NUMERICAL INVESTIGATION OF LONGITUDINAL COHERENCE IN A LINEAR TAPERED SASE FEL

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Abstract

We numerically investigate the longitudinal coherence in a linear tapered FEL based on self-amplified spontaneous emission, where the radiation has been shown to have a limited longitudinal coherence. The cases of different starting points and tapered amplitudes are simulated, and the results from GENESIS (3D code) are presented. It has been shown that longitudinal coherence can be improved distinctly by employing tapered undulators starting from the end of the exponential gain region and with an appropriate amplitude.

INTRODUCTION

Self-amplified spontaneous emission (SASE) [1] has become one of leading candidates for approaching the X-ray free-electron lasers (FELs) for the capability of generating high-brightness radiation down to hard X-ray wavelengths [2]. However, for an uniform-parameter undulator, the FEL efficiency at saturation is roughly given by the FEL scaling parameter ρ , where ρ is typically on the order of 10^{-3} in X-ray wavelength. Moreover, due to the fact that the SASE process starts up from incoherent shot-noise, the FEL spectrum at saturation consists of many spikes within a broad bandwidth, namely, the SASE FEL has a poor longitudinal coherence. Tapered undulator was proposed as a method mainly to enhence the FEL efficiency many years ago [3-6], and in some papers, spectrum cleaning was also briefly mentioned but mainly for the radiation in long wavelengths.

In this letter, we numerically investigate the tapered undulator for SASE X-ray FELs, with the goal of improving the radiation spectrum and an incidental consequence of increasing the radiation power. Our approach is using a long uniform undulator to start up the SASE process and bunch the electrons longitudinally and following a series of tapered undulators with a constant tapered rate. In this approach, the starting point and tapered rate of tapered undulator is the two key factors that directly affect the FEL radiation.

SIMULATIONS

Using time-dependent codes GENESIS, the SASE FELs with tapering was numerically explored for many cases of different starting points and different tapered amplitudes. The normal SASE FEL without tapering is also simulated for comparison. The relevant parameters used in simulations are listed in Table 1.

Considering the FEL physics, we start the tapered undulator from three different points: the middle of the exponential gain region, the end of the exponential gain region and the point near saturation. Marking the starting point as z_0, they are z_0=22.56m, 30.24m and 34.08m, corresponding to the three cases above respectively.

Table 1: Simulation Parameter Based on LCLS

Electron beam:	
Energy:	4.3 GeV
Energy spread:	0.025%
Peak current:	2000 A
Emittance:	1.2 mm·mrad
Undulator:	
Period:	3.0 cm
Undulator parameter *K*:	3.5
Segment length:	3.36 m
Radiation:	
FEL wavelength:	1.5095 nm

Without Tapering

The SASE FEL without tapering was simulated firstly. The gain curve of radiation power is given in Fig. 1 and the radiation spectrum at saturation is also presented. It is shown that the radiation power saturates at z=38.88 m (~20.4 gain lengths) and the exponential gain region covers from z=3 m to z=30.24 m. We also can find that the spectrum at saturation consists of many spikes in a wide frequency bandwidth.

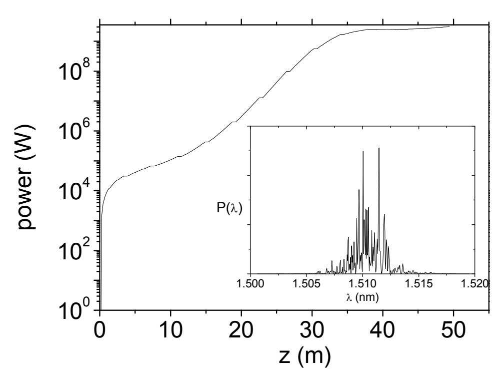

Figure 1: Radiation power of SASE FEL without tapering and the spectrum at saturation.

Tapering from the Middle of the Exponential Gain Region

In this case, the tapered undulator started from z_0=22.56 m, where the radiation power growth is in the middle of

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the exponential gain region. We scanned the tapered amplitude that is defined as the relative variation of undulator parameter K in unit length. The optimized tapered rate for power growth is obtained to be $\Delta K / K = 1.25 \times 10^{-4}$ m^{-1}.

The saturation power of tapering from z_0=22.56m more than doubles comparing with non-tapered, as shown in Fig. 2 (top), and the saturation length almost has no change. However, for all the tapered rates we have scanned, the radiation spectrum at saturation is similar with that of non-tapered. Figure 2 (bottom) shows the representative spectrum at saturation of tapering from z_0=22.56m. The only modification to the structure of the spectrum is the trend of moving to shorter wavelengths.

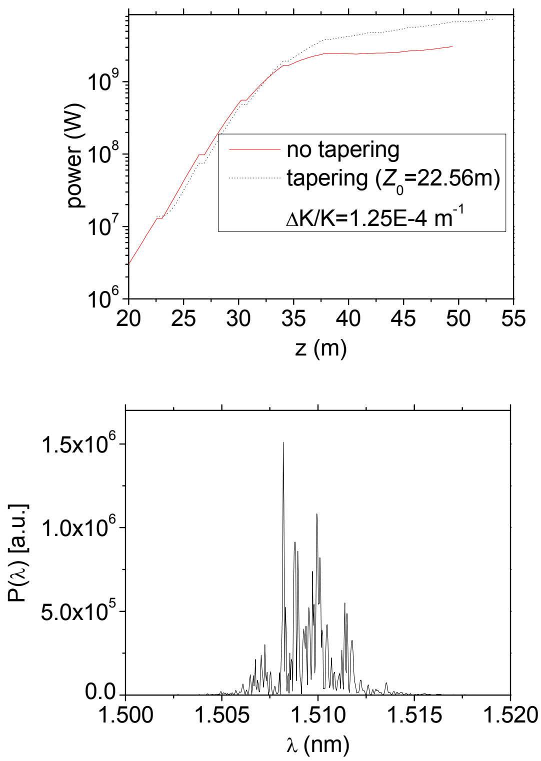

Figure 2: Tapering from the middle of the exponential gain region (z_0=22.56 m). **Top:** Radiation power curves with and without tapering. **Bottom:** Radiation spectrum at saturation of tapered FEL with tapered rate $\Delta K / K = 1.25 \times 10^{-4}$ m^{-1}.

Tapering from the End of the Exponential Gain Region

In this section, the tapered undulator started from z_0=30.24 m, where the exponential gain is near the end. The tapered rates have been scanned and the best one for power growth is $\Delta K / K = 2.87 \times 10^{-4}$ m^{-1}.

The power growth is depicted in Fig. 3 (top). It can be seen that the saturation power grows more than four times with the best tapered rate, but the saturation occurs in a larger undulator length. Then we focus on the radiation spectrum. In Fig. 3 (bottom), we give the radiation spectrum at saturation of two tapered rates that are $\Delta K / K = 2.87 \times 10^{-4}$ and 5.74×10^{-4} m^{-1}. With the tapered rate exceeding the best rate for power growth, the sidebands of the spectrum become suppressed and the centre spike at $\lambda = 1.5095$ nm stands out. Therefore, the longitudinal coherence is improved distinctly. However, it should be noticed that the best tapered rate for spectrum cleaning is about two times larger than that for power growth here.

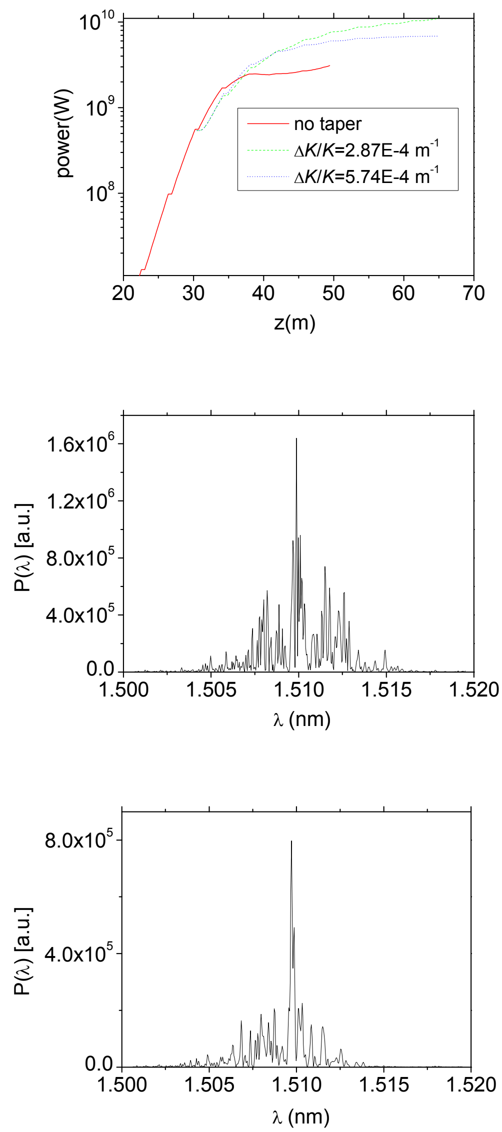

Figure 3: Tapering from the end of the exponential gain region (z_0=30.24 m). **Top:** Radiation power curves with and without tapering. **Middle:** Radiation spectrum at saturation of tapered FEL with tapered rate $\Delta K / K = 2.87 \times 10^{-4}$ m^{-1}. **Bottom:** Radiation spectrum at saturation of tapered FEL with tapered rate $\Delta K / K = 5.74 \times 10^{-4}$ m^{-1}.

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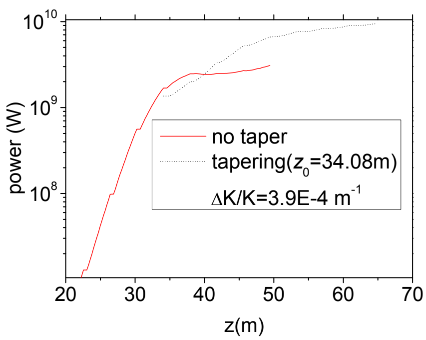
Tapering from the Point near Saturation

The saturation length without tapering is 38.88 m here. So we begin to use tapered undulator from z_0=34.08 m. The simulation results are shown in Fig. 4. The tapered rate $\Delta K / K = 3.9\times10^{-4}$ m^{-1} is proved to be the best rate for power growth. Comparing with the case of tapering from the end of the exponential gain region, the saturation power has a little decline but the saturation length is nearly the same. We also study the radiation spectrum at saturation of all the tapered rates we scanned. Figure 4 (bottom) gives a representative spectrum of tapering from the point near saturation. It is obvious that the spectrum here has no improvement.



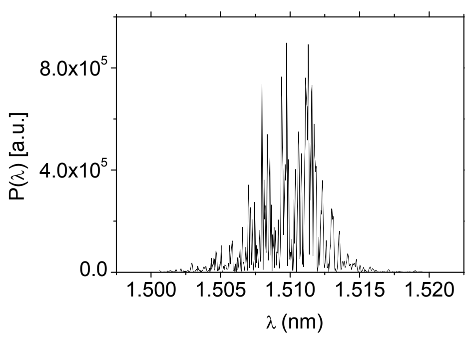


Figure 4: Tapering from the point near saturation (z_0=34.08 m). **Top:** Radiation power curves with and without tapering. **Bottom:** Radiation spectrum at saturation of tapered FEL with tapered rate $\Delta K / K = 3.9\times10^{-4}$ m^{-1}.

Comparing these three cases of different starting points, tapering from the end of exponential gain region gives the strongest enhancement to both the radiation power and spectrum, where the unique spike at $\lambda = 1.5095$ nm is extrusive and any others are suppressed. However, the best tapered rate for spectrum cleaning is larger than that for power growth. The tapered FELs starting from the other two points also can increase the radiation power, but with the tapered rates we have scanned, the spectum nearly has no improvement.

In addition, with the starting point moving backwards, the best tapered rate for power growth becomes larger. As here the linear tapered undulator consists of a number of segments with a constant tapered rate, there is no any tapered rate that can match the electron energy loss everywhere in the tapered undulator. Then, when starting point is closer to the saturation point, the electrons lose energy more rapidly, therefore, a lager tapered rate is needed to continue the synchrotron oscillations inside the ponderomotive potentials.

SUMMARY

We have simulated SASE FEL with and without linearly tapering. Three different starting points of tapered undulator have been studied with a scan of tapered rates. Simulation results show that the best starting point of the tapered undulator for both power enhancement and spectrum cleaning is the end of exponential gain region. When linearly tapering from the end of exponential gain region and with an appropriate tapered rate, the radiation spectrum will be distinctly improved and the radiation power will be greatly enhanced simultaneously. But the saturation length becomes longer.

The more detailed physics research is ongoing. And it is expected that a quantitative value of the best linear tapered rate will be given.

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