SATURATION OF THE NSLS DUV-FEL AT BNL

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Abstract

The Deep Ultra Violet Free Electron Laser (DUV-FEL) experiment has reached a milestone by saturating the Free Electron Laser using High Gain Harmonic Generation (HGHG) method in the Source Development Laboratory (SDL) at NSLS. It utilizes the 10 m long, 3.9 cm period NISUS wiggler. The goal of the project is to produce radiation at a wavelength less than 100 nm, utilizing the HGHG method. HGHG at 266 nm has been accomplished by seeding with the 800 nm Ti:Sapphire laser and observed saturation. The third harmonic at 88 nm accompanying the 266 nm is being used in an ion pair imaging experiment in chemistry. We discuss the measurement of energy, gain, spectrum, and pulse length of the FEL output. We also describe the diagnostics used for operating the FEL.

INTRODUCTION

There is a substantial interest in producing coherent radiation using single pass FELs from Deep-UV down to the X-ray regime [1]. In this article, we present the first demonstration of HGHG FEL in the ultraviolet at 266 nm with the seed laser at 800 nm. Previously, a proof of principle experiment has been done in the IR regime at ATF BNL [2]. In many applications an FEL operates in Self Amplified Spontaneous Emission (SASE) mode [3-6]. In this case the radiation starts from shot noise, therefore the light is not temporally coherent and the pulse-to-pulse energy fluctuation is big. In HGHG case [2,7,8] the electron is seeded by a conventional laser, therefore the radiation inherits the properties of the seed laser, producing excellent temporal and spatial coherence. The energy and central wavelength stability is limited by the accelerator stability and the spectral bandwidth is much narrower than SASE. The pulse length of the radiation can be controlled by the seed laser, thus enabling to produce ultra-short pulses.

OVERVIEW OF THE FACILITY

The accelerator consists of a Ti:Sapphire laser system, a 1.6 cell RF photo-cathode gun, 4 SLAC-type linac tanks and a 4-dipole chicane (Fig 1). A photo-cathode RF gun is illuminated by the tripled Ti:Sapphire laser at 266 nm producing 300 pC charge, 4 ps FWHM bunch length, and a 4.5 MeV energy electron beam with normalized emittance of 4-5 μm. The first two linac tanks accelerate the electron bunch with the second tank off-crest by 26^{o} to introduce an energy chirp. A 4-dipole chicane compresses the bunch to about 1 ps FWHM. The third linac tank is used to remove the remaining energy chirp with additional acceleration and the fourth tank accelerates the bunch to 177 MeV. This tank is also used for bunch length measurements using the zero-phasing method [9].

HGHG PROCESS

The three major components of the experiment are modulator, dispersive magnet, and radiator. The modulator is tuned to the wavelength of the seed laser. Its length is 0.8 m and has a period of 8 cm with K = 1.67. The 800 nm seed laser derived from the Ti:Sapphire laser with 9 ps FWHM pulse length interacts with the electron beam. This introduces an energy modulation in the electron bunch. A local bump is introduced by four trim magnets to bypass the seed laser insertion mirror. The Rayleigh range is estimated to be 2.4 m from the beam sizes measured at two pop-in monitor locations in the modulator. Then the dispersion magnet converts the energy modulation into a density modulation. The radiator is tuned to the 3rd harmonic of the seed laser at 266 nm. The NISUS wiggler (radiator) is 10 m long and has 3.89 cm period and 0.31 T peak field [10]. The synchronization between the electron beam and the seed laser is established by using a picosecond resolution streak camera at the end of the beam line. We obtain the temporal position of the SASE and seed laser pulse with the streak camera and adjust the delay stage for proper synchronization. The transverse alignment is established by overlapping the two beams on two pop-in monitors in the modulator. The HGHG output is optimized for maximum coherent radiation at the beginning of NISUS by varying the dispersion magnet current. Since the seed laser pulse is longitudinally chirped, only a small part of the bandwidth is seen by the electron beam with a bunch length of 1 ps. The wiggler is not long enough for SASE FEL to saturate because the typical gain length is about 0.8-1 m and SASE needs more than 20 gain length to reach saturation. Since HGHG starts from a pre-bunched electron beam, the radiation process begins coherently and saturates within the length of the wiggler.

DIAGNOSTICS AND MEASUREMENTS

The NISUS wiggler consists of 16 sections. Every section is equipped with a pop-in monitor, a four-wire system, and pancake magnets. Pop-in monitors utilizing Cerium doped YAG crystals are used to monitor the electron beam [11]. The four-wire system at each section can produce quadrupole fields providing additional focusing and a dipole field for trajectory corrections. Pancake shaped magnets located at the top and bottom of the wiggler provide a vertical magnetic field and can be used in horizontal trajectory correction [12,13]. A fiber coupled He-Ne laser is used for alignment through NISUS.

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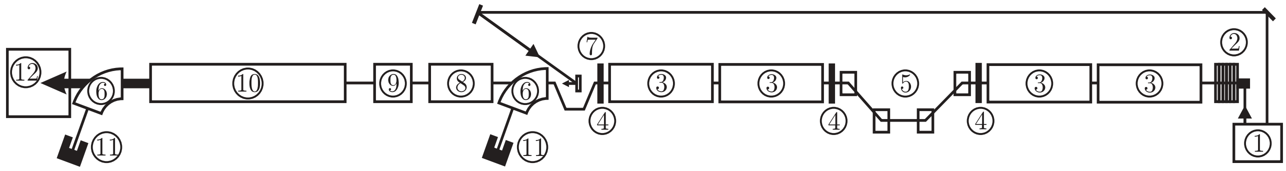

FIG.1: The NSLS DUV-FEL layout: 1-gun and seed laser system, 2-RF gun, 3-linac tanks, 4-focusing triplets, 5-magnetic chicane, 6-spectrometer dipoles, 7-seed laser mirror, 8-modulator, 9-dispersive section, 10-radiator (NISUS), 11-beam dumps, 12-FEL measurement area.

The position of the laser at each monitor is recorded and these positions are used as a reference for the electron beam trajectory. The position and the beam size of the electron beam at each pop-in monitor is measured and the trajectory of the beam is corrected using automated MATLAB and EPIC routines. This way we can easily calculate the emittance and the twiss parameters of the beam and adjust the upstream quadrupole currents to have a proper matching into the wiggler. A number of sections are also equipped with the detectors to measure the energy of the FEL. A calibrated joule meter is used to measure the total energy at the exit. A high-resolution spectrometer is used to measure the spectrum of the SASE and HGHG light.

Gain Measurement

We have two methods to measure the gain of the FEL. One is measuring the energy using the detectors along NISUS and the other is measuring the energy at the exit Joule meter by kicking the electron beam at different sections using the pancake magnets. Both methods are proven to be consistent with each other.

Fig 2 shows the energy of the HGHG outputs as a function of the distance in the wiggler using the kicking method and simulations of the gain with the TDA code [8] for two input seed powers. For the 1.8 MW input seed laser power the HGHG saturates near the end of the wiggler. For the 30 MW input seed laser power the HGHG saturates around the half of the wiggler. The TDA simulation predicts the power should go down after saturation but measurement shows the energy still grows very slowly. Since the electron beam has varying current and emittance along the bunch, different parts of the beam reach saturation at different times.

The HGHG output power stability is basically limited by the accelerator stability. The typical average output is approximately 100 μJ. Figure 3 shows the statistic of the pulse energy measurement which is 7 % over one minute. Since January 2003 the third harmonic at 88 nm which accompanies the 266 nm is being used for an ion pair imaging experiment [14], which has benefited from the stability of the HGHG output.

Spectrum Measurement

The spectrum of the FEL output was measured with a high-resolution spectrometer at the end of the beam line. Fig 4 shows the single shot HGHG and SASE spectra. The FWHM bandwidth of the HGHG pulse is 0.23 nm. Since the seed laser is 9 ps long and the electron beam is 1 ps long only 1/9th of the spectrum is seen by the electron beam.

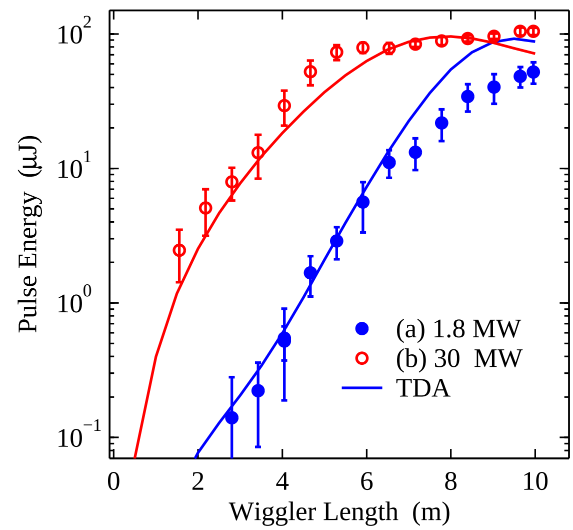

FIG. 2: Pulse energy vs. distance for two values of the input seed laser power: (a) 1.8 MW and (b) 30 MW. The solid curves are TDA simulation results.

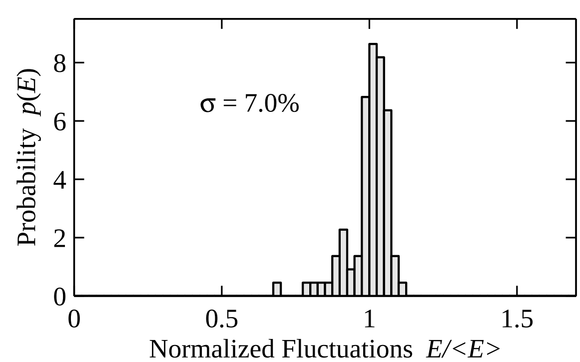

FIG. 3: Histogram of HGHG output pulse energy with 30MW seed power

The seed laser has ~ 6 nm bandwidth which 0.7 nm is seen by electron beam. At the third harmonic we expect 0.23 nm bandwidth which is precisely what was measured. The HGHG spectral brightness is 2×10^5 times larger than SASE because NISUS is not long enough to saturate.

To do a fair comparison we used the GENESIS 1.3 [15] code to calculate the spectrum of SASE after 20 m of NISUS structure (Fig 4). However, due to a larger bandwidth SASE has still an order of magnitude smaller spectral brightness.

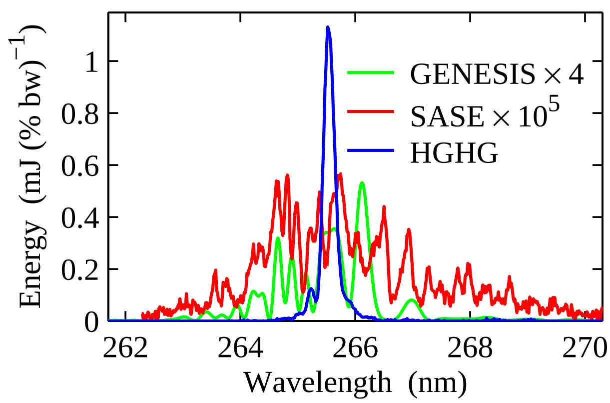

FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

Pulse Length Measurement

The average spacing between the spikes in the SASE spectrum gives an estimate the radiation pulse length according to

$$T_b = \frac{\lambda^2}{0.64 c \Delta\lambda} = 1 \text{ ps} \;\; [16].$$

The measured electron pulse length is 1 ps FWHM. We also used a multi-shot two-photon absorption pump-probe autocorrelator to measure the HGHG pulse length and obtained 0.63 ps FWHM (Fig 5).

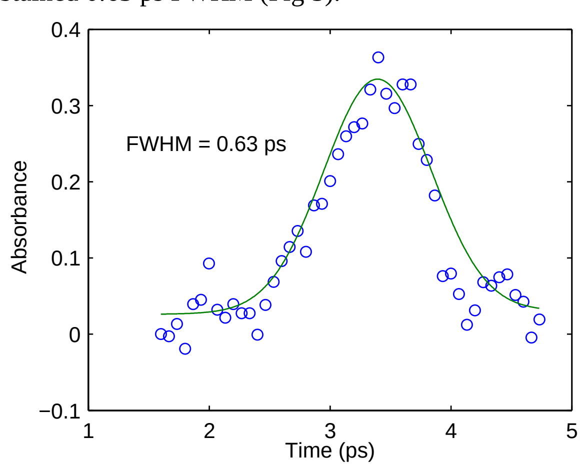

FIG. 5: Pulse length measurement of the HGHG output using two-photon absorption pump-probe autocorrelation for a seed power of 1.8 MW.

For a Gaussian Fourier transform limited beam, the pulse length should be $\tau = 0.44$ ps with the measured bandwidth of 0.23 nm, whereas for a square Fourier transform limited beam $\tau \cong 1$ ps. The measured 0.63 ps pulse length is near Fourier transform limited region.

CONCLUSION

The DUV-FEL experiment has successfully reached saturation. The output energy is measured to be 100 μJ corresponding to a power of 100 MW. The output is longitudinally nearly Fourier transform limited and the shot to shot stability is limited by the accelerator performance. The spectral bandwidth is very narrow and as expected. A first user experiment at DUV-FEL has started using the 88 nm third harmonic which accompanies the 266 nm HGHG.

ACKNOWLEDGEMENT

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