ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP073

HIGH-REPETITION-RATE SEEDING SCHEMES USING A RESONATOR-AMPLIFIER SETUP

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Abstract

The spectral and temporal properties of Free-Electron Lasers (FEL) operating on the basis of self-amplified spontaneous emission (SASE) suffer from the stochastic behavior of the start-up process that fluctuates on a bunch-to-bunch basis. Several so-called ”seeding”-techniques using external radiation fields to overcome this limitation have been proposed and demonstrated. The external seed is usually generated by high-power laser systems, which are not yet available with a sufficient laser pulse energy at the high repetition rates of superconducting FEL facilities. In this contribution we discuss several seeding schemes that lower the requirements for the used laser systems, enabling seeded operation at high repetition rates by the means of a resonator-amplifier setup.

INTRODUCTION

Recently, more and more FEL facilities worldwide have been built to meet the risen number of photon scientists' experiments. The first of those facilities is FLASH, the Free-Electron Laser in Hamburg [1, 2]. Many facilities use the self-amplification by stimulated emission of radiation (SASE) principle, which suffers from poor temporal and spectral properties due to the stochastic behavior of the start-up process.

Several seeding techniques [3] have been experimentally studied, from the direct-seeding approach, e.g. using High-Harmonic Generation (HHG) [4] to phase-space manipulation techniques like High-Gain Harmonic Generation (HGHG) [5–7] or Echo-Enabled Harmonic Generation (EEHG) [8, 9] using external laser fields, which are currently limited in target wavelength and repetition rate. For FLASH, the future use of these techniques is currently under study [10, 11] as well as for the European X-Ray Free-Electron Laser (EuXFEL) [12].

In contrast to the aforementioned laser-based seeding chemes, methods like active spectral filtering of SASE radiation allow for amplification of radiation without the need of an external seed laser, thus they are working at any wavelength or repetition rate and are not in the scope of this contribution.

Motivation

Most of the seeding techniques rely on the availability of laser systems with high power, short wavelengths, and high peak intensities. For the typical burst repetition rates of free-electron lasers driven by superconducting linear accelerators - 4.5 MHz at EuXFEL or 1.003 MHz at FLASH - and depending on the power needed, such laser systems are not easily available. A reduction in the repetition rate of the photon burst is sometimes not desired, as for the usual diluted samples a large number of FEL pulses is needed to get sufficient statistics. Some photon science experiments however only use a fraction of this repetition rate like time-of-flight measurements with typical timescales of several µs.

In the past, resonators at low-gain FELs have been investigated using time-independent simulation codes [13–16]. Recently, also some studies taking advantage of time-dependent and three-dimensional simulation codes have been performed [17]. The idea of building an optical cavity around an undulator at FLASH has also already been studied [18].

The usage of a resonator-amplifier setup for a seeded FEL is a promising approach to reach short wavelengths at the high repetition-rates of superconducting linear accelerators - reaching the water window at around 4 nm using HGHG seeding and 1 nm using EEHG.

First simulations relying upon a resonator setup to drive an High-Gain Harmonic-Generation seeded FEL operating at the 10^{th} harmonic for operating parameters in the FLASH parameter range are currently being conducted, showing promising results [19].

BASIC SETUP

An electron bunch generates radiation, either directly seeded or by the spontaneous undulator radiation, in an undulator called modulator. This modulator can consist of several undulator modules. Its main purpose is to imprint an energy modulation onto the electron bunch. The radiation is reflected by mirrors, then stretched and slightly monochromatized by a grating, and focused in the modulator again where it is overlapped with the next electron bunch. This set of hardware components is called resonator and can be seen in Fig.1. Eventually, after several fresh bunches, an equilibrium state will be reached where the radiation losses over a round trip are compensated by the generation of radiation in the modulator. The electron bunches can then be used in the different seeding schemes exploiting their beneficial longitudinal electron density distribution.

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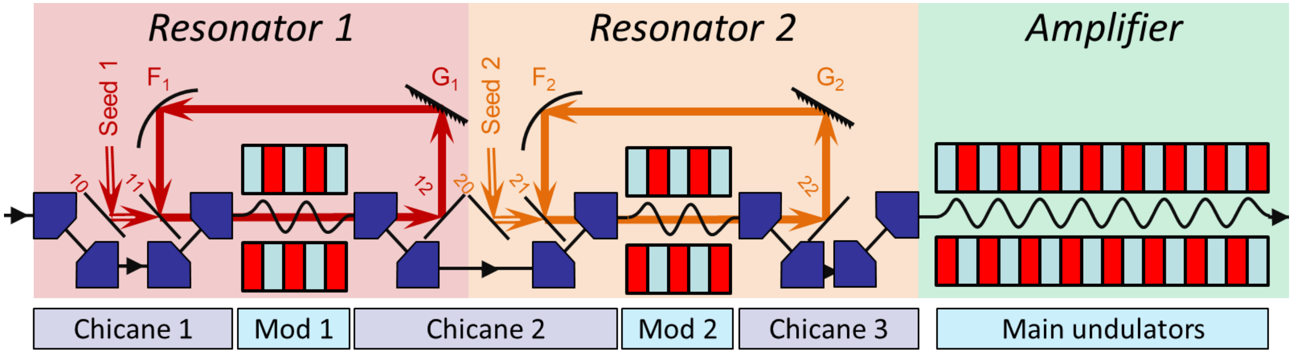

Figure 1: Resonator-amplifier setup. Each resonator consists of a small undulator, called modulator, two plain mirrors M_{11} and M_{12} (M_{21}, M_{22}), a grating G_1 (G_2) and a focusing element F_1 (F_2). In addition, through one element M_{01} (M_{02}) an external seed can be coupled into the optical cavity. The complete resonator is then enclosed by two chicanes to bend the electron beam around the optical elements on the modulator axis and to convert the energy modulation introduced in the modulator into a longitudinal electron density distribution. In the shown configuration both resonators share the second chicane. The resonators are followed by the amplifier, which is also used as the main undulator if the FEL is driven in SASE mode. The sketch does not reflect any scales. Also, the position of the optical components is only for demonstrative purposes.

HIGH REPETITION RATES IN BURST MODE

The following section focuses on several seeding schemes that are currently under study for the use with a resonator-amplifier FEL setup.

High-Gain Harmonic Generation

The most simple HGHG seeding approach exploiting the resonator-amplifier setup contains only one resonator. A seed beam can be coupled into the resonator for the first electron bunch. Two chicanes enclose the optical cavity to guide the electron beam around the needed optical components in the setup. By setting the second chicane to the correct values, the energy modulation in the seeded bunches is transformed into a longitudinal density modulation which enhances the bunching on the corresponding, shorter wavelength. For the FLASH case, the wavelength aimed at is around 4 nm.

Echo-Enabled Harmonic Generation

For EEHG, one needs two resonators and two chicanes. Each modulator is now enclosed by its own optical cavity. This allows for the two seed laser pulses to be specifically made for the requirements in the respective modulator. However, it adds complexity to the setup. If the mirrors of the optical cavity downstream the seed incoupling mirrors can be retracted, this setup also allows for classical EEHG and single-stage HGHG.

Of course one could think of using just one optical cavity and installing a delay stage in the chicane between the two resonators. In this path, attenuators can be installed to change the intensity of the seed in the second modulator. However, this also reduces the intensity of the seed reaching the first resonator again, reduces flexibility and limits the operation parameters in a way such that the energy reaching the second modulator is always lower than in the first. For hard X-ray FELs, wavelengths of below 1 nm might be reachable.

TECHNICAL CONSIDERATIONS

The path length in the optical cavity must allow for a round-trip time that corresponds to an exact multiple of the FEL burst repetition rate. For the FLASH, which operates at 1.003 MHz this mean the optical cavity needs to have a length of about 150 m. Here, in an actual experiment one has to consider basically two points.

1. While it is possible to have several round trips in the optical cavity, this also means that the losses in the optical cavity will accumulate. On the other hand, the footprint of the setup will be reduced by a factor equal to the number of round trips, making it less prone to thermal conditions of the environment.

2. A longer optical cavity reduces the number of mirrors to be passed by the radiation, enhancing the overall intensity that is overlapped with the following bunch, and reducing thermal stress on the optical components, e.g. by a larger beam size.

Seed Source

Although the resonator-amplifier setup can work in a completely unseeded manner, providing an external seed might improve the operation of this system. In the UV range, several laser options are available to drive the resonator-amplifier setup at the macro pulse repetition rate of 10 Hz.

For short wavelengths at high repetition rates one needs special seed sources paired with a self-sustaining radiation generation so that the seed source itself does not need to supply the high repetition rate the FEL will lase at.

One of such choices can be a laser system providing radiation at the third harmonic of a near infrared laser system. Such systems offer a broad tuning range, also in terms of

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wavelength, which means that using techniques that produce harmonics of these wavelength will provide gapless spectra. For short wavelength, one would like to reduce the harmonics needed. This can be done using an HHG source, which is available at 10 Hz and 62.3 nm with pulse powers of about 130 MW [20].

Further Considerations

For even shorter wavelength, one can use the frequency doubling technique [21] in addition to the seeding. If the beam line is equipped with variable gap undulators, one sets the final undulators to a harmonic wavelength of the target wavelength of the seeded FEL and produce radiation on that harmonic. By this, one is capable of reducing the harmonic number needed for the seeding, thus loosens the requirements for optical cavity and electron beam.

Some users want lower repetition rates. For example, usual time-of-flight measurements are performed on time scales in the frequency range of 100 kHz. In the future, this repetition rate requirements might be met by high-power lasers systems that are currently being developed. Of course, lower repetition rates could be mitigated by allowing a larger number of round trips.

Another idea that does not rely on a high rep-rate laser is to actually seed with the full rep-rate and prevent a number of bunches from lasing, so that the FEL radiation comes in rep-rates suited for the experiment. Possible ways of preventing lasing are to kick the bunch onto a non-lasing trajectory through the undulator, which can require a modification of the beam pipe, or even building up a complete bypass beam line. Continuous wave operating (CW) mode is connected to the previous concepts as the repetition rates are lower than in the burst mode operation. In the optimal case, this scenario is the same as for lower repetition rates with the exception of the necessity of a kicker system.

SUMMARY AND OUTLOOK

In this paper, we presented the approach of using a resonator-amplifier setup for seeding at the high repetition rates of Free-Electron Lasers driven by superconducting accelerators. We discussed the principle use of this technique for schemes like High-Gain Harmonic Generation or Echo-Enabled Harmonic Generation together with the option to use frequency doubling. We discussed the possibility to get continuous spectra from existing seed laser options.

In the future, further optimization studies have to be performed on the material for the used mirrors and gratings, used laser systems, and focal properties of the optical components used. In parallel, one has to show within which tolerances the system can be operated in terms of geometry (such as optical cavity length), arrival time jitter, bunch charge, and bunch length. From the technical side, one has to think of ways to stabilize the geometry of the setup over the long distances of several hundreds of meters.

Since the round trip photon beam will get longer every round trip due to the presence of the grating, one will get longer photon pulses from the seeded region of the electron bunch. In order to keep the photon pulses in the resonator short and thus maintain the temporal stability of the arrival time, a time-compensating monochromator has to be studied. This device should keep the pulse length short while still working as a monochromator. This would allow to keep a longer electron bunch and stabilize the arrival time of the photon pulse. Such devices are also foreseen to be used in the photon beam treatment at FLASH [22].

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