Polarization Control and Background-Free Harmonic Production in XFELs: Results from FLASH. In *Proc. of International Free Electron Laser Conference (FEL'17), Santa Fe, NM, USA, August 20-25, 2017*, number 38 in International Free Electron Laser Conference, pages 106–108, Geneva, Switzerland, Feb. 2018. JACoW. https://doi.org/10.18429/JACoW-FEL2017-MOP032.

[17] T. Tanaka. SIMPLEX: simulator and postprocessor for free-electron laser experiments. *J. Synchrotron Radiat.*, 22(5):1319–1326, Sept. 2015.

[18] S. Thorin, J. Andersson, F. Curbis, M. Eriksson, O. Karlberg, D. Kumbaro, E. Mansten, D. Olsson, and S. Werin. The MAX IV Linac. In *27th International Linear Accelerator Conference*, pages 400–403, 2014.

[19] S. Werin. *Accelerator technique.* Max-lab, 2.5th edition, 2006.

# 7 Appendix

Example of input file for a steady state simulation at 1.6 GeV electron energy, and 4 kA peak current. The corresponding lattice file is also included below, with the settings for FemtoMAX, with a of $a_w$ corresponding to a $K$-value of 2.1.

## Input file

---

```
&setup
rootname=Scan_energy
lattice=lattice_FemtoMAX.lat
beamline=FemtoMAX
lambda0=2.4518e-09
gamma0=3131.1
delz=0.015
shotnoise=0
seed=795715
npart=8192
nbins=4
&end

&profile_gauss
label=current
c0=4000.000000
s0=0.00e-6
sig=2.99e-06
&end

&beam
current=@current
gamma=3131.1
delgam=1.6
ex=4.000000e-07
ey=4.000000e-07
betax=12.0
betay=7.0
alphax=0.7
alphay=-0.7
xcenter=0
&end


&field
power=1.04e2
dgrid=1.000000e-03
ngrid=151
waist_size=6.000000e-5
&end

&track
beam_dump_step=3000
```

```
output_step=2
&end
```

## Lattice file

```
undu01 : undulator = { lambdau = 0.015, nwig = 333, aw = 1.4849, helical = false, gradx=0.0, ax=0.0 };

d : drift = { l = 1.000 };

FemtoMAX: line = {undu01, d, undu01};
```