EFFICIENCY ENHANCEMENT EXPERIMENT WITH A TAPERED UNDULATOR IN A SINGLE-PASS SEEDED FEL AT THE NSLS SDL

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Abstract

The experimental observation of FEL efficiency enhancement using a tapered undulator in a single-pass seeded FEL at the NSLS SDL is reported. The last 2.5 m of the 10 m NISUS undulator was linearly tapered so that the magnetic field strength at the end of the undulator was reduced by 5 %. The FEL energy gain along the undulator was measured for both the tapered and un-tapered undulators. We observed that the FEL efficiency was more than doubled by applying the taper. The experimental results are compared with the numerical simulation code, GENESIS1.3 [1].

We also observed a multi-ring structure in transverse FEL distributions with a tapered undultor.

INTRODUCTION

A single-pass free electron laser (FEL) is capable of generating high brightness coherent radiation, and its wavelength can be tuned by changing an electron beam energy or strength of a periodic magnetic structure called an undulator. One of the main directions of the FEL developments is to generate a high brightness coherent femtosecond x-ray pulses for future light sources [2]. Another is to generate high average power infrared radiation for Navy directed energy applications. For the latter purpose, the National Synchrotron Light Source (NSLS) Source Development Lab (SDL) of Brookhaven National Laboratory (BNL) has comprehensively studied the efficiency enhancements of a single-pass seeded FEL [3].

In principle, the FEL is saturated at certain energy due to the phase trapping of the electrons in the troughs of the ponderomotive wave formed by the beating of the undulator and the radiation fields. After the trapping, the FEL radiation and electron keep exchanging the energy, which prevents the radiation from growing further. The radio of the saturated power to the input electron power is called an efficiency. One approach for improving the efficiency is to apply an energy (or frequency) detuning, so that a little higher energy electrons can sustain the resonance longer. Recently, the effect has been experimentally demonstrated in a single-pass seeded FEL configuration [3]. Another approach for the improvement of the efficiency is to taper, i.e., gradually decrease, the magnetic field of the undulator [4, 5]. Previous experiments at microwave frequencies have demonstrated the substantial increase in the efficiency of a single-pass FEL [6]. There are other proposals for the improvement of efficiency such as RF injection [7].

In the paper, we present the experimental observation of efficiency enhancement by linearly tapering the last quarter of the 10 m NISUS undulator at the NSLS-SDL. The gain curves, i.e., the FEL energy vs the undulator length, are plotted with and without a taper, and the experimental results are compareed with the three-dimensional numerical code, GENESIS1.3.

The spatial distribution with the taper are also measured.

EFFICIENCY ENHANCEMENT BY AN TAPERED UNDULATOR

In a Self-Amplified Spontaneous Emission (SASE) FEL, the wavelength of radiation generated by a planar undulator is peaked at,

$$\lambda_r = \frac{\lambda_u(1 + K^2/2)}{2\gamma^2}, \quad (1)$$

where λ_u is the undulator period, K is the undulator parameter, and γ is the initial electron energy normalized with its rest mass. The seeded FEL has the same characteristic when the seed laser with the same wavelength, λ_r, is injected [3].

The saturation power is approximately given by $P_{sat} \sim \rho P_e$, where ρ is so-called the Pierce parameter and P_e is the input electron power. Thus, the efficiency equals to ρ. The typical ρ of high gain FEL's in a visible region is in the order of 10^{-3} to 10^{-4}. When the radiation reaches the saturation and the electrons are trapped in the troughs of the ponderomotive wave, the radiation can no more extract the energy from the electrons. Supposed that the undulator parameter, K, is decreased as the electron energy γ becomes lower, the resonance condition presented in Eq.(1) can be sustained further. Since the undulator parameter is proportional to the magnetic field, i.e., $K = 0.94B_0[T]\lambda_u[cm]$ where B_0 is the magnetic field and λ_u is the undulator period that is normally fixed, we decrease the magnetic field strength by opening an undulator gap.

Numerical simulation

In order to optimize a taper, we ran time dependent GENESIS calculation under the same condition as experiments at the NSLS-SDL. The major experimental parameters are shown in Table 1. For the experiment described in

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Table 1: Major experimental parameters

Undulator parameter K	1.1
Undulator period	3.89 cm
Undulator length	10 m
Electron energy	101.4 MeV
Peak current	230 A
Electron bunch duration (FWHM)	1.4 ps
Energy spread (rms)	0.1 %
Normalized Emittance	4 mm.mrad
Seed laser wavelength	793.5 nm
Seed laser bandwidth (FWHM)	1.5 nm
Seed laser pulse duration (FWHM)	4.5 ps
Seed laser energy	10 kW

the paper, the electron energy is set on resonance as shown in Eq.(1).

The result of the numerical simulation is shown in Fig. 1. The black curve is the gain curve without a taper. The FEL light gains the energy exponentially until it reaches the saturation at z∼8 m. The saturation energy is 47 μJ. After the saturation, the energy does no more increase. The red curve in Fig. 1 is the gain curve with a taper. One can see that the the FEL energy continuously grows until the end of undulator.

By scanning the length and the strength of the taper, the largest enhancement is obtained when the taper starts at z=7.5 m, which is a half meter (or one gain length) upstream from the saturation point, and the magnetic field at the end is 5 % less than that without a taper. In the following, we shall call such a taper the 5% taper. Note that in the numerical calculations, both linear and quadratic tapers were tested, but no significant difference was found between them. Therefore, we chose the linear taper for simplicity.

As a result, the maximum FEL energy with the 5 % taper was 177 μJ, which is higher than the saturation energy without a taper by a factor of 3.7.

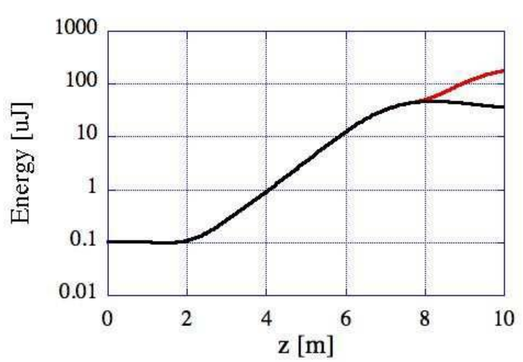

Figure 1: Simulation result of gain curves with taper (red) and without taper (black).

Experiment

The NSLS-SDL is capable of applying a taper on the NISUS undulator. The undulator consists of 16 sections and a joint between each section can remotely and independently be moved. The undulator gap control is operated by the LabVIEW program and the gap at each section is read-backed, so it is possible to quickly adjust the taper while the FEL is being operated. In the experiment, we opened undulator gaps at the last four sections (2.5 m) to linearly decrease the magnetic field along the undulator. While the FEL is turned on, the strength of the taper was scanned and optimized so that the efficiency enhancement was maximized. Consequently, the output energy became maximum when the taper was set to 5 %, the same amount as the simulation shows.

The experimental result is shown in Fig. 2. The black curve is without a taper, and the red is with the 2.5 m long and 5% taper. Since there is a shot-to-shot fluctuation in FEL energy due to the fluctuation of the e-beam distribution and the timing jitter between the e-beam and the seed laser, the statistics of the FEL light at each section are measured and its average is plotted in Fig. 2. Note that the two gain curves well overlap all along the untaped sections, which verifies the repeatability of the FEL generation.

The gain curve without a taper (black curve) is saturated around z=8 m, and the energy starts decreasing beyond the saturation. These are in consistent with the numerical simulation. From z=9 m, the FEL light regains the energy unlike the simulation result. However, the nonlinear effect without a taper is out of the scope of the paper, so we shall not discuss it further.

The gain curve with the 5% taper (red curve) continuously grows until the the middle of the last section, z=9.7 m. The authors attribute the energy loss at the last 0.3 m to the early saturation.

The saturation energy without a taper was 60 μJ and the maximum energy with the 5% taper was 134 μJ. The enhancement was the factor of 2.2. Therefore, the enhancement was more than doubled by a tapered undulator. However, the enhancement was smaller than that expected by the simulation. In the simulation, the energy keeps increasing until the end of the tapered undulator, but the gain curve obtained in the experiment slightly drops at the last half section. The inconsistency of the enhancement between the experiment and the numerical simulation will be kept studied.

One of the notable features of a SASE FEL is the transverse coherence. Since the higher spatial modes of the light have stronger diffraction than the fundamental mode, the fundamental mode will eventually be dominant as the light evolves in an exponential gain regime. The feature is also valid for the seeded FEL as far as the light evolves well in an exponential gain regime. The output transverse profile of the seeded FEL is dominated by the fundamental mode rather than the initial profile of the seed laser.

In the taper experiment, we observed non-Gaussian FEL

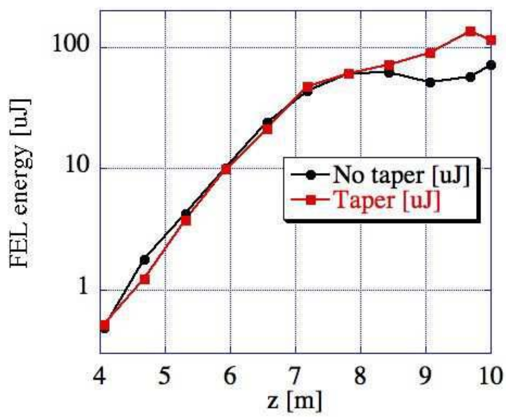

Figure 2: Experimental result of gain curves with taper (red) and without taper (black).

profiles both in SASE and seeded FEL. In the transverse FEL profile measurement, a mirror is inserted in the middle of each section, and the FEL light reflected by the mirror is transported to a CCD camera. The focusing optics is set for the near-field measurement at the mirror, and the intensity of the FEL light is attenuated by neutral density filters by couples of orders of magnitude to avoid the saturation of the CCD camera. Under the normal untapered situation, the near-field distribution of either SASE or seeded FEL forms Gaussian distribution. However, when the undulator is tapered, the distributions of SASE indicate a multi-ring structure at the last one or two sections (see Fig. 3 (a)). Note that the SASE light is not saturated until the end of the undulator under the conditions listed in Table 1. It follows that the SASE is not on resonance at the tapered sections. The seeded FEL also shows the higher modes when the saturation point is not optimized for the 2.5 m taper (see Fig. 3 (b)). The detail will be studied.

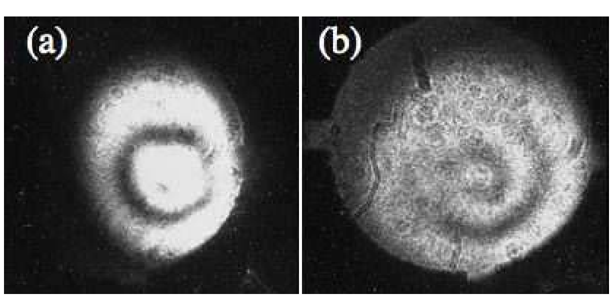

Figure 3: Multi-ring spatial structures in (a) SASE FEL and (b) seeded FEL.

SUMMARY

We observed the enhancement of the FEL efficiency by using a tapered undulator. The efficiency was more than doubled by applying the taper in such a way that the undulator magnetic field linearly decreases by 5 % at the last 2.5 m of the 10 m undulator. The optimum taper, 5%, are consistent between the experiment and the numerical simulation, although the efficiency enhancement observed in the experiment, i.e., a factor of 2.2, is smaller than that in the simulation, 3.7.

Multi-ring structures were observed both in SASE and seeded FEL spatial distributions.

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