EXPERIMENTAL STUDY OF STORAGE RING FEL OUTPUT POWER SCALING WITH ELECTRON BEAM ENERGY SPREAD*

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Abstract

Accurate simultaneous measurements of storage ring free-electron laser (SRFEL) average power output and electron beam energy spread has been achieved at the Duke FEL Laboratory. It is well known that the SRFEL power is limited by the electron beam synchrotron radiation power and the induced energy spread of the electron beam. The two-wiggler spectrum of an optical klystron can be used to determine the energy spread of the electron beam. Measuring the interference pattern of the modulated spontaneous spectrum with the FEL turned on, we are able to study the FEL power output as a function of electron beam energy spread. As the energy spread increases, the modulation in the two-wiggler spectrum reduces, resulting in a smaller FEL gain. During this process, the operation of an optical klystron degrades back to that of a conventional FEL. This paper reports our recent experiment study of transition of the FEL operation from an optical klystron to a conventional FEL.

INTRODUCTION

An optical klystron (OK) is a free-electron laser (FEL) configuration which has been used to enhance the FEL gain. An optical klystron consists of two wigglers separated by a dispersive magnet, namely the buncher magnet. The first wiggler modulates the electron energy and the buncher provides micro-bunching of the electron beam. In the second wiggler, the partially bunched electron beam interacts with the light field, yielding an improved FEL gain. Conventionally, storage ring free-electron lasers (SRFELs) use the optical klystron configuration to reach a higher FEL gain. However, it is well known that the extracted SRFEL power is limited by the induced electron beam energy spread and synchrotron radiation power that emitted by the electron beam in the storage ring [1]. For this reason, the dependence of SRFEL power on the electron beam parameters, such as the beam current and the energy spread, is of particular interest to study.

The FEL power P_{FEL} of an optical klystron FEL can be expressed in terms of the laser-induced energy spread of the electron beam and the total synchrotron radiation power P_{SR} as [2] [3],

$$P_{FEL} = P_{SR} 8\pi^2 (N_w + N_d)(\sigma_\epsilon^2 - \sigma_0^2) f, \qquad (1)$$

$$P_{SR} = \frac{4\pi}{3} \frac{r_e m_e c^2 \gamma_0^4}{\rho_0} \frac{I}{e},$$
$$f = e^{-8\pi^2 (N_w + N_d)^2 \sigma_\epsilon^2},$$

where f is the modulation factor, $\sigma_\epsilon = \sigma_\gamma/\gamma_0$ is the relative rms energy spread due to FEL interaction, $\sigma_0 = \sigma_{\gamma_0}/\gamma_0$ is the relative rms energy spread with the FEL turned off, N_w is the number of wiggler periods for each wiggler, N_d is the dispersion parameter describing slippage numbers by which the FEL photon overruns the electron in the buncher magnet, r_e is the electron classical radius, m_e is the electron mass, e is the elementary electron charge, c is the speed of light, γ_0 is the normalized synchrotron electron energy, ρ_0 is the average radius of curvature of the storage ring bending magnets, and I is the beam current. From Eq. 1, P_{FEL} could be optimized as [4],

$$P_{FEL} = 2P_{SR} \frac{\sigma_\epsilon^2 - \sigma_0^2}{\sigma_\epsilon} e^{-1/2}, \qquad (2)$$

by setting the buncher magnetic field so that $N_d = 1/(4\pi\sigma_\epsilon) - N_w$ to maximize the FEL power. The corresponding energy spread for this optimization is $\sigma_\epsilon = 1/[4\pi(N_w + N_d)]$.

As the energy spread increases to a value significantly larger than $1/[4\pi(N_w + N_d)]$, the operation of an optical klystron FEL degrades back to that of a conventional FEL. The optimization in Eq. 2 fails and Eq. 1 is expected to become,

$$P_{FEL} \propto P_{SR} \frac{\sigma_\epsilon^2 - \sigma_0^2}{\sigma_\epsilon}. \qquad (3)$$

In this paper, we study the dependence of FEL power on the electron energy spread and beam current. We report the measurement results of the energy spread with the average out-coupled FEL power. The operation mode transition from an optical klystron FEL to a conventional FEL is also shown in the data. The energy spread is measured using the spontaneous radiation spectrum of two wigglers.

ENERGY SPREAD MEASUREMENT

Review of Traditional Methods

Accurate non-invasive measurements of the electron energy spread is critical for beam dynamics study of the storage ring FEL . The traditional method measures the energy spread by measuring the transverse beam size at large dispersive locations of the storage ring. The beam size is given by,

$$\sigma_x = \sqrt{\beta_x \epsilon_x + (\eta_x \sigma_\epsilon)^2}, \qquad (4)$$

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where β_x is the beta function, ϵ_x is the horizontal emittance, η_x is the eta function at the source point. Many storage ring based light source facilities such as APS implemented this method for electron beam energy spread measurement. This type of measurement is indirect and the accuracy is limited by the knowledge of lattice parameters β_x and η_x. Furthermore, on the Duke storage ring, a small dispersion at the bending magnet source point made it difficult to resolve the energy spread. Undulator radiation spectrum at high harmonics was also used to determine the energy spread of the electron beam [5]. Although the dispersion function at the source was not required in this type of measurement, the emittance effect has to be considered. Both of the above methods are indirect. A well-known, more direct method of measuring the beam energy spread is to use the two-wiggler spontaneous radiation spectrum of the electron beam. This method is described in the following section.

Direct Method Using OK Spectrum

With an optical klystron, the more direct measurement of the electron beam energy spread is readily available. The spontaneous radiation spectrum of a single electron going through the optical klystron is the interference pattern of two optical wave-packets emitted by the same electron passing through two wigglers in sequence. The optical phase difference of the two wave-packets is controllable using the buncher magnet. The buncher can be set to optimize the spectrum modulation to facilitate spectrum fitting in determining the electron beam energy spread.

The intensity of this interference pattern of one electron emission is given by [6],

$$I(\lambda) = I_0 \left[\frac{\sin(\pi N_w \frac{\lambda-\lambda_r}{\lambda_r})}{\pi N_w \frac{\lambda-\lambda_r}{\lambda_r}} \right]^2 \times \left\{ 1 + \cos\left[2\pi (N_w + N_d) \frac{\lambda_r}{\lambda} \right] \right\}, \quad (5)$$

where λ is the radiation wavelength and I_0 is a normalization factor. The resonance wavelength λ_r is given by:

$$\lambda_r = \frac{\lambda_w}{2\gamma_r^2}(1 + \frac{K_w^2}{2}), \quad (6)$$

where λ_w is the wiggler period, γ_r is the dimensionless electron energy at resonance, K_w is the dimensionless wiggler parameter. For an electron beam, the inhomogeneous effects depends on the electron energy should be taken into account. The resulting spectrum of a collection of individual electrons with various energies is broader than that of a single electron. Considering this broadening effect, the spectrum of an electron beam is the integration of Eq. 5 with respect to all possible electron energies as given by,

$$I(\lambda) = I_0 \int_{\infty}^{\infty} \left[\frac{\sin(\pi N_w \frac{\lambda-\lambda_r}{\lambda_r})}{\pi N_w \frac{\lambda-\lambda_r}{\lambda_r}} \right]^2 \times \left\{ 1 + \cos\left[2\pi (N_w + N_d) \frac{\lambda_r}{\lambda} \right] \right\} N(\gamma; \gamma_0, \sigma_\gamma^2) d\gamma, \quad (7)$$

where $N(\gamma; \gamma_0, \sigma_\gamma^2)$ is the distribution function of the electron energy γ. To facilitate the data analysis, this distribution is typically assumed to be a Gaussian distribution where γ_0 is the mean and σ_γ is the standard deviation.

In the situation of a small energy spread, in which the broadening of one-wiggler spectrum is negligible, Eq. 7 could be approximated and rewritten as [6],

$$I(\lambda) = I_0 \left[\frac{\sin(\pi N_w \frac{\lambda-\lambda_r}{\lambda_r})}{\pi N_w \frac{\lambda-\lambda_r}{\lambda_r}} \right]^2 \times \left\{ 1 + f \cdot \cos\left[2\pi (N_w + N_d) \frac{\lambda_r}{\lambda} \right] \right\}, \quad (8)$$

where f is the modulation factor. The measurement of this modulated spontaneous spectrum could be used to determine the electron beam energy spread by fitting Eq. 7 or Eq. 8. For accurate determination of the energy spread, we choose $N_d \geq N_w$ to enhance spectrum modulation.

In our study, the broadening of the two-wiggler spectrum due to the electron beam emittance is small compared to that caused by the electron beam energy spread. Therefore, the emittance effect on the two-wiggler spectrum can be neglected.

EXPERIMENTAL RESULTS

At the Duke FEL Laboratory (DFELL), we operate two SRFELs [7]. One is the OK-4 FEL with two planar wigglers, the other is the OK-5 FEL with two helical wigglers. The electron beam spontaneous spectrum from any one of the two-wiggler systems can be used to measure the electron beam energy spread. The spontaneous radiation spectra are measured using a miniature high-resolution fiber optic spectrometer HR4000 which provides an FWHM optical resolution of 0.025 nm in the spectral range of 200 to 1100 nm. To produce reliable spectra, the electron radiation is directly injected into the spectrometer without using the optical fiber. Fig. 1 and Fig. 2 show the measured spectra for different currents. The circles are the measured spectra, solid curves are the fitting results of Eq. 7 and dashed curves are the fitting results of Eq. 8. As can be seen, solid curves are better fits compared to the dashed curves as the energy spread becomes higher. This effect suggests that the inhomogeneous broadening of one-wiggler spectrum is not negligible as the energy spread increases, and consequently the two-wiggler FEL operation transits from an optical klystron FEL to a conventional FEL.

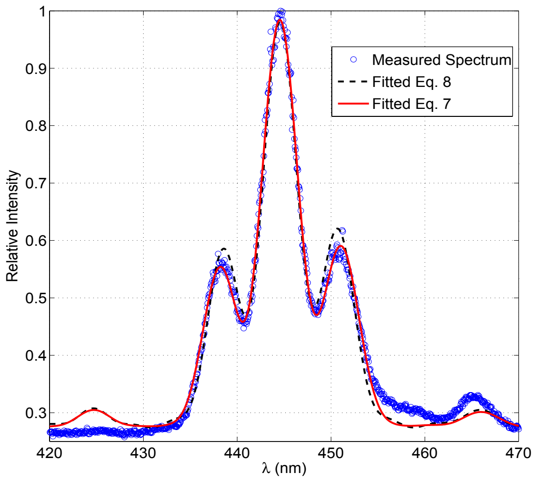

Figure 1: OK-4 spectrum with a single-bunch electron beam. Beam current is 5.87 mA, beam energy is 425 MeV, $N_d = 31$, and $N_w = 33$. The fit energy spread is $\sigma_\epsilon = 1.55 \times 10^{-3}$ by the solid curve.

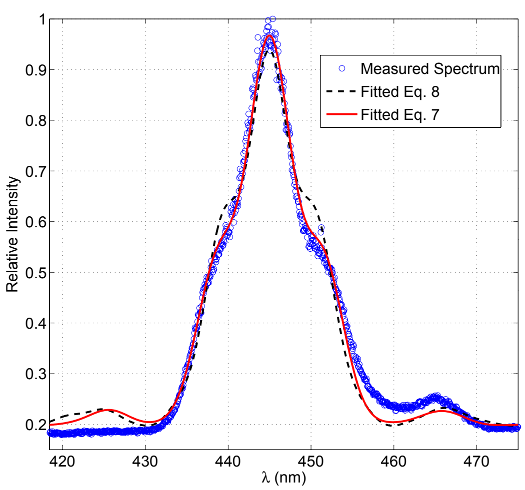

Figure 2: OK-4 spectrum with a single-bunch electron beam. Beam current is 10.61 mA, beam energy is 425 MeV, $N_d = 31$, and $N_w = 33$. The fit energy spread is $\sigma_\epsilon = 2.57 \times 10^{-3}$ by the solid curve.

PRELIMINARY RESULTS OF FEL OUTPUT POWER EVOLUTION

The output power is measured by a broadband power meter. The average FEL output power is plotted as a function of fit energy spread as shown in Fig. 3. The crosses with error bars are the measured output power, the dashed curve is the fitting result of Eq. 1 and the solid curve is the fitting result of Eq. 3. As can be seen, Eq. 1 is closer to the data when the energy spread is small and it dramatically deviates from the data when the energy spread increases. On the other hand, Eq. 3 seems to be an adequate model for a wide range of the energy spread as measured in this experiment. This indicates that the FEL transition from an optical klystron to a conventional FEL starts as the relative energy spread increases to a value larger than 1.9×10^{-3}.

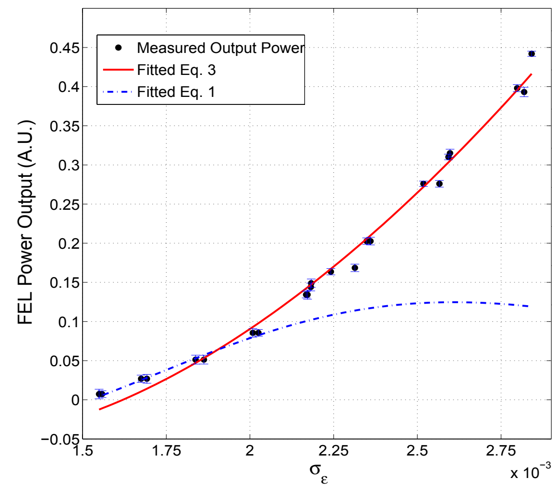

Figure 3: Measured FEL output power as a function of the energy spread of the electron beam. Beam energy is 425 MeV, $N_d = 31$ and $N_w = 33$.

SUMMARY

We take advantage of the unique FEL wiggler configuration at the DFELL to measure the energy spread and FEL output power simultaneously. The FEL power and energy spread relationship is studied and the transition from optical klystron FEL operation to conventional FEL operation is observed. The measurement shows that the spectrometer had non-uniform frequency response as seen in the shoulders of the wiggler spectra which were consistently asymmetric with a higher intensity at the long wavelength side. The spectrometer will be calibrated in the future so that the systematic errors can be reduced significantly. With improved diagnostics, we will continue to study the two-wiggler FEL operation with different lasing wavelengths and electron beam energy and current.

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