PERFORMANCE OF THE OPTICAL KLYSTRON ETLOK-III FOR DEVELOPING INFRARED STORAGE RING FREE ELECTRON LASERS*

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Abstract

Oscillations of free electron lasers (FELs) with the compact storage ring NIJI-IV in a wade wavelength region of 1-12 μm are planned in National Institute of Advanced Industrial Science and Technology (AIST). The optical klystron ETLOK-III for developing infrared FELs has been installed in a long straight section of the NIJI-IV. The ETLOK-III has two undulator sections of 7 periods and one 75 cm dispersive section. The maximum K value was estimated to be about 10.4 from a measurement of magnetic field. Fundamental and higher harmonics of spontaneous emission from the ETLOK-III were observed with large gaps. The modulation of the spectra of the spontaneous emission suggested that the maximum FEL gain would be about 2% in the visible and near-infrared regions.

INTRODUCTION

Oscillations of broad-band free electron lasers (FELs) have been studied with the storage ring NIJI-IV at National Institute of Advanced Industrial Science and Technology (AIST). Although the NIJI-IV is a compact storage ring with a 29.6 m circumference, it has two 7.25 m straight sections. The optical klystron ETLOK-II has been installed in one of the straight sections so as to realize FEL oscillations in a shorter wavelength region [1]. The NIJI-IV FEL system advanced the record of the shortest FEL wavelength down to 212 nm in 1998 [2]. It achieved the FEL oscillations at the wavelength of 198 nm in 2003, and became the third device which realized storage ring FELs in the VUV region [3]. Output power of an FEL at a wavelength around 200 nm was increased to 0.5 mW by using cavity-mirrors with higher transmission. Preliminary experiments of photoelectron emission microscopy were carried out, and the good spatial resolution was obtained with video-rate time resolution.

A new optical klystron ETLOK-III for FEL oscillations in the infrared region was installed in the other straight section in this February. Although many infrared FEL facilities based on linear accelerators are operating, no storage ring FEL has been achieved in the wide infrared region. However, the storage ring FEL has the advantage of a narrow line width and stability of the lasing wavelength compare with the linear accelerator FEL. It can be used as well as synchrotron radiation that passed a monochromator. Then, we have planed FEL oscillations with the ETLOK-III in a wavelength region of 1-12 μm [4]. The infrared storage ring FEL will be applied for not only a light source of photoelectron emission microscopy but also generation of a hard X-ray beam by the Compton backscattering process [5]. In this article, we explain the feature of the optical klystron ETLOK-III, and report results obtained from the spontaneous emissions of the ETLOK-III.

OPTICAL KLYSTRON ETLOK-III

Design

A planar undulator with bump magnets was remodelled into the ETLOK-III [4]. The 3 m undulator had magnets with 20 cm period. The magnet material was SEREM-N38H with a remanent field higher than 1.24 T. Magnets of undulator sections of the ETLOK-III reuse those of the old undulator. Then, number of the periods in one undulator section is 7. The gap of the undulator sections can be changed between 36 and 150 mm. The dispersive section of the ETLOK-III was designed so that N_d, which is a number of periods of the FEL wavelength passing over an electron in the dispersive section, became about 90 due to the then electron-beam qualities. In order to obtain the large N_d, the length of the dispersive section is set to be 72 cm and free spaces of 1.5 cm are installed between the dispersive section and the undulator sections. The gap of the dispersive sections can be changed between 36 and 188 mm. However, the magnets in the dispersive section are inserted between tables which fix the magnets of the undulator sections, so that the gap of the dispersive section must be smaller than addition of the gap of the undulator section and 38 mm.

. Figure 1 shows the outline of the ETLOK-III. The magnetic field on the center axis of the ETLOK-III under the some gap conditions was measured before the installation. The measured value of the magnetic field is about 4% larger than the designed one, and the maximum K value is 10.4.

Because the dispersive section is long, the NIJI-IV electron beam with comparatively low energy meanders greatly in it. When the uniformity of the magnetic field is insufficient horizontally in the dispersive section, the electron beam is kicked in it and comes off the center axis of the ETLOK-III. The calculated horizontal distribution of the magnetic field in the dispersive section under the minimum gap condition is shown in Fig. 2. Width of the magnet is small with 88 mm, so that the magnetic field weakens by 7.6 % at the point of 20 mm away from the center axis. Therefore, it is necessary to move an axis of the electron-beam orbit from the center axis of the ETLOK-III or to change the magnetic field in the dispersive section. Because the shift of the electron beam in the dispersive section is large, the latter idea would be

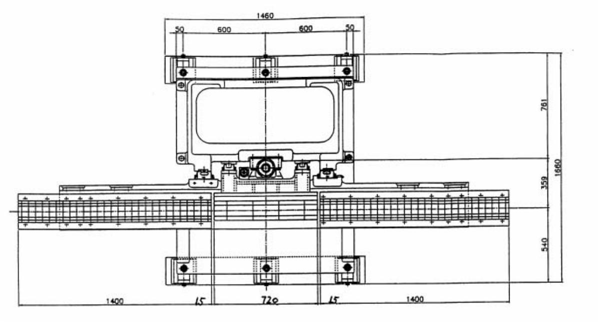

Fig. 1. Outline of the optical klystron ETLOK-III.

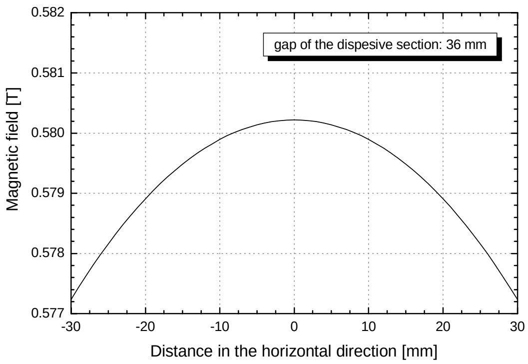

Fig. 2. Calculated magnetic field at the center of the dispersive section of the ETLOK-III. The gap is set to be the minimum of 36 mm.

more practicable. We plan an improvement that the magnetic field of the both end magnets of the dispersive section is shunted by iron plates and a steering coil is attached to a vacuum chamber in the dispersive section. At present, a small steering coil which can compensate for the magnetic field of ~2×10^{-3} T are attached, and the gap of the dispersive section can be set down to 120 mm.

Influence for the electron beam parameters

The ETLOK-III arranges the magnets horizontally, so that it has a vertical focusing effect. This effect causes vertical tune shift and distorts the vertical betatron function due to asymmetrical arrangement of the ETLOK-III in the straight section. Present betatron tunes of the NIJI-IV electron beam are 2.291 in the horizontal direction and 1.394 in the vertical direction, and the magnetic field of quadrupole magnets is adjusted with the gap of the ETLOK-III to keep the tunes. Figure 3 shows calculated betatron functions and dispersion functions with and without the ETLOK-III at the same betatron tunes. As this figure shows, vertical betatron function in the long straight sections decreases due to the strong vertical force with the ETLOK-III. Natural emittance also

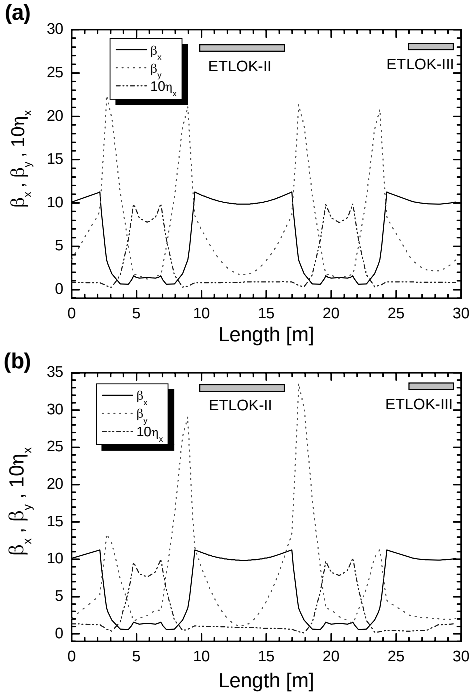

Fig. 3. Calculated betatron functions (horizontal β_x and vertical β_y) and dispersion function (η_x) without (a) and with (b) the ETLOK-III.

decreases by about 5%. Therefore the vertical beam size would become small about 10% at the center of the ETLOK-III. When the gaps are minimum, total radiation power from the NIJI-IV is about 6% stronger than that without the ETLOK-III. We can expect that the power of the short-wavelength FEL from the ETLOK-II enhances.

OBSERVATION OF THE SPONTANEOUS EMISSION

The optical klystron ETLOK-III has been installed in the NIJI-IV in this February, and the electron-beam current has been over 200 mA with the undulator gap of 125 mm. The electron-beam energy is set to be 340 MeV. Because the electron beam is kicked at the exit of the dispersive section, the undulator gap is set to be over 95 mm and the spontaneous emission is observed in the visible and near-infrared regions. Uniform area of the magnetic field in the ETLOK-III is narrow horizontally, so that the electron beam must be passed in parallel to central axis of the ETLOK-III in order to obtain symmetry spontaneous emission. A photograph of the spontaneous emission observed with the undulator gap of 140 mm is shown in Fig. 4.

Spectra of the spontaneous emission were measured by a photodiode array with a monochromator which had the resolution of 0.2 nm. Because the dispersive section has a parabolic distribution of magnetic field in the horizontal

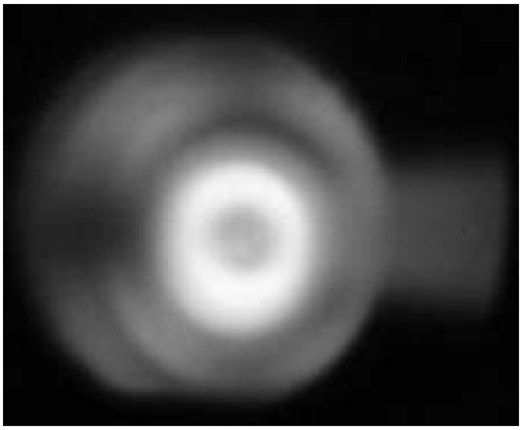

Fig. 4. Photograph of the spontaneous emission from the ETLOK-III. The gaps of the undulator section and the dispersive section are 140 and 150 mm, respectively.

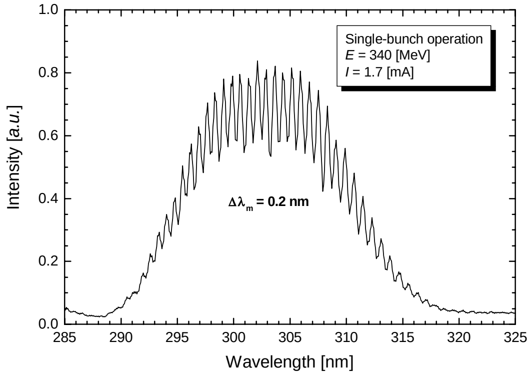

Fig. 6. Spectrum of the third harmonic emission from the ETLOK-III. The gaps of the undulator section and the dispersive section are 115 and 150 mm, respectively.

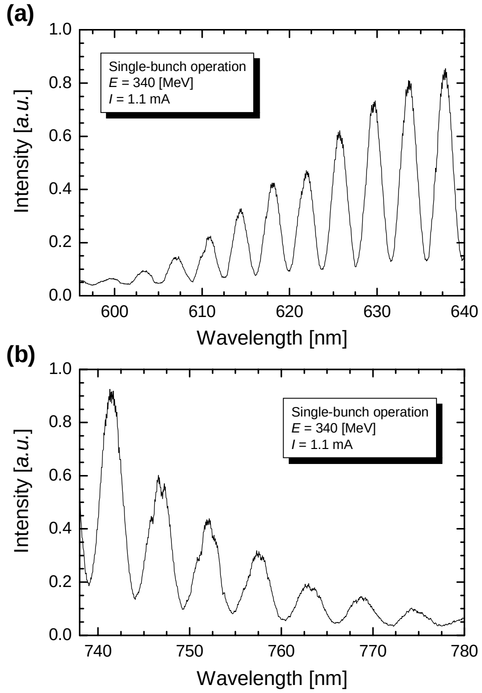

Fig. 5. Spectrum of the spontaneous emission from the ETLOK-III: (a) the end of the short wavelength and (b) the end of the long wavelength. The gaps of the undulator section and the dispersive section are 125 and 160 mm, respectively.

direction, precise adjustment of the electron-beam orbit is necessary so as to obtain a large modulation factor for the spontaneous emission. Figure 5 shows a spectrum of spontaneous emission with the undulator gap of 125 mm and the dispersive gap of 160 mm. The resonant wavelength measured in this condition was about 690 nm, and it was agreement with the wavelength estimated from the measurement of magnetic field in the ETLOK-III. The value of N_d estimated from intervals of the modulation of the fundamental was about 140. The value calculated from the magnetic field in the dispersive section was about 150. The difference between the measurement and the calculation would suggest that the adjustment of the electron-beam orbit was insufficient. Moreover, energy spread of an electron bunch can be estimated by using the modulation factor [6]. The energy spread measured with the undulator gap of 125 mm was $2.7\pm.0.2\times10^{-4}$, which was close to the natural energy spread of 2.6×10^{-4}.

The spectra of the higher harmonic emission were also investigated in the ultraviolet and the visible regions. Further precise adjustment of the electron-beam orbit is demanded for the higher harmonics. Figure 6 shows a spectrum of the third harmonic emission with the undulator gap of 115 mm and the dispersive gap of 150 mm. Relative width of the spectrum of the third harmonic emission was about 19 in Fig. 6. Because the theoretical one was 21, the spectrum was a little broader. The measured interval of the modulation of the third harmonic emission at the resonant wavelength was about 0.75 nm, and it was slightly narrower than the theoretical one of 0.72 nm. The modulation factor for the third harmonic emission which was removed an influence of the measurement system was smaller than that estimated from the modulation for the fundamental emission. We have not ascertained the whether these results were caused by misalignment of the electron-beam orbit or distortion of the magnetic field in the ETLOK-III yet. However, N_d can be decreased by closing the undulator gap. Because the modulation factor become over 0.6 with the narrow undulator gap, it will be possible to obtain FEL oscillations which amplify the third harmonic emission in the infrared region.

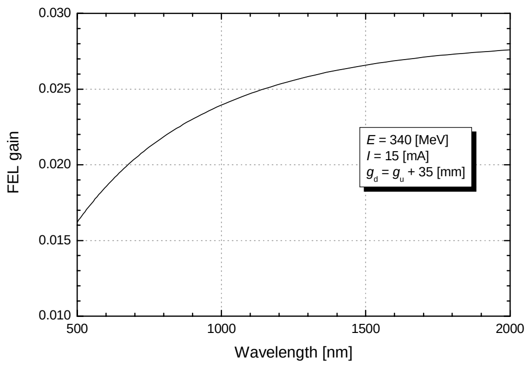

Fig. 7. Relationship between the wavelength and the estimated FEL gain at the electron-beam current of 15 mA. The gap of the dispersive section is set to be 35 mm wider than the gap of the undulator section.

We can estimate the maximum FEL gain from the observed spectra of the spontaneous emission. Figure 7 shows a relationship between the wavelength and the estimated FEL gain in the visible and the near-infrared regions. Though the *K* value is comparatively small (<3.5) in those regions, the maximum FEL gain is expected to be about 2% at the electron-beam current of 15 mA [3]. Because high-reflection mirrors of 99.8% or more are available in those regions, the FEL oscillations will be realized with the ETLOK-III. However, we have not operated the NIJI-IV with the undulator gap under 95 mm due to the bend of the electron-beam orbit in the dispersive section yet. It is impossible to evaluate the maximum FEL gain in the longer wavelength region for the present. We will improve the dispersive section to compensate non-uniformity of the magnetic field, so that it will allow us to observe the spontaneous emission with the narrower undulator gap.

CONCLUSIONS

We have installed the optical klystron ETLOK-III for developing infrared FEL oscillations in the long straight section of the storage ring NIJI-IV. The number of the 20 cm magnetic period in an undulator section of the ETLOK-III is 7, and the length of the dispersive section with two 1.5 cm free spaces is 75 cm. The maximum *K* value was designed to be about 10, and it was estimated to be 10.4 from the measurement of the magnetic field. We have also observed the spontaneous emission from the ETLOK-III in the visible and near-infrared regions. It was noted that the maximum *K* value which was estimated from the fundamental wavelength of the spontaneous emission on the axis of the electron-beam orbit was about 10.4. Value of N_d estimated from the measurements of the magnetic field in the dispersive section was also in accord with that obtained from the spectra of the spontaneous emission. The maximum FEL gain which was evaluated with the NIJI-IV electron-beam qualities and the performance of the ETLOK-III was about 2% in the visible and near-infrared regions. Then, it will be possible to realize FEL oscillations with the fundamental and higher harmonics in the regions.

Now an improvement of the dispersive section is planed in order to store the electron beam with the narrower gap of the ETLOK-III. In the mid-infrared region, the maximum FEL gain would be higher due to the higher *K* value. Because N_d becomes smaller, it would be easy to oscillate the FELs with higher harmonics. We will investigate the performance of the optical klystron ETLOK-III in the higher *K* value region.

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REFERENCES

[1] T. Yamazaki *et al.*, Nucl. Inst. and Meth. **A331** (1993) 27.
[2] K. Yamada *et al.*, Nucl. Inst. and Meth. **A445** (2000) 173.
[3] K. Yamada *et al.*, Nucl. Inst. and Meth. **A528** (2004) 268.
[4] N. Sei *et al.*, Jpn. J. Appl. Phys. **41** (2002) 1595.
[5] N. Sei *et al.*, Nucl. Inst. and Meth. **A483** (2001) 429.
[6] D. A. G. Deacon *et al.*, App. Phys. **B34** (1984) 207.