# HIGH POWER OPERATION OF THE THz FEL AT ISIR, OSAKA UNIVERSITY

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*Abstract*

To enhance the power of the THz FEL, we have developed a 27 MHz grid pulser for the thermionic electron gun. It makes the bunch intervals 4 times longer and increases charge of the bunch 4 times higher than the dc-beam injection scheme whereas the beam loading is the same as that in the dc scheme. In this new operation mode, where a single FEL pulse lases in the cavity, we have succeeded in obtaining the micropulse energy exceeding 200 μJ at a wavelength of 67 μm.

## INTRODUCTION

The THz FEL has been developed using the L-band electron linac system at the Institute of Scientific and Industrial Research (ISIR), Osaka University. The first lasing was demonstrated at wavelengths from 32 to 40 μm in 1994 [1]. Some years later, the linac system was substantially upgraded for higher stability and reproducibility of its operation. In addition, the pulse duration of the klystron modulator was expanded from 5 to 10 μs for FEL, so that the THz-FEL reached the power saturation first time at a wavelength of 70 μm [2]. The FEL currently operates over the wavelength range from 25 to 150 μm [3].

We pursue research on the upgrade of the FEL to expand the wavelength range and to increase the FEL power. One of the key factors to achieve such objectives is a higher beam current, which is expected to increase FEL gain and the saturation power of the FEL [4]. We are, therefore, developing a new operation mode of the linac system for higher bunch charge.

In the present scheme of the linac operation for the FEL, an electron pulse with a current of 0.6 A and a duration of 8 μs is extracted from the electron gun, and pre-bunched at the rf frequency of 108 MHz using the sub-harmonic buncher system. The electron beam that is a train of bunches at 9.2 ns intervals for the 8 μs duration is accelerated using the 1.3 GHz rf structures consisting of a pre-buncher, a buncher, and a 3 m long acceleration tube of the travelling wave type. The electron beam with the charge of 1 nC/bunch is transported via the FEL beamline to the THz-FEL. In this operation, the rf power measured at the exit of the traveling-wave acceleration tube is reduced to 24% of that without the electron beam. Therefore, the beam loading is too high to further increase the beam current [5].

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On the other hand, the optical cavity of the FEL is 5.531 m long, and accordingly, the round-trip time of a light pulse is 36.9 ns, meaning that four FEL pulses independently arise and develop in the cavity. Because a single FEL pulse is sufficient to lase, we can increase the bunch charge four times higher by expanding the bunch interval to 36.9 ns whereas the beam loading in the acceleration tube is kept at the same level. Therefore, we have developed a simple and compact grid pulser system for the electron gun to generate a train of electron pulses with a peak current of 2.4 A and a duration of 5 ns at intervals of 36.9 ns, which corresponds to the repetition frequency of 27 MHz, continuing for 8 μs.

In this paper, we will report recent results of the THz-FEL in high power operation using the electron beam of 4 nC/bunch.

## EXPERIMENTAL SETUP

The schematic drawing of the L-band linac and FEL system at ISIR is shown in Figure 1. The electron beam is extracted from the electron gun with the thermionic cathode operating at -100 kV DC and pre-bunched using the three-stage sub-harmonic buncher (SHB) system. The SHB system consists of two 108 MHz 1/4 wavelength resonators and one 216 MHz resonator. The electron beam is bunched and accelerated with 1.3 GHz travelling-wave RF structures, including a pre-buncher, a buncher, and a 3 m long acceleration tube. The accelerated electron beam is tuned using the diagnostic beamline with the analysing magnet and the Faraday cup so that the electron energy is constant over the pulse and the instantaneous energy spread is small. After beam tuning, the electron beam is transported via the FEL beamline to the FEL that consists of a planar type permanent magnet wiggler and an optical cavity. The THz-FEL beam is transported from the accelerator room through the shielding wall to the experimental station in the measurement room.

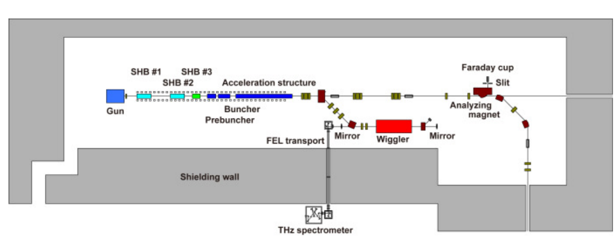


Figure 1: Schematic diagram of the L-band linac and the FEL system at the ISIR, Osaka University.



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### *Grid Pulser*

To drive the electron gun at the repetition frequency of 27 MHz, we developed a simple and compact grid pulser system using a field effect transistor (FET). To extract electron pulses with a peak current of 2.4 A from the cathode (YU-156, Eimac), the output pulse height from the grid pulser is required to be over -150 V. For the efficient capture of electrons by the SHB system, the pulse duration is required to be less than 5 ns (FWHM), which corresponds to the half-period of the 108 MHz rf. To meet requirements for the voltage and the speed, we selected two candidates for the FEL (2SK408 and 2SK410, Hitachi), and developed a delayed shunt circuit for the gate of the FET to determine the pulse duration and to reduce the trail of the output pulse by grounding the gate and removing remaining charge in it. The schematic diagram of the grid pulser circuit is shown in Fig. 2. The input pulse train at the repetition frequency of 27 MHz for the duration of 8 μs is amplified by the transistor amplifier and divided into two lines. A pulse in the main line triggers the FET on the gate stage and a high voltage pulse is generated on the drain stage. The pulse in the other line is delayed using a coaxial cable and turns the transistor to shunt the base stage of the FET.

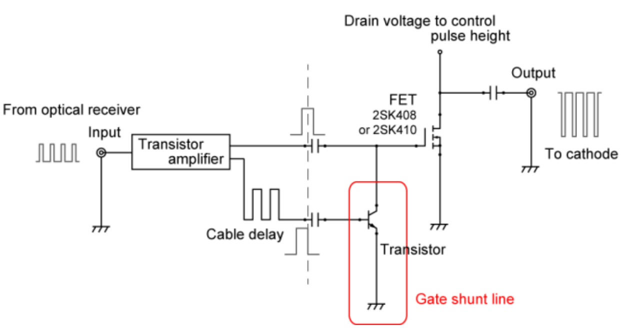



Figure 2: Schematic diagram of the grid pulser circuit.

In order to determine the optimal delay for shunting, the output signal of the grid pulse was measured for several cable lengths of the delay-line. The results of the measurement are shown in Fig. 3. As the results of these measurements, we select the delay-line length 40 cm longer than the length of main line.

Figure 4 shows the time profile of the electron beam generated using the grid pulser and measured with a core monitor at the exit of the electron gun system. The peak current of each bunch is almost constant, and the bunch repetition frequency is 27 MHz. The bunch duration of the electron beam is measured to be less than the specification, 5 ns.

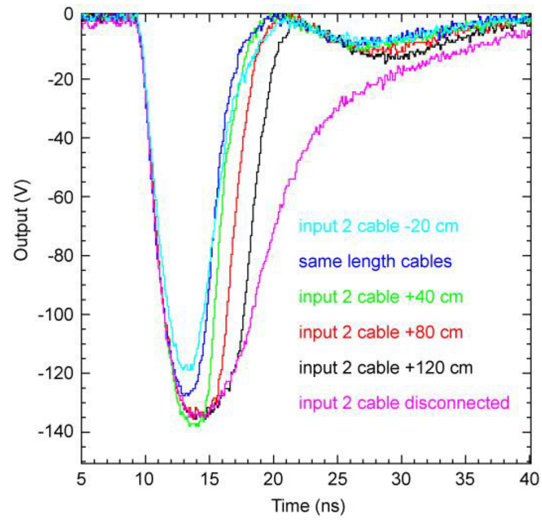
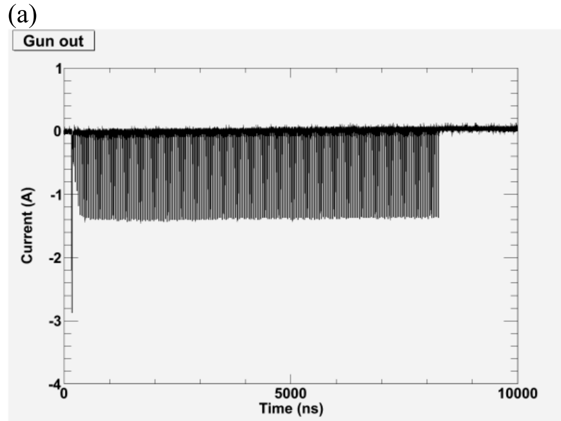



Figure 3: Tuning result of the delayed shunt timing.

(a)




(b)

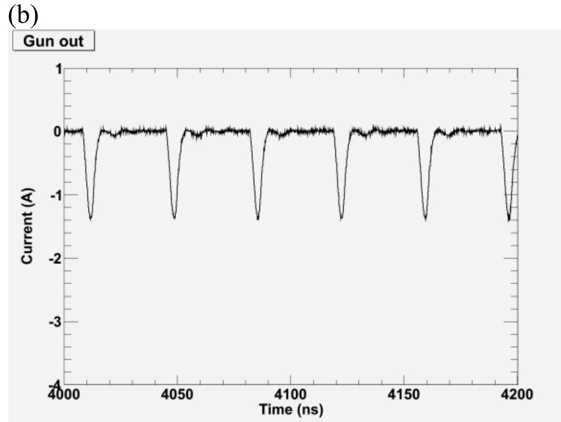



Figure 4: The waveform of the electron beam generated with the new grid pulser system. This waveform shows the core monitor signal measured at the exit of the electron gun. (a) full length waveform of the generated electron beam. (b) horizontal axis is expanded.



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### *Beam Loading*

Figure 5 shows the RF power exiting the acceleration tube in the 108 MHz operation with the beam current of 0.6 A (a) and that in the 27 MHz operation with a current of 2.0 A (b). As expected, the beam loading in in the 27 MHz operation with 2.0 A is lower than that in the 108 MHz operation with 0.6 A.

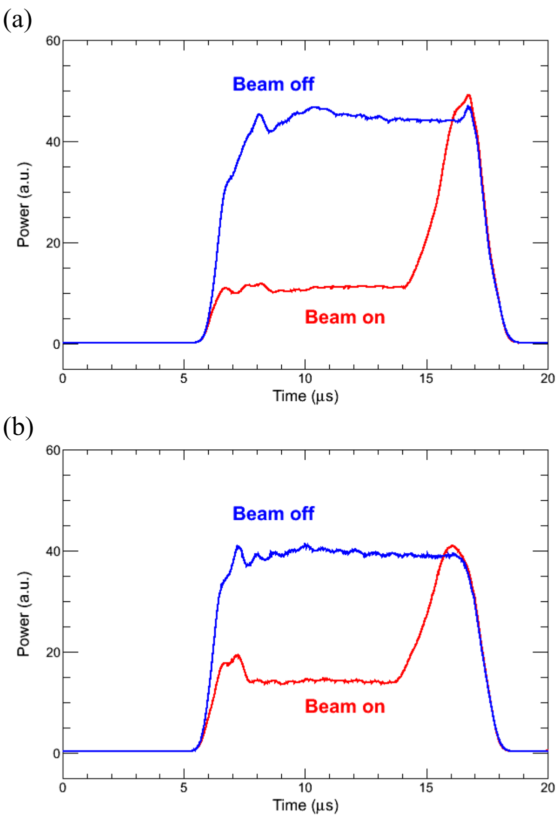


Figure 5: Beam loading at the acceleration tube for the dc-injection with the beam current of 0.6 A (a) and the 27 MHz operation with the peak current of 2.0 A (b).

### *Electron Beam Spectra*

To generate a high quality and high intensity FEL, the electron beam with a constant energy and small energy spread is necessary.

The time-resolved energy spectrum of the electron beam was measured using an analysing magnet and the Faraday cup with a slit. The signal from the Faraday cup is measured with an oscilloscope by changing the magnetic field of the analysing magnet, so that a two-dimensional energy spectrum of the electron beam is obtained. The typical spectra in both operations are shown in Fig. 6. In both cases, the projected spectral width is about 1% and the r.m.s. uniformity of the peak energy through the macropulse after 2 μs is estimated to be about 0.1%. After the beam tuning, we achieve a similar quality of the electron beam in the energy spectra.

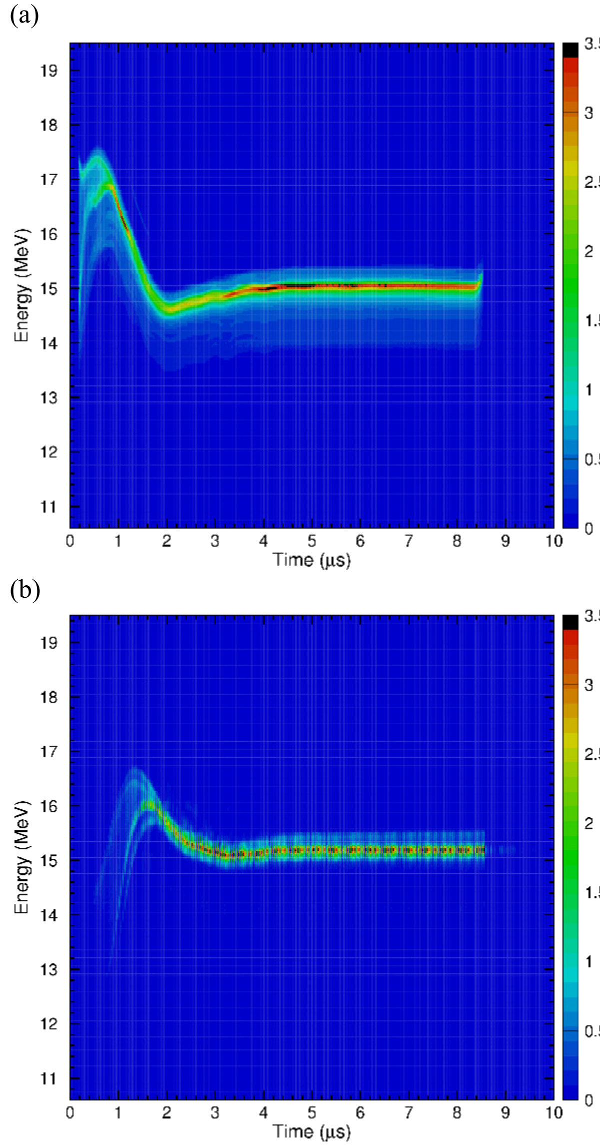


Figure 6: The typical energy spectra of the electron beam. (a) the dc-injection operation. (b) the 27 MHz operation.

## RESULTS

By using the 27 MHz operation of the electron beam, we generate the THz-FEL with the pulse interval of 36.9 ns and with the macropulse length of a few microseconds. As the preliminary results, the maximum macropulse energy is achieved to 26 mJ for the wavelength of 67 μm at the user area. The wavelength of the FEL is variable by changing the magnetic field strength of the wiggler, that is, by changing the gap length of the wiggler. Figure 7 shows the variation of the macropusle energy of the FEL by changing the gap length of the wiggler for the 27 MHz operation and the dc-injection (108 MHz operation) cases, respectively. At present, the macropulse energy of the FEL at the 27 MHz operation is two times larger than that at the 108 MHz operation. Roughly speaking, because the number of pulses is reduced in one-quarter, the



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micropulse energy is increased eightfold in the 27 MHz operation.

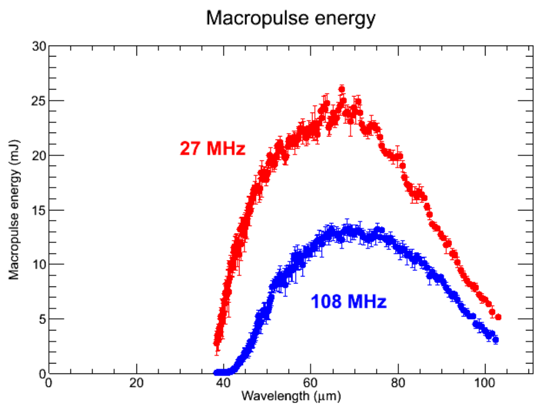


Figure 7: Macropulse energy of the FEL in the 27 MHz operation (red) and the 108 MHz operation (blue).

The time structure of the FEL macropulse is measured by using a fast response THz detector (Molectron, pyroelectric detector P-5). The typical waveform of the observed signal is shown in Fig. 8. From the measured waveform, the maximum micropulse energy is estimated to be 200 μJ for the wavelength of 67 μm. By assuming the pulse duration of 20 ps which is typical bunch duration of the electron beam accelerated by the L-band linac, the peak power of the THz pulse is estimated to be 10 MW, and by focusing it with the radius of 200 μm, the peak intensity is estimated to be 16 GW/cm$^2$.

The typical specifications of the THz-FEL at the ISIR are listed in Table 1.

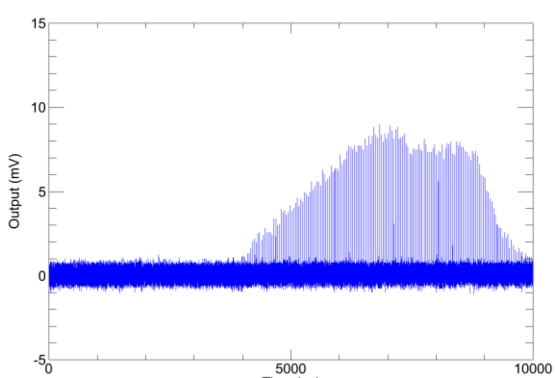


Figure 8: Typical waveform of the generated THz-FEL measured by a fast pyroelectric detector.

## CONCLUSION

By increasing the bunch charge of the electron beam combining a new grid pulser system and the sub-harmonic buncher system, we achieve the intensification of the micropulse energy of the FEL in eight times compared with the dc-beam injection scheme. As a preliminary result, the peak intensity is estimated to be 16 GW/cm$^2$ at the wavelength of 67 μm. This intense coherent and monochromatic THz radiation will open various research fields such as nonlinear responses of the materials in the THz region. The present results are not final ones. After optimization of various parameters and measurements of the THz pulse duration by the several methods, we will have more intense THz pulse and more precise characterization of that.

Table 1: Typical Specifications of the THz-FEL at the ISIR (Preliminary)

| Parameter | value |
|---|---|
| Wavelength range | 25 – 150 μm |
| (Frequency) | 2 – 12 THz |
| Macropulse energy at user area | >10 mJ (70 μm) |
| Repetition rate of macropulse | 5 Hz (max. 10 Hz) |
| Macropulse duration | 2 ~ 6 μs |
| Bunch separation | 9.2 ns or 36.9 ns |
| Energy stability of macropulse | 3 ~ 7% (r.m.s.) |

## ACKNOWLEDGMENT

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