A DIRECT ELECTRON BEAM ENERGY SPREAD MEASUREMENT SYSTEM FOR BEAM INSTABILITY AND FEL RESEARCH*

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Abstract

One of critical beam parameters for the storage ring based light sources is the energy spread of the electron beam. An accurate measurement of the energy spread remains a challenge. It is well known that the energy spread of the electron beam can degrade the spontaneous radiation spectrum of an Optical-Klystron (OK) which consists of two wigglers separated by a buncher magnet. The reduced modulation in the spectrum can be used to determine the energy spread of the beam. This paper describes our newly developed energy spread measurement system employing a compact and versatile spectrometer. This system is used in the beam instability research and Free-Electron Laser (FEL) research. In particular, by measuring the increase of electron beam energy spread we have studied the onset of microwave instability.

INTRODUCTION

The energy spread of the electron beam in the storage ring is a very important beam parameter which can impact the performance of a variety of storage ring based light sources. In particular, it is critical for the operation of the optical-klystron (OK) FEL in which the FEL gain enhancement mechanism depends on a small enough energy spread of the beam. However an accurate measurement of the relative energy spread at the 10^{-4} level remains a challenge. The traditional techniques only provide indirect measurements of the energy spread using one of the following methods: (1) measuring the optical beam size at the location of a large eta-function and then separate the contribution by the energy spread from that by the transverse emittance; (2) by measuring the bunch length (e.g. using a streak camera) and then project the energy spread by rotating an assumed longitudinal beam distribution in the phase space. The direct measurement of the energy spread using the interference of the optical-klystron radiation spectrum is a well-known technique [1] for more than two decades. However, this technique has not been used to study the onset of the microwave instability for which a small beam current is required and the relative energy spread is small at the 10^{-4} level. At Duke University, we have recently developed an energy spread measurement system which employs a compact and versatile spectrometer. By measuring the increase of electron beam energy spread, we have studied the onset of microwave instability. In addition to the beam instability research, this system is also being used for FEL research.

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OPTICAL KLYSTRON SPECTRUM

The Optical Klystron [2] is a magnetic device consisting of two wigglers separated by a dispersive section (a buncher magnet) in which the path length of electron orbit changes depending on the energy of the electron. The optical klystron configuration is commonly used for storage ring based FELs to enhance the gain, for example, both Duke FEL and ELETTRA FEL used the optical klystron to achieve lasing in the VUV region [3, 4].

The spectrum of the spontaneous radiation emitted by an optical klystron results from the interface pattern of two light pulses emitted by two wigglers which is separated in time due to the dispersion section. This is the same principle of a conventional interferometry. Instead of measuring the interference in space in a conventional interferometry, we measure the interference in the frequency domain, i.e. measuring interference spectrum. The OK spectrum is modified for the electron beam with a finite energy spread, resulting in reduction of the intensity modulation of the interference pattern. The intensity distribution of an OK spectrum can be expressed as [2]:

$$I(\lambda) = I_0\left(Sin\,(\pi N_W\,\frac{\lambda-\lambda_r}{\lambda_r})\,/(\pi N_W\,\frac{\lambda-\lambda_r}{\lambda_r})\right)^2 \times[1+M\cdot Cos\,(2\pi(N_W+N_d)\frac{\lambda_r}{\lambda}] \quad (1)$$

with the modulation amplitude of the OK radiation

$$M = \exp\left(-\frac{1}{2}\left(4\pi(N_W+N_d)\frac{\sigma_E}{E_0}\right)^2\right) \quad (2)$$

where N_d is the dispersion parameter (slippage between the electron beam and optical beam), N_W is the number of wiggler periods for each wiggler, λ is the OK radiation wavelength, λ_r is the center wavelength of wiggler spectra, and σ_E/E_0 is the electron beam energy spread. It is clear that the measurement of the OK spectrum is a way to measure the energy spread directly.

ENERGY SPREAD MEASUREMENTS

Duke Free-Electron Laser Laboratory (DFELL) operates several storage ring based FEL light sources, including the OK-4 FEL consisting of two planar OK-4 wigglers, the OK-5 FEL consisting of two helical OK-5

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wigglers, and the DOK-1 FEL, a distributed optical klystron FEL which operate all four wigglers together [5]. The two OK-4 wigglers are hosted in the middle of the 34 meter long south straight section with a buncher magnet sandwiched between the two wigglers.

To measure the energy spread, we used the OK-4 FEL. The electron beam energy in the storage ring was 280 MeV. The spontaneous radiation was extracted from a mirror located downstream from wigglers.

For spectrum measurement, a compact and versatile spectrometer was used with a resolution of about 0.5 nm (Ocean Optics USB4000 Miniature Fiber Optic Spectrometer with Grating #5 whose groove density is 1200 g/mm [6]). The initial stored beam current was around 2 mA in the single-bunch mode. We took spectra for the beam current from 2 mA to about 30 μA. With matlab fitting (Equation 1), we obtained N_W, N_d, M and λ_r. From these fitted parameters, we calculated the energy spread using Equation (2).

Fig. 1-4 show the measured spectra for different currents and voltages of the radio-frequency (RF) cavity. Blue solid curves are fitting results and blue dash curve are the calculated radiation spectra for a single wiggler with monochromatic electron beam.

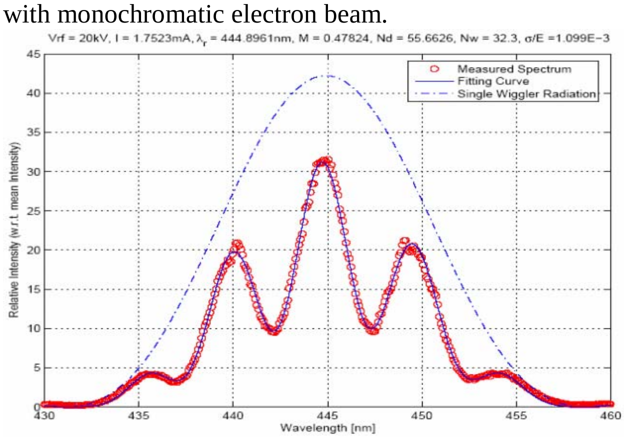

Figure 1: OK-4 spectrum with RF voltage of 20 kV, electron beam current of 1.75 mA, and the fitted energy spread is 1.1×10^{-3}.

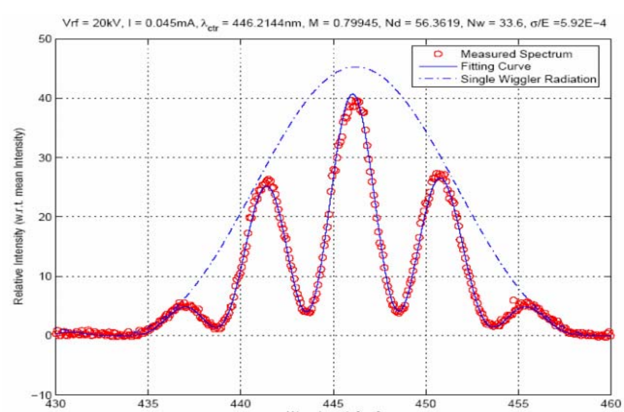

Figure 2: OK-4 spectrum with RF voltage of 20 kV, electron beam current of 0.045 mA, and the fitted energy spread is 5.9×10^{-4}.

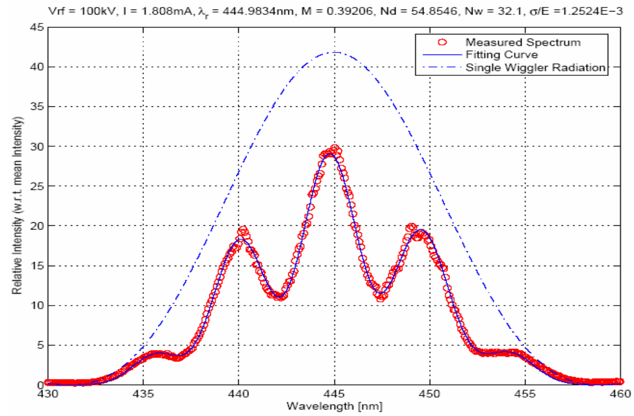

Figure 3: OK-4 spectrum with RF voltage of 100 kV, electron beam current of 1.81 mA, and the fitted energy spread is 1.3×10^{-3}.

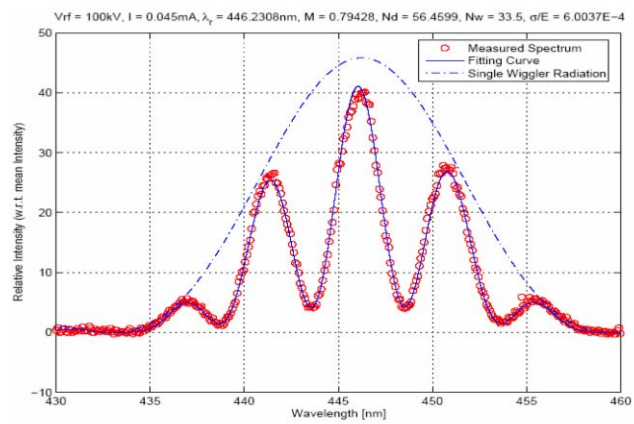

Figure 4: OK-4 spectrum with RF voltage of 100 kV, electron beam current of 0.045 mA, and the fitted energy spread is 6.0×10^{-4}.

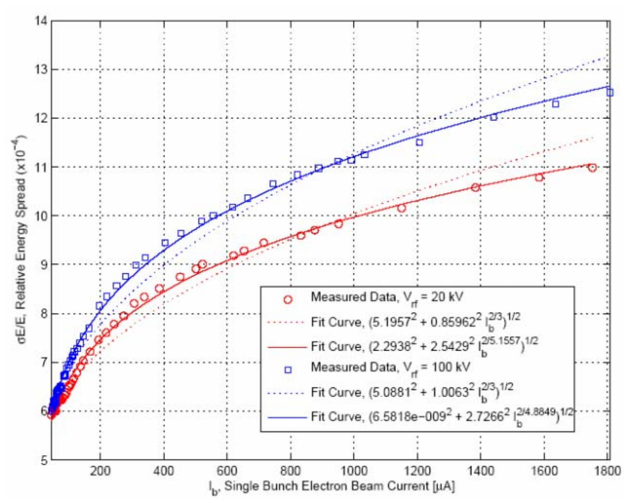

Figure 5: Energy spread vs. single bunch electron beam current for Vrf = 20 kV (red) and Vrf = 100 kV (blue). Solid curves are fitted with $\sqrt{\sigma^2 + A^2 I_b^{2/3}}$, while dash curves are fitted with $\sqrt{\sigma^2 + A^2 I_b^{2/\alpha}}$.

With the fitting results, we plot the curve of energy spread vs. electron beam current. According to a simple impedance model, the dependency of the energy spread on current should follow the 1/3rd-power-rule; however the experiment results do not follow this prediction (Fig. 5). Instead a 1/5th-power dependency is observed (Fig. 5 and Fig. 6). It is also worth pointing out that the measured energy spread of the electron beam at low current remains a few times the theoretical value at zero current. We are investigating a number of factors which contributed to inhomogeneous broadening of measured spectra.

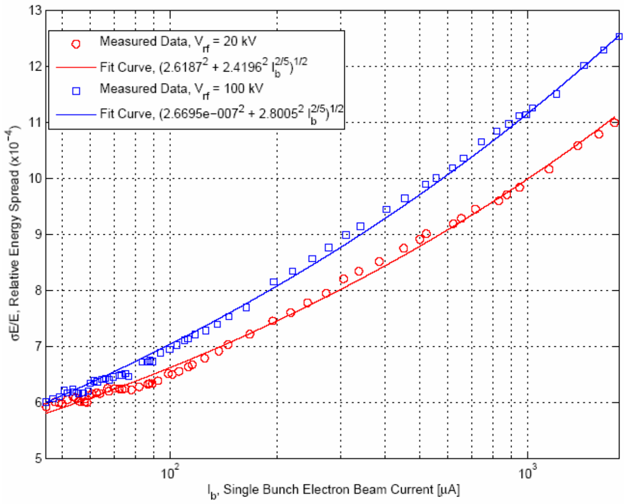

Figure 6: Energy spread vs. single bunch electron beam current for Vrf = 20 kV (red) and Vrf = 100 kV (blue). Dash curves are fitted with $\sqrt{\sigma^2 + A^2 I_b^{2/5}}$.

While the energy spread measurement using OK spectra is known for more than two decade, this work has used it for the study of the onset of the microwave instability for the first time. The new findings in our study demonstrate that in despite of the uncertainty in determining the absolute energy spread of the electron beam, this technique is extremely sensitive to the change of the energy spread. This is demonstrated by comparing two measured spectra with an identical magnetic lattice, but with a change of the RF voltage from 20 kV to 100 kV. By compressing the electron beam to increase the peak current, the energy spread of the electron beam will increase if it is above the microwave instability threshold. By measuring the change of the energy spread as a function of the beam current, we have determined that the microwave instability threshold for the Duke storage ring to be about 40 µA at 280 MeV. This number is lower than the number from the bunch length measurements which were much less reliable at low beam current.

SUMMARY

The electron beam energy spread in the Duke storage ring has been measured using a newly developed spectrometer system with a two-wiggler optical klystron. Using this system, we have successfully studied the onset of microwave instability by measuring the increase of energy spread as a function of the single bunch current. We find that the dependency of the energy spread on current does not follow the simple scaling law predicted by a simple impedance model.

The measured energy spread of the electron beam at low current remains a few times the theoretical value at zero current. Further investigations are needed to understand the impact of inhomogeneous broadening of the spectra due to beam emittance and the wiggler field errors and orbit errors.

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