Ultraviolet high-gain harmonic-generation free-electron laser at BNL


National Synchrotron Light Source, Brookhaven National Laboratory, AFT, Bldg 725C, Box 5000, Upton, NY 11973, USA

Abstract

We report the first experimental results on a high-gain harmonic-generation (HGHG) free-electron laser (FEL) operating in the ultraviolet. An 800 nm seed from a Ti-Sapphire laser has been used to produce saturated amplified output at the 266 nm third-harmonic. The results confirm the advantages of the HGHG FEL: stable central wavelength, narrow bandwidth and small pulse energy fluctuation. The harmonic output at 88 nm, which accompanies the 266 nm radiation, has been used in an ion pair imaging experiment in chemistry.

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1. Introduction

There is great interest in utilizing a high-gain single-pass free-electron laser (FEL) to generate intense, short pulse radiation in the spectral region from the deep ultraviolet down to hard X-ray wavelengths [1]. The most widely studied approach has been self-amplified spontaneous-emission (SASE). In a SASE FEL [2–5], the amplifier is seeded by the shot noise in the electron beam. SASE can produce short wavelength radiation with high peak power and an excellent spatial mode. However, the output has limited temporal coherence (coherence time much shorter than the pulse duration) and chaotic shot-to-shot intensity variations.

An alternate single-pass FEL approach is high-gain harmonic-generation (HGHG) [6–7], which is capable of producing temporally coherent pulses. In HGHG: (1) a small energy modulation is imposed on the electron beam by interaction with a seed laser in a short undulator (the modulator) tuned to the seed frequency ω; (2) the energy modulation is converted to a coherent longitudinal density modulation as the electron beam traverses...
a three-dipole chicane (the dispersion magnet); (3) in the second undulator (the radiator), tuned to the \( n \)th harmonic of the seed frequency, the micro-bunched electron beam emits coherent radiation at the harmonic frequency \( n \omega_0 \), which is then amplified until saturation. In HGHG, the light output is derived from a coherent sub-harmonic seed pulse; consequently, the optical properties of the HGHG FEL are a map of the characteristics of the high-quality seed laser. This has the benefit of providing better stability and control of the central wavelength, narrower bandwidth, and smaller energy fluctuations than SASE. Furthermore, HGHG has the potential to produce light pulses with duration much shorter than the electron bunch length.

The basic principle of the HGHG has been demonstrated at IR with the second harmonic [7]. Recently we reported the HGHG experiment in the UV region [8]. Here we give a more detailed report on the results obtained with the deep ultraviolet FEL (DUV-FEL) at the National Synchrotron Light Source of Brookhaven National Laboratory. The DUV-FEL design and commissioning are discussed in Refs [9–11]. In October 2002, we achieved the third harmonic HGHG starting from a seed at 800 nm with saturated output at 266 nm. We have measured HGHG output as a function of the undulator length for the first time. Since January 2003, the harmonic output at 88 nm accompanying the 266 nm fundamental has been used in an ion pair imaging experiment [12] in chemical physics as its first user application [13]. The experiment benefited from the high stability of the HGHG output. Here we report observations of the HGHG process: initial coherent generation, exponential amplification and saturation. We describe the key properties of HGHG, emphasizing its high stability and narrow bandwidth.

2. Basic description of the NSLS DUV-FEL

The layout of the facility is as illustrated in Fig. 1. The injector is comprised of a photocathode RF gun, illuminated by a frequency-tripled Ti:Sa laser at 266 nm, producing a 300 pC, 4.5 MeV, 4 ps (FWHM) electron bunch with normalized emittance of 3–5 \( \mu m \). Two SLAC-type 2.856 GHz linac sections accelerate the electron beam up to 77 MeV. The second linac tank provides an energy chirp for the bunch compressor [14] (a four-magnet chicane). The third linac tank, located after the chicane, removes the residual energy chirp, with additional acceleration. The last tank is used to complete the acceleration to the desired energy. It is also used in combination with the downstream spectrometer magnet for bunch length measurement, employing the “zero-phasing” technique [15,16].

To allow injection of the seed, a combination of four dipole trims produces a “local bump” of the trajectory to bend the electron beam around the laser seeding mirror. Then follows the energy modulating undulator which has an 8 cm period with \( K = 1.67 \), so it is resonant to 800 nm at 177 MeV. Following the modulator is a 30 cm long dispersion magnet which converts the energy modulation to microbunching of the electron beam. Next is the 10 m long “NISUS” undulator [17] with 3.89 cm period, 0.31 T peak field, and equal focusing in the horizontal and vertical planes by means of canted poles. Since NISUS was not designed for the DUV-FEL, its parameters are not ideal for this application. Its period is longer and the electron transverse focusing is weaker than optimum—25 m betatron wavelength at 177 MeV. The resulting gain length of \( L_G \approx 0.8 \) m is too long for the system to reach SASE saturation. However, there is sufficient gain to saturate as an HGHG FEL. Every section of the long undulator is equipped with horizontal and vertical dipole correctors as well as quadrupole trims based on a 4-wire system. The electron trajectory and the transverse beam sizes are measured using Cerium-doped YAG-crystal profile monitors [18]. More details about the DUV-FEL system can be found in [9–11].

3. The experimental results

The photo-cathode laser with a pulse energy of 60 \( \mu J \) at 266 nm is set at 60° before the RF crest, and the tank 2 phase is set at 23° before the RF crest. The charge in a typical electron bunch is
As shown in Fig. 2, the current profile as measured using the zero-phasing method has a FWHM pulse length after compression of 1 ps with a current averaged within the pulse to be 300 pC/1 ps = 300 A. The measured projected normalized emittance after bunch compression is about 4.7 μm. The slice emittance is smaller, measured to be between 2.5 and 3.5 μm.

The trajectory in the NISUS undulator was corrected [19] using the trim dipoles to within 200 μm peak to peak about a straight line determined by referencing the pop-in monitors to a HeNe alignment laser. The beam size as measured from the pop-in monitors provides reliable data for matching the electron beam into the NISUS (see Fig. 3), and for measurement of the projected emittance, with results exhibiting excellent agreement with the emittance as measured by a quadrupole scan. The projected energy spread is estimated to be 0.05% rms for the compressed bunch.

The 800 nm seed input is derived from the same chirped-pulse-amplified Ti:Sapphire laser system that drives the photocathode RF gun [20]. A separate compressor leaves a residual chirp in the 9 ps (FWHM) seed pulse, so that the bandwidth seen by the 1 ps electron bunch is only 0.8 nm. A few nanometer tuning range can thus be obtained by varying the delay of the seed pulse relative to the electron bunch. This also varies the seed power since the stretched pulse is not a flat-top.

The synchronization between the 1 ps electron bunch and the 9 ps seed laser was achieved first using a streak camera at the end station measuring both the seed at 800 nm and SASE at 266 nm. Later, it was improved by using the HGHG signal. During the HGHG operation, the dispersion magnet current and the electron beam energy are varied to optimize the output. When the dispersion magnet current is 110 A, the maximum excursion in the dispersion magnet is measured to be $x_m = 2.1 \text{ mm}$ by a monitor at its center, the dispersion [7] is found to be $d\psi/d\gamma = 32\pi \lambda_{\text{rms}}^2/(3s\lambda_s\gamma) \approx 5.4$, where $\psi$ is the ponderomotive phase in the NISUS, $s = 30 \text{ cm}$ is the dispersion section length, $\lambda_s = 266 \text{ nm}$, and $\gamma = 346$ the normalized beam energy. When the dispersion is optimized for maximum bunching, i.e., maximum initial coherent generation in the first part of NISUS, its value can be used to calculate the energy modulation. When combined with the measured seed laser Rayleigh range of 2.4 m and the modulator parameters, this in turn provides information about the laser intensity at its overlap with the electron bunch.
The output pulse energy versus distance for two different seed powers: (a) $P_{in} = 1.8$ MW and (b) 30 MW is presented in Fig. 4. The data was taken using a single downstream detector and sequentially kicking the beam away from the undulator axis using the 16 correctors uniformly distributed along NISUS. As a check, this data was compared with a set of measurements by 5 photodiode detectors installed on the side of NISUS. Gain lengths measured by these two methods agree. At $P_{in} = 1.8$ MW, with $d\psi/d\gamma = 8.7$, the gain length is found to be 0.8 m.

For $P_{in} = 30$ MW, $d\psi/d\gamma = 3$, the output single shot spectrum of HGHG is shown in Fig. 5, together with the single shot SASE spectrum when the seed was turned off are presented. The average spacing between the SASE spectral spikes is used to estimate the pulse length \[ T_b = \frac{\lambda^2}{0.64c\Delta\lambda} = 0.9 \text{ ps} \], about equal to the result of 1 ps electron bunch length obtained from the zero-phasing technique. Note that the HGHG spectral width of Fig. 5 is very nearly equal to the width of a single spike in the SASE spectrum. This is evidence of the very high temporal coherence of the HGHG output. The HGHG spectral brightness is $2 \times 10^5$ times larger than the SASE as shown in Fig. 5, because NISUS is too short to achieve SASE saturation. So this is not an appropriate comparison. If the NISUS length was doubled to 20 m, the SASE would reach saturation, but because of its broader bandwidth it would still have an order of
magnitude lower brightness than the HGHG, as calculated by the code GENESIS [24] (see Fig. 6). A histogram of the shot-to-shot HGHG output pulse energy for a 30 MW seed is shown in Fig. 7 (lower right plot). The rms intensity fluctuation is seen to be small, only 7%, mostly due to variation of the electron beam parameters. In Fig 7 it is visible that between about 14–20 s after counting started there was a minor glitch in the system parameters that contributes to the increased base size of the histogram, thus increases the fluctuation from 3.8% to 7%. The HGHG output energy can also exhibit a slow drift if the electron beam parameters change slowly. But we have observed the HGHG output to be stable, with typical output energy of 100 μJ. Since the slippage of laser pulse relative to the electron bunch over the whole NISUS (256 periods long) is $256 \times 0.266 \mu m / c \approx 200 fs$ which is 5 times smaller than the 1 ps electron pulse length, the SASE fluctuation would be $1/\sqrt{5} \approx 44\%$ for an idealized electron beam.

4. Analysis

The time-independent approximation as used by the code “TDA” is valid, because the slippage is much smaller than the electron bunch length. Furthermore, as a rough approximation, we

![Fig. 6. The HGHG single shot spectrum versus a simulated saturated SASE spectrum for a NISUS wiggler with doubled length of 20 m to reach saturation.](image)

![Fig. 7. Histogram of HGHG output pulse energy with 30 MW seed power (lower right) versus a SASE histogram (upper right) obtained under the same condition. The two plots at the left show the shot to shot fluctuation within about 40 s.](image)
neglect the detailed time-structure of the electron bunch. When the seed power is low, as in the $P_{in} = 1.8$ MW data of Fig. 4a, there is a significant exponential growth. From the measured gain length of 0.8 m, we can estimate the electron beam parameters. Since the current is $\sim 300$ A, an analytical gain length calculation [22] indicates that the slice emittance is below 3 $\mu$m. Since the measured slice emittance is between 2.5 and 3.5 $\mu$m, the analytical solution also indicates the local rms energy spread should be smaller than the measured projected value of $5 \times 10^{-4}$. In fact, if we assume the local rms energy spread to be $10^{-4}$ and the emittance to be 2.7 $\mu$m, the simulation by a modified TDA code [7] reproduces the measured gain length of 0.8 m and predicts saturation at the end of the NISUS—as observed. The Pierce parameter [23] for this case is $\sim 3 \times 10^{-3}$. Since the simulation predicts an output peak power of 130 MW and we measure the average pulse energy to be 60 $\mu$J, we estimate the radiation pulse length in this case ($P_{in} = 1.8$ MW) to be 0.5 ps, which is consistent with the pulse length we measured by an auto-correlation method (see Fig. 8). This suggests that only the part with highest peak current of the 1 ps electron bunch significantly contributes to the output. The simulated pulse energy vs. distance curve in Fig. 4a shows good agreement of the simulation with the measured data.

At the higher seed power of 30 MW, the autocorrelation of the 266 nm output indicates the pulse length is $\sim$ 1 ps (in agreement with the SASE output pulse length of 0.9 ps estimated from the spacing of the spikes in Fig. 5), showing that in this case the whole electron bunch contributes. For the 30 MW seed, the coherent radiated energy in the initial part of the NISUS undulator is more than a factor 50 greater than that for the low power seed of 1.8 MW, and saturation is reached at 5 m after amplifying the initial coherent radiation by only a factor of 10. The fact that we need a gain of only 10 to bring the initial coherent emission to saturation shows that coherent radiation is the dominant feature in the HGHG process. This greatly reduces the required undulator length and makes the system much less sensitive to electron beam parameter variation. Hence the HGHG is very stable, as illustrated in Fig. 7. Analysis suggests that the apparent slow growth after the saturation at 5 m instead of the drop of power as indicated by the simulation is due to the fact that the whole bunch contributes to the output, and individual slices having different currents reach saturation at different rates. Since the whole bunch is contributing to the output, part of the beam is mismatched. To take this into account we do not use the slice emittance in the simulation, rather the emittance is approximated by the measured projected emittance of 4.7 $\mu$m. The rms energy spread is assumed to be $1 \times 10^{-4}$. The simulation results show reasonable agreement with the pulse energy vs. distance data shown in Fig. 4b.

The bandwidth within a 1 ps slice of the chirped seed is 0.8 nm (0.1% bandwidth) and the chirp in the HGHG output is expected to be the same, i.e., $0.1\% \times 266$ nm = 0.26 nm. This is in agreement with the measured FWHM bandwidth of 0.23 nm observed in Fig. 5. A Fourier-transform limited flat-top 1 ps pulse would have a bandwidth of 0.23 nm, while a FWHM 1ps Gaussian pulse would have bandwidth of 0.1 nm.

5. Summary

The coherent generation and the ensuing exponential growth of the HGHG light at 266 nm...
has been observed to be in agreement with theory. The output exhibits the predicted and designed high intensity stability and a nearly Fourier-transform limited bandwidth.

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**References**


