Linacs for FEL in China

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Abstract

R.F.Linac basec FEL has the features of broad spectral range, pico-second pulses, high peak power etc. Therefore linacs are widely adopted as the accelerated electron sources to drive FEL in the optical wavelength range for various applications.

In China, there are three Institiutes working on FEL with linacs as drivers. The Beijing IR-FEL is the foremost development which had achieved saturated lasing in December, 1993. In Shanghai Institute of Nuclear Studies, a 2.5--800 micron broad-band user faclity is in its early stage of construction. At Institute of Atomic Energy, Beijing, a L-band linac Far-IR FEL facility is being pursued and the injector of that linac has being completed and its characterristics measured.

Besides, there are quite a few Institutes working on the R&D of components of linac based FEL. At the China Academy of Engineering Physics, Chengdu, a 1-1/2 cavity thermionic-cathode microwave electron gun had been manufactured and measured. It is also cooperating with Beijing University in the study of photo-cathode materials. Superconducting rf cavity and undulator of different types are also being studied at different Institutes.

Introduction

The developments of FEL in China started in early eighties. Different types of accelerators were employed to provide the accelerated electrons. Among them, R.F. linacs and Induction linac are used for Compton regime FEL and pulsed high voltage generators are used for Raman regime FEL. As is the trend of FEL developments worldwild, RF linacs are most often used. Thus FEL opens another direction of the application of Linacs besides those for high gradient , high power , high reliability , high duty factor etc. This area of applications of linacs emphasizes mainly on the high quality of the electron beam i.e. low emittance, low energy spread, high intensity and high stability. The diverseness of the application of linacs explains clearly the importance of linac developments. From FEL point of view, the linacs have the advantages of wide energy tuning range and hence laser wavelength tuning range, energy chirping to provide pico-second laser pulse, the un-used energy of the electron beam can be recovred, possible high peak and average power etc.These properties are desirable as FEL driver.

In this report, three rf linac based FEL facilities in China will be discribed, with emphasis on the linac technologies rather than full treatment of the FEL systems. Among them, the Beijing IR-FEL facility of the Institute of High Energy Physics, which had lased to saturation at the end of 1993,will be discussed in more details.

(1) Beijing IR- FEL Facility [1]

The schematic diagram of Beijing FEL (BFEL) is shown in Fig.1 and its operational parameters are given in Table 1.This facility uses a microwave electron gun as the electron source and an Alpha magnet to compress the beam.The bunched beam is injected into a S-band constant gradient, unit relative phase velocity linac section and accelerated to about 30 Mev. After passing through an achromatic and nearly isochronous beam transport line, electrons are injected into a NdFeB permanent magnet undulator, and then, after a 180 degree isochronous

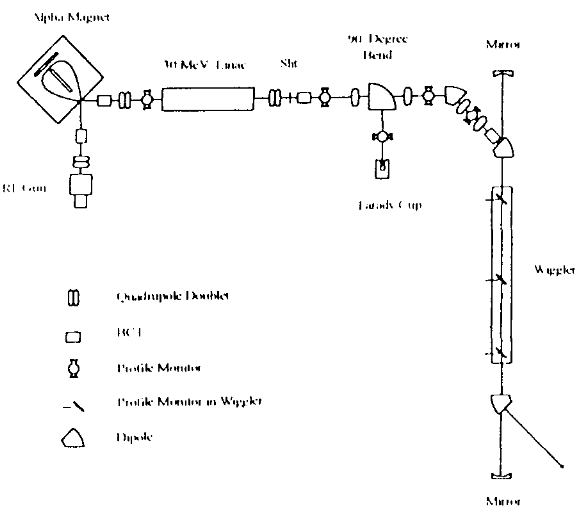


Fig.1 Schematic layout diagram of BFEL

and achromatic bend, the energy of the spent beam is analyzed by a macro-pulse time resolved spectrometer. The optical resonator is composed of a Zn/Se mirror coated with multiple-layer dielectrics.

Some features of BFEL are as follows: (1) The linac used is a modified Slac constant gradient wave guide with four circular holes on some disks of the section which create a separation of the dispersion curves of EH_{11} mode but produce little purterbation of the dominant TM_{01} mode.[2] Thus the BBU threshold value should be increased with practical no effect on the dominant mode. Experimentally, no apparent beam loss or emittance growth were observed at 200ma without any magnetic focussing. To faciliatate the alignment of the accelerated beam ,the exit diameters of the couplers were reduced to 1cm by inserting plugs. The temperature fluctuation of the linac section was controlled to a high degree of constancy (45 ± 0.03^{o}) by a special feedback circuit.

Table 1. BFEL system parameters

Electron beam	
Macropulse length	4.5μs
Macropulse repetition rate	3.125Hz
Micropulse length	3-4ps
Micropulse repetition rate	2856MHz
Beam energy	24-28Mev
Energy spread (FWHM)	0.7%
Macropulse current	150-200mA
Normaized emittance at rf gun exit	20 πmm-mrad
Undulator II	
Priod	3cm
Number of periods	50
Gap	1.15cm
K value	1.17
Electron trajectory deviation	50μm
Harmonic contents	1%
Optical cavity	
Cavity length	215.9cm
Operating wavelength	9-11μm
Mirror radii, upstream	174cm
down stream	170cm
Mirror reflectance, upstream	99.5%
down stream	99.0%
Rayleigh length	76.5cm

(2) The thermionic cathode microwave electron gun which generate an electron beam with continuous energy distribution from zero up to 1.2 Mev.over a phase spread of about 120 degrees. Because of the energy difference, this beam debunches from the gun to the Alpha magnet and from the Alpha magnet to the linac entrance. The Alpha magnet is used to overbunch the beam so that a net bunch width of about 4 ps is obtained at the linac entrance. The bunch width will practically be maintained during acceleration in the linac. This bunch compression scheme is the key element of the success of FEL operation. In our gun, LAB6 crystal with <100> cut is used as the cathode material which gives both comparatively high current density and emission stability.

However, the thermionic cathode microwave electron gun has the inherited problem of back-bombardment which causes energy and intensity variation of the macropulse beam current due to beam loading effect in the gun cavity. After passing throtheugh the energy defining slit of the alpha magnet, these variations are converted into variation of the charge distribution in the micropulse. This has imporTnt effect on the performance of the FEL. The back-bombardment can be reduced by a transverse magnetic field to deflect the returned eectrons away from the cathode surface. The location and strength of this transverse deflecting magnetic field are critical issues for the reduction of back-bombardment.[3] The arrangement with one magnet near the cathode and one at the exit of the gun is adopted. Fig. 2 shows how the accelerating field of the gun cavity varies with the deflecting magnetic field as a consequence of beam loading effect. The current ramp at the exit of the gun as read by a BCT reduces from 40% to 25%with the application of the deflecting field while the emittance of the beam is only slightly affected. Under the present arrangements, BFEL can run at a macro-pulse length of 4.5micro-secind at 3.125 repetition rate.

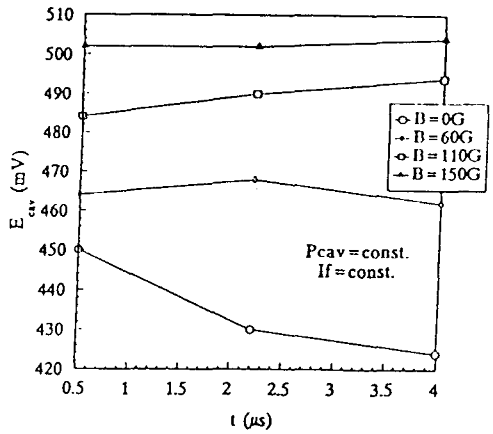
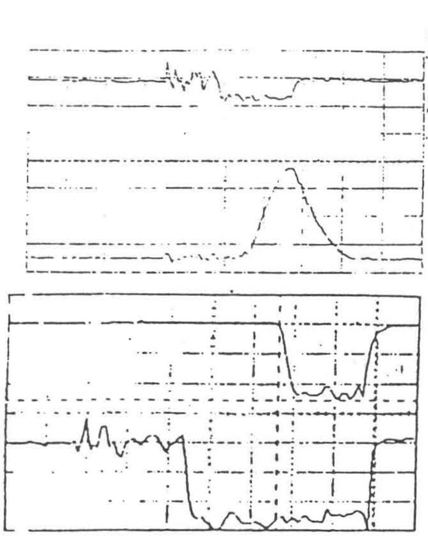


Fig. 2 Cavity field vs. time at diffenert deflecting Field.

(3) With the energy defining slit in the alpha magnet set for the maximum energy of the gun , the injection time of the electrons to the linac is determined by the time constant of the gun cavity which sets the gowth rate of the beam energy . This is generally shorter than the filling time of the linac and therefore, the system is operated in an early injection mode.

(4) The rf phase jitter between the electron bunches and the accelerating field in the linac is another critical issue for the FEL operation. Because of the differences in the time constants of rf gun and the linac section, it is vital to have flat amplitude and phase pulse wave forms from the modulator and the high power klystron. With much efforts, we succeeded in achieving a modulator high voltage pulse ripple of ±0.3% and pulse to pulse fluctuation of ±0.1%. The corresponding amplitude and phase variations of the klystron rf power output are about ±1% and ±1. 5 degree respectively.

The FEL output is shown in Fig.3 where Fig.3 (a) and (b) give the wave forms before and after all the operating parameters are optimized. The profile intensity distribution is shown in Fig.4 which demonstrate the situation that the system is operated as TM_{00} and the optical beam quality is nearly diffraction limited. The laser intra-resonator peak power is 20MW and the small signal gain is 32%.



(a)

(b)

Fig. 3 Laser output waveforms (a) before saturation, (upper trace, electrom beam; lower trace, laser output.) (b) after saturation, (upper trace, laser output; lower trace, electron beam.)

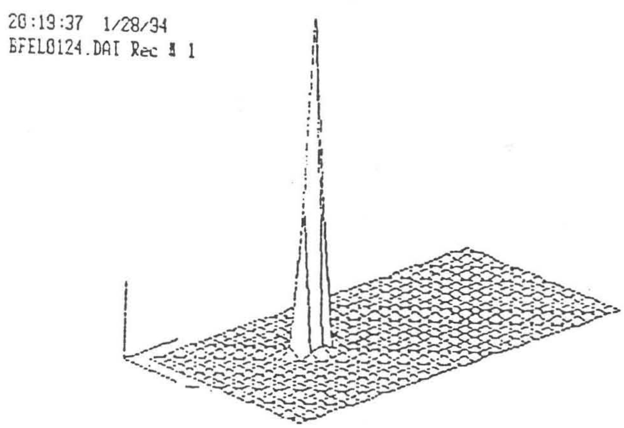


Fig. 4 Spatial distribution of the laser beam

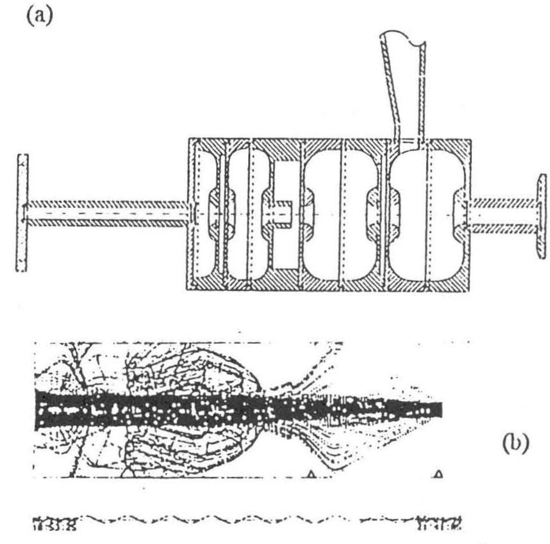
Though BFEL has already lased to saturation, there are still much room for improvement of its performance. In the following, some contemplated up-grading programs are listed.

(1) A special adaptive feed-forward system [4] for both the gun and the linac to improve the homogeniety of electron bunches as well as to control the long time drift of the operating points of the system will be incorporated. Therefore, one low power klystron ampllifier has to be added. The necessary components are being ordered.

(2) Several measures have been taken to further reduce the back-bombardment effect in order to run the gun at longer macropulse width. First, a magnetron rf gun test stand and a Yag laser have been set up to test the idea of using laser with decreasing power during the macropulse to assist in heating the cathode to compensate the increase of temperature caused by the back-bombardment.

(3) As another approach, in cooporation with Qinghua University a 3.5 cavity rf gun as shown in Fig.5 is being developed. This is a pi mode coupled cavity chain with four

(a)



(b)

Fig. 5 3.5 cavity rf gun, (a) schematic diagram (b) electron orbits

accelerating cavities and three coupled cavities. The design philosophy is to minimize the back-bombardment power by using the various cavity lengths as variable parameters. The first two are short cavities with adequate field strength to enhance capture of the emitted electrons from the cathode while at the same time not to affect the emittance too much. The last two cavities are mainly for the purpose of acceleration. The performance of this design is: at 1.3 MW input rf power, the electron beam generated has an energy of 1.4 Mev. with 900 ma current and normalized emittance of 2 pi mm mr. Fig.5 (b) shows the electron orbits along the cavity chain. Assuming operated at 6 micro-sec. pulse length and with the repetition rate of 50 Hz. and cathode diameter of 3mm, the back-bombardment power is only 10 W. in comparison of about 80 watt under similar operation conditions for one cavity gun presently used. This represents a significant improvement. The code used for this desigh includes Schottky effect, space-charge effect and beam loading effect.[5]

(2) Shanghai Wide-band FEL User Facility [6]

The general layout of the Shanghai FEL (SFEL) is given in Fig.6. The injector of SFEL consists of sub-harmonic buncher

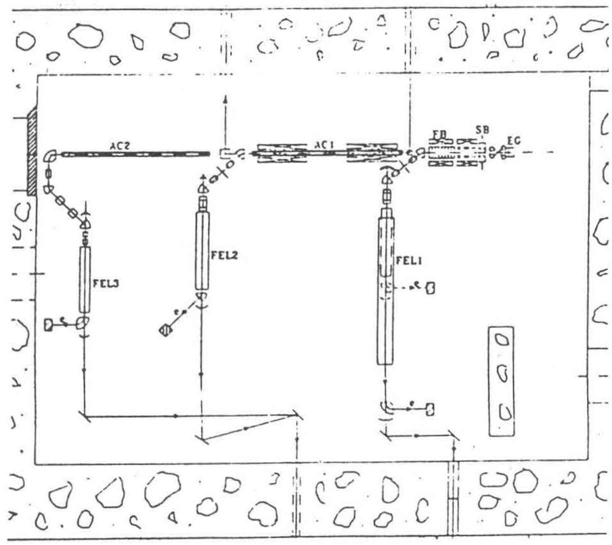


Fig.6 Schematic layoff diagram of SFEL

high gradient buncher and Slac type accelerating sections. It can be seen that the whole facility consists of three different undulators driven by three different energy electron beams. The first beam is from the injector itself, with energy of 2~3 Mev. and produces FIR radiation with wavelength from 200~800 μm. The second beam is produced after the injected beam is 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 ~ 25μm. The third beam, being accelerated by two accelerator sections to an energy of 40 ~ 50 Mev., produces Mid-IR radiation of 2.5 ~8μm. It is believed that these wavelength range will cover the applications of FEL in life science, material science, and bio-medical science that are the major intended fields of applications of SFEL. The use of rf grid controlled triode electron gun and buncher combinations allow easy control of the micro-pulse peak energy, separation between micro-pulses and width of macro-pulse. These parameters are of concerns to the users in doing experiments.

The above mentioned scheme is the beginning stage of the project. To further extend the wavelength range to near-IR, visible and UV , three more accelerator sections and a storage ring will be added in the future.

The present status of SFEL is that the accelerator sections are already available. RF ns grid controlled triode electron gun, high power, long pulse klystron modulator, high gradient buncher and sub-harmonic buncher are under construction.

(3) L-band High Brightness Injector for a FIR-FEL [7]

At China Institute of Atomic Energy, a L-band high brightness injector has been built and tested.This injector is intended to be used in connection with a 3π/4 mode high gradient accelerating section with 34 coved cavities to accelerate to 20 Mev. for FIR-FEL research.

The injector consists of a 100kv, 3 ns triode electron gun, one quarter wavelength reentrant coaxial resonater sub-harmonic buncher of 108 Mhz and one TW 3π/4 mode buncher of 1300 Mhz. composed of 7 cavities. 3π/4 mode structure are used for both the buncher and the accelerator section for the purpose of avoiding regenerative BBU associated with the high current operation of the system.

At the present stage of development, the performance of the injector is: electron energy 1.8 Mev.; pulse current, >50 A; micropulse width, ~40 ps; normalized emittance,0.02-0.03 cm-rad.

Summary

Three rf linac based FEL facilities are described above. In fact, there are other activities related to rf linac based FEL being carried out in China. There is a theoretical group at Institute of Applied Physics and Computational Mathematics working on FEL theories. A group of China Academy of Engineering Physics in cooperation with Beijing University are working on the cathode material study for the photo-cathode rf gun. Beijing Universty also had started the super-conducting cavity research with the purpose of building high duty factor FEL in the future. At Qinghua University, an emittance measurement device is being developed to give more precise value of emittance measurements which is of interest to FEL research. Undulators of various types, hybrid, circular polarized and optical klystron, are also being developed at various Institutes.

References

[1] J.L. Xie, J. J. Zhuang et al, Nucl. Instr. & Meth. A272 (1988) 40;A296 (1990) 244;A331 (1993) 204; A341 (1994) 34
[2] C.G. Yao, IEEE NS-32 (1985) 2968
[3] V. Kushnir and Gang Wang, private communication
[4] R.S. Zhang et al. Nucl. Instr. & Meth.,A324 (1993) 421
[5] C. X. Tang, private communication
[6] X. F. Zhao, Private communication
[7] W.Z. Zhou, T. L. Yang et al., Nucl. Instr. & Meth., A341 (1994) ABS 37.