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SIMULATION STUDIES ON AN XUV HIGH-GAIN FEL OSCILLATOR AT FLASH

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Abstract

Externally seeded high-gain FELs are capable of providing fully coherent radiation with high shot-to-shot stability at wavelengths down to the soft X-ray range (with the use of harmonic conversion schemes). However, present seed laser sources are not suitable for the generation of short-wavelength FEL radiation at high repetition rates. As a result, such setups have been unable to make use of the full repetition rate of superconducting machines. Cavity-based FELs have been proposed as one possible way to overcome these limitations, allowing to combine short wavelengths and high repetition rates, while preserving the full coherence. We present simulation studies for such a high-gain FEL oscillator planned for FLASH, which is aimed at the generation of fully coherent radiation at 13.5 nm and the repetition rate of 3 MHz. Moreover, achieving bunching on that wavelength would make it possible to generate fully coherent radiation at much shorter wavelengths with the use of harmonic conversion schemes.

INTRODUCTION

FELs operating in self-amplified spontaneous emission (SASE) mode deliver high-power FEL output and allow wavelength tunability down to the X-ray range. However, SASE radiation has only a limited temporal coherence and low shot-to-shot stability. Temporal coherence as well as stability are improved in externally seeded setups [1]. In this case, the setup relies on a seed laser as a coherent source, and the FEL radiation inherits its coherent properties. In this way, fully coherent FEL radiation at the wavelength of the seed laser or, with the use of harmonic conversion schemes, its harmonics can be generated. The limitation of such schemes lies in the availability of suitable seed laser sources. For instance, externally seeded FELs, generating output FEL radiation in XUV range have been limited in the repetition rates of tens of Hz due to the lack of sufficiently high-power laser sources at appropriate wavelengths. So, such schemes have been unable to make full use of the ultra-high rep rates (several MHz) of electron bunches at superconducting linear accelerators, such as FLASH [2, 3].

Cavity-based FELs promise the generation fully coherent FEL pulses without relying on a seed laser. The basic principle is to store the FEL pulse in a cavity and reuse it for seeding the bunches at the desired repetition rate. The repetition rate has to be matched to the cavity length. For the choice of the operation wavelength of the cavity, the availability of mirrors is critical. As long as the FEL gain is larger than the losses in the cavity, the power rises from pass to pass, making it possible to start from shot noise in the first pass and build up the power to the steady state level. There have been several proposals for hard X-ray cavity-based FELs operating in both low-gain [4, 5], and high-gain [6, 7] regimes, based on high-reflectivity crystal mirrors. The use of multi-layer mirrors in the XUV range was considered as well [8]. Cavity-based FELs have also been proposed as the first stage in multi-stage setups [8, 9].

Here, we introduce an ongoing cavity-based FEL project at FLASH and present the first simulation results.

SETUP

In the framework of the XRAY project (XUV generation by Resonator-Aided seeding with ultra-high repetition rate and Yield) an XUV high-gain FEL oscillator setup is being implemented at FLASH. A scheme of the setup is shown in Fig. 1. Variable-gap undulators are enclosed in a cavity, which is formed by two end mirrors. One of the end mirrors is curved and provides focusing of the intra-cavity field, necessary for maintaining a reasonable spot size in the undulators.

For the experiment at FLASH, the repetition rate of 3 MHz will be used in burst mode. The cavity round-trip length is chosen to be 100 m, so that a single pulse is stored in the cavity. At normal/quasinormal incidence, Mo/Si multi-layer mirrors will be used, which provide above 65% reflectivity (per mirror) at 13.5 nm [10]. The operation in high-gain regime, which implies exponential FEL amplification within a single pass, would allow the system to tolerate these significant losses and regenerate the power from a fraction of the power left from the previous pass. The expected reflectivity bandwidth exceeds the natural FEL bandwidth, so the mirrors do not provide a significant monochromatisation. For the current experimental setup no dedicated monochromator is considered. It can, however, be implemented at a later stage, once a stable operation of the scheme is tested.

SIMULATIONS

Simulation Setup

The simulations for the setup were done in multiple passes, splitting the FEL amplification and the propagation in the cavity between two codes. The FEL process is simulated using Genesis 1.3 version 4 [11], which is a time-dependent, three-dimensional FEL simulation code. The propagation of the optical field outside of the undulator section is done in Ocelot [12], a python-based simulation toolkit aimed at the study of FELs and synchrotron light sources. In the first pass, FEL process starting from shot noise is simulated in Genesis 1.3 and the output field is passed to Ocelot. There,

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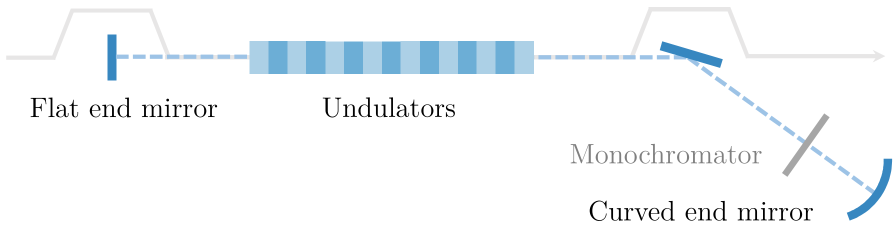

Figure 1: Scheme of the oscillator setup. The electron beam path is shown with a solid grey line, while the path of the FEL pulse is shown with a dashed blue line. The monochromator, shown symbolically, is currently only implemented in the simulations.

the field is propagated up to the curved mirror, focused, and propagated back to the entrance of the undulator. The intensity of the field is scaled by the effective reflectivity R, which accounts for the total losses in the cavity. In the current study we assume R to be constant. The output field from Ocelot is then passed back to Genesis 1.3, where it is used as a seed for a fresh electron bunch.

In the following, we show simulations for the setup with a monochromator, which are important in order to understand its influence and consider its potential future use. The monochromator is implemented in Ocelot in the form of a Gaussian filter in frequency domain and we assume its central wavelength and bandwidth to be constant. The electron bunch length is matched to the monochromator bandwidth in order to support Fourier-limited pulses. The main simulation parameters are summarized in Table 1.

Table 1: Simulation Parameters

Quantity	**Value**
Beam energy	1.2 GeV
Beam current (flattop)	500 A
rms energy spread	100 keV
Radius of curvature of focusing mirror	60 m
Cavity round-trip length	100 m
Relative monochromator bandwidth	2.5×10^{-4}

Simulation Results

We expect the power in the oscillator to increase until it reaches a steady state. It is of absolute importance to know the steady state power and to be able to control it. This is required for keeping the power below the damage threshold of the mirrors. Furthermore, it is relevant for experimental needs, for instance, if a part of the field has to be extracted. Alternatively, we can foresee the possibility to use the oscillator for electron beam manipulation in the first stage of a multi-stage setup, which also requires precise control of the power. As for the number of passes in which the steady state is reached, it is an important parameter due to the burst mode operation. There is only a limited number of bunches in the bunch train, hence we would like to minimize duration of the buildup phase.

This requires the understanding of the different factors affecting the buildup and the steady state. In general, these include effects influencing the FEL gain or the losses in the cavity, e. g. mirror losses, focusing, cavity detuning, FEL tuning etc. Here we will focus on the effect of two parameters – the mirror reflectivity and the electron beam energy.

We look at the way the peak output power changes as a function of number of passes through the cavity. In Fig. 2, power buildup curves are shown for different values of the effective reflectivity R. Notice that the power stays at a shot noise level for several passes, then quickly rises and comes to a steady state, where the FEL amplification exactly balances the losses in the cavity. The plot shows, that the steady state power, as well as the buildup duration depend on the effective reflectivity R. As one would expect, a higher reflectivity results in a faster buildup and a higher steady state power. Note that the mirror damage threshold is not considered here, so no constraints were set on the power level.

The influence of the electron beam energy γ on the power buildup is illustrated in Fig. 3. The figure shows power buildup curves corresponding to different values of $\Delta\gamma = \gamma - \gamma_0$, where $\gamma_0 = 2348.5$ is the reference beam energy. Such a dependence on beam energy is largely caused by the monochromator, and the magnitude of the effect generally depends on the monochromator bandwidth, which we consider to be fixed (see Table 1). The monochromator ensures that the seed pulse has a narrow bandwidth centered around a fixed wavelength (13.5 nm), which prevents a possible drift in the wavelength from pass to pass. In order to provide maximum gain, the FEL should be tuned to the seed wavelength according to the resonance condition [13]

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \qquad (1)$$

where λ is the radiation wavelength (center of the FEL bandwidth), λ_u – the undulator period, K – the undulator parameter. We are working at a fixed K, so the tuning is done with the beam energy γ. In the first approximation, γ has to fulfil $\lambda = \lambda_{seed}$. Choosing a different γ results in a decrease of the FEL gain and, additionally, an increase of the losses in the monochromator. This explains why the power buildup is γ-dependent.

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In Fig. 3, one can also notice a certain trade-off between the buildup duration and the steady state power. The beam energy yielding the highest steady state power provides a comparatively slow buildup. In our understanding, this effect is due to the interplay between optimal coupling and seed power in the amplification. Higher γ values which are optimal for higher seed powers provide a high-power steady state, but perform poorly at the lower power levels of the early buildup phase. Achieving a combination of fast buildup and high steady state power would require, e.g., ramping the beam energy from pass to pass.

In summary, we can see that in the presence of a monochromator, detuning the FEL by changing the beam energy also provides a possibility for tuning the steady state power. In the absence of a monochromator, different knobs for tuning the output power have to be considered.

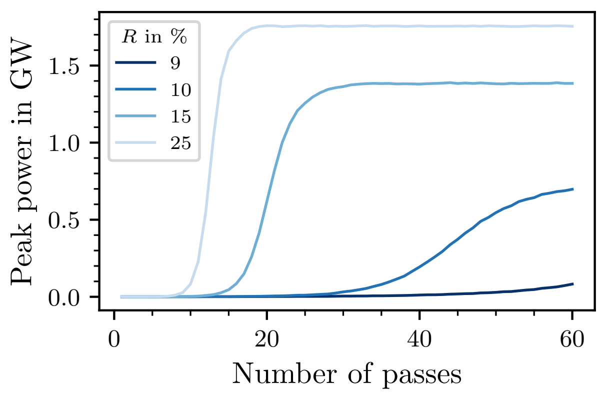

Figure 2: Power buildup curves for different effective reflectivities at a fixed electron beam energy $\gamma_0 = 2348.5$.

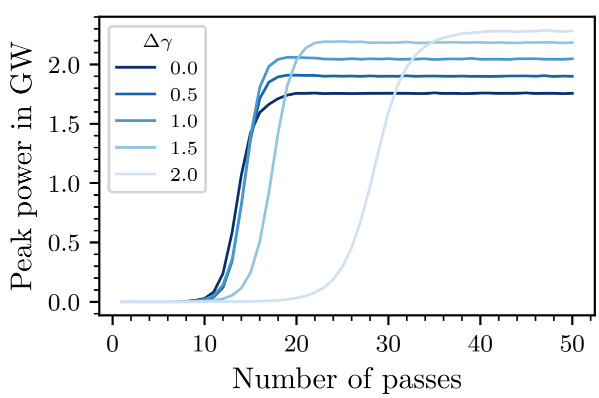

Figure 3: Power buildup curves for different beam energies γ at a fixed effective reflectivity $R = 25\%$. $\Delta\gamma$ is the difference of the beam energy and the reference energy $\gamma_0 = 2348.5$.

Next, we explore how the radiation spectrum changes until the steady state is reached. We consider the setup with $R = 10\%$ and the beam energy of $\gamma_0 = 2348.5$, optimized for a fast buildup. Normalized spectral intensities for different passes are shown in Fig. 4. The first pass shows, as expected, a SASE spectrum. In the third pass, multiple peaks can still be seen, since the seed power is still rather low and not significantly above the shot noise level. Passes 30 and 50 show the operation in the seeded regime, where a clear, single peak is seen. Notice the narrowing of the bandwidth towards the steady state.

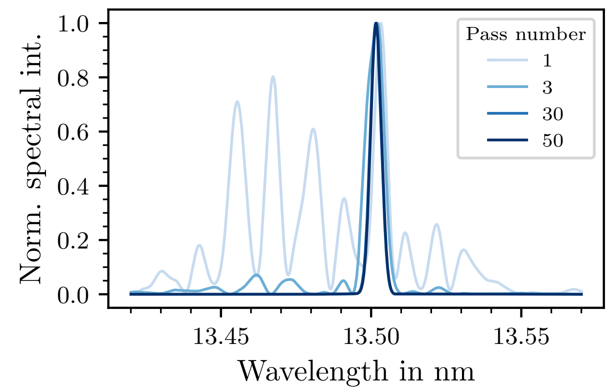

Figure 4: Spectra at different passes for the case with $R = 10\%$ and $\gamma = \gamma_0 = 2348.5$.

CONCLUSION AND OUTLOOK

XUV high-gain FEL oscillator is a promising scheme for delivering narrow-bandwidth FEL pulses in XUV range at MHz repetition rates. We have shown simulations for such a setup with an implemented monochromator. The simulations illustrate the influence of cavity losses and electron beam energy on the power buildup in the oscillator. They also showed that the monochromator allows the oscillator to reach seeded operation in several passes, resulting in a stable, single-peak spectrum.

In parallel to the hardware installation at FLASH towards the demonstration of an XUV high-gain FEL oscillator, further simulations will be done to study the behavior of the oscillator. In particular, the power buildup in the absence of the monochromator and the effect of the cavity detuning have to be further considered, as well as the influence of jitters and misalignment on the performance of the setup. The possibility for undulator tapering can also be studied in tandem with the beam energy dependence.

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