HIGH HARMONIC SEEDING AND THE 4GLS XUV-FEL

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Abstract

The Fourth Generation Light Source (4GLS) project, proposed by the CCLRC in the U.K., will include free electron lasers in the XUV, VUV, and IR. It is proposed that the XUV-FEL, operating between 8-100 eV, be seeded by a high harmonic (HH) source, driven by an ultrafast laser system. This offers advantages in longitudinal coherence, synchronization, and the potential for chirped pulse amplification and pulse shaping. We discuss the issues of HH generation relevant to its use as a seed (energy, spectrum, tunability, synchronization and time structure) and the current planned implementation in the 4GLS XUV-FEL.

INTRODUCTION

A long-standing concern in short-wavelength FEL development has been the limitations of spontaneous sources. It has become clear that seeded sources are preferable to spontaneous sources, for reasons of both stability and the advantages conferred by longitudinal coherence. A number of seeding methods have been proposed, including high-gain harmonic generation (HGHG), 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.

Seeding with high harmonics is attractive since it permits a great deal of control over the seed radiation through comparatively simple manipulations of the ultrafast laser that pumps the HH generation. Pulses of individual harmonics can be made extremely short, down to a few femtoseconds, and 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 in the FEL to achieve higher output energies, or even of pursuing more elaborate pulse shaping.

Unfortunately, the efficiency of HH generation falls rapidly at shorter output wavelengths, so that for soft X-ray facilities, sufficiently energetic sources have not yet been demonstrated. However, in the wavelength range planned for the 4GLS XUV-FEL, sources currently available could provide sufficient energy for seeding, and the available energy will increase with coming improvements in ultrafast laser technology.

In addition to the issue of sufficient optical energy for seeding, a number of other concerns must 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. In the following sections, we address the energy, tunability and other issues, and outline the currently planned implementation of the seeding in the 4GLS XUV-FEL.

SEED ENERGY

The 4GLS XUV-FEL will operate between 8-100 eV. Our simulations of the XUV-FEL [1], using GENESIS 1.3 [2], use 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 [1].

Measurements of harmonic yields have been made by many research groups using Ti:Sapphire based ultrafast systems, and we show a scaled synopsis of several recent results [3-5] in Fig. 1. The experiments represented here (unconnected points on the plot) were conducted with pulse energies in the fundamental ranging 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 [6]. Ultrafast laser technology is developing very rapidly though, and there is no fundamental limit to higher power systems. A number of recent developments, including the use of optical parametric chirped pulse amplification [7], high power Yb:YAG lasers [8], and enhancement cavities [9-11], offer new opportunities for larger systems. Several 100-Watt kilohertz system designs have been proposed [12], and will likely be demonstrated soon.

HH generation is also a very active research area, and a number of efforts are focused on extending the wavelength range and yield of harmonics. Recent experimental work [5] using two-color driving 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 has the lowest harmonic efficiency 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.

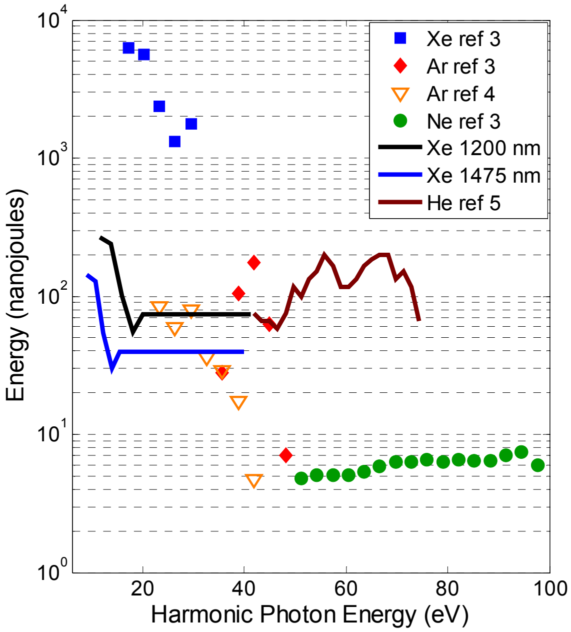

Figure 1. Recent experimental results scaled by energy and wavelength. The unconnected points were taken with an 800 nm fundamental, and are scaled here to a pulse energy of 14 mJ. The solid Xe curves show the projected range of harmonic yields for the NOPA (2 mJ pulse energy), tuning between 1200 and 1475 nm. The dashed 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.

TUNING

The simplest way to tune between the harmonic orders is by controlling the amplitude and phase of the fundamental. This can be as simple as a chirp [13-15], but more general adaptive pulse shaping [16-19] allows greater tuning range and greater control over the harmonic pulse width. This minimizes the impact of tuning on synchronization, and tuning can be done rapidly once the system has been calibrated. However, it does not function well at low harmonic orders, as 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. Reitze et al [17] 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.

The disadvantage of a tunable fundamental is the drop in total efficiency due to frequency conversion losses and the lower harmonic efficiency [20] at longer wavelengths. 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 efficiency 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% [21]. The harmonic efficiency drops as λ^{-3} [20,22,23], so it is 15-30% of the harmonic efficiency at 800 nm. Fortunately, at these lower energies, the harmonic efficiencies are high enough that, even with the losses, an adequate seed power is 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. For higher photon energies, above 40 eV, the Ti:Sapphire fundamental is used, and tuning is done by adaptive control.

Developments in laser technology will probably make this two-track system unnecessary in the near future, as new kilohertz ultrafast sources in the 1-2 micron wavelength range exceed 10 Watts average power [12]. Because the high energy cutoff of harmonic production increases with λ^2 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 pump 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.

OTHER ISSUES

Spectral and temporal qualities of the harmonic pulse must also be considered in seeding. 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 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 [24]. This concerns primarily the seeding efficiency, as the spatial coherence increases dramatically as the pulse is amplified to saturation.

Because HH is used to generate attosecond pulses, the question of subfemtosecond structure affecting the FEL seeding is raised. There are fundamental reasons for expecting little effect from this structure. Sub-femtosecond structure arises from the coherent superposition of multiple harmonics. Since the FEL radiator's bandwidth is restricted to a single harmonic order, it effectively acts as a filter, and the time profile of an individual harmonic, which is smooth, is the relevant temporal shape. In any case, any sub-femtosecond structure would be periodic, with a period equal to one-half of the optical period of the HH pump, *ie* 1.3 fsec for a pump wavelength of 800 nm, and so slippage between the optical pulse and the electron bunch would smooth out any sub-femtosecond structure. We have verified this smoothing effect in a GENESIS simulation [1].

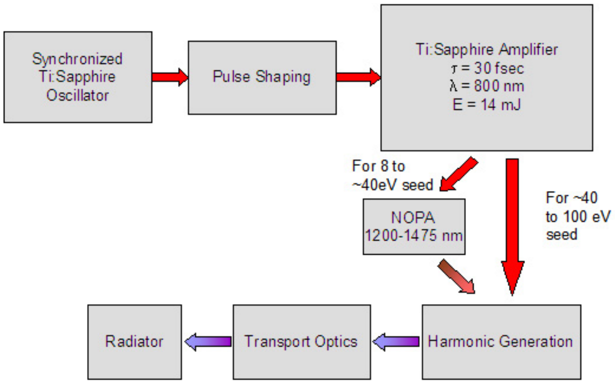

Figure 2. Diagram of HH seeding for the XUV-FEL

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 will be 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 [6], and expected improvements to the laser technology will likely substantially increase the power available.

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.

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 [25]. Waveguide geometries [26] may be beneficial for the low photon energies, where the pump pulse energy is lower, Modulated waveguide geometries [27] 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 system design to demonstrate the feasibility, using present-day technology, of seeding the 4GLS XUV-FEL using high harmonics. Current technology is capable of supplying sufficient seed energy, and expected improvements are likely to increase the available power and simplify the implementation.

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