FREE ELECTRON LASER RESEARCH IN CHINA

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China has endeavored in the field of FEL research since the mid-eighties. Compton regime, Raman regime, Electromagnetic Pumping, Cherenkov FEL, and Harmonic Generator FEL, etc. based on the RF linac accelerator, induction linac accelerator, pulsed-line accelerator, and storage ring have all been developed. These experimental projects are in various stages of development and are discussed in sequence. Theoretical analysis, numerical simulation and components research related to FEL also will be mentioned briefly.

INTRODUCTION

Free Electron Laser is well known for its stringent requirements on the quality of the electron beam taking part in the beam-wave interaction. Thus, research on FEL serves both the purposes of exploration of its potential applications and promotion of the development of accelerator physics and technology.

FEL research and development have been taking place in China since the mid-eighties.[1] The primary purpose is to study the physics and learn the technology. Now, after some facilities have been completed and lased to saturation, the applications of these facilities has become the object of exploration. Furthermore, in order to satisfy the requirements of various applications, the quality - such as the intensity and spectral stability, etc. - of the laser produced and the ease of operation of the system will come to attention and deserve research efforts.

In the following, the RF linac based Compton regime FEL, including Beijing IR-FEL of the Institute of High Energy Physics; FIR-FEL of the Institute of Atomic Energy; wide-band user facility of the Institute of Nuclear Physics, and FIR-FEL of the Academy of Engineering Physics will be presented first. Then, the Induction linac based Raman regime FEL amplifier of the Academy of Engineering Physics and the pulsed-line accelerator based Raman FEL, E.M. pumped oscillator and Cherenkov FEL of several institutes will be discussed. Finally, the storage ring based UV harmonic generator of China University of Science and Technology will be described. Also, theoretical achievements, computer-code developments and system components studies will be mentioned briefly.

I. IR-FIR FEL

1.1 IR-FEL of The Institute of High Energy Physics (BFEL) [2]

Figure. 1 shows the schematic layout of BFEL. This facility has a microwave electron gun with a LaB_6 cathode of <100> cut for high stability and high emission. The maximum energy of the electrons from the gun cavity is 1.2 MeV and the beam current is about 200 mA at the entrance of the linac with a bunch width of about 4 ps. The thermionic cathode microwave electron gun proves to be a very compact and convenient way for the production of short electron bunches with good beam quality for IR-FEL. However, it has the draw-back of back-bombardment that causes intensity variation of the beam current during the macropulse accompanied by energy variation due to the beam loading effect in the gun cavity. By using two deflecting magnetic fields along the gun cavity, the back-bombardment effect can be significantly reduced.[3] BFEL operates stably at a macropulse length of 4.5 μs and repetition rate of 3.125 Hz.
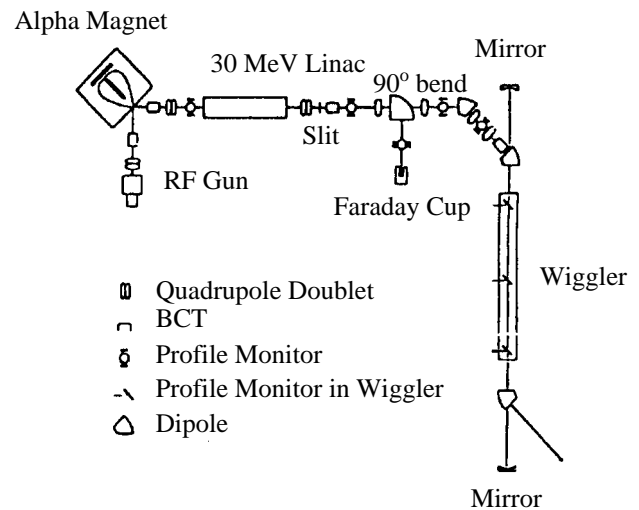

Figure 1: Schematic diagram of Beijing FEL

The electrons generated from the gun and compressed by the Alpha magnet are injected into an S-band, constant gradient unit relative phase velocity linac section and are accelerated to about 30 MeV. The linac section used is a modified SLAC-type constant gradient waveguide with four extra circular holes on some disks. These holes create a separation of the dispersion curves of EH_{11} mode but little perturbation of the dominant TM_{01} mode.[4] Thus, the

BBU threshold value should increase with practically no effect on the acceleration process.

After passing through an achromatic and a nearly isochronous 90° beam transport system, electron bunches are injected into an undulator. The undulator is planar type with NdFeB permanent magnets, consisting of 50 periods of 1.5m long. The magnets have the size of 7.5 mm × 7.5 mm × 40 mm. The optical cavity is a near concentric resonator consisting of two ZnSe mirrors with ZnSe/TuF4 multilayer dielectric coating. After being extracted from the downstream mirror, the laser beam passes through a telescopic pipe and is sent to the diagnostic room.

The typical result of lasing is as illustrated in Figure 2. The laser builds up in about 2 μs corresponding to about 100 round trips in the optical cavity. The saturated output power level is about 2 KW at the HgGdTe detector. Since both the outcoupling factor and the macropulse duty factor are about 1%, the intra-cavity average optical power is estimated to be 200 KW and the peak power 20 MW. The spatial distribution of the laser at the diagnostic room as measured with a LMP-32 × 36 elements pyroelectric detector located in the focal plan of a lens, is about twice the diffraction limit as illustrated by Figure 3.
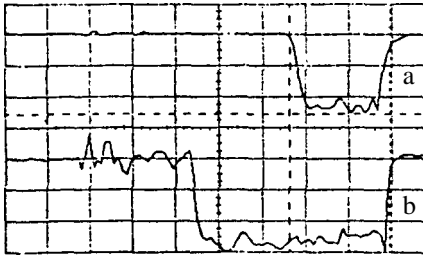

Figure. 2: BFEL macropulse at saturation (1 μs/div) (a) laser, (b) electron beam
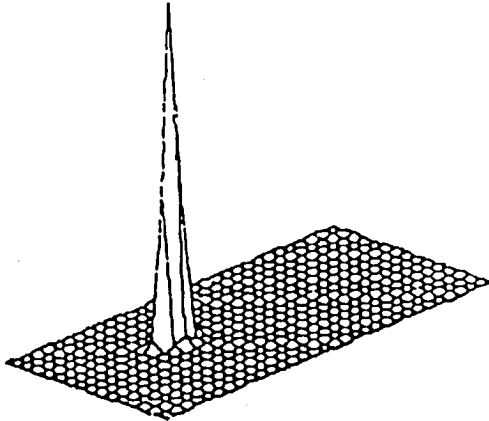

Figure. 3: Spatial distribution of the laser beam

The wave-length range of the system was, so far, limited by the spectral range of the reflectance of the mirror. An upgrading program is under way to expand the laser wavelength coverage and to improve the operational stability. To summarize, the general characteristics of the laser are given in Table 1.

Table 1: Summary of the laser characteristics

Total spectral range	9 - 11 μm
Output energy in optical macropulse	2 - 10 mJ
Average power in macropulse	200 KW
Peak power	200 MW
Spectral width	0.3 - 2%
Small signal gain	32%
Optical extraction efficiency	0.48%
Beam divergence	2 mrad

(1.2) FIR FEL of the Institute of Atomic Energy [5]

In the Institute of Atomic Energy (IAE), an L-band high brightness injector has been built and tested. It is planned to add some $3\pi/4$ mode high gradient accelerator section to make it a driver of FIR-FEL.

The injector consists of a 100 KV, 3 ns triode electron gun, one-quarter wavelength reentrant coaxial resonator sub-harmonic buncher of 108 MHz and one TW $3\pi/4$ mode buncher of 1300 MHz composed of 7 cavities. This particular mode was adopted for both the buncher and the accelerator section because of its high BBU threshold which is important for the high current operation of the system.

The performance up to now is given in the following

Injector energy	1.8 MeV
Micropulse current	> 50 A
Micropulse width	~ 40 ps
Normalized emittance	0.02 cm-rad

(1.3) Wide-band FEL User Facility of the Institute of Nuclear Physics and the Institute of Optics and Fine Mechanics [6]

A wide-band FEL user facility (SFEL) is being built at the Shanghai Institute of Nuclear Physics, China Academy of Sciences. The driver of SFEL consists of a triode electron gun, sub-harmonic buncher and a high gradient buncher as injector and SLAC type accelerator sections as accelerator. The injector produces micropulses of 59.5 MHz repetition rate of 6 - 10 ps long and 20 - 100 A current. The designed macropulse width is 6 - 8 μs.

SFEL uses three different undulators driven by three different energy electron beams to cover a wide wavelength range. The first beam is from the injector itself with energy of 2 - 3 MeV and produces FIR radiation with wave-length from 800 - 2000 μm. The second beam is produced after the electrons from the injector are accelerated by one accelerator section to an energy of about 30 MeV. This beam, after passing through the second undulator, produces Mid-IR radiation from 10 - 25 μm. The third beam, being accelerated by two more accelerator sections to an energy of 40 - 50 MeV produces radiation of 2.5 - 8 μm. The wave-length range is designed to cover the applications of FEL in life science, material science and bio-medical science. The use of RF grid controlled triode electron gun and buncher combination allows easy adjustment of bunch separation, which is of concern for time resolved experiments.

The above mentioned scheme is for the first phase of the project. To further extend the wave-length range to UV, three more accelerator sections and a storage ring will be added as the second phase.

The present status of SFEL is that the accelerator sections are available. Buncher is under measurement, gun and modulator being delivered and other components under construction.

(1.4) FIR FEL of China Academy of Engineering Physics [7].

Construction of an FIR-FEL facility using a thermionic microwave electron gun as injector operated at 1.3 GHz has been started at China Academy of Engineering Physics.

The electron beam from the injector has the following characteristics:

Energy	1.8 MeV
Peak micropulse current	10 A
Micropulse Width	~35 ps
Macropulse current	450 mA
Macropulse width	4 μs
Beam normalized emittance	15 π mm-mrad
Beam energy spread	<1.5%

II. MM-WAVE FEL

(2.1) Raman FEL Amplifier of China Academy of Engineering Physics (CAEP) [8]

The induction linac-based FEL amplifier (SG-1 FEL) of CAEP was started in 1987. Spontaneous emission experiment, constant parameter undulator, and variable parameter undulator amplifier experiments were carried out in sequence up to 1994.

SG-1 FEL amplifier is composed of an induction linac, beam transport system, undulator, microwave source, and diagnostic system as shown in Figure 4.
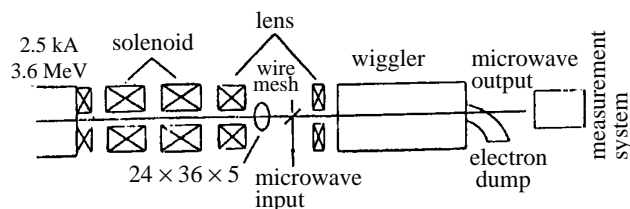

Figure. 4: Schematic layout of SG-1 FEL of CAEP

The induction linac is composed of a 4-cell injector and an 8-cell accelerator. Each injector cell provides 250 kV, 100 ns pulse voltages to give a total 1 MV for the diode gun with felt cathode. The electron beam is generated from the gun passing through an axial magnetic guiding field and is generated from the gun passing through an axial magnetic guiding field and is injected into the accelerator where each cell gives 300 kV acceleration.

The measured output electron beam parameters are:

Electron Energy	3.5 MeV
Electron Current	2.5 A
Energy Spread	2%
Emittance	0.43 cm-rad.
Beam Brightness	10^8 A/(m-rad)^2

The accelerated beam passes through a beam transport system of solenoid and lens of 2 m long and then goes through an emittance selector into the undulator. The current there is about 800 A.

The undulator is of electromagnetic type which has parabolic pole face for double focusing. The period of the undulator is 11 cm and length is 3.96 m with nominal field level of 3.1 KG. Every two period shares one separate power supply so that different tapered fields can be produced. Peak magnetic field is continuously variable from 1.4 - 3.4 KG on the axis while the two-period at the entrance and at the exit are lower strength for orbit control. The transmission efficiency of the undulator is greater than 80%.

Microwave source for SG-1 amplifier is a 20 kW, 34.4 GHz, 0.35 μs pulse-width magnetron. The microwave power entering the undulator region is about 7 kW. Rectangular wave-guide with TE_{01} mode is used for beam-field coupling. The amplified signal frequency and power are measured with dispersion line and crystal detector.

The experimental measurements of the SG-1 system were first performed with the amplification of the spontaneous emission. Power output of 400 mW at 100 A was obtained which compares reasonably with the result of 600 mW according to numerical simulation. Results of the amplification of a seeding signal are illustrated by Figures 5 through 7.
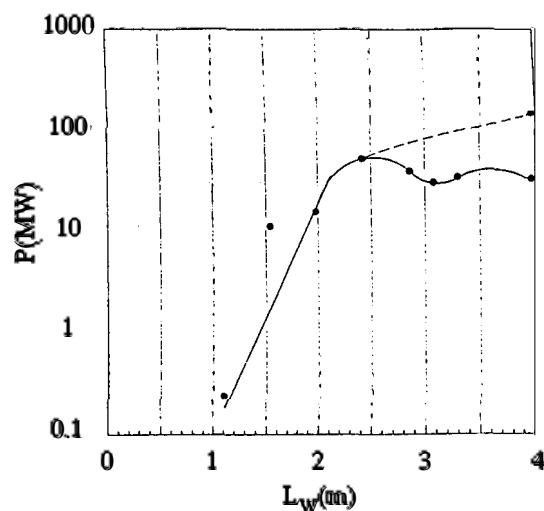

Figure. 5: SG-1 power output vs undulator length. Dashed line: Tapered undulator, Solid line: Constant parameter undulator (3.1 KG)
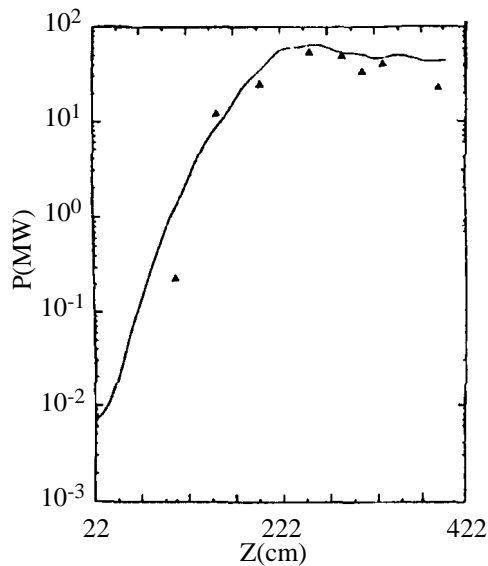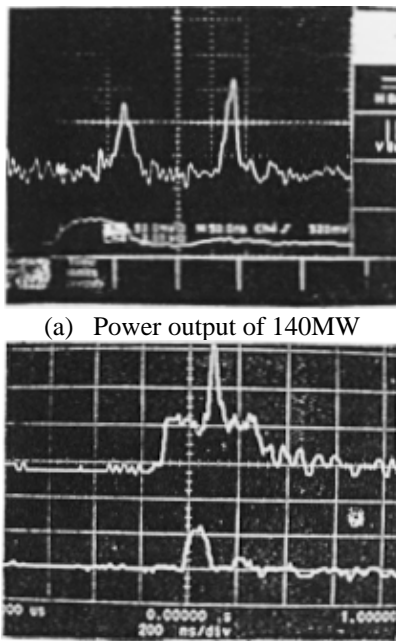
Figure. 6: Comparison between experiments (dots) and simulation (solid line)

(a)   Power output of 140MW

(b) Upper trace-microwave drive, Lower trace-electron beam

Figure. 7: Output waveforms of SG-1 FEL

(2.2) Pulse-line Accelerator FEL and Electromagnetic Pumped FEL [8][9]

FEL with wavelength of several mm has been realized in China since mid-eighties. The Shanghai Institute of Optics and Fine Mechanics first produced a superradiant emission of 8 mm wavelength and 1 MW power with a 0.5 MV pulse-line accelerator. The Southwest Institute of Applied Electronics, in cooperation with the University of Electronic Science and Technology of China (UESTC), performed similar experiments with an annular beam of 0.7 MV, and radiation of 32 GHz was observed. Later, amplifier experiment without axial guiding magnetic field and with a

1.5 m, 3.45 cm period undulator and 280 A was carried out which produced output power of 7.6 MW at 37 GHz.[10]

Electromagnetic pumping FEL was first implemented in UESTC where a system that produced simulated radiation with an interaction region separated from the BWO pump wave generator was used.[11] The radiation generated by the BWO serves as an electromagnetic undulator which as the advantage of producing up-shifted frequency radiation with relatively low source voltage.

Electron beam of 0.6 MeV and 3 - 5 KA generated by a pulse-line accelerator passes through the slow-wave structure of BWO at the down-stream and generates microwave of 3 cm wavelength as an electromagnetic pump source for the FEL interaction region located at the up-stream. Stimulated radiation of 3 - 8 mm wavelength is produced at the output window and detected with a crystal detector.

(2.3) Cherenkov FEL

CFEL has been pursued in China in several institutes. [12] Here, only the case of multilayer dielectric loaded waveguide CFEL [13] will be given as an illustration. The calculated longitudinal field distribution with multi-layer dielectric in a plane waveguide shows that the first fundamental mode TM^1_{01} has very favorable field distribution for beam-wave interaction. The dielectric loss is also found to be lower than the conventional waveguide and the interaction area is increased. The CFEL oscillator consists of five ceramic plates of 445 mm long, 0.6 mm at top and bottom, and 1.2 mm for the others in a 26 mm $\times$ 16 mm waveguide driven by a pulsed-line generator. The solid electron beam generated was cut into sheet beams by a metallic screen. About 80% of the generated beam entered the cavity. The useful beam current is 280 A at 500 KV. The radiation power of 33.4 GHz is in close agreement with that predicted from the dispersion relation. The output radiation power of 1.7 MW was measured with a calibrated crystal detector at the end of the dispersive delay line. The corresponding efficiency was about 1.2%.

III. UV FEL

FEL Harmonic Generator at Hefei National Synchrotron Radiation Laboratory [14]

At Hefei National Synchrotron Radiation Laboratory, a project has started to build an optical klystron installed in one of the straight sections. A third-harmonic of Nd glass laser of wavelength 3533 Å is used as input to produce third harmonic of 1178 Å VUV harmonic coherent radiation for application research.

The electron beam and the optical klystron parameters are given in the following:

Energy	301.6 MeV
Energy spread	1.74×10^{-4}
Beam current	50 mA
Bunch length	12.3 mm
Emittance	2.36×10^{-2} mm-mrad
Number of bunches	45
Rotating frequency	4.8 MHz
Energy damping time	0.195 s
For the optical klystron:	
Period	7.2 cm
No. of period	2×12
Field strength	0.3247 T
Gap	3 cm
Length of dispersion section	21.6 cm
Dispersion field strength	0.7837 T

It was estimated that with this arrangement, each bunch can produce 1.7×10^5 photons at 1178 Å coherently.

IV. THEORETICAL ANALYSIS AND NUMERICAL SIMULATION

Besides the construction of experimental facilities as given above, considerable theoretical work on FEL has been accomplished in China. A new analytical method of describing different kinds of longitudinal mode evolution was proposed. It is a one-dimensional, unified theory that includes the effects of pre-bunching, self-bunching and co-bunching caused by strong external field. Co-bunching is responsible for the emission of harmonics and synchrotron sidebands.[15] Linear space-charge wave theory was developed to analyze the bunching process and beam-wave interaction of FEL.[16] Several computer codes have been completed to guide the design and tune-up of the above mentioned facilities. For example, for SG-1, the simulation is made with a 3-D code, WAGFEL, which--besides other things--includes the space charge effect, transition region of undulator entrance effect, etc.[17] This code, after comparing with the experimental data of SG-1 FEL and also with ETA-ELF,[18] proves to be a reliable means to guide the experimental design.

V. COMPONENT DEVELOPMENTS

Various FEL component developments, such as super-conducting RF gun research, multiple cavity microwave electron gun, etc. are also being carried out. Peking University has started a super-conducting microwave electron gun project with Nb cavity operated at 1.5 GHz. The preliminary test of the prototype showed it can stand an accelerating field of 12.6 MV/m and a Q of 2×10^9 at 2.1K.[19] Figure 8 shows the 3-1/2 cavity thermionic cathode electron gun being developed jointly by Qinghua University and the Institute of High Energy Physics.[20] According to the simulation, the back-bombardment power

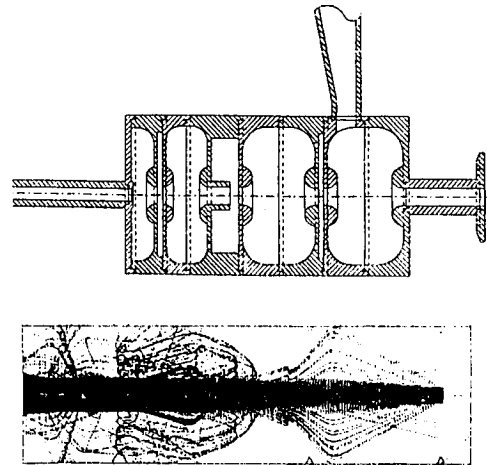is only one-eighth of the single cavity case through optimization of various parameters.

Figure 8: A 3-1/2 cavity RF gun under development. Schematic diagram of the cavity and electron orbits

REFERENCES

[1] Xs.W. Du, the First Asian Symposium on FEL (1993)
[2] J.L. Xie et al, Nuc. Instr. & Meth. A341 (1944) 34
[3] V. Kushnir and Gang Wang, private communication.
[4] C.G. Yao, IEEE NS32 (1985) 2968
[5] W.Z. Zhou et al, Nucl Instr. & Meth. A341 (1994) ABS 37
[6] X. F. Zhao et al, the First Asian Symposium on FEL (1993)
[7] K.S. Hu, private communication
[8] Z.X. Hui et al, the First Asian Symposium on FEL (1993)
[9] S.G. Liu, Proc. 17th Inter. Conf. on IR & MM (1992)
[10] K.S. Hu, High Power Laser and Particle Beam, 2 (1990) 158
[11] Z. Liang, Proc. of 7th National FEL Symposium (1991) 130
[12] C.L. Li, High Power Laser and Particle Beam, 3 (1991) 136; 147
[13] Q.Y. Wang et al, Appl. Phys. Lett. 59 (1991) 2378
[14] D.H. He et al, Proc. of 7th National FEL Symposium, (1991)
[15] M. Yu, High Power Laser and Particle Beam, 3 (1991) 127
[16] S.G. Liu, Inter. J. Electronics, 72 (1992) 161
[17] Z.H. Yang et al, High Power Laser and Particle Beams, 1 (1989) 60
[18] T.J. Orzechowski, Proceedings of the Beijing FEL Seminar, (1989) 347
[19] C.E. Chen et al, the First Asian Symposium on FEL (1993)
[20] C.X. Tang, private communication.