A STUDY OF BROAD-BAND FREE ELECTRON LASER WITH A CONPACT STORAGE RING NIJI-IV

N. Sei, K. Yamada, H. Ohgaki, H. Ogawa, M. Yasumoto, T. Mikado

Photonics Research Institute, National Institute of Advanced Industrial Science and Technology
1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, JAPAN

Abstract

The oscillations of free electron lasers (FELs) have been studied with a compact storage ring NIJI-IV at National Institute of Advanced Industrial Science and Technology (AIST: former ETL). In a short wavelength region, we achieved lasing at a wavelength of 212 nm, which was the shortest record for FELs in 1998. In order to further shorten the FEL wavelengths, RF system was improved to increase the RF input power from 2 to 10 kW, so that the peak electron density in a bunch became over 9×10^{16} m^{-3}. We also plan for FEL oscillations in the infrared region so as to generate quasi-monochromatic and energy-variable hard X-rays with FEL-Compton backscattering process. The aim of the FEL wavelength is a renge between 1 to 10 μm. We just produce a 3.55-m optical klystron. The maximum FEL gain at 10.6 μm would be estimated to be over 2%.

1 INTRODUCTION

A study to shorten the FEL wavelength has been carried out with the compact storage ring NIJI-IV at the AIST. The first lasing of FELs was achieved at the wavelength of around 590 nm in 1992 [1], and the first lasing of FELs in the UV region was achieved at around 350 nm in 1994 [2]. It was difficult to further shorten the FEL wavelength because a head-tail instability limited peak-electron density in an electron bunch. Then we inserted sextupole-quadrupole-sextupole magnets in the short straight sections of the NIJI-IV to correct the chromaticities in 1997. The peak-electron density was remarkable enhanced by the chromaticity correction (> 6×10^{16} m^{-3}) [3], so that we achieved FEL oscillations at the wavelength of 212 nm, which was the shortest record for FELs in 1998 [4]. RF system in the NIJI-IV was improved to increase the RF input power from 2 to 10 kW in 1999-2000 [5]. This improvement led the FEL wavelength to go down to 211 nm. We challenge a lasing below 200 nm at present.

We also propose an FEL-X project [6], which aims to hard X-ray generation through FEL-Compton backscattering with infrared FELs in the NIJI-IV. In order to obtain the hard X-ray with the energy of 0.1-1 MeV, it is necessary to generate infrared FELs at the wavelength of 1-10 μm. The infrared FEL experiments will be executed in a long straight section which is located on the opposite side of the ultraviolet FEL line in the NIJI-IV. We just produce a 3.55-m optical klystron.

In this article, present status of the short-wavelength FEL experiments and outline of the FEL-X project are discussed.

2 SHORTENING FEL OSCILLATIONS TOWARD THE VUV REGION

The FEL wavelength was shortened down to 212 nm by chromaticity correction in 1998 [4]. But the tunable wavelength range was only 3 nm in the 215-nm FEL experiments. This fact suggested that the effective FEL gain was not enough and it was difficult to oscillate FELs below 200 nm. In order to enhance the FEL gain, it was necessary to improve the NIJI-IV FEL system. Though microwave instability was observed over ~ 2 mA in the single-bunch operation, improvements of the RF system of the NIJI-IV were given to priority by its superannuation.

The old RF cavity had damage on its surface due to electric discharge, so that we could not input power of 1.2 kW or more into the RF cavity. The natural bunch length was long with 70 ps. Then we decided the increase of RF input so as to shorten the bunch length. A new RF cavity was inserted into the NIJI-IV in 1999. The cavity body and the electrodes are dual structures, and enough cooling water flows in the gap. This efficient cooling system allows us to supply the RF input of 10 kW. Moreover, the RF cavity has two plungers and

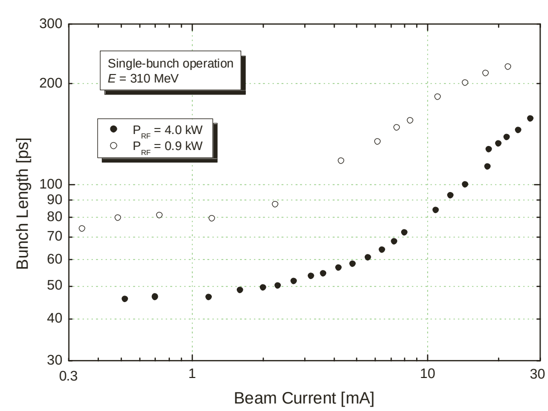

Fig. 1 Dependence of bunch length on the beam current.

compensates a shift of the resonant frequency in the high RF-power operation. A power supply for the RF cavity was renewed in 2000. This power supply can input the power of ~ 10kW in the RF cavity. We usually operate the power supply with the power of 4 kW to keep the vacuum condition.

Dependence of the bunch length on the electron-beam current was measured by a streak camera, and the bunch compression due to increase of the RF input was observed. As Fig.1 shows, the natural bunch length becomes about 40 ps, which is in agreement with the theoretical estimation. The bunch length is shortened even in high current region, and it is about 170 ps at 30mA. The peak-electron density in a bunch becomes over 9×10^{16} m^{-3} [7]. The tunable wavelength range is enhanced from 211 to 218 nm, so that the maximum FEL gain is estimated to be over 2.5% at 200 nm. We just improve the vacuum chambers of the NIJI-IV to suppress the microwave instability. The wavelength of the NIJI-IV FEL would rush into the VUV region after this improvement.

3 TEMPORAL STRACTURE OF THE NIJI-IV FEL

Temporal structure of the NIJI-IV FEL was investigated by a dual-sweep streak camera. The FEL micropulse penetrates repeatedly from the cavity mirror by revolution frequency of the electron bunch. It is known that a row of the micropulses forms a certain kind of macro-temporal structure. Though a quasi-stable CW lasing was observed at the best synchronism in the NIJI-IV FEL experiments, it was difficult to keep this state. The pulse width and spectral bandwidth were <15 ps and 0.06 nm FWHM at the best synchronism. The macropulse of the NIJI-IV FEL was observed near the best synchronism as well as other storage ring FELs. The typical macropulse lasing is shown in Fig. 2, where the FEL wavelength is 214 nm and the FEL gain in the cooling state is about 2.7%. It is noted that micropulse is modulated with a frequency of 100 Hz and an amplitude of ~20 ps in Fig. 2a. This modulation would be caused by the electricity oscillation of power supplies. The drift of the micropulse from the synchronism indicates the detuning length of 0.7 μm in the optical cavity.

The effective FEL gain can be obtained by using a temporal structure of FEL intensity. As Fig. 2c shows, amplitude of the effective FEL gain is only ~ 0.04%. Because the repetition period of the macropulse is mach shorter than the radiation damping time of the electron bunch, the micropulse raises up before the electron bunch is not cooling sufficiently. The macropulse has asymmetry shape, and the amplification time is longer than the attenuation time.

When the macropulse structure appears in lasing, the effective FEL gain is caused by a periodical vibration of the electron-beam energy spread. This vibration can be

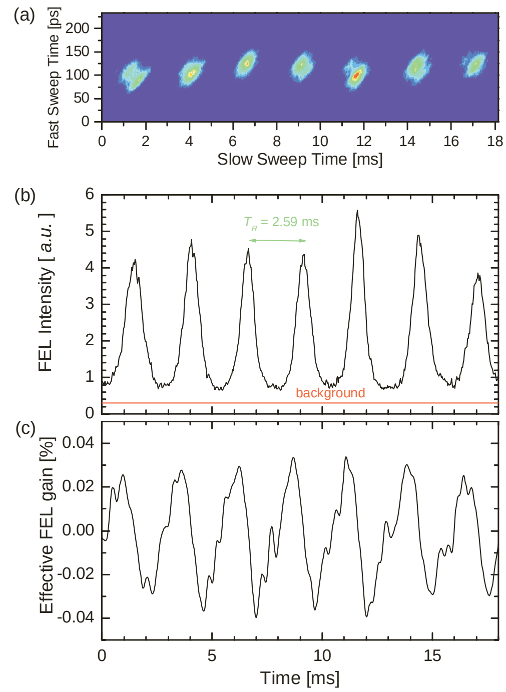

Fig. 2 Example of temporal structure of the FEL-macropulse: (a) dual-sweep streak camera image; (b) FEL intensity; (c) Effective FEL gain.

confirmed by observing the bunch length. Fig. 3 shows a typical vibration of the bunch length in the FEL oscillation of 300 nm. The bunch length and the FEL gain in no lasing are about 150 ps and > 3%, respectively. The electron-bunch length is enhanced by heating effect of the FEL oscillation, and the FEL gain in lasing becomes down to about the cavity loss. Amplitude of the vibration is about 1.5% of the average bunch length in Fig. 3, so that the effective FEL gain would be ~ 0.05%. This result is almost consistent with estimation from the shape of the macropulse intensity.

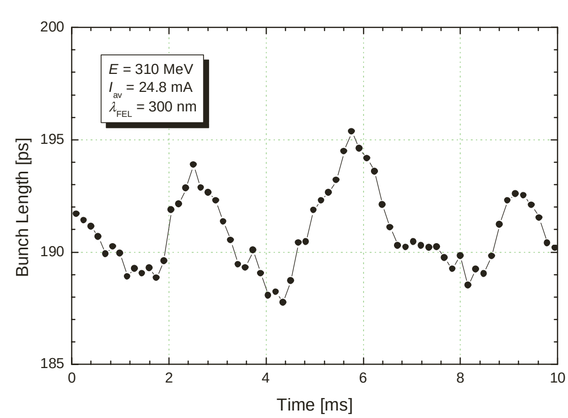

Fig. 3 Example of the bunch length in the FEL oscillation.

4 FEL-X PROJECT

Tunable and monochromatic hard X-ray beams are demanded in fields of medical diagnostics, microscopy, and material science. FEL-X project aims to obtain such a hard X-ray beam (0.1-1 MeV) by FEL-Compton backscattering process. A storage ring FEL as an incidence laser has advantage of the space-time overlapping because the FEL oscillation achieves it naturally. The peak power of the FEL in an optical cavity is strong, so that a high-yield photon beam can be expected by FEL-Compton backscattering process. The photon energy in the FEL-X project is comparatively low, so that the electron-beam loss caused by the inverse Compton backscattering would be negligible.

In FEL-Compton backscattering process, the photon energy E_p is given with the electron-beam energy in unit of its rest mass γ by following equation [7]:

$$E_p \approx 3.65\times10^{-28}\frac{\gamma^4}{\lambda_u^3 B_0^2}$$

where λ_u is the undulator period and B_0 is the peak magnetic field of the undulator. Considering the electron-beam energy of 250-450 MeV in the NIJI-IV, we select λ_u = 20 cm and $B_0 \sim 0.5$ T for the new insertion device in the FEL-X project. Therefore the expected FEL wavelength would be 1-10 μm. In order to enhance the FEL gain, an optical klystron type is adopted. The new optical klystron FELOK-III has two undulator sections and one dispersive section, and its length is 3.55m. The number of the period in an undulator section is 7 and the length of the dispersive section is 72 cm. Outline of the ETLOK-III is illustrated in Fig. 4. The maximum K value is 10.04. The maximum N_d, which is the number of periods of the FEL wavelength passing over an electron in the dispersive section, is over 90 at the wavelength of 10.6 μm where we aim for FEL oscillations in the first stage of the FEL-X project. We just produce this optical klystron.

FEL gain estimated with the present electron-beam qualities would be over 2% at 10.6 μm [7]. As the FEL wavelength becomes short, a filling factor grows because the FEL size becomes near to electron-beam sizes in the optical cavity. Therefore the FEL gain does not decrease so much below the wavelength of 10 μm. We will also challenge FEL oscillations with higher harmonics below the wavelength of 3 μm. The filling factor is enough large in a short wavelength region of 3 μm or less, so that an FEL gain for the third and fifth harmonics is large with over 3%. Then it will be not difficult to achieve FEL oscillations with the higher harmonics. The expected yield of the hard X-ray beam which will be generated by this infrared FEL will be 10^5-10^6 per second with an energy spread of 3% [8].

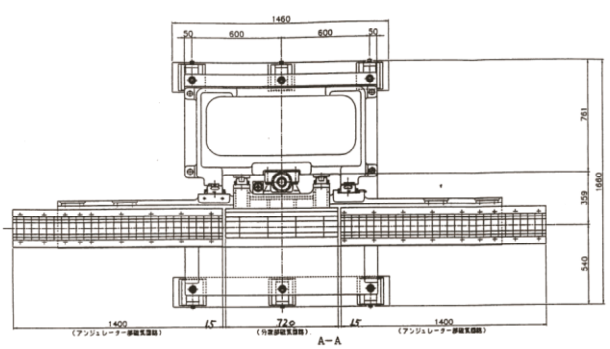

Fig. 4 Outline of the new optical klystron ETLOK-III

5 CONCLUSIONS

We reported the recent FEL experiments in the deep UV region. The electron-bunch length was shortened by the improvement of the RF system in the NIJI-IV, so that the peak-electron density became over 9×10^{16} m^{-3}. We achieved FEL oscillations in the wavelength region of 211-218 nm. The FEL gain is over 2.5% at 200 nm. We investigated temporal structure of the FEL oscillations, and observed the quasi-stable CW lasing and the FEL macropulse. We just renew the vacuum chambers of the NIJI-IV so as to decrease longitudinal broad-band impedance. The FEL gain will be large enough to lase in VUV region.

We also explained the FEL-X project. Hard X-ray beams with the energy of 0.1-1 MeV and the yield of 10^5-10^6 per second with an energy spread of 3% are expected in the FEL-X project. We just produce the new optical klystron ETLOK-III for the FEL-X project. The estimated FEL gain of the ETLOK-III will be 2-3% and the expected FEL wavelength will be 1-10 μm.

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