Sustained Saturation in a Free-Electron Laser Oscillator at Perfect Synchronism of an Optical Cavity

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The first observation of sustained saturation in a free-electron laser (FEL) oscillator at perfect synchronism of an optical cavity is presented. A simultaneous measurement of FEL power and absolute detuning length of the optical cavity (δL) has clearly shown that the FEL efficiency becomes maximum at $\delta L = 0.0 \pm 1\ \mu$m, although it has been considered that only a transient state exists at $\delta L = 0$ due to the well-known laser lethargy effect. The observed efficiency detuning curve is well reproduced by our numerical simulation including a small shot-noise effect.

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A free-electron laser (FEL) oscillator as a high-power and wavelength-tunable coherent light source is on the way to industrial applications [1], and there has been broad interest in investigating the lasing dynamics of FEL oscillators [2]. In FEL oscillators, optical cavity shortening from perfect synchronism is required to compensate the "laser lethargy," which is a phenomenon that FEL optical group velocity becomes somewhat slower than the speed of light in vacuum because there is no gain at the beginning of FEL interaction [3]. The perfect synchronism is the cavity length, where the cavity round-trip time for vacuum speed of light equals the injection period of electron bunches. Extraction efficiency from electron beam power to FEL radiation depends on the cavity shortening from the perfect synchronism and becomes maximum at the detuning length (δL) slightly shorter than $\delta L = 0$. An analytical study reproduces an efficiency detuning curve measured in FELIX well and shows that the measured maximum efficiency is located at $\delta L = -0.1\lambda$ [2], where λ is the FEL wavelength. At the perfect synchronism of FEL oscillators, the optical pulse centroid is retarded on successive passes and the optical pulses finally dissipate. Only a transient state therefore exists at the perfect synchronism. This transient evolution of the optical pulses at $\delta L = 0$ is supported by numerical and analytical studies [3,4].

Recently a high extraction efficiency was demonstrated in the Japan Atomic Energy Research Institute FEL (JAERI-FEL) oscillator [5]. The efficiency detuning curve obtained was well reproduced by our numerical simulation [6], which indicates that the efficiency is maximum at the perfect synchronism and the lasing is sustained. However, no measurement has been made at FEL oscillators with enough accuracy to claim the lasing at $\delta L = 0$ [1,2,7]. For an experimental confirmation of the lasing at $\delta L = 0$, we made a simultaneous measurement of FEL power and absolute detuning length. In this Letter, we show that the JAERI-FEL oscillator has the maximum extraction efficiency at the perfect synchronism.

The JAERI-FEL facility driven by superconducting linear accelerator with a frequency of 499.8 MHz has been developed to provide a quasi-cw far infrared (FIR) laser of a 1 ms long macropulse at 10 Hz repetition rate [8]. The layout of the facility is shown in Fig. 1. The parameters for the electron beam and the FEL are listed in Table I. The peak current, 100 A, was estimated from the bunch length, 5 ps FWHM, measured with a synchroscan streak camera (M1954-10, Hamamatsu) at the center of the undulator. The above bunch length is almost comparable to trigger jitter of the streak camera and the bunch may have the shorter length and the higher peak current. Energy spread was measured to be 1.2% rms with an energy analyzer placed after the undulator. Horizontal and vertical normalized emittance were measured just after the final accelerator as listed values. The horizontal emittance is expected to have the larger value due to the coherent synchrotron radiation through our 180° bending arc [9]. The estimated normalized horizontal emittance is 80 mm mrad inside the undulator.

The experimental setup is shown in Fig. 2. The absolute detuning length was measured with a mode-locked Ti:sapphire laser (Tsunami 3960, Spectra-Physics) synchronized with the frequency of 83.300 00 MHz, which is the eighth harmonic of the electron bunch repetition rate and supplied from the same rf source used for the accelerator system [10]. The pulse width of the laser is about 80 fs FWHM. The laser pulses were injected into the optical cavity through a glass window, which does not transmit FIR light, and a center hole with 2 mm in diameter on an upstream cavity mirror. The stored pulses were coupled

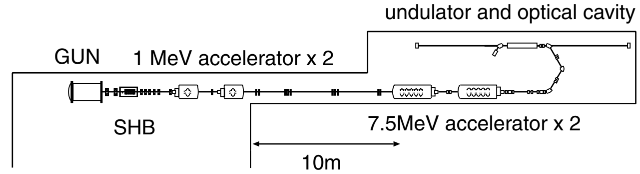

FIG. 1. Layout of the JAERI-FEL facility.

TABLE I. JAERI-FEL parameters.

Parameter	Measured
Kinetic energy	16.5 MeV
Average current	5.3 mA
Bunch charge	0.51 nC
Bunch length (FWHM)	<5 ps
Peak current	>100 A
Energy spread (rms)	1.2%
Normalized emittance (rms)	40 mm mr(x), 22 mm mr(y)
Bunch repetition	10.4125 MHz
Undulator period	3.3 cm
Number of undulator periods	52
Undulator parameter (rms)	0.7
Optical cavity length	14.4 m
Rayleigh range	1.00 m
Mirror radii	6 cm
Output wavelength	22 μm

out through the same hole and detected by an avalanche photo detector (C1536-01, Hamamatsu). The detector signal is enhanced by the pulse stacking, if an optical cavity is tuned at an appropriate length [11]. The laser has the frequency jitter less than 10 Hz, which corresponds to the effective cavity length change less than 1.7 μm. In order to reduce the jitter effect, the mean value of the photo detector signal over 200 ms duration was measured by a digital oscilloscope (TDS 684B, Tektronix) at a peak detection mode. The measurement was repeated 5 times at each detuning length. The experimental results exhibit a clear resonance peak as shown in Fig. 3, where each error bar is the standard deviation of the five repeated measurements. The centroid of the resonance peak was determined with the accuracy of 0.01 μm, by fitting the data with Gaussian distribution.

The FEL light was coupled out by a gold-coated scraper mirror of 18 mm in diameter, which was installed at 0.5 m away from the downstream mirror and 23 mm from the center axis of the optical cavity, and was extracted through a KRS5 window. The FEL power was measured with a power meter placed near the window and acquired by the oscilloscope in the same manner as the Ti:sapphire signal. The typical maximum power was 4.4 W at a macropulse duration of 0.4 ms with a 10 Hz repetition rate. This measured power is equal to 1.1 kW at a macropulse average.

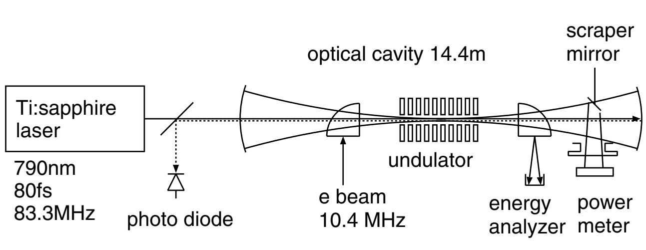

FIG. 2. An experimental setup for a simultaneous measurement of FEL power and absolute cavity length.

The experimental data are plotted as open circles in Fig. 3. For the calibration from the FEL power to the efficiency, we measured average energy loss of the electron beam over an entire macropulse at several detuning lengths. The loss measurement was made with the energy analyzer placed after the undulator, which has the energy acceptance of 20%, and the measurement was restricted to the larger detuning length beyond $\delta L = -10$ μm where the total energy spread was 17%. The FEL power and Ti:sapphire signal were simultaneously measured at equal steps of 0.2 μm around the maximum FEL power within 2 min. This quick measurement is necessary to reduce the uncertainty caused by slowly evolving drifts of the cavity length due to thermal strain and other sources. A separate measurement confirms that the maximum FEL power is held with variation of 2.3% rms and the amplitude change of the Ti:sapphire signal is 2.0% rms over 2 min.

As shown in Fig. 3, the peak of the FEL efficiency curve coincides with the resonance peak of the Ti:sapphire signal within the accuracy of 0.1 μm. This is the first demonstration of sustained saturation at the perfect synchronism. As the maximum efficiency is 6% with the electron beam power of 88 kW, the extracted FEL power should be 5 kW at a macropulse average. The total loss of the optical cavity with and without the scraper mirror was measured to be 7.6% $\pm$ 0.3% and 3.3% $\pm$ 0.2%, respectively, from a cavity ring down of FEL with a Ge-Cu detector. The FEL coupling rate from the cavity is therefore estimated to be about 30% on the assumption of coupling rate of 50% at the scraper mirror itself [12]. The transmittance of a KRS5 window for $\lambda = 22$ μm light is about 70% in normal incidence. Consequently, the estimated output FEL power from the measured efficiency is consistent with the experimental value of 1.1 kW with the power meter.

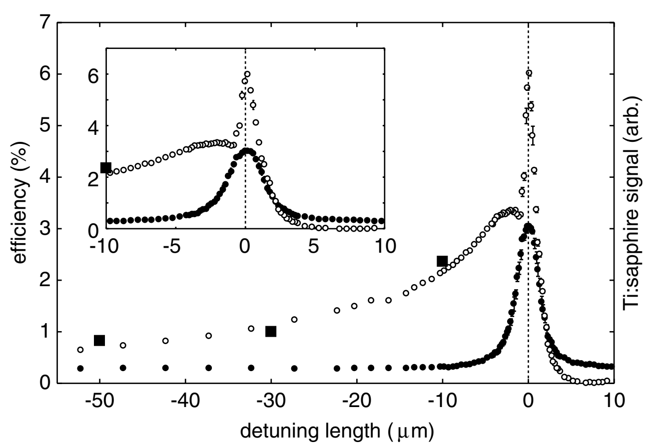

FIG. 3. FEL efficiencies (open circles) and Ti:sapphire signals (solid circles) as a function of detuning length. The enlargement around $\delta L = 0$ μm is also shown. The symbols without error bars have error less than their size. The absolute vertical scale was calibrated by an average energy loss of the electron beam over an entire macropulse (solid squares) at several detuning lengths.

We have also checked the accuracy of the simultaneous measurement by considering a possible disturbance on the electron bunch interval. Both monotonous change and random jitter of the bunch interval degrade the accuracy of the measurement. The former is introduced by monotonous beam-energy shift in a macropulse coupled with non-isochronous beam transport. Temporal profiles integrated over successive 1000 electron bunches were measured every 0.1 ms of macropulses at the undulator center with the synchroscan streak camera. Their centroids were the same with one another within 0.5 ps. If a systematic shift of 0.5 ps exists between 0.1 and 0.4 ms in a macropulse, it is equivalent to 0.17 fs per bunch. The effective shift of the detuning length due to the monotonous change is therefore less than 0.05 μm.

The other disturbance, random jitter of the electron bunch interval, can affect the FEL efficiency curve, especially when the curve has a fine structure. The random jitter in JAERI-FEL is estimated to be less than 100 fs from a steep peak narrow as 1 μm around $\delta L = 0$ μm in the efficiency curve (see Fig. 3), as discussed in the following. The optical pulses are pushed by 26 μm until the optical power decreases to $1/e$ due to the cavity loss of 7.6%, if the cavity length is shifted by 1 μm. On the other hand, the random jitter of 100 fs is equivalent to longitudinal fluctuation of 30 μm and is almost equal to the above mentioned pushed distance. The steep peak therefore would be dull with the jitter larger than 100 fs, and we could not determine the position of the maximum efficiency in the detuning curve with enough accuracy to claim the lasing at $\delta L = 0$. In the present case, however, we can obtain the detuning length at the maximum FEL efficiency with the accuracy less than the data interval (see Fig. 3). The effect of the random jitter is therefore less than ± 0.1 μm. The present small random jitter is owing to the reduction of the random jitter of our electron gun [13]. In the end, the largest uncertainty in the present detuning length measurement is equal to or less than the data interval of 0.2 μm.

An interesting feature of the efficiency detuning curve in JAERI-FEL is the steep peak at $\delta L = 0$ μm. The efficiency gradually increases from $\delta L = -30$ to -1 μm, but is sharply enhanced from -1 to 0 μm, as shown in Fig. 4. The enhancement of the efficiency is about 80%. The steep peak has not been observed in other FELs [1,7,14]. A numerical analysis is made to characterize the lasing behavior by using a 1D time-dependent code based on a macroparticle model [15]. A shot noise of the bunch is also introduced into the simulation according to Penman's method [16], which gives the effective shot noise derived from statistical consideration. An efficiency curve simulated with the dimensionless beam current [17], $j_0 = 50$, is shown as solid triangles in Fig. 4 and agrees well with the experimental data, while $j_0 = 33$ is derived from the beam parameters in JAERI-FEL. The main reason for the difference of the current j_0 may be attributed to our experimental uncertainty of the peak current of the electron bunch. The single pass FEL gain is proportional to j_0.

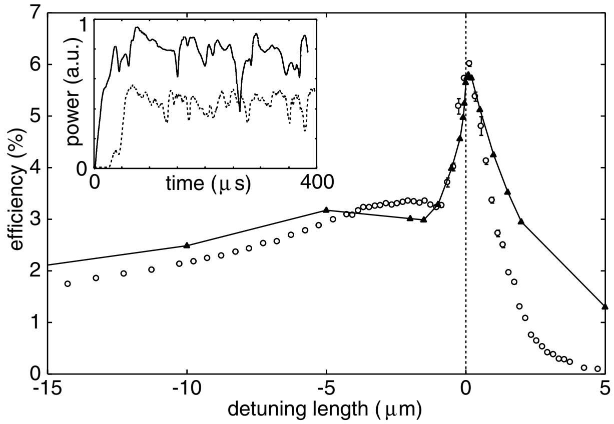

FIG. 4. The open circles are typical efficiencies as a function of detuning length in JAERI-FEL. The solid triangles are our numerical results, which agree with the measured efficiency curve well. The solid line is a guide to the eye. The inset shows typical optical macropulses at the perfect synchronism from our simulation (solid line) and an experiment (dashed line).

It was also found that our numerical simulation without the shot noise gives a result consistent with the studies by Colson [3] and Piovella [4], in which no stationary lasing exists at a perfectly synchronized cavity with nonzero loss. Thus the small shot noise largely affects the lasing dynamics at the perfect synchronism, although the coherent component of the shot noise has small power, 10^{-10} of the saturated FEL power in our simulations, and does not affect the efficiency curve directly. Typical optical macropulses at $\delta L = 0$ μm from the simulation (solid line) and an experiment (dashed line) are shown in the above left in Fig. 4 with an arbitrary unit in the vertical axis. They are similar to each other and clearly show the sustained behavior of the FEL saturation at $\delta L = 0$ μm. Details of our numerical simulation will appear elsewhere [6].

It should be noticed that the numerical study by Colson, which shows only a transient FEL evolution at $\delta L = 0$, also includes a shot-noise effect and uses the coupling mode parameter $\mu_c = 2$ similar to the present study [3]. The parameter μ_c is defined as $\mu_c = N\lambda/\sigma_e$, where N is the number of undulator periods and σ_e is the rms electron bunch length [18]. The main difference is the dimensionless beam current, $j_0 = 50$, in JAERI-FEL, while $j_0 = 5$ is used in the simulation by Colson. In order to study the lasing dynamics at smaller j_0, we measured efficiency curves at three different rms undulator parameters of $a_w = 0.70$, 0.49, and 0.31 by widening the undulator gap. The currents j_0 are estimated to be 50, 27, and 11, respectively, on the definition of $j_0 \propto (a_w[JJ])^2$ [17]. Here, $[JJ]$ is the Bessel function for a planar undulator. The detuning length of each efficiency curve was calibrated by the Ti:sapphire laser, independently. The experimental

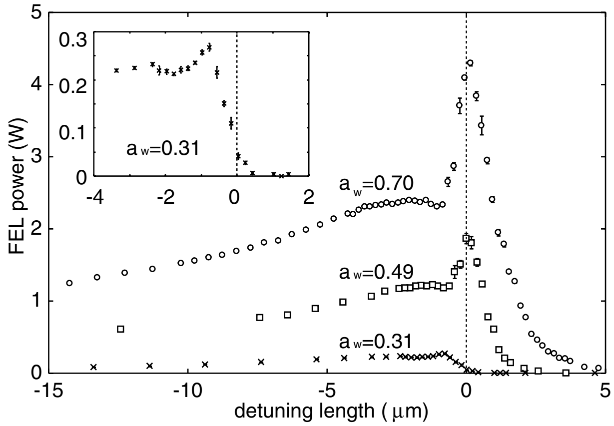

FIG. 5. FEL power measured as a function of detuning length with different undulator parameters: 0.70 (open circles), 0.49 (open squares), and 0.31 (crosses). The macropulse duration is 0.4 ms at a 10 Hz repetition rate. The enlargement around $\delta L = 0$ μm for $a_w = 0.31$ is also shown in the inset.

results shown in Fig. 5 exhibit that the lasing dynamics at the perfect synchronism depends on the dimensionless beam current, and the sustained saturation at $\delta L = 0$ disappears at $j_0 = 11$. This result is consistent with the Colson's simulation at $j_0 = 5$.

Some numerical studies have shown that a shot noise can affect shape of an efficiency detuning curve, already [15,19]. They have focused only on the behavior in the region longer than $\delta L = 0$, however. The present study in JAERI-FEL suggests that the efficiency becomes maximum at the perfect synchronism when the dimensionless beam current is large enough, and that the shot noise affects the lasing dynamics at the perfect synchronism.

In conclusion, we have observed sustained saturation in FEL oscillators at perfect synchronism for the first time, although it has been considered that a transient solution exists only at the perfect synchronism due to the laser lethargy, so far. The FEL efficiency becomes maximum at the perfect synchronism, if the dimensionless beam current is large enough. The efficiency detuning curve is well reproduced by our numerical simulation including a shot-noise effect.

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