PROSPECTS OF CASCADED HARMONIC GENERATION FELS*

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Abstract

Harmonic generation in Free Electron Lasers (FELs) encompasses many techniques for using an input seed laser to produce FEL radiation at a frequency that is multiples above that of the seed laser itself. This allows for the advantages of seeded FELs to be preserved, while extending the reach of these FELs to photon energies far above those produced by conventional laser sources. Many new projects are underway to make use of these methods, including the FERMI@Elettra [1] facility which envisions the use of two harmonic generation stages to reach photon energies above 100 eV. Different methods of harmonic generation are discussed, as well as the technical challenges to overcome in attempting to chain together multiple harmonic stages in an FEL.

INTRODUCTION

Harmonic generation in an FEL [2] is a promising technique for achieving high-intensity photon sources at short wavelengths. Among the benefits of this design is that the output is seeded by a laser signal, allowing for excellent frequency and timing control. The resulting output has the potential of being a transform-limited pulse, and the output power is not limited by the input power but instead by the saturation level of the FEL itself. In addition, the FEL output is at a harmonic of the laser signal, so that the required laser wavelength is longer than the desired output wavelength.

Multiple stages of harmonic generation can be combined into a cascade, where the output from each stage is used as the input seed for the next stage. A harmonic cascade allows conventional laser sources to be used to produce photons at extremely high energies. There are several facilities which plan to use a harmonic cascade as a source for experiments. Among these are FERMI@Elettra, which is to consist of two FELs, one with a single harmonic stage producing radiation in the 100 – 40 nm range, and one with two harmonic stages producing radiation in the 40 – 10 nm range. BESSY [3] is developing an FEL with up to four stages of harmonic generation, yielding wavelengths ranging from 50 nm down to as low as 1.2 nm. Both of these facilities plan to use conventional laser sources. An additional possibility is seeding with a High-Harmonic Generation (HHG) signal [4], which uses a short, intense laser pulse passing through a gas jet to generate many high harmonics of the initial laser. Such sources would drastically reduce the total harmonic conversion required in an FEL, but much work remains to be done to ascertain their suitability for use in this way.

This paper will begin with the FERMI@Elettra design to illustrate the harmonic generation process and to show some of the fundamental issues which need to be considered for a harmonic cascade. Sources of noise can degrade the FEL output, and phase noise is particularly important to consider for large harmonics. Simplified models are used to characterize the major constraints which must be considered for a harmonic cascade. Future prospects are

FERMI@ELETTRA SIMULATIONS

The electron beam parameters for FERMI@Elettra are: 1.2 GeV energy, 1.5 micron emittance, and depending on the beam compression the current can range from 400 A to 1 kA and the energy spread can range from 100 to 200 keV. The seed laser is tunable in the range 240 – 360 nm, has a peak power of 100 MW, and the pulse duration can be up to 1 ps. The first modulator has a period of 16 cm and is 3.04 m long. At the first harmonic, the undulators have a period of 6.5 cm and are in sections of 2.34 m length. The final radiator for the second harmonic has a period of 5 cm and is in sections of 2.4 m length. The initial modulator produces an energy oscillation in the electron beam with the same period as the wavelength of the seed laser, as the relative phase between the undulator field and the laser field when they both overlap the electrons determines the energy transfer. A dispersive chicane follows this modulator, converting the energy modulation into bunching at the wavelength of the seed laser. When this bunching is sufficiently strong, there are significant components at harmonics of the fundamental wavelength. Subsequently, the electron beam passes through undulators tuned to a harmonic of the seed laser, and radiates at that harmonic.

For the two-stage FEL, termed FEL-2, there are then two possibilities, as shown in Fig. 1. In the “fresh-bunch” approach, the radiation produced at the end of the first stage is made to overlap the electron beam in another modulating undulator after passing through a delay chicane. As a result, the radiation pulse produces an energy modulation in a region of the electron beam closer towards the head of the bunch, which was relatively unperturbed by the first stage of the FEL. The second stage produces a harmonic of the output from the first stage in the same way as the first stage generates a harmonic of the seed laser. In the “whole-bunch” approach, the first stage is continued until there is sufficient energy modulation at the harmonic to continue to the next stage. The electron beam is then passed through a dispersive chicane to enhance the bunching at the desired final harmonic. In the final radiator, the same section of

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electron beam radiates at this higher harmonic.

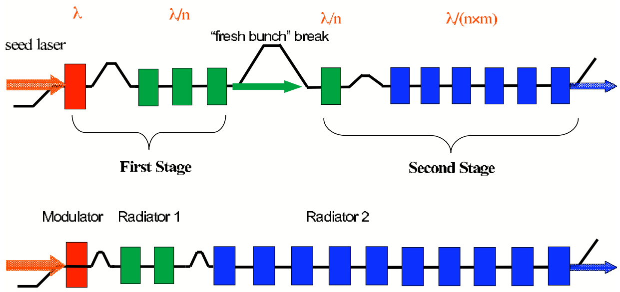

Figure 1: Two possible configurations for the FEL-2 line of the FERMI@Elettra facility: fresh-bunch (top) and whole-bunch (bottom).

An example from the FERMI@Elettra optimization study will motivate the topics discussed below. A realistic longitudinal beam distribution from accelerator studies is shown in Fig. 2. The central current is roughly 500 A. Note that there is a strong parabolic shape to the slice energy as a function of longitudinal position. More recent designs have advanced far towards removing this feature, but it serves as a useful reference. A whole-bunch configuration starting with a 240-nm seed laser with 1 ps duration FWHM produces 10 nm output with 0.1 mJ per pulse, and with peak power of 400 MW. The output power and phase (modulo 2π) resulting predicted by simulations using GENESIS [5] are shown in Fig. 3. The phase shows a strong quadratic dependence which mirrors the energy variation, and which leads to a broad, fluctuating spectrum as shown in Fig. 4. Applying an appropriate linear chirp to the seed laser is quite effective at cancelling the phase variation, resulting in the sharp spectrum shown on the same figure. While this demonstrates that a parabolic energy profile can be cancelled with a linear frequency chirp in the seed laser, proper tuning may be challenging and more complex phase space distributions will not be amenable to this type of a fix. Avoiding such features in the beam profile therefore becomes a high priority when high longitudinal coherence and spectral brightness are desired.

ENERGY AND PHASE ERRORS

A simplified view of harmonic generation in an FEL serves as a useful starting point for considering the challenges faced in designing a harmonic cascade FEL, as touched on above. In Fig. 5, a slice of the electron beam is modelled as a collection of mono-energetic beamlets, each one with a uniform distribution in longitudinal position (here expressed as phase). Note that phase increases towards the head of the bunch. After the modulator and dispersive chicane, the phase space distribution is folded over to produce significant bunching centered at the zero phase.

The spread in energies for the original beam results in a finite width for the microbunch, as a consequence of the

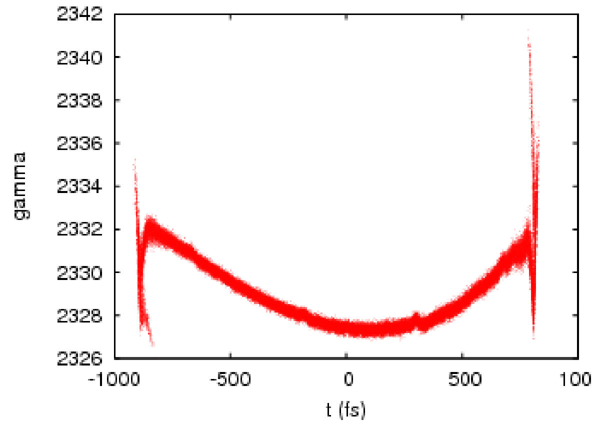

Figure 2: Preliminary phase space distribution from FERMI@Elettra study.

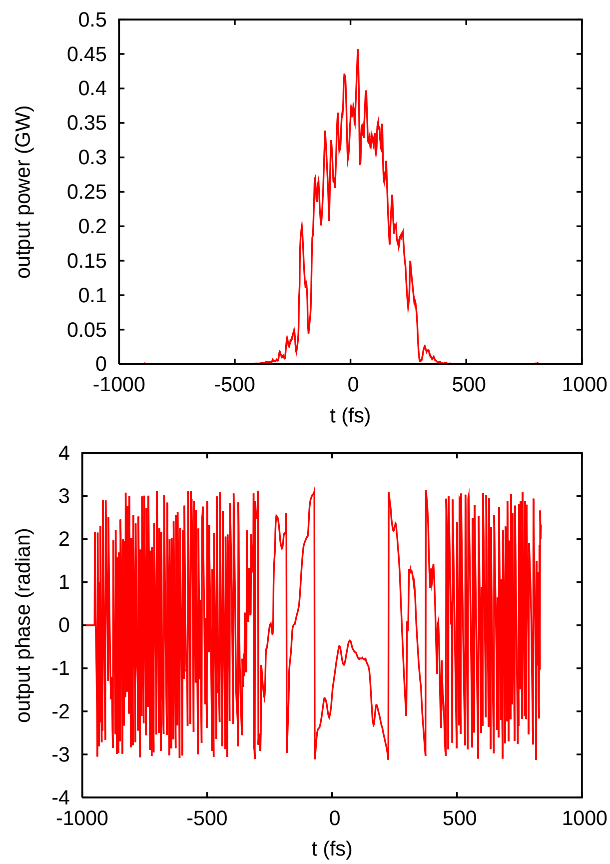

Figure 3: Output power and phase at 10 nm using whole-bunch approach.

conservation of phase space. There are more subtle issues which can be understood with this picture, however. Effective bunching, especially at higher harmonics, requires an energy modulation much larger than the initial energy spread. Roughly, this requires that the energy modulation, γ_M, satisfy

$$\gamma_M \geq (n-1)\sigma_\gamma, \tag{1}$$

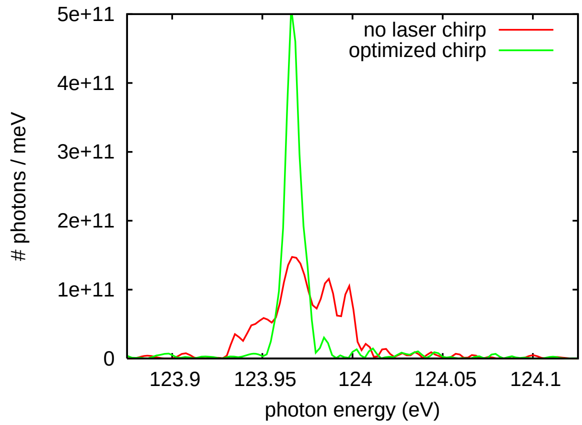

Figure 4: Output spectrum using laser seed with no chirp (red) and with optimized chirp (green).

where n is the harmonic number and σ_γ is the energy spread. The degree of bunching generated at the harmonic will be sensitive to the slice energy spread. Furthermore, because each energy value corresponds to a different phase for the microbunching, longitudinal variations in the average beam energy will lead to offsets in the timing of the microbunches. As the microbunches are separated by n wavelengths in terms of the harmonic output, these fractional timing offsets can have a large effect on the coherence of the output radiation.

To further understand the effect of longitudinal energy variation in the beam, we consider a similar effect where phase offsets are introduced within the seed laser itself. In Fig. 6, the bunching produced by a seed laser with a linear frequency chirp is compared to that produced by a seed laser with no chirp, but for an electron beam with a quadratic energy chirp. Both variations are greatly exaggerated compared to that which would be encountered in practice. The vertical bars indicate the phases of successive microbunches. It is apparent that a chirped seed laser can produce the same changes in timing structure as a chirp in the electron beam energy. This explains how a linear chirp in the seed laser can fix the output from an electron beam having a parabolic energy profile. Note that a linear energy chirp would simply produce a uniform offset in output wavelength. This is generated as the modulated electron beam passes through the dispersive chicane, where it is either compressed or stretched depending on the sign of the energy variation. Curvature in the energy profile leads to more complicated perturbations, as some sections of the beam are compressed and others are stretched. This can lead to sidebands in the spectrum or broadening, which would degrade the output radiation to be no longer transform-limited. This effect is made worse at high harmonics, as seen in Fig. 7. Here, an arbitrary small phase error is introduced to a pure Gaussian pulse. The effect is barely visible in the spectrum of the fundamental, but at the 24th harmonic the spectrum is drastically altered. At the fundamental, the signal is still transform limited, but

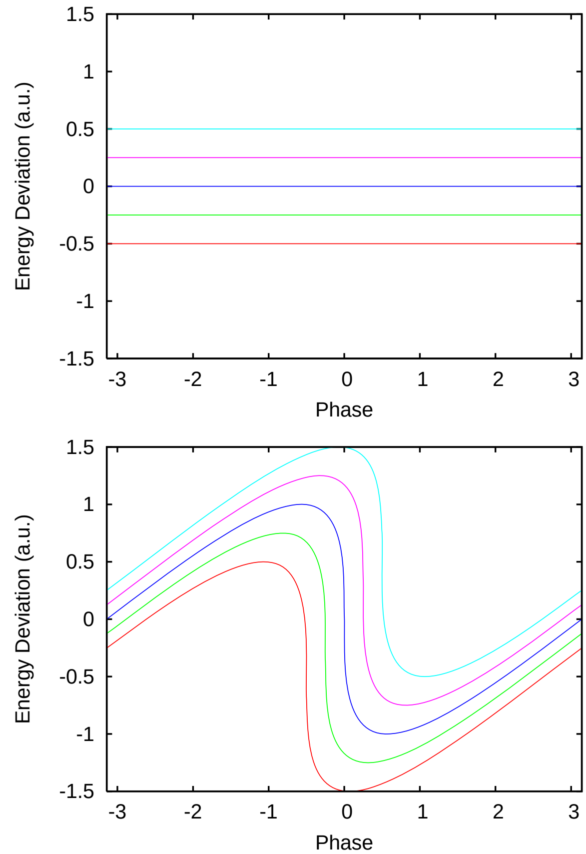

Figure 5: Illustration of bunching process as it affects electrons having different energies.

the pulse is still unsuitable for harmonic generation beyond a certain limit. This introduces added complexity to the design of the seed laser, as the constraints are more stringent than usual and are not a typical part of the vocabulatory of laser sources. In particular, even short pulses (i.e., a small number of wavelengths) will require a clock-like regularity of the field oscillation in order to function optimally as an FEL seed.

Macroparticle Noise

Because electrons at different energies are bunched at different phases, there are additional concerns for the proper simulation of harmonic generation. Typically, macroparticle noise in FEL simulations are controlled by starting with pseudorandom particle distributions, and using subsets of particles uniformly spaced in phase. Deviations from this uniform spacing are chosen to mimic the expected statistical fluctuations. However, an efficient bunching process will put most particles of a given energy at a single phase, so the final phase distribution will only depend on the initial energy distribution. In the example above, there will only be five bunches centered about the zero phase. Different choices of modelling the energy distribution will thus lead to different bunching pa-

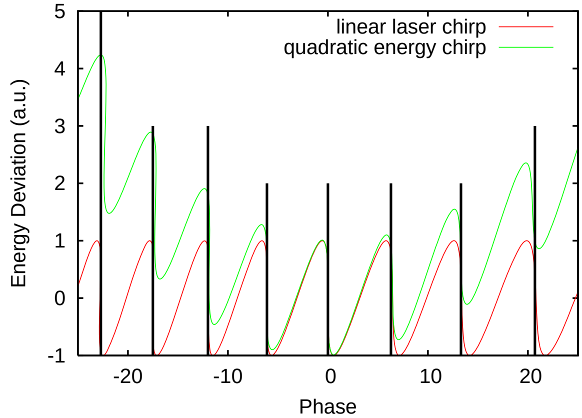

Figure 6: Comparison of bunching process for a flat beam seeded by a chirped laser, versus a beam with quadratic energy variation and no laser chirp. Vertical bars indicate the phases of successive microbunches.

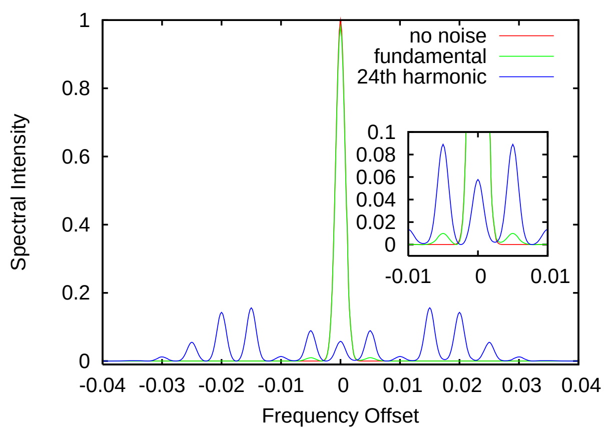

Figure 7: Spectra of Gaussian pulse with oscillating phase error, at original frequency and at 24th harmonic.

rameters. Furthermore, especially for large energy spread and harmonic number, the discrete nature of the bunching will lead to noise in the bunching parameter as the gaps between energy levels become resolved. The macroparticle noise for an optimally bunched beam will be given by $n\sigma_\gamma/N_\gamma\gamma_M$, where N_γ is the number of energies sampled by the distribution. Sampling more phases will not reduce this macroparticle noise, and may even make the problem worse if it is done at the expense of the number of discrete energies sampled. There is as of yet no known robust method to control this effect in simulations. It becomes increasingly difficult to get simulation results to converge as the initial energy spread in the electron beam is increased, especially when the nominal seeded bunching is already low.

POWER FLUCTUATIONS AND ENERGY OFFSETS

While phase distortions can reduce the longitudinal coherence of the FEL output, power fluctuations are also a major concern. There are many possible sources of power fluctuations, but typically the most important one is energy offsets in the beam. Note that while phase errors accumulate due to longitudinal variation of the slice beam energy, it is the difference between the slice energy and resonant energy which determines the output power. Shot-to-shot jitter in beam energy is thus a significant concern for output power flucuations. The sensitivity of the FEL to relative energy offsets is typically the larger of $1/N_U$ or the FEL parameter [6], $\rho_{\text{FEL}} = \lambda_U/L_G$. Here, N_U is the number of undulator periods, λ_U is the undulator period, and L_G is the exponential gain length, all for the final undulator where the gain length is longest and the number of undulator periods is largest.

Reducing the sensitivity of the FEL involves a trade-off with trying to optimize the peak output power. One method is simply to reduce the number of undulator periods, at the cost of greatly reduced average power. A more efficient method is to introduce either variations in the magnetic field strength of the undulator, or phase offsets between undulator sections. Examples are shown in Figs. 8 and 10; the latter example is from a pseudorandom variation in the undulator field strength which drastically reduces the dependence on beam energy and reduces the peak power by a factor of 30. The evolution of the power and bunching for the example labelled “phase 3” are shown in Fig. 9. Note that the configuration is specific to the given length of undulator, at which point the various beam energies come close to each other in performance, but after passing through different dynamics.

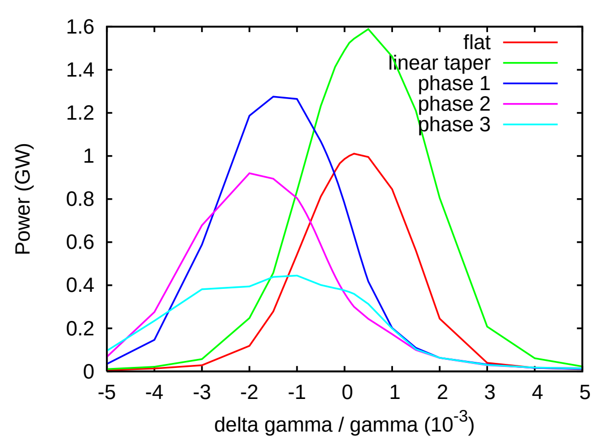

Figure 8: Sensitivity of FEL output power to beam energy offsets, for variations of the fine tuning.

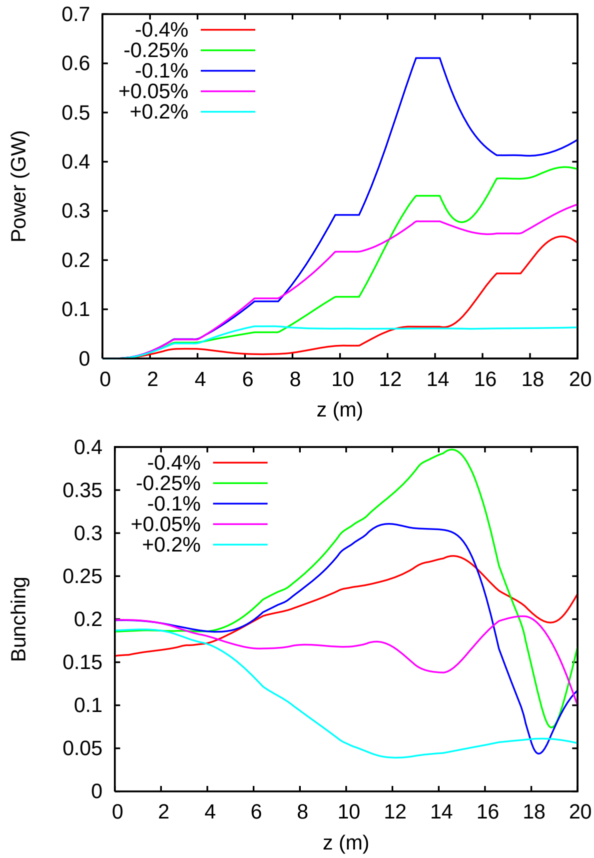

Figure 9: Power and bunching evolution in the FEL, for different electron beam energies, using the “phase 3” example in the previous figure.

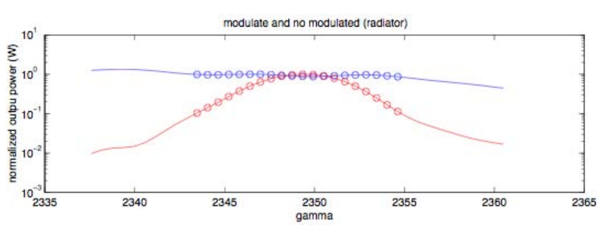

Figure 10: An example of extreme reduction in the sensitivity of FEL output to electron beam energy through pseudo-random tapering. Peak power in the tapered example (blue) is a factor of 30 below that in the nominal case (red), but is stable to much larger energy variations. Courtesy of G. De Ninno and E. Allaria.

CHALLENGES FOR HARMONIC CASCADES

The desire for even shorter wavelengths leads one to consider more ambitious harmonic cascade FEL designs, as in the BESSY multi-stage FEL. As the goal is moved to shorter wavelengths, the tendency is to consider more energetic electron beams. One motivation is the reduced effectiveness of the FEL when the normalized emittance is much larger than $\lambda_r/4\pi\gamma$, where λ_r is the radiation wavelength and γ is the relativistic factor of the beam. This is due to a combination of reduced electron density and increased spread in longitudinal velocities. Another is the challenge of satisfying the resonance condition,

$$\lambda_U = \frac{2\gamma^2}{1 + a_U^2}\lambda_r, \qquad (2)$$

where a_U is the normalized strength of the undulator field. The FEL parameter also tends to drop drastically as the beam energy is reduced, which further constrains tolerances on energy jitter and energy spread.

The high harmonic numbers involved also introduce complications. Attempting to take a single, large harmonic jump becomes very impractical, as the required energy modulation must be extremely large or the energy spread must be very low in order to satisfy Eq. 1. This leads to an additional problem, that for larger energy modulations the beam will debunch more rapidly. If the gain length is longer than the debunching length, the electrons will not be trapped in the ponderomotive well and the FEL will not reach saturation. A rough requirement to reach saturation is

$$\gamma_M \le \gamma\lambda_U/16L_G. \qquad (3)$$

Together with Eq. 1, this limits the range of acceptable energy modulations, and also imposes a maximum allowed energy spread.

Ultimately, many smaller harmonic stages become required. This adds to the complexity, and does not eliminate the sensitivity to phase noise and energy variations which depend on the total harmonic multiplication factor. The noise-to-signal power ratio within a given bandwidth can be expected to grow as the square of the total harmonic power through the harmonic generation process. The seeded FEL process must also compete with spontaneous FEL emission which may amplify the noise along the FEL, as well as spontaneous growth in energy spread.

As the energy modulation itself increases the slice energy spread with each harmonic multiplication stage, fresh-bunch delays between stages will ultimately be required. Each delay to an unseeded section of the electron beam introduces constraints on synchronization and reduces the maximum duration of the output pulse for a given electron distribution. While it may be possible to alternate between fresh-bunch and whole-bunch stages, these considerations lead to challenging electron source and acceleration requirements. Numerical simulations also require more resources and care when large harmonics are desired.

One attractive option is to take advantage of rapid advances in HHG sources, and seed the FEL at much shorter wavelengths than conventional lasers can achieve. There has been much recent activity studying the feasibility of HHG sources as an FEL seed [7, 8, 9]. While further characterization of these sources is clearly needed to make reliable predictions, some facts are already apparent. First, the typically low peak power in these signals is not an obstacle to their use. In particular, amplifying a signal is much less difficult than conversion to a harmonic (hence the $(n-1)$ factor in Eq. 1). In addition, the HHG sources typically have durations of less than 100 fs, which favors experiments based on timing rather than spectral widths, and slippage between the radiation and the electrons will smooth out some phase noise components. Ultimately, HHG sources could be used to seed X-ray FELs which use only a single stage of harmonic generation.

While the challenges for developing cascaded harmonic FELs are daunting, they link together a large range of technologies; small improvements on many fronts may open up new horizons for seeded FELs in the future. It is clear that the lasers used as seeds for the FEL require more detailed characterization. In addition to improved or novel sources for seeding, advances in electron sources, acceleration, undulator design, and optics will enable more ambitious projects in the future. In the meantime, current facilities on the horizon will offer experience and testing grounds for new ideas, as well as provide opportunities for performing advanced scientific research.

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