SEEDED HARMONIC GENERATION SCHEMES

T. Shaftan*, A. Doyuran$, E. Johnson, S. Krinsky, H. Loos, J.B. Murphy, G. Rakowsky, J. Rose, B. Sheehy, J. Skaritka, X.J. Wang, Z.Wu, L.H. Yu
NSLS, BNL, Upton, NY 11973, USA

Abstract

High-gain Free Electron Lasers (FELs) are being developed to serve as short-wavelength, tunable, high-brightness radiation sources for advanced user applications. The widely studied approach in the high-gain FELs is known as self-amplified spontaneous emission (SASE) [1,2]. The SASE FEL delivers radiation pulses with high peak power and tuneable central wavelength. However, the output in general has limited temporal coherence and chaotic shot-to-shot intensity fluctuations. An alternative scheme is seeded harmonic generation, which is capable of producing temporally coherent pulses.

We begin this paper with a review of several high-gain FEL schemes, which utilize electron beam, premodulated by an external radiation source. In such a scheme the FEL process does not take off from noise, as in the SASE case, but from beam bunched coherently. This ensures stable central wavelength, narrow bandwidth and small pulse-to-pulse energy fluctuations of the output.

As an example of seeded FEL operation we present recent experimental results of the DUV FEL (BNL) [3]. At DUV FEL an 800 nm seed is used to produce saturated radiation at the third harmonic (266 nm). The third-harmonic of FEL output at 88 nm has been used in an ion pair imaging experiment in chemical physics as one of the first user application of seeded HG FEL [4].

INTRODUCTION

High-gain FELs have been proposed as powerful light sources for the short-wavelength range. Ultrashort radiation pulses from VUV to X-ray provide a unique possibility for studying fast processes in a large variety of scientific applications. Output radiation tuneability and coherence are important measures of the FEL performance. High-gain FEL based on the SASE principle [1,2] delivers short radiation pulses with full transverse coherence and tuneable central wavelength. However, the output has limited longitudinal coherence, due to the fact that the radiation is developed from the incoherent shot noise in electron beam. This degrades radiation pulse and spectrum shapes into a set of short spikes, randomly distributed and varying from pulse to pulse.

For an initially premodulated beam, i.e. when the beam density contains a coherent bunching at the FEL resonant frequency, the FEL radiation output preserves full longitudinal coherence. In this case FEL acts as an amplifier of the external seed. Due to the nonlinearity of the FEL process, not only the fundamental harmonic can be amplified, but the higher harmonics too. This allows for frequency multiplication and the generation of radiation in VUV and X-ray wavelength regions [5].

Seeding by an external source offers an opportunity to control the output pulse properties by controlling the shape of the input seed pulse. Nowadays conventional lasers are capable of providing ultra-short pulses with high peak power. Using the Harmonic Generation approach, one can shift and amplify the seed laser pulse in the short-wavelength region, preserving the flexible temporal format of the seed and generating short radiation output.

Other important benefits of seeded HG scheme are high stability, control of the central wavelength and much smaller energy fluctuations than in the SASE case.

This paper does not give a complete review of the field. It opens with a discussion of several concepts and ideas in seeded harmonic generation FELs, and then reviews experimental results on the demonstration of the seeded FEL radiation properties in the Deep Ultra-Violet Free Electron Laser (DUV FEL, BNL), which is described as an example of the seeded High Gain Harmonic Generation FEL [3]. A few proposed seeded FEL projects now being designed are mentioned in the conclusion.

THE CONCEPT AND IDEAS OF THE SEEDED HARMONIC GENERATION

We shall begin with the description of the High Gain Harmonic Generation (HGHG) scheme [6]. In the HGHG FEL a coherent seed interacts with an electron beam in the first (energy-modulating) undulator, which is tuned to be resonant to the seed laser frequency. The resulting energy modulation is then converted to spatial bunching while the electron beam traverses a dispersive section. In the second undulator, which is resonant to the harmonic of the seed frequency, the microbunched electron beam initially emits coherent radiation and then amplifies it exponentially until saturation is achieved.

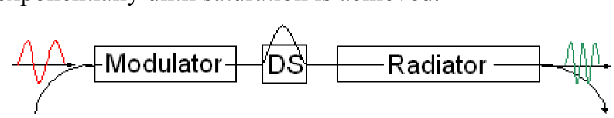

Figure1: High Gain Harmonic Generation(HGHG) scheme

Conventional lasers operate at wavelengths longer than 200 nm, hence to use one stage HGHG FEL reaching to x-ray region would require extremely high harmonic on the order of a thousand. This is not practical since it would require unachievable high input seed power and

* Corresponding author: shaftan@bnl.gov
$ Present address: UCLA Department of Physics, Los Angeles, CA 90024, USA

low electron beam energy spread. Also, use of very high harmonics would result in low stability of the output [7].

A better approach is to cascade several stages of HGHG and use a low harmonic number for each stage. Each stage consists of one modulator, a dispersion section, and one radiator. Light from the previous stage is used as a seed for the beam in the next cascade stage. Therefore, the FEL process in each stage will be the same as in a single one [8]. During the process, the output radiation disturbs the energy spread in a part of the e-beam, which interacts with the seed. In order to achieve the best efficiency to carry out the next stage of HGHG, a fresh part of the electron beam must be used.

There are two ways of supplying new electrons to the FEL interaction region. The first is to shift the laser (i.e., the output radiation from the previous HGHG stage) toward the front part of the same electron beam, so that the laser will interact with a "fresh" part of the same electron beam. The second way is to introduce a new electron bunch for each stage, so that again the laser will interact with a "fresh" bunch. The first case represents the essence of "fresh bunch technique" [8]. For the first case, special chicane magnet, or "shifter", is used to "shift" the seed pulse to the "fresh" part of the same electron beam.

An example of an FEL project based on the cascading principle is described in [9]. Calculations show that the cascaded HGHG-based FEL can provide a short transform-limited pulse at 1 nm with the peak power in GW range. In addition, the third harmonic at 3.3 A will reach a peak power of tens of MW.

Synchronization between the seed laser pulse and the electron bunch is a critically important issue in carrying out cascading HGHG stages to achieve intense temporally coherent X-ray pulses. This sets a tight constraint on the acceptable level of the timing jitter between electron and seed laser beams.

Another suggested approach in the seeded harmonic generation uses the electron beam premodulated in an FEL oscillator before entering the cascaded stages [10]. This project consists of a relatively low energy linac (750 MeV) and three sections: an oscillator at 150 nm, an amplifier tuned at the fifth harmonic of the oscillator, and a second amplifier operating at a harmonic of the first amplifier. The seedless amplification is accomplished by the beam bunching induced in the oscillator and in the second section, which plays the role of amplifier and modulator. The equivalent input seed, associated with the bunching generated in the modulator, allows the growth of coherent radiation until saturation occurs. The FEL device based on this proposed scheme can provide an output at the wavelength of 6 nm.

Several schemes have been suggested to generate a short pulse in a seeded harmonic generation FEL. The first approach is called Chirped Pulse Amplification (CPA) and is well known in the conventional lasers society. In CPA the radiation from the seed laser is stretched to provide a wavelength chirp. When coupled to an electron beam inside a modulator, the seed radiation introduces an energy modulation on the electron bunch, which has been prepared with an energy chirp to match the chirp in the optical pulse. The chirped coherent radiation produced by such a beam is amplified as it traverses the radiator and is recompressed optically. The preservation of phase coherence provided by this scheme results in a device which can yield 4-fs pulses at a wavelength of 88 nm [11]. Initial CPA experiments have been performed at the DUV FEL [23].

The second technique is based on "manipulating" the energy spread along the electron bunch [12]. Since the FEL process is very sensitive to the value of the local energy spread, only a "cold" portion of the beam radiates. The required shaping of the energy spread is performed by passing the electron beam through a two-stage FEL amplifier seeded by an optical pulse. The system consists of two undulators separated by an electron bypass and optical pulse shaping system. The first undulator operates in the linear regime and produces short radiation pulse naturally synchronized with the electron bunch. Leaving the first undulator the electron bunch is guided through a bypass, and the light enters the pulse shaping system. The shaping system produces a pulse with zero value of optical field in the central area, which is amplified up to saturation in the second undulator. Large energy spread is induced in most of the electron beam due to the FEL interaction process, and only a small part of the electron bunch (near the center of the zero area light pulse) is capable of producing radiation at the wavelength of 6 nm in the following amplifier SASE FEL. According to [12], the described FEL design can provide soft X-ray pulses with 30 fs duration.

The FEL tuneability aspect is very important for many user applications. In the seeded FEL scheme the seed controls the FEL output wavelength. Therefore, if one wants to tune wavelength of the HGHG laser, he has to establish tuneable seed laser. Modern conventional lasers can provide a tuneable seed in the wavelength range of a few percent. For instance, the tuning range of the Ti:Sa laser system is limited by 3.5 % [14]. Using Optical Parametric Amplification of the seed, the wavelength tuning range can be extended up to 30% [15]. Some inconveniences of tuning seed laser wavelength are discussed below.

Since modern high-gain FELs utilize photocathode RF-gun, the gun laser system naturally serves as a source of the seed for an FEL [3]. This approach provides an accurate synchronization between electron beam and seed laser, which would be difficult to achieve otherwise. Under such circumstances the wavelength variation would cause retuning of the laser oscillator, thus retuning the laser wavelength. In turn, this affects the amount of electrons, derived from the gun, since cathode quantum efficiency depends on the laser photon energy and spot size.

Another issue comes from seed laser alignment considerations. For reliable HGHG performance, seed laser and electron beam must be overlapped inside the modulator with a high accuracy. Changing wavelength affects seed laser beam size and trajectory along the transport line, as well as in the coupling region. It also affects relative timing between electron and seed laser beams, if dispersive optics is used. Since laser optics is naturally chromatic it has to be retuned for any particular value of wavelength. In addition, smooth retuning of the laser wavelength may be a time- and effort-consuming procedure.

An alternative technique for the tuneable HGHG FEL utilizes a seed with fixed wavelength. The essence of the technique [13] is in the compression of the chirped electron bunch in the HGHG dispersive section. Since the whole beam undergoes compression, the laser-induced modulation along the bunch also must be compressed with the same compression factor. Therefore prebunched electron beam enters the radiator with a new bunching wavelength. Changing the value of the energy chirp together with the seed laser power allows for a smooth tuning of the FEL output wavelength. Applying this scheme to the DUV FEL we experimentally demonstrated the wavelength tuning range of one percent. Straightforward upgrade of the DUV FEL dispersive section is in progress. This will increase the tuning range up to 3 percent. Let us note that the idea of changing the FEL output wavelength using bunch compression in a chicane was previously discussed in [25].

As it has been shown [13,24], the tuning range is mostly limited by the FEL dynamics of the chirped beam in the radiator. In order to overcome the limitations we proposed a dedicated scheme of the tuneable HGHG FEL. In this scheme the secondary RF system is included into FEL magnetic system. First RF section imparts a chirp in the beam, which, being compressed in DS, gets unchirped in the second RF section. Therefore chirp is provided only locally and the beam enters the radiator having no correlated energy spread. Use of the dedicated scheme (Fig. 2) for the case of DUV FEL can extend the estimated tuning range up to 20%.

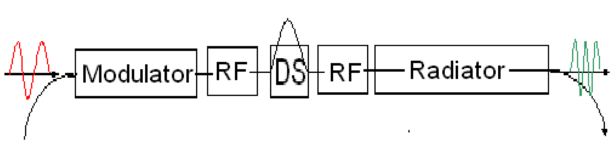

Figure 2: Dedicated scheme for the tuneable HGHG FEL. RF sections are located before and after dispersive section locally providing the energy chirp required for the wavelength compression.

SEEDED HARMONIC GENERATION EXPERIMENTS

In this chapter we review some of the experimental results obtained at DUV-FEL facility (NSLS, BNL) [3,16]. The layout of the facility is shown in Fig. 3. The accelerator begins with a BNL/SLAC/UCLA 1.6 cell photocathode RF gun, illuminated by a frequency-tripled Ti:Sa laser at 266 nm. Currently the RF gun is able to produce a 300 pC, 4.5 MeV, 1.7 ps (RMS) electron beam with emittances of 3-4 mm·mrad at the repetition rate of 2.5 Hz. Following are two SLAC-type 2.856 GHz linac sections, which accelerate the electron beam up to 77 MeV. The second linac tank provides the energy chirp for the bunch compression, by running the electron bunch off-crest of the RF wave. A four-magnet chicane with variable field strength compresses the bunch length down to 1 ps (FWHM), which is appropriate for the FEL operation. The third linac tank, installed after the chicane, performs the residual energy chirp cancellation, as well as providing additional acceleration. The last tank is used for the acceleration to the nominal energy of 175 MeV.

The main component of the FEL magnetic system is the radiator, comprised of the 10 m long undulator (NISUS) with 3.89 cm period and 0.31 T peak field. 80 cm long, 10 periods undulator with adjustable gap serves as the modulator. A short (30 cm) dispersive section is located between the undulators.

The 800 nm seed input is derived from the same Ti:Sa laser system, that drives the photocathode RF gun but a separate optical compressor is used to produce a linearly chirped 9 ps (FWHM) seed pulse.

The FEL modulator is tuned to be resonant to the 800 nm wavelength of the seed laser. The radiator parameters are optimised for a 3^{rd} harmonic of the seed (266 nm). In experiments, described below, we have measured the properties of the FEL output at 266 nm.

Fig. 4 shows the measured single-shot spectra of HGHG and SASE. The SASE spectrum was measured while blocking the seed light; the SASE output is far from saturation. Even when saturated, the broad SASE bandwidth would result in the order of magnitude lower brightness than HGHG.

Measurements show that the HGHG FEL output has a smooth gaussian transverse profile. This indicates that the HGHG FEL output is highly transversely coherent.

An important measure of the FEL quality is the magnitude of pulse-to-pulse energy fluctuation. We have observed the pulse energy for a relatively long period of 30 seconds. The statistics is shown in Fig. 5. The calculated value of the RMS HGHG fluctuation of 7 % is found to be much smaller than for the SASE case (41 %). Again, the direct comparison is difficult since the SASE output is not saturated. We also note that the measured value of the HGHG fluctuation is affected by the accelerator instabilities (broad pedestal around the narrow peak on the HGHG histogram is due to a fluctuation of the electron beam parameters).

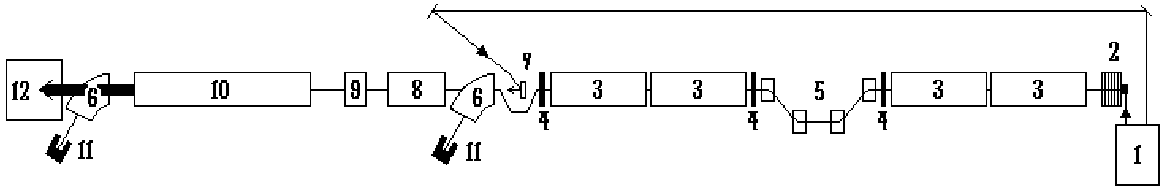

Figure 3: The DUVFEL layout. 1 – gun and seed laser system, 2 – RF gun, 3 – linac tanks, 4 – focusing triplets, 5 – magnetic chicane, 6 – spectrometers dipoles, 7 – seed laser mirror and electron beam local bump, 8 – modulator, 9 – dispersive section, 10 – NISUS wiggler (radiator), 11 – beam dumps, 12 – FEL user experimental area.

As a follow-up to the successful commissioning of HGHG at 266 nm, an energy upgrade is in progress at the DUV FEL. The modification of the accelerator is going to increase the maximum energy up to 300 MeV. This will enable a new mode of operation with the goal of placing the coherent HGHG output fundamental at 100 nm.

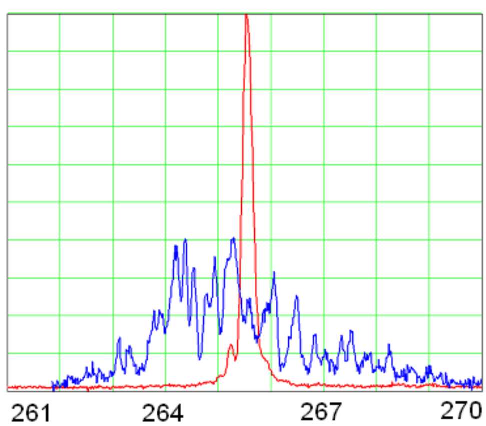

Figure 4: Single-shot HGHG spectrum exhibiting a 0.1% FWHM bandwidth (red curve). Blue curve represents SASE spectrum (magnified by the factor of 10^5). Horizontal axis is scaled in nanometers.

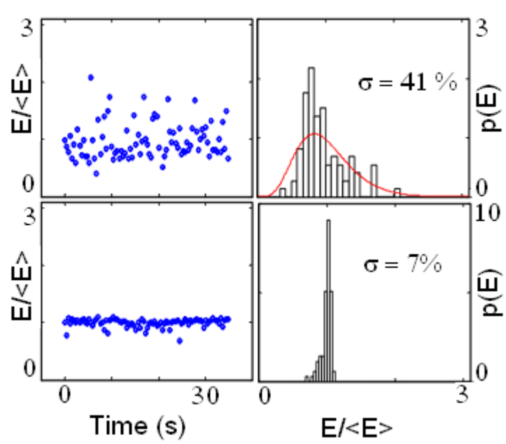

Figure 5: Time dependence and histograms of HGHG and SASE output pulse energies.

CONCLUSION

The experimental results discussed above demonstrate excellent quality of the HGHG radiation. In addition to the fundamental harmonic at 266 nm (100 uJ), the FEL output contains a significant amount (~1 uJ) of the third harmonic (88 nm). Such a short wavelength, in combination with a short pulse length (measured value of 0.6 ps at 266 nm), makes DUV FEL an attractive laser for the experiments in chemistry and material science. The 88 nm output has been used in an ion pair imaging experiment [4] in chemical physics as the DUV FEL first user application.

The abovementioned ideas on carrying the seeded HG FEL light down to a shorter wavelength range has initiated the design of several VUV and X-ray FEL projects. The following table gives an insight on the current proposals.

Table 1: Seeded HG FEL projects worldwide.

Project	λ_{FEL}, nm	Power, MW	Pulse length, fs
DUV FEL (BNL) [3]	266 (100)	100	600
SDUV FEL (Shanghai) [17]	264 (88)	140 (at 88 nm)	
LUX (LLBL) [18]	240 -- 1	11 (1 nm)	200-10
MIT-Bates [19]	100 -- 0.3	4e3	50/1
MAX-4 (Lund) [20]	260 – 0.76	~50	
ELF (ELETTRA) [21]	100 – 1.2	3e3 (1.2 nm)	100
ARC-EN-CIEL (France) [22]	200 -- 0.82	4e3 (14 nm)	~20

All of these HG FEL proposals utilize the benefits coming from the fast progress in the conventional laser community. Seeding with fs-pulses and using high-harmonic generation in gases are the proposed options to further improve the seeded HG FEL radiation parameters. Some of the projects consider a multi-user mode of operation, including a set of FELs with tens of user stations.

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