ISSUES IN HIGH HARMONIC SEEDING OF THE 4GLS XUV-FEL

B. Sheehy, Sheehy Scientific Consulting, New York, USA; J.A. Clarke, D. J. Dunning, N. R. Thompson, CCLRC, ASTeC, Daresbury Laboratory, Warrington, UK; B. W. J. McNeil, SUPA, Department of Physics, University of Strathclyde, Glasgow, UK

Abstract

Using High Harmonics (HH) as a seed for free electron lasers is currently under consideration in a number of proposed facilities. An HH seed source is independent of machine dynamics, and allows for extensive manipulation of the seed pulse using well-established techniques of ultrafast laser physics. These allow for rapid tuning, and may enable the extension of chirped pulse amplification and even pulse shaping for coherent control to short wavelengths. In addition, there are advantages in terms of noise and synchronization. There are a number of issues involved in the implementation of HH seeding: energy, tunability, coherence, temporal structure, etc. We discuss these issues and their application in the 4GLS XUV-FEL.

INTRODUCTION

The limitations of spontaneous sources have motivated a great deal of development in short-wavelength FEL design. For reasons of stability, coherence and bandwidth, SASE sources are disadvantageous relative to coherent alternatives. A number of seeding methods have been proposed, including high-gain harmonic generation, several self-seeding techniques, and using high harmonic generation to produce sufficient radiation at the fundamental resonant wavelength of the radiator to directly seed the FEL.

The attraction of seeding with high harmonics is that a great deal of control over the seed radiation can be had by using well-known ultrafast laser techniques to control the fundamental that drives the HH generation. Harmonic pulses can be made extremely short, down to a few femtoseconds, and tuning is relatively simple. Demands on timing and synchronization with the electron bunch are less stringent than in other techniques. Also, the coherent transfer of phase information from the HH pump to the harmonics opens the possibility of creating a chirped HH seed and performing chirped pulse amplification [1] in the FEL to achieve higher output energies, or even of pursuing more elaborate pulse shaping.

The efficiency of HH generation is currently too low for FEL seeding at soft X-ray energies. However, in the wavelength range planned for the 4GLS XUV-FEL (8-100 eV), available sources could provide sufficient energy for seeding at kHz repetition rates, and the available energy will increase with coming improvements in ultrafast laser technology.

A number of other issues must also be addressed. Tunability is required, and must be provided in a way that minimizes downtime and perturbations to timing and synchronization. Other spectral and temporal properties have also been raised as issues. We address these issues and discuss the implementation of seeding in the 4GLS XUV-FEL.

ENERGY AND TUNABILITY

The 4GLS XUV-FEL will operate between 8-100 eV. We have simulated the XUV-FEL [2], using GENESIS 1.3 [3], using 100 kW peak seed power for output photon energies below 30 eV, and 30 kW for energies between 30 eV and 100 eV. For 30 fsec pulses, this is equivalent to 3 nJ and 1 nJ pulse energies respectively. This is three orders of magnitude above the spontaneous power generated in the first gain length due to intrinsic density fluctuations in the electron bunch, and, in simulations produces an output pulse with good contrast [2].

A number of groups have measured harmonic yields from Ti:Sapphire based systems, and we show a scaled synopsis of recent results [4-6] in Fig. 1. The experimental results represented here (unconnected points on the plot) were obtained using fundamental pulse energies from 3-50 mJ, and we have scaled the results to an energy of 14 mJ – the energy of the Ti:Sapphire system described below. These scaled yields exceed our requirements by over three orders of magnitude at the low energy end of the XUVFEL operating range, and by a factor of six at the high energy end.

The scaling energy of 14 millijoules was chosen because such a laser system has been demonstrated at kHz repetition rates [7]. This is conservative, as ultrafast laser technology is developing very rapidly, and extension to higher powers is not constrained by a fundamental limit. A number of recent developments, eg the use of optical parametric chirped pulse amplification [8], high power Yb:YAG lasers [9], and enhancement cavities [10-12], offer new opportunities for larger systems. Several 100-Watt kilohertz system designs have been proposed [13], and are likely to be demonstrated soon.

There is also considerable effort in the community focused on extending the wavelength range and yield of harmonics. Recent experiments [6] using two-color fields demonstrated an enhancement of over 2 orders of magnitude in the harmonic yield in Helium, producing 150 nanojoules in the 38th harmonic (59 eV), using only 2.8 mJ in the pump laser. Fig. 1 also shows the results of that experiment (scaled from the experimental energy of 2.8 mJ to 14 mJ). Since Helium is the least efficient of the rare gas targets used, it is reasonable to expect that when these techniques are extended to other gases and longer pump wavelengths, available seed energies over the XUV-FEL operating range will increase substantially.

The simplest and most versatile way to tune between the harmonic orders is through control of the amplitude and phase of the fundamental. This can be as simple as a chirp [14-16], but more general adaptive pulse shaping [17-20] allows greater tuning range and greater control over the harmonic pulse width. This method presents minimal impact on synchronization during tuning, and is rapid once the system has been calibrated. The tuning range is of the order of $q\Delta\nu$, where q is the harmonic order and $\Delta\nu$ is the bandwidth of the fundamental, so the method does not work well at low harmonic orders. Reitze et al [18] demonstrated complete tunability (i.e. a tuning range exceeding the separation of adjacent harmonics) down to 40 eV in Argon using 28 fsec, 800 nm pulses, a tuning range of $2.2q\Delta\nu$. At some energy below 40 eV, complete tunability will be lost. For this reason in the current design, a tunable fundamental is used for the low-energy end of the XUV-FEL energy range.

Using a tunable fundamental entails a double loss, from the frequency conversion losses as well as the drop in harmonic efficiency at longer wavelengths [21]. Conversion to wavelengths shorter then 800 nm, where the harmonic efficiency is higher, is possible, but then the harmonic orders used to reach the very low end of the tuning range are smaller, and complete tunability cannot be obtained there. For an infrared source tunable from 1200 nm to 1475 nm, complete tunability would be obtained. Conversion efficiencies for commercial noncollinear phase-matched optical parametric amplifier (NOPA) systems in this range, pumped by a Ti:Sapphire system, are typically ~10%, while laboratory systems have reported efficiencies of 20% [22]. The harmonic efficiency drops as λ^{-3} [21,23,24], so it is 15-30% of the harmonic efficiency at 800 nm. Harmonic efficiencies are high enough at these lower energies that sufficient seed power can still be produced. Fig. 1 shows the projected range of the tunable source's harmonic yields in Xenon using the expected wavelength scaling of the harmonic efficiency, and assuming 15% conversion efficiency in the NOPA. Above 40 eV, tuning is done using adaptive control of the Ti:Sapphire fundamental

Developments in laser technology will probably make this two-track system unnecessary in the near future, as new high-power kilohertz ultrafast sources in the 1-2 micron wavelength range are developed [13]. Because the high energy cutoff of harmonic production increases with λ^2 [25], at longer wavelength, gases with higher harmonic efficiency can be used to generate higher photon energies, offsetting some of the wavelength-dependent drop in efficiency. A longer fundamental wavelength also increases the wavelength range over which adaptive tuning may be used, since the harmonic order q for a given wavelength increases and the harmonic spacing decreases. For example, assuming an adaptive tuning range of $2q\Delta\nu$, a source with a fixed wavelength of 1.8 microns and 20 fsec pulse width could cover the entire XUV-FEL energy range using only adaptive tuning.

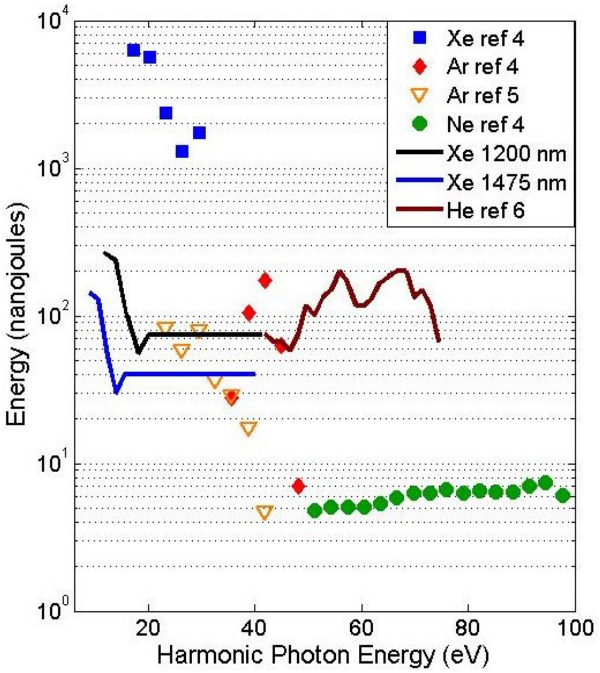

Figure 1 Recent high harmonic generation experimental results scaled by energy and wavelength. The unconnected points were taken with an 800 nm fundamental, and are scaled here to a pulse energy of 14 mJ. The solid Xe curves show the projected range of harmonic yields for the NOPA (2 mJ pulse energy), tuning between 1200 and 1475 nm. The solid He curve shows the results of a two-color experiment using 800 and 400 nm fundamentals, scaled to a 14 mJ pump energy. The minimum energy for seeding the XUV-FEL with a 30 fs pulse is 1 nJ

COHERENCE, STRUCTURE AND CONTRAST

Other spectral and temporal qualities of the harmonics must also be considered. Over the design range of the XUV-FEL, the gain bandwidth of the FEL radiator is both larger than the bandwidth of individual harmonics, and much smaller than the separation between harmonics. This allows for efficient seeding without requiring the separation of harmonic orders in the seeding optics. The transverse spatial coherence of harmonics depends sensitively on the generation geometry, but very high coherent flux has been measured [26]. This concerns primarily the seeding efficiency, as the spatial coherence increases dramatically as the pulse is amplified to saturation.

Because harmonics are used to generate attosecond pulses, there is some question whether subfemtosecond temporal structure could affect seeding. There are, however, fundamental reasons for expecting little effect from this structure. Sub-femtosecond structure arises from the coherent superposition of multiple harmonics; it is essentially an interference effect. Since the FEL radiator's bandwidth is restricted to a single harmonic order (the harmonic separation is ~3 eV, while the FWHM gain bandwidth of the radiator lies in the range of .04-.4 eV) it effectively acts as a filter, and the time profile of an individual harmonic, which is smooth [27], is the relevant temporal shape. Furthermore, the period of any sub-femtosecond structure is quite short – half of the fundamental optical cycle – so that, even if multiple harmonics could be amplified, slippage would tend to smooth out any short scale structure. We have considered the attosecond structure issue in our simulations however, and it is discussed in greater detail in Ref. [28].

An issue in all seeding techniques is the achievable contrast between the coherent output pulse and any incoherent background. This is of particular concern in experiments involving nonlinear interactions, as lower-order interactions with the background pedestal surrounding the main pulse can alter the target's initial state before the main pulse arrives or the product state after the main pulse is over, so that both the height of the background and the length of the window over which it persists are important. Our simulations [2,28] show that, for the minimal seed power, we obtain, over the XUV-FEL energy range, contrasts of 10^{-2} to 10^{-3} immediately beneath the main pulse, dropping to 10^{-5} to 10^{-7} within a picosecond on either side of the pulse.

The background consists of SASE evolving in the unseeded part of the bunch, and so the context of these numbers should also be considered carefully. First, the contrast improves with increasing seed power, as the length to saturation decreases and the ratio of the coherent seed power to spontaneous power in the wings of the pulse increases. The feasibility simulations were done with minimal seed power but, depending on the energy and tunability required, orders of magnitude more may be available. The simulations were also done with a Gaussian longitudinal electron bunch distribution with a FWHM pulse width of 625 fs; more sharply peaked distributions would also improve contrast, as the gain in the wings would drop accordingly. The full parameter space has not yet been explored with respect to contrast, and these aspects will be investigated further in future design work. A more detailed discussion and simulation results may be found in Ref [2].

IMPLEMENTATION

The current design for implementing HH seeding in the 4GLS XUV-FEL is shown schematically in Fig. 2. An ultrafast Titanium Sapphire oscillator producing 30 fsec, 800 nm pulses is synchronized at a subharmonic of the accelerator RF frequency. Pulses are selected at 1 kHz and amplified to 14 mJ. Amplifier chains capable of this power presently exist [7], and systems with higher output are expected to appear soon.

After amplification, the pulse is switched into one of two paths, depending on the FEL photon energy. For low energies (8 to approximately 40 eV), a tunable pump pulse is generated using a noncollinear optical parametric amplifier (NOPA) operating between 1200-1475 nm. At higher energies (40 - 100 eV), the 800 nm light is used for HH generation, and adaptive tuning is used. Pulse shaping for the adaptive tuning can be done either before the amplifier, as shown here, or afterwards.

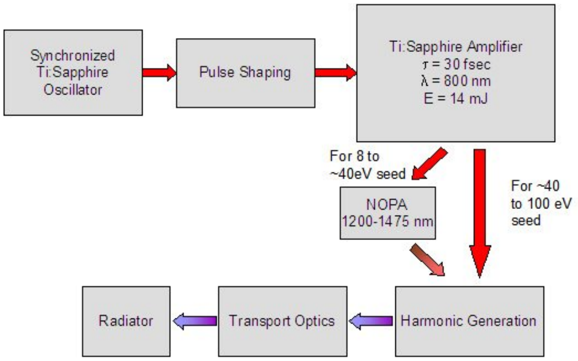

Figure 2 Block diagram of high harmonic seeding for the 4GLS XUV-FEL

The geometry for the HH generation is still under study. A loose focusing geometry in a variable length cell is the simplest to implement over the entire range of the XUV-FEL and is equivalent to waveguide geometries at sufficiently high power [29]. Waveguide geometries [30] may be beneficial for the low photon energies, where the pump pulse energy is lower, Modulated waveguide geometries [31] may provide greater efficiency, but it may be difficult to implement multiple configurations to cover the entire wavelength range. Efficient materials (eg SiC) for grazing incidence optics are available for the optics coupling the HH seed into the radiator.

SUMMARY

We have developed a design to establish the feasibility of seeding the 4GLS XUV-FEL with high harmonics. Currently available technology is capable of supplying sufficient seed energy, and tuning may be accomplished with a tunable fundamental at the low-energy end of the XUV-FEL operating range, and with pulse shaping of a fixed-frequency fundamental at higher energies. Technological improvements are expected to increase the available power and simplify the implementation. Spectral and temporal properties of the harmonics appear to be commensurate with the requirements for seeding.

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