

MEASURED PERFORMANCE OF THE FREE ELECTRON LASERS AND ELECTRON BEAM IN THE COMPACT STORAGE RING NIJI-IV

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Abstract

The temporal performance of the free electron lasers and the electron-beam qualities have been measured with the compact storage ring NIJI-IV at the electron-beam energy of 310 MeV. It was found that the pulse width and spectral width kept decreasing after the peak of the FEL macropulse intensity. It was confirmed that the bunch length and the energy spread increased due to the FEL oscillations. The ratio of the FEL gain to the cavity loss estimated from the beam qualities on and off FEL oscillations was almost in accord with the ratio evaluated directly with the measured data of the FEL gain and the cavity loss.

INTRODUCTION

A study of broad-band free electron lasers (FELs) has been developed with the compact storage ring NIJI-IV at the AIST. Although the circumference of the NIJI-IV is 29.6 m, it has two 7.25 m straight sections. A 6.3 m optical klystron ETLOK-II has been installed in one of the straight sections, and a 14.8 m optical cavity has been set on the extended part of this long straight section. The FEL oscillations have been achieved with the ETLOK-II at a wavelength region between 211 and 595 nm [1]. At present, we are aiming at the FEL oscillations in the VUV region. Moreover, a new optical klystron ETLOK-III for infrared FELs will be installed at the other straight section. FEL oscillations will be realized with using the higher harmonics from the ETLOK-III in a wavelength region between 1 and 12 μ m [2].

In order to advance the enhancement of the FEL wavelength region, we have renewed old vacuum chambers to low-impedance ones in the NIJI-IV. Because it was confirmed that the microwave instability was suppressed below the beam current of 15 mA, the longitudinal broad-band impedance became below 2 Ω [3]. The peak electron density in an electron bunch was expected to become 1.4 times or more before the improvement.

It is necessary for the enhancement of the FEL wavelength region to estimate the FEL gain accurately. Then, we checked the evaluation of the FEL gain based on the one-dimension theory of the storage ring FEL by investigating the NIJI-IV electron beam qualities before the improvement of the vacuum chambers [4]. The increase of the beam sizes was measured on the FEL

oscillations, and the enhancement of the energy spread due to the FEL oscillations was estimated from the increase of the beam sizes. The increase of the bunch length due to the bunch heating was also measured with a dual streak camera. In this article, we report the measured performance of the FEL and the electron beam qualities on and off the FEL oscillations in detail.

NIJI-IV ELECTRON BEAM

The electron beam qualities on the FEL oscillations at the wavelength of 300 nm were measured. The electron beam energy in the NIJI-IV was about 310 MeV. The electron bunch vibrated longitudinally by the amplitude of 3-9 μ m and the period of 100 Hz. We ascertained that the power supply of the main magnets had line noise with the same period, but we could not remove it completely. The bunch length gently increased up to the beam current of 2-3 mA because of the potential well distortion. As Fig. 1 shows, the bunch length increased rapidly above 2-3 mA. The energy widening was also observed above the threshold beam current, so that the microwave instability would cause the increase of the bunch length and energy spread. The electron bunch had the complex shape in the higher current region where the microwave instability was remarkable. However, we regarded one standard deviation of a Gaussian fitting to the bunch shape as the bunch length. Because the bunch length is proportional to the

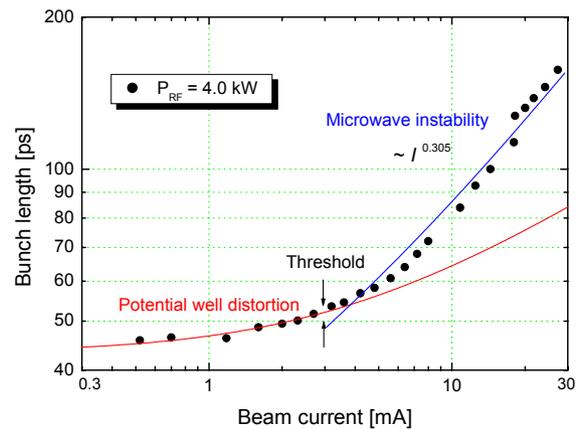


Fig. 1: Dependence of the bunch length on the beam current.

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energy spread, the bunch length $\sigma_l(I)$ at the beam current of I is described by

$$\sigma_l(I) \cong \sigma_{lp}(I) \left[\frac{\sigma_\gamma(I)}{\sigma_{\gamma 0}} \right]^{1+\delta_\gamma}, \quad (1)$$

where $\sigma_{lp}(I)$ is bunch length included an effect of the potential well distortion, $\sigma_\gamma(I)$ is energy spread and $\sigma_{\gamma 0}$ is natural energy spread [4]. The exponent δ_γ is ideally zero. Experimental value for the exponent δ_γ which was estimated by the fitting curve was about -0.06 , and it was near an ideal value zero.

The beam sizes at the dispersive section of the ETLOK-II were measured. Because the betatron functions changed considerably in the long ETLOK-II, the beam sizes averaged through the ETLOK-II are needed to estimate the gain of the NIJI-IV FEL system. The ratio of the averaged beam size to the local beam size at the dispersive section was 1.01 in horizontal direction and 1.40 in vertical direction. The horizontal beam size was almost constant in the observed beam current, and it was about 0.85mm. The vertical beam size gently increased due to the multiple Touschek effect as the beam current increased. It was about 0.27 mm at the beam current of 30 mA.

The peak-electron density in a bunch, ρ_p , can be calculated with the bunch length and the beam sizes. The increase rate of ρ_p became small above ~ 10 mA due to the beam instabilities. The obtained maximum ρ_p was about $1.0 \times 10^{17} \text{ m}^{-3}$. The FEL gain at relative beam energy γ is proportional to the peak-electron density. The FEL gain for the fundamental wavelength of an optical klystron, G_0 , is described by the one-dimension theory as following equations [5]:

$$G_0 = 1.12 \times 10^{-13} \lambda_u^2 N_u^2 (N_u + N_d) K^2, \quad (2)$$

$$[J_1(\xi) - J_0(\xi)]^2 f \rho_p F_f \gamma^{-3}$$

$$\xi = K^2 (4 + 2K^2)^{-1}, \quad (3)$$

where λ_u , N_u , f and F_f are period of the undulator sections, period number of the one undulator section, modulation factor and filling factor, respectively. A factor N_d is the interference order due to the dispersive section, and it was set to be 68, which was optimum value for the FEL gain in the beam-current region of 20-30 mA. The maximum FEL gain estimated with these equations was about 4.6% for the wavelength of 300 nm.

FEL AND ELECTRON BEAM

We observed the temporal and spectral structure of the FEL micropulse. It is known that the cavity-mirror loss except the optimum wavelength increases as the exposure of the optical klystron radiation increases [6]. Although the FEL gain on the FEL oscillations depends on the cavity detuning length strictly, it is approximately equal to the loss of the optical cavity. Therefore, the cavity loss can be evaluated by the threshold beam current for the FEL oscillation. In the case of the small cavity detuning length, the FEL micropulse composes the macropulse and

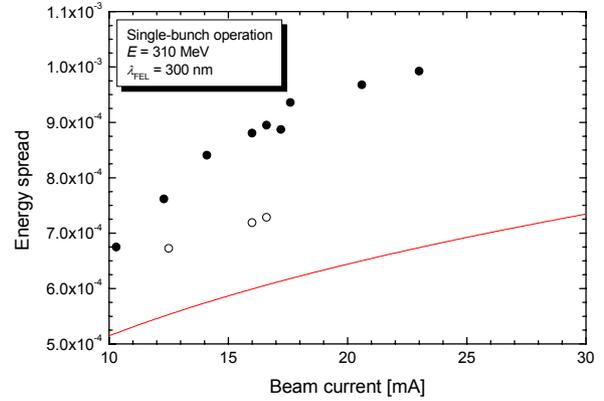


Fig. 2: Energy spread estimated from the horizontal beam size on the FEL oscillations (solid circle) and RF detuning of 2000 Hz (open circle).

the macropulse period depends on the detuning length. When the exposure was comparatively little and the cavity loss was about 1%, the macropulse period was 3.5-5 ms. When the cavity loss became about 2%, the macropulse period decreased down to 2.5-3.5 ms. We observed that the pulse width of the FEL micropulse was minimized in the macropulse mode when the FEL intensity did not become the maximum but decreased. We also observed that the spectral width decreased more than 1ms after the peak of the FEL intensity. These features of the FEL micropulse in the macropulse mode can be explained with simple one-dimension finite difference equations based on the bunch heating theory. The results obtained from the simulations were reported in another paper [7].

We measured the electron-beam qualities on the FEL oscillations at the cavity loss of 2%. According to the bunch heating theory, the interaction between the FEL and electron beam enhances the energy spread. Then we observed the beam sizes at the BM3 where the dispersion function was about 0.31. The horizontal beam size on the FEL oscillations increased as much as 1.1-1.2 times compared with that off the FEL oscillations. The FEL oscillation did not cause an effective change in the vertical beam size. The energy spread estimated with the machine functions on the FEL oscillations is plotted in Fig. 2. This figure shows that the energy spread with RF detuning of 2000 Hz also was enhanced by the bunch heating.

The bunch length on the FEL oscillation was observed to increase due to the bunch heating. The increase rate of the bunch length and energy spread is shown in Fig. 3. The increase rate of the bunch length had a peak at around 10 mA, and it decreased in the higher beam current. The reason was in the bunch shape. The bunch shape off the FEL oscillation was peaky at around 10 mA, and it became like a bell over 20 mA. Because the microwave instability was suppressed by the enhancement of the energy spread on the FEL oscillation, the bunch shape became close to Gaussian. Then, the standard deviation of

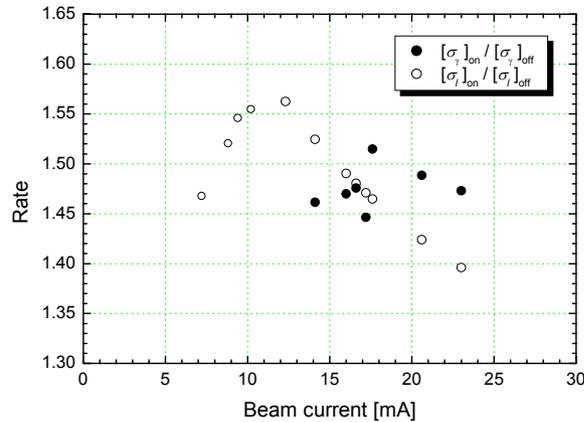


Fig. 3: Increase rate of the bunch length and energy spread due to the bunch heating.

the bunch length was increased easily at around 10 mA, and it was not easy to increase in the higher current region. In the case of the energy spread, the increase rate was almost constant over 12 mA. The reason is that the FEL gain is also constant in the beam-current region.

Considering the observed bunch length and energy spread on and off the FEL oscillations, we can obtain a ratio of the FEL gain to the cavity loss. Because the FEL gain is given by eqs. (2) and (3), the ratio R_G is given by the following description [4]:

$$R_G \equiv \frac{[G_0]_{off}}{[G_0]_{on}} = \frac{[\sigma_l]_{on} [f_\gamma]_{off}}{[\sigma_l]_{off} [f_\gamma]_{on}}, \quad (4)$$

where suffixes “on” and “off” represent the state of the FEL oscillation. The R_G evaluated from the data in the FEL experiments is plotted in the Fig. 4. We knew the FEL gain from eq. (2) and the cavity loss from the threshold beam current of the FEL oscillation, so that we could evaluate R_G directly without using eq. (4). Because the optical cavity slowly shifted from the best tuning in the low beam-current region where time passed from the start of the FEL experiment, the ratio calculated with eq. (4) tended to be undervalued. However, it is noted that the ratio calculated with eq. (4) was almost in accord with the ratio evaluated directly. This fact suggests that the evaluation of the energy spread was correct.

CONCLUSIONS

We have measured the NIJI-IV electron-beam qualities and the temporal feature of the FEL micropulse. We noted that the pulse width and spectral width kept decreasing after the peak of the FEL macropulse intensity. The bunch length and energy spread were observed to increase due to the bunch heating while the FEL oscillated. The increase

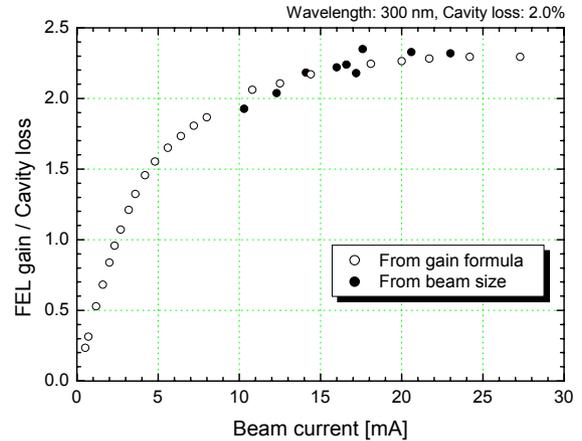


Fig. 4: Ratio of the FEL gain to the cavity loss estimated from the beam qualities on and off the FEL oscillations (solid circle) and the measured data of the FEL gain and the cavity loss (open circle).

rate of the bunch length gently decreased over ~ 10 mA because the bunch shape off the FEL oscillation changed due to the microwave instability. The increase rate of the energy spread was almost constant. The ratio of the FEL gain to the cavity loss estimated from the beam qualities on and off the FEL oscillations was almost in accord with the ratio evaluated directly with the measured data of the FEL gain and the cavity loss. Then we can conclude that the FEL gain estimation based on the well-known one-dimension theory is applicable to the NIJI-IV FEL system.

We have replaced the vacuum chambers in the NIJI-IV so as to suppress the microwave instability. The longitudinal broad-band impedance have been confirmed to be below 2Ω . We will investigate the new electron-beam qualities and the feature of the FEL micropulse in the VUV region.

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