TIME LOCKING OPTIONS FOR THE SOFT X-RAY BEAMLINE OF SwissFEL

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Abstract

SwissFEL is an FEL facility presently under construction at the Paul Scherrer Institute that will serve two beamlines: Aramis, a hard X-ray beamline which is under construction and will provide FEL radiation in 2017 with a wavelength between 0.1 and 0.7 nm; and Athos, a soft X-ray beamline which is in its design phase and is expected to offer FEL light in 2021 for radiation wavelengths between 0.7 and 7 nm. A passive synchronization of the FEL signal to a laser source is fundamental for key experiments at Athos, such as time-resolved resonant inelastic X-ray scattering (RIXS) experiments. In this paper we explore different options to achieve this time synchronization by means of energy modulating the electron beam with an external laser.

INTRODUCTION

The SwissFEL facility, presently under construction at the Paul Scherrer Institute, will provide SASE and self-seeded FEL radiation at hard (1–7 Å) and soft (7–70 Å) X-ray FEL beamlines [1]. SwissFEL will operate with electron beam charges varying between 10 and 200 pC and beam energies from 2.1 to 5.8 GeV. The hard X-ray beamline, Aramis, is expected to have the first user experiments in 2017, while the soft X-ray beamline Athos will lase by 2021.

Pivotal experiments for Athos, such as time-resolved resonant inelastic X-ray scattering (RIXS) experiments [2], require a very precise knowledge of the arrival time of the FEL pulse. More generally, pump-probe experiments need an accurate synchronization between the pump and the probe (FEL pulse). This can be achieved with a passive synchronization between the FEL pulse and a conventional laser. One possibility would be to use a laser-based seeding scheme, either direct seeding with a strong HHG source [3] or by employing more complicated layouts like the High-Gain Harmonic Generation (HGHG) [4] and the Echo-Enabled Harmonic Generation [5] schemes. However, laser-based seeding has at present limitations at a radiation wavelength of around 5 nm [6], and going beyond seems very difficult due to shot noise degradation issues [7] from the spontaneous undulator radiation. An alternative approach to passively lock the FEL pulse with an external laser is by energy modulating the electrons that will produce FEL radiation via interaction with a laser pulse in a wiggler magnet. Unlike the methods mentioned above, which induces a coherent signal at the resonant wavelength, the following methods slice the bunch by allowing the bunch to drive the SASE FEL amplification only where it had an overlap with the laser signal.

One possibility to do that is with the ESASE (Enhanced-SASE) mechanism [8], in which a dispersive section (normally a magnetic chicane) is used to convert the energy modulation of the electrons into a density modulation prior to the FEL generation in the undulator beamline. The higher current will drive the FEL amplification faster than the unmodulated beam.

Another option [9] is that the electrons are injected after the modulator directly into the radiator without the need of any dispersive section. The modulation generates an effective energy chirp in the beam that can be exactly compensated with a linear tapering of the undulator field [10]. By tapering one can force that only a very short slice of the bunch produces FEL radiation, while the rest of the electrons will not lase since the tapering will bring them out of the resonance condition. This scheme requires a more powerful laser system than in the ESASE configuration.

The ideal configuration is with an one-period modulator and a few-cycle laser pulse – in such a case a perfectly synchronized FEL pulse is generated. If the modulator has more periods, several short FEL pulses will be generated, which will not be perfectly locked since the modulation and therefore the FEL signal are lengthened. The advantage of this latter option is that the required laser power will be reduced.

In this contribution we will explore the ESASE and the "energy chirp" schemes to achieve the time synchronization of the FEL pulse. Figure 1 shows a schematic layout for these two options.

SIMULATION SETUP

The numerical simulations are done for a radiation wavelength of 1 nm, considering the layout for the soft X-ray beam line Athos with 4 m long undulator modules and 75 cm intra-undulator break sections, which hold the focusing quadrupole and the measurements of the beam positions. The FEL process in the radiator section is simulated with

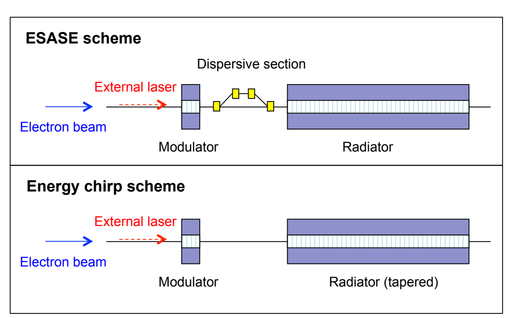

Figure 1: Conceptual layout for slicing the electron beam by an external signal. Either a current modulation or a strong energy chirp (upper and lower plot, respectively) is used to select the part of the bunch which lases.

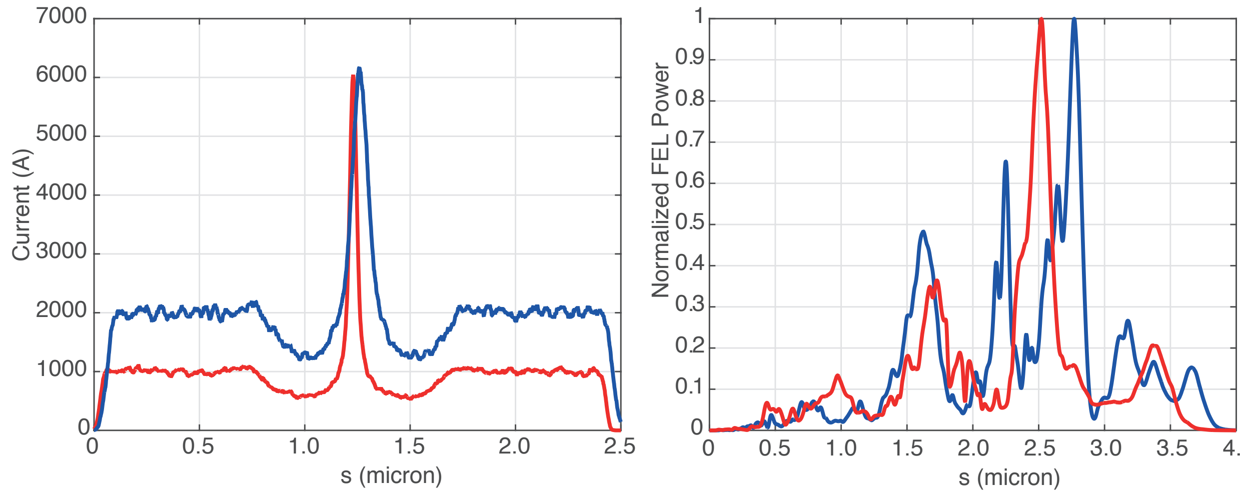

Figure 2: Current and FEL profiles (left and right plot, respectively) for an input beam with 1 and 2 kA beam current (red and blue line, respectively).

Table 1: Parameters of Soft X-ray Beamline at SwissFEL, Used for Simulations

Parameter	Value
Current (flat top)	1–2 kA
Charge	200 pC
Mean energy	3 GeV
RMS energy spread	350 keV
Normalized emittance	300 nm
Average β-function	10 m

the code Genesis 1.3 [11]. Table 1 shows the properties of the electron beam distribution that we used as input for the simulations. The considered normalized emittance value is consistent with our measurements at the SwissFEL Injector Test Facility [12]. We assume that the laser has a wavelength of 800 nm, and that the dispersive section in the ESASE scheme imposes an R_{56} of 0.6 mm.

PERFORMANCE OF ESASE SCHEME

Unlike an HGHG source, where the induced current modulation has a significant harmonic content at the final wavelength, the current spike length in the ESASE scheme is longer than the FEL wavelength. The synchronization occurs because the enhanced current provides locally a faster amplification than the rest of the electron bunch. A strong contrast between current spike and initial current yields a better signal-to-noise of the time-locked FEL pulse.

This argument is only valid if the amplification within the current spike does not suffer from slippage effects with reduced gain in this so called “weak super radiance” regime [13]. To avoid this problem the rms current spike length σ_s has to fulfill the condition [14]:

$$\sigma_s \geq 2L_c \quad , \qquad (1)$$

where L_c is the cooperation length. For the SwissFEL case of 1 nm the cooperation length is 50 nm and thus the FWHM of the spike has to be longer than 200 nm. The left plot of Fig. 2 shows two current profiles, where the current has been enhanced in the spike by factors of 3 and 6, respectively. The lower the input current of the electron bunch, the shorter the current spike. For the two cases studied the FWHM lengths are 120 nm and 50 nm, both not fulfilling the criteria for the minimal spike length. As expected the performance suffers and hardly any signal is seen in the profile among the noise (right plot of Fig. 2). Higher compression factors by the ESASE scheme do not help because the spike length drops inversely proportional to the current while the cooperation scales only as $I^{-1/3}$.

The only possible optimization is to increase the spike length by increasing the laser wavelength. At least 2 micron is needed for 1 nm FEL wavelength but at the lowest photon energy the cooperation is about 7 times longer pushing the wavelength of the laser modulation field into the IR range of about 15 microns. While ESASE would work well for hard X-ray FELs it is not considered a viable option for the soft X-ray beam line of SwissFEL.

PERFORMANCE OF LOCAL ENERGY CHIRP AND STRONG TAPERING

An alternative approach is to induce a strong energy modulation. If this beam is injected into an untapered undulator then the slippage will shift the radiation into parts of the bunch where the beam energy does not match the resonance condition any longer. This can be compensated by applying a taper to the undulator field. For the modeling we assume a peak-to-peak energy modulation of 20 MeV as shown in Fig. 3 by a sinusoidal single-cycle laser signal. The strongest chirp (around 4 micron in the plot) will be compensated by the taper. In all other parts of the bunch the electrons are shifted out of resonance due to the taper, where the two

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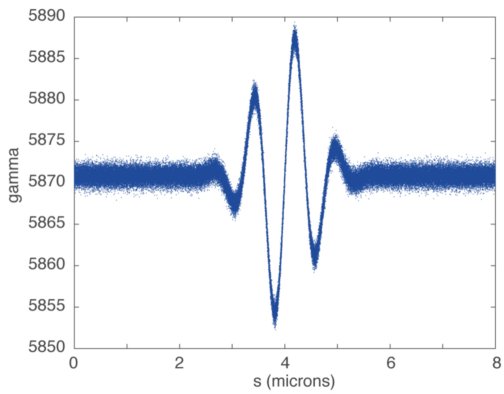

Figure 3: Energy modulation used for the simulation for the injection into a strongly tapered undulator.

smaller positive chirps at 3 and 5 microns have the tendency to stay in resonance the longest. For the best performances we were required to apply stronger taper than needed for the central part. While it degrades the peak power a little bit the two adjacent positive chirps are suppressed even stronger and the contrast ratio between signal and noise is improved. The radiation profile at the end of the taper is shown in Fig. 4 .

It is also possible to change both the sign of the energy chirp and taper gradient with the same efficiency in the slicing performance. If only one sign is flipped then the slicing process selects not one but two areas where the FEL performance is kept in resonance, resulting in two spikes with 3 fs separation and a relative wavelength difference of about 0.3%.

Because the taper gradient is strong a stepwise taper with the 4 m long undulator modules for the soft X-ray beam line of SwissFEL, significantly reduces the performance. Within the 4 m the slippage is sufficiently large to be off resonance either in the beginning or the end of the module and the amplification is reduced. In the same moment the parts which are supposed to be suppressed can stay longer in resonances. Overall the signal-to-noise ratio breaks down

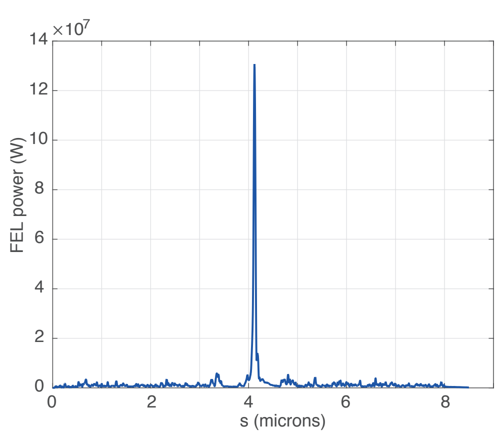

Figure 4: Radiation profile towards the end of the undulator for the strongly tapered undulator field.

and no clear sliced signal is visible. Therefore we consider a smooth linear taper to be mandatory.

A limitation of the valid slippage region is given because the strong energy modulation can only be applied roughly over half the laser wavelength. In our case it is 400 nm. Compared to the two ESASE cases it is 3.5 or 8 times longer, respectively, and allows for a significant build-up of the FEL power. In the case studied we reached 130 MW peak power till the spike reached the upper end of the positive energy chirp (around 4.2 microns in Fig. 3). A reduction in the taper gradient brings up the peak power to saturation at about 5 GW but also reduces the signal-to-noise ratio because two adjacent spikes, 800 nm before and after the main spike, become noticeable in amplitude. However further amplification is possible by either inverting the taper gradient to allow the radiation spike to slip into the region of negative chirp while staying in resonance or by shifting the radiation field into regions of the electron bunch with a small delay of one to two microns, where the beam quality has not been exhausted by the FEL process.

Overall this method seems to be feasible for the soft X-ray FEL beam line at SwissFEL. In particular the design for the undulator modules allows for a linear taper. The APPLE III type modules can generate a transverse gradient, which then translates into a linear taper when the module is rotated around the yaw axis.

ENERGY MODULATION

An external laser provides the input field for the energy modulation based on the interaction with the electron beam in the magnetic field of the modulator undulator. We assume a Ti:Sapph laser system with a wavelength of 800 nm because it generates short but highly intense laser pulses. Because of a wavelength 800 time longer than the FEL wavelength, the modulator parameters are rather extreme with a possible configuration for an undulator with a period of 25 cm and a K-value of 25. Multiple periods are possible but it lengthens the region of the energy modulation due to the slippage within the modulator. In particular single-cycle energy modulations are not possible unless the number of periods is reduced to one. The laser field has to scale inversely with the number of undulator periods. As a consequence reducing the modulator length from 10 to 1 period requires a peak power 100 times larger.

The reduction in the modulator length can actually be extended below a single undulator period. In fact half a period should be sufficient, which corresponds to a single dipole. In the case of the soft X-ray beamline at SwissFEL the transfer line to the undulator has several dipoles. The last one has a bending angle of 2.5 degrees. Replacing the modulator undulator with the last dipole has the additional benefit that the laser can be injected on a straight path with sufficient clearance for the laser optics, unlike a modulator, where the electron beam has an additional bypass chicane so that the laser can be coupled in on a straight line. Also the exit of the last dipole in the transfer line has the smallest

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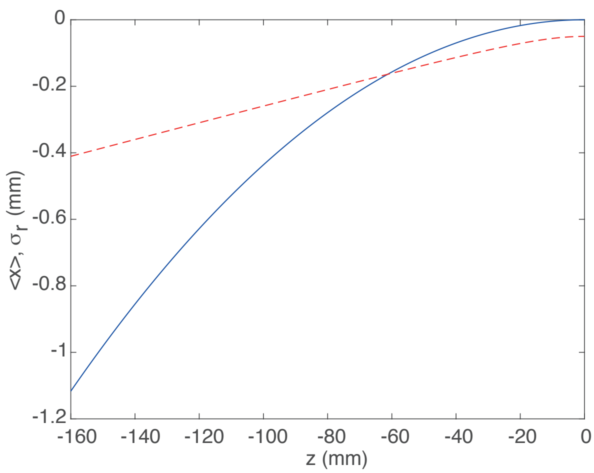

Figure 5: Electron orbit (blue line) and radiation field envelope (red dashed line) within a dipole for energy modulation.

dispersion and therefore the energy modulation is coupled only weakly to a change in the orbit in the order of one micron or less.

In the following we are considering the modulation by means of a dipole. From the simulations presented above a peak-to-peak energy modulation of 0.63% is needed. The laser is aligned that its waist is placed at the exit of the dipole with a direction colinear to the design orbit after the dipole. The bend radius is stronger than the divergence of the laser field so that the electron will fly into the field within the last few centimeters of the dipole. The relation of the orbit to the converging laser field is shown in Fig. 5 for a waist size of 100 µm and a laser wavelength of 800 nm.

The change of the electron energy is given by

$$\begin{aligned} \dot{\gamma} &= \frac{e}{mc^2}\vec{v}\cdot\vec{E} \\ &\approx \frac{eE_0}{mc^2}v_0 \sin\left(\frac{v_0}{R}t\right)\frac{w_0}{w(z)}e^{-\frac{x^2}{w(z)^2}}\cos(\phi(z)), \quad (2) \end{aligned}$$

where v_0 is the total electron velocity, R the bending radius of the dipole, E_0 the maximum field amplitude of the laser field, w_0 the mode size at the waist, $w(z) = w_0\sqrt{1 + z^2/z_r^2}$, z_r the Rayleigh length of the converging laser field, and $\phi(z)$ the interaction phase

$$\phi(z) = kz - \omega t + \phi_0 + \tan^{-1}(z/z_r) \quad , \qquad (3)$$

with k and ω the wave number and frequency of the laser field, respectively, and ϕ_0 the injection phase of the laser. The time is chosen so that at $t = 0$ the electron has reached the exit of the dipole with $x, z = 0$. Contributions of any field components in the z-direction have been ignored.

The change in energy is shown in Fig. 6 for $\phi_0 = 0$. Initially the energy is oscillating because the electron moves under an angle, where the interaction phase is varying rapidly up to the point where the electron propagates parallel to the field towards the exit of the dipole. However here the transverse velocity component is also vanishing and the interaction is zero. The major energy change occurs in the last 200 ps for the case presented. Integrating Eq. 2 for various phases gives the net energy change of the electron as shown in Fig. 7.

To match an energy modulation of 0.64%, used for the simulation presented above, an absolute variation of about ±10 MeV is needed. Changes in the waist sizes can be balanced with the power of the laser pulse. In Table 2 various configuration are listed, which are providing the same energy modulation. Larger spot sizes require more radiation power however the optimization towards the smallest values are

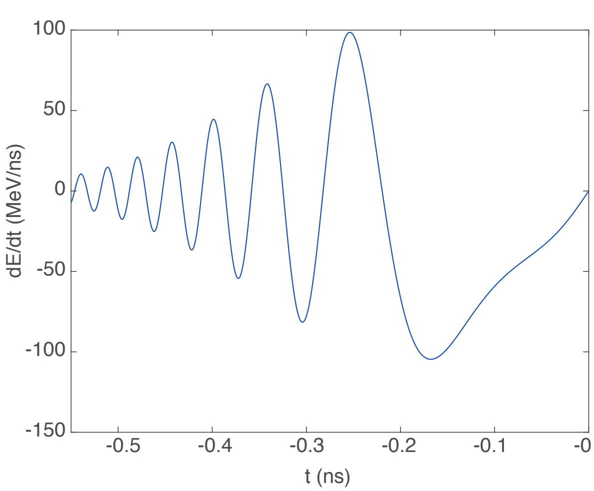

Figure 6: Instantaneous energy change of the electron, interacting with a laser field within a dipole.

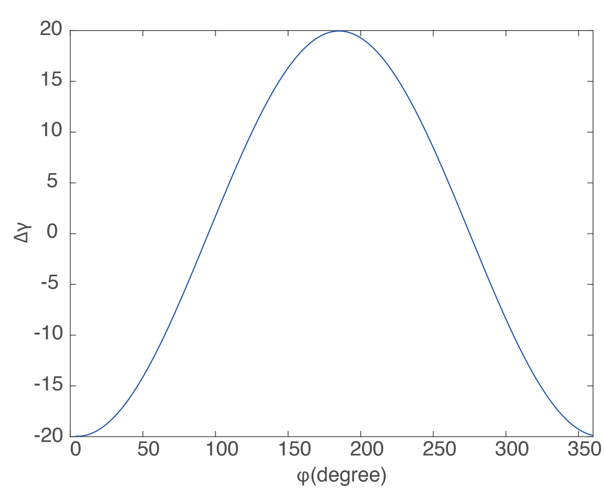

Figure 7: Performance of the energy modulation with a dipole magnet. The amplitude of the laser has been scaled to obtain a peak-to-peak modulation of 20 MeV.

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Table 2: Various Laser Parameters to Obtain the Needed Energy Modulation foR Slicing

Waist Size	Power
60 µm	420 GW
120 µm	740 GW
180 µm	1600 GW

limited by the need for a homogeneous energy modulation for all transverse positions of the electrons within the beam distribution. Therefore the waist has to be significantly larger than the electron beam size. Typical values for SwissFEL are about 45 microns, thus for practical reasons the limit in the laser spot size is given by 100 microns.

We would like to emphasize that the use of a dipole as the modulator is driven by the idea to generate a single attosecond FEL pulse, which is time-locked to the laser pulse. Therefore the overall energy of the laser pulse is about 2.5 mJ, assuming a pulse duration of 3 fs, which seems reasonable for a Ti:Sapph laser system.

TIMING SYNCHRONIZATION

The preferred method of compensating an energy chirp with a strong linear taper yields an FEL spike, which is located close to the end of the positive chirp around the maximum in the energy modulation. Because the start-up is still based on the shot noise of the spontaneous radiation the position is not precise but if the undulator length is matched so that the radiation spike moves with its group velocity over the maximum length of the chirp, then those spikes which are generated at the beginning of the chirp close to the minimum in the energy modulation have the largest amplification. The simulations for different shot-noise seeds yield always the maximum spike within 40 degrees of the energy modulation wavelength, locking the FEL within 300 attosecond to the phase of the external laser signal. This resolution is only preserved if the laser source utilizes a carrier envelope phase stabilization. Otherwise the phase of the laser signal is undefined and the jitter of the FEL pulse is at least 3 fs. For the single spike operation the CEP stabilization is mandatory to provide a matching chirp to the taper of the undulator field.

CONCLUSION

To stabilize the arrival time of the FEL pulse the signal can be locked with an external laser signal. Unlike seeding, which has its challenges to provide a sufficient signal to drive the FEL below 5 nm, slicing is rather robust because it only restricts the region within the electron bunch, where SASE amplification can occur. With a carrier envelope phase stable laser signal the synchronization can be brought down to below 1 fs.

For the wavelength considered for the soft X-ray beam line at SwissFEL, the ESASE scheme has the disadvantage that the FEL process in the induced current spikes suffers significantly from slippage and no good signal can be generated. More favorable is to compensate a strong energy chirp with a linear tapering of the undulator field. A sub-femtosecond spike is generated, which is significantly larger than the background signal and phase locked to the laser signal applying the energy modulation.

To aim for a single spike multi-period modulator have to be avoided. Instead the interaction between electron beam and the laser field can be generated by a single dipole magnet. The expected power is in the order of one Terawatt with a pulse duration of about 3 fs, which in reach of existing Ti:Saphh laser systems.

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