THE STATUS OF THE HIGH-GAIN HARMONIC GENERATION FREE-ELECTRON LASER EXPERIMENT AT THE ACCELERATOR TEST FACILITY

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Abstract

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL) is an accelerator and beam physics user facility capable of producing a high-brightness, 70-MeV electron beam. Currently, a high-gain harmonic generation (HGHG) free-electron laser (FEL) experiment is underway at the ATF. This is a collaborative effort between BNL and the Advanced Photon Source (APS). The experiment consists of two phases: 1) self-amplified spontaneous emission (SASE) and 2) HGHG. Here, a brief introduction to the HGHG theory, measurements in the SASE phase, the recent modifications in preparation for the HGHG phase, and future plans will be discussed.

1 INTRODUCTION

A free-electron laser (FEL) experiment is being commissioned at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). There are two distinct project phases. In the first phase, the system will be operated in the self-amplified spontaneous emission (SASE) [1] mode. In the second phase, high-gain harmonic generation (HGHG) to full saturation at 5.3 μm will be attempted [2]. Here, a brief description of the HGHG theory, the experimental design parameters and layout, and future plans will be discussed.

2 HGHG THEORY

In a SASE FEL, the spontaneous emission "noise" serves to ignite the FEL bunching process, resulting in a noisy output. In seeded FEL operation, the output quality is directly related to the quality of the seed. Also, the point of saturation along the undulator reveals the maximum available power and should occur in the shortest distance, for practical design purposes. From the linear theory, a high peak current, low emittance, and low energy-spread electron beam is required, as well as a properly shimmed undulator, to reduce magnetic error effects on the electron beam trajectory. To reach shorter wavelengths in these modes of operation, however, requires even higher currents, while maintaining this low energy spread and emittance at increasingly higher energies to produce a sufficiently short gain length and, in turn, saturation point.

Another possible mode of FEL operation capable of providing a very desirable output light beam is HGHG. Here, a coherent radiation source, at a subharmonic of the desired output radiation wavelength, enters a first undulator for energy modulation. Following this modulation, where the electron beam is forced to be resonant with the seed radiation, a dispersive section is traversed, where spatial bunching is induced with a strong higher harmonic content. The beam then enters a second undulator, the radiative section, tuned to resonance to the desired harmonic. (In this particular experiment, the second harmonic is of interest.) Coherent radiation and ultimately saturation at this higher harmonic is then achieved within a reasonable number of undulator periods and with an excellent beam quality, as compared to the SASE process. Recall that this better beam quality is defined by the coherent seed source. This method could quite possibly be extended to higher energies, where the radiator is tuned to a much higher harmonic, to achieve saturation in the UV, VUV, or x-ray regime. A schematic of the HGHG process is provided in Figure 1.

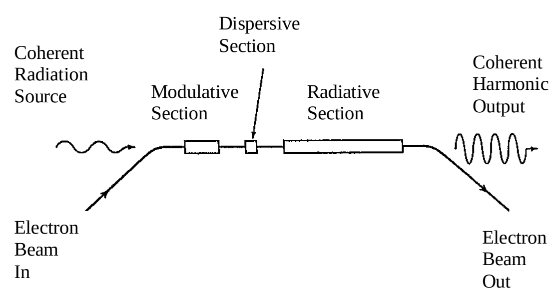

Figure 1: HGHG process

The existing ATF photocathode rf gun, linac, and coherent seed radiation source, a CO_2 laser, define the electron and seed beam parameter base found in Tables 1

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and 2, respectively [3]. The value of the energy was specifically tailored to achieve the FEL resonance condition with an existing radiative section, supplied by the Advanced Photon Source (APS). The modulative section and dispersive sections for HGHG operation were designed, manufactured, and measured by BNL. These magnet parameters are found in Table 3.

Table 1: Designed electron beam parameters for HGHG

γ	82
Normalized Emittance	4 π mm mrad
Peak Current	110 A
Micropulse Length	4 ps
Energy Spread	0.043%

Table 2: CO_2 seed laser beam parameters

Wavelength	10.6 μm
Input Seed Power	0.7 MW
Pulse Length	100 ns
Sliced Pulse Length	10-100 ps
Rayleigh Range	0.76 m

Table 3: Magnet parameters

Modulative Section	
Length	0.76 m
Undulator Period	7.2 cm
Number of Periods	9
Peak Magnetic Field	0.158 T
Dispersive Section	
Length	0.30 m
Magnetic Field	0.5 T
Induced Dispersion	1.5 ($d\psi/d\gamma$)
Radiative Section	
Length	1.98 m
Undulator Period	3.3 cm
Number of Periods	60
Peak Magnetic Field	0.47 T
Betatron Wavelength	3.75 m

Experimental results for the SASE and HGHG modes of operation were predicted with the 1D analytical models and TDA3D simulations [4], in which a waterbag distribution was employed. In HGHG simulations, the electromagnetic field variation at the exit of the modulative section is mapped into an in-house code that tracks the particles through three horizontal corrector magnets (the dispersive section). This output is then mapped back into TDA3D with only one variation imposed in the code - that the integration over the phase bucket is opened to 2 π instead of π, since the interest is shifted to the second harmonic. These modifications must be implemented, since TDA3D is monochromatic and cannot simulate multiple harmonics simultaneously.

Based on these TDA3D simulations and power spectrum scaling [5], the expected SASE output power spectrum at 5.3 μm is found to be 15 times larger than the spontaneous emission. The HGHG simulations predict a saturation power at 5.3 μm of 37 MW after 1.8 m.

3 EXPERIMENTAL LAYOUT

The drive-laser system for the ATF photocathode gun is composed of a diode-pumped Nd:YAG oscillator coupled to a Nd:YAG amplifier. The amplifier is capable of delivering 40 μJ to the magnesium cathode. The 1.6-cell 2856-MHz photocathode rf gun and emittance compensation solenoid produce the high current, low emittance, and low energy spread beam necessary, with beam energies exceeding 5 MeV. The solenoid corrects the emittance before it is “frozen” in the linac. The ATF linac is composed of two 3-m accelerating structures, yielding up to 70-MeV electrons. After the linac exit, beam is transferred to an experimental area, where the modulative, dispersive, and radiative sections, as well as the optical diagnostics, exist.

4 SYSTEM COMMISSIONING

The optical diagnostics line is composed of exit windows, point-to-point optics, a scanning spectrometer, and a point detector. Also, five YAG crystal screens are mounted on actuators inside the radiative section to determine the electron trajectory in reference to a surveyed He-Ne alignment laser. A straight electron beam trajectory is important in both phases of operation, since simulations reveal a trajectory tolerance of < 100 μm. Full detail of the electron beam diagnostics and trajectory correction procedure are described separately in these proceedings [6].

Since the electron beam quality almost singly defines the resulting output spontaneous and SASE radiation, electron beam measurements are required relative to the radiation signal. The electron beam measurements can then be used along with the linear theory and simulation to compare the results against theory. Necessary electron beam measurements include the longitudinal current distribution, emittance, and energy spread.

The electron beam bunch length and corresponding charge distribution are measured by varying the rf phase of the second linac section to induce a linear dependence of the particle energy on longitudinal position. A collimating slit in a dispersive region behaves as an energy filter, passing a narrow slice in time [7], where a Faraday cup reveals the transmitted charge. In Figure 2, a measured longitudinal bunch shape with a charge of 1.1 nC is shown. The normalized emittance, as measured by a quadrupole magnet scan, was determined to be 5 mm-mrad.

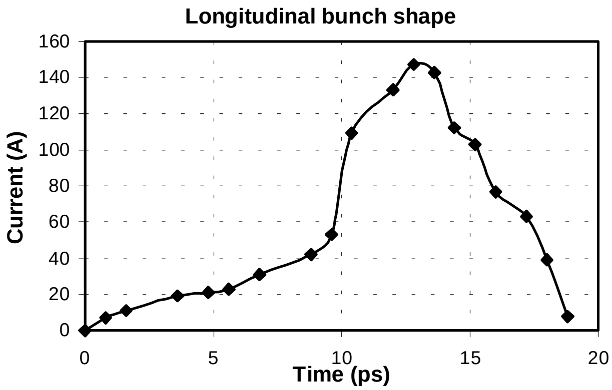

Figure 2: Longitudinal bunch shape for 1.1 nC

For the electron beam described above, a scan of output radiation intensity versus bunch charge was performed, by adjusting the width of the momentum slit to gradually reduce the charge. The result is presented in Figures 3 and 4, where the radiation signal and ratio SASE over spontaneous radiation are shown as functions of the bunch charge, respectively. The exponential rise above spontaneous points toward the existence of SASE output radiation. In Figure 4, the ratio of SASE radiation power over the spontaneous emission approaches 40.

The ratio of SASE radiation over spontaneous radiation can be calculated analytically and compared with experiment. The analytical estimate for start-up noise is based on a three-dimensional linear theory for an electron beam with step-function profile, zero energy spread, and zero angular spread. This idealized model for start-up noise can be used because the betatron motion is negligible during the start-up process. The output power of the SASE radiation is given by

$$\left(\frac{dP}{d\omega}\right)_{SASE} = \frac{1}{9} e^{\frac{L_\omega}{L_G}} C_0 \left[\frac{2L_G}{L_\omega} \left(\frac{dP}{d\omega}\right)_{Spon}^{L_\omega} \right]$$

where L_ω and L_G are the wiggler and power gain lengths, respectively [1]. The calculation of the gain length and SASE ratio were performed for different sections of the electron beam based upon the measured bunch shape shown in Figure 2. This results is an estimated ratio of the SASE over the spontaneous radiation of 25. Considering the random SASE fluctuations that may have occurred and influenced each recorded radiation measurement during the charge scan, this estimate corresponds surprisingly well with the ratio in Figure 4, where the gain ratio approaches 40.

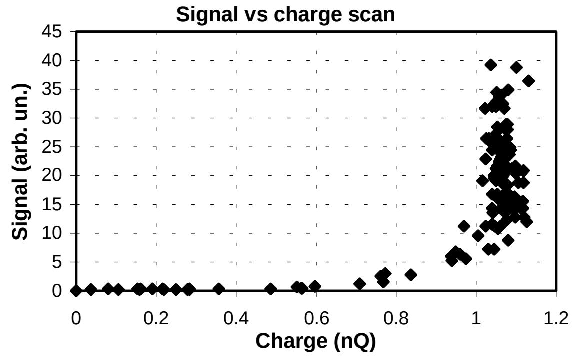

Figure 3: Signal versus charge

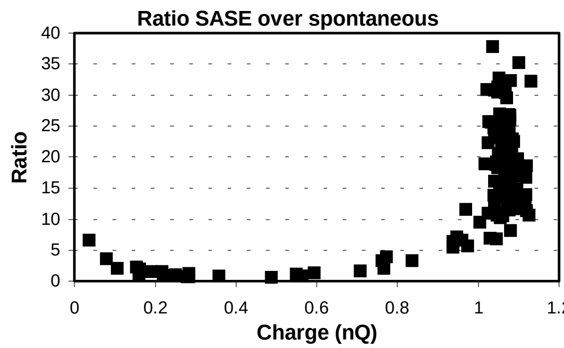

Figure 4: The ratio of SASE over spontaneous radiation versus charge

6 CONCLUSIONS AND FUTURE PLANS

The ATF at BNL is currently commissioning a two-phase FEL project. The SASE phase is nearly complete and the HGHG phase is scheduled to begin over the next few months.

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