Storage Ring Free Electron Laser in Visible Region on NIJI-IV

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Abstract

Oscillations of free electron laser (FEL) at two wavelength regions around 595 nm and 488 nm were achieved on the electron storage ring NIJI-IV at Electrotechnical Laboratory (ETL) last year. In the first lasing around 590 nm, electron beam energy was about 240 MeV, and the laser oscillation was obtained at the beam current from 1.1 mA/bunch to 0.2 mA/bunch. The laser linewidth was observed to be 0.4 nm, including the detector resolution (0.2 nm). The macro-temporal structure of the storage ring FEL that varied with the FEL gain was observed. In the laser oscillation at 488 nm, electron beam energy was about 265 MeV and the beam current at the oscillation threshold was 0.8 mA/bunch.

Introduction

The series of FEL experiments at 599 $\sim$ 592 nm on the storage ring TERAS had been carried out at ETL [1]. But it was difficult to achieve FEL oscillation at shorter wavelengths due to the short straight section (1.8 m) of the ring. Then, FEL experiments on NIJI-IV have been started at ETL in collaboration with Kawasaki Heavy Industries Ltd., aiming at FEL oscillation in ultraviolet region.

NIJI-IV was designed for FEL studies, and a beam was successfully stored in the ring in February 1991[2]. NIJI-IV has two long straight sections (7.25 m), in spite of relatively short circumference (29.6 m). In order to obtain the enough FEL gain even in ultraviolet region, a 6.3-m optical klystron (OK) has been installed in one of the straight sections. After several kinds of preparatory experiments, the first lasing around 590 nm was achieved on August 18, 1992 [3]. And the oscillation wavelength was successfully expanded down to 488 nm on September 18, 1992.

Oscillation experiments around 350 nm are going on at higher beam energy. In this paper, however, the outline of the FEL experiments in visible region is presented below.

Technical Elements of FEL Experiments

The overall arrangement of FEL experiments is shown in Fig. 1. There are three important elements to achieve a FEL oscillation.

Storage Ring

The source of FEL is bremsstrahlung from charged particles which move in the priodic electromagnetic field. Therefore, high quality of charged particle beam is required to obtain an intense and bright output light. Storage rings, which generally offer electron beam with very small energy spread and low emittance, are accelerators suitable for FEL operation at short wavelengths.

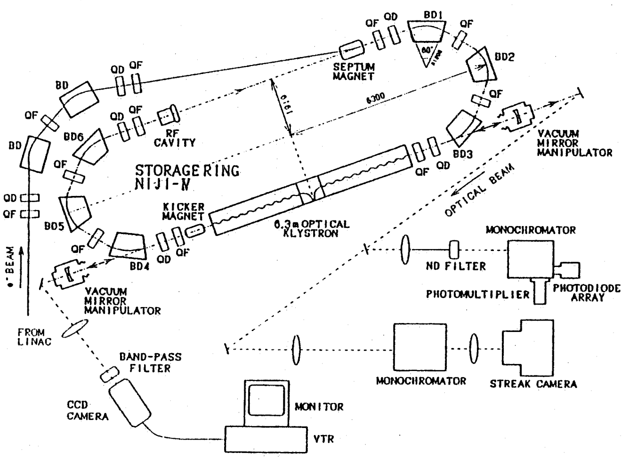

Figure 1: Overall arrangement of FEL experiments on NIJI-IV.

The storage ring NIJI-IV is of a compact racetrack type with a triple-bend-achromat lattice [4]. Although 16 bunches are revolving in the ring with present injection system, only one bunch can be synchronized with an identical light pulse inside the optical cavity, and the rests do not contribute to the laser peak gain. Moreover, the coupling between these bunches induces a beam instability which degrades the beam quality. In order to avoid unnecessary damage of the optical cavity mirrors and improve the beam quality, a two-stage RF-KO method was used to realize single-bunch mode. But the oscillation experiments in visible region were actually carried out in a 2-bunch mode to avoid an excessive loss of the beam current during the RF-KO process.

The ring parameters are given in Table-1. The streak camera was used to measure the electron bunch length in the optical cavity (see Fig. 1). As shown in Tabel-1, the electron bunch length in the full 16-bunch mode is longer than that in single-bunch mode. Taking account of this fact, the full-bunch mode has the disadvantage of the lower electron current density which is proportional to the FEL gain. The electron beam transverse size was also measured by using a CCD camera which was focused around the center of the OK (see Fig. 1). Table-1 shows that the horizontal size σ_x is more than 2 times as large as the vertical size σ_y. Because the distortion of beam cross section is a cause of poor overlapping with an optical pulse, this situation is undesirable for FEL oscillations. A skew quadrupole magnet has been installed in the ring to improve beam transverse size, and the effect is going to be investigated in the near future.

Table 1: NIJI-IV characteristic parameters in the FEL exprimen ts around 590 nm.

		MESUREMENT
Energy	E	240 MeV
Natural emittance	ϵ_N	1.3 $\times 10^{-7}$ mrad
Momentum spread	$\frac{\Delta p}{p}$	2.5 $\times 10^{-4}$
Beam size		
horizontal	σ_x	0.74 mm
vertical	σ_y	0.30 mm
Bunch length	σ_l	53 mm

Optical Klystron

The core of FEL system is an undulator. In order to enhance the FEL gain, NIJI-IV has a long 6.3-m OK which is composed of three sections, that is, two undulator sections (US) and a dispersive section (DS) [5]. The number of magnetic period in each US are 42 with the period λ_0 being 72 mm. The length along the averaged motion of an electron in DS is 216 mm, and the total length of OK is 6.288 m. The gaps of the these sections can be changed between 35 mm and 300 mm in any combination.

The central wavelength of the spontaneous-emission spectrum λ_γ varied with the US's gaps G_u. λ_γ is given by

$$\lambda_\gamma = \frac{\lambda_0}{2\gamma^2}\left[1 + \frac{K^2}{2} + \gamma^2\theta^2\right] \qquad (1)$$

where γ is the electron energy and θ the angle of observation with respect to the electron trajectory axis. K is the deflection parameter of the US and given by $K = 93.4 B_0 \lambda_0$ in SI units. B_0 expresses the peak magnetic field of undulator. As illustrated in Fig. 2, the comparatively large deviation from eq.(1) was observed. The cause of this deviation is regarded as the incomplete alignment of the electron trajectory axis with OK central axis.

The shape of the spontaneous-emission spectrum was similar to Figs. 4 (1a) and (2a). The N_d value, which represents the number of periods of light of wavelength λ_γ passing over an electron in DS, can be varied up to about 100. However, the FEL gain may decrease by making the N_d value larger according to the effective degradation factor [6]. In FEL experiments, the DS gap was 56 mm and the actual N_d value was close to 57 from the simulation. Since the N is as large as the N_d, the fine structure peculiar to OK was not remarkable.

Optical Cavity

The laser cavity is composed of very low-loss concave dielectric multilayer mirrors (SiO_2/TiO_2). The cavity loss of these mirrors used in FEL experiments around 590 nm has been measured by a cavity-decay-time method to be about 96 ppm at 585 nm.

The mirrors were set inside the high-vacuum mirror manipulator with 5-axis controller. The mirrors can be adjusted by stepping motors and piezoelectric actuators with accuracy better than 0.2 μm. In order to enhance the FEL gain, the angles of cavity mirrors were carefully adjusted to make a proper resonant output mode. The cavity length can be roughly tuned by observing the pulse shape of output light with a streak camera. Figs. 3(a)-3(c) show the pulse shape of output light in detuned condition

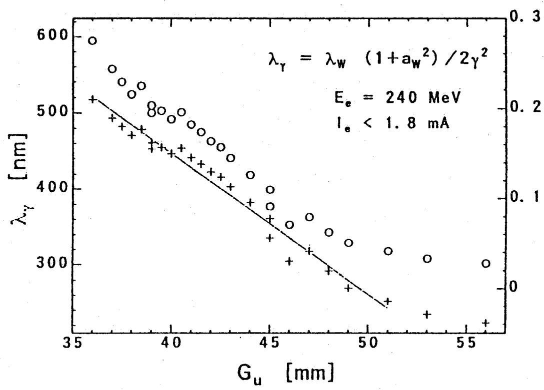

Figure 2: The central wavelength of the spontaneous emission spectrum λ_γ versus undulator gap G_u (circle). The mark of plus is the calculated value of a_W in term of λ_γ.

by +40μm, almost tuned condition and detuned conditions by -40μm. Because this measurement was made in full-bunch mode, the width of output light pulse which completely synchronized with an electron bunch inside the optical cavity was about 0.35 ns longer than the width of the electron bunch in single-bunch mode. Although the resolution of this method depends on the relation between cavity loss and the bunch length, it is better than $\pm$ 20 μm in the case of FEL experiments around 590 nm.

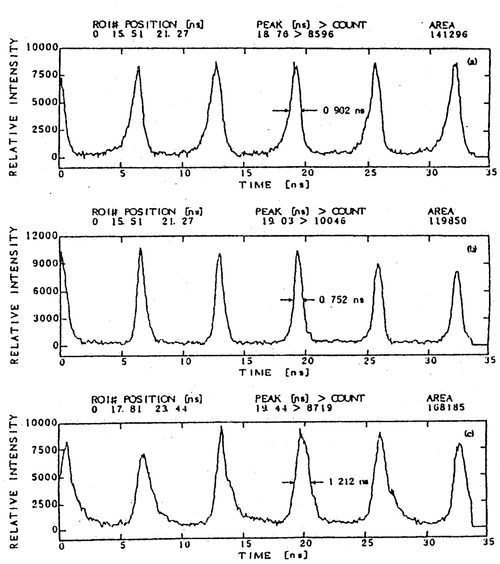

Figure 3: The pulse shape of output light with streak camera in full-bunch mode. (a): detuned by -40μm. (b): almost tuned. (c): detuned by $+40\mu$m.

FEL Oscillation

When the optical cavity length was tuned precisely observing output spectrum, the lasing was observed in addition to above preparations and adjustments. The typical output spectra during this process are seen in Fig. 4. In this figure, (1a) and (2a) show spontaneous emission spectra which are resonant inside the cavity. (1b) and (2b) show spectra just on oscillation threshold. (1c) and (2c) show spectra during oscillation.

In the first lasing around 590 nm, electron beam energy was about 240 MeV, and the laser oscillation was obtained at the beam current from 1.1 mA/bunch to 0.2 mA/bunch. The maximum peak intensity of oscillated light was about 55 times as high as that of the detuned output light, and the laser linewidth was observed to be 0.41 nm. Taking into account the detector resolution (0.21 nm), the actual linewidth should be much smaller. The wavelength of laser oscillation was varied by controlling the electron beam energy. Then the laser oscillation from 594.5 nm (240 MeV) to 588.7 nm (241 MeV) was observed.

In the laser oscillation at 488 nm, electron beam current was about 265 MeV and the electron beam current was 0.8 mA/bunch. The maximum peak intensity of oscillation was only 12 times as high as that of the detuned output light. The laser linewidth was observed to be about 0.3 nm, including the detector resolution. Because this oscillation was just above threshold, the laser oscillation immediately stopped, so that the other FEL parameters were unable to be measured.

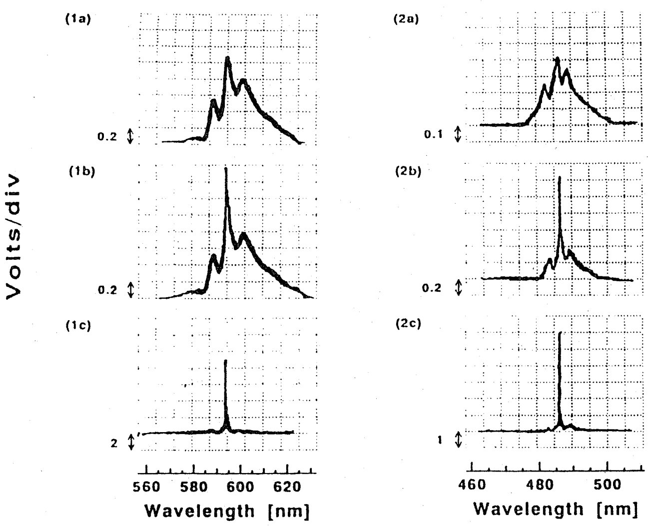

Figure 4: The typical output spectra during the adjustment of the cavity mirrors. $\lambda_\gamma \sim 595$ nm in (1a)–(1c). $\lambda_\gamma \sim 488$ nm in (2a)–(2c).

The macro-temporal structure of FEL oscillation should be dominated by the two parameters, τ_s and τ_0 [7]. τ_s is the synchrotron damping time and its theoretical value is 72 ms in our case. τ_0 is the laser rise time starting from the laser-off condition and given by

$$\tau_0 = \frac{\Theta}{g_0 - p} \tag{2}$$

where $\Theta = 99$ ns is the distance between bunches, p is the cavity loss, and g_0 is the unsaturated gain. If g_0 is much larger than p so that laser oscillation is stable, the laser is resonant with a period $T_R = 2\pi\sqrt{\tau_0\tau_s/2}$.

Fig. 5. shows the macro-temporal structure of the peak power during laser oscillation around 590 nm. The sampling time of the system was so long (33 ms) that the macro-temporal structure would have been hidden if τ_0 had been shorter than about 1 ms. The laser oscillation looks like chaos [7], but quasi-periodic behavior undoubtedly exists in Fig. 5. The shapes of the quasi-periodic pulses are non-symmetric, and the rise time is longer than the decay time [6]. The macro-temporal structure in Fig. 5(a) was measured before that in Fig. 5(b). The peak heights of laser pulse in Fig. 5(a) are comparatively uniform and large, on the contrary that in Fig. 5(b) are random and small. T_R in Fig. 5(a) is 120 $\sim$ 160 ms, and T_R in Fig. 5(b) is 200 $\sim$ 250 ms. These results can be explained in term of varying FEL gain. The excess of FEL gain over cavity loss may be estimated to be below 10^{-4} in Fig. 5(a). Fig. 5(b) represents that the peak wavelength tends to vary with the peak height. However, the observable shift of the peak wavelength is small (about 0.2 nm) because the observed spectra were different from an actual spectrum of spontaneous emission due to the long sampling time of system.

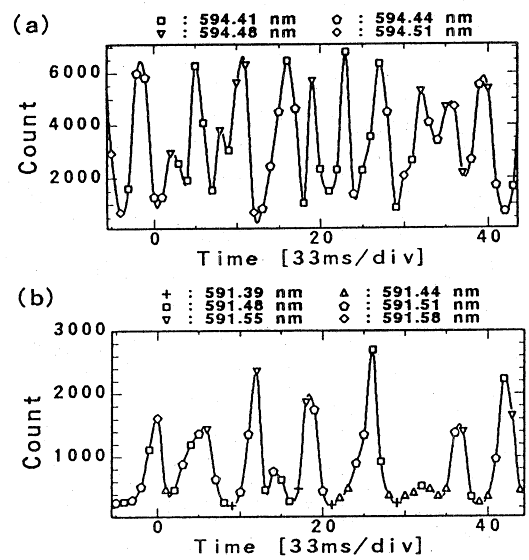

Figure 5: The macro-tempral structure of laser oscillation. Each electron beam currrent per bunch is 0.92 (a) and 0.76 (b) respectively.

Conclusion

The oscillation of FEL in visible region has been observed and the interesting results have been obtained. Especially, the macro-temporal structure of FEL is important clue to investigate FEL mechanism. At present, the optimal condition of FEL gain in ultraviolet region is investigated by using experimental parameters.

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