RECENT PROGRESS OF THE NIJI-IV VUV/IR FEL*

N Sei[#], K. Yamada, H. Ogawa, M. Yasumoto, K. Y. Watanabe, Research Institute of Instrumentation Frontier, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Abstract

Studies of free electron lasers (FELs) in a broad wavelength region from the VUV to the IR have been developed with the compact storage ring NIJI-IV at AIST. In the DUV and VUV regions, the FEL is used as an intense light source for real-time surface observation with the photoelectron emission microscopy. To extend the application field of the NIJI-IV FEL, experiments to obtain FEL oscillations at the wavelength below 195 nm are going on and the renewal of the optical cavity is planed. In addition, a 3.6-m optical klystron, ETLOK-III, for developing IR FELs has been installed in one of the straight sections of the NIJI-IV. Fundamental and higher harmonic spontaneous emissions from the ETLOK-III were observed in the visible and near-infrared regions. It was expected that the FEL gain for the 3rd harmonics exceeded 6%. An improvement of the electron-beam transport system is also going on to obtain space for an optical cavity of IR FELs.

INTRODUCTION

Free electron lasers (FELs) from the vacuum ultra-violet (VUV) to the middle infrared (IR) are being developed with the compact storage ring NIJI-IV at AIST. In studies to shorten the FEL wavelength, we achieved FEL oscillations at the wavelength of 212 nm with Al_2O_3/SiO_2 multilayer mirrors in 1998 [1]. The shortest lasing wavelength was down to 198 nm in 2003, and the NIJI-IV FEL reached to the VUV region [2]. FEL experiments with using low-loss cavity mirrors optimized around 195 nm are being carried out now. Moreover, renewal of an optical cavity is scheduled. Bases of the new optical cavity are made of granite, so that they will be able to absorb vibrations from the floor and to prevent a change of cavity length. Two mirrors are installed in a new mirror chamber which is set on the base.

Application experiments with using deep ultra-violet (DUV) and VUV FELs are also being developed [3]. Because the work function of transition-metals lays around 5 eV, FELs with the wavelength of about 200 nm are suitable as an intense light source to observe chemical reactions which are occurred on the surface of the transition-metals. We observed a Palladium surface, where CO and O_2 gasses were introduced with various conditions, in combination with photoelectron emission microscopy (PEEM).

In order to realize storage ring FEL oscillations in the IR region, we developed an optical klystron ETLOK-III and installed in a long straight section of the NIJI-IV in 2004 [4]. Spectra of spontaneous emission from the ETLOK-III with deep modulations have already been observed in the visible and near-infrared regions. FEL gain would be enough high to realize oscillations in those regions. However, it was difficult to store an electron beam in a condition of narrow undulator gap below 80 mm because of distortion of the electron-beam orbit generated in the dispersion section. To avoid the distortion of the electron-beam orbit, we attached iron plates to shunt magnetic field of the both end magnets in the dispersive section and inserted a pair of thin steering coils between the vacuum chamber and the magnets of the dispersive section. The plate can be moved on the side of the end magnet, so that the position of the plate is adjusted with the gap of the dispersive section. We also plan to improve electron-beam transportation system from a linear accelerator TELL to obtain space where a mirror chamber of an optical cavity for the IR FELs will be located. In this article, we present recent progress of the NIJI-IV VUV/IR FEL system.

IMPROVEMENT OF ELECTRON-BEAM TRANSPORTATION SYSTEM

A beam line which is set on the extension of the TELL is used as the present electron-beam transportation from the accelerator room to the pion room where the NIJI-IV is set. Because the electron-beam transportation passes by the side of the bending magnet (BM6) in the NIJI-IV, there is no space to set a vacuum chamber of an optical cavity for the IR FEL [5]. The bending magnets of the electron-beam transportation system shift the electron-beam orbit in the NIJI-IV by about 0.2 mm. Then, we plan to use a new beam line which is 2.48 m away in parallel from the present one. In the accelerator room, the new electron-beam transportation uses a bending magnet which branches the electron beam from the TELL to a storage ring TERAS. A new bending magnet which distributes the electron beam to the pion room has been installed on the electron-beam transportation of the TERAS. Vertical inner size of a vacuum chamber in the bending magnet is 36 mm and it is half of that of the old vacuum chamber. We have already confirmed that it does not disturb electron-beam injection to the TERAS. We will improve the electron-beam transportation in the pion room and complete the improvement next winter.

In the improvement of the electron-beam transportation, it should be considered that Twiss parameters of the electron-beam transportation at the exit are matched to ones of the NIJI-IV at the septum magnet. As Fig. 1 shows, beam envelopes at the end of the electron-beam transportation hardly change before and after the improvement. Because a vertical beam size in the new electron-beam transportation is smaller than that in the

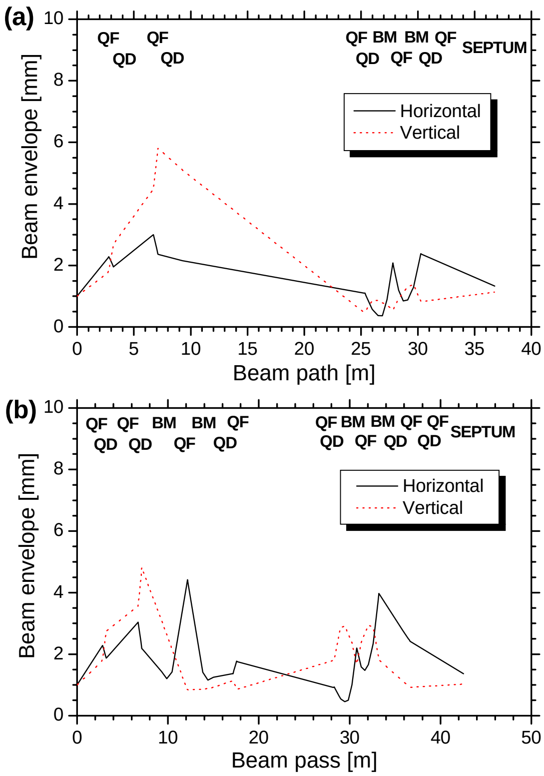

Figure 1: Calculated beam envelopes in the electron-beam transport systems before (a) and after (b) the improvement. The beam sizes, angular spread and energy spread at the last beam position monitor in the Linac room are assumed to be 1 mm, 1 mrad and 0.5%, respectively.

present one, it is expected to increase efficiency of electron injection. However, performance of the TELL electron beam is not so stable. It will be necessary to adjust focusing force of quadrupole magnets from the estimated value in order to obtain an optimum operation point.

SHORT-WAVELENGTH FEL EXPERIMENTS

For developing new applications, FEL oscillations around 195 nm and below are being tried with using two kinds of low-loss Al_2O_3/SiO_2 multilayer mirrors manufactured by Japan Aviation Electronics Industry, Ltd. They were manufactured with ion beam sputtering technique. The original cavity losses of those two kinds of mirrors were 2.6% and 1.9% at a minimum-loss wavelength of 195 nm, respectively. However, the losses rapidly increased up to 4.2% with 58 mA-h exposure and 8.0% with 23 mA-h exposure, and the minimum-loss wavelength was shifted to a shorter wavelength by exposure to the optical klystron radiation as shown in Fig. 2. The mirrors which had the lower loss before the exposure were more sensitive in degradation due to the exposure. It is known that mirror degradation includes both surface and volume degradations [6,7]. The latter

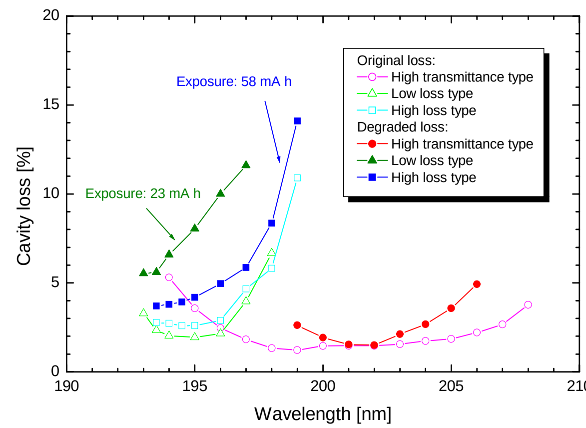

Figure 2: Cavity losse as a function of wavelength. Triangle and quadrangle represent low original-loss type and high original-loss type, respectively. For the reference, the cavity loss of the mirrors for FELs around 200 nm is shown by circle.

Figure 3: Photograph of the new stand and adjustment system.

type is instantaneously caused by the exposure to the optical klystron radiation, and saturates at relatively low level. The cavity loss at an optimum wavelength hardly increases even if the exposure increases. Then, the cavity loss after exposure was at least 3.7% in the FEL experiments. This value was almost equal to the maximum FEL gain obtained with the NIJI-IV FEL system around 195 nm, so that we have not realized FEL oscillations. It would be necessary for the lasing to develop low original-loss mirrors which sufficiently suppress the volume degradation.

In order to stabilize FEL oscillation, we plan to renew an optical cavity in the short-wavelength FEL system. Although the cavity mirrors are located at height of 1.48 m from the floor level, weight of a present stand supporting a mirror chamber is only 20-30 kg. The mirror chambers are influenced easily by change of the cavity length and vibrations from the surroundings, so that it is difficult to obtain a stable cw mode in the FEL oscillations. Then, we will install granite with the weight of about 2t as the new stand. It has already been reported that a massive stand is effective to dump the vibrations from the surroundings [8]. We adopt linear stages and optical mounts manufactured by Newport Co. (M-MTM100PP.1, M-MVN80 and SL20AN) as adjustment system of the new mirror chambers. The cavity length can be adjusted with a precision of 0.1 μm and rotation of the cavity mirror can be controlled with the resolution of 0.8 μrad. Figure 3 shows a photograph of the new stand and adjustment system. Two cavity mirrors can be installed in the new mirror chamber at the same time. We can expect that it is easy to observe the spontaneous emission and to carry out FEL oscillations in a wider wavelength region. It would considerably improve the environment of the FEL experiments. The new optical cavity has already completed and it will be installed in the short-wavelength FEL system instead of the old one this autumn.

LONG-WAVELENGTH FEL PRELIMINARY EXPERIMENTS

A lot of FEL facilities have been constructed and FELs have been used for various applications in the middle-infrared region where there are few useful light source. Most of those FEL facilities use a Linac as an accelerator device. Typical pulse width of the Linac FEL micropulse is from 0.5 to 5 ps due to the property of the Linac electron beam. A lot of applications which use the characteristic of the short pulse have been carried out. However, typical line width of the Linac FEL is over 10^{-3} because of the short pulse. The Linac FEL is too wide to apply to some experiment, such as near-field infrared microspectroscopy. On the other hand, the typical line width of a storage ring FEL is about 10^{-4}, and it can be used as well as synchrotron radiation passed through a monochromator. Photon flux of the storage ring FEL at a wavelength of 10 μm is about 10^{17} /s for the average power of 1 mW. This photon flux is far larger than that of IR beam lines set in conventional storage rings.

Paying attention to this fact, we have advanced the development of the storage ring FEL in the IR region [5]. An optical klystron for the IR FEL, ETLOK-III, has been installed in one of the long straight sections of the NIJI-IV [4,5]. Spectra of the spontaneous emission from the ETLOK-III were measured in the visible and near-IR regions. Relationship between the wavelength and the maximum FEL gain estimated from the measured spectra is shown in Fig. 4. It is noted that the maximum FEL gain is over 2% in those regions. The maximum FEL gain for the third harmonics is estimated to be over 6% in the visible region due to rather large N_d, which is a number of periods of the FEL wavelength passing over an electron in the dispersive section. Because high-reflection mirrors of 99.8% or more are available in the visible and near-IR regions, it will be easy to realize FEL oscillations in those regions if we install mirror chambers in the long-wavelength optical cavity.

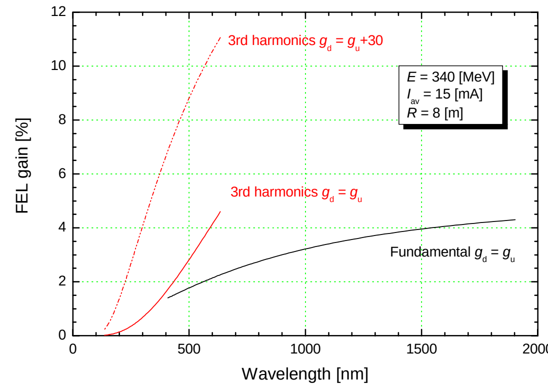

Figure 4: Relationship between the wavelength and the estimated FEL gain at the electron-beam current of 15 mA.

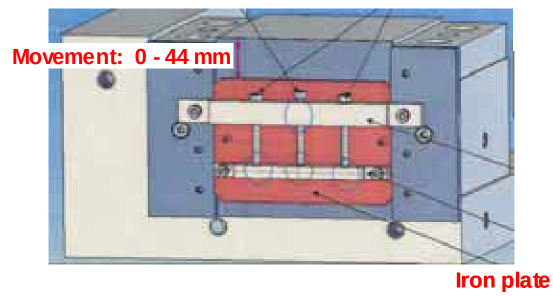

Figure 5: Layout of the iron plate attached on the end magnet of the dispersive section.

However, the electron beam passes in the magnetic field of the dispersive section which is not uniform in the horizontal direction. The electron beam is kicked in the dispersive section due to the long length of the dispersive section and the low energy of the electron beam. In a case of a narrow gap of the dispersive section, the distortion of the electron orbit is too large to be ignored. 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 cannot be opened from the gap of the undulator section over 38mm. Therefore, we could not observe the ideal spontaneous emission in the middle IR region. For cancelling the kick force with a pair of thin steering coils putted on the vacuum chamber, it is necessary to enlarge the thickness of the coils. The parameter N_d decreases due to the thick coils, so that the FEL gain also decreases. Therefore, in addition to the 3-mm thickness coils, we attached 5-mm iron plates to shunt magnetic field of the both end magnets in the dispersive section. Thickness of a holder included with the iron plate is 14 mm, and the dispersive section can be changed independently of the undulator sections. As the Fig. 5 shows, the plate can be moved form the level of the dispersive magnet to 44 mm on the side of the dispersive magnet. The coils only have to correct 230 A turn due to the movement of the plates when the dispersive gap is between 42 and 188 mm. We have not carried out experiments to estimate effect of the plates to the electron beam yet. They will be carried out next year.

APPLICATION OF DUV/VUV FEL

Though the average power of the NIJI-IV FEL is 1 mW or less in the DUV and VUV regions, the line width is rather narrow, about 3×10^{-4}. The NIJI-IV FEL is suitable to investigate resonances closed in a narrow band and to obtain high spatial resolution in surface observation. We have considered that the NIJI-IV FEL can be applied as a light source of PEEM experiments, and we have developed real-time observation of physical and chemical reactions generated on surface of the transition-metals [3].

The short-wavelength FEL was transported in the air to the measurement room where the PEEM system (STAIB Instrumente, type 350) was located. This PEEM system has three sets of electron lenses and a micro channel plate equipped with a fluorescent screen. By viewing the focused images on the fluorescent screen with a CCD camera, transient phenomena can be monitored with video-camera time resolution of 33 ms. Although the ideal spatial resolution of this system is 80 nm, the value of spatial resolution estimated from experiments is about 300 nm. The outline of the PEEM system is illustrated in Fig. 6.

In order to investigate utility of the NIJI-IV FEL in the PEEM measurements, we observed a Palladium surface, where CO and O_2 gasses were introduced with various conditions, with the FEL-PEEM system. The FEL with the wavelength of 202 nm and the intensity of 500 mW/cm^2 was used in the experiments. It could be observed that adsorption and desorption of the gases on the Palladium surface were generated optionally with the changes of the gas pressure and the temperature of the surface. The details of the FEL-PEEM measurements are described in another our article of these proceedings [9]. We also plan to use the NIJI-IV FEL at the wavelength around 200 nm as a light source for analysis of protein structure. It is expected that the UV/VUV FELs will be applied further by using a characteristic of the variable wavelength.

CONCLUSIONS

Many efforts for developing the FEL oscillations from the VUV to the IR region and the FEL application were made with the compact storage ring NIJI-IV. For the UV/VUV region, extension of FEL oscillations to the shorter-wavelength region could not be achieved, but the renewal of the optical cavity and the FEL-PEEM measurements were advanced. We could observe that adsorption and desorption of the CO and O_2 gases on the Palladium surface depend on the changes of the gas pressure and the temperature of the surface. For the IR region, the spectra of the spontaneous emission from the ETLOK-III were measured below the near-IR region. It

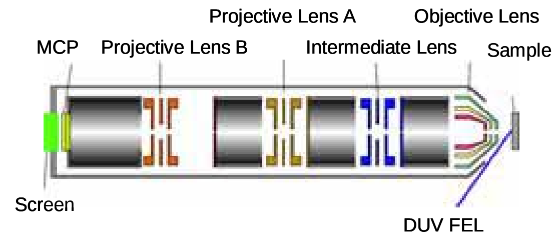

Figure 6: Schematic layout of the PEEM system.

was expected that the maximum FEL gain in this wavelength region was over 2% and it would be easy to realize FEL oscillations. In order to observe the spontaneous emissions in mid-IR region, we improved the dispersive section of the ETLOK-III to compensate the distortion of the electron orbit. The improvement of the electron-beam transport system to obtain space for the optical cavity of the IR FEL will be completed next winter. It will be expected to extend the application field for the NIJI-IV FEL and to estimate the FEL gain in the mid-IR region in near future.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Hohara for his help in this work.

This work was supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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