Efficiency and Spectrum Enhancement in a Tapered Free-Electron Laser Amplifier

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We report the first experimental characterization of efficiency and spectrum enhancement in a laser-seeded free-electron laser using a tapered undulator. Output and spectra in the fundamental and third harmonic were measured versus distance for uniform and tapered undulators. With a 4% field taper over 3 m, a 300% (50%) increase in the fundamental (third harmonic) output was observed. A significant improvement in the spectra with the elimination of sidebands was observed using a tapered undulator. The experiment is in good agreement with predictions using the MEDUSA simulation code.

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The free-electron laser (FEL) is a tunable coherent radiation source from THz to x ray with femtosecond time-resolution capability. Progress was made recently in marching toward the x ray in a self-amplified spontaneous emission (SASE) FEL that successfully lased from soft x ray down to 1.5 Å [1,2], a laser-seeded FEL amplifier [3], and high gain harmonic generation (HGHG) FEL [4] in the deep ultraviolet (DUV). In the meantime, there is a growing effort to further improve the short wavelength FEL performance, and a tapered undulator is one technique proposed to improve the SASE FEL efficiency and spectral quality [5].

It has long been known that undulator tapering can enhance the efficiency in FELs [6,7]. Saturation occurs due to the phase trapping of the electrons in the troughs of the ponderomotive wave formed by the beating of the undulator and radiation fields. As the interaction proceeds, the electron beam loses energy and becomes trapped. In effect, the electrons have lost enough energy to drop out of resonance with the wave. However, the efficiency can be increased further by acceleration of the electrons. This can be accomplished in several ways. One is to reduce the amplitude of the transverse oscillation by gradually reducing the magnetic field strength and/or increasing the undulator period. This was demonstrated in a 35-GHz microwave FEL amplifier [8]. However, it was pointed out that the metal waveguide used in the 35 GHz tapered FEL experiment [9] played a critical role in improving the FEL efficiency, and the performance of the optical tapered FEL could be significantly degraded due to the reduced amount of optical guiding in the region of the tapered undulator. Earlier theoretical studies and numerical simulations also indicated that a tapered undulator could be explored to improve the FEL amplifier spectral brightness and sideband reduction [10]. Recently simulation and experiment [11,12] have demonstrated a significant harmonic content in a single-pass high gain FEL. However, no prior experiment has studied the harmonic efficiency and spectral brightness enhancement in a tapered-undulator FEL amplifier.

In this Letter, we report on a single pass, laser-seeded FEL amplifier experiment using a tapered undulator at the Source Development Laboratory (SDL) of the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory (BNL). This work extends the tapered FEL amplifier to the optical regime and demonstrates spectral improvement for the first time. The evolution of output radiation energy along the undulator was measured for both uniform and tapered undulators. We observed a 300% efficiency enhancement at the fundamental, and 50% at the third harmonic using a tapered undulator. Significant improvement of the FEL spectra and elimination of sidebands were also experimentally observed. Good agreement was found between the measurements and the predictions of the MEDUSA simulation code [11,13].

The NSLS SDL is a laser linac facility featuring a high-brightness electron source, a 4-magnet chicane bunch compressor and an *S*-band SLAC type traveling wave linac [14]. The 100 MeV high-brightness electron beam passes through the NISUS undulator [15], which is a 10-m long planar undulator consisting of 16 sections of 62.5 cm each, with a period of 3.89 cm. One unique feature of the NISUS undulator is that the gap of each section can be remotely adjusted. We implemented a taper in the undulator amplitude by separately changing the gap in the last four sections, which resulted in an amplitude taper starting at about 7 m. The maximum field reduction due to tapering is 4%–5% compared to the uniform undulator. The spent electron beam is sent to the beam dump through a dipole magnet while the radiation is transported to the diagnostic station, where the FEL energy was measured using a calibrated pyroelectric detector (Molectron model J3S-10).

The seed laser, which is also the photo-cathode drive laser, is a Ti:sapphire laser based on chirped pulse amplification (CPA). The amplified laser pulse is split into two, and then goes through two independent optical grating compressors. One compressed laser pulse is frequency tripled to the UV for the photo-cathode rf gun, and the other beam is compressed to about 6 ps (FWHM) with a residual frequency chirp for the seed pulse. Using a single laser for both electron beam generation and amplifier seed minimizes the timing jitter. The seed laser passes through a band pass filter before interacting with the electron beam, it has a central wavelength of 793.5 nm and a bandwidth of 1.5 nm (FWHM). The principal parameters in the experiment, and as used in the simulations, are summarized in Table I.

SASE was first used to optimize the electron beam and the trajectory correction inside the undulator. To ensure the electron energy is on-resonance, the center of the SASE spectrum was set to coincide with the seed laser by adjusting the electron energy. The FEL evolution was characterized by steering the electrons to the wall using the four-wire correctors at each section to terminate the interaction at various points along the undulator.

MEDUSA was used to optimize the undulator tapering using a simple linear taper model. MEDUSA is a three-dimensional simulation code that includes time-dependence, harmonics, and start-up from noise [11,13]. It models the optical field as a superposition of Gaussian modes. Electron trajectories are integrated using the three-dimensional Lorentz force equations in the combined magnetostatic and optical fields. An explicit polychromatic expansion of the fields can be employed along with the time-dependence to treat the evolution of the fundamental and harmonics in the time-domain. Based on the beam parameters listed in the Table I, MEDUSA predicts the best performance can be achieved by linearly tapering the wiggler amplitude ($\Delta B_w/B_w$) in the last quarter of the NISUS undulator (2.5 m) downward by 4%.

In order to realize the maximum efficiency of the taper, the starting point of the undulator taper should be about one gain length ahead of the FEL saturation point. With fixed electron beam parameters, we set the FEL saturation length to about 7 m by adjusting the seed laser energy. Based on the MEDUSA simulation, a 4% linear tapering was first set by continuously linear tapering each of the last four NISUS undulator sections. Because of the uncertainty in the NISUS gap readback (± 20 μm), each section of the tapered undulator was adjusted to maximize the FEL output. This resulted in a piecewise linear taper that differed from a simple linear taper by no more than 20%. Figure 1 shows the averaged FEL output for both uniform and tapered undulators. The good overlap of the output between the uniform and tapered undulators before the tapering point indicates that there is no significant phase drift during the experiments (<0.5 ps).

We also plot the comparison between the optimized experimental data (dots including error bars) and MEDUSA simulation (lines) in Fig. 1. The sources of the FEL output fluctuation are mainly due to laser intensity (both photocathode drive laser and seed laser) and timing jitter of the electron beam relative to the rf system. The experiment and simulation are in substantial agreement. In the case of a uniform undulator, we find an output pulse energy of 113 ± 28 μJ compared to 100 μJ from the simulation. The measured tapered output is 283 ± 68 μJ, which agrees with the MEDUSA prediction of 336 μJ. Within our experimental conditions, the relative FEL power fluctuations for uniform and tapered undulator are comparable. The maximum tapered FEL output observed is about 400 μJ (note that the 283 ± 68 μJ quoted above is the average and the standard deviation in the statistics) that gives an enhancement of over 300% with respect to the uniform undulator. To ensure the efficiency improvement is not due to the detuning effects [16], the electron energy was monitored during the tapering experiments.

With the taper optimized for the fundamental, we also characterized the third harmonic for both uniform and tapered undulators. To avoid the potential contamination from the FEL fundamental, two omega optical UV band pass filters 266BP10 were employed, which have center wavelengths of 266 nm and bandwidths of 10 nm. The

TABLE I. Experimental parameters.

Electron Beam	
Energy	101.37 MeV
Bunch charge	350 pC
Peak current	250–350 A
Bunch duration	1–2 psec
Energy spread	0.1%
Normalized emittance	3–4 mm-mrad
Undulator (NISUS)	
Period	3.89 cm
Peak amplitude	3.016 kG
K	0.775 (rms)
Length	10.0 m
Start-taper point	7.0 m
Taper magnitude ($\Delta B_w/B_w$)	-4%
Radiation	
Wavelength	793.5 nm
Seed power	10 kW

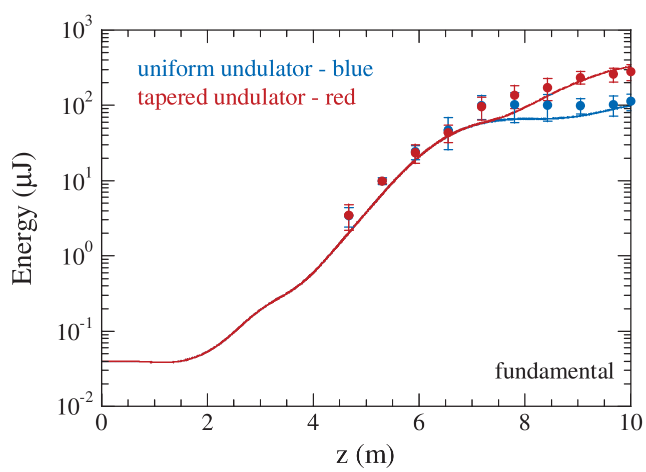

FIG. 1 (color). Comparison between the experiment and simulation for the fundamental for both uniform and tapered undulators.

combined transmission of the two UV filters at the fundamental of 800 nm is 10^{-6}, which is at least 3 orders of magnitude less than is expected of the third harmonic. The evolution of the third harmonic for both the experiment (dots) and simulation (lines) are presented in Fig. 2 for the uniform and tapered undulators. The measured third harmonic output is 1.06 ± 0.17 μJ for the uniform undulator and 1.42 ± 0.16 μJ for the tapered undulator. This compares well with the MEDUSA simulations which produced 0.89 μJ for the uniform undulator and 1.27 μJ for the tapered undulator. While the third harmonic energy is about 34% higher in the tapered undulator than in the uniform undulator, it is about 0.93% of the fundamental for the uniform undulator and drops to about 0.50% of the fundamental for the tapered undulator. Thus, the relative power between the third harmonic and the fundamental has dropped when going from the uniform to the tapered undulator in this experiment. The discrepancy between the experiment and simulation is that the simulation shows a dip in the third harmonic power between 6.8–7.2 m corresponding to overbunching at the harmonic near saturation. This is commonly found in harmonic simulations; however, it is not seen in the experiment. This may be related to the discrete points where FEL data can be taken along the NISUS undulator, and the separation between the data points is 62.5 cm, which is much longer than the harmonic gain length (~25 cm).

The FEL spectra were measured along the undulator using a single-shot spectrometer while the electron beam was steered off the trajectory at a few selected locations. We made a comparison between the spectra obtained in the experiment and simulation for both the uniform and tapered undulators. A comparison between the fundamental spectra found in the experiment and simulation at 6.0 m along the undulator is shown in Fig. 3. Note that the accuracy of the spectral measurements is limited by the bandwidth of the filter; hence, the experimental spectra may be shifted by ± 0.5 nm. The spectra in the figure are obtained prior to saturation (at about 7.0 m) and are in substantial agreement as to both the center wavelength and the linewidth.

Comparison between the spectra from the experiment and simulation for the uniform (left) and tapered (right) undulators is shown in Fig. 4 at 8.5, 9.5, and 10.0 m. We observe that the spectra are in remarkable agreement between the experiment (red) and simulation (blue) with respect to the center wavelength, linewidth, and presence of sidebands for the tapered undulator. However, the discrepancies between the experiment and simulation become increasing large as the distance increases beyond saturation in the uniform undulator. In the case of a tapered undulator, the resonance is maintained over the extended length and sidebands are suppressed [10], which is not the case for the uniform undulator where sidebands grow rapidly beyond saturation.

The discrepancy between the experiment and simulation for the uniform undulator is not large at 8.5 m, which is 1.5 m beyond saturation. The shift in the center wavelength is still within the range of uncertainty of the spectrometer and the bandwidths and sideband magnitudes between the experiment and simulation are comparable. The discrepancy increases at 9.5 m. The shift in the center wavelength is beyond the range of uncertainty in the spectrometer, but the linewidth and sideband magnitudes are comparable. At 3.0 m beyond saturation, however, the spectra are radically different and the experiment shows substantially more sidebands and spikiness. We attribute the increase in the discrepancy with distance beyond saturation in the uniform undulator to a number of factors. In the experiment, there are shot-to-shot fluctuations and noise, measurement uncertainties, and imperfections in the undulator. The simulation assumes a Gaussian electron beam, which is an idealization that may result in less sideband growth than the actual distribution.

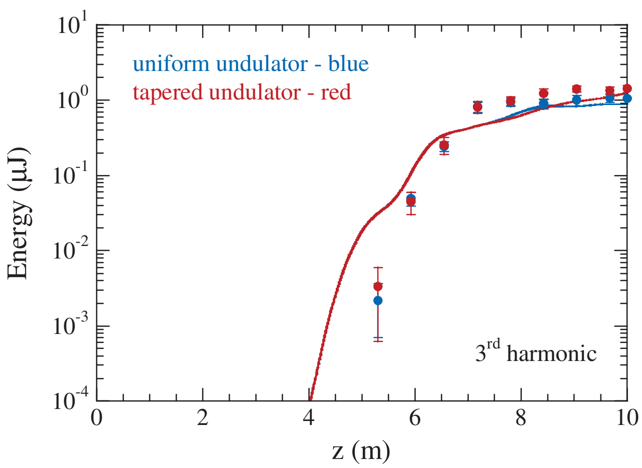

FIG. 2 (color). Comparison between the experiment and simulation for the third harmonic for both uniform and tapered undulators.

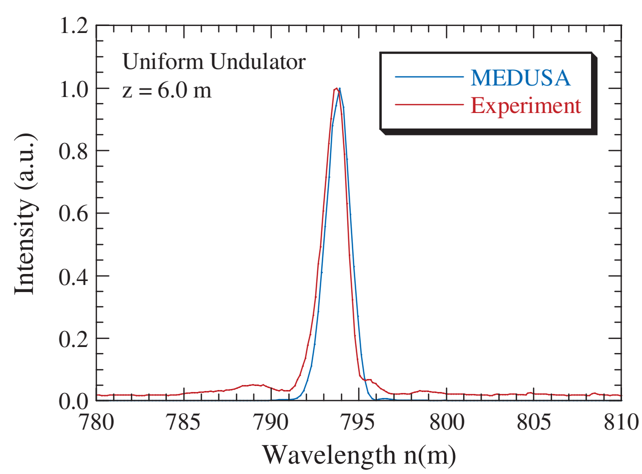

FIG. 3 (color). Spectral comparison from experiment and simulation at 6.0 m, before the taper begins.

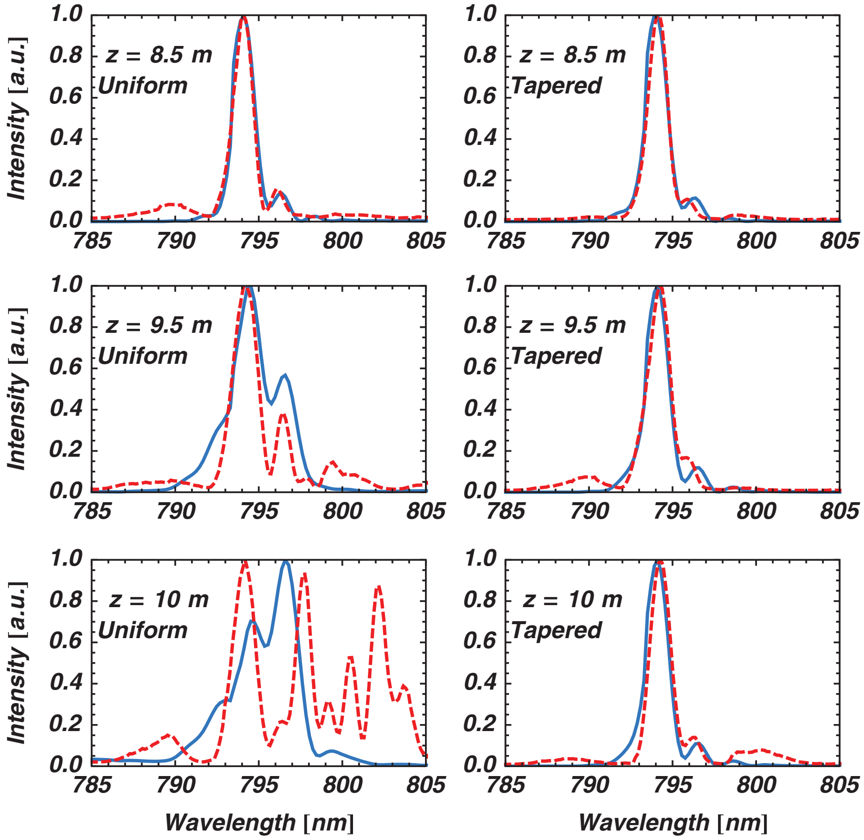

FIG. 4 (color). Spectra for the experiment (red) and simulation (blue) for uniform and tapered undulators.

In summary, we performed the first experiment to measure both the fundamental and third harmonic efficiency enhancement in a tapered undulator. In comparison with the results for a uniform wiggler, the tapered wiggler resulted in an efficiency enhancement of about 300% for the fundamental and 50% for the third harmonic; hence, it is clear that a tapered undulator will not only enhance the fundamental, but also the harmonic output in an FEL. The FEL spectral brightness enhancement and significant sideband reduction were experimentally demonstrated for the first time. This could be explored in the future to improve the spectral brightness of both laser seeded and SASE x-ray FELs. It should be noted that the undulator taper parameters in the experiment are subject to the constraints imposed by the design of the NISUS undulator and have not been fully optimized for the third harmonic. The experimental results are in substantial agreement with predictions using the MEDUSA simulation code.

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[1] P. Emma (LCLS team), *Proceedings of PAC 2009*, H3PBI01 (IEEE, Vancouver, Canada, 2009).
[2] W. Ackermann *et al.*, Nat. Photon. **1**, 336 (2007).
[3] G. Lambert *et al.*, Nature Phys. **4**, 296 (2008).
[4] X. J. Wang *et al.*, *Proceedings of FEL 2006*, (BESSY, Berlin, Germany, 2006), p. 18.
[5] W. M. Fawley *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **483**, 537 (2002).
[6] P. Sprangle *et al.*, Phys. Rev. Lett. **43**, 1932 (1979).
[7] N. M. Kroll *et al.*, IEEE J. Quantum Electron. **17**, 1436 (1981).
[8] T. J. Orzechowski *et al.*, Phys. Rev. Lett. **57**, 2172 (1986).
[9] W. M. Fawley, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 550 (1996).
[10] J. Chen and A. Bhattacharjee, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 363 (1996).
[11] H. P. Freund *et al.*, IEEE J. Quantum Electron. **36**, 275 (2000).
[12] A. Tremaine *et al.*, Phys. Rev. Lett. **88**, 204801 (2002).
[13] H. P. Freund, Phys. Rev. ST Accel. Beams **8**, 110701 (2005).
[14] J. B. Murphy and X. J. Wang, Synchrotron Radiation News **21**, No. 1, 41 (2008).
[15] D. C. Quimby *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **285**, 281 (1989).
[16] X. J. Wang *et al.*, Appl. Phys. Lett. **91**, 181115 (2007).