SEEDING OPTION FOR THE SOFT X-RAY BEAMLINE OF SWISSFEL

S. Reiche*, R. Abela, H. Braun, B. Patterson, and M. Pedrozzi
Paul Scherrer Institut, Villigen PSI, 5232, Switzerland

Abstract

The X-ray FEL facility SwissFEL, planned at the Paul Scherrer Institute, is primarily based on the SASE operation of a hard (1-7 Å) and soft (7-70 Å) X-ray beamline. However the soft X-ray FEL beamline is foreseen to allow for seeding down to 1 nm. The intrinsic shot noise in the electron bunch demands excellent state-of-the-art seeding sources and strategies. This presentation discusses various seeding options for SwissFEL and evaluates them regarding performance and risk of implementation.

INTRODUCTION

The purpose of seeding for FELs is threefold: overcoming the inherent limitation of longitudinal coherence in a SASE FEL configuration (and thus improving on the brilliance of the FEL output signal), synchronizing the FEL signal with an external signal, and improving the stability of the FEL power from shot-to-shot by introducing a well-defined seed signal different to the white noise of the spontaneous radiation within the FEL bandwidth. However, the major advantage of the FEL is its free tunability of the resonant wavelength by changing either the energy of the driving electron beam or the strength of the undulator field. Therefore any seeding source has to exhibit the same tuning ability. The fundamental problem is to find a suitable source, which can be tuned as the FEL. Most of the time some limited tunability can be achieved due to the inherent bandwidth of the seeding source or by Chirped Parametric Amplification (CPA) [1]. Another approach is the quasi-continuous spectrum of higher harmonics of High-Harmonics Generation (HHG) sources [2], where the frequency bands of the different harmonics are overlapping. However this only applies to short seed signal and thus the induced longitudinal coherence is significantly shorter than the electron bunch length. Of particular interest is the combination of the two methods to achieve a fully tunable source. E.g. in a HHG, based on 800 nm Ti:Saph laser, the separation between the 41st and 43rd harmonics is only about 5% and thus tuning the wavelength of the drive laser by 5% would allow to select any wavelength in the region below 20 nm with a harmonics of the HHG source without the restriction of a short seeding pulse.

Once a tunable seed source has been identified it has to fulfill a second constraint, which is to overcome the shot noise power of the electron beam. Seeding with a power below the power level of the spontaneous radiation would result in a SASE performance. This puts a limit on the lowest wavelength, which can be achieved. While seeding sources typically have lower efficiency in its output power at shorter wavelength, the shot noise power actually grows as [3]: $P_n \approx \rho^2 \omega_0 \gamma mc^2/2$, where ρ is the FEL parameter, ω_0 is the resonant wavelength and γmc^2 the electron energy. For SwissFEL [4] parameters at 5 nm and a beam energy of 2.1GeV the shot noise power is around $P_n = 100$ W. Note that for seeded FELs only 1/9th of the power couples to the exponentially growing mode and that further losses are given by the mode mismatch between the seeding mode and the FEL eigenmode (optimum cases have about 50% coupling efficiency). Thus a seeding power level, which is equivalent to the shot noise power level, would be around 2kW. For an improved signal-noise ratio the seeding power has to exceed that value by a wide margin (10-100 times).

Direct seeding is the simplest concept, where the seeding source has the same wavelength as the final FEL. However the demands for a sufficient seed power cannot be fulfilled with the currently existing technology, but it is one of the major areas of research to extend the HHG spectrum below 10 nm..

The High-Gain Harmonic Generation (HGHG) [5] is actually not a seeding method but a mechanism to convert an input seed to shorter wavelengths. The underlying principle is the non-linear dynamics of the high-gain FEL process generating a rich harmonic content in the electron distribution, which is often enhanced by a succeeding dispersive section. When injected into an undulator, which is resonant on any of the harmonics, the bunching on that harmonic generates a coherent seed signal, which is well above the shot-noise power level of an unbunched beam. The biggest drawback of cascading HGHG stages is that each stage increases the energy spread in the electron beam and thus reduces the efficiency in the final amplifier. While straightforward SASE FEL typically reaches power levels at saturation above 1 GW it is not necessarily the case for several stages of HGHG. One proposal to overcome this intrinsic increase of the energy spread is to remove the energy modulation after bunching has been achieved [6]. This can be done by a ”silence” following the modulator, removing the energy modulation after a phase slippage of 180 degrees.

High-Harmonic Generation (HHG) is the most promising candidate for a seed source at short wavelength. The underlying mechanism is the harmonic up-conversion of a conventional drive laser within a noble gas. A large number of odd harmonics of the drive laser are present in the spectrum and one of these harmonics can be used as the seed for the FEL. Currently, energies of a couple of nano-Joules

* sven.reiche@psi.ch

per harmonic down to 10 nm have been measured [7]. For shorter wavelength the efficiency of the HHG sources drops below the shot noise power lever making them unsuitable to seed at wavelength below 10 nm.

Recently, the new idea of echo-enabled harmonic generation was proposed by G. Stupakov [8] as an alternative method to induce a current modulation on a much shorter length scale than the seed laser. The process can be split into two steps. The first step imprints an energy modulation on the electron beam and then shears this modulation by a dispersive section (e.g. magnetic chicane). The result is a band structure in the energy distribution. The second step applies again an energy modulation and dispersion. The individual bands are converted into current spikes with a spacing on a higher harmonics of the drive laser. In theory the echo-enabled harmonic generation has the best efficiency of harmonic generation (about 10% current modulation at 5 nm) and very low demands on the seed laser, however there hasn't been a proof-of-principle experiment yet to demonstrate its efficiency, difficulties to operate and the impact of degrading effects (loosing the energy band structure in the second modulator and chicane).

SEEDING STRATEGIES FOR SWISSFEL

The goal for seeding at the soft X-ray beam line ATHOS of SwissFEL is to reach 1 nm, which is challenging for any kind of seeding source. Assuming that any source is Ti:Saph based, operating at 265 nm, it means an overall harmonic conversion of 265. The situation is also complicated because the Athos beam line operates at two energies: 2.1 GeV and 3.4 GeV. Only at the higher energy, 1 nm can be reached in the final radiator.

All seeding schemes have in common that there is one undulator (d'Artagnan) before the final radiator, which would extend the wavelength range towards longer wavelength. At 2.1 GeV the resonant wavelength range of d'Artagnan would be about 7 nm to 25 nm, which translate to 2.6 – 9.5 nm at 3.4 GeV. The configuration for the different seeding scheme under discussion here are shown in Fig. 1.

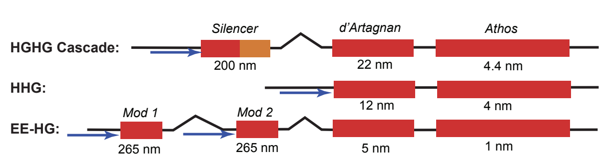

Figure 1: Configurations for the different possible seeding schemes of the Athos beamline.

These two energy modi give a long cascade, starting from 265 or 200 nm (3rd or 4th harmonic of Ti:Saph laser) a significant disadvantage because it would require an additional stage which further increases the energy spread. For an HHG source, the requirement would be to reach a wavelength of at least 9 nm with sufficient power (>10 nJ). Then a possible conversion scheme would be 3rd harmonic to 3nm and then again 3rd harmonic to 1 nm. Unfortunately the Athos undulator is limited to 2.8 nm, so that the second stage would be accomplished by d'Artagnan itself. An even better performance can be expected if the HHG seed would be available at either 6 nm, for conversion to 2 nm and then 1 nm, both with the Athos undulator, or 5nm with a direct conversion to 1 nm. The echo-enabled harmonic generation has the least problems with the higher energy as long as the modulators are resonant with 265 nm. The bunching would be introduced to 6 nm or 5 nm and then treated the same as a possible HHG source.

For a HHG seed, the radiation will be directly injected into d'Artagnan, most likely requiring a bypass or dogleg before d'Artagnan. This is also required for the EE-HG scheme with two short modulators and two dispersive sections prior to dArtagnan. Both of these schemes allow for a rather fixed length of d'Artagnan because the input signal of d'Artagnan can be controlled by either the energy of the HHG signal or the configuration of the EE-HG scheme. The long HGHG cascade with silencer enforces much more stringent requirement for the electron beam parameters. Any fluctuation would alter the performance of the intermediate stage of the undulator d'Artagnan, resulting in insufficient bunching (FEL gain too low) or spoiled energy spread (FEL gain too high) which is then carried over into the final stage of the cascade.

SIMULATION RESULTS

HGHG Cascade with Silencer

The HGHG cascade has 3 stages with a large harmonic conversion after the first modulator. The first stage is tuned to a wavelength of about 200 nm, assuming the 4th harmonic radiation of a Ti:Saph laser. It is also the only stage, which is equipped with a silencer. The first stage is less than 4 meter long with the phase shifter after the first two third of the undulator. The period length is 10 cm and the undulator parameter has a value of 11.5, which allows for a gap larger than 6 mm. The seed pulse with a radiation power of 2 MW is longer than the electron bunch to avoid the reduced efficiency of the silence due to slippage. Nevertheless the silencer only removes a fraction of the induced energy spread, ending up with an rms energy spread of 2MeV. The bunching factor at the end of the first stage is about 20% which is large enough so that the emitted radiation in the silencer has about the same amplitude as the seed laser, resulting in a change of the radiation phase and thus reducing the efficiency of the silencer.

With the conversion to the 9th harmonic and then to the 5th harmonic the final radiator Athos is tuned to 4.4 nm at 2.1 GeV. The intermediate stage (d'Artagnan) is only 4 m long and saturation is achieved in Athos after 20 m. The cascade relies on FEL amplification in d'Artagnan to enhance the initial bunching of 6 percent at 22 nm to an end-value of about 20%. This is inherently difficult because the cascade operates with the same bunch, meaning that driving the electron beam too much into saturation will reduced the amplification in later stages.

Saturation is achieved after 20 m, however the saturation power reaches barely the 1 GW power level due to blow-up of the energy spread in the previous stages. Also the initial bunching of 1% in the final radiator is rather low and the FEL suffers from a poor signal-to-noise ratio.

Overall the performance of the HGHG cascade is not satisfying, resulting in low output power and a system which is very sensitive to fluctuations in the beam parameters. In addition the system is only configured for an operation at 2.1 GeV, which would allow 1 nm radiation only by parasitic emission at 3 nm in the final radiator. If 3.4 GeV has to be considered, the cascade needs another stage to cover the shift in Athos and d'Artagnan by a factor of 3 in the tuning range.

HHG Seeding

Seed sources, based on High Harmonic Generation offer the best choice in terms of shortest wavelength available and thus, requiring only a single stage of HGHG. Experiments have shown wavelengths down to 10 nm with an energy of about 5 nJ in the selected line of the spectrum [7] , which is sufficient to seed above the shot noise power level of the electron bunch. The HHG configuration seeds d'Artagnan at around 12 nm with a beam energy of 2.1GeV and then perform a single harmonic conversion to the 5th harmonic, to drive the FEL process in the Athos beam line into saturation. Radiation at 1 nm can be obtained by the parasitic emission at 3 nm. One important advantage of this configuration is that it allows for a future upgrade of the HHG source without reconfiguring the FEL. If it is possible to push the wavelength of the seed source down to 6 or 5 nm than the FEL can be operated at 3.4 GeV.

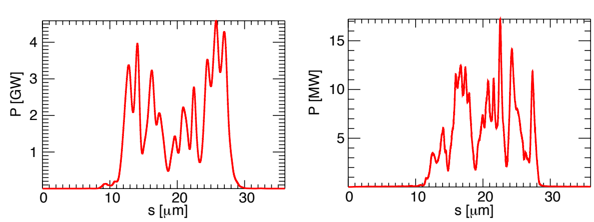

Figure 2: Radiation pulse profile at 3 and 1 nm in the Athos undulator at saturation (left and right plot, respectively).

For the case of SwissFEL the needed energy per harmonic is about 5 nJ, corresponding to a seed power of 100kW with a rms pulse length of 20 fs. The effective seed level is sufficient to overcome the shot noise of the electron beam.

After a 12 m long d'Artagnan the signal is converted to the 3rd harmonic and saturation is obtained after 10 m in the Athos beamline. Note that saturation is defined at the point of the smallest bandwidth in the output of the FEL. Although the power is further increased beyond 10 m, the spectrum quickly broadens up and the pulse becomes noisy and "SASE-like". At saturation the rms bandwidth is 0.08%, which is a factor 6 better than the case when Athos is operated as a SASE FEL, reaching saturation after 20 m.

Unlike a seed derived directly from a Ti:Saph, the HHG pulse length is limited to a few tenths of femtoseconds. Therefore the system is sensitive to the arrival jitter of the electron beam. With the given bunch length of SwissFEL any jitter larger than roughly 30 fs will result in shots where there is no or very little overlap between electron bunch and seed pulse. There won't be sufficient bunching at the exit of d'Artagnan and Athos would operate as a pure SASE FEL.

One advantage of a HHG seed is the ability to drive the FEL in a superradiant mode [9]. If the length of the seed signal is comparable to the cooperation length of the FEL than the radiation power continues to grow beyond saturation together with a shortening of the FEL pulse. The underlying mechanic is that the FEL spike slips into a part of the electron bunch, where the FEL process hasn't spoiled the beam quality. Even the parasitic 3rd harmonic reaches a power level of almost 1 GW. The FWHM of the resulting superradiant spike is less than 1 fs.

Echo-enabled Harmonic Generation

Echo-enabled Harmonic Generation has the potential to imprint a high harmonic current modulation on the electron beam, which is then driving the FEL. This is unlike the HHG seed where the seed is done by a radiation field. Here the starting component of the radiator is the current modulation, induced by a combination of two modulators and two dispersive sections. The layout of the EE-HG section is based on a beam energy of 3.4 GeV and an upper value of the energy spread of 250 keV. This would allow for an operation at one nanometer in the final amplifier (Athos) as well as the operation at a longer wavelength (e.g. with a beam energy of 2.1 GeV). The seed wavelength is around 250 nm, the 3rd harmonic of Ti:Saph laser. For a resonance at 3.4 GeV the modulators have a period length of 20 cm and an undulator parameter value of 15. Operation at 2.1GeV would require reducing the undulator strength to a parameter value of about 9. Both modulators have 20 periods, resulting in the generic SwissFEL module length of 4 m. To modulate the electron beam with an amplitude at least 3 times larger than the maximum energy spread of 250 keV, a radiation power of 100 MW is required. The second modulation is somehow less demanding with a radiation power of about 20 MW.

When the EE-HG beamline is tuned to the 60th harmonic, the required R_{56} for the 2 chicanes are 12 mm and 0.21 mm, respectively. The value of 12 nm is rather demanding and the complexity of the first chicane is comparable to the last bunch compressor of the SwissFEL linac. Nevertheless a current modulation of 8% can be achieved at around 4 nm, which makes this methods superior in theory than the HHG seed. Also there is a strong bunching of about 4% at 2 nm. If the complexity of the bunch compressor is too demanding, an alternative scheme would be to modulate the 30th harmonic and then used the parasitically modulation at the 60th harmonic. With a seeding wavelength of 4-5 nm in d'Artagnan a single harmonic conversion can be done in the Athos beam line, reaching the target wavelength of 1 nm. The performance in the final radiator Athos is shown in Fig. 3, obtaining saturation at 1.4 nm after 10 m.

A time-dependent simulation of the EE-HG is very challenging, because the modulation process typically mixes a lot of slices together. The distance, over which the first chicanes spreads out the first energy modulation is a few microns. This smears out the current profile and secondary effects, such as a residual chirp, cannot be neglected. Unfortunately almost all FEL codes require a correct representation of the shot noise, which is done by the methods of beamlets, a subset of macro particles, which represent a physical correct bunching [10]. Because these beamlets cannot be split, the mixing of the slice by the first chicane yields a numerical problem. In addition, effects such as CSR in the bunch compressor, as well as the increase of the width of the energy bands in the phase distribution by quantum effects have to be studied.

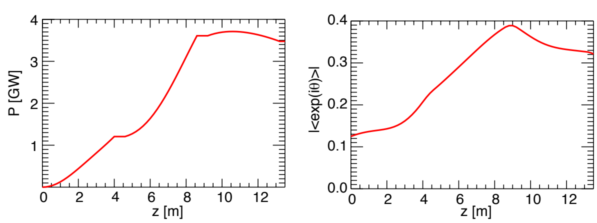

Figure 3: Radiation power and bunching at 1.4 nm in the final radiator Athos.

Comparison

From all proposed scheme, the simple HGHG cascade has the poorest performance, the most complex configuration and works only at 2.1 GeV electron beam energy. Therefore it is not an option for the seeding scheme of SwissFEL. Comparing HHG with EE-HG, seeding with an HHG has the advantage that there have been successful seeding of FELs with HHG at longer wavelength [11] as well as that the requirement for a seed at 12 nm has been demonstrated. The configuration with seeding into d'Artagnan would allow for a future upgrade of the HHG source, going down to 5 nm, and operation at 3.4 GeV. The EE-HG is in theory the better seeding source but the idea is fairly new and hasn't been demonstrated yet. There are some questions still unanswered, such as degrading effects (CSR, quantum fluctuation), preservation of the bunching to the FEL. On the other hand the core part of the FEL, the FEL beam lines d'Artagnan and Athos, are identical for EE-HG and HHG seeding. Some space in front of d'Artagnan would be needed to build for the EE-HG scheme. The estimated length requirement would be about 4 m for each module and the last magnetic chicane, while the first chicane would be more of the order of 10 to 15 m.

CONCLUSION

Seeding for a FEL wavelength down to 1 nm is challenging though not impossible. Proposed systems such as multi-stage HGHG cascade have the disadvantage that they become very sensitive to beam fluctuation if the cascade is pushed to the limits. Therefore seeds at shorter wavelength are preferable. Possible candidates are High Harmonic Generation, which derives a short wavelength seeding source from a noble gas and a powerful laser at longer wavelengths, or Echo-Enabled Harmonic Generation, where the seed is generated as a modulation in the current profile. Both schemes would use the same configuration of d'Artagnan and Athos. In addition, both schemes also would allow for an operation at both 2.1 and 3.4 GeV electron beam energy. While the HHG scheme has some experimental verification at longer wavelength, there hasn't been any demonstration of a seed signal, which would be sufficient for SwissFEL. On the other hand, the EE-HG is a novel idea and there haven't been any experiments at all. However the scheme could be tested at the 250 MeV injector of PSI [12].

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