COMPACT STORAGE RING FREE ELECTORON LASER WITH THE NIJI-IV

N. Sei, T. Yamazaki, K. Yamada, S. Sugiyama, H. Ohgaki,
T. Mikado, R. Suzuki, T. Ohdaira, H. Toyokawa, M. Kawai*, M. Yokoyama*

Quantum Radiation Division, Electrotechnical Laboratory
1-1-4 Umezono, Tsukuba, Ibaraki 305, JAPAN
* Kawasaki Heavy Industries, Ltd.
118 Futatsuzuka, Noda, Chiba 278, JAPAN

Abstract

The studies of free electron lasers (FELs) with a compact storage ring NIJI-IV are carried out at the Electrotechnical Laboratory. The NIJI-IV, dedicated to FELs, is a racetrack-type ring and has 7.25-m straight sections though the circumference is 29.6 m. In order to obtain sufficient FEL gain, a 6.3-m optical klystron (ETLOK-II) has been installed in one of the straight sections. The electron beam is injected at the energy of 310 MeV, and the energy is adjusted according to the condition of FEL experiments. Oscillation of FELs has been achieved at several wavelengths between 594.5 and 299.0 nm. The electron-beam qualities have been improved to shorten the wavelength of the FEL oscillation in the UV region.

1 INTRODUCTION

Storage ring NIJI-IV dedicated to FELs in the ultraviolet (UV) region was constructed at the ETL in 1990[1]. Generally a storage ring which has large circumference has advantage of higher gain because it is easy to realize lower emittance and to install a longer insertion device in the ring. The NIJI-IV, however, is a compact ring with 29.6-m circumference, so that some device are given to the design. A triple-bend-achromatic lattice realizes a low-emittance beam for a small radius of curvature of 1.2 m. The NIJI-IV is a racetrack type, and it is able to have long two straight sections which are about 50% of the circumference. A 6.3-m optical klystron ETLOK-II has been installed in one of the straight sections since 1992[2]. The number of magnetic periods in each normal undulator section is 42 with the period of 72 mm. The length of a dispersive section is 216 mm. The gaps of these sections can be changed between 35 and 300 mm in any combination, and the maximum deflection parameter K is about 2.29. An optical cavity which is composed of high-reflectivity mirrors with a 10-m radius of curvature and a 3-cm diameter has been set on the extended line of the ETLOK-II. The mirrors are set inside high-vacuum mirror chambers with 5-axis manipulators and they can be adjusted with a precision better than 0.2 μm. The distance between the mirrors is 14.8 m, so that only one bunch can be synchronized with an identical light pulse inside the optical cavity. In order to avoid unnecessary damage of the mirrors and improve the beam qualities, rf-KO method is usually used to full 16-bunch beam to realize single-bunch mode.

FEL experiments with the NIJI-IV were started in 1992. The first lasing at around 590 nm of an FEL was achieved in August 1992, and the oscillation wavelength was successfully expanded down to 488 nm in September 1992[3]. In section II, the results of the early FEL experiments in the visible region are descried. After these experiments, the septum magnet was improved and the operation mode of the ring was changed to the original design in 1993[4]. This improvement reduced the emittance, and lasing of FELs in the UV region was achieved in April 1994[5]. The characteristics of the FELs at around 350 nm are discussed in section III.

In order to shorten the wavelength of an FEL in the UV region, we needed to suppress the electron-beam instabilities at high current. A simple rf-phase feedback system was useful for the decrease of a self-coupled bunch instability, but a limitation of bunch current was left because of a head-tail instability[6]. So, combinations of two sextupole magnets and a quadrupole magnet installed in the all short straight sections in 1997. We recently observed the clue that the head-tail instability would be suppressed, and lasing of FELs at 300nm was achieved on March 20, 1998. In section IV, the outline of these improvements is discussed.

2 FEL OSCILLATIONS IN THE VISIBLE REGION

FEL experiments in the visible region were not made in the originally designed tune, and the natural emittance was rather high as Table 1 shows. In this region of wavelength, however, the electron beam energy was rather low (240 MeV at 595 nm and 265 MeV at 488 nm, respectively), so that electron-beam qualities were

Table 1
Calculated machine parameters of the storage ring NIJI-IV at 300 MeV

Parameters	Before1993	After 1993
Betatron tune ν_x	1.595	2.230
ν_y	1.300	1.344
Momentum compaction factor	0.251	0.0884
Natural emittance [m rad]	3.99×10^{-7}	4.91×10^{-8}
Relative energy spread	2.13×10^{-4}	2.28×10^{-4}
Bunch length [mm]	35	22
Chromaticity ξ_x	-1.61	-3.37
Chromaticity ξ_y	-2.22	-4.82

not pessimistic[3,4] and high-reflectivity mirrors were available. Therefor it was easy to exceed the threshold of FEL oscillations which appeared at the beam current of 0.2 mA/bunch (at 595 nm) and 0.8 mA/bunch (at 488 nm). The gain estimated from the measurements of the beam qualities was about 700 ppm at the threshold beam current of 595-nm FELs. This value is much larger than the initial cavity loss which is about 96 ppm. The difference should be caused by the mirror degradation which occurs immediately after exposure due to the radiation from OK[7]. The lasing wavelength was continuously varied by increasing the beam energy by 1 MeV from 594.5 nm to 588.7 nm. The FEL power had not been measured.

Time structure of the output spectra of FELs was observed by a photodiode array with the time resolution of 33 ms. The macro-temporal structure of FEL oscillations was not cw even when the cavity length was preciously tuned to the circumference. The periodic pulse with the period of 120-160 ms appeared in the macro-temporal structure. This period suggests that the effective gain would be below 0.1%. Then we needed to improve the electron-beam qualities in order to shorten the wavelength of FELs to the UV region.

3 FEL OSCILLATIONS IN THE UV REGION

Before FEL experiments in the UV region were started, we improved the septum magnet and the vacuum chambers of the ring in 1993[4]. As the result, the injection efficiency was greatly progressed and the maximum stored current increased up to 376 mA. The operation mode was changed to obtain a stored beam of higher quality. We were able to expect improvements of the emittance and the bunch length in the new mode as Table 1 shows.

Reduction of the emittance was effective to decrease the beam area at the center of the optical cavity. The vertical beam size in the new mode was especially about 70% as large as that in the old mode. The beam divergence at the center of the OK was measured by observing the spontaneous-emission spectra from the OK. The emittance became 7×10^{-8} m rad at the beam current of 1 mA, and this value was a little larger than the natural emittance of 5.2×10^{-8} m rad.

Table 2
Characteristics of the FEL at around 350 nm

Wavelength	348.8 ~ 353.1 nm
Laser line width	< 0.2 nm
Threshold current	3.8 mA
Average laser power (vs. resonated light)	~ 300 times
Macro-pulse Width	~ 2 ms
Macro-pulse period	6 ~ 20 ms
Micro-pulse peak power	~ 100 mW

The bunch length in the single-bunch operation was measured by using a streak camera. We observed a limitation on the single bunch current of ~10 mA, which would be cause by a head-tail instability. However, the momentum compaction factor became smaller, so that the bunch length in the new mode was 20% or more shorter than that in the old mode. Actual FEL experiments were made with a beam current of 4-10 mA and the bunch length during lasing would be 140-180ps. Dependency of the energy spread on the beam current was estimated by measuring the modulation factor of the spontaneous-emission spectra versus the dispersive section gap. An energy widening was also observed even from low current, and it suggests that a microwave instability contributes to the bunch lengthening. The typical energy spread in the single-bunch operation was 5.2×10^{-4} at the beam current of 5 mA.

FEL oscillations at around 350 nm was achieved with the electron-beam energy of 310 MeV in 1994[5]. Table 2 describes main results in the experiments. Though the width of a micro-pulse was not measured at this wavelength region, it was supposed to be a few tens ps according to the measurement at the visible region in 1996. Actual FEL gain which was estimated by the threshold current was a little lower than the value calculated with the beam parameters. One of the reasons would be the degradation of the electron-beam quality which was caused by a coupled-bunch instability due to the imperfect single-bunch operation. Misalignment between the electron-beam axis and the magnetic centerline of the OK would also decrease the FEL gain. The macro-temporal structure of FEL oscillations was almost periodical and it was not stable. In order to realize a stable FEL and shorten the wavelength of an FEL in the UV region, we needed to suppress the electron-beam instabilities at high current.

4 STABILIZATION OF THE ELECTRON-BEAM AND RECENT RESULTS

Some electron-beam instabilities were observed in the NIJI-IV FEL system. The spectrum analysis suggested that a bunch oscillation came from self-induced coupled bunch instability. Longitudinal feedback system is widely used for the cure to the coupled-bunch instability and shortens the bunch length. So we tried to install a simple longitudinal feedback system that consisted of a phase detector and a phase shifter. This feedback system effectively suppressed the coupled-bunch instability and shortened the electron bunch[6]. However, it could not exceed a threshold, about 10 mA/bunch, without loosing the bunch. We concluded that there should be enough 6-pole field to compensate the choromaticity that could suppress a head-tail instability. Quadrupole and 6-pole magnets were designed to be install in a restricted space between bending magnets where dispersion function was large enough to compensate the chromaticities in the operation mode.

Then we installed a 6-QF2-6 triplet unit between bending magnet 1 and bending magnet 2 in December 1996 and the rest of 6-QF2-6 triplet units in each of the short straight sections in December 1997. The operation mode of the ring was slightly changed due to the injection efficiency again. However, we confirmed in the actual experiment that the 6-QF2-6 triplet units were able to compensate the both chromaticities. The chromaticities were adjusted to a little plus value in this operation mode. We can store higher current (~ 20 mA) keeping a short length comparatively. This result suggests that the head-tail instability is sufficiently suppressed due to chromaticity compensation. We also measured a dependence of the energy spread on the electron-beam current. According to this measurement, the energy widening which was mainly caused by a microwave instability was observed above the electron-beam current of 2 mA. The threshold current of the microwave instability with the 6-pole magnets is much higher than that without the 6-pole magnets. The reason would be an exchange of an RF electrode which was made at the same time as the installation of 6-QF2-6 triplet units.

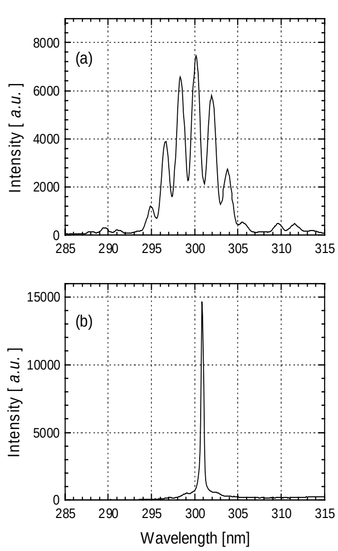

Fig. 1 Output spectra of spontaneous emission(a) and lasing (b). The deflection parameter is 2.0.

These electron-beam parameters have been measured since March 1998, and lasing at around 300 nm was achieved on March 20. The electron-beam energy was about 309 MeV, and the wavelength of FEL oscillations varied from 299.0 to 302.4 nm owing to adjustment of the slippage number N_d. Figure 1 shows the output spectra with photodiode array. Figure 1a shows a spectrum of the spontaneous emission with the dispersive gap of 36.8 mm (N_d ~ 120), and figure 1b shows a spectrum during oscillation with the same condition of the gap. The peak wavelength and the bandwidth of the spectrum in figure 1b are 300.8 nm and 0.31 nm, respectively. Here it should be noted that the bandwidth contains the spectral resolution of the measurement system (more than 0.25 nm). The actual bandwidth would be much shorter. The threshold current of the FEL oscillation was only 1.3 mA/bunch, and the FEL gain at 300 nm estimated by the measurement of the cavity loss would be about 0.5 % at this current[8].

We are going to continue the FEL experiments at this wavelength region to investigate FELs and electron-beam characteristics. We will also challenge to shorten the wavelength of FELs down to 240 nm in near future.

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