ETL STORAGE-RING FEL----OSCILLATION EXPERIMENTS IN VISIBLE

T. Yamazaki, K. Yamada, S. Sugiyama, H. Ohgaki T. Noguchi, T. Mikado, M. Chiwaki, R. Suzuki, T. Tomimasu*, and M. Kawai**
Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba City, Ibaraki 305, Japan
* FEL Engineering Co., 2 Kyomachibori, Nishi-ku, Osaka City 550 Japan
** Kawasaki Heavy Industries Ltd., 1-1 Kawasaki-cho, Akashi, Hyogo 673, Japan

Abstract

Oscillation of a free electron laser (FEL) has been achieved on the electron storage ring TERAS of Electrotechnical Laboratory (ETL) at 598 nm in Mar. 1991, which was the first visible FEL in Japan. In the present paper, the oscillation experiment, and the progress after the first oscillation are described.

Introduction

Storage ring is regarded as one of the most favorable accelerators for short-wavelength FEL's because of its excellent beam quality at high energy. Basic studies on optical klystron (OK), optical cavity, and electron beam for FEL, have been carried out for several years at an 800-MeV electron storage ring TERAS of ETL[1], and the FEL gain was successfully measured[2] in 1989. The FEL reached oscillation threshold in Feb. 1991, and the first oscillation was observed[3] in Mar. 1991. Since then, the beam current has been increased, and some additional data have been accumulated. The outline of the ETL storage-ring FEL and the recent results are described in the following.

Experiment

The plan view of the ETL storage ring TERAS dedicated to synchrotron-radiation research is shown in Fig.1. The main characteristics of the ring have been described in ref.2. Fig.2 shows the present experimental arrangement for the FEL oscillation.

Optical klystron

An optical klystron (OK)[4] shown in Fig.3 is used to enhance the gain, since the straight section of the ring is as short as 1.8m. The permanent-magnet blocks are made of NEOMAX-35. The period in each usual-undulator section (US) is 76mm with 8 periods in each. The length of the dispersive section (DS) is 228mm and the total length is

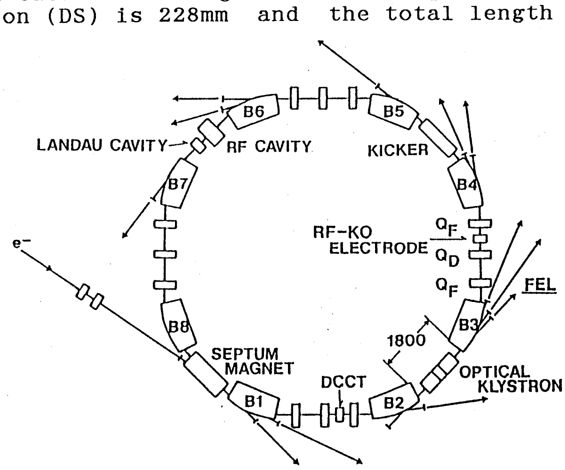

Fig.1 ETL storage ring TERAS

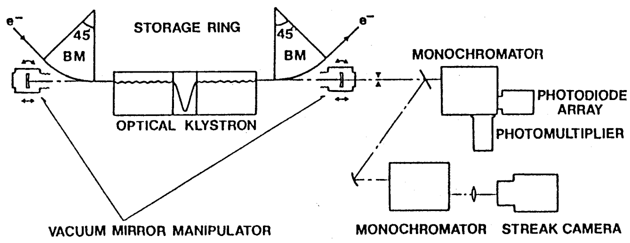

Fig.2 Experimental arrangement for ETL FEL

1.47mm. The gaps of the US's and the DS can be changed independently. During the present experiments, the gap in the US's was 40.3mm and that in the DS was 58.5mm. The value of the deflection parameter K was 2.2 and that of N_d, the average number of optical wavelengths passing over an electron in the DS, was 73.5. The electron orbit in the OK is schematically shown in Fig.2. The shape of the spontaneous-emission spectrum is close to that shown in Fig.6(a), where the fine structure peculiar to OK is seen. It is the origin of the gain enhancement, because a Madey's theorem says that the gain is nearly proportional to the slope of the spectrum[5].

Optical cavity

The laser cavity is composed of low-loss concave dielectric multilayer mirrors. The initial loss in each mirror has been measured by a cavity-decay-time method to be about 42ppm including the 30-ppm transmission for output coupling. However, the downstream mirror is very susceptive to damage due to exposure to higher harmonics of spontaneous emission. According to our experiment, the cavity loss increases quite rapidly with exposure. Thus, the round-trip loss during the FEL oscillation is deduced to range up to $4 \sim 5 \times 10^{-4}$. With more exposure, even the wavelength region of low loss becomes narrower, and the optimum wavelength tends to shift toward the longer side.

For the precise overlapping of light pulses with electron bunches, a pair of vacuum mirror manipulators with accuracy better than 0.2μm, driven by stepping motors and piezoelectric actuators, are used. The

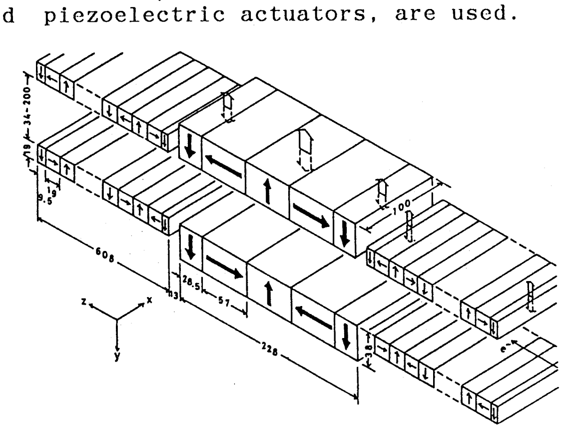

Fig.3 ETL optical klystron

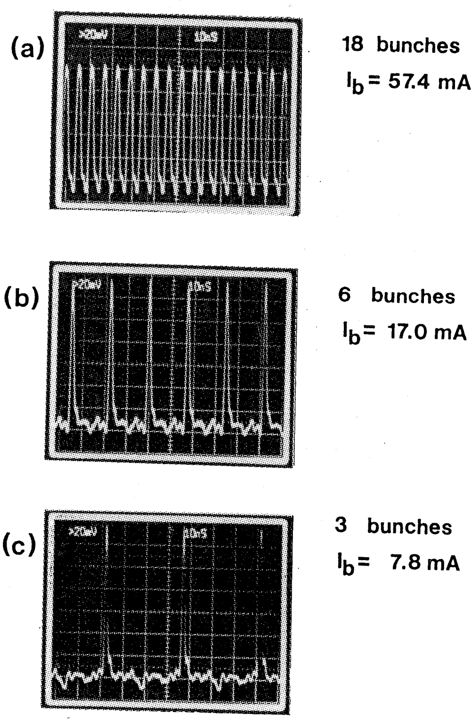

Fig.4 Bunch selection by RF-KO

cavity length can be roughly tuned by observing, with a streak camera, the temporal shape of a part of the light penetrating the downstream cavity mirror (Fig.2). The resolution of this method is about ± 15μ m, depending of course on the cavity loss and bunch length.

Electron beam

The quality of the stored beam in the full 18-bunch mode has been presented precisely in ref.1.

After the ring has been filled at about 300MeV, the number of bunches is reduced to 3 by a two-stage RF-KO (radio-frequency knock-out) method. The bunch spacing in this mode is just twice the cavity length. The rf signal is fed to the perturbation electrode (Fig.1). Fig.4 shows the bunch structure (a) before the RF-KO, (b)after the first-step RF-KO, and (c)after the final RF-KO. Recently, the first-step RF-KO is carried out during the fill of the ring. This greatly moderates the coupled-bunch instability, and the final current in excess of 10mA/bunch has been achieved. Then, the beam energy is ramped down to 231MeV in order to accommodate the FEL experiment at around 600nm.

Finally, the Landau cavity shown in Fig.1 with twice the ring frequency is powered, and then the position of the tuner and the phase of the RF are adjusted to stabilize the beam. Fig.5(a) shows the frequency spectrum of the beam when the Landau cavity is not powered, and (b) powered and conditions adjusted. The central frequency is 343.24MHz which is twice the ring frequency, and the scale of the abscissa is 100kHz/div. The coherent synchrotron oscillation has been successfully suppressed in the case of (b). The energy spread and the bunch length has been observed to be dramatically reduced after the stabilization[2]. Systematic measurement of the parameters in the 3-bunch mode is yet to be made.

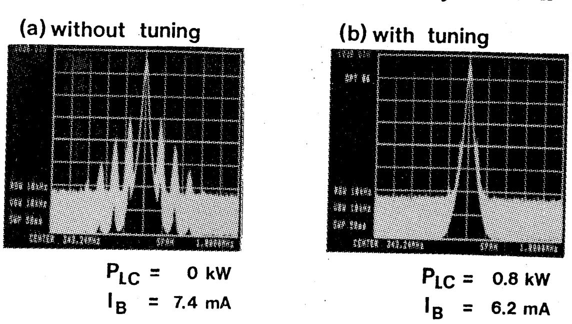

Fig.5 Electron-beam stabilization

Gain measurement

The method for measuring the FEL gain by introducing an external laser and the results have been reported precisely in ref.2. The peak gain with the beam current 1.6mA/bunch was 1×10^{-4}. It should be noted, however, that the beam quality during the oscillation experiment is much better than that during the above measurement. The Madey's theorem mentioned above has been confirmed also.

Oscillation experiment

The arrangement for the oscillation experiments is shown in Fig.2. A half of the output light is introduced to a monochromator combined with a highly sensitive photodiode array and real-time spectrum is observed to detect instantaneous change of the undulator-radiation spectrum, which accompanies the laser oscillation. The spectral resolution and the sampling time of the system are 0.21nm and 33ms, respectively. Alternately, this monochromator is combined with a photomultiplier to observe temporal change of the output-light intensity. The other half of the output light is branched to the streak camera for the tuning of the cavity length.

Results and discussion

With the above setup, the lasing can be observed after the following procedures. The angles of the mirrors have to be adjusted carefully to obtain the TEM_{00} mode of the light beam. Then the cavity length is tuned precisely observing the output spectrum. The fine tuning of the Landau cavity (the phase and the tuner) is necessary at this stage, and then the oscillation is observed when the FEL gain exceeds the cavity loss.

Fig.6 shows the output spectra obtained with the photodiode array connected to a computer, when the electron-beam current was 8~5mA/bunch. In the figure, (a) shows a spontaneous-emission spectrum after penetrating the downstream mirror when the electron-beam quality is not as adequate as to begin oscillation, and (b) shows spectra near oscillation, and (c) shows a spectrum during oscillation with a filter in front of the monochromator to observe the peak intensity.

The lasing wavelength is 598nm and the linewidth is about 0.26nm, including the resolution of the detection system. The peak intensity of the lasing spectrum is as high as 10^4 times that of the spontaneous emission. The lasing wavelength is shifted from a wavelength which gives a maximum of the spontaneous emission toward the longer side. The amount of the shift is 0.17 times the

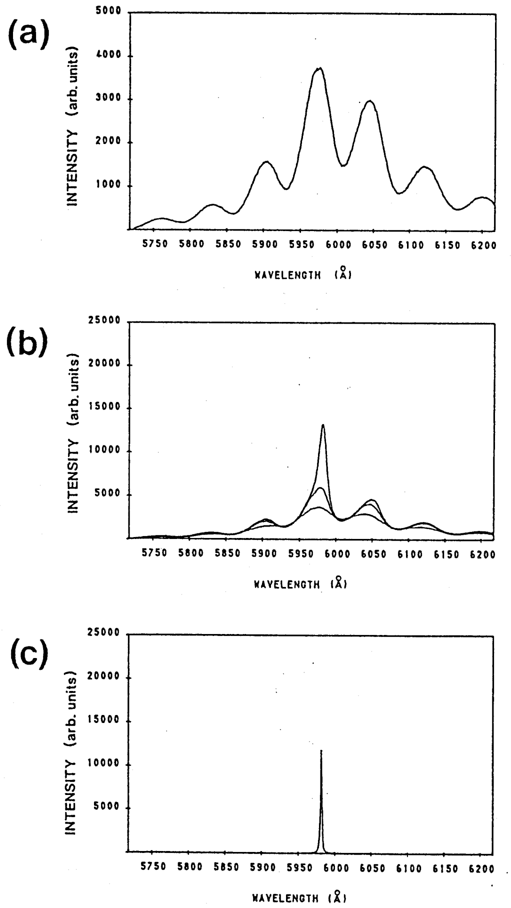

Fig.6 Output spectra

fringe distance, while the Madey's theorem predicts the shift of 0.25. In the ACO experiment, the shift was 0.15 of the fringe distance[6]. The ACO group attributed the discrepancy to the multimode component of the spontaneous-emission spectrum. In the present case, however, the TEM_{00} mode has been confirmed before the oscillation, and then, there might be another reason.

The peak power of the micro-temporal laser pulse was measured by a PIN photodiode to be about 10mW with current 4mA/bunch. With new cavity mirrors, the oscillation continues for more than 40min. According to a measurement of the time structure of lasing with a photomultiplier, the laser oscillates in a random-pulse manner with macropulses separated by 5~ 30ms. Each macro-temporal pulse consists of micro-temporal pulses separated by 35ns (electron-bunch period). It is probably due to some transverse beam instability and/or ion trapping.

Q-switching was tried mainly at 2.5 Hz by modulating the RF frequency. In this case, the spectral peak intensity was increased, but the laser oscillated less frequently than in normal operation. This seems to be also due to the instability mentioned above. If the slow beam fluctuation can be well suppressed, a pulsed oscillation with higher peak power is expected with the low-frequency Q-switching.

Recently, the electron-beam quality has been further improved, and the peak beam current was increased as mentioned before. As a result, simultaneous lasing at two wavelengths (599 and 592nm) has been achieved with electron energy 234MeV, as demonstrated in Fig.7. This suggests the tunability of the present FEL system over at least 7nm.

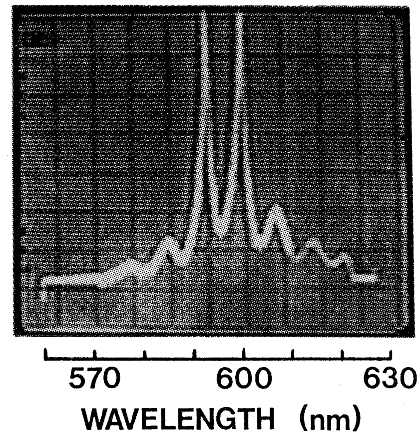

Fig.7 Simultaneous lasing of two lines

Conclusional remarks

The lasing of the storage-ring FEL at ETL has been observed. Wavelength tunability has also been confirmed. Experiment is still continuing to search the conditions for stable oscillation. Systematic measurement of the electron-beam parameters under the lasing condition are also under way. For the next-step, a racetrack-shaped storage ring NIJI-IV for FEL was constructed[7] under the cooperation with Kawasaki Heavy Industries, Ltd., and the maximum stored-beam current has reached 70mA recently. The circumference and the length of the long straight section are 29.6m and 7.25m, respectively. A 6.3-m optical klystron to be installed is now being designed. We expect to obtain the peak gain of at least a few percent in the visible region and to achieve laser oscillation even in the UV region around 350nm.

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