OPERATION OF NEAR-INFRARED FEL AT NIHON UNIVERSITY*

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Abstract

The near-infrared FEL at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University has been operated for a variety of scientific applications since 2003. The stability of the FEL power was improved appreciably by the advanced stability of the 125MeV electron linac. Currently fundamental FEL wavelength ranges from 1 to 6 microns, which is restricted by the electron energy and the optical devices. The higher harmonics in the visible region is also available [1]. The maximum macropulse output energy of 60mJ/pulse has been obtained at a wavelength of 1725 nm. The short FEL resonator length at LEBRA results in relatively high optical energy density on the surface of the resonator mirrors; present copper-based Ag mirrors in use at LEBRA are not durable enough for long-term operation. Generation of intense harmonics by means of nonlinear crystals has been tested. The preliminary results have demonstrated the conversion efficiencies of 3 to 9% for the second harmonic generation by the fundamental FEL in the wavelength region from 1400 to 1800nm.

INTRODUCTION

The electron linac at LEBRA has a conventional configuration. It consists of the DC electron gun with a dispenser cathode, the prebuncher which is a 7-cell travelling wave structure, the buncher which is a 21-cell travelling wave structure and three 4-m long regular accelerating sections. The specifications of the electron linac are listed in Table 1. Schematic layout of the accelerating structures, the RF system and the beam lines for FEL and parametric X-ray (PXR) generations are shown in Fig. 1.

The FEL beam line and the optical resonator system have been installed to provide the near-infrared FEL for various studies [2]. To increase the FEL gain, magnetic bunch compression has been performed in the 90-degree bending system [3].

Table 1: Main parameters of the LEBRA linac.

Accelerating rf frequency	2856	MHz
Klystron peak output rf Power	30	MW
Number of klystrons	2	
Electron energy	30~125	MeV
Energy spread (FWHM)	0.5~1	%
Macropulse beam current	200	mA
Macropulse duration	20	µsec
Repetition rate	12.5	Hz

Table 2: LEBRA undulator parameters.

Resonator length, L	6.718	m
Undulator period	48	mm
Undulator length	2.4	m
Number of periods	50	
Maximum K (rms)	1.35	

To generate a monochromatic and spatially coherent X-ray beam, the PXR beam line has been installed next to the FEL beam line.

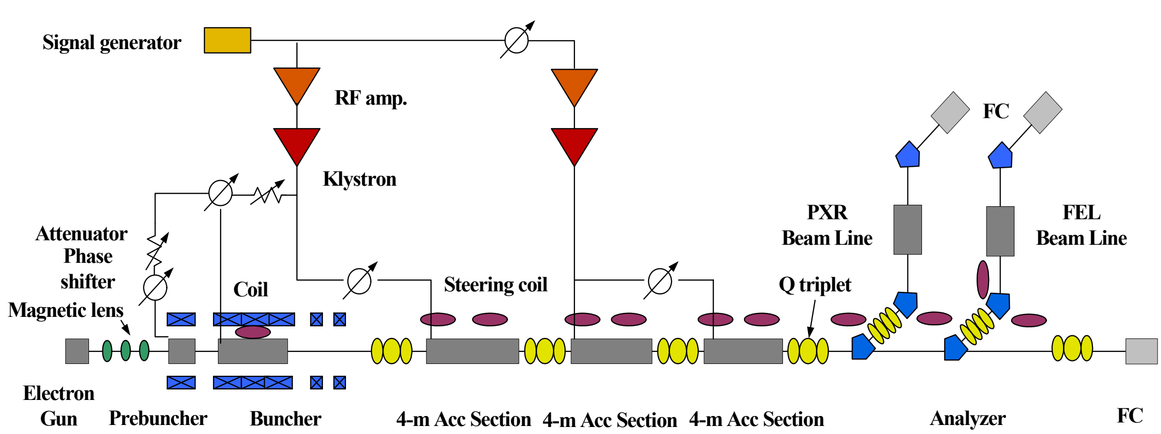

Figure 1: Schematic layout of the accelerating structures, RF system and the FEL and the PXR beam lines

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The undulator consists of a planar Halbach-type permanent magnet, where the electron beam is wiggled in the vertical plane. The specifications of the FEL system are listed in Table 2. The optical beam is extracted through the small coupling hole made in the mirror center. The light beam extracted from the optical resonator is collimated using the beam expander that consists of an ellipsoidal mirror and a parabolic mirror, and then transported to the experimental rooms through the vacuum ducts.

In this paper, the wavelength dependence of the FEL intensity, the time structure of the FEL pulse and the problem of the resonator mirror damage are reported. Also, the results of the experiments for generating the harmonics by means of nonlinear optical crystals (NLO) are discussed.

CHARACTERISTICS OF FEL LIGHT

Correlation between the oscillating wavelength and the optical energy per macropulse

The FEL output power is very sensitive to the change of the orbit and the focusing of the electron beam, and it also depends on the adjustment of the optical resonator and the extent of damage of the resonator mirrors. Hence, the reproducibility of the FEL power level is not very good even at the same electron energy and the same undulator gap width. However, there is a rough correlation between the oscillating wavelength and the optical energy per macropulse. The dependences of the output FEL energy on the wavelength have been obtained for various electron energies in the wavelength region from 1160 to 6130nm as shown in Fig. 2.

In the short wavelength region the saturation level is relatively high, though the gain is small and the loss is large. The FEL macropulse duration becomes short near the oscillation limit at the short wavelength end where the saturation is not achieved stably. In the long wavelength region the macropulse duration is relatively long and the saturation is stable. However, due to the relatively low saturation level and small output coupling, the energy of the FEL extracted from the optical resonator decreases gradually with increased wavelength.

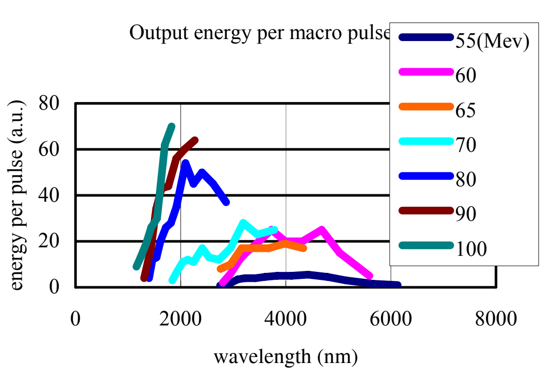


Figure 2: Wavelength dependence of the output energy per macropulse.

In the LEBRA FEL, the output energy per macropulse has the maximum at the wavelengths around 2000 nm. The maximum record of 60mJ/pulse has been achieved at the wavelength of 1725nm.

Pulse structure

To increase the peak electron beam current, the electron bunch has been compressed by using the 90–degree bending magnet system placed just upstream of the FEL system. The analysis of the energy spectra of 100-MeV electron beam obtained by the acceleration in different RF phases suggests that the bunch length of approximately 3ps (FWHM) at the exit of the linac has been compressed to 1ps (FWHM) or less at the entrance of the FEL system. This implies that we can expect a very short FEL pulse.

Since the FEL pulse is a coherent wave packet, the approximate pulse length can be deduced from the measurement of autocorrelation width. A typical shape of the autocorrelation traces measured at a wavelength of 1500 nm by using a Michelson interferometer is shown in Fig. 3. In this figure the horizontal axis expresses the position of the movable mirror measured along the optical axis in the interferometer, in units of micron, and the vertical axis expresses the relative intensity of the light detected by means of an InGaAs photo diode. The FEL pulse width of approximately 60 μm in spatial domain or 200 fs in time domain has been deduced from this trace.

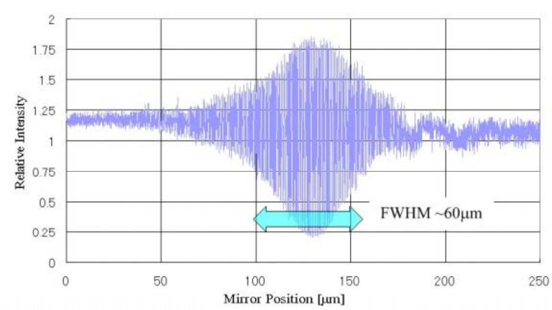


Figure 3: Autocorrelation trace at the wavelength of 1500nm.

By using the same method, the pulse width of the second and the third harmonics have been deduced approximately to be a half and two third the width of the fundamental FEL, respectively. The intensities of these harmonics have been measured by means of a Si photo diode.

Mirror damage

To oscillate FEL over the wide region of wavelengths, protected silver-coated copper mirrors have been used for the optical resonator. In fact, this type of mirror has an extremely high reflectance at the wavelength region longer than 0.4 μm, and has demonstrated the highest durability ever experienced at LEBRA as a FEL resonator mirror. Use of protected silver-coated silicon mirrors was attempted. The mirrors suffered serious damage soon after the FEL oscillation started. A photograph of the damaged silicon mirror and its expanded image around the coupling hole are shown in Fig. 4. In this figure, it looks that the coated silver was melted and the silicon substrate was excavated. On the contrary, the copper mirrors were usable at least several months, although the FEL power level decreased gradually and the mirrors eventually had to be replaced.

Figure 4: Damages on the surface of the Ag coated silicon. Entire mirror (25mm in diameter) and close up around the coupling hole.

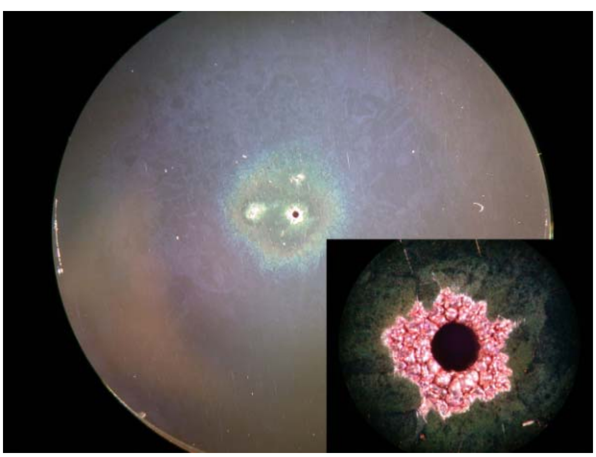


Figure 5: Damages and discoloration on the surface of the Ag-coated copper mirror. Entire mirror (25mm in diameter) and close up around the coupling hole.

A demounted mirror and its expanded image around the coupling hole are shown in Fig. 5. Different from the case of the silicon mirror, the surface over the wide area near the center of the mirror has discolored. The coated silver around the coupling hole has been lost; the copper substrate is visible and it looks melted. Degradation of the resonator mirrors by the damage on the surface is a serious problem in generating a high power FEL. As mentioned previously, the micropulse width of the LEBRA infrared FEL has been estimated to be as short as 200 fs. Therefore, damage to the mirrors could be due to extremely high energy density caused by very short FEL pulses in the optical resonator. Under the present situation, the resonator mirrors have to be replaced every three or four months.

The FEL beam radius on the resonator mirror can be enlarged by shortening the Rayleigh range. Then the energy density may be reduced sufficiently so that mirror damages can be avoided. When the Rayleigh range is shortened, the resonator mirrors have to be adjusted very precisely so as to keep the confocal condition. Since there has been found no other efficient solutions, mirrors with smaller curvature radii will be tested if the lifetime of the mirror can be increased.

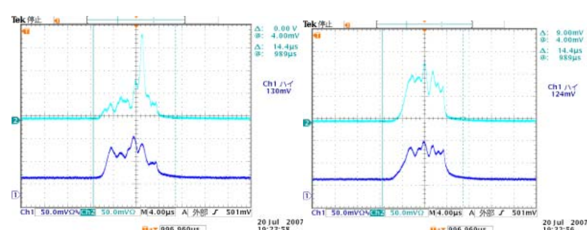
HARMONIC GENERATION USING NLO

Preliminary experiments for generating harmonics [4] of the FEL by using NLO devices have been performed. The $KTiOPO_4$ (KTP) crystals have been used for second harmonic generation (SHG) and third harmonic generation (THG). The cutting angle and the antireflective coating of the crystal for SHG were optimized for the fundamental wavelength of 1500 nm and the second harmonic of 750 nm. Similarly the crystal for THG was optimized for corresponding wavelengths. The conversion efficiencies of SHG obtained with the NLO have been 3 to 9% for the fundamental wavelengths from 1400 to 1800nm as listed in table 3. Typical macropulse waveforms of fundamental FEL, nonlinear second harmonic and SHG are shown in Fig. 6. The SHG waveform is similar to the fundamental one. The THG waveform was also observed, however the conversion efficiency was far smaller than 1%.

Table 3: Fundamental and second harmonic wavelengths, energies per macropulse and conversion efficiencies.

1^{st} nm	2^{nd} nm	1^{st} mJ	2^{nd} mJ	efficiency %
1400	700	~3	~0.15	~5
1500	750	~4.5	~0.4	~9
1600	800	~6	~0.45	~7.5
1700	850	~7.5	~0.6	~8
1800	900	~9	~0.3	~3

A KTP crystal works under Type-II phase matching



(a) (b)

Figure 6: Macropulse waveforms of fundamental and second harmonic: (a) fundamental (lower trace) and nonlinear harmonic (upper trace), (b) fundamental and SHG.

condition. Hence the second harmonic is generated from two fundamentals with their polarization planes at right angles to each other. Due to the group velocity mismatch between the two components of fundamental light, the conversion phenomenon occurs only within about 1 mm in depth from the surface of the crystal, which restricts the conversion efficiency. If it is necessary to increase the conversion efficiency, other kinds of crystal should be used.

REFERENCES

[1] Y.Hayakawa, et al, “Characteristics of the fundamental and the higher harmonic generation at LEBRA”, Nucl. Inst. and Meth. A 507 (2003) 404-408.

[2] K.Hayakawa, et al, “The LEBRA 125 MeV electron linac for FEL and PXR generation”, Proc. LINAC2004, Luebec, Aug. 2004, p 90.

[3] K.Yokoyama, et al. “Bunch length measurements at LEBRA”, Proc. LINAC2004, Luebec, Aug. 2004, p 411.

[4] P.A.Franken, A.E.Hill, C.W.Peters, and G.Weinreich. “Generation of Optical Harmonics”, Phys. Rev. Lett. 7, 118-119 (1961).