NEW RESULTS OF THE HIGH-GAIN HARMONIC GENERATION FREE-ELECTRON LASER EXPERIMENT*

A. Doyuran^{a,†}, M. Babzien^a, T. Shaftan^a, S.G. Biedron^b, L. H. Yu^a, I. Ben-Zvi^a, L.F. DiMauro^a, W. Graves^a, E. Johnson^a, S. Krinsky^a, R. Malone^a, I. Pogorelsky^a, J. Skaritka^a, G. Rakowsky^a, X.J. Wang^a, M. Woodle^a, V. Yakimenko^a, J. Jagger^b, V. Sajaev^b, I. Vasserman^b

^aBrookhaven National Laboratory, Upton, New York 11973

^bAdvanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439

Abstract

We report on the experimental investigation of high-gain harmonic generation carried out at the Accelerator Test Facility at Brookhaven National Laboratory. A seed CO₂ laser at a wavelength of 10.6 μm was used to generate FEL output at a 5.3- μm wavelength. The duration of the output pulse was measured using a second-harmonic intensity autocorrelator, and the coherence length was measured using an interferometer. We also measured the energy distribution of the electron beam after it exited the second undulator, observing behavior consistent with that is expected at saturation. The intensity of the harmonic components of the output at 2.65 μm and 1.77 μm were determined relative to that of the 5.3- μm fundamental. Finally, using a corrector magnet upstream of the radiator, steering effects on the trajectories of the electron and light beams were studied.

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contracts Nos. DE-AC02-98CH10886 and W-31-109-ENG-38 and by Office of Naval Research Grant no. N00014-97-1-0845.

†E-mail: adoyuran@ic.sunysb.edu

I. Introduction

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First lasing of a high-gain harmonic-generation (HGHG) free-electron laser (FEL) was reported in refs. [1,2]. Here, the latest results characterizing the HGHG FEL output are presented. The experiment was carried out at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory in collaboration with the Advanced Photon Source at Argonne National Laboratory. A schematic of the HGHG layout is shown in Figure 1. A coherent 10.6- μm seed provided by a CO_2 laser interacts with the electron beam in the first (energy-modulating) undulator, which is tuned to be resonant to 10.6- μm . The resulting energy modulation is then converted to spatial bunching while the electron beam traverses a dispersive section (a three-dipole chicane). In the second undulator, tuned to be resonant at 5.3 μm , the microbunched electron beam initially emits coherent radiation and then amplifies it exponentially until saturation is achieved. We have carried out measurements of the radiation at the radiator fundamental wavelength (5.3 μm), as well as at the second harmonic (2.65 μm) and the third harmonic (1.77 μm).

In previous work [2], the spectral distribution of the FEL output in the neighborhood of 5.3 μm was characterized using a single-shot imaging technique. The bandwidth of the HGHG output was found to be 15 nm FWHM, much narrower than the self-amplified spontaneous emission (SASE) bandwidth. In this note, we report results of measurements of the output pulse duration using a second-harmonic intensity autocorrelator, as well as the coherence length using an interferometer.

The electron beam parameters exhibit some small daily variation about the working point. Typical parameters are 0.8 nC charge, 6 ps FWHM pulse length, and 5 mm-mrad normalized emittance. The repetition rate of the ATF is 1.5 Hz, and the

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repetition rate of the CO₂ laser, limited only by its pulse forming network, is once every 15 seconds. The remaining FEL parameters are given in Figure 1.

II. Autocorrelation

We constructed a background-free intensity autocorrelator using second-harmonic generation in a $5 \times 5 \times 1 \text{ mm}^3$ AgGaSe₂ nonlinear crystal. The group velocity mismatch [3] and geometric beam overlap in the crystal allow better than 0.5-ps resolution. The resolution of 1 ps is predominantly determined by the fluctuations of the electron beam and the CO₂ laser performance. The output radiation is measured with a single-element InSb photoconductive detector. The signal versus delay time (between the two arms of the autocorrelator) is shown in Figure 2. Assuming a Gaussian pulse shape, the pulse duration is found to be $8.4/\sqrt{2} = 5.9 \text{ ps}$. For an HGHG output pulse with energy 100 μJ and pulse length 5.9 ps, the output power is 17 MW, within a factor of two of the theoretical prediction of 35 MW.

III. Interferometer

An interferometer was used to investigate the temporal coherence of the HGHG output. The retroreflecting mirror in one arm was tilted off-axis and translated while the fringe contrast of the interference pattern was recorded on a thermal imaging camera, as shown in Figure 3. Note that in order to collect more light we added a cylindrical mirror to produce a line-type image on the thermal camera. The variation of fringe contrast as a function of mirror displacement, plotted in Figure 4, is a measure of the coherence length of the pulse. The optical coherence length is measured as 1.6 mm, or 5.3 ps, based upon

the delay change. The close agreement between pulse duration and coherence length indicates nearly full longitudinal coherence.

IV. Steering

Using a small corrector magnet located 18.4 cm upstream of the radiator, we studied steering effects on electron and light beam trajectories. Five cerium-doped yttrium aluminum garnet (YAG) beam position measurement screens located at regular spacing through the radiator were used to observe the electron trajectory. A thermal imaging camera 1.7 m downstream of the end of the radiator was used to measure the deviation of the light beam. Steering correctors were varied separately in each plane to induce a maximum electron beam offset of 1.0 mm (horizontal) and 0.5 mm (vertical) on the fifth YAG screen, situated 18 cm downstream of the exit of the radiator. The electron beam steering produced a maximum HGHG output centroid displacement of 2.5 mm (horizontal) and 1.0 mm (vertical) at the thermal camera.

The horizontal steering of the electron beam did not cause observable intensity reduction. Figure 5 shows the horizontal (top) and vertical (bottom) trajectories for the two cases. The measured shift of the optical HGHG output position at the thermal camera and the shift of the electron beam position on the fifth YAG screen suggest that HGHG output follows the electron beam.

When we steered the electron beam vertically by 0.5 mm at the fifth YAG screen, we observed about 1 mm displacement at the thermal camera. In this case, the intensity of the output was reduced because the radiator is a planer wiggler, i.e., the magnetic field increases as one moves out of the midplane in the vertical direction. Due to the change in

magnetic field, the resonant wavelength shift is about 25 nm. Since the bandwidth of the HGHG is 20 nm, this field change causes the electrons to lose resonance with the radiation generated earlier in the wiggler.

V. Electron Beam Modulation and Output Radiation Harmonics

The electron beam energy modulation was determined using the electron energy spectrometer after the radiator section. In the HGHG process, energy modulation of the electron beam is generated in two ways: (1) through the initial interaction of the seed laser and electron beams in the modulator; and (2) through the HGHG FEL interaction itself in the radiator. The energy modulation produced in the radiator dominates. The electron beam images after the spectrometer (a) with CO₂ laser on, and (b) with the CO₂ laser off, are shown in Figure 6. With the CO₂ laser on, the energy modulation is seen to be 2.5%.

The amount of modulation, as well as the strength of the higher harmonics, indicates that saturation or near-saturation has been reached. The higher harmonics have been studied theoretically in refs. [4-7]. Here, we have measured the fundamental (5.3 μm), second (2.65 μm), and third (1.77 μm) harmonics relative to the radiator as a function of electron energy modulation, using the InSb detector in conjunction with the appropriate bandpass and neutral density filters, to produce similar signal levels on the detector. The responsivity of the InSb detector is a factor of 0.67 less at 2.65 μm and a factor of 0.5 less at 1.77 μm as compared to the 5.3- μm responsivity. For the fundamental (5.3 μm), a 10-nm bandpass filter with 80% transmission through this band was used with 1×10^6 attenuation. For the second harmonic (2.65 μm), a 35-nm bandpass filter

with 75% transmission through this band was used with 1×10^3 attenuation. For the third harmonic (1.77 μm), a 35-nm bandpass filter with 60% transmission through this band was used with 1×10^4 attenuation.

In Figure 7, we plot the harmonic contents (μJ) of the first three harmonics versus electron beam energy modulation (%). The rapid increase of the harmonic intensities at 2.65 μm and 1.77 μm as the electron energy modulation approaches 2.5% is strong evidence of saturation. In Table 1, the theoretical predictions and experimental measurements of the ratios of the harmonic-to-fundamental energies are presented for a 2.5% electron beam energy modulation. One sees that there is good agreement between experiment and theory.

VI. Conclusion

New results in the HGHG experiment have provided additional confirmation of theory. For the HGHG output, we used an autocorrelator to measure the intensity pulse length and an interferometer to measure the coherence length of the HGHG output. The agreement of these two measurements indicates full longitudinal coherence. Using a spectrometer, we have previously determined [2] the single-shot spectrum in the neighborhood of 5.3 μm to have a 15-nm FWHM bandwidth. The measured pulse duration of 5.9 ps and bandwidth of 15 nm correspond to a time-bandwidth product that is a factor of ~ 1.7 larger than the minimum. However, the bandwidth and pulse duration measurement were not carried out on the same day, therefore the e-beam pulse shape might not be identical for the two measurements. To more precisely investigate the time-bandwidth product, we plan to carry out the spectral and pulse duration measurements in

a single run. The intensity of the second (2.65 μm) and third (1.77 μm) nonlinear harmonics relative to the radiator section resonant wavelength (5.3 μm) were measured to be in reasonable agreement with theory, and their nonlinear dependence on electron energy modulation provides strong evidence of saturation. Finally, the ability to steer the HGHG output will be useful in the future as a technique to align cascaded HGHG sections in an x-ray FEL [8-10].

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Figure 1: HG experiment schematic and design parameters.

Figure 2: Signal versus delay after adjusting one arm of the autocorrelator.

Figure 3: Contrast of the interference pattern on a thermal imaging camera from the interferometer.

Figure 4: Variation of fringe contrast as a function of mirror displacement revealing the coherence length of the HGHG radiation pulse.

Figure 5: Horizontal and vertical trajectory of the electron beam after steering.

Figure 6: The energy modulation of the electron beam image after the energy spectrometer (a) with and (b) without the CO₂ beam present.

Figure 7: Harmonic content (μJ) versus electron beam energy modulation (%).

Figure 1

Autocorrelator Measurement

Figure 2

Figure 3

Interferometer Measurement

Figure 4

Electron Trajectory in the wiggler

Figure 5

Figure 6 (a)

Figure 6 (b)

Figure 7

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Table 1: The theoretical and experimentally measured harmonic-to-fundamental ratios.

Table 1

Wavelength	Simulation	Experiment
2.65 μm	6×10^{-4}	2×10^{-4}
1.77 μm	1×10^{-2}	0.8×10^{-2}

Fundamental Harmonic Output of The Radiator Section as a Function of Electron Beam Energy Modulation

5.3 μ Fundamental radiation (μ J)

Energy Modulation of The electron Beam (%)

For a modulation of 2.5% Harmonic/Fundamental

	simulation	Analytical Theory	Experiment
2 nd harmonic	$6 \cdot 10^{-4}$ Biedron et al.	$3 \cdot 10^{-4}$ Juhau Wu	$1.5 \cdot 10^{-4}$
3 rd harmonic	10^{-2} Biedron et al.	10^{-2} Z.R. Huang	10^{-2}

Conclusions

- The single-shot spectrum of HGHG has been measured and it is consistent with the multi-shot spectrum measurement
- HGHG can be steered by steering the electron beam and we observe optical guiding
- The pulse length of the HGHG has been measured using two different methods
 - ❖ Autocorrelator measures the intensity pulse length of the beam.
 - ❖ Michelson Interferometer measures the coherence length of the beam.Since they are in a very good agreement, pulse is fully coherent.
- Preliminary harmonic content of the HGHG has been measured and observed very good agreement with the theoretical simulations