POWER INTENSIFICATION OF LEBRA FEL BY RF PHASE MODULATION *

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Abstract

In general, maximum gain and maximum power of a free-electron laser (FEL) oscillator are not simultaneously satisfied at an identical optical resonator length. If the resonator length is adjusted at the middle in the macropulse duration of the electron beam, both maximizing conditions can be satisfied simultaneously, which will result in a large FEL output power compared with a normal operation. An attempt has been made to intensify the FEL output by applying the above consideration to the LEBRA FEL system. Instead of the resonator detuning control in the macropulse, an equivalent effect has been realized by modulating the accelerating RF phase of the electron linac, which changes the electron bunch intervals. The output FEL energy per macro pulse has been approximately doubled by the technique compared with that in the normal operation.

INTRODUCTION

In the free-electron laser (FEL) system based on a short-bunch electron beam from a pulsed linac, a large FEL gain is obtained by a relatively large detuning of the optical resonator length, resulting in fast build up and wide macropulse of FEL. However, the maximum saturated FEL power is obtained at a smaller detuning length, where the gain is relatively small and the build up is slow, which results in narrow macropulse width [1].

Operation of the FEL system usually adopts the resonator length in between the above detuning lengths so that the FEL energy per macropulse is maximized. However, it can be considered that a wide macropulse width and a high saturation level are satisfied simultaneously if the resonator detuning can be controlled in the electron beam macropulse so that the detuning adjusted to get a large gain is shifted to get a high saturation level after saturation is almost achieved.

The experiment of the FEL intensification based on the above consideration has been performed at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University, using the 125-MeV linac and the near-infrared FEL system [2].

Although it is difficult to change the resonator length in the electron beam macropulse, an equivalent effect is obtained by modulation of the linac accelerating RF frequency, which results in modulation of the beam bunch intervals instead of the resonator detuning length. The method is possible so long as the frequency modulation is in the range of the pass band in the accelerating tubes. A linear phase modulation of the RF is equivalent to a frequency modulation, having a guaranteed continuity of phase. Therefore, the phase modulation technique has been adopted for the experiment.

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FREQUENCY SHIFT AND DETUNING LENGTH

The optical resonator length L is expressed by $n\lambda_0$ in terms of the free-space wavelength λ_0 of the accelerating RF and the integral or half-integral number n. Then, change in the RF wavelength $\delta\lambda$ equivalent to a small resonator detuning length δL ($\delta L << L$) is expressed by -$\delta L/n$. The relation between the RF frequency modulation δf and the equivalent resonator detuning length satisfies

$$\delta f = -f_0 \frac{\delta\lambda}{\lambda_0} = f_0 \frac{\delta L}{L},$$

where f_0 is the RF frequency corresponding to the wavelength λ_0. The linac is operated in pulse mode, which allows us to make frequency modulation by a linear phase modulation in place of making direct frequency shift. The phase modulation is preferable since the continuity of phase is guaranteed in principle.

The phase modulation $\delta\phi$ [rad/sec] corresponding to the frequency modulation δf is given as $2\pi\delta f$. For L=6718 [mm] and f_0=2.856 [GHz] as in the case of LEBRA, detuning of the resonator by δL=1 [μm] is equivalent to the frequency modulation of 425 Hz and the phase modulation of 2.67 [mrad/μsec], respectively. Since the detuning δL is comparable with the FEL wavelength, the maximum frequency modulation is expected to be approximately 3 kHz for the LEBRA FEL system. Detuning of the optical resonator by the RF frequency modulation is applicable when the RF system, including the accelerating structures, has a wide pass band compared with the necessary frequency modulation range.

EXPERIMENTAL SETUP

Injector

The injector is the 2.856-GHz RF electron linac with maximum electron energy of 125 MeV, which consists of conventional structures equipped with no devices dedicated to FEL. The macropulse beam current extracted from the linac in normal operation is 100mA, and then approximately 80 mA is injected into the FEL beam line. The electron bunch length is approximately 1 psec which corresponds to the approximate micropulse peak current of 30 A [3]. As shown in Fig. 1, the RF power for the

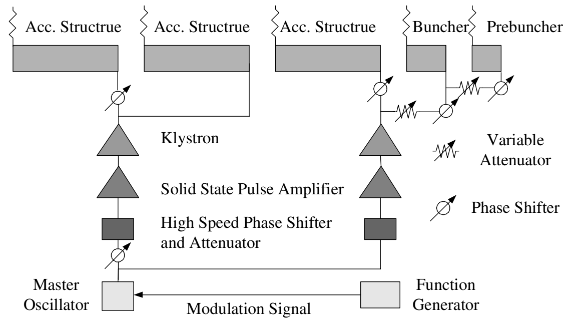

Figure 1: Schematic diagram of the RF system in the LEBRA FEL injector linac.

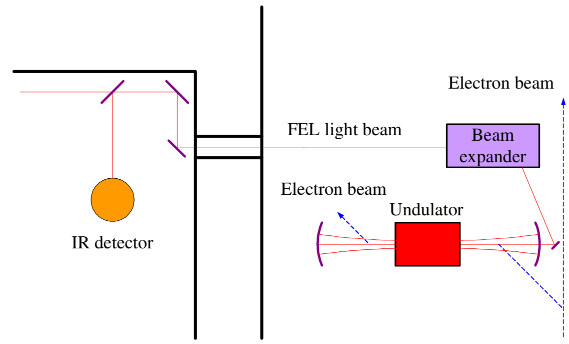

Figure 2: Schematic diagram of the LEBRA FEL oscillator and beam transport system.

prebuncher, buncher and 3 regular accelerating tubes is supplied by two klystrons. The phase modulating signal generated by a function generator is applied to the master RF oscillator.

Undulator and Optical Resonator

The electron beam from the linac is injected into the FEL beam line after momentum analysed in the 90° deflecting magnetic system. The bunch length is compressed in the system using the magnetic bunching effect which is based on the path length difference depending on the electron energy. A schematic diagram of the LEBRA FEL system and the optical beam transport system is shown in Fig. 2.

The Halbach-type planar FEL undulator consists of NdFeB permanent magnet arrays. The undulator period length is 48 mm, and the number of periods is 50. The maximum *K*-value (RMS) of 1.4 is obtained at the minimum gap width of 24 mm. The optical resonator consists of two copper-based, silver-coated mirrors separated by $64\lambda_0$ (=6718 mm) from each other, where the FEL power is extracted from one of the mirrors through the coupling hole bored on the central axis of the mirror. The extracted FEL beam is guided to the experimental rooms after being collimated by the beam expander optics system. Main parameters of the undulator and the optical resonator are listed in Table 1. Lasing of FEL at LEBRA has been achieved in the near-infrared region from 0.9 to 6 μm by the combination of the undulator gap width and the electron beam energy.

In the experiment an LN_2-cooled InSb detector has been used for the measurement of the FEL power waveform. On the other hand, a thermopile detector has been used for the measurement of the total FEL energy at each macropulse.

Table 1: Parameters of the FEL system at LEBRA.

Configuration	Halbach type	Planar
Period Length	48	mm
Number of Periods	50	
Gap Width	24 - 34	mm
K-value (RMS)	0.7 - 1.4	
Resonator Length	6718.04	mm
Rayleigh Range	1.467(@*r*=4m)	m
Coupling Hole	0.3 - 0.5	mm

EXPERIMENT

Basic Experimental Conditions

Most of the experiment has been performed in the FEL wavelength region from 2 to 3 μm, which is due to relatively high FEL gain and resultant stable saturation in the LEBRA FEL system. Main results discussed in this section were obtained at an FEL wavelength of λ_L=2.44 μm, where the electron beam energy was 80 MeV and the macropulse beam current in the FEL beam line was 85 mA.

Energy Displacement by Phase Modulation

Since the RF amplifiers and the accelerating structures have pass bands of the order of MHz, modulation of the RF frequency only by a few kHz has little effect on the impedance. The electron energy, however, can be slightly affected by the change of relative RF phase between the accelerating sections, due to the phase shift dependence on the RF frequency and the length of the waveguide to each section.

Displacement of the electron energy due to the RF frequency modulation in the beam macropulse was measured with a strip-line type beam position monitor (BPM) placed on the beam line of the 90° deflecting magnet system, where the beam position linearly depends on the beam energy [4]. It was proved in the measurement that a small shift of the beam position in the macropulse was induced by linear phase modulation which was turned on in the middle of the macropulse. Analysis of the signal from the BPM showed that the beam energy displacement is 0.022 % for frequency modulation of 1 kHz. The displacement of the beam energy depends on the acceleration condition. However, for assumed frequency modulation of 3 kHz the displacement is small compared with the beam energy spread of 0.5 % (FWHM). Thus, the energy displacement can be considered to have little effect on the FEL power.

Detuning

The build up of the FEL in the macropulse waveform is usually observed at a nearly saturated level using suitable filters, which does not reflect the FEL gain in the small signal regime. Direct observation of the build up waveform and the gain in the small signal regime has to allow injection of high power FEL into the detector, which is capable of unrecoverable damage to the detector. Thus, direct measurement of the small signal gain is not necessarily a simple subject. In the experiment, the resonator length corresponding to maximum FEL gain has been determined by the detuning which gives the minimum delay time of the build up near the saturation from the head of the electron beam pulse. The correlation between the detuning length and the FEL energy per macropulse has also been measured.

Coarse adjustment of the resonator length has been made with a stepping motor. Fine adjustment has been made using a piezoelectric actuator which was calibrated with a laser displacement meter.

Behaviour of the FEL power waveforms for various detuning lengths is shown in Fig. 3. Dependence of the FEL energy per macropulse on the detuning length is also shown in Fig. 4. Delay time of the build up is least at δL = -1.26λ_L, which suggests that the FEL gain is maximum around this point. As shown in Fig. 3, detuning less than this value leads to a larger delay time which implies smaller gain; however, the power saturation level is

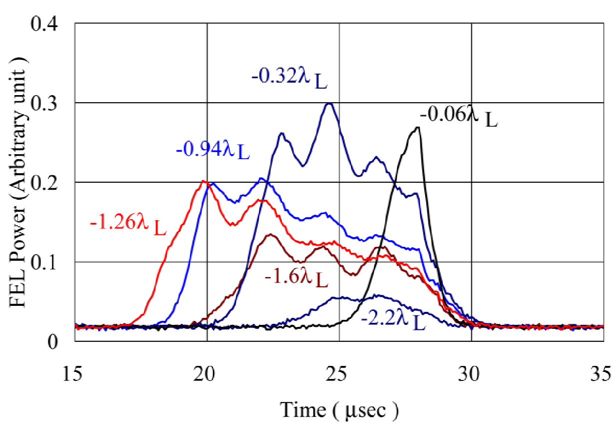

Figure 3: Behaviour of the FEL power waveforms for various detuning lengths. The detuning lengths are shown in units of λ_L.

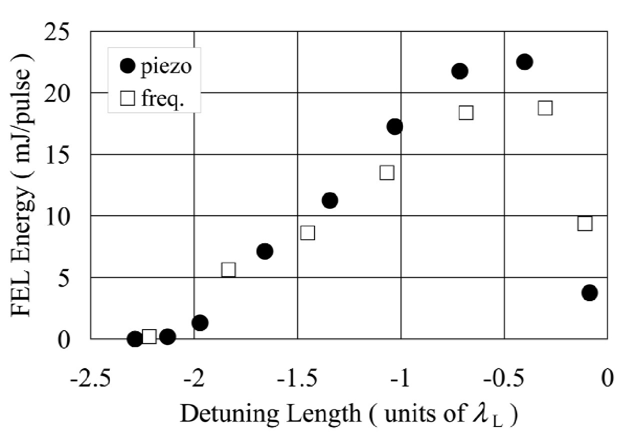

Figure 4: Dependence of the FEL energy per macropulse on the resonator detuning length (squares) and on the equivalent RF frequency modulation (filled circles).

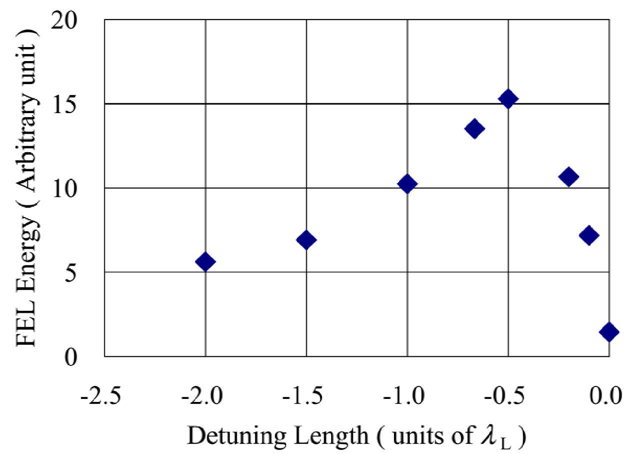

Figure 5: The result of detuning simulation by GENESIS based on the same beam condition as in the experiment.

gradually increased. In Fig. 4 the origin of detuning length was determined by extrapolation of the detuning curve based on the assumption that the FEL output vanishes at zero detuning length. The filled circles show the behaviour of the detuning curve measured using the piezoelectric actuator. On the other hand, the squares were resulted from equivalent detuning effect by modulation of the linac accelerating frequency, which shows the same behaviour as which is in normal detuning procedure.

Figure 5 shows the result of detuning simulation by GENESIS [5] based on the same beam condition as which was in the experiment. Though the behaviour is different in large detuning length region, the FEL energy is peaked around at -0.5λ_L in agreement with the experimental result.

The FEL macropulse width is relatively narrow in small detuning length region. Thus the total FEL energy is not necessarily high, even though the saturation level is high. The maximum saturation level can be obtained in proximity to the zero detuning length.

Phase Modulation

The experimental result on the detuning curve and the power waveforms has shown that a fast build up and a high saturation level of FEL are not satisfied at the identical detuning length. In order to satisfy the two requirements, the detuning length has to be adjustable in the beam macropulse so that the relatively large detuning length in the early phase of lasing is shifted to nearly zero detuning after build up. This technique has been realized by linear modulation of the linac accelerating RF phase.

Figure 6 shows the phase modulation signal applied to the master RF oscillator together with the electron beam and the FEL power macropulses. In Fig. 6 the phase modulation is initiated with a delay time of 5.7 µs after the head of the electron beam pulse. However, the actual delay time is 6.3 µs due to another 600 ns delay associated with the master oscillator and signal cables.

Fig. 7 shows the effect of the detune shift by the phase modulation at the delay times 5.8, 6.3 and 6.8 µs, which is

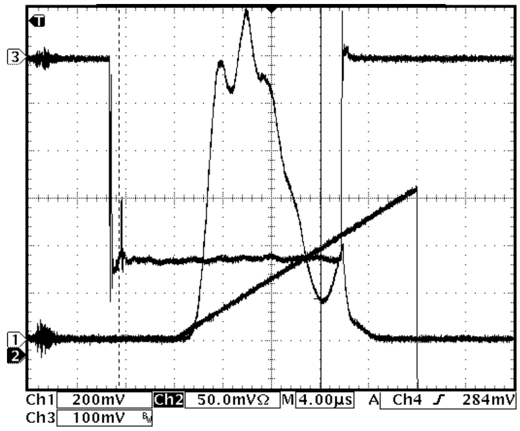

Figure 6: Timing of the phase modulation signal (sawtooth) applied to the master RF oscillator.

compared with the normal detuning curve in Fig. 4. The horizontal scale is in units of λ_L. The detuning length for the resonator was fixed to -λ_L in the measurement, where the FEL gain can be considered to be maximal. The detuning range by the phase modulation is 0 to 0.01 rad/µsec, which corresponds to the frequency modulation of 0 to 1592 Hz and the equivalent resonator length modulation of 0 to 1.53λ_L, respectively. The detune shift by the phase modulation in the macropulse shows the same effect as the detuning of the resonator length in the region δL < -0.5λ_L. However, the FEL energy is still increased when the detuning is shifted to δL ~ 0, in contrast to the fact that the FEL output rapidly decreases and finally vanishes in the normal detuning curve. The delay time of the phase modulation has effects on the maximum FEL energy and corresponding detune shift. The maximum FEL energy has been obtained at the delay time 6.3 µs and the detune shift to approximately zero detuning length. The intensification by the phase modulation resulted in 20 % for λ_L=2.44 µm.

Another result obtained by a similar experiment at λ_L=2.82 µm is shown in Fig. 8, where the maximum FEL energy has been obtained at the delay time 6.8 µs and the detune shift to approximately zero detuning length. The FEL energy has been increased to twice the peak value obtained by the normal detuning.

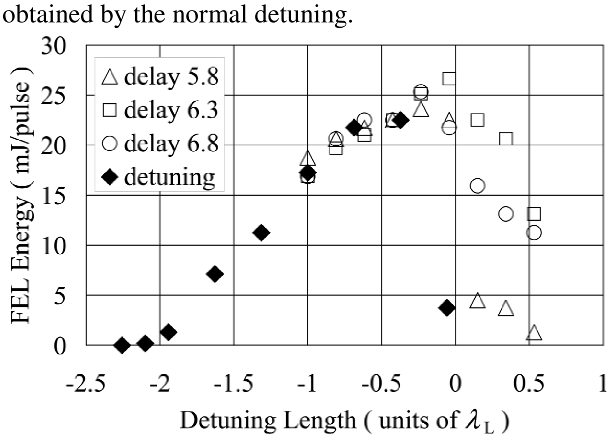

Figure 7: The effect of the detune shift by the phase modulation at the delay times 5.8, 6.3 and 6.8µs, respectively.

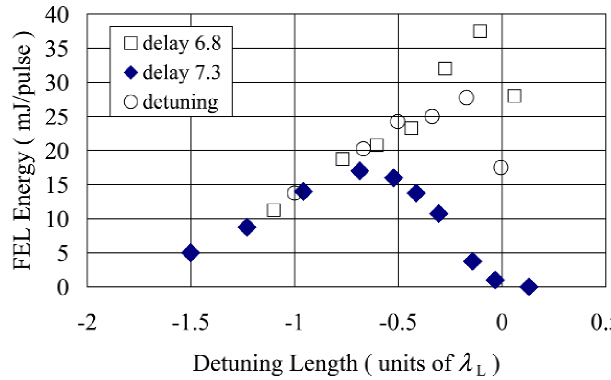

Figure 8: Result of the phase modulation at λ_L=2.82 µm. Intensification is significant at the zero detuning length.

CONCLUSION

The detuning length of the FEL optical resonator giving the maximum FEL gain has been deduced from the measurement of the build up timing near the saturation of the FEL power waveform at LEBRA. Modulation of the linac accelerating RF phase has been proved to have the same effect with the normal resonator length detuning. An experiment has been performed to investigate the effect of the detune shift by the phase modulation in the beam macropulse. With the above resonator detuning length, the FEL energy has been intensified by a factor 1.2 to 2 by the phase modulation which was initiated near the saturation. The maximum FEL energy per macropulse has been obtained with the phase modulation equivalent to the detune shift to zero detuning length.

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