OVERVIEW OF SEEDING METHODS FOR FELS

S. Reiche*
Paul Scherrer Institut, Villigen PSI, 5232, Switzerland

Abstract

In recent years enormous progress has been achieved in the theoretical understanding and experimental demonstration of FEL seeding. The state of the art for FEL seeding should be reviewed and compared to HHG, HGHG, EEHG techniques. The potential of various seeding methods and their promise to produce radiation pulses that approach the transform limit in a range of experimental configurations at different user facilities should be explored.

INTRODUCTION

The purpose of seeding for FELs is threefold: overcoming the inherent limitation of longitudinal coherence in a SASE FEL configuration [1] (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 unlike the white noise fluctuation of the spontaneous radiation within the FEL bandwidth. 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 in the same range as the FEL.

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 SASE performance. This puts a limit on the shortest wavelength, which can be achieved. While seeding sources typically have lower efficiency in their output power at shorter wavelength, the shot noise power actually grows as [2]

$$P_n \approx \rho^2 \omega_0 \gamma mc^2/2, \qquad (1)$$

where ρ is the FEL parameter [3], ω_0 is the resonant wavelength and γmc^2 the electron energy. As an example, for SwissFEL [4] parameters at 5 nm and a beam energy of 2.1 GeV 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 2 kW. For an improved signal-to-noise ratio the seeding power has to exceed that value by a wide margin (10-100 times).

DIRECT SEEDING

Direct seeding refers to any methods, where the seed signal has the same wavelength as the resonance wavelength of the FEL with a power level above the shot noise power but below saturation power of the FEL. Note that the 1D theory puts a limit on how much seed power can be coupled to the exponentially growing mode. Only one ninth is amplified and it requires about two gain lengths till any change in the radiation power becomes measurable, overcoming the lethargy regime of a seeded FEL. The coupling efficiency is further reduced in the 3D model because some mode matching between the seed mode and the fundamental FEL eigenmode [5] is required. With strong distortion of the phase front or unmatched mode sizes, the effective seed power is significantly reduced. Finally, the bandwidths have to be matched as well. If the seed signal has a bandwidth larger than then FEL bandwidth (e.g. by seeding with a pulse length shorter than the coherence length of the FEL) only a fraction is picked up and amplified. Note that in this case the peak brightness of the FEL output is not improved with respect to a SASE FEL because the entire FEL bandwidth is excited.

Towards shorter wavelength High Harmonic Generation (HHG) in noble gases is the most promising seed source

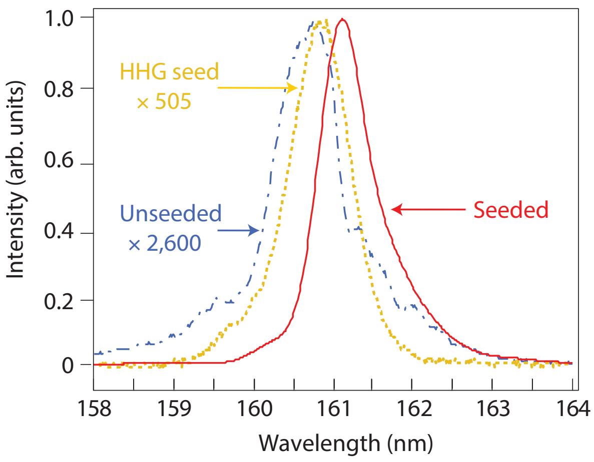

Figure 1: Spectra of seeded and SASE FEL at the SCSS Test Facility. The SASE spectrum was scaled in amplitude to fit in the plot [7].

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* sven.reiche@psi.ch

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for direct seeding [6]. In the HHG process a strong drive laser field strips off electrons from the atoms by tunnel ionization and accelerates them away from the atom. A half cycle later these electrons are accelerated back towards the ions with a chance of recombination. In this case a photon is emitted with an energy much higher than the drive laser but phase locked. The resulting spectrum exhibits a rich content of odd harmonics, reaching into the VUV region and thus suitable for seeding. The HHG process preserves the transverse coherence properties of the drive laser though the ongoing ionization of the noble gas by electrons, which are not recombined, makes the phase matching between the drive laser and the emitted photons difficult. In reality only short pulses of a few tens of fs can be achieved with enough spectral purity in the harmonics to be suitable for seeding.

There have been several experiments, which have demonstrated successful seeding of an FEL with an HHG signal down to 39 nm [7–9] (see Fig. 1). However it became apparent that towards shorter wavelength the HHG sources need to deliver much more spectral power to overcome the shot noise limit of the electron beam. This is the current focus of the HHG research. Methods with corrugated capillaries or counter propagating laser beam can reduce the limitation by the phase mismatch while longer drive wavelength can reach harmonics at shorter wavelengths. In addition long transport lines of the HHG signal should be avoided. The best solution would be a HHG source inline with the undulator axis, using an electron bypass (chicane or dogleg) to overlap the radiation with the electron beam.

SEEDING BY ELECTRON BEAM MANIPULATION

Instead of providing a radiation field the FEL can also be seeded with a coherent bunching at the resonant wavelength. In the beginning of the FEL the beam will emit coherently and the power will grow linearly till the FEL amplification process starts after a few gain lengths. The induced bunching must be significantly above the shot noise level.

The primary method is based on the energy modulation of the beam with a seed laser, where both wavelength and power are reasonably achievable. The induced energy modulation is converted into a current modulation by a dispersive section (magnetic chicane), following the modulation stage. If the contrast between energy modulation and energy spread is large the current spike is rather pronounced and exhibits higher harmonics. In a second stage the FEL, also called the radiator, is tuned to one of the harmonics. The emission is only partially coherent but sufficient to start the FEL process. Figure 2 shows the general configuration of such a scheme for the first proof-of-principle experiment [11].

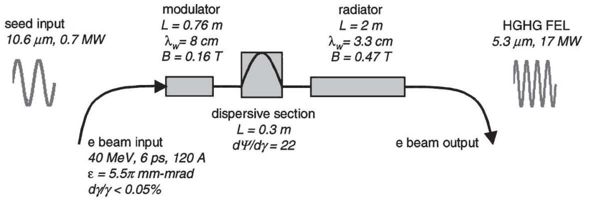

Figure 2: Schematic Layout for the proof-of-principle HGHG experiment at SDL [11].

The limiting factor is the induced energy modulation $\Delta\gamma$. The maximum bunching at the nth harmonic is given by $b_n = \exp(-(n\sigma_\gamma/\Delta\gamma)^2/2)$ and drops quickly when the energy modulation gets smaller than the product of intrinsic energy spread σ_γ and harmonic number. Therefore high harmonic conversions require large energy modulations. On the other hand the final energy spread, as seen in the final radiation stage, still has to fulfill the requirement of $\sigma_\gamma/\gamma_0 \ll \rho$, where ρ is the FEL parameter and of the order of 10^3 for soft X-ray FELs. If the condition is violated the beam will emit partially coherently in the radiator but will not drive the FEL to saturation. The consequences are the need to operate these FELs with a much smaller energy spread than comparable SASE FELs and therefore a restricted use of laser heater to preserve the beam transport from the electron source to the undulator, including acceleration and compression.

The required degree of energy modulation can be supplied either directly by a high power seed laser or a FEL process in the modulator, which is stopped at the optimum energy level. The latter scheme is referred to as the High Gain Harmonic Generation FEL [10] and has been successfully tested at various facilities down to the soft X-ray range of about 10 nm [11, 12] .

The limitation in the achievable harmonic of the HGHG scheme is overcome in a more complex configuration with two modulators and dispersive sections prior to the final radiator, in the so-called echo-enable harmonic generation (EEHG) FEL scheme [13, 14]. The purpose of the first stage is to overcompress the energy modulation well beyond maximum bunching with a strong magnetic chicane. The phase space then exhibits narrow bands instead of a continuous smooth distribution at the beginning of the seeding section. The second stage will then operate as a HGHG stage generating a current spike for each band. To achieve maximum bunching the current spikes of all energy bands need to be spaced at the final radiation wavelength to add up coherently. A typical phase space distribution for the different stages of the EEHG process is shown in Fig. 3.

The advantage of the EEHG compared to the HGHG is that the first stage artificially reduces the intrinsic energy spread per band due to the strong overcompression, which allows much higher harmonic conversion in the HGHG stage at the cost of a slight increase in the energy spread. In theory this method can achieve very high harmonics with a bunching efficiency of up to $b_n = 0.39/\sqrt[3]{n}$. The scheme has been demonstrated successfully at lower harmonics number [15, 16] but its potential for achieving very high numbers makes it an attractive alternative to HGHG

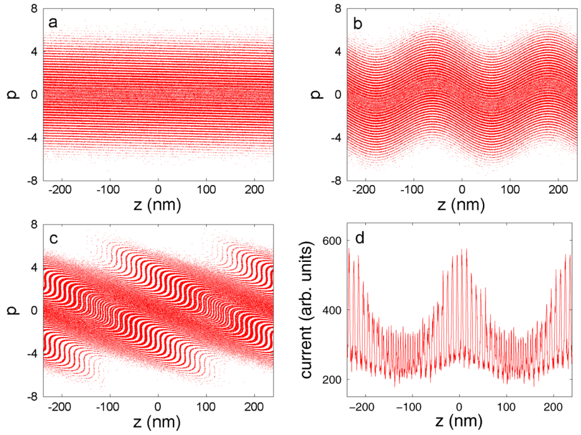

Figure 3: Longitudinal phase space distribution in a EEHG configuration after the first modulator and chicane (a), the second modulator (b) , and the second chicane (c). The resulting current profile is shown in the lower right plot (d).

methods despite its intrinsic and complex coupling of two energy modulation and two chicane strengths. The limiting factor is the ability to preserve the energy bands throughout the seeding line and avoiding any blurring effects. There are two sources of degradation: the quantum fluctuation in the emission of photons of the incoherent synchrotron and undulator radiation [17] and intra-beam scatterering [18]. While the first can be mitigated with gentle bending angles and long chicanes the latter requires a layout as compact as possible. Both limits the practical use of EEHG for wavelengths exceeding 1 nm.

CASCADES AND HYBRID CONFIGURATION

When direct seeding or HGHG/EEHG seeding is not sufficient to reach the desired wavelength the processes can be combined or chained together. The most common approach is the cascaded HGHG where the output of the radiator from the first stage is used as the modulating signal of the second stage. As an example, if both stages have a harmonic conversion of $n = 5$ the final harmonic conversion would be 25. A third stage would yield an overall harmonic of 125.

The problem is the accumulated energy spread for each stage, which can easily degrade the performance of the final radiator. In addition the shot noise is amplified with the harmonic conversion and even a strong input signal can get lost in the noise of the final radiator.

The problem is partially solved by supplying an unused part of the electron bunch for each cascading stage. This is done with a delaying chicane between the radiator of the previous cascade and the following modulator. However this fresh bunch cascade requires that the entire process operates only locally with a slice of the bunch moving slowly from the tail to the head of the bunch for each cascading step. The amount of electrons contributing to lasing in the final radiator is small and the overall pulse energy is smaller than in SASE operation. This penalty gets larger the more cascading stages are needed. So far only two stage cascades have been operated successfully.

SELF-SEEDING MECHANISM

All the previous methods require an external signal synchronized to the beam arrival time at the undulator location. To avoid shots with no overlap the stability of the jitter in the seed signal and the beam arrival time needs to be less than the bunch length. Therefore most externally seeded FELs foresee a lower current to relax the arrival tolerance. As a result the FEL parameter and the power at saturation are reduced. In addition the lower FEL bandwidth restricts the amount of energy modulation of the seeding schemes reducing the ability to scale to very short wavelength in the 1 nm range.

If the requirement for an externally locked FEL pulse is given up the seed signal can be derived from the same bunch in a two stage configuration (see Fig. 4). The first stage operates as a SASE FEL but stops before saturation. That way the beam preserves the ability to amplify an external signal to full saturation. Following the SASE FEL the electron beam and radiation field are separated and the radiation is filtered to select a narrow bandwidth. The filtered signal is then recombined with the electron beam and injected into the second stage of the FEL, operating as an FEL amplifier. The electron bypass has two purposes: primarily, to match the arrival time of the beam with the filtered signal and, secondarily, to remove the induced bunching by the momentum compaction factor of the chicane. This configuration is referred to as “self-seeding”.

The initial idea was proposed for the soft X-ray facility FLASH [19] but had the conceptual difficulties that the delay in the photon path way would require a long electron bypass line, where the transport needs to be control by a lot of quadrupole and sextuple magnets to preserve the electron beam properties. It was never realized. It was later picked up by a novel concept in the hard X-ray regime using features in the transmission around the stop band of a Bragg reflection [20]. The transition between total Bragg reflection to almost full transmission has frequencies component which are significantly delayed by the crystal and ringing off behind the main SASE signal of the first stage.

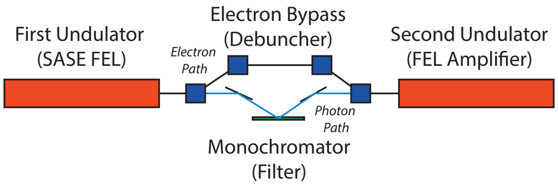

Figure 4: Schematic layout for a self-seeding configuration.

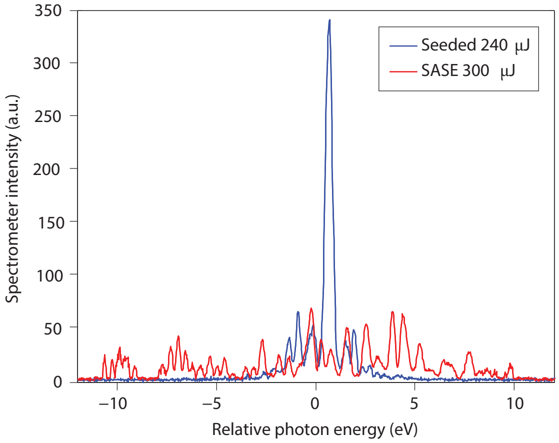

Figure 5: Sample Spectra at LCLS for SASE and self-seeded operation [21].

The electron bunch is delayed and overlaps with the trailing signal, which is the interference of the two edge frequencies of the stop band. For photon energies around 8 keV the seed signal has still a significantly large amplitude well above the shot noise level. The attractive feature of this method is that the overall delay is of the order of a few tens of fs and that a small chicane can easily be integrated in the undulator line. The method has been successfully demonstrated at LCLS [21]. A narrowing of the FEL bandwidth by a factor 50 has been measured (see Fig. 5) though the system has become inherently sensitive to the jitter in the electron beam energy, dominating the 100% intensity fluctuation by the missing overlap between the central FEL wavelength and the fixed seed wavelength of the diamond crystal of the Bragg reflector from shot to shot.

One inherent problem with Bragg and the similar Laue diffraction is that the delayed part of the transmitted field, which is seeding the second stage, exhibits a transverse shift in the position due to the effective index of diffraction around the Bragg stop band [22]. This effect is mitigated for near perpendicular incident angles. Therefore the Bragg diffraction has to be optimized for the different wavelengths, utilizing various planes of the crystal lattice.

Recently a more compact design of a soft X-ray self-seeding chicane was found with a length less than 4 m [23]. Although the resolving power is around 5000 and therefore not sufficient to yield full longitudinal coherence for LCLS like bunches it still gives a significant improvement in the bandwidth. An experiment at LCLS is foreseen in early 2014.

A narrow-bandwidth filter of the self-seeding schemes stretches the short SASE spikes with a coherence length typically smaller than the bunch length to a coherence length much longer than the bunch length so that in the second stage a well-defined radiation phase is spread over the entire bunch. This effect can also be achieved if the slippage is increased to cover the entire bunch. In SASE FELs the slippage is one radiation wavelength per undulator period and the characteristic cooperation length L_c is

$$L_c = \frac{\lambda}{\lambda_u} L_g \qquad (2)$$

and the length gets shorter for shorter wavelength λ assuming an overall constant gain length L_g. There are several methods proposed [24–27] to artificially increase the slippage per gain length by either breaking up the undulator and interleaving the modules with small chicanes delaying the bunch or by operating on a sub-harmonic of the FEL, where the slippage is increased by the harmonic number. All methods reduce the FEL bandwidth up to a point where the bunch length is limiting the spectral width. At this point these methods are equivalent to self-seeding methods except that they avoid filters intercepting the radiation. These are attractive alternatives if the heat load on the monochromator, mirrors or crystal is an issue. Similar to these slippage enhancing methods is the feedback of a fraction of the FEL signal to the succeeding bunch in a high repetition machine. There the slippage is accumulated over many turns, defining the regenerative amplifier FEL (RAFEL) [28].

COMPARISON AND SUMMARY

While the SASE FEL is an established and robust method to generate coherent X-rays, seeding allows for more stability in the output power, an increase in the spectral brightness and/or the synchronization with an external signal. There are three common approaches: direct seeding with HHG, induced bunching with HGHG or EEHG as well as self-seeding. Each has been successfully demonstrated though the records for the shortest wavelength was done at LCLS at a wavelength of 1.5 Å with self-seeding.

Direct seeding has its limitations due the growing shot noise for shorter wavelengths, which requires increased power with a narrower band width. HHG as the most promising source can offer attractive solutions for seeded FEL above 30 nm but it requires a significant improvement and R&D towards shorter wavelengths. It is unlikely that in the next couple of years wavelengths below 10 nm become feasible with direct seeding

HGHG made tremendous progress towards shorter wavelength down to 5 nm with a fresh bunch technique in a cascade configuration. Shorter wavelengths seem feasible, but they operate with long bunches and lower current as compared to SASE FELs at the same wavelength. The pulse energy is lower but the signal is well synchronized to an external signal. One fundamental limit is the energy spread, which has to be smaller for short wavelength. This can yield a conflict with the need to artificially increase the energy spread with a laser heater to preserve the beam brightness during transport.

No apparent limitations occur in self-seeding schemes, which can be extrapolated to very short wavelength in the Ångstrom regime, assuming a sufficient filter exists to clean up the spectrum. The electron beam parameters are the same as for SASE operation and an increase in the FEL brilliance is achieved. The drawback is that the FEL pulse is not locked to an external signal.

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