Status of the free electron laser experiments with the storage ring NIJI-IV in 1999

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Abstract

The studies to shorten the wavelength of free electron lasers (FELs) are carried out with the compact storage ring NIJI-IV at the Electrotechnical Laboratory. Sextupole-quadrupole-sextupole (SQS) magnets were installed in all of the short-straight sections of the NIJI-IV to correct chromaticities. They sufficiently suppressed a head-tail instability, so that peak-electron density was remarkably increased and was over 6×10^{16} m^{-3}. We achieved oscillations of FELs around 300, 240 and 215 nm. The shortest wavelength with the NIJI-IV FEL system was down to 212 nm. In order to realize an FEL oscillation in the VUV region, we improve the RF system of the NIJI-IV at present.

1. Introduction

We achieved the lasing of an FEL in the UV region in 1994 by changing the operation mode of the NIJI-IV [1]. The oscillation was observed at the wavelength of 349- 353 nm, and the available FEL gain was about 1%. However, we could not accomplish to further shorten the wavelength due to a limitation of the peak-electron density in a bunch. The main reason of the limitation was a head-tail instability, which was occurred at the beam current of ~ 10 mA [2]. Then we designed the SQS magnets to correct the chromaticities and installed them in all of the straight sections. They perfectly corrected the chromaticities and suppressed the head-tail instability sufficiently. The peak-electron density in a bunch was enhanced up to 6×10^{16} m^{-3}or more [3]. This improvement led the shortening wavelength of FELs. We achieved FEL oscillations around 300, 240 and 215 nm in 1998 [4]. The shortest wavelength with the NIJI-IV FEL system was 212 nm, which was the record of the shortest FEL wavelength at that time.

However, the available FEL gain was about 2.0% at 200 nm, and it was difficult to lase in the VUV region. We decided to improve the RF system in the NIJI-IV and already renewed the RF cavity [5]. The new RF cavity was designed so as to feed RF input of 10 kW and to stabilize the electron beam with control of the higher order modes (HOMs). We also plan to improve the RF power supply to increase the maximum RF input from 2 to 10 kW this autumn. In this article, we report the installation of the SQS magnets, FEL oscillations below 300 nm and improvement of the RF system.

2. SQS magnets

When the FEL experiments around 350 nm were carried out, the NIJI-IV did not have enough sextupole magnets. The horizontal and vertical chromaticities were evaluated to be −2.67 and −4.17, respectively. The head-tail instability was observed above 10 mA, and it limited the peak-electron density in a bunch to 1.3×10^{16} m^{-3} or less. The proper location for sextupole magnets was on each side of the QF2 magnet in the short-straight sections, where the dispersion function was large in the operation mode. However, there was only a small space of 47 cm for a quadrupole and two sextupoles magnets.

We therefore developed a compact SQS magnet which had small pole length by using a small bore of 45 mm as Fig. 1 shows. Two sextupole magnets, SF and SD, were designed to correct the horizontal and vertical chromaticities with the magnet current of 5.00 A at the electron energy of 310 MeV. The SQS magnets were installed in December 1997 and the injection of the electron beam was restarted in January 1998. The chromaticities were measured by observing tune shifts with change of revolution frequency. As the result of the measurement, it was found that both chromaticities were corrected to be zero in the case of SF = 5.09 A and SD = 4.99 A. It should be noted that this result agrees with the designed beam current. In order to suppress the head-tail instability sufficiently, the chromaticities are corrected to be small positive value generally. Then we adjusted the horizontal and vertical chromaticities to 0.08 and 0.15 in the operation.

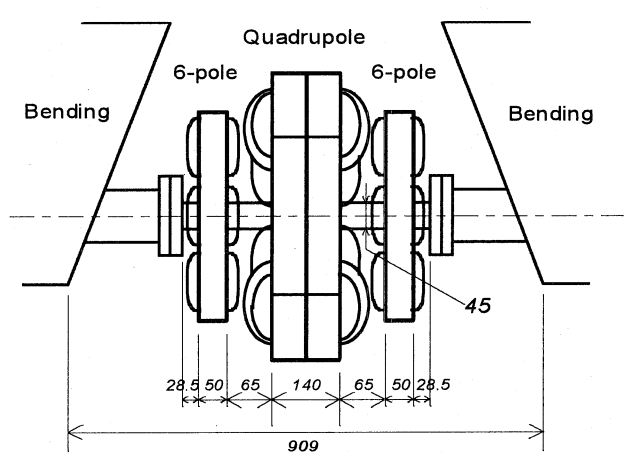

Fig. 1 Overview of the SQS section

3. FEL oscillations below 300 nm

We could obtain higher beam current of ~ 30 mA with using the chromaticity correction in the single-bunch operation. Though the anomalous bunch lengthening was observed above 2 mA, the bunch length was comparatively short. The typical value was about 220 ps at 20 mA. We also observed energy widening above 2 mA, so that a microwave instability occurred from low beam current. However, the peak-electron density in a bunch increased as the beam current increased, and it was over 6×10^{16} m^{-3}. Therefore we can conclude that the head-tail instability is sufficiently suppressed by the chromaticity correction. The FEL gain also increased remarkably, so that we achieved the FEL oscillations below 300 nm in 1998.

Fig. 2 illustrates three wavelength regions in which we succeeded the FEL oscillations. The wide ranges around 300 and 240 nm suggest that effective FEL gain is enough large. In those wavelength regions, HfO_2/SiO_2 multi-layer mirrors were used as the mirrors of the optical cavity. Their initial cavity loss was 0.26 and 0.54% at 300 and 240 nm, respectively. The maximum FEL gain at 300 and 240 nm were evaluated to be 3.2 and 2.5% by measured electron-beam qualities [3]. The cavity loss increased due to the exposure of the undulator radiation. In the case of the mirrors optimized at 240 nm, the cavity loss became 1.53 % after 77 mA· h exposures. The threshold current of the FEL oscillation was about 8 mA at 240 nm, and the FEL gain was estimated to be 1.55 %. Therefore this estimation of the FEL gain is in good agreement with the result of the mirror degradation. The peak power of the FEL micro-pulse was estimated to be about 200 and 40 mW at 300 and 240 nm, respectively.

The available FEL gain was about 2.2% at wavelength of 215 nm. In the case of the HfO_2/SiO_2 multi-layer mirrors, an FEL oscillation is not realized due to a large light-absorption loss. Then we selected Al_2O_3/SiO_2 multi-layer mirrors for the FEL experiment at 215 nm. By using the Al_2O_3/SiO_2 multi-layer mirrors in the optical cavity, the initial cavity loss was only 0.5%. We achieved the lasing around 215 nm in October 1998 [4], and the FEL wavelength was down to 212nm as Fig. 3 shows. The main parameters of the electron beam and the FELs below 300 nm are listed in Table 1.

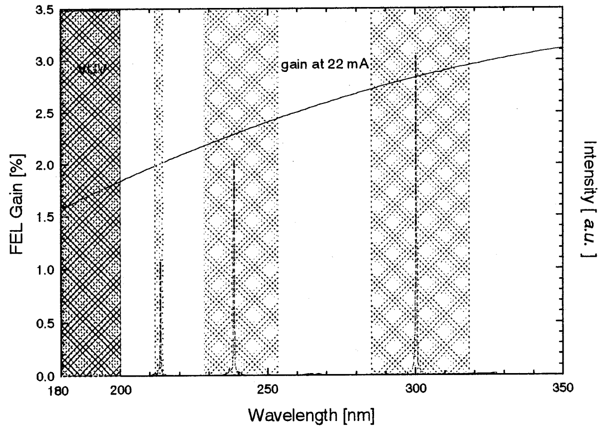

Fig. 2 Wavelength regions of FEL oscillations in 1998

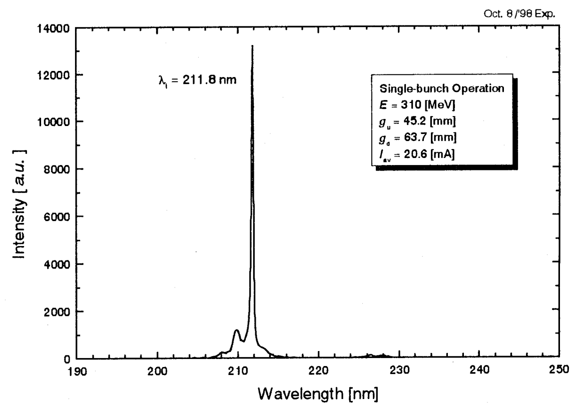

Fig. 3 A spectrum of the shortest-wavelength FEL

4. Improvement of the RF system

The tunable wavelength range was only 3 nm in the 215 nm FEL experiment. This fact suggests that it is difficult to realize FEL oscillations in the VUV region. In order to enhance the FEL gain, it was necessary to improve the NIJI-IV FEL system. Though we observed the microwave instability at low beam current, we decided to improve the RF system because of its superannuation [5].

A new RF cavity was installed in the NIJI-IV in January 1999. The basic design of the new RF cavity was not changed compared with the old one. It is a re-entrant type and its resonant frequency is about 162.2 MHz. But one of the electrodes of the new RF cavity can be moved by ±5 mm along the beam axis. It is possible to change the resonant frequency in the range of ±10 MHz by adjusting the position of the electrode. And it has two plungers which are the same sizes. Each plunger changes resonant frequency by 0.56 MHz. We can shift the resonant

Table 1
Main parameters of the FEL experiments below 300 nm

		300 nm	240 nm	215 nm
Electron-beam energy	[MeV]	309	309	309
Beam size (Horizontal)	[mm]	0.77	0.77	0.77
Beam size (Vertical)	[mm]	0.26	0.26	0.26
Bunch length (at 10 mA)	[ps]	170	170	170
Energy Spread (at 10 mA)	[%]	0.054	0.054	0.054
Defection parameter		2.02	1.70	1.54
Initial cavity loss	[%]	0.26	0.54	~ 0.5
Maximum FEL gain	[%]	3.2	2.5	2.2
Lasing wavelength range	[nm]	287-315	228-253	212-215
Peak micro-pulse power	[mW]	~ 200	~ 40	low

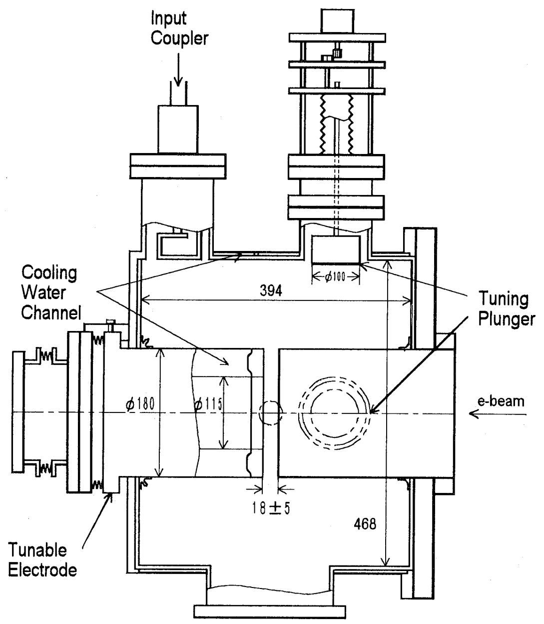

Fig. 4 Overview of the new RF cavity

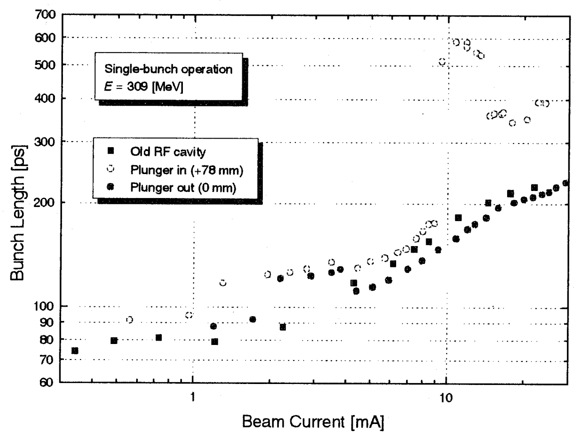

Fig. 5 Dependence of the bunch length on the beam current.

frequency of the HOMs by adjusting the positions of the plungers, so that we also control the stability of the electron beam. Moreover, the cavity body and the electrodes are dual structure, and enough cooling water flows in the gap. This efficient cooling system allows us to supply RF input of 10 kW, which would lead the natural bunch length to be shorter. The outline of the new RF cavity is shown in Fig. 4.

The Q-value of the new RF cavity was measured by transmission method. According to this measurement, the unloaded Q-value was about 6000 with pulling out the plungers. It is almost the same level as the unloaded Q-value of the old RF cavity (~ 6500). We investigated the shunt impedance of the new RF cavity by measuring synchrotron frequency. We use a relation that the effective RF power is roughly proportional to the fourth power of the synchrotron frequency at the low beam current. The shunt impedance is about 0.84 MΩ with the plungers located outside the cavity body. This value is almost same as that of the old RF cavity (~ 0.88 MΩ). The maximum RF input of the old RF cavity was about 1.2 kW due to discharge, but we can now operate the new RF cavity with the higher RF input of ~ 1.6 kW. Then the synchrotron frequency is several percent higher and the bunch length is several percent shorter as Fig. 5 shows. This result indicates that the FEL gain would enhance by several percent. We also plan to improve the RF power supply to increase the maximum RF input from 2 to 10 kW this autumn. This improvement will realize the enhancement of the FEL gain.

We observed that several HOMs in the frequency of ~ 700 MHz or more were induced in the RF cavity when the self-coupled bunch instability occurred remarkably. But it was confirmed that the bunch oscillation was considerably suppressed by pulling out the plungers over the surface of the RF body. This effect is also shown in Fig. 5.

5. Conclusions

We installed the SQS magnets in all of the short-straight sections of the NIJI-IV and corrected the chromaticities. The head-tail instability was sufficiently suppressed, so that the peak-electron density in a bunch was enhanced over 6×10^{16} m^{-3}. As a result, we achieved the FEL oscillations below 300 nm in 1998. The HfO_2/SiO_2 multi-layer mirrors were used as the mirrors of the optical cavity for the 300 and 240 nm FEL experiments. In the case of the 215 nm FEL experiments, the Al_2O_3/SiO_2 multi-layer mirrors were used. The estimation of the FEL gain is in good agreement with the measurement of the mirror degradation.

In order to enhance the FEL gain further, we renewed the RF cavity. The new cavity was designed to supply RF input of 10 kW and to stabilize the electron beam with control of the HOMs. It has an adjustable electrode and two plungers which are used to control the resonant frequency of the HOMs. The bunch length becomes several percent shorter due to the higher RF input. We also plan to improve the RF power supply so as to increase the maximum RF input from 2 to 10 kW this autumn. We expect that this improvement realizes the large enhancement of the FEL gain.

References

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