RECENT PROGRESS ON THE INFRARED FREE-ELECTRON LASER FACILITY OF ANHUI UNIVERSITY

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Abstract

Since May 2022, the researchers at Anhui University, Hefei, China have been constructing an internationally advanced infrared free-electron laser (IR-FEL) facility. The project mainly includes one FEL light source device, six experimental stations, and other supporting systems. The tunable IR-FEL system covers the mid-infrared to far-infrared bands. Its linear accelerators provide an electron beam energy of 12-55 MeV, adopting an oscillator-type FEL scheme to generate ultrashort laser pulses (maximum 100 mJ/pulse) with continuously tunable wavelengths (2.5-200 µm), quasi-monochromaticity, and high peak power. The system includes linear accelerators, oscillators, and an optical transmission system, along with electron beam diagnostics, synchronization control, and laser parameter measurement systems. The six experimental stations focus on high temporal, spatial, and energy resolution to realize the characterization and measurement of light-matter interactions, constructing an internationally advanced materials science research platform for light-matter interaction studies.

INTRODUCTION

The concept of the free-electron laser was first proposed by J. M. J. Madey at Stanford in 1971 [1]. Then in 1976, Elias and Madey at Stanford achieved the first successful amplified output from a free-electron laser amplifier experiment at the infrared wavelength of 10.6 µm [2]. In 1986, the University of Science and Technology of China and the Chinese Academy of Sciences conducted China's first accelerator-based free-electron laser research, and successfully obtained infrared spontaneous emission at a wavelength of 10 µm from an undulator [3]. Nowadays, there are various free-electron laser facilities around the world, with radiation wavelengths from millimeter waves to X-rays.

The infrared free-electron laser facility under construction at Anhui University includes a thermionic electron gun, two linear accelerators, one mid-infrared oscillator and one far-infrared oscillator. The whole 3D diagram of the IR-FEL facility is shown in Fig. 1.

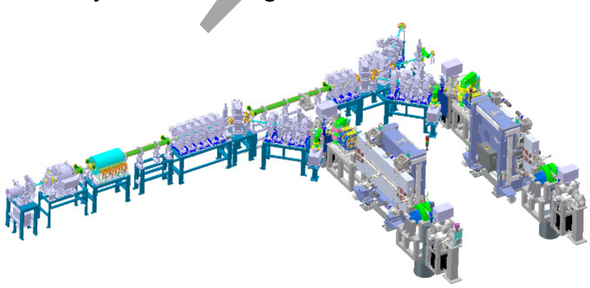

Figure 1: The infrared FEL facility at Anhui University.

There are six experimental stations in this IR-FEL facility. They are: ultrafast spectroscopy station under strong magnetic fields, scanning probe microscopy station under strong magnetic fields, magneto-optical station under strong magnetic fields, multi-field regulation station under strong magnetic fields, comprehensive characterization station, and laser diagnostics and energy materials station.

The year 2025 was a critical year for the construction of the Anhui University Free-Electron Laser Facility. During this year, breakthrough progress was made in key aspects such as the processing, commissioning, integration, and performance testing of core components for the infrared free-electron laser system, laying a solid foundation for subsequent system commissioning and stable operation. All six experimental stations have been fully constructed and commissioned, with some achieving high-level scientific research output and beginning to provide external services.

PROGRESS ON THE IR-FEL SYSTEM

At present, the IR-FEL project at Anhui University have fully entered the stages of component precision machining, system integration and commissioning, and performance verification. The project team carried out technical breakthroughs on key subsystems such as the linear accelerators, undulators, and microwave power sources, achieving landmark results in each area. The core specifications have all met or exceeded design standards, providing a solid foundation for achieving the goal of system integration and first lasing. The FEL hall under construction is shown in Fig. 2.

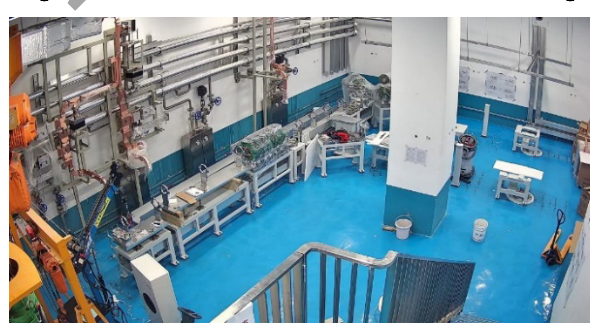

Figure 2: The IR-FEL hall under construction.

The details are as follows:

Electron Gun

The grid controlled thermionic high voltage electron gun passed the 100 kV withstand voltage test and was then concentrically aligned and welded with the cone tube supporting the cathode. All components, including the anode and the cathode focusing cup, were fabricated and processed through mechanical polishing followed by manual polishing, achieving a surface roughness of less than Ra 0.1 for both the cathode focusing cup and the anode. The alignment and installation of the grid-cathode assembly, anode, and cathode focusing cup were carried out using a laser tracker. After sealing with annealed silver wire, individual leak detection was performed, and the leak rate during the hood test for 10 minutes was better than 2×10^{-10} Pa·m³/s. The entire chamber of the electron gun system underwent low-temperature baking at 150 °C for over 72 hours for outgassing. After starting the ion pump, the vacuum level in the chamber reached 2×10^{-7} Pa. A high-voltage test was conducted for one day after connecting the high-voltage power supply, and the electron gun stably operated at 102 kV, meeting the conditioning requirements. The electron gun is shown in Fig. 3.

Figure 3: The electron gun undergoing high voltage test.

Linear Accelerators

The pre-buncher cavity, buncher cavity and accelerating tubes have been designed, fabricated and welded. The pre-buncher cavity body is fabricated in three parts: the curved surface and two end faces, all made of 316L non-magnetic stainless steel. The internal surfaces are machined and polished to a roughness of less than Ra 0.4. The accelerating tube and the buncher cavity are traveling-wave accelerating tubes made of pure oxygen-free copper. The next step is to conduct water cooling testing, and the integration and installation of the accelerators with other systems will be carried out as planned. The machined accelerating tubes are shown in Fig. 4.

Figure 4: The accelerating tubes.

Magnet System

The magnet system of this facility consists of 11 types of magnets, including 23 quadrupole magnets, 7 dipole magnets, 4 solenoids, and 2 independent bidirectional correction magnets. Design confirmation, fabrication, and some key performance tests have been completed, and the system is now in the final stage of testing, with some magnets already installed on site.

The manufacturing process for magnet cores includes lamination stamping, coordinate measuring machine (CMM) inspection, stacking, welding, and heating curing. The development of coils involves mold fabrication, winding, curing, insulation testing, and pneumatic testing. High-purity copper imported from Finland is adopted as the raw material.

Magnetic field measurement methods include point measurement and rotating coil measurement, with evaluation parameters covering the good field region, magnetic field gradient, effective length, integrated field, higher-order field components, and excitation curves. Among the quadrupole magnets that have completed magnetic field measurements, the good field region is ±12 mm, with a field uniformity error of less than 1‰. A quadrupole magnet under magnetic field measurement is shown in Fig. 5.

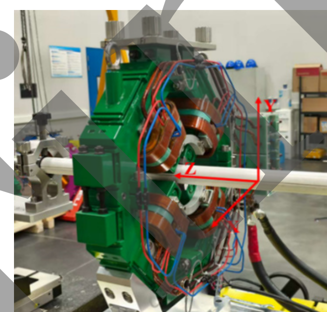

Figure 5: A quadrupole magnet under magnetic field measurement.

Undulators

The IR-FEL facility is equipped with two linearly polarized undulators, one for mid-infrared radiation and the other for far-infrared radiation. They have the same appearance but different magnetic field parameters. The appearance of the two undulators is shown in Fig. 6.

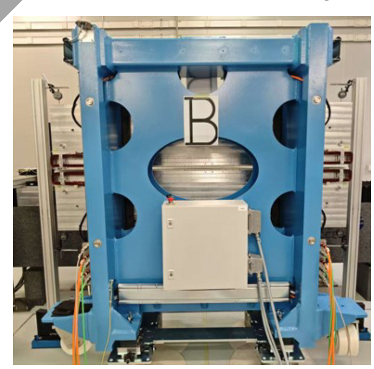

Figure 6: The appearance of the undulators.

Some magnetic parameters of the two linearly polarized undulators are shown in Table 1.

Currently, the two undulators have completed design, fabrication and testing, and have now been delivered to the IR-FEL hall at Anhui University. The technical staff have completed the preparatory work for the installation of the two undulators, including ground benchmark positioning, precise drilling of mounting holes, reinforcement of equipment support foundations, etc. The next step will involve positioning and installation of the two undulators.

Table 1: Magnetic Parameters of the Undulators

	Mid-infrared	Far-infrared
Period length	44 mm	52 mm
Number of periods	50	42
Undulator gap	17.4-40 mm	20-50 mm
Peak field	0.6-0.17 T	0.72-0.13 T
K value	2.69-0.7	3.45-0.7
1st field integral error	<0.5 Gs·m	<0.05Gs·m^2
2nd field integral error	<0.1 Gs·m^2	<0.05Gs·m^2
Peak field error	<0.5%	<0.5%
RMS phase error	<5°	<5°

Resonant Cavities

An oscillator consists of one undulator and one resonant cavity. In this IR-FEL facility, one resonant cavity is used for the mid-infrared beamline and the other for the far-infrared beamline. A resonant cavity is divided into three parts: supporting components and associated parts, cavity mirrors, and the alignment and guiding laser systems.

- Supporting components and associated parts: The supporting components and related parts for the mid-infrared and far-infrared resonant cavities have been fabricated and are now in assembly and welding. The control cabinets for the two resonant cavities have been manufactured. The precision hexapods for driving the resonant cavity mirrors have been assembled with the mirror chambers, and the communication program between their controllers and the resonant cavity control system has been successfully debugged. The mirror chamber of the resonant cavity is shown in Fig. 7.

Figure 7: A mirror chamber of the resonant cavity.

- Cavity mirrors: As oscillator-type FEL is adopted in this IR-FEL facility, two mirrors need to be installed at both ends of one undulator [4]. To meet different lasing output requirements, 16 mirrors with different central coupling aperture diameters and different radiuses of curvature have been designed. All these mirrors are made of oxygen free copper with gold-plated surface. They have now finished processing and will soon be inspected.
- Alignment and indicating laser systems: The alignment system is used to calibrate the laser optical axis of the resonant cavity with the central trajectory of the electron beam inside the undulator. The indicating laser system is used to adjust the visible laser to align with the optical axis of the resonant cavity and then emit it downstream, assisting in the installation of optical components for the downstream beamlines and experimental stations. To date, all purchased components for these systems have been procured and are now in processing.

CONCLUSION

2026 will mark a crucial stage for the completion and operation of the IR-FEL facility of Anhui University. It is expected to complete the installation of the facility in the second half of this year, initiate system integration and commissioning, and achieve stable laser output. Following lasing, continuous performance testing and optimization will be conducted to enhance the stability and reliability of the laser, striving to reach the advanced level of comparable international facilities.

At the same time, the full integration of the six experimental stations with the IR-FEL system will be promoted. The beam transmission and coupling efficiency will be optimized to achieve stable application of the FEL across all experimental stations.

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