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Development Strategy of Free Electron Laser Technology in China

Li Peng, Li Ming, Wu Dai, Zhou Zheng, Tang Chun

Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang 621900, Sichuan, China

Abstract: A free electron laser (FEL) is a large-scale scientific research device based on an electron linear accelerator that has been widely used in basic scientific research, such as in the fields of condensed matter physics, advanced materials and surface physics, atomic and molecular physics, chemistry, and biology. With the advancement of the FEL technology, light sources with higher power and shorter wavelength will be developed to satisfy the increasing demands of users. Herein, the necessity of development based on the characteristics of the FEL technology is introduced and the current development status of the technology in China and abroad is summarized. In addition, the existing problems in the development of the FEL technology in China are analyzed, and the ideas and goals for its development in China are proposed. By 2035, China should focus on making breakthroughs in long-wave FEL, X-ray FEL, new FEL, and FEL-based extreme ultraviolet (EUV) lithography light source technologies. Based on the research and analysis, some suggestions for the steady and healthy development of the FEL technology in China are presented, including devising scientific development strategies, increasing investment in fundamental research to promote independent innovation, strengthening multi-party cooperation to promote the transformation of scientific and technological achievements, promoting market application, and strengthening personnel training.

Keywords: free electron laser; infrared-terahertz FEL; extreme ultraviolet-FEL; X-ray FEL

1 Introduction

A free electron laser (FEL) is a radiant laser generated based on free electrons in a vacuum [1]. The main difference from a traditional laser is that the radiation wavelength does not depend on the stimulated medium but depends only on the energy of the electron beam and the undulator (periodic magnetic field for radiation). The wavelength of an FEL is completely tunable, and it can obtain wavelengths that other lasers cannot achieve, from terahertz to hard X-ray or even gamma ray wavelengths. Among these, terahertz, infrared, extreme ultraviolet, and X-ray wavelength ranges are abbreviated as THz-FEL, IR-FEL, EUV-FEL, and XFEL, respectively. Currently, the FEL technology, which is widely used in the fields of condensed matter physics, advanced materials and surface physics, atomic and molecular physics, chemistry, and biology, has promoted major technological innovations in the strategic safety, aerospace, energy and environment, medicine, chemical, and manufacturing industries.

Since the FEL principle was first proposed in 1971 [2], more than 50 FEL facilities have been built globally, and more than 20 are under construction or planned. Countries leading in science and technology attach great importance to the development of FELs and invest significant resources to catch up. In particular, XFEL [3, 4], as a new generation of probe light, allows penetration of the interior of matter for the first time to observe the evolutionary images of atoms and molecules at the nano- and microscale, and manipulation of the states of electrons, molecules, atoms, and even nuclei. New types of capabilities that promote the innovation of scientific research methods and models are expected to open up new scientific frontiers to trigger technological and industrial revolutions. For example, using XFEL to diagnose the time evolution behavior of nuclear materials, their alloys, and energetic

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Corresponding author: Tang Chun, researcher of Institute of Applied Electronics of China Academy of Engineering Physics. Major research field is optical engineering. E-mail: tangchun@vip.sina.com

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materials at the molecular/subatomic level, or the ultrafast kinetic behavior of nuclear metals or their alloys at a high energy density. The primary scientific goal of the first international XFEL (LCLS) in the United States is to serve nuclear materials science research and high-energy density physics research [5]. Development of the FEL technology is also an urgent research direction in China [6].

This article introduces the necessity of the development of the FEL technology, summarizes the current development status of the FEL technology in China and abroad, and proposes the key development direction of the FEL technology in China based on the technology gap between China and abroad. The main purpose of this article is to provide a reference for planning and development in related fields.

2 Demand for free electron laser

An FEL system includes three main components: an accelerator, an undulator, and a light beamline system (Fig. 1). Based on the relativistic electron beam generated by the accelerator, the periodic magnetic field of the undulator generates coherent radiation amplified by stimulated radiation. According to the amplification gain, the FEL principle is categorized into low gain and high gain, with the following advantages: (1) Arbitrarily adjustable wavelength, which is not limited in theory, and the radiation wavelength can be changed by adjusting the energy of the electron beam and the magnetic field of the undulator. (2) Good beam quality, as the FEL radiation is fully coherent in the lateral direction, and partially or even fully coherent in the longitudinal direction, also with good polarization. (3) High peak and average power, because there is no requirement for heat treatment and no absolute upper limit in theory, because the working environment is a vacuum. Therefore, as one of the most advanced light sources in the 21st century, FELs are predominantly used to generate laser wavelengths that are not easily produced by other light sources, with high peak power and high average power.

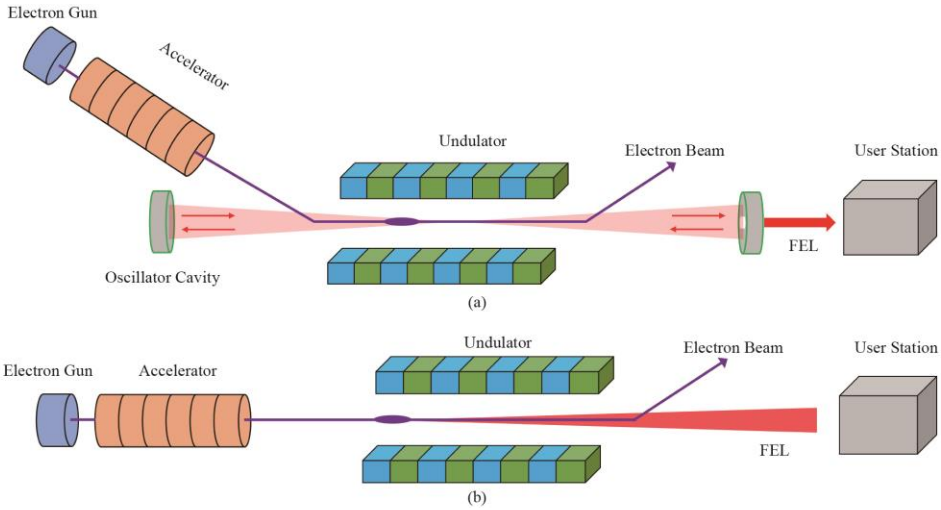

Fig. 1. Basic principles of a free electron laser (FEL).

2.1 Demand for radiation frequency

In terms of the spectrum, traditional lasers cannot easily generate specific frequencies or do not have high enough power, such as the terahertz waves between microwaves and infrared, short-wave X-rays, and even gamma rays. High-performance light sources are thus urgently required. FEL is the only technology in these frequency ranges that can achieve full spectrum coverage and provide high-power lasers, which have wide application prospects and are the key component for many interdisciplinary applications of photonic science.

2.2 Demand for radiated power

As FELs provide a high-brightness laser with a peak power of more than 1 GW and an average power of more than 1 kW, they have significant application potential in the fields of civil engineering and national defense security. EUV lithography is the most cutting-edge technology in the chip manufacturing industry. Moreover, this industry requires a new type of light source with power in the order of kW, which cannot be provided by the traditional laser plasma light source technology. FELs provide the advantages of wavelength design and extremely high power. Using an FEL, an EUV light source with a wavelength of 13.5 nm can be generated. International semiconductor companies

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have proposed advanced technical solutions for designing an EUV light source based on an FEL.

3 International Development status of FEL

3.1 Long-wavelength FEL

The long-wavelength FEL is primarily based on a low-gain resonant cavity, which is characterized by variable wavelength and high power. Further, it has been regarded as an ideal laser weapon, and the related research has become popular during the 1980s. However, because the FEL system is extremely complicated and challenging in technology, the corresponding technical equipment could not be successfully built. After the studies on FEL for defense applications declined gradually, scientific research on FEL becomes a leading role (Table 1).

The JLab IR facility [7] of the Jefferson Laboratory in the United States was originally developed as an FEL facility for laser weapon research, and it produced the world's first laser with an average power of more than 10 kW. The Dutch FELIX facility was constructed with a focus on scientific research and is currently the world's most extensive user facility. Additionally, the Russian NovoFEL facility [8] uses a low-frequency room-temperature accelerator route resulting in a huge volume, and it has become the operating facility with the highest average power. The German FELBE facility [9] is a long-wavelength FEL facility with the most comprehensive performance and the largest number of users. Further, it is the first THz-FEL facility based on superconducting accelerators with the largest number of experimental stations, the most expensive machine time, and the highest scientific research output. The FELBE facility facilitates publication of more than 100 papers each year (including in *Science* and *Nature*).

Table 1. International representative long-wavelength FEL facilities.

Country	Facility	Electron energy (MeV)	Radiation frequency (THz)	Repeat frequency	Accelerator type	Typical average power (W)	Peak power (kW)	Year of lasing
United States	JLab IR	80–150	21.4–330	Continuous Wave	Superconducting (Energy recovery)	14 000	250 000	2005
Netherlands	FELIX	15–45	0.2–100	10 Hz	Normal temperature	0.4	1.5	1992, 2011
Russia	NovoFEL	10–44	1.25–60	Continuous Wave	Normal temperature (Energy recovery)	100	2 000	2003, 2009, 2015
Germany	FELBE	15–35	1.2–75	Continuous Wave	Superconducting	10	5 000	2004, 2006, 2017

3.2 X-ray FEL (XFEL)

XFEL is based on high-gain single pass amplification and is a new technology, developed in the late 20th century (known as the "fourth-generation light source"), that has attracted widespread international attentions. The major developed countries have built or are currently constructing XFEL light sources to meet the needs of scientific research and national security (Table 2).

Table 2. International representative X-ray FEL (XFEL) facilities.

Country	Facility	Electron energy (GeV)	Radiation wavelength (nm)	Repetition rate (Hz)	Accelerator type	Peak power (GW)	Year of lasing
United States	LCLS	14.3	0.08–1.24	30	Normal temperature	40	2009
	LCLS-II	4.0	0.25–6.20	120	Superconducting	—	No Lasing
Germany	European XFEL	17.5	0.04–0.15	10	Superconducting	110	2017
Switzerland	SwissFEL	5.8	0.10–7.00	100	Normal temperature	21	2017
Japan	SACLA	8.0	0.06–2.82	60	Normal temperature	106	2011
South Korea	PAL-XFEL	10.0	0.10–10.00	60	Normal temperature	42	2016

The United States has technical advantages in terms of the XFEL technology, and the US Department of Energy (DOE) has organized several seminars to summarize the needs of national security, energy security, and science. Based on this, the world's first XFEL facility (LCLS) was built in 2009. Simultaneously, the construction plans of LCLS-II and Matter-Radiation Interactions in Extremes(MaRIE) were deployed to form a global XFEL capability system. LCLS-II, as an upgrade of LCLS, aims to perform more extensive cutting-edge scientific research [5]. The MaRIE project predominantly focuses on materials science research under extreme conditions and is used to address national security research needs in terms of nuclear devices, energy security, and cutting-edge science (including extension of the life of nuclear devices).

The world's first high-repetition-rate XFEL facility, European XFEL [10], which was established by Germany, Russia, the United Kingdom, France, Switzerland, and other countries, is based on superconducting accelerators, and it will lead the next ten years of FEL development. Equipped with a variety of extreme condition loading devices and diagnostic technologies, European XFEL has become a competitive technology resource used by many countries. The US nuclear technology laboratory is also applying to become a joint user in the high-energy-density experimental station (HED).

In addition, Switzerland has independently built the SwissFEL facility [11] to meet the country's research needs in the fields of biology, medicine, and nanomaterials, among others. Furthermore, Japan and South Korea have built XFEL facilities [12,13].

3.3 New type of FEL

In addition to the traditional XFEL facility based on magneto-static undulators, miniaturized XFEL light sources based on optical undulators have become a research hotspot. Related ideas were proposed as early as the 1970s; however, they were difficult to implement owing to the technical challenges at that time. Recently, the vigorous development of the laser technology has provided new opportunities for the realization of low-cost and compact XFELs. A quantum FEL system based on an optical undulator overcomes the performance limitations of a traditional XFEL in terms of the output photon energy, light source coherence, bandwidth, and other characteristics. Therefore, it will be a useful and powerful technical supplement to the XFEL technology.

4 Development of FEL in China

4.1 Achievements

Development of the FEL technology in China has also undergone a change from the demands of national defense to scientific research applications. Theoretical and experimental research on the FEL technology began in China in the 1980s, and the representative work in the early days included Raman-type FEL (1985), spontaneous emission of the undulator (1986), and free electron lasing based on the resonant cavity technology and the amplifier technology (1993). Since 2000, owing to the demand in photonic science for advanced light sources, a number of FEL facilities have been built in China, as shown in Table 3.

Table 3. Main FEL facilities in China.

Facility	Area	Radiation wavelength	Accelerator type	Status
BFEL	Beijing	5–50 μm	Normal temperature	Retired
FELiCHEM	Hefei	2.5–200 μm	Normal temperature	Under construction
CTFEL	Chengdu	71.4–428.5 μm	Superconducting	Operating
WILL	Chengdu	2.4–3000 μm	Superconducting	Planning
DCLS	Dalian	50–150 nm	Normal temperature	Operating
Dalian Advanced Light Source	Dalian	UV–Soft X-ray	Superconducting	Pre-research
SDUV-FEL	Shanghai	150–350 nm	Normal temperature	Operating
SXFEL	Shanghai	2–20 nm	Normal temperature	Operating
SHINE	Shanghai	0.05–3.1 nm	Superconducting	Under construction

The National Synchrotron Radiation Laboratory of the University of Science and Technology of China has performed many theoretical and experimental investigations on low-gain resonant cavity and long-wavelength FEL light sources. Currently, a tunable infrared light source (FELiCHEM) [14] is under construction, which will be used for large-scale research on energy chemistry. The Huazhong University of Science and Technology is also conducting research on a THz-FEL oscillator. Moreover, the Institute of China Academy Engineering Physics

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(CAEP) has carried out a series of theoretical and experimental studies on FEL oscillators. In 2005, it achieved the lasing of far-infrared outside terahertz FEL (FIR-FEL) based on 30-MeV electrons [15]. In 2017, the first high-average-power THz-FEL user facility (CTFEL), based on a superconducting accelerator, began operating [16].

High-gain, short-wavelength FEL light sources started to develop in China around 2000, and they covered the wavelength range from ultraviolet to soft X-ray. In 2009, the Shanghai Institute of Applied Physics developed China's first comprehensive research platform for high-gain FEL, the Shanghai Deep Ultraviolet Free Electron Laser (SDUV-FEL) [17]. In 2016, the Dalian Coherent Light Source (DCLS), built by the Dalian Institute of Chemical Physics, achieved lasing [18]. The soft X-ray FEL project undertaken by the Shanghai Institute of Applied Physics and Peking University began in 2014, with a wavelength of 8.8 nm and a photon energy of 0.14 keV, producing a fully coherent FEL output in January 2020 [19].

There are many FEL facilities under construction or planning. The Chinese Academy of Engineering Physics is carrying out a long-wavelength Western Light Source (WILL) project. Moreover, construction of a continuous EUV-FEL facility based on superconducting accelerators has been planned by the Dalian Institute of Chemical Physics. The Shanghai University of Science and Technology is constructing China's first hard X-ray FEL facility, in cooperation with the Shanghai Advanced Research Institute of Chinese Academy of Sciences. The electron energy of this facility is 8 GeV, the radiation photon energy is 0.4–25 keV, and the maximum repetition frequency of X-ray pulses can reach 1 MHz. This is significant for promoting the development of photonic science in China [20].

4.2 Problems

4.2.1 Strategic objectives to be established

The purpose of developing an FEL facility is to create a new type of light source that traditional lasers cannot produce easily or with sufficient power. As a large scientific facility, an FEL facility will be an innovation center for a city or even a region. However, the strategic planning of FEL facilities is not sufficiently clear in China; it does not significantly affect the research layout and innovation development of the corresponding regions.

4.2.2 Breakthrough in key technology

The theoretical development of FEL must be explored, and the domestic development of key components is yet to achieve a breakthrough, including the physical design and key issues with accelerators and undulators, high-repetition-rate and high-brightness photocathode electron guns, superconducting acceleration, low-power RF control, femtosecond synchronization, high-repetition-frequency beam measurement, superconducting undulators, beamline and other technologies, and user experimental station systems.

4.2.3 Industrial applications to be expanded

The current application of the FEL technology is focused on scientific research. The investment and construction of FEL facilities are mainly funded by large-scale national projects on scientific research equipment. Furthermore, the future development and applications of the FEL technology are limited by the lack of industrial applications and the insufficient cooperation between production, education, and research sectors. Thus, an expansion of industrial applications is urgently required for FEL development.

5 Development ideas for China's FEL technology

5.1 Development goal

To meet the strategic needs of the national economy and national defense development, particularly the technological needs of FEL in the fields of basic science, energy security, and national defense security, the following development goals are proposed: to achieve independent breakthroughs in key technologies and to realize localization of core components. Through policy guidance, strengthening innovation, and application integration, shorter-wavelength FEL light sources with higher power for scientific research can be built, and the applications in industry can be expanded. China should participate in global technological competition, which can establish relative technological advantages and promote high-end industrial applications of EUV-FEL in the near future.

5.2 Development route

5.2.1 Long-wavelength FEL technology

Some studies have proposed the following [21]: the physical field of biological neural signals could be high-frequency electromagnetic fields from terahertz to infrared, and the most likely frequency range is from terahertz to

100-terahertz. The relevant research in the range of 0.5–100 THz could be termed terahertz biology. In addition to biology, the demand for light sources in other fields is urgent; however, there is a lack of high-average-power and frequency-adjustable light sources in this band.

The construction of a high-average-power tunable FEL light source covering the entire infrared-terahertz frequency range is of great significance for cutting-edge scientific research. Based on the infrared-terahertz FEL technology, a comprehensive platform can be constructed in combination with strong terahertz light irradiation, strong magnetic field, low temperature, high pressure, and advanced measurement technology. This platform can be used to support many pioneering studies, including in the fields of condensed matter physics, new materials, advanced optics, optoelectronics, biology, medicine, and water science. Furthermore, it can support the development of multidisciplinary and multidomain industrial applications.

5.2.2 XFEL technology

According to the development trend of XFEL, a high-repetition-rate and high-photon-energy XFEL facility should be proposed in China (equivalent to the US MaRIE plan) that can compete with the existing and planned international XFEL facilities. This new facility should have experimental end stations and diagnostic technologies and will be used in materials research for aerospace and energy technology under extreme conditions, among others.

5.2.3 Novel FEL technology

The quantum FEL technology remains in the stage of principle verification and exploration [22]. However, it has potential advantages in terms of the facility scale and construction cost. It can be used to build a laboratory-scale hard X-ray coherent light source to meet the scientific research needs of colleges and universities. Therefore, China should devise a plan for the quantum FEL technology and pay attention to theoretical research and verification experiments, to meet the increasing demand for high-performance X-ray sources in China.

5.2.4 EUV lithography light source technology based on FEL

The industrial application of FEL, particularly as an EUV lithography light source, is one of its main development directions [23]. The Netherlands ASML Company, Japan EUV-FEL light source industrialization research society, and the United States Global Foundries are actively focusing on the EUV-FEL lithography technology and consider that it will be an important technical route after lithography at the 3-nm node.

Considering the high demand for independent and controllable key technologies related to the national economy and people’s livelihood in the new era, EUV lithography will be one of the technologies to be urgently required in China, and it will also create an important foundation for China’s future chip development. According to the “three-step” route of verification, principle prototype development, and industrialization layout, China’s EUV-FEL development route must be planned, and the application of EUV-FEL in industry must be promoted.

6 Suggestions

6.1 Scientifically formulate development strategies to ensure the implementation of scientific research

The FEL technology in China is in a vigorous development state, and many FEL projects have been proposed by numerous agencies. The formulation and demonstration of detailed development strategies and advanced R&D goals are recommended, with a focus on demand and the highlighted applications. The development goals of the FEL technology must be determined scientifically. Because FEL requires large-scale scientific research facilities, we should focus on strong cooperation and strengthening of organizational management to ensure that construction projects are completed on time and with high quality.

6.2 Strengthen basic investment and improve independent innovation

The FEL technology belongs to the category of national basic research, and the system is complex, the investment is costly, and the execution cycle is long. It is recommended that investment in the FEL technology be guaranteed by the government throughout the project construction and facility operation. Meanwhile, through the targeted funding of various projects, we will promote the comprehensive key components, encourage the emergence of scientific research innovations, achieve breakthroughs in the miniaturization technology of FEL, and actively promote its application development.

6.3 Strengthen cooperation and promote the transformation of achievements

Internationally, the construction of an FEL facility requires cooperation. The project implementation of an FEL is under the overall responsibility of the lead agency; the related equipment is researched and developed by the scientific institutions and manufactured by the enterprise organizations. This approach is conducive to the integration of scientific and technological research and development forces to coordinate technical research. Simultaneously, the processing and manufacturing capabilities of superior companies should be harnessed to achieve technological transformation in the process of device construction. Further, it is recommended to strengthen the technical cooperation between industries, promote the division of labor cooperation between scientific research institutions and advantageous enterprises, and encourage comprehensive development of the FEL field through cooperation between industry, universities, and research institutions.

6.4 Promote the combination of research and application

Industrial application is an important direction for the development of the FEL technology. The use of an EUV lithography light source in a demonstration project to realize the industrial transformation of the FEL technology is recommended. Through the implementation of the project, the “production, education, and research” disconnect will be eliminated, and a useful industrialization plan will be explored. The plan will accumulate experience and identify the direction for subsequent technology transformation and application. It is recommended to accelerate demonstration of the EUV lithography light source technology and its industrial development, encourage application of high-quality patents, and strengthen intellectual property management. The best method to achieve this is to establish a prototype platform to promote marketing of the FEL industry by introducing corporate power.

6.5 Create a cultural atmosphere and strengthen the cultivation of talents

Supporting and encouraging scientific research institutions to participate in international scientific and technological cooperation programs is recommended. Universities and research institutes should be guided to establish professional and market-oriented technology transfer departments. A group of high-level leading talents and key professional technical personnel must be trained to accelerate the innovation in FEL disciplines. Further, it is necessary to realize international technical exchanges and cooperation in the field of FEL.

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