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COMMISSIONING AND FIRST LASING OF THE FELiChEM: A NEW IR AND THz FEL OSCILLATOR IN CHINA*

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Abstract

A new infrared FEL named FELiChEM aiming at the energy chemistry has been constructed and commissioned at NSRL in Hefei. It consists of two FEL oscillators driven by one normal-conducting S-band linac with maximum beam energy of 60 MeV. The two oscillators generate the mid-infrared and far-infrared lasers covering the spectral range of 2.5-50 μm and 40-200 μm, respectively. First lasing was achieved at a wavelength of 15 μm with an electron energy of 35 MeV. Till now, we have observed the FEL signal from 3.5μm to 30 μm and achieved the maximum micropulse energy up to 27 μJ at 15 μm.

INTRODUCTION OF FELICHEM

Under the financial support of Natural Science Foundation of China, the project "Tunable Infrared Laser for Fundamental of Energy Chemistry" (FELiChEM) was started in 2015. It is a dedicated experimental facility aiming at energy chemistry research [1, 2]. The core device is a free electron laser (FEL) consisting of two oscillators driven by one normal-conducting S-band linac with maximum electron energy of 60 MeV.

Figure 1 shows the schematic layout of FELiChEM. Both the accelerator hall and the experimental hall are existed buildings and we were allowed to design the facility with this constriction. The electron accelerator is located in a 12m×16m semi-underground tunnel, as shown by the photo of Fig. 2. Two branches connected with the linac are the two oscillators. The branch using the electron beam bended from the end of the first accelerating tube is the far-infrared oscillator which generates the 40-200 μm FEL, while another one called the mid-infrared oscillator generates the 2.5-40 μm FEL. The output FEL pulses from the

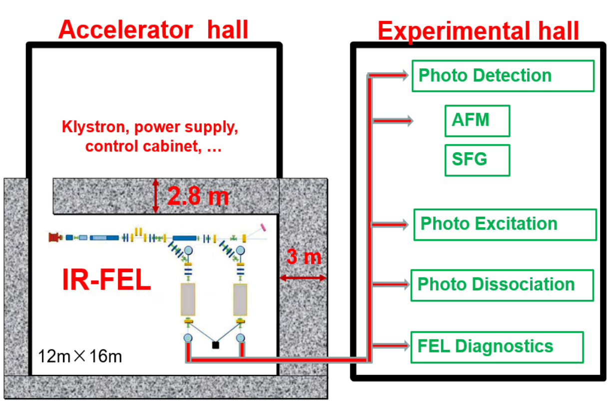

Figure 1: Schematic layout of FELiChEM.

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Table 1: Design Target of FELiChEM

Parameter	Specification
Covering spectrum	2.5 ~ 200 μm
MIR FEL oscillators	2.5 ~ 50 μm
FIR FEL oscillators	40 ~ 200 μm
Macro-pulse length	5~ 10 μs
Repetition of macro-pulse	10/20 Hz
Macro-pulse energy	~100 mJ
Micro-pulse length	1 ~ 5 ps
Micro-pulse energy	~ 50 μJ
Bandwidth	0.3 ~ 3 %

two oscillators share one beam line and are transported to the experimental hall, where the stations for FEL diagnostics, photo dissociation, photo excitation and photo detection are in one line. The total length of the beam line is about 36 m.

The users of these stations have brought out their requirements on the IR-FEL performance, as summarized in Table 1. In addition, some users have extra requirements, for example, the photo excitation and dissociation stations hope that the peak and average power of IR-FEL can be as high as possible. The design of the oscillator and the electron accelerator has been introduced in the Ref. [1-3].

Due to the delay of the civil construction, the installation of the accelerator was delayed by more than one year and was finished in June, 2018. Then in the next month we started the commissioning of the linac. Unfortunately, after two month the high-repetition grid pulser of the electron gun was broken suddenly and we had no choice but to wait it reworking. In May 2019, we restarted the commissioning, and observed the spontaneous radiation at the 15 μm wavelength in 9, June. On the same day, the first lasing up to 1 μJ per micropulse was detected at the same wavelength.

Next, we will briefly introduce the facility and the commissioning status, and then the first lasing results.

ELECTRON ACCELERATOR

The electron accelerator mainly consists of: an 80 kV electron gun, a 476 MHz subharmonic standing wave prebuncher, a 2856 MHz fundamental frequency traveling wave buncher, two 2856 MHz fundamental frequency traveling wave accelerating tubes separated by a magnetic compressor (chicane). Besides, a set of solenoid focusing coils are used from the gun exit to the end of the first accelerating tube.

The triode gun is driven by a grid pulser with the repetition frequency that can be switched in 476/238/119/59.5/29.5 MHz. For the operation safety of the grid pulser, we have turned down the high voltage from 100 kV to 80 kV,

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Figure 2: Photo of the accelerator and FEL oscillators in the semi-underground tunnel.

and re-optimized the following parameter setting of the linac. The pre-buncher works at a gap voltage of 34 kV and can compress the bunch by more than 20 times. The buncher shares the power with the first 2-meter accelerating tube from one klystron. Its input power is optimized at 5 MW and the rms bunch length can be compressed to 4.5 ps. After the second accelerating tube, the maximum beam energy can reach 60 MeV. The magnetic chicane is designed as an optional operation condition, which will be used in the future for enhancing the FEL performance.

Table 2: Summary of Electron Beam Parameters

Parameter	Target	Achieved
Electron Energy /MeV	15-60	25-60
Energy spread /keV	<240	<200@35MeV; <240@60MeV;
Bunch charge /nC	1.0	~1.2
Normalized rms transverse emittance / mm.mrad	<30	40~50
Micro-pulse rms length /ps	1-5	~4.5
Micro-bunch rep. rate /MHz	476/238/ 119/59.5/ 29.75	119/59.5 /29.75
Macro-bunch length / µs	5-10	1-6
Macro-pulse rep. rate /Hz	1-20	1-10

Seeing Table 2, we do not achieve the target value for several parameters. Currently, we cannot obtain the beam energy below 25 MeV due to a small problem with the power splitting between the buncher and the first accelerating tube, and this will be solved soon. The microbunch repetition rate, the macrobunch length and repetition rate are increased step by step because the beam loading effect at different beam current is also different so that we need to optimize the linac parameters carefully, especially the parameter setting of the LLRF feedforward. The measured beam emittance is much larger than the design value. The reason for this problem is that a part of the mechanical support for the solenoid around the buncher was magnetized by the magnetic field of the solenoid. We plan to replace this part in the next machine shutdown.

FEL OSCILLATORS

FELiChEM includes two oscillators covering the spectral range of 2.5-50 µm and 40-200 µm, respectively. Each oscillator consists of two important components: undulator and optical cavity. Their basic parameters are listed in Table 3 and detailed design can be found in Ref. [1].

Table 3: Summary of Oscillator Parameters

	Parameter	specification
MIR undulator	Period /mm	46
	Period number	50
	Undulator parameter *K*	0.5-3.2
MIR cavity	Cavity length /m	5.04
	Reyleigh length /m	0.78
	Reflectivity	99%
	Diameter of mirrors /mm	50
	Diameter of coupling holes /mm	1.0/1.5/2.5/3.5
FIR undulator	Period /mm	56
	Period number	40
	Undulator parameter *K*	0.5-3.3
FIR cavity	Cavity length /m	5.04
	Reyleigh length /m	0.78
	Reflectivity	99%
	Diameter of mirrors /mm	80
	Diameter of coupling holes /mm	1.0/2.0/4.0

In each oscillator, two spherical mirrors with Copper base and Gold coatings are used to form a symmetrical optical cavity. A planar permanent magnet undulator manufactured by KYMA is placed in the centre of the two optical cavities so that we have enough available space for beam transport and diagnostic on the two sides. The IR radiation is outcoupled from the downstream cavity, which contains multiple mirrors with different outcoupling hole sizes and mechanical conditioner for switching mirrors.

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In the MIR oscillator, to achieve the target radiation intensity and cover the spectral range of 2.5-50 μm, we use the 2.3-m-long undulator with a period length of 46 mm. Considering the optical size on the mirror for the FEL wavelength below 5 μm, the Rayleigh length of the cavity was optimized equal to one third of the undulator length. Based on the electron beam parameters given in Table. 2, the small signal gain is up to higher than 100% for most of the working region of the FEL wavelength. However, in the two sides of the wavelength region, it is still not high enough. We have carried out the time-dependent three-dimension simulation using the code *genesis* [4] combining with the code *OPC* [5]. As presented in Ref. [1, 2], the results show that the macropulse energy exceeds 100 mJ except for the wavelength shorter than 4 μm.

In the FIR oscillator, a 2.24-m-long undulator with a period length of 56 mm was used and the Rayleigh length of the cavity was selected equal to half of the undulator length. However, due to the serious diffraction effect of the long wavelength FEL, we need to add a waveguide to reduce the diffraction loss in the FIR oscillator. A planar waveguide with the height of b=10 mm is used inside the undulator chamber. We have calculated the small signal gain for the FIR-FEL by replacing the Gaussian mode of the optical beam by the fundamental waveguide mode, and the results show that the waveguide enhances the small signal gain by more than two times. In addition, according to the operation experience of CLIO and FELIX [6, 7], "spectral gap" may appear in this waveguide FEL. Considering this problem for FELiChEM, we have developed the simulation code for simulating overmoded waveguide FEL based on Genesis [8]. At present, we are working on accurately simulating the transport of the optical beam from the outer of the waveguide into the inner.

In our design of the FEL oscillator, one thing worth pointing out is the optimization of the important and complicated relations between the key parameters of the oscillator, including the cavity length L_c, the curvature radius of mirrors R_c, the stable factor of the resonator cavity g, the Rayleigh length Z_R, the optical beam size at the waist ω_0 and on the mirror ω_M, the far-field divergence angle θ_f, the angular tolerance requirement for the mirrors θ_m, and so on. Here, as different from other reference, we write the expressions of θ_f and θ_m as [9]

$$\theta_f = \frac{\lambda_s}{\pi\omega_0},\ \ \theta_{\mathrm{m}} = \theta_f(1+g)\,. \tag{1}$$

Here, λ_s is the FEL wavelength.

For the overall optimization, we plot these relations in one figure using dimensionless qualities, as shown in Fig. 3 [9]. From Fig. 3, one can find that the larger curvature radius of the mirror corresponds to longer Rayleigh length and larger tolerance to angular misalignment, but also to a smaller light spot on the mirrors, consequently higher power density on the mirrors and higher outcoupling rate. There is a trade-off between the smaller diffraction loss, the larger tolerance to the angular misalignment and the lower power density on the mirrors. Normally, the FEL oscillator is optimized close to a concentric resonator. For a near-concentric resonator, one can write $g \approx -1+x$, x<<1, so it has $\theta_m = \theta_f \cdot x << \theta_f$. For our MIR oscillator, we take the ratio of the curvature radius of the mirrors to the resonator length as R_c/L_c =2.756/5.04=0.547. Then from Fig. 3, we have Z_R = 0.15 L_c = 0.77 = L_u /3, ω_0/ω_M =1/3.41, θ_m/θ_f =0.172, g=-0.8278.

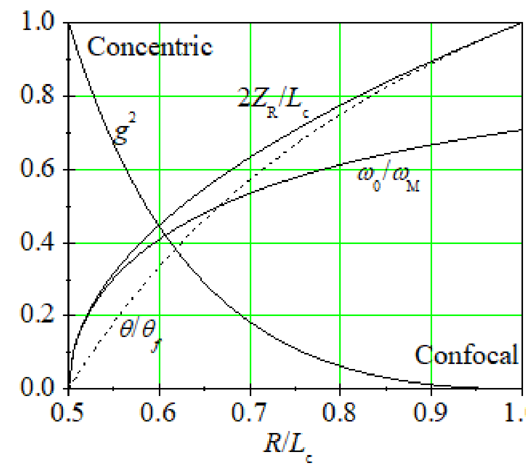

Figure 3: Overall optimization of several important relations between the key parameters of an FEL oscillator [9].

FIRST LASING RESULTS

In the end of May 2019, we started the commissioning of the linac. Then in Jun. 9, we started to detect the spontaneous radiation with a liquid-nitrogen cooled MCT (HgCdTe) detector whose working region is from 2-16 μm. Due to the strong space radiation dose inside the accelerator tunnel, we had to detect the IR signal in the experimental hall at the photo dissociation station (see Fig. 1) which is about 20 m far away from the outcoupling mirror. From the outcoupling hole, the IR light had to pass through a diamond window mounted under Brewster angle, and be reflected by two parabolic mirrors and five flat mirrors, then pass through a CsI window and arrive at the detector. We considered to lase at 15 μm with a comparatively high gain even for relatively low bean quality and optical transport loss.

To achieve first lasing the undulator parameter was set to K = 2.02. The electron energy was adjusted to 35 MeV at a current of 40 mA and a macropulse length of 6 μs. The former corresponds to a bunch charge of 1.2 nC at a repetition rate of 29.75 MHz. The electron beam was aligned to the cavity axis by monitoring the electrons with 3 Beryllium OTR view screens that can be moved into the electron beam path within the undulator vacuum chamber.

To detect the undulator spontaneous radiation, the downstream mirror was lifted up from the cavity axis. After a carefully scan of the position of the MCT detector at the light-emitting window, soon we observed the signal of the IR spontaneous radiation. Then we put down the outcoupling mirror with a 1.5 mm diameter hole into the cavity

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axis and expected to detect the undulator spontaneous radiation outcoupled from the hole. The pitch and yaw angles of both cavity mirrors were aligned with a precision of about 0.15 mrad using a red laser. As we wished, the signal from the hole was observed. Next, we begun to scan the cavity length in the step of two wavelength, and very soon, we found the intensity of the IR signal grew rapidly until the detector was saturated. A pyroelectricity probe was placed in front of the light-emitting window to replace the MCT detector, and obtained the FEL signal with the micropulse energy higher than 1 μJ. Figure 4 shows the photo of the light spot of the first lasing at 15 μm detected by pyroelectricity camera, and Fig. 5 shows the measured FEL intensity together with the beam current at different positions.

Subsequently, the detuning curve of the 15 μm FEL was measured and given in Fig. 6. One can see that lasing was observed over a cavity length scan range of 200 μm. Till now, we have observed the FEL signal from 3.5 μm to 30 μm with a gap at 20 μm. According to the design, the optical beam size of 20 μm FEL inside the undulator is smaller than the vacuum chamber so that it should not be the "spectral gap" as in a waveguide FEL. Further studies will be carried on.

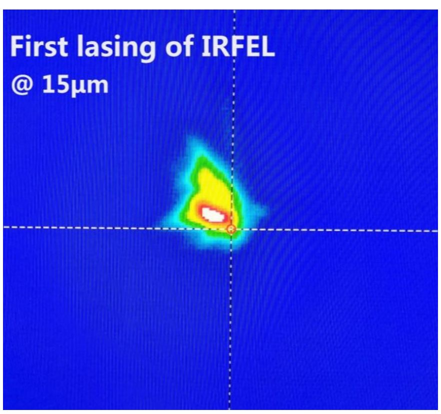

Figure 4: The photo of the light spot of the first lasing at 15 μm detected by pyroelectricity camera.

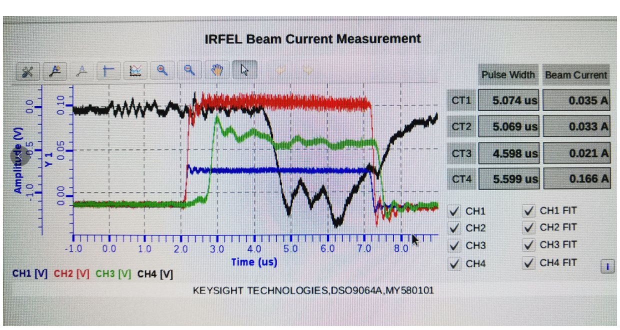

Figure 5: The measured electron beam current and FEL intensity. CT1: blue line, beam current at the exit of electron gun, 0.035 A corresponding to 1.2 nC per microbunch; CT2: red line, beam current at the exit of linac; CT3: green line, beam current before entering the beam dump; CT4: black line, FEL intensity detected at the photo dissociation station.

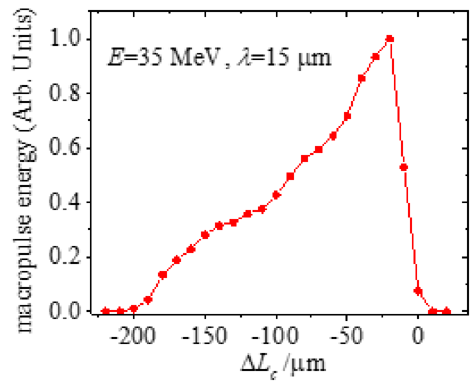

Figure 6: The measured detuning curve of the 15 μm FEL.

SUMMARY AND OUTLOOK

A new infrared FEL has been commissioned at the NSRL in Hefei. It will be dedicated for energy chemistry research. The oscillator FEL is operated with 15 – 60 MeV electrons from a normal-conducting S-band linac equipped with a gridded thermionic gun, and consists of two oscillators covering the spectral range of 2.5-50 μm and 40-200 μm, respectively. First lasing was observed at a wavelength of 15 μm with an electron energy of 35 MeV from the MIR oscillator. Till now, we have detected the FEL signal from 3.5μm to 30 μm with a gap at 20 μm and achieved the maximum micropulse energy up to 27 μJ at 15 μm.

In the near future, we will firstly commission the machine working at the microbunch repetition rate of 119/238/476 MHz, then increase the macrobunch length to 10 μs and raise the macrobunch repetition rate to 20 Hz. Meanwhile, we will do what we can do to improve the stability of the FEL pulses. After these works, we will provide the users the MIR FEL for commissioning of the end-stations, and at the same time, we will commission the FIR oscillator in timesharing mode.

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