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X.J. Wang, Y. Shen, T. Watanabe, J.B. Murphy, J. Rose and T. Tsang

NSLS, Brookhaven National Laboratory, Upton, NY

National Synchrotron Light Source
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973
www.bnl.gov

THE FIRST LASING OF 193 NM SASE, 4^{TH} HARMONIC HGHG AND ESASE AT THE NSLS SDL*

X.J. Wang, Y. Shen, T. Watanabe, J.B. Murphy, J. Rose and T. Tsang, BNL, Upton, NY 11973, USA

Abstract

The first lasing of three types of single-pass high-gain FELs, SASE at 193 nm, 4^{th} harmonic HGHG at 199 nm and ESASE at the Source Development Lab (SDL) of Brookhaven National Laboratory (BNL) is reported. The saturation of 4^{th} harmonic HGHG and ESASE FELs was observed. We also observed the spectral broadening and instability of the 4^{th} harmonic HGHG.

INTRODUCTION

After the successfully experimental demonstration of Self-Amplified Spontaneous Emission (SASE) and High-Gain Harmonic Generation (HGHG) around the world[1-4], great progress was made recently in reducing the SASE wavelength [5-6]. We present recent progress in both SASE and HGHG at the the National Synchrotron Light (NSLS) Source Development Lab (SDL). The new lasing of three types of the single-pass high-gain FELs at the NSLS SDL, SASE at the 193 nm, the first lasing of the 4th harmonic HGHG and ESASE is reported in this paper.

After a short description of the SDL facility, we will present the preliminary experimental characterization of new lasing of three types of single-pass high-gain FELs. We will first discuss the experimental characterization of the new lasing of a SASE FEL at 193 nm. The first lasing and saturation of the 4^{th} harmonic HGHG at 199 nm with a 795 nm seed laser is presented. With the same experimental setup of the 4^{th} harmonic HGHG, we observed first lasing of the laser enhanced SASE at 210 nm after detuning the electron beam energy. The first successful demonstration of ESASE [7-8] not only will open a new avenue to improve the performance of a SASE FEL, but will also greatly expand the HGHG tunability.

THE NSLS SDL

The SDL is a laser linac facility dedicated for linac based light source technology R&D and applications. The main components of the SDL are a high-brightness electron accelerator, an RF synchronized Ti:Sapphire laser system, a High Gain Harmonic Generation (HGHG) FEL, together with sophisticated electron and photon beam instrumentation. The accelerator system of the SDL consists of a 1.6 cell BNL photo-injector driven by the Ti:Sapphire laser system and a S-band traveling wave linac. After the recent electron beam energy upgrade [9], the maximum electron beam at the SDL is about 250 MeV. The magnetic chicane bunch compressor at the SDL produces sub-ps long electron bunches with a peak current of a few hundred amperes. The high brightness electron beam transits the three magnets used for the HGHG and laser seeded FEL amplifier (Fig.1): a modulator undulator, a dispersion magnet and the 10 m long radiator undulator (named NISUS) (Table 1).

One of the unique features of the SDL laser system is that it was designed in such a way that a single laser system is used to drive both the photocathode RF gun and to provide a seed laser pulse. This setup make it possible to achieve sub-ps timing jitter between the seed laser and the electron beam. The seed laser used for the experiment has a bandwidth of 7 nm (FWHM), the pulse length can be adjusted from 100 fs to 6 ps (FWHM). Table 1 lists the undulators, seed laser and electron beam parameters used for the single-pass high-gain FELs presented here. The matching optics for the seed laser focuses the seed laser into the HGHG modulator on axis while a mini-chicane is used to manipulate the electron beam to by-pass the seed laser mirror. There are 16 beam profile monitors (BPM) uniformly distributed along the NISUS and they have been used both for e-beam matching and trajectory studies. There is a dipole magnet after the NISUS undulator which bends the electron beam to the beam dump. The beam profile monitor in front of the beam dump was used to monitor the electron beam energy and energy modulation. The FEL radiation can also be transported by a periscope to the diagnostic station for characterization. The diagnostics station allows us to characterize the FEL output.

Table 1: the SDL accelerator, seed laser and HGHG magnet parameters.

e-beam Energy (MeV)	180 - 210
e-beam peak current (A)	300 - 400
e-beam bunch length (FWHM, ps)	~ 1
Emittance (rms, mm-mrad)	2 - 4
Seed laser wavelength (nm)	795
Seed laser pulse length (FWHM, ps)	~ 2 - 3
HGHG modulator period (cm)	8
HGHG modulator length (m)	0.8
HGHG modulator K	1.67 -3.02
HGHG dispersion magnet R_{56} (mm)	0 - 5
HGHG radiator period (cm)	3.89
HGHG radiator length (m)	10
Undulator parameter of the radiator	1.1

#xwang@bnl.gov

Figure 1: The SDL HGHG magnets and schematic of the 4th harmonic HGHG.

FEL CHARACTERIZATION

The major steps of the single-pass FEL experiment are electron beam and trajectory optimization, seed laser and e-beam synchronization, and FEL output characterization.

193 nm SASE Characterization

We first present the experimental characterization of a SASE FEL generated by the HGHG radiator – NISUS undulator. SASE was first used to optimize the electron beam and its trajectory inside the NISUS undulator. For the NISUS undulator, the shortest SASE FEL wavelength at the SDL should be about 150 nm when the electron beam energy chirped is taken into consideration. The UV Ocean Optics spectrometer and joulemeter used for characterizing the FEL are in the open air, which limits the minimum observable SASE wavelength to about 193 nm. Fig.2 is the shortest single-shot SASE spectrum obtained. The spectrometer resolution is about 0.7 nm. The maximum SASE energy is about 1 μJ when 5% transmission is assumed.

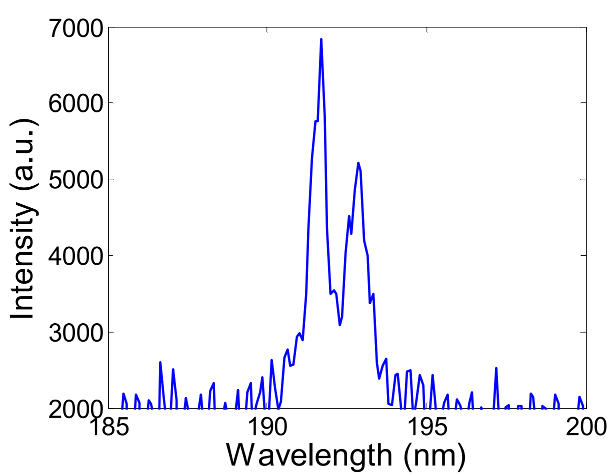

Figure 2: the shortest SASE spectrum at the SDL.

The First Lasing of the 4th Harmonic HGHG

To improve the performance of the SASE FEL, BNL has been performing R&D on laser seeded and HGHG FELs. Prior to April 2006, the shortest wavelength achieved is the 3rd harmonic HGHG at 266 nm [4].

As part of the recent electron beam energy upgrade [9], extensive modification of the HGHG modulator was done to make it possible to achieve HGHG at harmonics as high as seven . A new vacuum chamber and a stronger motor drive were installed. After the successful lasing of SASE at 193 nm, the electron beam energy was tuned to 202.5 MeV for the 4th harmonic HGHG with the seed laser at 795 nm. The synchronization of the seed laser and electron beam was realized in two steps. First we observed the SASE and seed laser using a fast photo-diode at the diagnostics station to make the two of them within 100 ps. The final synchronization was realized by observing the electron beam energy modulation while adjusting the seed laser delay line. With the seed laser pulse length at about 2 ps (FWHM) and a peak power of 50-100 MW, we successfully observed the first lasing of the 4th harmonic HGHG at 199 nm (Fig. 3). The slight difference of the measured central spectrum from the 199 nm could be explained by the seed laser bandwidth, and that will be discussed in more detail later.

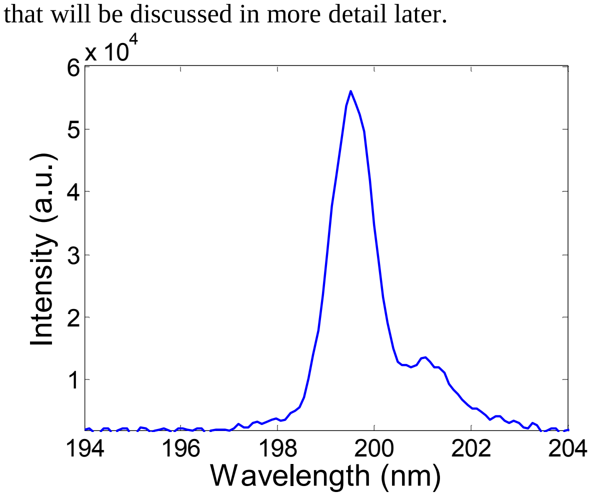

Figure 3: the 4th harmonic HGHG spectrum.

The HGHG dispersion magnet was adjusted to optimize the output of the 4th harmonic HGHG. The HGHG energy was measured at the diagnostics station while the electron beam was steered off the trajectory along the NISUS undulator. Fig. 4 plots the maximum energy of the 4th harmonic HGHG along the NISUS using the techniques just described. It can be clearly seen that the energy growth of the HGHG deviates from the exponential growth which indicates the saturation of the 4th harmonic HGHG.

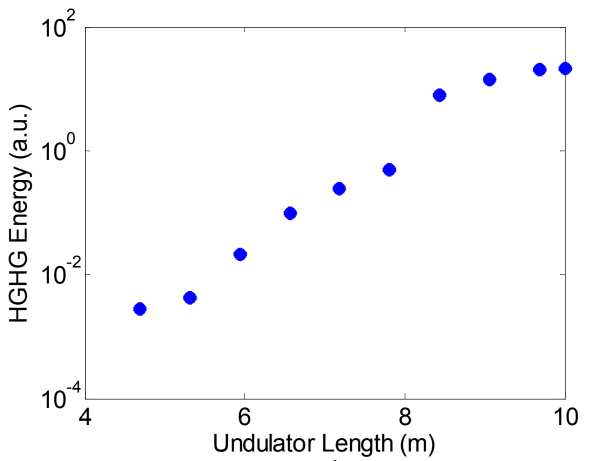

Figure 4: the log plot of the 4th harmonic HGHG energy along the NISUS undulator.

Experimental Characterization of the HGHG Spectrum Broadening and Instability

As we pointed out earlier, the HGHG spectra stability and width are not as stable and narrow as we expected. We decided to explore this more by taking hundreds of single-shot HGHG spectra using the UV spectrometer with 0.7 nm resolution. Fig. 5 plots four of the typical HGHG spectrums obtained. The electron beam energy stability is one of the first considerations for the source of this instability. We measured the shot-to-shot electron beam energy fluctuation to be about 0.2% (Full width), which could contribute to about 0.4% fluctuation in the HGHG spectrum. But we observed as large as a 2% fluctuation of the HGHG spectrum. After carefully analyzing the data, we concluded that the dominant source of the HGHG spectrum fluctuation is the seed laser bandwidth.

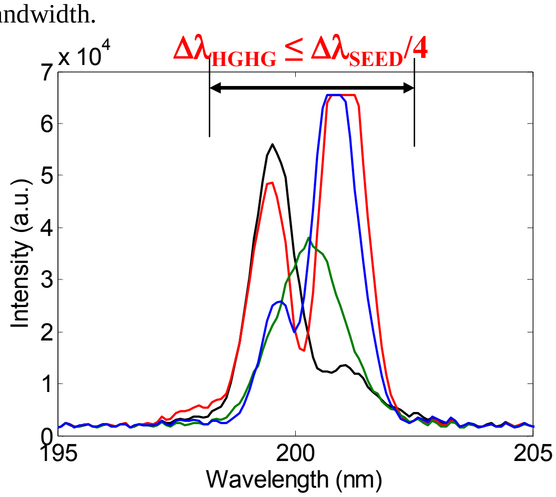

Figure 5: the 4th harmonic HGHG spectra.

In all of the previous HGHG experiments [4], the seed laser pulse length is much longer than the electron beam bunch length. The effective seed laser bandwidth sampled by the electron beam is much narrower than the seed laser bandwidth. So the HGHG bandwidth observed in earlier experiments is dominated by the electron beam bunch length. In our 4th harmonic HGHG experiment, to increase the seed laser power, the seed laser pulse length employed is comparable to the electron beam bunch length (2 ps vs. 1 ps). When timing jitter and drifting are taken into consideration, the electron beam will sample the full range of the seed laser bandwidth. Fig. 5 shows the HGHG spectral fluctuation is about 2%, which is comparable to the seed laser bandwidth. The spectral broadening shown in Fig. 5 is well above the spectrometer resolution, which could be explained by the electron beam distribution and mismatch between the electron beam energy and the seed laser [10].

The First Lasing of ESASE at 210 nm

We also explore the tuning range of the HGHG modulator undulator. For this study the seed laser wavelength and power were kept constant while the electron beam energy was adjusted. We observed no significant change in electron beam energy modulation as the electron beam energy was adjusted from 190 MeV to 208 MeV. This corresponds to ± 5% energy tuning. Since our modulator has only 10 periods, the observed tuning range is well within our expectation.

Taking advantage of the large tuning range of the HGHG modulator, we moved the electron beam energy to 197 MeV to demonstrate ESASE [7-8]. The resonance wavelength of the HGHG radiator at 197 MeV is about 210 nm, which is beyond the seed laser bandwidth. We successfully observed first lasing of a laser enhanced SASE FEL at the 210 nm (Fig. 6) using the same HGHG arrangement. The intensity of the ESASE is a couple orders of magnitude stronger than SASE without the seed laser.

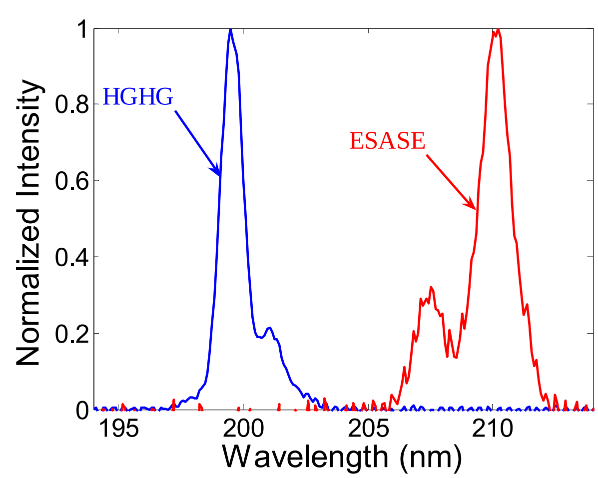

Figure 6: ESASE Spectrum vs. 4th harmonic HGHG.

SUMMARY AND ACKNOWLEDGMENT

We present the new lasing of a SASE FEL at 193 nm, and the first ever lasing of the 4th harmonic HGHG and ESASE. We have experimentally investigated the spectral instability and broadening of the HGHG FEL; the bandwidth of the seed laser is one of the major sources of the HGHG spectral instability. This observation could have important implications for a future X-ray FEL based on a cascaded HGHG concept, where a short broad band seed laser will be employed. By taking advantage of the large tuning range of the HGHG modulator we have successfully demonstrated the first lasing of the so called ESASE. Our experiment shows that ESASE not only will open a new avenue to improve the performance of a SASE FEL, but will also greatly expand the HGHG tunability. More detailed analysis and simulation of the experiments presented here will publish in the future.

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