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First Lasing of the CAEP THz FEL facility Driven by a Superconducting Accelerator

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Abstract. China Academy of Engineering Physics terahertz free electron laser (CAEP THz FEL, CTFEL) is the first THz FEL oscillator in China, which was jointly built by CAEP, Peking university and Tsinghua university. The stimulated saturation of the CTFEL was reached in August, 2017. CTFEL consists of a GaAs photocathode high-voltage DC gun, a superconducting RF linac, a planar undulator and a quasi-concentric optical resonator. The terahertz lasers frequency is continuously adjustable from 2 THz to 3 THz. The average power is about 20 W and the micro-pulse power is more than 0.3 MW.

1. Introduction

Free electron lasers (FELs) can be the most powerful tool as terahertz power sources. It has many advantages, such as monochrome, high-power, linear-polarization and continuously-tunable frequency. Many FEL oscillator facilities, such as ELBE in Germany [1], FELIX in Holland [2], UCSB in the USA [3] and NovoFEL in Russia [4], have played important roles in the THz sciences. In the near future, more than 20 FEL facilities have been planned to build in the whole world, of which there will be at least 8 ones operating in the THz range [5]. X-ray FEL Oscillators also have a rapid development in recent years[6, 7].

CAEP THz FEL (CTFEL) facility is the first high average THz source based on FEL in China [8, 9], which is driven by a DC gun with a GaAs photocathode [10, 11] and two 4-cell

1.3 GHz super-conducting radio frequency (SRF) accelerator [12, 13]. The repetition rate of CTFEL is 54.167 MHz, one over twenty-four of 1.3 GHz. The effective accelerating field gradient is about 10 MV/m.

CTFEL has achieved the stimulated saturation in August, 2017[14, 15]. The terahertz wave frequency is continuously adjustable from 2 THz to 3 THz. The average power is about 21 W and the micro-pulse power is more than 0.3 MW. This paper gives an introduction of this facility and its THz laser characters.

2. Facility components

2.1. Overview

Figure 1 shows the layout of the CTFEL facility. High average power high-brightness electron beam is emitted from the high-voltage DC gun equipped with a GaAs photocathode. The beam is then energized by a 24-cell RF superconducting accelerator and gain kinetic energy from 6 MeV to 8 MeV. Passing through an achromatic section, the beam then goes into the undulator magnet field and generates spontaneous radiation. The radiation resonates in the THz optical cavity and reaches saturations.

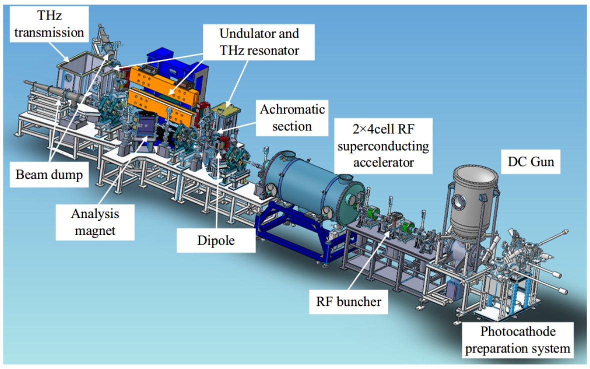

Figure 1. The layout of the CTFEL facility

Table 1 gives more information of the electron beam. The accelerator is designed to operate in both CW and macro-pulse mode. It is now working in macro-pulse mode in the first step. The typical pulse duration and repetition rate are 1 ms and 1 Hz, respectively. The duty cycle will upgrade to >10% in 2018 as the step two. And the CW operation will be reached in the step three.

Table 1. Electron beam parameters

Parameters	Design goal	Unit
Bunch charge	10∼100	pC
Micro-pulse repetition	54.167	MHz
Macro-pulse repetition	1∼20	Hz
Duty cycle	10^{-5} ∼1	
Kinetic energy	6∼8	MeV
Normalized emittance	<10	μm
Micropulse length (RMS)	1.5∼3	ps
Energy spread	∼ 0.2	%

2.2. High-voltage DC electron source

Figure 2 shows the system of the high-voltage DC electron source, which consists of a photocathode preparation chamber, a load-lock system, a drive laser, a high-voltage DC gun and some beam elements such as three solenoids and an RF buncher. The electron source can provide 320 keV high brightness beams both in CW mode and in macro-pulse mode. The average current has reached 1 mA∼5 mA. The micro-pulse length is compressed to less than 4 ps (RMS) by the RF buncher.

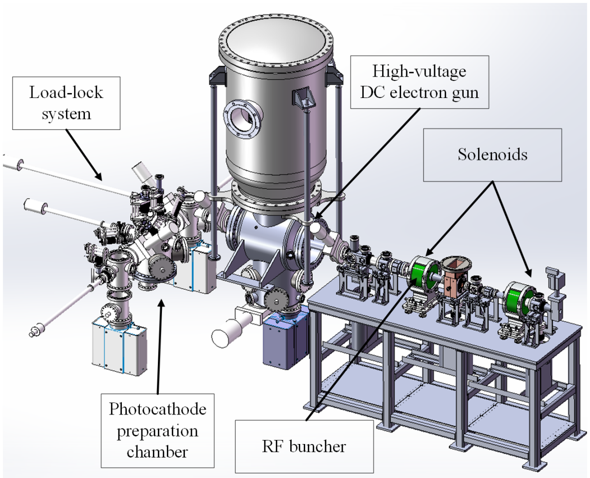

Figure 2. The high-voltage DC electron source

2.3. RF superconducting accelerator

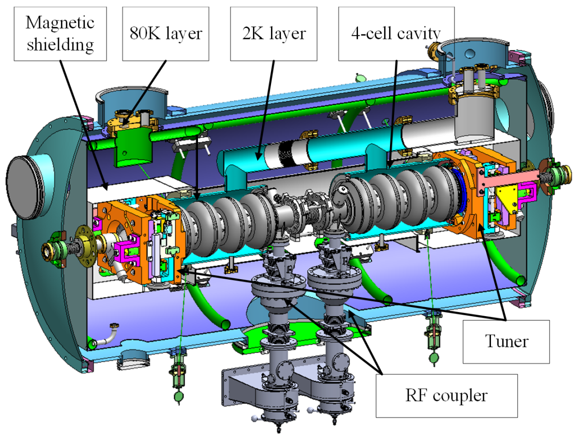

Figure 3. The RF superconducting accelerator

Owing to the advantages of superconducting RF technology in CW mode operation, a 24-cell superconducting linac module has been adopted to accelerate 320 keV, 1∼5 mA electron beams from the DC-gun up to an energy of 6∼8 MeV. The 24-cell module is composed of two SRF cavities, two power couplers, two tuners and a cryostat, as shown in Fig. 3. With the goal of 5 mA, 54.17 MHz CW beams, the components have been designed accounting for higher-order modes (HOMs), beam loading and cryogenic issues. The phase stability of the low-level RF

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control system is 0.1 , and the amplitude stability is better than 0.05%. After the acceleration, the normalized emittance of the beam is less than 8 mm·mrad , and the relative energy spread is less than 0.2%.

2.4. Undulator and THz resonator

The THz wave is generated and resonates in the undulator and the THz optical cavity system, as shown in Fig. 4. The electron beam and the THz wave travels through a THz waveguide together. The wave guide is in the undulator magnetic field. The undulator has a period of λ_u=38 mm. The field B_0 is tunable from 0.2 T to 0.55 T.

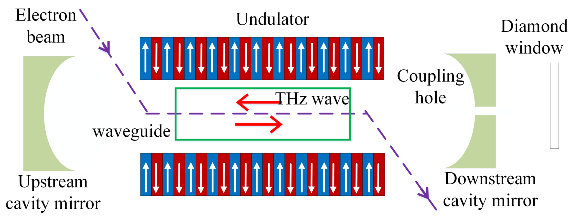

Figure 4. The undulator and the THz optical cavity

The THz wave is reflected back and forth through a waveguide[16]. The two cavity mirrors form a quasi-concentric optical resonator. The terahertz laser power is then extracted by a hole of 2.4 mm in diameter on the downstream mirror, and then goes through a diamond window to transmit to the users lab.

3. THz laser parameters

Table 2 shows the main parameters in the step one of the THz laser downstream the coupling hole.

Table 2. THz laser parameters

Parameters	Value	Unit
Tunable frequency range	1.87∼3.3	THz
Spectral FWHM	2∼3	%
Macro-pulse average power	∼20	W
Macro-pulse repetition	1∼20	Hz
Macro-pulse length	0.3∼2	ms
Micro-pulse RMS length	400∼500	fs
Micro-pulse interval	18.5	ns
Micro-pulse power	>0.3	MW
Minimum transverse radius	<0.5	mm
Polarization	Horizontal	

Figure 5 shows some measurement results of the THz laser at the users lab. Figure 5 (a) is the average power measured by a TK absolute energy meter. The THz average power is given by [17]:

$$P_{avg} = \frac{V}{0.49T\tau r_{ji}}, \tag{1}$$

where V is the output voltage of the energy meter, which is about 1260 mV in Fig. 5 (a). The other parameters are as follows: The parameter $T \approx 0.55$ is the transmission of the TPX window. The pre-calibrated r_{ji} is about 0.233 mV$\cdot\mu$J^{-1}. The factor 0.49 means that the absorption of the energy meters metal film is about 49%. The macro-pulse duration is measured by a GeGa detector, and is 920 μs, as shown in Fig. 5 (b). All the results indicate that the macro-pulse average power is about 21 W. The energy of macro-pulse is about 20 mJ.

Figure 5 (c) shows the electron beam signal for comparison, detected by a Fast-Current-Transformer (FCT). Because of the lack of feed-forward system, the macro-pulse of the electron beam is longer than the THz macro-pulse.

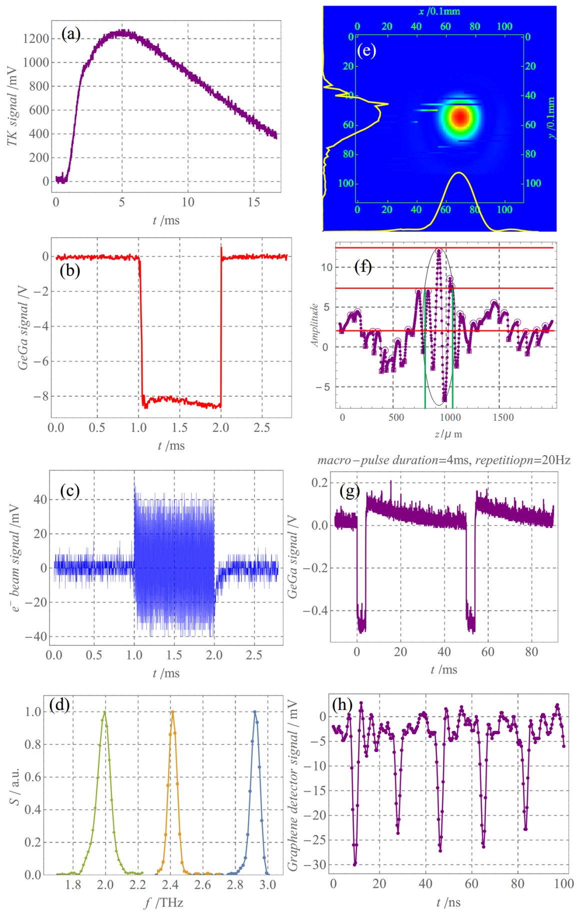

Figure 5. The THz laser measurement

The spectrum measured by a Fourier spectrometer (Bruker VERTEX 80V) at three single spots is shown in Fig. 5 (d). The frequency is adjusted by both the undulator gap and the electron energy. Figure 5 (e) is the THz beam transverse profile captured by a pyroelectric array camera "Pyrocam IIIHR (15 cm downstream the focal point). The beam fulfill the transverse Gaussian distribution. The minimum beam size around the focal point is estimated as less than 1 mm in diameter.

Figure 5 (f) is the "energy versus moving-mirror" curve in the time domain caught by the Fourier spectrometer.The spectral FWHM is a little wider than the theoretical simulation because the micro-pulse length is a little shorter, typically as short as about 400 fs (RMS), caused by the phase slippage, making the peak power more than 0.3 MW.

An example of high-duty-cycle running is shown in Fig. 5 (g), where the macro-pulse duration is 4 ms and the macro-repetition rate is 20 Hz, making the duty-cycle about 8%.

Figure 5 (h) shows the THz micro signal captured by a graphene detector[18, 19], whose rising time is less than 1 ns.

At last, the power density was so strong that it damaged the terahertz attenuator and the TK energy meter, as shown in Fig. 6.

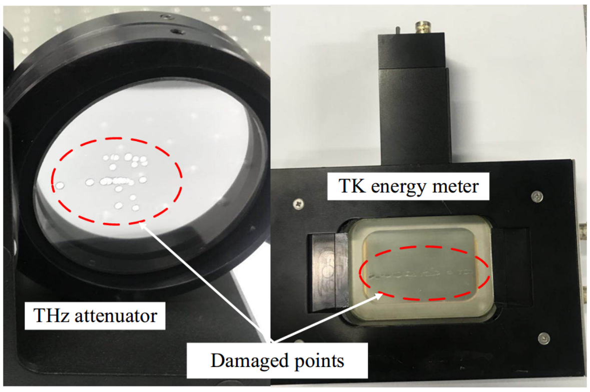

Figure 6. The damage caused by the THz laser

4. SUMMARY

This paper has briefly introduced the CTFEL facility, the first THz free electron laser oscillator in China. This facility mainly consists of the high-brightness high-voltage DC electron source, the CW RF superconducting accelerator and the undulator-optical-cavity system. The CTFEL facility provides monochrome, high-power, linear-polarization, and frequency-continuously-tunable THz laser. The terahertz frequency is continuously adjustable from 2 THz to 3 THz. The average power is more than 20 W and the micro-pulse power is more than 0.3 MW. CTFEL will be working as an user facility, and will greatly promote the development of the THz science and its applications on material science, chemistry science, biomedical science and many other cutting-edge areas in general.

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