FEL STUDIES IN CHINA

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Abstract

In this paper the FEL study in China is presented The physical design and research of the Beijing FEL oscillator (BFEL), using the electron beam from a 30MeV rf. lince, and of the SG-1 FEL, using the beam electron from a 4 MeV induction linc, are discussed. Then we set forth the technical features, the desired goals and experimental results for the sub systems of BFEL and SG-1 FEL.

Key words Free electron laser, linac, wiggler.

Introduction

The theoretical research of FEL in China commenced in the mid 1970s, but experiments commenced later in the mid 1980s. In 1985 Shanghai Inst. of Optics and Fine Mechanics (SIOM) yielded 1MW in output power at wavelength 8 mm, based on 0.5MeV pulseline accelerator. In1987 Southwest Inst. of Applied Electronics produced an experiment by using 0.7 MeV pulseline accelerator. The annular beam is injected into the FEL interaction region and radiation at 32 GHz has been observed. The energy extraction efficiency from beam is only 0.6%. These experiments were characterized by small efficiency due too poor quality of electron beam. In recent year, Inst. of applied electronics had performed an experiment of raman FEL, based on EPA 74 accelerator without axial guiding magnetic field, in which 7.5 MW radiation at 32 GHz has been observed. At the same time induction linac of 4 MeV with qualitative electron beam is projected for SG-1 FEL amplifier by China Academy of Engineering Physics (CAEP) and a 30 MeV rf. linac is being upgraded by Inst. of High Energy Physics (IHEP) to provided electron beam for BFEL oscilator in the infrared region. The FEL with electromagnet wave pump is projected by University of Electronics Science and Technology of China. The cherenkov FEL experiment is produced by Changsha Polytechnic Inst. and the superconducter accelerator is studies by accelerator lab. of Peking University. Now the FEL research in China is intensely produced both in theoritical and experimental aspect.

Design and development of Beijing FEL (1)

IHEP in cooperation with SIOM have started a compton regime rf. linac based FEL research, which be called Beijing FEL (BFEL). In the first phase of the project, a 30 MeV rf. linac is being upgrated. Design parameters of the BFEL are chosen with reference to both the analytical formulae and the single particle, one dimentional numerical simulation. The small signal gain G can be expressed as follow (2)

$$G=G_0F(\Delta\gamma/\gamma,\ \varepsilon,N) \tag{1}$$

$$G_0=0.135A[J_0(\frac{1}{2}\frac{K^2}{1+K^2})-J_1(\frac{1}{2}\frac{K^2}{1+K^2})]^2 \tag{2}$$

$$A=4\pi^2(\frac{2\lambda_s}{\lambda_w})^{1/2}(\frac{L\lambda_s}{\Sigma_L})(\frac{I_p}{I_0})\frac{K^2}{(1+K^2)^{3/2}}(\frac{\Delta\omega}{\omega})^{-1} \tag{3}$$

where F is a correction factor related to the energy spread of the electron beam and the undulator periods N; J_0 and J_1 are the Bessel function; λ_s and λ_w are the wavelength of the radiation and the underator respectively; L is the undulator length; Σ_L is the minimum average cross section of laser beam in the optical resonator; $I_0=1.7\times10^4$A (Alfven current); $K^2=b_w/2k_wc^2$, $b_w=eB_w/mc$; B_w and k_w are the undulator field intensity and wave number, respectively; $(\Delta\omega/\omega)$ is the homogeneous line width; and I_p is the peak current.

The length of time required for the radiation to build up to saturation can be estimated according to the following simple formula if one assumes the gain to be constant

$$\tau=\frac{ln(S_a/S_0)\times 2L_c}{c\,ln[(1+G)(1-\alpha)]} \tag{4}$$

where S_a/S_0 is the ratio of the saturated power to the spontaneous emission power; α, the total resonator loss; and L_c, the length of the optical resonator If taking $S_a/S_0=10^{10}$ then one obtains the simple relation

$$\tau(\mu s)=\frac{0.154\,L_c(m)}{(G-\alpha)}, \tag{5}$$

In table 1, the overall physical parameters are given and the schematic for the BFEL is shown in fig 1,

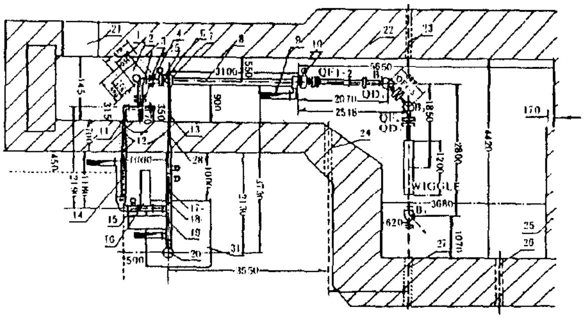


Fig. 1 Schematic of BFEL system

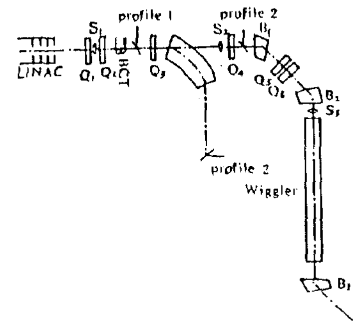


Fig. 2 The layout of the beam transport system

Table I
Physical parameters of Beijing FEL project

Microwave Gun:	$I_p = 10/20$ A $E = 0.9 \pm 0.1$ MeV $\Delta\phi = 4°$ $I = 110/220$ mA $\epsilon_{n,x,y} < 30\,\pi\,mm{\cdot}mrad$
Linac:	$E = 10$ MeV $-$ 30 MeV $I_{(BBU)} = 300$ mA $\tau_{(e\,beam)} = 4\ \mu s$ $\tau_{(modulator)} = 5\ \mu s$ $\Delta\gamma/\gamma = 0.5\%$ $\Delta f/f = 10^{-6} - 10^{-7}$
Wiggler: (uniform, planar, NdFeB)	$\lambda_w = 3$ cm $N = 50$ $L_w = 150$ cm $g = 0.8$ cm $K = 1 \sim 1.1$
Optical Resonator: ($ZnSe/ThF_4$)	$L_0 = 251.926$ cm $\alpha \le 5\%$ $L_R = 67$ cm $W_0 = 1.5$ cm $G = 8 \sim 13\%$ $\lambda_s = 7 \sim 25\,\mu m$

The microwave gun (3), because of its relatively high peak current, low emittance, and narrow longitudinal phase width when used in conjunction with a momentum analyzer, is adopted in this project, and the LaB_6 cathode is contemplated. The injected beam from the microwave gun, after being momentum analyzed, has a pusle width of a few picoseconds so that the time-dependent RF field effects can be minimized. To reduce emittance growth due to space-charge effects in a microwave gun, high RF field with linear RF radial field distribution will be used. The ratio of emitted current in the presence of strong electric field to normal no field emission current is given by

$$J_E/J_0 = e^{4.403\sqrt{\cos\phi\, E\,(V/cm)}/T\,(°K)} \qquad (6)$$

The layout of the beam transport system is given in fig. 2, which shows tow 45° bending magnets and six quadrupole magnets with a total length of about 5.3 m. Bending magnets B1, B2, and quads Q_5, Q_6 form a symmetrical achromatic bending system to bend the beam from the accelerator by 90° into the optical resonator. $Q_{1,2}$ $Q_{3,4}$ form a matching section to adjust the beam waist to the center of the undulator. For an unnormalized emittance of 0.5 mm·mrad, the diameter of the waist can be adjusted up from 0.2mm by changing the exciting currents of the magnets. Fig. 3 shows typical beam envelope σ_x, σ_y variations along the beam line in both horizontal x and vertical y directions.

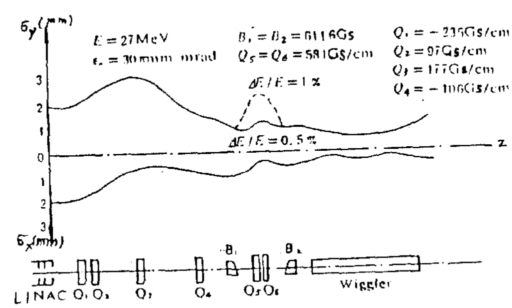


Fig. 3 Beam envelope

The optical resonator configuration in our first attempt to obtain a laser oscillation uses curved mirrors composed of a $ZnSe/ThF_4$ multilayer stack on a ZnSe substracte, which is reported to have a maximum reflectance of 99.8 % at 10.6 μm and is not seriously by radiation enviroment, The mirrors will be remotely tilted for optimum alignment and for the end mirror, a motorized micrometer will be used for resonator tuning. Due to the transparency of ZnSe, preliminary alignment can be made with a He-Ne visible laser. In the next step, gold-plated copper mirrors will be used for a wider tuning range.

A rotating ZnSe plate at Brewsters angle near the entrance mirror is used for output coupling. Varying the coupling from zero to 2 % by rotating the plate is being considered.

The magnetic material for the construction of the undulator is neodymium iron boride(NdFeB) instead of the more generally used REC. The reason for this choice is that NdFeB has higher B_r as well as H_c values. The magnetic energy density almost doubles that of REC , while the market price in China is half that of REC. Therefore NdFeB is adopted even though the temperature coefficient is inferior to REC. The structure of the undulator is shown in fig.4. Planar design is chosen for convenience. It is composed of 400 identical NdFeB permanent magnets ($7.5\times7.5\times40$ mm^3)arranged to provide 50 periods with matching parts at each end to give a zero-integrated field.

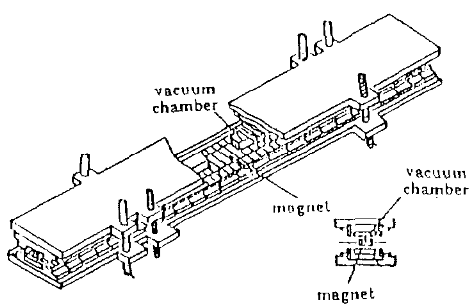


Fig.4 The structure of the undulator

The curves of variation of the on-axis field and K value against the gap separation, obtained from theoritical calculation as well as from measurement, are quite good agreement.

The construction of BFEL will be performed at the december 1990.

Design and development of SG-1 FEL

SG-1 FEL is a raman regime free electron laser amplifier, which is being projected and constructed by CAEP.with wavelength of 8.6 mm, based on induction linac Simulations of SG-1 FEL are made using a 3-D FEL code (WAGFEL)(4), which evolves the electrons energies the ponderomotive phase according to the averaged single-particle equations and the fields according to paraxial wave equations. In order to verify the relibility of code WAGFEL the comparision between numerical simulations using WAGFEL and the experimintal data ETA / ELF of LLNL is made. It shows that the experimental detuning curves for 1, 2 and 3 m long wiglle's agree very well with our simulations.

The SG-I FEL contains a 4 MeV induction linac, beam transport system, tapered wiggler and microwave source. In table 2, the overall physical parameters are given and the layout of SG-I FEL is shown in fig.5.

Table 2

Physical parameters of SG-1 FEL

Induction linac	E = 3-4 MeV
	I_e = 500 A
	$B_n = 5\times10^3$ A / (πcm rad)^2
	$\Delta E/E$ = 3 %
	ε_n = 0.77 πcm-rad
	τ = 60 ns
Wiggler	λ_w = 11 cm
	B_w = 3100 G
	$\Delta B_w/B_w > 25$ % (taper)
	N = 30
	$\alpha = K_y/K_x$ = 1.4-2
Input and output	P_{in} = 20 kW
	f_o = 34.6 GHz
	$P_{out} = 1\text{-}2\times10^8$ W
	η = 10-20 %

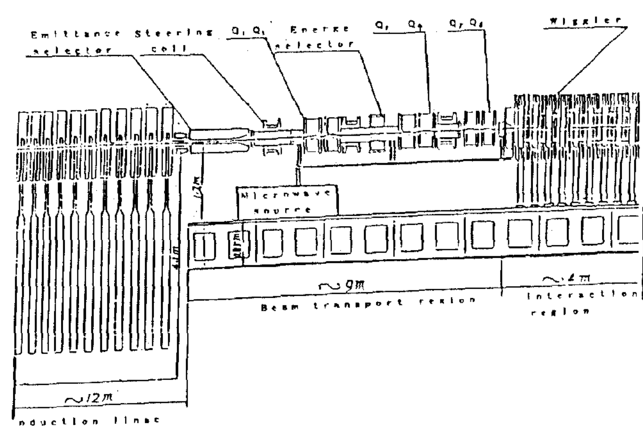


Fig.5 The layout SG-I FEL

The 4 MeV induction linac consists of a 1 MeV injector and 10 accelerator cells. Each cell can give the electron beam an energy increment of 0.25 - 0.30 MeV It is known, an accelerated beam must have high brightness to appropriate for FEL system and the brightness is proportional to the inverse square of emittance. So the cathod of injector diode is finely designed to provide electron beam with small emittance. The diode has a planar configuration and its emitter is made of velvet, showing in fig.6.

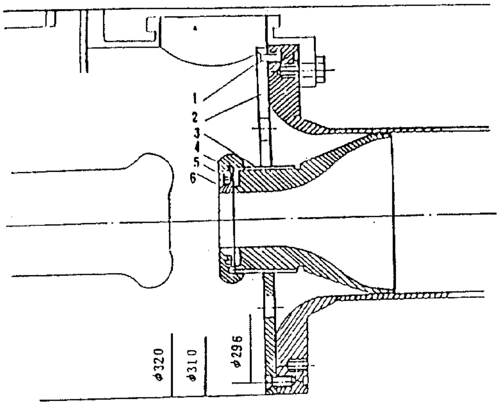


Fig.6 The configuration of diode

Preliminary measurements of the beam emittance of injector have been performed. From these measurements the emittance is estimated to be 70 cm mrad.

The beam transport system consists of a emittance selector, a energy selector, tow steering coils and six quads. Quads Q_3-Q_6 form a matching section to adjust the beam waist to appropriated its position in the wiggler.

In contrast to an FEL oscillator, whose wiggler length is approximately one-half of a synchrotron wavelength long, and through which the laser beam may pass hundreds of times, a tapered wiggler of FEL amplifier can be exceeding long, but is a single pass divice. We have developed a new shielded-pulsed electromagnet wiggler with parabolic pole surface to provide horizontal focusing of electron beam (7). The magnetic field of the wiggler with parabolic pole surface is given by

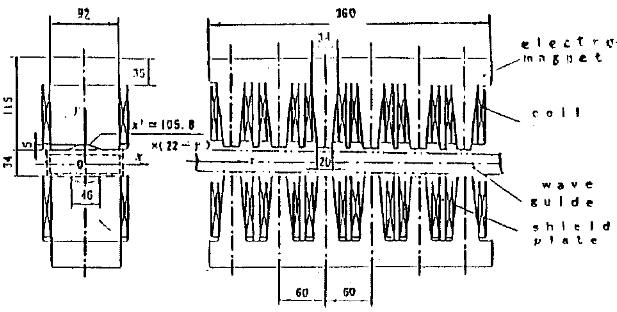
$$\vec{B}_w = B_0 \{\cosh K_x X \cosh K_y \cos K_w Z \hat{Y} + (K_x/K_y) \sinh K_x X \sinh K_y Y \cos K_w Z \hat{X} + (K_w/K_y) \cosh K_x X \sinh K_y Y \sin K_w Z \hat{Z}\} \quad (7)$$

with $K_x^2 + K_y^2 = K_w^2$

More importantly, this field ensures that the longintudinal velocity of an electron remains constant over a betatron period. Without this property, the electrons could detrap from the ponderamotive well with serious consequences for the FEL performance.

The focusing property is dependent by coefficient $\alpha = K_y/K_x$. For our case the optimum value of α is 1.4-2. The shield plate is used for enchancing the field strength. It has been found that the field strength can improve by a factor of 15-20 %.

The layout of the shielded-pulsed electromagnet wiggler is shown in fig.7.



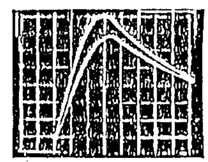


Fig.7 Shielded-pulsed electromagnet wiggler

The input signal is provided by magnetron oscillator, operating at 34.6 GHz with output power 20-30 kW. As shown by numerical simulation, the output power of SG-I FEL would be 100-200 MW and the efficiency would be 10-20 %.

The experiments of SG-I FEL will be produced in 1991.

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