The 6th Symp. on Accelerator Science and Technology, 1987, Tokyo, Japan (© Ionics, Tokyo, 1987)

MEASUREMENT OF BEAM ENERGY SPREAD WITH AN OPTICAL KLYSTRON AT TERAS

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ABSTRACT

Energy spread of the ETL electron storage ring TERAS has been measured by the use of an optical klystron. The principle of the method and the results of the measurement are described. The method is shown to be quite convenient and efficient though some refinement is necessary.

INTRODUCTION

Reducing the energy spread of electron beam is one of the most critical factors for obtaining a high gain of free electron laser (FEL) by the use of an optical klystron (OK).1 Conversely, the energy spread can easily be known by measuring the spontaneous-emission spectrum from the OK.[2,3] The optical klystron (or transverse optical klystron (TOK)) is an insertion device composed of two usual undulators separated by an energy dispersive section with stronger magnetic field. The structure, vertical magnetic field, and the horizontal electron trajectory in the case of ETL-TOK, as an example, are shown in Figs.1 and 2. The principle of the energy spread-measurement with OK is described in the next section, and then, experimental results, and discussion follows.

SPONTANEOUS-EMISSION SPECTRUM OF OK AND ITS INHOMOGENEOUS BROADENING

A Madey's theorem describes that the small-signal gain of an FEL device is proportional to the slope of the spectrum of spontaneous-emission from the device.[4] The spectrum of the emission from an electron with arbitrary motion observed at a point far from the electron is written as eq.(1), and for the case of an OK, it is rewritten as eqs.(2)-(5).

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2\omega^2}{4\pi^2 c^3} \left| \int_{-\infty}^{\infty} \vec{n}\times(\vec{n}\times\vec{\beta})\exp(i\omega(t-\vec{n}\cdot\vec{r}/c))dt \right|^2 \quad (1)$$

$$= \frac{e^2\omega^2}{4\pi^2 c^3} \left| \int_{0}^{L_{optical\ klystron}} \beta_x \exp(i\omega(t-z/c))\, dz/c \right|^2 \quad (2)$$

$$= \frac{e^2\omega^2}{4\pi^2 c^3} \left| \int_{0}^{L_u} \beta_x \exp(i\omega(t-z/c))\, dz/c + \int_{L_u+L_d}^{2L_u+L_d} \beta_x \exp(i\omega(t-z/c))\, dz/c \right|^2$$

$$= \frac{e^2\omega^2}{4\pi^2 c^3} \left| \int_{0}^{L_u} \beta_x \exp(i\omega(t-z/c))\, dz/c + \exp(i\alpha)\int_{0}^{L_u} \beta_x \exp(i\omega(t-z/c))\, dz/c \right|^2$$

(∵ $\beta_x(z + (L_u+L_d)) = \beta_x(z)$ ($z < L_d$) as seen in Figs.1and 2)

$$= \frac{e^2\omega^2}{4\pi^2 c^3} \left| (1+\exp(i\alpha))\int_{0}^{L_u} \beta_x \exp(i\omega(t-z/c))dz/c \right|^2$$

$$= 2\, \frac{d^2 I}{d\omega\, d\Omega}(\text{undulator})\ (1 + \cos(\alpha)) \quad (3)$$

$$\left.\frac{d^2 I}{d\omega\, d\Omega}\right|_{total} = 2\sum_i \frac{d^2 I_i}{d\omega\, d\Omega}(\text{undulator})\ (1 + \cos(\alpha_i)) \quad (4)$$

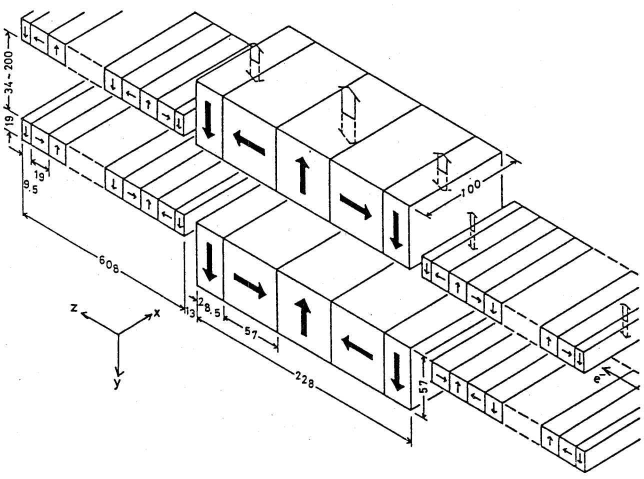

Fig.1 Structure of ETL-TOK.

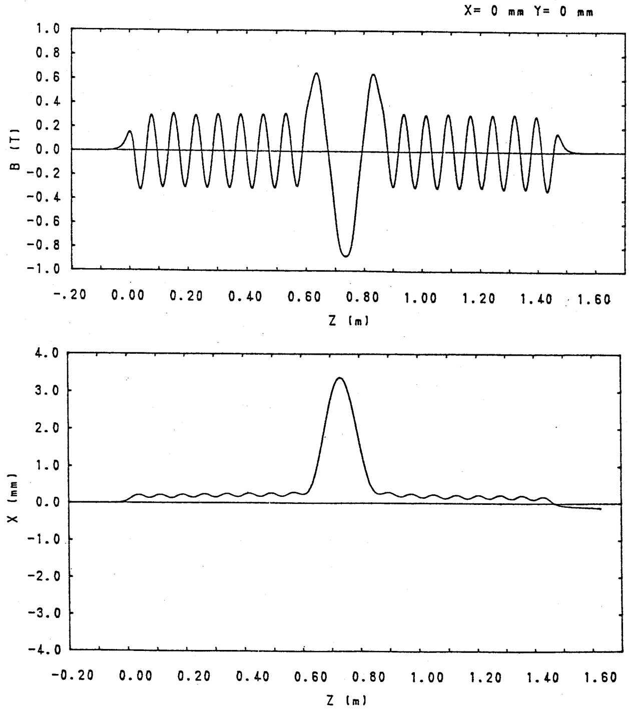

Fig.2 Magnetic field (above, gap=40mm) and elctron trajectory (below, for 240MeV) in ETL-TOK.

$$\left.\frac{d^2 I}{d\omega\, d\Omega}\right|_{total} = 2n\, \frac{d^2 I_i}{d\omega\, d\Omega}(\text{undulator})\ (1 + f\cdot\cos(\alpha)) \quad (5)$$

(n : total number of the electrons)

$\alpha = T_u+T_d - (L_u+L_d)/c = (N + N_d)\gamma_r^2\lambda_r/\lambda\gamma^2$.
α is the phase difference between the light field and the electron caused by the delay of the electron from the laser radiation in passing the first undulator and the dispersive section. T_u and T_d are the transit time in one undulator and the dispersive section, respectively. L_u, L_d, and $L_{optical\ klystron}$ are the length of one undulator, dispersive section, and the OK, respectively, and γ_r is the relativistic factor at the resonance energy. λ is the wavelength of the

laser radiation and λ_r the wavelength where the N_d is defined (the peak of the spectrum is used in our measurement). The relationship between λ_r, γ_r is expressed as

$$\lambda_r = \lambda_w/\gamma_r^2 (1 + K^2/2),$$

where λ_w is the period of the undulators. f is a modulation degradation factor described later. **n** is the unit vector in which direction the spectrum is calculated, **r** the electron position, β the electron velocity in units of light speed c, and e is the electron charge.

$$N_d = \frac{L_d}{2\lambda_r \gamma_r^2} \left(1 + \frac{e^2}{L_d m^2 c^2} \int_0^{L_d} \left[\int_0^u B(z)\, dz \right]^2 du \right) ,$$

where $2\pi N$ and $2\pi N_d$ are the phase that the laser radiation passes over the electron with the resonance energy in one undulator and the dispersive section, respectively. Here, B(z) is the magnetic field in the dispersive section, and m is the electron mass.

The integral which appears in Eqs.(1)-(3), expressing the interaction of the transverse electron motion and the radiation electric field, is composed of the contribution from the two identical undulators with period N, and there is a phase difference between them created in the dispersive section, which is a measure of bunching enhancement. The phase difference causes the interference between the light from these two undulators and manifests the fast modulation in the spectrum of spontaneous emission as in Eq.(4).

The spontaneous emission of an electron beam is the sum of that of individual electrons, and the differences in the characteristics between electrons such as the energy, the magnetic field which the electron feels, cause the the broadening of the spontaneous emission spectrum. For example, the energy spread of the electron beam causes the difference in delay time in the dispersive section and its spread causes the spread in the phase α , which causes the shift of the positions of the peaks and valleys of the spectrum and finally the degradation of the modulation of the summed spectrum of these electrons. The effects are called the inhomogeneous broadening. The resultant factor of degradation of modulation f(<1) is factorized as $f=f_E \times f_r$, where f_E is due to the energy spread and f_r , which is usually very small is due to the other residual effects. f_E for the gaussian energy spread with σ_E is written

$$f_E = \exp(-8\pi^2 (N + N_d)^2 (\sigma_E/E)^2) \qquad (6)$$

The effects which cause the broadening occurs mainly in the dispersive section. The effects in the undulators only cause the broadening of the undulator spectrum which is the envelope of the modulation, but the effects in the dispersive section degradate the modulation. The main effects in the dispersive section are the intrinsic energy spread of the electron. beam and the non-uniformity of the magnetic field coupled with the finite emittance of the beam.

EXPERIMENT

The spectra of the spontaneous emission from our OK (ETL-TOK) installed in ETL-TERAS electron storage ring were measured at 217MeV, with which our FEL experiment is intended at visible wavelength, after the ramp-down of the energy from the injection energy 320MeV. The structure of the ETL-TOK has been reported precisely in ref.5.

The experimental arrangement is shown in Fig.3. The spontaneous-emission light from the OK is reflected by a spherical concave mirror with f=2000mm. The spontaneous emission with angle θ with respect to the OK axis is focused and made a ring of radius f $\times \theta$ at the focusing length, and a rainbow-like ring pattern is observed there. A pin-hole was placed on the center of this rainbow ring to extract the spontaneous-emission light just on the axis of the OK. The selected light is focused on an entrance slit of a monochromator with resolution 0.3nm, and detected by a photomultiplier(PM) with a pre-amplifier. The signal of the PM is lead to a lock-in amplifier driven by a light chopper placed after the pin-hole. The output of the lock-in amplifier is digitized by an ADC board installed in a personal computer. The scanning of the wave length of the monochromator was controlled by the same personal computer synchronized with the AD conversion.

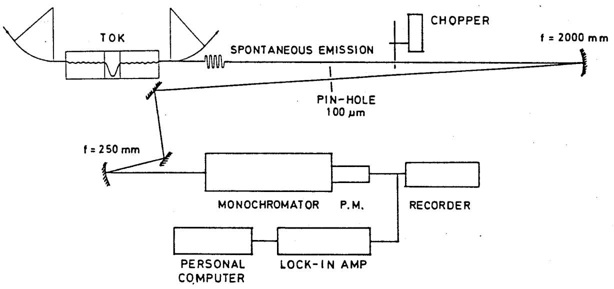

Fig.3 Experimental arrangement for measurement of spontaneous-emission spectrum.

The measurement of the spontaneous-emission spectra was, at first, made with the N_d=130. The thickness of the permanent magnet (NEOMAX-35 manufactured by Sumitomo Special Metal Co.) which composed the three pole wiggler of the dispersive section was 57mm as shown in Fig.1. However, the anomalous energy spread was too serious with the condition. Recently, the thickness of the magnet in the dispersive section was altered to be 38mm. With this configuration, the influence of the energy spread was greatly moderated at the expense of the N_d value (N_d=75), and the measurement of the energy spread with the higher stored current was made possible as will be described later.

RESULTS

An example of the spontaneous-emission spectra is shown in Fig.4. It was obtained when the stored current was as low as 0.28 mA, with the 57-mm thickness of the magnet in the dispersive section. The modulation effect characteristic of the OK is clearly seen. Fig.5 shows the spectrum with the beam current 16 mA and with the same OK as in Fig.4. The modulation is drastically worse than that in Fig.4 due to the increase in energy spread with beam current.

An example of the spectra after the N_d has been reduced to 75 is shown in Fig.6. Though the beam current was as high as 21 mA, the modulation is much better than in Fig.5.

The energy spread was calculated from the measured spontaneous-emission spectra using eq.(6) with the assumption that all the broadening was only due to the energy spread. Fig.7 shows the resultant energy spread as a function of stored current. At more than 5mA, it has the same dependence as the bunch length in shown in Fig.8, as has been described in a previous report,[6] and is proportional to (stored current)$^{1/3}$. Below a few mA, some amount of deviation to larger value than this dependence is seen. This might be because of the existence of other residual effects which cause the degradation of modulation. The alignment of the electron beam with the OK axis was not checked strictly in our experiment, but it is probably important because the steering of the beam have sometimes improved the modulation.

CONCLUSION

The energy-spread measurement of the stored beam in TERAS, which is usually fairly difficult, has been made directly and easily by the use of an optical klystron. The present result is consistent with the bunch-length measurement made earlier. The precision

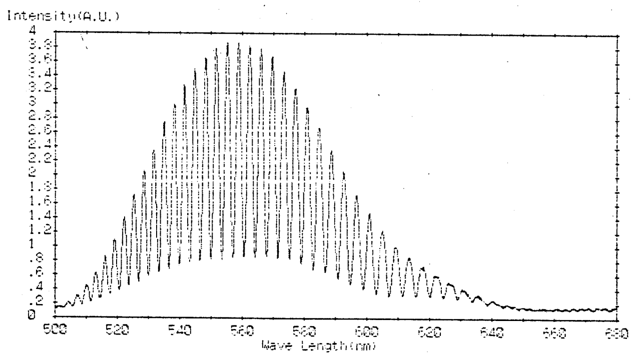

Fig.4 Spontaneous-emission spectrum, with 217MeV, 0.28mA, and N_d=130.

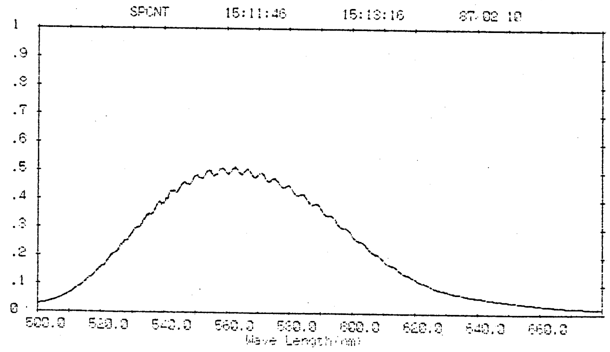

Fig.5 Spontaneous-emission spectrum, with 217MeV, 16mA, and N_d=130.

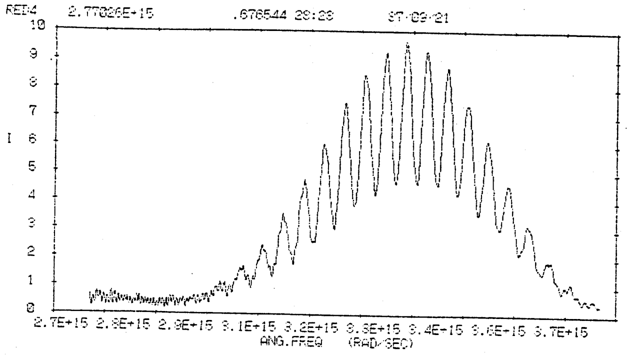

Fig.6 Spontaneous-emission spectrum, with 217MeV, 21mA, and N_d=75.

in the alignment of the axis of the OK and the electron beam is important to reduce the other effects and probably a good alignment will lead to the small broadening by other effects and precision of energy-spread measurement.

The measured energy spread is much greater than the natural energy spread of TERAS calculated with MAGIC which is a few 10^{-4}. One of the origins of this anomalous energy spread is the coupled bunch instability induced by the RF cavity because a large sidebands exist in the frequency spectrum of the SR light. The three-bunch operation mode, which is the smallest number of bunches for our FEL oscillation, is intended in order to reduce the coupled bunch instability, whose strength is proportional to the total stored current, and to obtain higher current per bunch. It will also help reducing the energy spread.

REFERENCES

1) P.Elleaume, Theory of Optical Klystrons, Nucl. Instrum and Methods, A250, 220 (1986).
2) D.A.G.Deacon et al., Optical Klystron Experiment for the ACO Storage Ring Free Electron Laser, Appl. Phys., B34, 207 (1984).

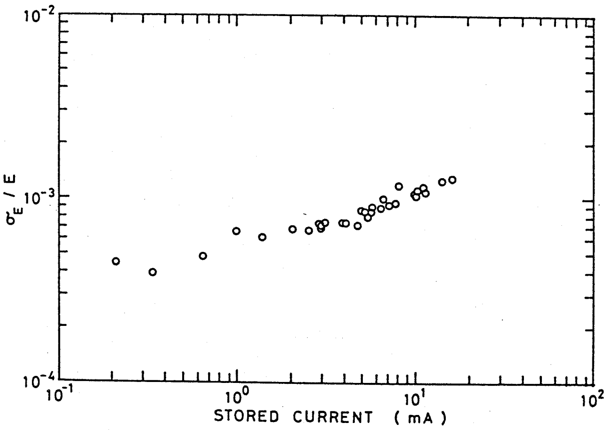

Fig.7 Normalized energy spread vs. stored current for N_d=130.

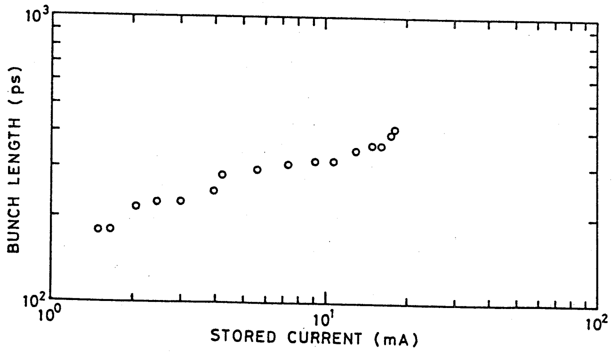

Fig.8 Measured bunch length vs. stored current.

3) J.M.Ortega et al.,Energy Spread Measurements on the ACO Storage Ring, Nucl.Instrum and Methods, A273, 254(1985).
4) J.M.J.Madey, Relationship between Mean radiated energy, Mean Squared Radiated Energy and spontaneous Power Spectrum in a Power Series Expansion of the Equation of Motion in a Free Electron Laser, Nuovo Cim. 50, 64 (1979).
5) T.Yamazaki et al., ETL-TOK for ETL-SRFEL, TELL-TERAS Activity Report 1980-1986, Linac and Storage Ring Facilities, Electrotechnical Laboratory, P.72, March 1987.
6) T.Nakamura et al., The Spontaneous Emission spectrum of TOK, TELL-TERAS Activity Report 1980-1986, Linac and Storage Ring Facilities, Electrotechnical Laboratory, p72, March 1987.