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First lasing of a high-gain harmonic generation free- electron laser experiment☆

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Abstract

We report on the first lasing of a high-gain harmonic generation (HGHG) free-electron laser (FEL). The experiment was conducted at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL). This is a BNL experiment in collaboration with the Advanced Photon Source (APS) at Argonne National Laboratory. A preliminary measurement gives a high-gain harmonic generation (HGHG) pulse energy that is 2×10^7 times larger than the spontaneous radiation. In a purely self-amplified spontaneous emission (SASE) mode of operation, the signal was measured as 10 times larger than the spontaneous radiation in the same distance (~ 2 m) through the same wiggler. This means the HGHG signal is 2×10^6 times larger than the SASE signal. To obtain the same saturated output power by the SASE process, the radiator would have to be 3 times longer (6 m). Published by Elsevier Science B.V.

1. Introduction

At the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL), a free-electron laser (FEL) experiment based on the high-gain harmonic generation (HGHG) principle [1–3] has achieved first lasing at 5.3 μm. In HGHG, a coherent seed at a wavelength at a subharmonic of the desired output radiation interacts with the electron beam in an energy-modulating section. This energy modulation is then converted into spatial bunching while traversing a dispersive section (a three-dipole chicane). In the second undulator (the radiator), which is tuned to a higher harmonic of the seed radiation, the microbunched electron beam first emits coherent radiation and then amplifies it exponentially until saturation is achieved. Harmonic generation using a seed laser is well known and has been verified experimentally and analyzed [4–6]. However, HGHG, i.e., harmonic generation followed by an exponential growth to achieve saturation is realized for the first time in our new experiment. Here, a description of the HGHG experiment and the preliminary results will be discussed.

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2. The experiment

A schematic representation of the HGHG apparatus is illustrated in Fig. 1. The existing ATF photocathode RF gun, linac, and coherent seed radiation source, a CO_2 laser, define the electron and seed beam design parameters found in Fig. 1. The value of the energy satisfies the FEL resonance condition with an existing radiator section, provided, modified and measured by the Advanced Photon Source (APS). The modulator section and dispersive section for HGHG operation were designed, manufactured, and measured at BNL. These magnetic component parameters are also found in Fig. 1. Based on these design parameters, the output power as predicted by theory and simulation is 35 MW in 2 m of the radiator.

As a first step, SASE was measured at 5.3 μm. We carried out several sets of measurements at different currents and emittances. For example, the results of one experiment had a current of 120 A (0.8 nC in 6 ps FWHM) with an emittance of 5.5 mm mrad and a global energy spread of $\sim 0.6\%$. The measured ratio of SASE to spontaneous radiation for this case was 13.6 and can be compared to the theoretical ratio of 13.2. All of these SASE measurements were taken with a bandpass filter at 5.3 μm with 2% bandwidth and an InSb point detector. The set of measured SASE over spontaneous ratios are plotted in Fig. 2, along with the design and compared with theory. The solid lines were calculated using an analytical formula [7]. The good agreement between the experimental data and theory gives us great confidence in the reliability of the current and emittance measurements. From these results, we decided to operate our HGHG experiment around 120 A and 5.5 mm mrad.

Next, we turned on the dispersion section and closed the gap of the mini-undulator (the modulator) to be resonant at 10.6 μm, and we corrected the trajectory to compensate for these changes [8]. Then we began seeding with the CO_2 laser. Adjustment of an optical trombone length synchronizes the electron beam and the CO_2 laser, thus creating an energy modulation. The modulated beam passing through a dipole (part of the spectrometer) generates at the end of the HGHG beamline an electron beam profile whose horizontal axis corresponds to the energy spread. In Figs. 3a and b, the horizontal distribution corresponds to the energy distribution without and with energy modulation, respectively. By adjusting the optical trombone length, we can vary the CO_2 arrival time relative to the electron beam. The square of the energy modulation is proportional to the CO_2 power. When the energy modulation squared is plotted versus the delay time in the optical trombone, the CO_2 pulse width was determined to be ~ 300 ps. Combined with the CO_2 pulse energy measurement, this yields a CO_2 power of 500 MW. We attenuated the laser beam by a factor of 3 to protect the input window and obtained a large energy modulation as shown in Fig. 3b.

With SASE and energy modulation confirmed, we started to measure HGHG. We routinely aligned the CO_2 laser for energy modulation and

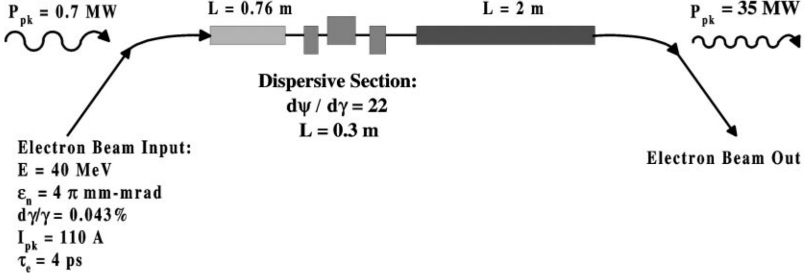

Fig. 1. Schematic representation of the HGHG experiment.

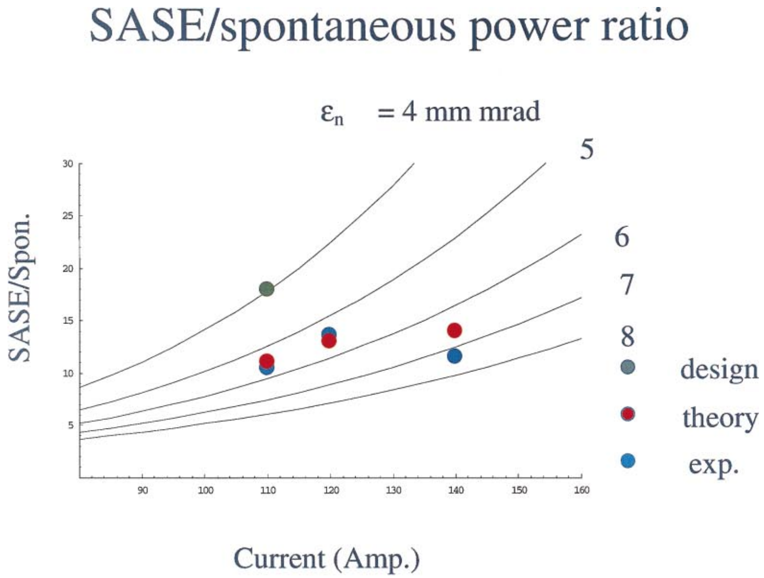

Fig. 2.

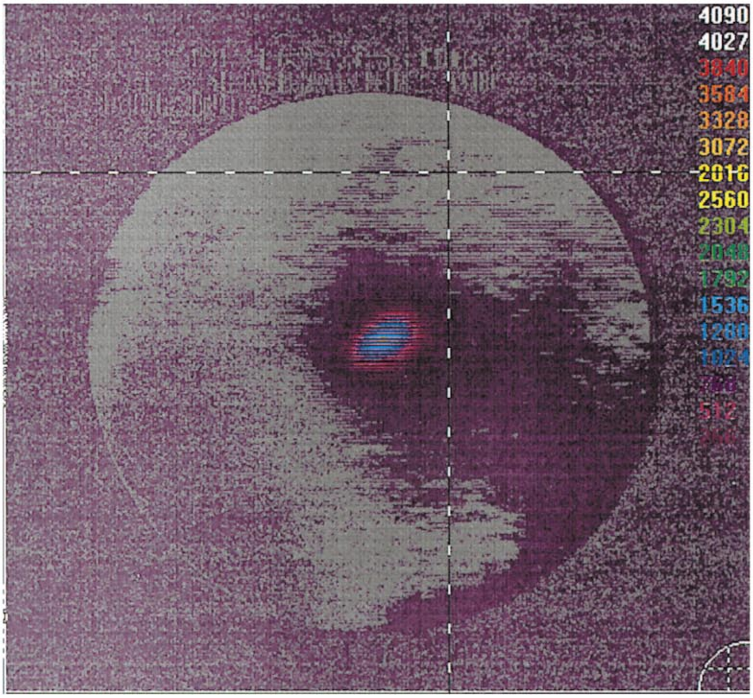

Fig. 4.

Fig. 2. Ratio of SASE over spontaneous radiation power measured, compared with the analytic theory, and design value.

Fig. 4. HGHG output radiation profile by a Pyroviewer thermal camera.

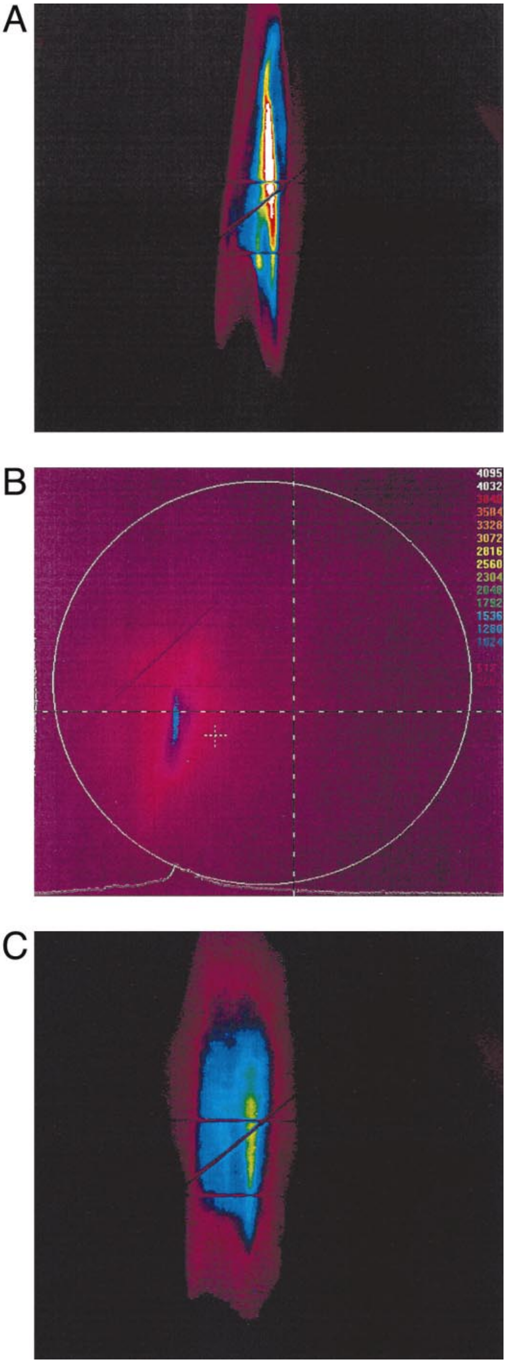

Fig. 3. (a) Energy spread without energy modulation; (b) energy modulation generated by CO_2 power of about 150 MW; (c) energy modulation with CO_2 power of about 0.5 MW and HGHG lasing to saturation.

carried out a SASE measurement by simply not triggering the CO_2 laser before HGHG. For the maximum charge in a SASE measurement (~ 0.8 nC), the detector signal is 1.6 V. When we attenuated the CO_2 laser by a factor of 1000 (attenuated to a power of about 0.5 MW) and placed 10^6 attenuation in front of the same InSb detector and then triggered the CO_2 laser, the HGHG signal at this same charge was measured as 4.5 V. Therefore, the HGHG signal is 3×10^6 larger than the SASE signal in the same length of undulator (1.98 m). The attenuation of 10^6 was based on the specification of the manufacturer, hence we still need to verify this further by our own calibration.

Based on these sets of measurements, we know that the pulses have energies of the order of tens of μJ. A Pyroviewer thermal imager was then used to measure the transverse profile of the output radiation as shown in Fig. 4. The measurement was performed using two magnesium fluoride short-pass filters for blocking the CO_2 laser and a 2% bandpass filter at 5.3 μm. Additional tests were provided by recording the image for each of the following conditions: (1) the electron beam off with the CO_2 laser on, and (2) the CO_2 laser off and the electron beam on. Both cases produced no image except background. This confirms that the image depends on the presence of both the electron beam and CO_2 laser. Finally, to further confirm the radiation is indeed the 5.3 μm radiation, the above-described bandpass filter was removed and the image barely changed. In addition, the uniformity of the transverse profile indicates excellent transverse coherence, although this must be verified in the future.

Next, we measured the HGHG pulse energy directly using a Joule meter. The maximum output of the Joule meter during this run was 65 μJ. During this run, we also measured the electron beam pulse length to be ~ 6 ps FWHM. If we assume the radiation pulse is also 6 ps (actually, it is more likely to be shorter), then the output would be 11 MW. Since we know the spontaneous radiation power is 0.5 W, as confirmed by measurement within the observation solid angle at the InSb detector and by theory, we again show the HGHG output is 2×10^7 times larger than the spontaneous power.

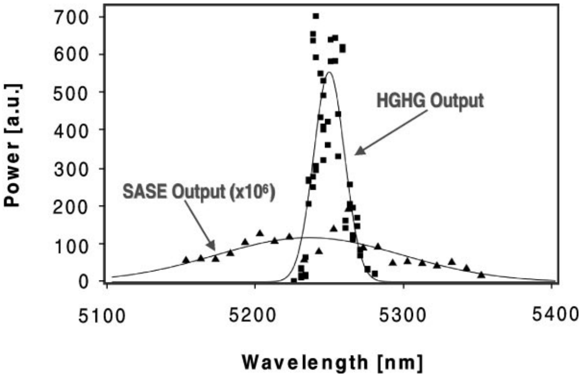

Fig. 5. HGHG power spectrum (resolution 5 nm) plotted with SASE spectrum measured using the same detector but multiplied by a factor 10^6.

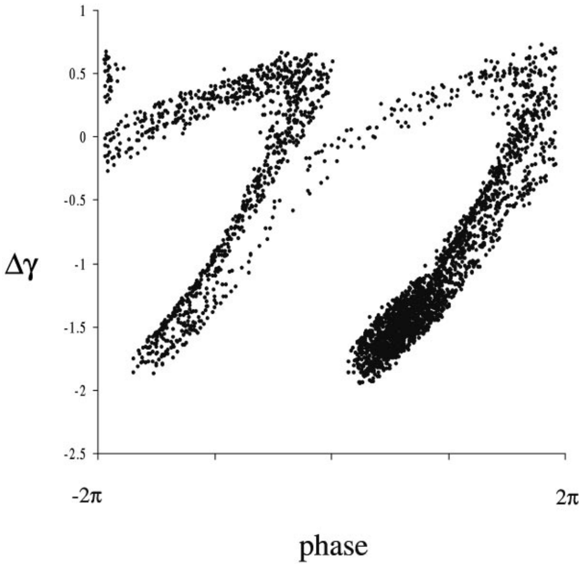

Fig. 6. Phase-space diagram showing large energy modulation at the exit of the radiator.

We then measured the first HGHG spectrum. The result is shown in Fig. 5. The HGHG output radiation is sent through a beam-splitter, one part is sent to a Joule meter and the other through the spectrometer. For each individual shot, the output of the spectrometer is divided by the output of the Joule meter, this normalized power spectrum is plotted as a function of wavelength. This figure shows a bandwidth of ~20 nm. The large fluctuation in the spectrum indicates that the spectrum changes from shot to shot, even though it remains in the bandwidth of 20 nm. This fluctuation is not expected from HGHG theory and might be due to e-beam pulse shape change; it needs to be further studied. If this pulse is Fourier-transform limited, this 20 nm bandwidth can be used to calculate the radiation pulse length, which is about 2 ps. We are presently preparing a pulse-length measurement; if we can confirm the 2 ps duration, then the peak power would be 32 MW. This number would be closer to the theoretically predicted 35 MW. The SASE spectrum from the same radiator, multiplied by a factor of 10^6, and the HGHG spectrum, are shown in Fig. 5 for comparison. The SASE bandwidth is six times larger than the HGHG bandwidth.

With attenuation of 1000 times, the CO_2 power is of the order of 0.5 MW. At this power, we found that the HGHG signal was maximized. The

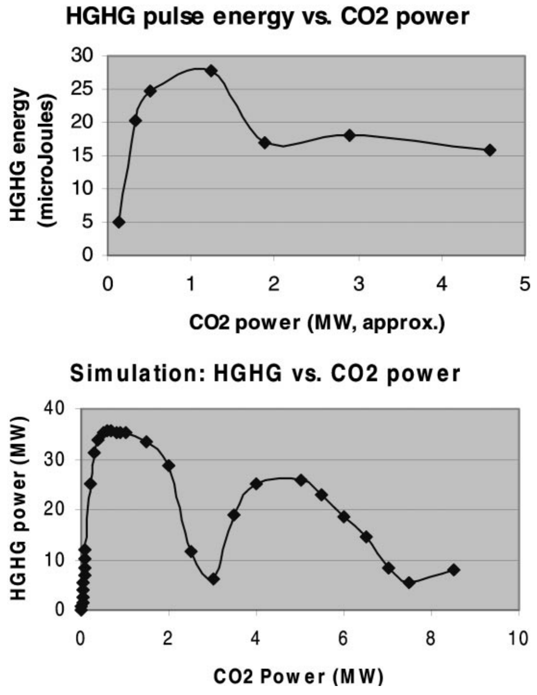

Fig. 7. HGHG output energy vs. CO_2 power, as compared with the theory.

energy-modulation diagram obtained using the electron energy spectrometer, as described above, is shown for this condition in Fig. 3c. This shows an energy modulation of nearly 1%, which is equal to the Pierce parameter, which is ~ 0.009, indicating that the system was saturated. If we compare this value with the theoretical calculations of the phase-space distribution at the exit of the radiator shown in Fig. 6, we can immediately recognize the double-band structure in Fig. 3c. This corresponds to the particles trapped in the phase-space bucket.

We also measured the HGHG output energy as a function of the CO_2 power, as shown in Fig. 7. When we compare this with the theoretical value of the output HGHG power versus CO_2 power, we find a clear similarity. The quantitative comparison of these two curves is not warranted because the experimental conditions are not exactly the same as the design conditions.

3. Conclusions

The preliminary results of the first lasing of the HGHG experiment at the ATF have confirmed some of the theoretical predictions. The SASE results are in good agreement with the theory, seeding with the CO_2 laser produced the anticipated energy modulation, and HGHG was demonstrated by converting 10.6 μm seed into high-power 5.3 μm radiation. This output was 2×10^7 larger than the spontaneous emission.

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