FEL GAIN MEASUREMENT WITH A NOVEL METHOD

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Abstract

A novel method to measure temporal development of the FEL power has been developed using a silicon bolometer, which response linearly to input over a wide range[1]. The Si bolometer has the time resolution of ~1 ms, which is much longer than the FEL macropulse of a few μs, so that it measures energy in the macropulse. The number of amplifications is changed by varying the pulse length of electrons from the gun of the linac and energy in the FEL macropulse is measured at a wavelength ~100 μm with the detector and appropriate Teflon absorbers. The energy development of the FEL macropulse is measured over eight orders of magnitude from a very low power level close to the incoherent radiation up to the FEL power saturation. The temporal development of the FEL power is derived from the energy development as a function of the number of amplifications. Then the FEL gain is derived from the power development. We measured energy development in the macropulse and derived the FEL gain at some cavity lengths. The maximum FEL gain thus evaluated is about 56 percent, which agrees with calculation by the Super-Mode theory.

INTRODUCTION

We are conducting experiments on free-electron laser (FEL) physics using the THz-FEL based on the L-band electron linac at the Institute of Scientific and Industrial Research, Osaka University.

The gain of FEL is one of the most principal parameters of FEL and can be derived from the temporal development of the power in the FEL macropulse which is composed of many micropulses. The FEL gain was ever evaluated from a single saturated macropulse, but the macropulse was measured in a narrow range, which is limited by the dynamic range or the sensitivity of the detector. Therefore we insist that such the measured FEL gain concerned the power saturation and evaluated lower.

We measured some terahertz FEL macropulses with a germanium-gallium semiconductor detector, which has fast, ~10 ns, response, and derived the temporal development of the FEL power in a wide range with the macropulses overlapped. But we confirmed that the detector did not response to input power linearly. The gain evaluation needs a precise measurement of the variation of the FEL power and we concluded that the detector was not appropriate for the gain evaluation.

Therefore we have adopted a silicon bolometer as the detector which responses to input linearly over a wide range, ~5 decades. The detector measures energy of the FEL macropulse because of its slower response, ~1 ms, than the length of FEL macropulse. We measure the energy of macropulse with varying the number of FEL amplifications. The amplification can be varied by a control of the number of electron bunches or the beam length. The FEL power development is derived from the difference of the energy. We report the novel method for FEL gain measurement.

BACKGROUND OF EXPERIMENT

Figure 1 shows L-band linac and THz-FEL of ISIR, Osaka University. On the FEL experiment, we generate an electron beam of which the length is 8 μs from the electron gun, bunch the beam to a bunch array of which the interval is 9.2 ns with the subharmonic bunchers drived on 108 MHz and the 216 MHz and accelerate the beam to 12~18 MeV. The accelerated beam is led into THz-FEL, which is composed of a wiggler of which the magnetic period is 6 cm and the number of periods 32 and an optical resonator of which the cavity length is 5.531 m, then radiates FEL on 2~3 THz (25~150 μm).

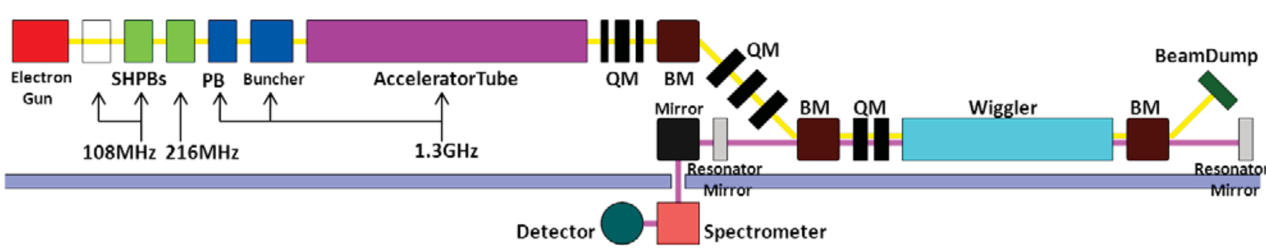

Figure 1: Diagram of L-band linac and THz-FEL.

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We experimented for the evaluation of the FEL gain with this setup. Table 1 shows the parameters for this experiment.

Table 1: Main Parameters

Beam	
Enegy	15.0 MeV
Energy spread (FWHM)	1.56%
Charge / bunch	0.5 nC
Bunch length	20 ~ 30 ps
Normalized emittance	100 ~ 150π mm mrad
Thz-FEL	
Wiggler gap	30 mm
Magnetic field	0.42 T
K-value	1.55
Wavelength	105.8µm
Cavity loss / pass	11%

And we measured the energy development of the FEL macropulse with varying the cavity length of the optical resonator.

MEASUREMENT OF FEL ENERGY

We measured the energy of the FEL macropulses with the Si bolometer as we varied the length of the electron beam from the electron gun. The black dots in Fig. 2 show the development of the FEL energy.

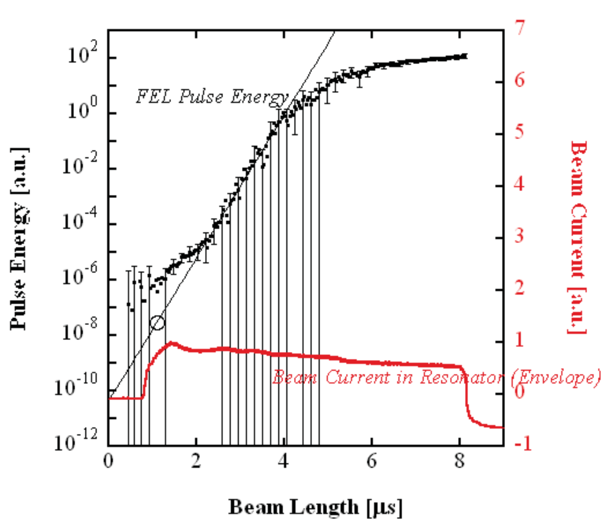

Figure 2: Measured energy development of FEL macropulse.

We could measure the FEL energy development over eight orders of magnitude. The FEL energy developed exponentially above 2.5 µs on the beam length, then slowly by FEL saturation. The energy developed in spite of the saturation because the macropulse length kept developing after the peak power was constant. Under 2.5 µs, the energy developed linealy. We have estimated that the incoherent radiation was dominant in this region and the FEL amplification started already in the region because the beam was injected into the resonator.

Therefore we estimated the point from which the FEL started to amplify. We assumed that the incoherent radiation is seed of FEL.

We fitted a linear function to the region under 2.5µs and defined the point in time where the fitting curve was closest to zero as the FEL start point. The beam is injected into the resonator around the estimated point. Then we fitted an exponential function to the sharp development by the FEL amplification after 2.5 µs and defined the point of value which was at the estimated point in time as the FEL start point of value. The black circle in Fig. 2 shows the FEL start point.

DERIVATION OF FEL POWER DEVELOPMENT

Method to Derive FEL Power

From the difference of the measured energy, we derive the power of FEL with a model of the temporal spectrum of the FEL macropulse.

In n amplifications, the peak power, P_n, and the energy, E_n, of the FEL macropulse radiated from the optical resonator is written as

$$E_n = P_0 + \sum_{i=1}^{n} P_k + \sum_{j=1} (1-\alpha)^j P_n \qquad (1)$$

where P_0 is the power of the FEL start-up and α is the cavity loss of the optical resonator. The second term of Eq. 1 is the energy of the amplification regime and the third term is the one of attenuation regime after the beam injection finished. From Eq. 1, P_n satisfies

$$P_n = (1-\alpha)P_{n-1} + \alpha D_n \qquad (2)$$

with the difference of the energy, D_n. And the energy of the FEL start-up, E_0 is written as

$$P_0 = \alpha E_0 \, . \qquad (3)$$

Derived FEL Power Development

We derived the temporal development of the FEL power from the measured energy with Eqs. 3, 4. Figure 3 shows the derived FEL power development over 9 decades.

The derived FEL power develops exponentially in 30 amplifications and slowly over 80 amplifications. Then the power is saturated. Under 30 amplifications, the development is slow too. This region corresponds with the region of FEL energy development where the intensity of spontaneous radiation is dominant. As the difference of the energy is larger than the FEL power on this region, we guess that the FEL power cannot be extinguished from the variation of the spontaneous radiation intensity.

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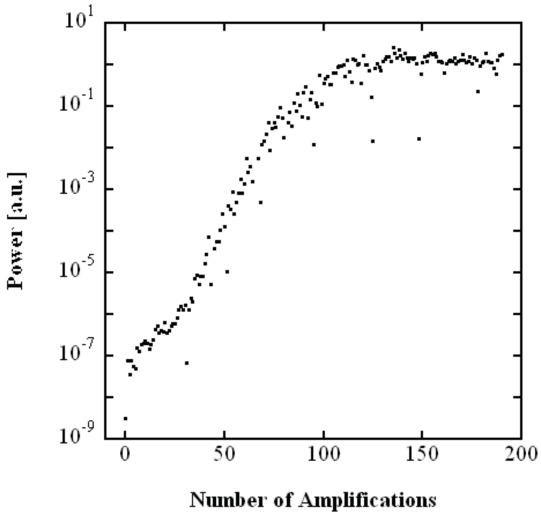

Figure 3: Temporal development of FEL power.

EVALUATION OF FEL GAIN

The FEL gain is evaluated from the ratio of the FEL power before and after amplification. The gain, g_n is written as

$$\frac{P_n}{P_{n-1}} = G_n = (1 + g_n)(1 - \alpha) \qquad (4)$$

where G_n is the net gain including the cavity loss of the optical resonator. But the measured power develops unstably, so that the variation of gain which is evaluated with Eq. 4 fluctuates too.

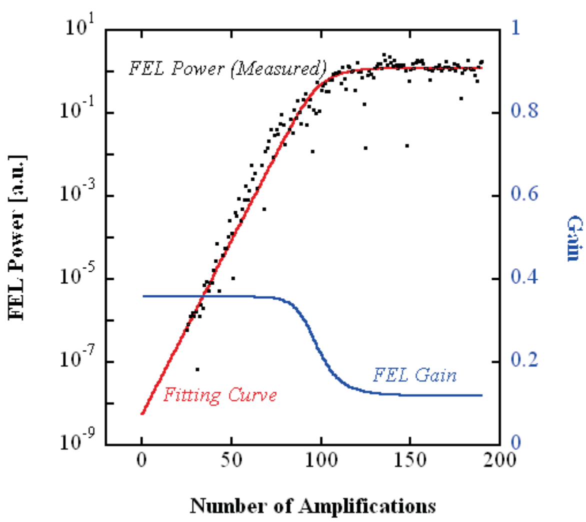

Figure 4: Power development and FEL gain.

Therefore we analyzed the power development by a fitting with the FEL gain model[2] and evaluated the variation of the FEL gain. The gain, g_n is the function of n,

$$g_n = \frac{0.85 g_0}{1 + {}^{P_{n-1}}/_{P_s} - 0.14\, {}^{P_{n-1}}/_{P_s}\left(1 - {}^{P_{n-1}}/_{P_s}\right)} \qquad (5)$$

where g_0 is small signal gain coefficient and P_s is saturation intensity, which is the power when $g_n = g_0/2$. And the FEL power follows

$$P_n = (1 + g_1)\cdots(1 + g_n)(1 - \alpha)^n P_0 \qquad (6)$$

from Eq. 4. We construct the model of the FEL power development from Eqs. 5, 6.

This model is fitted the power development excluding from the initial linear region, then the small signal gain and the variation of the gain are derived. Figure 4 shows the fitting curve to the power development and the variation of the gain as a function of the number of amplifications. From Fig. 4, we can recognize that the gain is constant under 70 amplifications then it falls suddenly and converge to the value of the cavity loss of the optical resonator. This convergence shows that the gain reachs the saturation which is the gain and the loss are equal.

Then we evaluated the small signal gains with this method at some cavity lengths of the optical resonator. We converted the cavity length to the detuning length which is the length from the synchronism of optical cavity. The black circles in Fig. 5 are the evaluated small signal gains of detuning length.

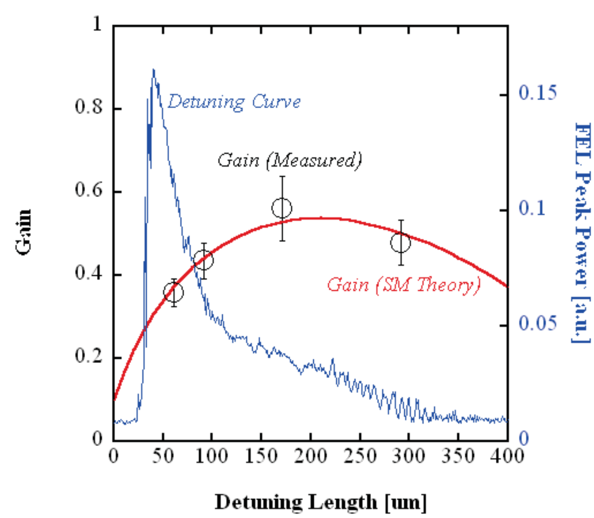

Figure 5: Small signal gain vs detuning length and comparison to Super-Mode theory.

On this experiment, the FEL gain is the largest at the hillside of detuning curve and the gain is 56% per a amplification.

And we compared the gains with the calculation by the Super-Mode theory[3] which is shown as the red line in Fig. 5. The evaluated gains agree with the value from the theory well as the value and the variation.

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SUMMARY

We developed the method to measure temporal development of FEL power over a wide range with Si bolometer. On this experiment, we derived the power development over 9 decades from the measured energy of the FEL macropulse over 8 decades and the evaluated position of the FEL start-up. Then the FEL gain is evaluated from the power development by fit with the FEL gain model. We could derived that the maximum of gains which was evaluated with varying the cavity length of the optical resonator was 56% at the hillside of the detuning length. And the gains agreed with the calculation of the Super-Mode theory well.

We are conducting to measure the region in a few amplifications directly with a more accurate method for the measurement. Therefore we will analysis from FEL start-up to FEL saturation.

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