Demonstration of a High-Power FEL Oscillator with High Extraction-Efficiency

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Abstract

IR-FEL lasing over kilowatt average power has been demonstrated at JAERI-FEL driven by a superconducting linac. The lasing is distinguished from other FEL oscillators by its high extraction-efficiency, 6%, and unique cavity-length detuning curve. The lasing at JAERI-FEL has the maximum power at the perfect synchronism between the optical pulse and the electron bunch, while usual FEL oscillators require cavity-length shortening to compensate laser lethargy. Numerical analyses show that the lasing observed at JAERI-FEL is a new type of FEL lasing : quasi-stationary superradiance, which gives extraction efficiency higher than the theoretical prediction previously reported. Our analyses also indicate that long stable macro-pulses generated by superconducting linac are indispensable to establish this new type of lasing.

1 INTRODUCTION

A superconducting RF structure is the most efficient accelerating device to convert RF generator power into charged particles energy, because the energy dissipation in the cavity is small as negligible. This small energy dissipation realizes operation of the cavity with large Q value, which enable to control RF amplitude and phase precisely by feedback loops. These excellent properties of the superconducting linac contribute to the high-power free-electron lasers in the IR region recently developed at JAERI (Japan Atomic Energy Research Institute) [1] and TJNAF (Thomas Jefferson National Accelerator Facility) [2].

In JAERI-FEL, we have demonstrated high-power lasing over 2kW average power with FEL extraction efficiency of $\eta_{fel} \simeq 6\%$ at the wavelength of $22\mu m$. The lasing obtained at JAERI-FEL is distinguished from other FEL oscillators by large extraction efficiency and a unique cavity-length detuning curve, which shows maximum FEL power at $\delta L = 0$. In this paper, we describe experimental results of high-power and high-efficiency lasing. Characterization of the lasing by numerical simulation is also presented.

2 THE SUPERCONDUCTING LINAC

The superconducting linac for JAERI-FEL consists of the injector, the main accelerator and the beam transport as shown in fig.1. The injector system includes a thermionic gun of 230kV, a normal-conducting sub-harmonic buncher driven at 83.3MHz, two single-cell superconducting cavities as pre-accelerators driven at 499.8MHz. The electron gun with thermionic cathode is driven by a grid-pulser and produces electron bunches having 0.51nC charge and 810ps pulse-width at 10.4MHz repetition. The electron bunch is compressed by velocity modulation applied in the sub-harmonic buncher and a following free drift after the buncher. The electron bunch is further compressed during another drift after the pre-accelerators and finally becomes short as 5ps (FWHM). This procedure of two-stage bunch compression is designed to generate an electron bunch with short duration and small emittance. Since the final bunching is conducted at 2.2MeV, which is larger than usual injector design, we can minimize the emittance dilution caused by space charge and nonlinear RF force. The electron bunch has pulse length of 5ps and peak current of 100A at the full energy. Transverse emittance after the bunch compression is 20 π mm-mrad in normalized value, which is the smallest one among similar type of injectors ever designed for FELs.

The two-stage bunch compression also contributes to small timing jitter in electron bunch interval after the full acceleration. The longitudinal phase space is rotated almost linearly during the bunch compression and becomes upright shape at the main accelerator. The final longitudinal position of electrons is, therefore, less sensitive to perturbation of the initial longitudinal position, that is timing-jitter at the gun. Controlling the nonlinear higher-order components in the longitudinal phase space transformation is thus important for the small timing jitter as well as making a very short electron bunch. In the JAERI-FEL injector, we have shown that the nonlinear terms can be minimized by well-designed two-stage compression scheme. The timing-jitter after the full acceleration is estimated to be less than $100fs$ from the measurement of FEL property [3][4].

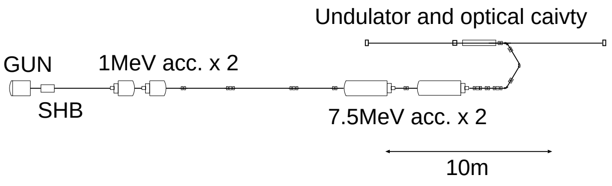

Figure 1: Layout of JAERI FEL.

3 HIGH-POWER LASING AT JAERI-FEL

In the summer of 1999, JAERI-FEL achieved 300W in average power [5]. The FEL power, P_{fel} is determined by $P_{fel} = \eta_{fel}\ \eta_{opt}\ P_{beam}$, where P_{beam} is the beam power, η_{fel} is the extraction efficiency from the beam power into laser power and η_{opt} is the efficiency of optical cavity. In

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JAERI-FEL, laser beam power stored in the optical cavity is out-coupled by on-axis hole or small scraper mirror. These out-coupling methods provide optical cavity efficiency : $\eta_{opt} \sim 0.5$ [6]. Classical FEL theory shows that the FEL efficiency is, in the limit of long bunch, inversely proportional to the number of undulator periods : $\eta_{fel} \sim 1/(2N_u)$. Substituting JAERI-FEL parameters : $N_u = 52$ and $P_{beam} = 90kW$, we find the theoretical limit of maximum FEL power as $P_{fel} \sim 400W$. We consider that the FEL power of 300W obtained at the summer of 1999 is basically determined by this classical scaling law of long bunch limit.

After the 300W lasing, we improved the injector performance to make shorter electron bunch. We optimized drift length between the SHB and the pre-accelerator and reduced timing jitter of electron bunch generated by grid-pulser. As a result of these improvements, the bunch length has been shortened from 30ps to 5ps (FWHM), which is comparable to the slippage distance in JAERI-FEL : $N_u\lambda \simeq 1.1$mm[7]. The extraction efficiency is now determined by superradiant scaling law of a short-bunch FEL oscillator[8]: $\eta_{fel} \propto \sqrt{1/\alpha_0}$, where α_0 is the total loss of the optical cavity. This scaling law suggests that the FEL efficiency can be increased by decreasing the total loss. We made numerical studies to investigate possible lasing of JAERI-FEL in the superradiant regime and concluded that the FEL power is certainly increased by operating the FEL in the superradiant regime. According to the numerical prediction, we optimized optical cavity design for reducing the total loss with keeping moderate efficiency, $\eta_{opt} \sim 0.5$. Transverse beam optics through the accelerator to the undulator was refined to obtain small beam size in the undulator. After these efforts, high-power IR-FEL lasing over 2kW in average was demonstrated[1]. The FEL efficiency has been largely enhanced and become $\eta_{fel} \simeq 6\%$. This high extraction-efficiency comes with broadening of lasing bandwidth, which is a common feature of superradiant regime.

The lasing observed at JAERI-FEL has unique property in the cavity-length detuning curve, which cannot be explained by analytical theory of superradiance. The lasing at JAERI-FEL shows the maximum power at the perfect synchronism of the optical pulse and the electron bunch, while usual FEL oscillators require cavity-length shortening to compensate laser lethargy, retardation of optical pulse group velocity due to FEL interaction. The lasing at the perfect synchronism in JAERI-FEL has been confirmed by absolute measurement of the optical cavity length using pulse stacking of external Ti:Sapphire laser locked with the RF master oscillator[4].

4 NUMERICAL ANALYSES

A numerical simulation has been conducted to characterize lasing behavior observed in JAERI-FEL. The simulation is based on a one-dimensional time-dependent FEL code[3]. The experimental detuning curve is well reproduced by simulation with dimensionless current parameter $j_0 = 50$, total cavity-loss $\alpha_0 = 0.06$, electron bunch length $L_b = 5ps$(FWHM) with triangular shape. We plot numerical results in fig.2 to compare with the experimental result.

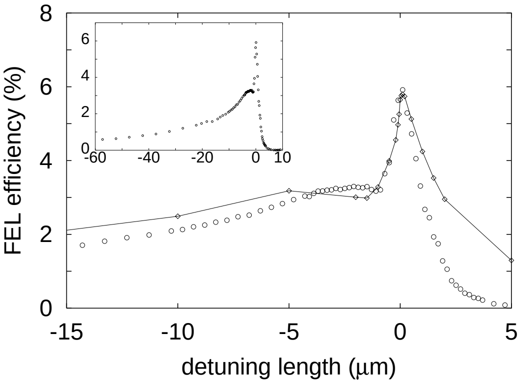

Figure 2: Cavity-length detuning curve from the experiment (○) and the simulation (solid line) . Whole structure of the experimental curve is also shown.

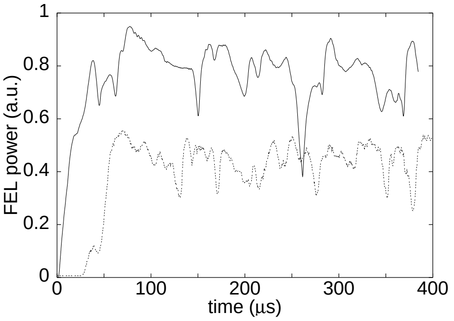

Figure 3: Typical optical macropulses at $\delta L = 0$ in the simulation (solid-line) and in the experiment (dashed-line).

Typical optical macropulses for $\delta L = 0$ from the simulation and the experiment are shown in fig.3. Both curves indicate similar structure, large fluctuation with time scale around $10\mu s$. The experimental curve has time lag in the beginning of macropulse due to the transient period of beam-load compensation, which is not included in the simulation.

In the numerical simulation, we also see lasing behavior depending on cavity-length detuning, where FEL pulses have three types of temporal structure: single supermode, limit cycle, chaotic spiking. These results agree with previous analytical studies[8]. Figure 4 shows temporal profile of an FEL pulse for $\delta L = -3\mu m$, as an example of chaotic spiking lasing.

In fig.4, we also plot an FEL pulse for $\delta L = 0$, which shows quiet different aspect from previously reported lasing dynamics. A single optical spike has large amplitude and keeps almost the same position in the rest frame of vacuum speed of light, though the amplitude and the position of spike have random fluctuation every round trip. Since the optical spike has the characteristics of superradiance,

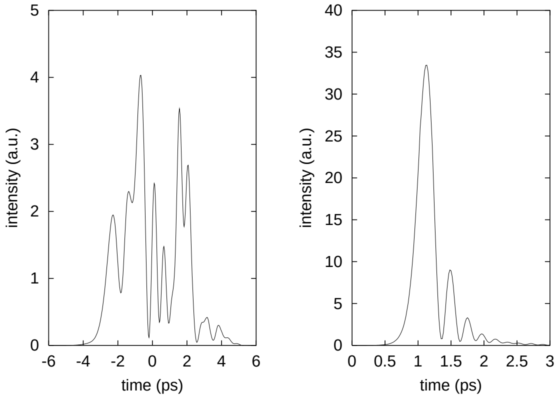

Figure 4: Numerically obtained FEL pulses at the 4000th round trip : $\delta L = -3\mu m$ (left) and $\delta L = 0$ (right).

we call it quasi-stationary superradiance. This type of lasing are seen at $-0.5\mu m < \delta L < 5\mu m$, which corresponds to the steep peak of the detuning curve. The discontinuous jump of extraction efficiency in the detuning curves is, therefore, considered as the transition of lasing dynamics from the chaotic spiking-mode to the quasi-stationary superradiance.

5 DISCUSSIONS

The analytical theory of FEL oscillators in superradiant regime shows that the maximum efficiency, $\eta_{max} \simeq 1.43/4\pi N_u\sqrt{\alpha}$, occurs at $\delta L_{opt} \sim 0.181 N_u \lambda g \alpha^{3/2}$, where g is the small-signal gain parameter averaged over slippage distance, $\alpha = \alpha_0/g$ is normalized loss of the optical cavity[8]. From the parameters used in our simulation, we find $g = 20$, $\eta_{max} = 4\%$, and $\delta L_{opt} = -0.7\mu m$. This efficiency peak at small negative δL appears as a shoulder of the detuning curves in fig.2. We see that JAERI-FEL has the higher extraction-efficiency at $\delta L = 0$, which is nearly twice as the superradiant scaling law.

Lasing at $\delta L = 0$, the perfect synchronism of optical cavity length and electron bunch interval, has been reported in transient regime of a short-pulse FEL oscillator[9], but sustained lasing at $\delta L = 0$ has never been reported in both analytical and experimental studies. We discuss, in the following, the reason why lasing at $\delta L = 0$ never reported.

A series of experiments with varying the gain parameter and the total cavity-loss in JAERI-FEL shows that the lasing at $\delta L = 0$ only occurs in high-gain regime[4]. We also see that the lasing at $\delta L = 0$ requires start-up period as long as 50μsec, that is 500 round trips as shown in fig. 3.

The cavity-length detuning curves in the experiments have a steep peak, the width of which is around $1\mu m$. This steep peak may become dull or disappear, if electron bunch has large timing jitter, which is equivalent to random jitter of the cavity-length detuning. We have found that the steep peak of $1\mu m$ cannot survive for timing jitter larger than 100fs [3][4].

As a result of above consideration, we conclude the lasing at $\delta L = 0$ only occurs in a high-gain FEL oscillator with electron bunches of long macro-pulse and small timing jitter. Such an FEL oscillator is only realized by superconducting linacs. This is the reason why JAERI-FEL has demonstrated the high-efficiency lasing at $\delta L = 0$ for the first time.

Figure 4 shows that the FEL pulse for $\delta L = 0$ has time duration of 250fs (FWHM), which is shorter than four cycles of optical field, $\lambda = 22\mu m$. An experimental validation of this ultrashort FEL pulse has been made and will be reported elsewhere[10].

In a high-gain FEL oscillator with a perfectly synchronized optical cavity, we have seen that a ultrashort optical pulse is generated and it overtakes a fresh electron bunch with FEL interaction every round trip in the same manner. This is equivalent to the optical pulse interacting with a long electron bunch through a long undulator, which is a SASE-like FEL amplifier. Note that the electrons in our SASE-like amplifier keeps quiet and does not start to lase until the optical pulse begins interaction with them, while an optical pulse in usual SASE-FELs consists of many superradiant spikes as a results of simultaneously initiated SASE interaction in the whole electron bunch.

6 SUMMARY

We have presented experimental results and numerical characterization of high-power and high-efficiency lasing obtained at JAERI-FEL. The lasing is considered as the generation of quasi-stationary superradiant optical spikes with ultrashort time duration, which is equivalent to a SASE-like amplifier. It has been shown that this type of lasing is only realized by superconducting linacs which provide electron bunch trains of long macropulses with small timing jitter.

7 REFERENCES

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