CURRENT FEL DEVELOPMENTS IN CHINA

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Abstract

To provide background for the discussion of China's status of FEL developments, a brief review of FEL physics together with the highlights of world-wide developments are first presented. Then, information of the current FEL experimental facilities in China will be reported. The mainstream of China's present activities follows the sequence: S-band linac driven IR FEL, higher average power IR FEL, harmonic generation FEL and SASE/HGHG short wavelength FEL. Based upon the experience gained in the construction of the existing facilities, the plan of realization of short wavelength FEL in China is discussed.

1 Introduction

China had built a parasitic SR light source, a dedicated 2nd generation light source and a 3rd generation light source already. In order to satisfy the ever increasing demands of the users, a new advanced 3rd generation addition SR source is being considered to be built at Shanghai (SSRF) and the pre-fabrication R&D has been already finished. Obviously,, coherent light sources based on FEL principle to supplement the SR and conventional lasers are a welcomed addition.

Generally speaking, satisfactory coherent light source in the IR and X-ray region of the electromagnetic spectrum are still in lacking even in view of the very impressive developments of synchrotron radiation and conventional lasers. FELs have already become user facilities in IR region and are now developing towards higher average power. Short wavelength FEL, especially in the X-ray region, where FEL can provide coherent light with peak brightness of 10 order of magnitude higher in comparison with that of the 3rd generation SR from the undulators. With this tremendous enhancement in brightness together with 2 order of magnitude increase in time resolution and full transverse coherence, it is quite obvious that new exciting scientific opportunities could be expected in this spectrum realm[1].

In the following, basic physics of FEL will be briefly reviewed and the current worldwide status will be given to facilitate the discussions. Based upon this background, the route that has been followed and planned to pursue in China will be presented.

2 A Brief Review of FEL Physics and Worldwide Developments

2.1 Modes of FEL operation

Generally speaking, when space charge effect is neglected, a relativistic electron beam interacting with the undulator and the optical fields will be micro-bunched so that they could radiate coherently to constitute FEL. It is called Compton regime FEL and its operation can be classified into two kinds according to the gain of the system: small signal gain and exponential high gain. For small signal gain, the optical fields has to interact with the electron bunches many times in the optical cavity to reach saturation. On the other hand, for short wavelength region, as no effective mirrors are available, only high gain mode with a single pass of the high quality electron beam through a long undulator can realize saturation. This mode of operation is called Self Amplified Spontaneous Emission (SASE).

2.2 Simplified analytical results of FEL system

For the purpose of illustrating the basic characteristics of different kinds of FEL devices that will be discussed in the following, some results of the simplified 1-D analysis will be given below[2]. First of all, the radiation wavelength for the output along the undulator axis is given by the resonant condition:

$$\lambda = \lambda_u (1 + a_u{}^2) / 2\gamma^2 n \qquad (1)$$

where λ_u is the undulator period, γ, the beam energy divided by the rest energy, n, the harmonic number and

$$a_u = e\lambda_u B / 2\pi mc = 0.093 B(kG)\lambda_u(cm) \qquad (2)$$

where B is the undulator field strength.

The gain of the system consisting of the undulator, optical field and the electron beam can be derived from the dispersion relation with the results that the system generally supports three propagation constants of the waves with one of them causing the wave amplitude to grow exponentially. This growing wave is dominant for the exponential high gain regime while all waves should be taken into accounts for small signal gain mode. Under homogeneous energy assumption, the maximum **small signal gain** in single pass is, in practical units:

$$G = 0.85 g_0 = 0.85 \times (16\pi/\gamma)\lambda[m]L[m]J[a/m^2]N^2\xi f_b^2(\xi)/1.7\cdot 10^4$$

$$\propto JL^3\lambda^{3/2}F(B,\lambda_u) \qquad (3)$$

where $f_b(\xi) = J_0(\xi) - J_1(\xi)$, $\xi = (1/2)(a_w^2/1 + a_w^2)$

and $F(B,\lambda_u)$ indicates slowly varyijg function of the undulator magnetic field strength and undulator period, and L is the length of the undulator; N, the number of the undulator periods and J ,the electron beam current density. This formula is useful for the preliminary design of a FEL oscillator system. It indicates that how the gain is dependent on some physical quantities of the system. To ensure the system can start to oscillate, the gain has to be larger than all the losses of the system.

The IR FEL, in comparison with the conventional laser sources, has the advantages of tunability, high repetition rate, short optical pulse, high peak power and can be operated in the chirped mode. Up to 1999, the statistics of worldwide relativistic e-beam-short wavelength FEL facilities is 32 existing facilities with wave length extending from 0.1947 μm to 340 μm, among them 24 are RF Linac driven and also 17 facilities are being proposed [3].

For **high gain** situation, the gain can be expressed as:

$$G \cong (1/9)\exp(4\pi\sqrt{3}\rho z/\lambda_u) \qquad (4)$$

where

$$\rho = \{(1/32\pi^2)(a_u\lambda_u/\gamma)^2(I/I_A)([J_0(\xi) - J_1(\xi)]^2/r_b^2\gamma)\}^{1/3} \qquad (5)$$

The parameter ρ is called FEL parameter.

When optical power growth is written as $P = P_0 e^{L/L_g}$ where

$$L_G \approx \lambda_u / 2\sqrt{3}\pi\rho \qquad (6)$$

is called the gain length which characterizes the gain of the system.

The above analysis holds under the assumptions: beam emittance $\varepsilon < \lambda/4\pi$, beam energy spread $\sigma_E < \rho$, also L>> L_G and the gain length shorter than the radiation Raleigh range $L_G < \pi w_0^2/\lambda$ where w_0 is the radiation beam radius.

For practical cases, ρ is about 10^{-3} for X-ray FEL where the peak current of a few KA, normalized emittance around 1 mmmr and beam energy of tens of GeV are required. Then the gain length is about several meters. For saturation to occur, the undulator length should be longer than about 10-20 L_G and the saturated power is about ρ times the beam power. Obviously, the technical requirements for short wave length SASE mode of operation is much more stringent than the small signal gain oscillator at IR wave length range. Fortunately, FEL and next generation linear collider have similar technical requirements of the physical parameters, The latest developments in both fields, such as the photo-cathode RF gun injection which can produce high bunch current with low emittance, the bunch compression, the emittance preservation, the highly precision of the undulator fabrication and alignment and high precision beam monitoring are the most important developments that makes the realization of both next linear collider and X-ray FEL possible. Experimentally, UCLA/LANL, LANL, BNL/APS, Osaka University, VISA, Leutl of APS, TTF of Tesla, and Sunshine of Stanford have demonstrated SASE mode of operation in IR, Visible and UV. Recently, LEUTL becomes the first to demonstrate saturation at both 530 nm and 385 nm[4]. It seems the SASE approach to X-ray FEL is well on its way and both

SLAC and DESY are working on its realization[5] [6] .

3 Current FEL Projects in China

The general situation of FEL research in China had been reported before. Here we will update the status of those projects that is currently under active developments. The mainstream of China's present activities follows the sequence: S-band linac driven IR FEL, harmonic generation FEL, higher average power IR FEL and SASE/HGHG short wavelength FEL. .

3.1 Beijing Free Electron Laser Project (BFEL)

Beijing FEL had lased to saturation in 1994[7] and since then was being converted into a user's facility. The present schematic diagram of the facility is shown in Fig.2.. As can be seen, the accelerated electron bunches

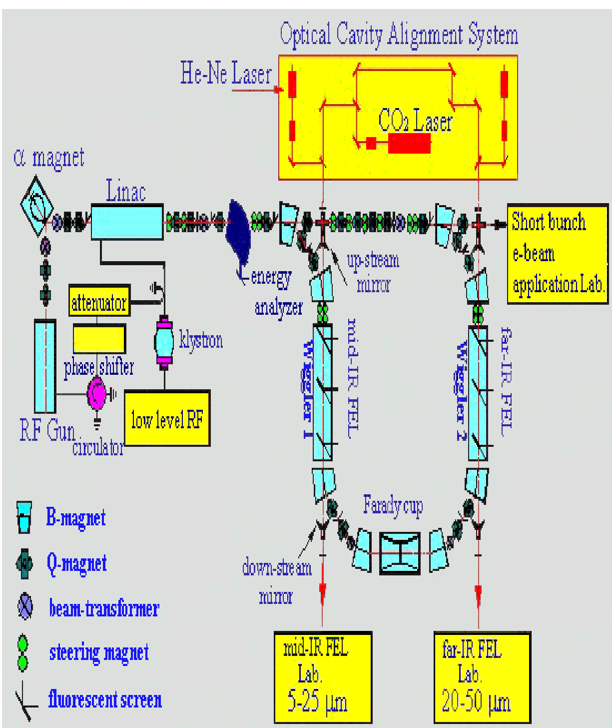

Fig. 1 Schematic Diagram of BFEL

are used in threedifferent modes that can be controlled by turning on and off the bending magnets in the straight beam line. Counting from the upstream, if the first bending magnet is on, the electron beam passes through the first undulator and radiation of 5-25 μm will be produced. If the first bending magnet is off and second is on, the beam will pass through the second undulator to produce radiation of 20-50 μm . If both bending magnets are off, then the electron bunches will go straightforward to the short electron bunch experimental station where two experimental stations: a coherent synchrotron radiation of far IR and a Compton back scattering, are

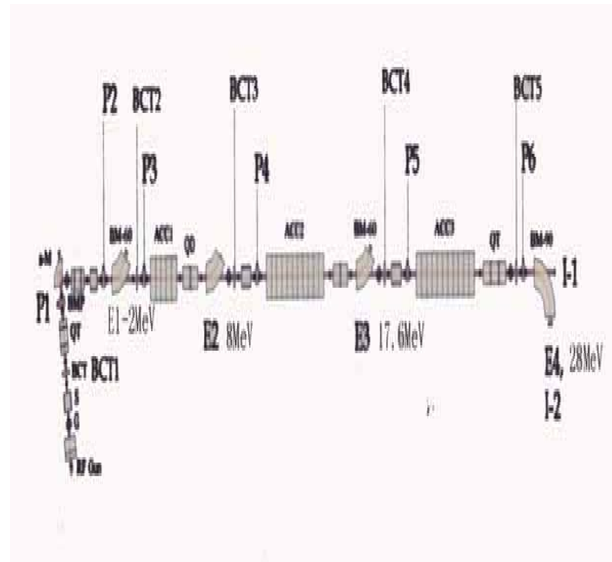

Fig.2: Schematic Diagram of L-band FEL of CAEP

under construction. The relative rms laser output fluctuation is 1.06% and had run continuously near 200 hours each run.[8].Up to now, more than twenty experiments using BFEL had been performed.

3.2 IR FEL of the Academy of Engineering Physics. (CAEP)

CAEP has finished the construction of a 28 MeV L-band linac driven IR FEL that is now in the process of tuning-up [9]. And also the design of a 10 MeV super-conducting Linac is in progress. The schematic diagram of the 28 MeV system is shown in Fig.2 with the initial performance: output current is 290ma at 28 MeV with 25ps micropulse and 4.5 μs macropulse and the energy spread is less than 0.7%.

CAEP has also developed an L-band photocathode RF gun with 2-1/2 cavity axial coupled bi-periodic structure. The photo-cathode used is Cs_2Te for its high quantum effeciency and moderate vacuum requirement. The output energy of the electrn beam is 2MeV with microbunch current of 70A and emittance of 4 mmmrad[10].

3.3 Harmonic Generator of Hefei National Synchrotron Radiation Laboratory

Using an optical klystron placed in one of the straight sections of the 800 MeV storage ring, it is planned to use the third harmonic of Nd glass laser as seed signal to

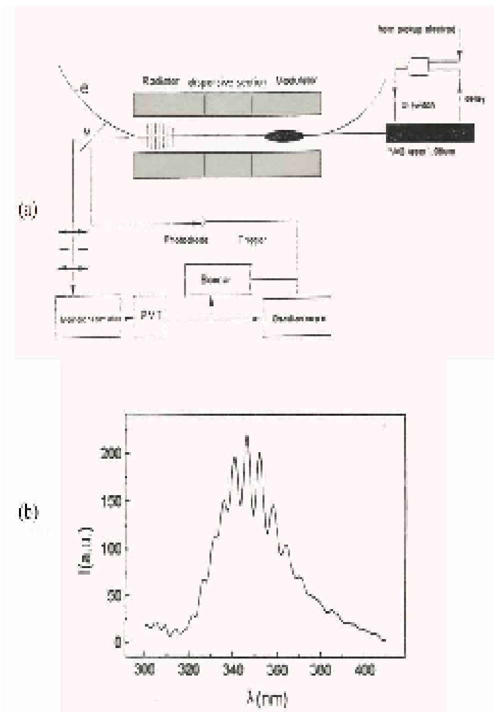

Fig.3: Harmonic generator of Hefei: (a) Schematic of the layout, (b) Modulation effect of the seed laser

produce third harmonic of 1178 A VUV coherent radiation [11]. In this way, the frequency of the Nd:YAG output can be raised 9 times.

The up-to-date arrangement of the system and preliminary experimental result showing the modulation effect of the seed laser observed are shown in Fig.3 [12]

3.4 Superconducting RF gun injector development of Peking University

To lay the foundation for the development of high average power FEL, Institute of Heavy Ion Physics, Peking University has succeeded in realizing a DC-RF superconducting Photocathode injector {13}. This novel design combines the features of a photocathode DC Pierce gun for electron production and superconducting RF cavity for acceleraation.

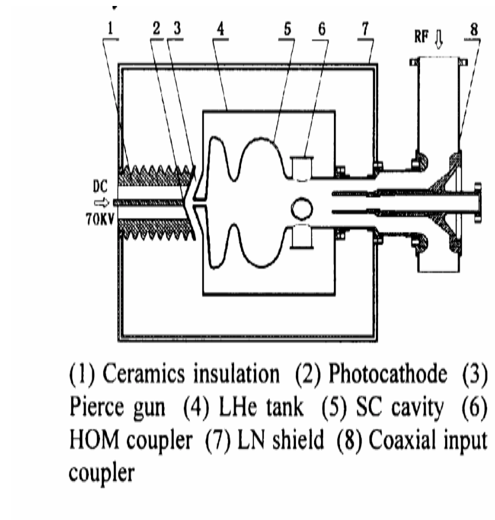

Fig.4: Configuration of DC-RF SC injector

Aschematic diagram of the injector is shown in Fig.4. Simulation shows the optimized design emittance is less than 3π mm-mrad and single bunch charge is not lower than 60 pC with a repetition rate of 81.25 MHz for average current about 5 mA. It is clear this injector can serve as the first step in the realization of a high average power FEL in China.

Table 1: Preliminary Design Parameters of SSRF DUV FEL

(A) FEL parameters	
Laser wavelength (nm)	300-75
Bandwidth ($\Delta\lambda / \lambda$)	$\sim 10^{-4}$
Pulse width	ps to sub-ps
Peak power (MW)	200-400
Energy/pulse (mJ)	~1
Rep.rate (Hz)	50-100
(B) Electron beam parameters	
Energy (MeV)	300
Normalized emittance (mm-mrad)	6
Global energy spread	0.25%
Local energy spread	0.1%
Peak current (A)	300-500
Pulse width (ps)	3-5
Rep. Rate (Hz)	50-100

3.5 Raman mm FEL at SIOFM

A Raman FEL with pseudospark discharge electron source is under development at Shanghai Institute of Optics and Fine Mechanics [14]. In this system, a compact Marx generator is used to produce 300 kV high voltage pulse to initiate the discharge. Electron beam of 10 kA with low emittance has been obtained and it can be operated without guiding magnetic field. Simulation indicates that with a small period undulator a saturated

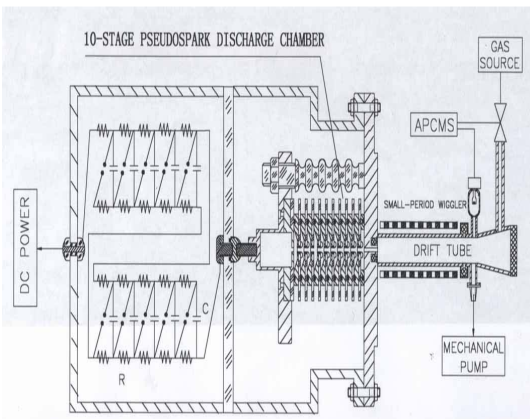

Fig.5: Schematic of the compact Raman mm

power of 98 MW at wavelength of 4-7mm can be obtained. The schematic layout of the system is given in Fig.5.

4 Proposal of DUV-FEL of SSRF

As a supplement to the proposed Shanghai Synchrotron Radiation Facility (SSRF), the injector linac of the facility will also be used as a DUV FEL driver. The designed peak power of this SDUV-FEL in comparison with that of other light sources is given in Fig.6.

This project is a collaboration of the Institute of High Energy Physics, the Hefei synchrotron radiation Laboratory and Shanghai Institute of Nuclear Studies. The main idea is to build a short wavelength FEL coherent light source to complement the SSRF light source to extent its scope of applications and at the same time, study the technical problems related to short wavelength FEL. The wavelength should be as short as is consistent with the 300MeV energy linac as determined by Eq. (1) above. There are several possible approaches to this goal, such as SASE, HGHG[15][16] , nonlinear

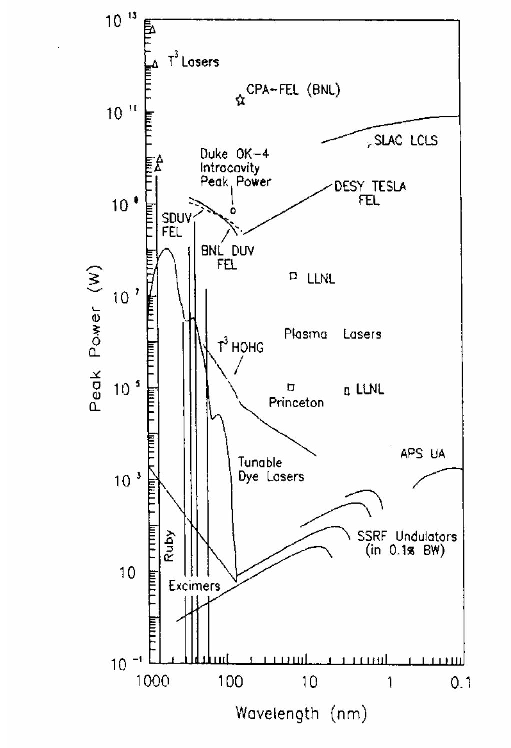

Fig.6: Designed peak power of SDUV-FEL in comparison with other light sources

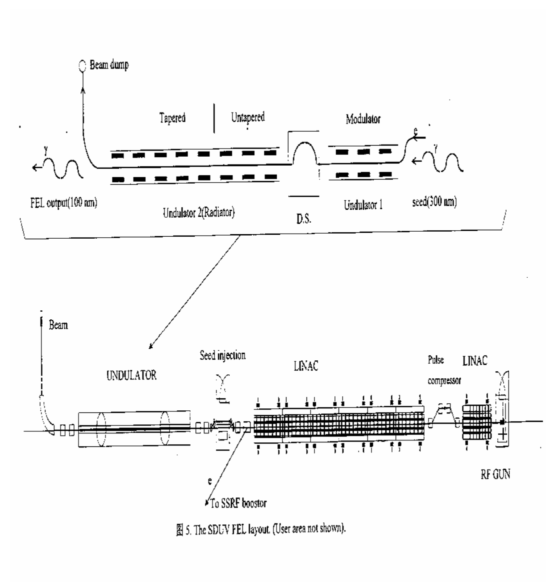

Fig. 7: Schematic layout of SDUV-FEL

harmonics and others[17] [18]. HGHG scheme will be adopted because of its many important features, such as it can produce shorter wavelength radiation, more stable output and shorter FEL pulse together with shorter undulator length though one has to pay the price of more complicated configuration and wavelength tuning.

There are several basic technological challenges we have to face for short wavelength FEL [19], namely, high brightness electron source, brightness preserving linac acceleration system, high precision magnetic and mechanical tolerance undulators and monitoring systems. All these are the subjects of pre-fabrication research.

Fig.7 is a part of the schematic diagram of SSRF where the 300MeV linac locates. This linac serves the purposes of driver of DUV FEL and injector to the booster which in turn plays the role of full energy injection to the main ring of 3.5 GeV storage ring [20].

This DUV FEL is now in the conception design stage with preliminary design parameters given in table 1[11]

The driver linac consists mainly of the S-band photo-cathode RF gun, 11sections of constant gradient SLAC type accelerator wave guide, chicanes and optical klystron .

The RF gun is 1-1/2 structure with pure metal cathode. The driving laser is a quadrupled Nd:YLF laser sysrtem. The electron bunches are compressed by a chicane system with a linear energy phase correlation achieved by phase adjustment between the linac sections. The peak current will increase to 300-600A after the compression.

The optical klystron as usual consists of modulator section, dispersion section and radiator section. The radiator has exponential gain of the harmonics of the seed laser frequency until saturation is achieved. The optical klystron is a planar hybrid NdFeB permanent magnet undulator. BPM with resolution better than 10μ will be installed between undulators.

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