EXPERIMENTAL INVESTIGATION OF SUPERRADIANCE IN A TAPERED FREE-ELECTRON LASER AMPLIFIER*

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Abstract

We report experimental studies of the effect of undulator tapering on superradiance in a single-pass high-gain free-electron laser (FEL) amplifier. The experiments were performed at the Source Development Laboratory (SDL) of National Synchrotron Light Source (NSLS). Efficiency was nearly tripled with tapering. Both the temporal and spectral properties of the superradiant FEL along the uniform and tapered undulator were experimentally characterized using frequency-resolved optical gating (FROG) images. Numerical studies predicted pulse broadening and spectral cleaning by undulator tapering Pulse broadening was experimentally verified. However, spectral cleanliness degraded with tapering.

INTRODUCTION

The Source Development Laboratory (SDL) in National Synchrotron Light Source (NSLS) at BNL experimentally demonstrated the superradiance in a single-pass high-gain laser-seeded free-electron laser (FEL) amplifier [1]. Efficiency and spectrum enhancement by undulator tapering for a long-pulse seeded FEL were also experimentally verified at the SDL [2]. After these two achievements, we have started investigating the effect of undulator tapering on superradiance by using a short seed pulse. Both the temporal and spectral properties of the radiation along the uniform and tapered undulator were experimentally characterized using frequency-resolved optical gating (FROG) images. The 3-D time-dependent FEL code GENESIS [3] was used to simulate the superradiance process with and without tapering, and its results were compared against the experimental results.

The experiments reported here were carried out at the SDL, which consists of an S-band BNL type rf gun, a 250-MeV linac, a 4-magnet chicane bunch compressor, and a Ti:sapphire laser system that generates both a UV laser for the photoinjector and an IR seed laser. The 100-MeV electron beam passes through the 10-meter NISUS planar undulator [4]. The gap of each section (total 16 sections) of this undulator can be separately adjusted. For the tapered undulator experiment, the gaps in the last four sections (~7 m to 10 m) were gradually changed so that the undulator field linearly decreased to the field 6% lower at the undulator exit. The spent electron beam is diverted to a beam dump through a dipole magnet while the output radiation is sent to a diagnostic station equipped with a pyroelectric detector, a spectrometer, and a commercial Grenouille configuration FROG [5].

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Table 1: Experimental Parameters

Electron Beam	
Energy	101.1 MeV
Bunch Charge	350 pC
Peak Current	250-350 A
Bunchlength (FWHM)	1-2 ps
Energy spread (rms)	0.1%
Normalized emittance	3-4 mm-mrad
Undulator (NISUS)	
Period	3.89 cm
Undulator parameter K	1.1
Taper starting point	7 m
Taper maginitude ($\Delta B/B$)	-6%
Radiation	
Seed laser wavelength	789.5 nm
Seed laser pulselength (FWHM)	120 fs
Seed laser power	10 MW

SIMULATIONS

Using GENESIS, the superradiance FEL with and without tapering was first numerically explored. The results are shown in Fig. 1. The relevant parameters used in the simulations are listed in Table 1. As argued in [1], the fact that the output pulselength is shorter than the pulselength of the unchirped seed pulse (120 fs) means that the radiation is in the superradiant regime. With a 6% linear taper starting from z = 7 m, the pulselength broadens and the spectrum becomes narrower and cleaner, i.e., has less spikes.

In these simulations, the current distribution is assumed to have an asymmetric triangular distribution with 1 ps rise time and 0.2 ps decay time at half maximum. The seed pulse was delayed so that the seed pulse is placed near the peak of the current distribution at the undulator entrance.

EXPERIMENTAL RESULTS

Without Tapering

FROG images vary significantly from shot-to-shot, due to the timing jitter between the seed laser pulse and the electron beam and the shot-to-shot fluctuations in the electron bunch current distribution and energy. However, the results shown on Fig. 2 represent typical retrieved

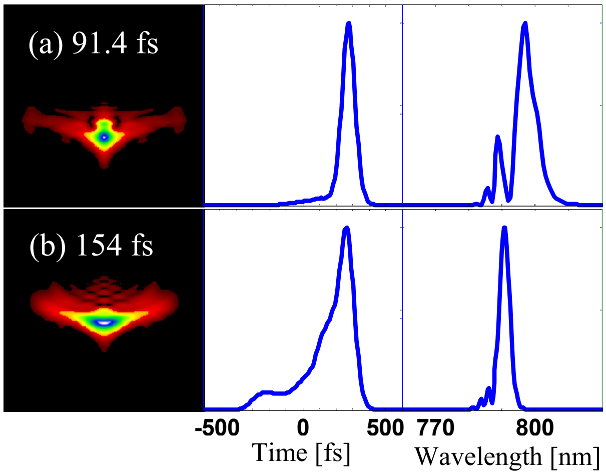

Figure 1: Each row corresponds to a simulation result. The FWHM pulse duration of the main temporal peak is also shown for each case. The three columns, starting from left, show FROG images, temporal and spectral distributions. Amplitudes are normalized. No taper is applied for (a), but 6% linear taper starting from z = 7 m for (b).

FROG images observed at the end of the undulator when no taper was applied.

The huge differences in the temporal and spectral properties can be explained by detuning, as discovered in another investigation at the SDL [6]. The electron beam energy can vary as much as 1% in a typical operation from shot to shot. Before bringing in the seed laser to the undulator, we use SASE spectra to determine the beam energy resonant with the seed laser. With this method, for some shots, the beam energy will be higher than the resonant energy. Thus, for these shots, the beam is positively detuned so that the direct seed amplification is weak or non-existent in this case. However, the seed laser can still coherently bunch the electron beam while slipping through the bunch due to some overlapping between the FEL gain bandwidth and the seed laser bandwidth. This can result in a significant amplification in the portion of the electron bunch where the seed laser pulse has already passed through. This case is manifested by Fig. 2(a). For the case of Fig. 2(b), the detuning is not as large. Therefore, the coherently bunched portion (a small hump on the left) is starting to exponentially grow, but still much weaker than the directly amplified seed pulse (a tall peak on the right). Figure 2(c) represents a shot where the beam energy was close to the resonant energy so that only a strong superradiance spike is present with a very small shoulder. Because of the competition between these two physical processes, namely, the direct seed amplification leading to superradiance and the coherent bunching in the slippage region, the interpretation of some of the experimental results becomes difficult.

Figure 2(c) must be in the superradiant regime because of the pulselength of 74 fs, but the FROG image appears qualitatively different from the numerical prediction

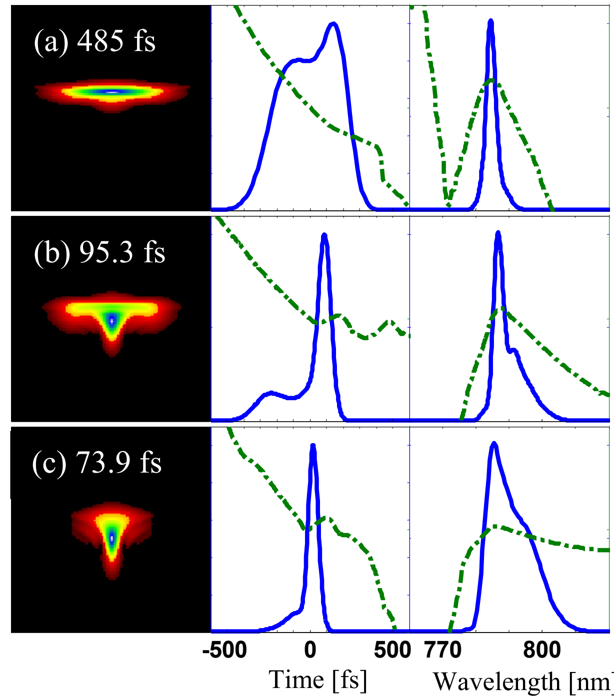

Figure 2: Each experimental FROG result is a row in the figure labelled by the FWHM of the main temporal peak. The three columns, starting from left, show retrieved FROG images, temporal and spectral distributions including phase. Amplitudes (blue) are normalized and phases (green) are plotted from -10 to +10 rad.

shown in Fig. 1(a). The spectrum in Fig. 2(c) is also free from the sidebands shown in Fig. 1(a). The cause of these discrepancies between simulations and experiments is currently under investigation.

With Tapering

The gain curves with and without tapering are shown in Fig. 3. These curves were obtained by kicking the electron beam at different positions along the undulator after which the beam-radiation interaction terminates. The final output energy with tapering is nearly 3 times larger than that without tapering, which is consistent with the experimental result done using a long seed pulse [2].

Figure 4 shows the radiation pulselength evolution along the undulator. The results from the simulations shown in Fig. 1 are also shown in Fig. 4 as solid lines. Each experimental pulselength value shown was obtained by first sorting all the recorded shots at each undulator position in an ascending order of pulselength, and then by taking the average of the first 10% of the sorted shots. The experiment and simulation agrees well for the non-tapered case, but not so well for the tapered case. The main reason for this is due to the more complicated pulse structures often observed for the tapered case as evident in Figs. 5(a) and (b). The sudden dip at z = 9.7 m for the tapered case is not due to actual pulse shortening but due to the FWHM calculation algorithm capturing only the very narrow peak (such as the rightmost narrow spike in

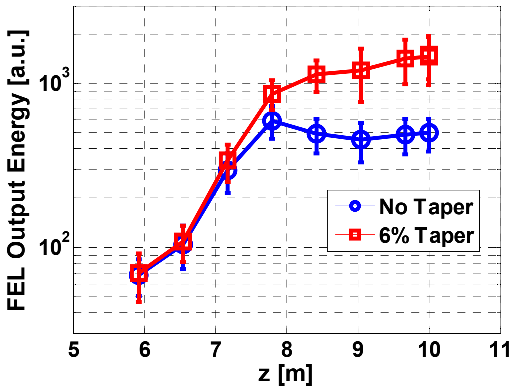

Figure 3: Gain curves with and without tapering.

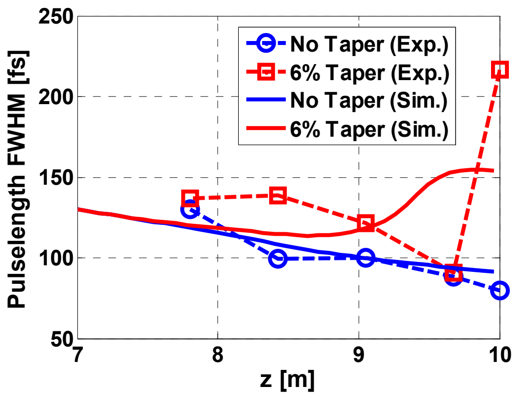

Figure 4: Radiation pulselength (FWHM) evolution along the undulator. Blue and red lines are for non-tapered and tapered cases, respectively. Solid and dashed lines are for simulations and for experiments, respectively.

Fig. 5(a). So, the general trend of continuous pulse broadening along the undulator for the tapered case is consistent in both experiment and simulation.

The complicated pulse structures with tapering, as shown in Fig. 5, are likely caused by, again, the fact that superradiance and coherent bunching in the slippage region are competing. With tapering, the resonant wavelength is reduced. If the beam energy is resonant originally without tapering, then the electron beam effectively becomes positively detuned in the tapered region. Thus, the radiation growth in the slippage region can outpace that of the seed pulse, which can result in more spikes in addition to the superradiant spike moving ahead. This is a speculation and cannot be demonstrated directly with simulations at this point because we are lacking a good agreement in the FROG results even for the simpler, non-tapered case.

In Fig. 5, the spectra also show multiple peaks, i.e., have degraded with tapering, while the simulations predicted the opposite as shown in Fig. 1. This is yet another indication of the inadequacy of the current model, and requires a further investigation on the assumptions used in the numerical studies.

SUMMARY

We have performed first experiments with a tapered

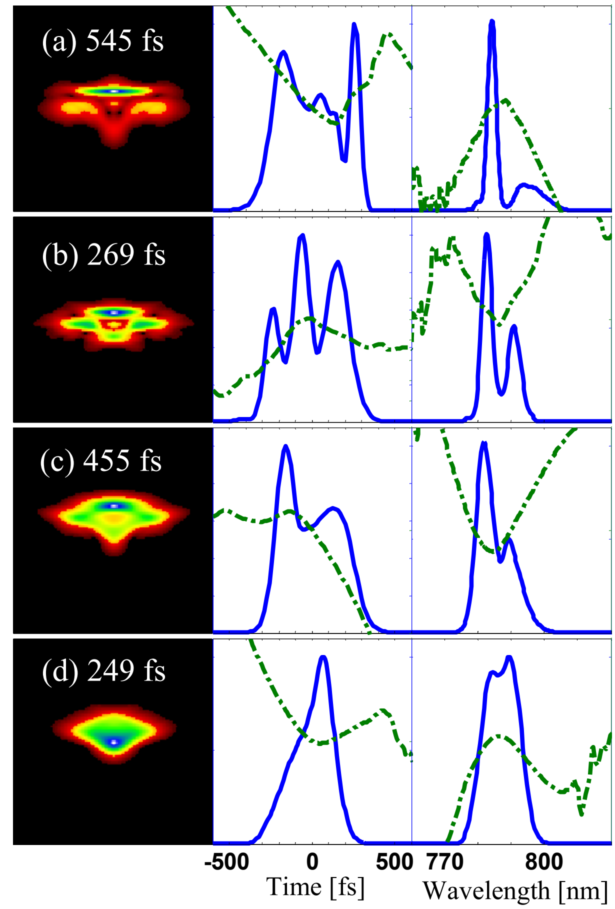

Figure 5: Typical experimental FROG results for the tapered case.

undulator and a short seed laser pulse. Pulse broadening with tapering expected from simulations was experimentally confirmed. However, the experimentally obtained spectra degraded with tapering, whereas the simulations predicted improvement. A further numerical study is under way to resolve this issue.

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