THE FIRST EXPERIMENTAL OBSERVATION OF FEL AMPLIFIER EFFICIENCY IMPROVEMENT USING ELECTRON BEAM ENERGY DETUNING AT THE NSLS SDL

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Abstract

The first experimental observation of efficiency enhancement using electron energy detuning in a single-pass laser seeded Free-Electron Laser (FEL) amplifier is reported. Our experiments show that it is possible to double the FEL efficiency by increasing the electron energy by +0.7 % relative to the resonance energy. The measurement of the laser seeded FEL spectra versus energy detuning shows that the peak wavelength of the FEL radiation is determined by the seed laser. The experimental results are discussed using FEL theory and a three-dimensional simulation code GENESIS1.3 [1].

INTRODUCTION

One of the advantages of the FEL is the ability to produce high power laser light without the conventional thermal issues associated with other laser systems [2]. In addition, the operating wavelength of the FEL can be adjusted according to the application. Because of the advantages, the FEL has been regarded as one of the promising approaches to generate Megawatt (MW) average power laser at 1 μm wavelength. Such an application is called directed energy application [3, 4].

In order for the FEL to realize the MW average power output, it is required to optimize the efficiency of the FEL process. Supposed that the interaction between the electron beam and the radiation is strong enough in the undulator, the radiation power grows exponentially as the electron beam goes through the undulator. According to the steady-state theory of a single-pass FEL, the radiation is saturated at ρP_e due to the deposition of the electron energy to the radiation. Here, ρ is the Pierce parameter and P_e is the input electron power. After the saturation, the electrons with lower energy no more resonate with the radiation as it does in the exponential gain regime. Instead, the mutual energy deposition between electrons and radiation is repeated.

To overcome the saturation, several schemes have been proposed and tested. One is to taper an undulator, in which the field strength of the undulator is gradually decreased after the saturation so that the electrons with lower energy can maintain the resonance with the radiation [5, 6]. Another is to detune the electron energy, in which the input electrons with slightly higher energy can resonate with the radiation longer than the normal (resonant) case [3]. The detuning effect had been theoretically and numerically studied [7, 8, 9, 10]. The study indicates that the growth rate is deteriorated by the detuning, while the saturation power can be enhanced by optimizing the detuning. It is an advantage of the detuning scheme that the scheme does not require any modification of the experimental setup; only the requirement is to change electron beam energy. As far as authors know, however, the detuning effect in a single-pass FEL had not been experimentally verified.

In a self-amplified spontaneous emission (SASE) FEL, in which no external seed laser is supplied, the radiation wavelength is shifted when the electron energy is changed. Thus, the wavelength of the output radiation is inevitably resonated with the incident electron energy and no enhancement of FEL efficiency due to the detuning should be expected. In a seeded FEL, where an external laser is injected and then amplified via interaction with electrons, the wavelength of the radiation may be affected by both electron energy and the seed laser. Eventually, it may enhance the efficiency of the amplification to detune electron energy in terms of the wavelength of the seed laser.

In the paper, the experimental demonstrations of efficiency enhancement by the electron energy detuning is reported. The experimental results are compared with the numerical simulation and interpreted by FEL theory.

DETUNING EXPERIMENT

The experiments were conducted at the Source Development Laboratory (SDL) of National Synchrotron Light Source (NSLS), Brookhaven National Laboratory (BNL). The picosecond (ps) electron pulse generated by a photoinjector is compressed to 1.5 ps by a chicane-type bunch compressor. The compressed e-beam passes through a 10 m long planar undulator, of which period is 3.89 cm and the undulator parameter is K=1.1. The seed laser generated by a Ti:Sapphire laser system is compressed to 6 ps, with the frequency chirp being slightly negative. Passing through a bandpass filter, the seed laser has the central wavelength of 795 nm and the bandwidth of 1.5 nm at Full Width at Half Maximum (FWHM). The major experimental parameter are summarized in Table. 1.

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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	98 - 102 MeV
Peak current	380 A
Electron bunch duration (FWHM)	1.5 ps
Energy spread (rms)	0.1 %
Normalized emittance	2-4 mm.mrad
Seed laser wavelength	795 nm
Seed laser bandwidth (FWHM)	1.5 nm
Seed laser pulse duration (FWHM)	6 ps
Seed laser energy	4 kW

Efficiency measurement

For a planar undulator, the wavelength of the FEL radiation, λ_r, is written as,

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

where λ_u is the undulator period and γ is the electron energy normalized with its rest mass. In general seeded FEL experiments, the electron energy is adjusted to satisfy Eq.(1) for a given wavelength. In what follows, such an energy is called the energy on resonance. In our experiment, the energy on resonance was determined by measuring SASE spectrum without the seed laser.

In Fig. 1, the energy gains in the undulator on resonance and with two detuning cases are plotted; one is 0.7 % higher (+0.7 % detuning) and another is 0.5 % lower (-0.5 % detuning) relative to the energy on resonance. All the three data are shown with root-mean-squared (rms) error bars, but at most of points, the error bars are overlapped with the dots. In -0.5 % detuning case, the seed laser energy is dominant until 7.8 m, because both transversely and longitudinally the seed laser size is larger than the electron beam. The simulation results on resonance and with detuning were also presented in Fig. 1. The gain curve on resonance is shown by the solid curve, and those with +0.5 and -0.5 % detuning are respectively shown by dotted and dashed curves.

It is obvious in both experiment and simulation that the gains with detuning are asymmetric between positive and negative detuning; the negative detuning degrades the gain by more than one order of magnitude, while the positive detuning enhances it by factor of two. To interpret it, we recall one-dimensional steady-state theory [7, 8, 9, 10]. First, at the early stage of amplification, small-signal gain theory indicates that the direction of energy deposition between electrons and radiation is opposite depending on the direction of detuning. In Fig. 1, the radiation energy with negative detuning is deposited to electrons once, while that with positive detuning immediately gains energy from electrons. On resonance, there is no energy deposition, which is also presented by the theory. Next, in a high gain regime, a cubic equation for time-dependent gain of FEL radiation in the form $exp(i\lambda\tau)$ is written as,

$$\lambda^3 - \delta\lambda + 1 = 0, \tag{2}$$

where λ is an eigenvalue, of which negative imaginary part gives the growth rate, and δ is the normalized energy detuning $\delta = (\gamma^2 - \gamma_R^2)/2\gamma_R^2\rho$. In Eq.(2), the efficiency parameter is assumed to be small, $\rho \sim 0$. The preferable instability exists only when the detuning is smaller than the threshold, i.e., $\delta < \delta_{th} \sim 1.89$, where two of the three eigenvalues in Eq.(2) have imaginary part. The maximum growth rate, $Im\lambda = \sqrt{3}/2$, occurs at no detuning, $\delta = 0$. It has also been shown with the aid of numerical simulation that as the electron energy goes higher, the saturation energy becomes higher until it reaches the threshold, $\delta \sim \delta_{th}$. Since the efficiency parameter ρ of the experiment is in the range of 0.003 through 0.004, the threshold corresponds to the electron energy detuning of +0.55 to +0.75 % (shown grey in Fig.1). One can see in Fig. 1 that both experiment and numerical simulation represent the characteristics predicted by the theory and numerical simulation; the positive detuning in the range of threshold enhances the output energy, whereas the same amount of detuning but in negative direction just degrades the gain due to the combination of energy deposition to the electrons in small-signal gain regime and degraded gain in high gain regime.

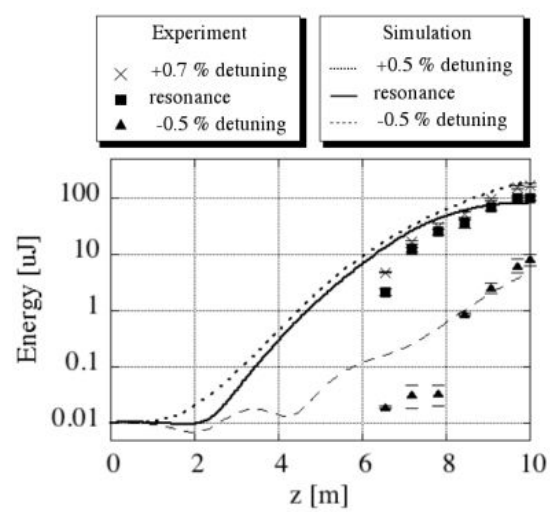

Figure 1: Gain curves on resonance and with detuning.

To see the detuning effect more clearly, the output energy of FEL radiation was plotted as a function of the electron energy in Fig. 2. The dots with peak-to-peak error bars are experimental data and the solid line is evaluated by the time-dependent simulation under the same condition as the experiment. The output radiation energies are normalized with those on resonance in both experiment and simulation results. The energy on resonance is 102 and 82 μJ respectively for the experimental and the numerical results. In

Fig. 2, the asymmetry between positive and negative detuning is again clearly observed. The negative detuning of 0.5 % deteriorates the FEL gain by one order of magnitude, while the positive detuning of 0.7 % enhances the gain by 70%. In addition, further detuning by a half percent in a positive direction, i.e., total detuning of +1.2 %, does no more enhance the gain, but suppresses it. It is because the detuning goes beyond the threshold δ_{th} (grey in Fig. 2). The experimental result agrees with the simulation result except for two things in detail; the enhancement of the energy in the experiment is lower than that of by simulation, and the amount of the detuning that gives the enhancement is +0.7 % in experiment and +0.5% in simulation. It is because there was an electron energy jitter in the experiment, so the energy enhancement at the detuning was smoothed out by taking the average. In fact, the maximum energy given at the +0.7 % detuning was 206 μJ, which is more than 2 times higher than the average energy on resonance.

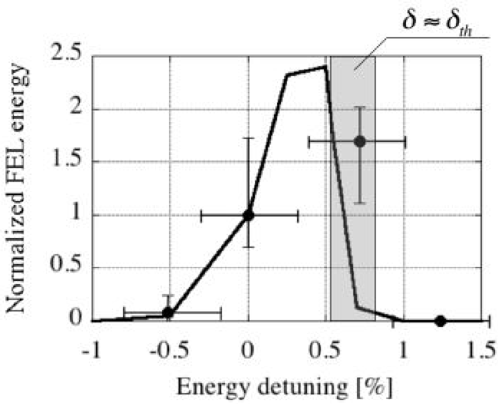

Figure 2: FEL output energy vs electron energy detuning. Solid line is simulation and dots are experimental result.

Spectral measurement

The spectra of the seeded FEL pulse were also measured. Figure 3 represents the example spectra of seeded FEL on resonance (solid line) and with the positive detuning at the threshold $\delta \sim \delta_{th}$ (dashed). The positive detuning in the experiment (Fig. 3 (a)) is +0.7 %, and that in the numerical simulation by GENESIS1.3 (Fig. 3 (b)) is +0.5 %.

It is both experimentally and numerically verified in Fig. 3 that the peak wavelength of output seeded FEL pulse is not notably shifted by detuning electron energy. In both cases, the difference of the peak wavelength between on resonance and with the positive detuning is much less than 1 nm. It follows that the seeded FEL spectrum with detuning is dominated by the seed laser, so the detuning scheme does not induce the undesirable frequency shift in the output pulse. Note that the detuning of +0.7 % in electron energy corresponds to the down-shift of SASE spectrum by as much as 11 nm.

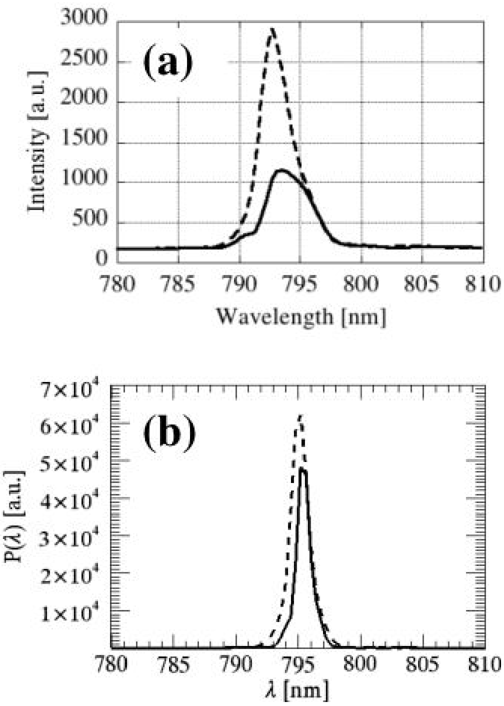

Figure 3: Spectra of laser seeded FEL on resonance (solid line) and with positive detuning at the threshold $\delta \sim \delta_{th}$ (dashed). (a) experiment and (b) GENESIS calculation.

CONCLUSION

We experimentally observed the efficiency enhancement by the electron energy detuning. By applying the energy detuning of +0.7 %, the efficiency was doubled. Both the further detuning and the opposite detuning significantly degrades the efficiency. The results were well consistent with one-dimensional steady-state theory as well as the three dimensional numerical simulation.

The spectra of seeded FEL pulses on resonance and with detuning were also measured. It was verified that the peak wavelength of seeded FEL with detuning was almost same as that on resonance both by the experimental result and the numerical simulation. It indicates that the detuning scheme works without modifying the seeded FEL spectrum substantially.

The study gives fundamental knowledge for implementing seeded FEL experiments as well as designing the high power FEL such as a directed energy application.

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