EXPERIMENTAL CHARACTERIZATION OF A SASE FEL IN THE EXPONENTIAL GAIN AND SATURATION REGIMES

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Abstract

The NSLS Source Development Laboratory (SDL) has been a world leader in the development of laser seeded free electron lasers (FELs). Recently we initiated an experimental program to investigate a Self-Amplified Spontaneous Emission (SASE) FEL in both the exponential gain and the saturation regimes. To improve the performance of a SASE FEL, we will explore new techniques such as detuning and undulator tapering. We have achieved saturation of a SASE FEL in the visible to near infrared (IR) spectra for the first time at the NSLS SDL. We have observed spectral narrowing in the exponential gain regime and spectral broadening in the saturation regime. The experimental results are compared with simulations employing the GENESIS code [1].

INTRODUCTION

The worldwide development of single-pass free-electron lasers (FELs) has been motivated by the desire to generate high-brightness coherent femtosecond x-ray pulses for the next-generation linac-based light sources [2]. One of the proposed methods is to use a Self-Amplified Spontaneous Emission (SASE) FEL because a high-power laser seed is not required to generate high-brightness light at any wavelength.

The Source Development Laboratory (SDL) at the National Synchrotron Light Source (NSLS) has grown over the last decade into a state-of-the-art, fully operational research facility for FEL and high-brightness electron beam development. The SDL has been leading the world in the development of laser seeded FELs and is an ideal platform to explore novel ideas for advancing FELs. Recent experimental achievements at the SDL include the first lasing of High Gain Harmonic Generation (HGHG) FELs [3,4], the first characterization of a single-pass high-gain FEL in the superradiance regime [5], the first demonstration of efficiency enhancement by detuning [6] and by undulator tapering, which also improves the spectra in the saturation regime [7]. With increasing interests in SASE FEL technology, the experimental program at the SDL has been recently extended to examine the transverse and spectral properties of a SASE FEL from the exponential gain through to saturation regime and to explore new techniques to improve the SASE FEL. The initial results of this study are reported in this paper.

OPTIMIZATION OF A SASE FEL

The ultimate goal of our research is to experimentally verify efficiency enhancement of a SASE FEL by tapering an undulator and compare its transverse and spectral properties with those for a uniform undulator [8]. To reach this goal we need to first achieve saturation of a SASE FEL with a uniform undulator as early in the undulator as possible so that tapering can have a sufficient interaction length to generate an observable effect.

Experiments & Simulations

The experimental parameters for the study reported here are summarized in Table 1. The initial experimental results for a SASE FEL energy gain curve before optimization is shown as the solid blue curve in Fig. 1. The gain curve was normalized to 1 at z = 10 m. The error bars represent one standard deviation of shot-to-shot energy fluctuations. The SASE FEL appears barely saturated at the end of the undulator before optimization. The gain length L_G in the exponential gain regime for this curve is 0.43 m.

Table 1: Experimental Parameters

Undulator Parameter K	1.1
Undulator Period	3.89 cm
Undulator Length	10 m
Electron Energy	100.7 - 103.2 MeV
Normalized Energy Spread	0.1 %
Radiation Wavelength	758 - 796 nm
Normalized Emittance	1 - 4 mm-mrad
Electron Bunch Charge	190 - 350 pC
Electron Bunch Length (FWHM)	500 - 660 fs
Peak Current	300 - 500 A

In order to achieve saturation earlier, the interaction region between the electron beam and the FEL light must be made as long as possible by trajectory correction. Reducing L_G also helps the FEL Saturate earlier since the SASE FEL saturation length is ~$20L_G$ [2]. Since $L_G(1\mathrm{D}) = \lambda_u / \left(4\sqrt{3}\pi\rho\right)$, where λ_u is the undulator period and ρ is the so-called Pierce parameter, the peak

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current of electron beam should be increased. One way to increase the peak current is to increase the bunch charge by depositing a higher UV laser energy on the cathode, but the space charge effect is also enhanced and degrades emittance. Another way is to compress the beam in the gun by operating the RF gun at a lower RF phase [9]. Compressing the electron beam inside the RF gun has two benefits; one is the higher peak current, and the other is the reduction in transverse emittance due to the time dependent effects [10].

With these basic physical principles in mind, we attempted to maximize the SASE FEL output energy experimentally by (1) iteratively re-aligning the electron beam trajectory with the trim dipoles and the so-called 4-wire coils [11], (2) minimizing dispersion, (3) matching the electron beam at the undulator entrance, and (4) longitudinally compressing the electron beam in the RF gun. The red solid curve in Fig. 1 shows the experimental gain curve after optimization. This is the first time SASE FEL saturation has been observed at the SDL. The saturation point is at around z = 9 m, which is 1 m upstream of the end of the undulator. At this location, we managed to increase the normalized energy more than 3 times by optimization. The dip at around z = 8.4 m is most likely due to a residual trajectory error.

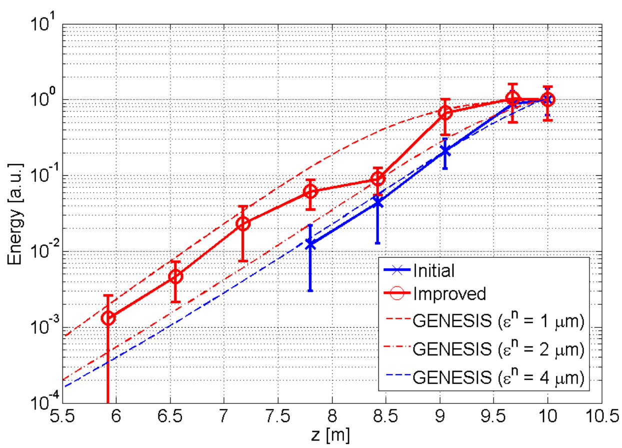

Figure 1: Experimental energy gain curves before (solid blue) and after (solid red) optimization of SASE FEL. Saturation is observed at 9-m in the 10-m long NISUS undulator. GENESIS results are shown as the dashed and dash-dotted lines in red and blue with different normalized emittances, charges, and bunch lengths.

Also plotted in Fig. 1 are the simulation results from GENESIS [1]. The red dashed and dash-dotted curves assume 190 pC charge with 500 fs FWHM bunch length, simulating the improved experiment, while the blue dashed curve assumes 350 pC and 660 fs, simulating the initial experiment. The improved experimental gain curve lies between the simulation curves with normalized emittance of 1 mm-mrad (dashed red curve) and 2 mm-mrad (dash-dotted red curve). The initial experiment gain curve is close to the simulation curve with 4 mm-mrad normalized emittance. These results support that compression of the electron beam in the RF gun indeed led to reduced transverse emittance in the experiment. Furthermore, the comparison of two red simulation curves show that improved transverse emittance helps the FEL light saturate early significantly.

We also obtained single-shot SASE FEL spectra along the undulator. The average values of the rms spectral bandwidth at each undulator location are plotted in Fig. 2. The blue curve corresponds to the case before optimization and the red curve corresponds to the case after optimization. The pre-optimization bandwidth evolution curve exhibits a decreasing trend and a plateau towards the end. The decreasing part fits well with the well-known $1/\sqrt{z}$ dependence for the SASE exponential gain regime [2], with the last three data points near the saturation region excluded from the fitting. The post-optimization bandwidth curve shows a plateau followed by an increase. The increasing trend is similar to the simulation result in a previous study at Argonne National Laboratory [12], and an indication of saturation due to the emerging sidebands generated by synchrotron oscillations of electrons trapped in the ponderomotive potential well. Hence the spectral bandwidth evolution curves also confirm the saturation of the SASE FEL after optimization.

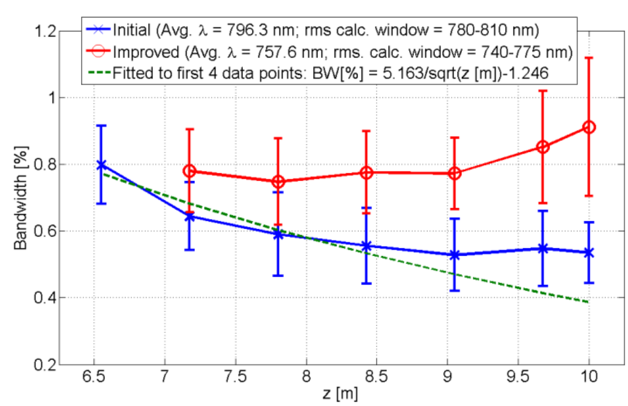

Figure 2: Experimental evolution curve of the spectral bandwidth along NISUS before (blue) and red (after) optimization of SASE. The bandwidth is narrower and decreasing in the barely saturated case, but broader and increasing in the case of deep saturation.

SUMMARY

We have achieved clear saturation of a SASE FEL at ~800 nm for the first time at the NSLS SDL. The observed spectral narrowing in the exponential gain regime and the broadening in the saturation regime are in qualitative agreement with SASE FEL theory. To further improve the SASE FEL performance, we are planning to increase the charge/bunch to 1 nC and optimize the electron beam bunch compression in the magnetic chicane bunch compressor.

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