The Shanghai FEL User Facility*

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Abstract The Shanghai FEL User Facility (SFEL) for interdisciplinary studies is based on a rf linear accelerator. The prime goal of SFEL is to provide a broadly tunable laser beam from near-IR to far-IR with tens of MW at peak power. A linear accelerator will operate in three modes: ~ 3 MeV mode, 20 ~ 30 MeV mode and 40 ~ 50 MeV mode. In 20 ~ 30 MeV mode, the accelerator consists of a ns grid gun driven at 476 MHz, a 476 MHz subharmonic buncher, a 2856 MHz T-W type of buncher with high field gradients, and a SLAC type linac.

Keywords Free electron laser, Linear accelerator, Far infrared radiation, Near infrared radiation

1 Introduction

Free electron laser (FEL) has come to be known as an exciting new type of coherent radiation source with the merits of high peak and average power, broad tunability and a flexible temporal pulse structure. FEL user facilities have been increasingly applied to biological, medical and material studies in recent years. Up to now FEL covering the spectral range from visible to near-UV have been generated by rf linac.[1] The microsecond electron pulses (macropulses) produced by a rf linac consist of a large number of short micropulse from a few ps to ten ps. This temporal format of electron pulses are especially desirable for biomedical and material researches.

The Shanghai Free Electron Laser User Facility (SFEL) at SINR is based on a rf-linac. The prime goal of SFEL is to provide a broadly tunable laser beam and to make interdisciplinary science studies. SFEL will be executed in three stages: start stage, earlier stage and later stage. In the start stage (by the end of 1996) the major goal is the development of a high brightness injector, including a ns-grid gun driven at 476 MHz, a 476 MHz subharmonic buncher (SB) and a 2856 MHz T-W type of buncher with high field gradients, and a high stability modulator with 6μs flat top for a 30 MW klystron. During the earlier stage, the linear accelerator will operate in three mode: the injector mode (~3MeV), the injector+Acc1 mode(20~30MeV), and the injector+Acc1+Acc2 mode (40~50MeV), therefore, IR-FEL will be provided, including near-IR(3~8μm), middle-IR (10~25μm) and far-IR(200~800μm) with peak power of 1~10 MW(micropulse), average power of 1~10kW(macropulse), and spectrum width of $10^{-2} \sim 5 \times 10^{-3}$.

2 Accelerator performances

A s-band rf linac will operate in three modes, in the hope of reaching electron beam energy range of 3~50 MeV, and getting a broadly tunable laser beam, and more flexibility in applications.

2.1 The injector mode (~3 MeV mode)

In this operation mode, the injector consists of a thermionic triode gun driven by a grid voltage pulse at 476 MHz, a 476 MHz SB and a 2856 MHz T-W type buncher with high field gradients. Electron beam leaving the injector is bended into the wiggler 1, where far-IR FEL oscillator experiments in 200~800μm wavelength region can be performed.

2.2 The injector + Acc1 mode (20~30 MeV mode)

The Acc1 is a constant gradient travelling-wave accelerating section, i.e. a 3 m long SLAC type linac structure with $2\pi/3$ mode. Electron beam leaving the injector would be sequently injected into the Acc1 and accelerated to 20~30 MeV at the end of the Acc1, then transported

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into wiggler 2, where 10~25μm FEL can be obtained in oscillator operation mode.

2.3 The injector + Acc1 + Acc2 mode (40~50 MeV mode)

The Acc2 is the same as the Acc1. Electron beam leaving the Acc1 would be sequently injected into the Acc2, and accelerated to 40~50 MeV at the end of Acc2, then transported into the wiggler 3, where FEL oscillation in wavelength region of 3~8μm is expected.

The laser beam characteristics, which can be obtained from above three operation modes, and the related accelerator performances are summarized in Table 1. In this way SFEL is able to deliver FEL from hundreds of μm to 3 μm with tens of MW at peak power and to become a powerful tool for the biomedical and material science study.

Table 1 The main parameters of SFEL

Operation mode	FEL1	FEL2	FEL3
Beam energy/MeV	~ 3	20 ~ 30	40 ~ 50
Beam energy spread/%	1 (slit)	1	±0.5
Micropulse peak current/A	20~30	50~100	>50
Micropulse length/ps	~10	~6	~6
Macropulse length/μs	6~8	6~8	6~8
Micropulse repeatation/MHz	476	476	476
Macropulse repeatation/Hz	3.125~12.5	3.125~12.5	3.125~12.5
Beam normalized emittance		50~100πmm·mrad	
Laser wavelength/μm	200~800	10~25	3~8
Laser band spread/%	1~5	1~0.5	1~0.5
Micropulse peak power/MW	1~4	10~50	~10
Macropulse peak power/kW	1~4	10~20	1~10
Micropulse energy/μJ	10~40	100~200	100
Macropulse power/mJ	4~20	~100	~100
Macropulse amplitude stability/%	10	10	10
Spot position stability($\sigma_{x,y}$)	0.1	0.1	0.1

3 Main components of the accelerator

The performance of FEL system depends critically on the beam quality in terms of the high peak current of micropulse, the low emittance, the small energy spread, and the timing jitter of the micropulse. And one has to care about all these from the very beginning.

3.1 The ns grid gun with 476 MHz

In order to produce a high peak current of micropulse and hence a high FEL gain, and allow the accelerator to work at low average current (down to tens of milliampere during the macropulse), a ns classical Pierce gridded gun with a thermoelectronic dispenser cathode is used as electron source of Acc1 injector. The gun cathode, manufactured by EIMAC Co.(Y646B model), has a 8mm diameter. The grid-cathode spacing is 0.15mm with a screening fraction of about 15%~20%. The grid cut-off voltage is only ~30V (drive voltage of 100~150V), and allows a very short pulse of cathode emission with a high repeatation. By the subharmonic bunching process the gun must produce only 1.5 A, 1ns pulse with 476 MHz repeatation during the 8 μs macropulse in synchronism with the original 476MHz of subharmonic cavity.

Keeping the filament voltage and current at the nominal values of 6.3 V and 1.4A respectively, the peak current emitted by the cathode can reach up to 2.5 A for a gridcathode net drive of 70V. This cathode is sufficient because we need only ~1.5A.

The gun electrodes are shaped to provide the best qualities of beam at the gun exit for a given current of 1.5 A. In order to get the smallest emittance for 100keV and 1.5A, the electrode geometry was modelled using the "ETP Code" of SLAC.[2] The code predicts that distance between the cathode and the anode is ~24mm, the anode hole diameter is 8mm. The beam diameter is ~5 mm at the exit of the anode hole with a normalized emittance of 10~ 15πmm ·mrad in the range of 1.5~2.0 A at 100 kV.

While the gun is running the pressure is 1.33μPa in the cathode-anode space for a dispenser cathode. Inside the gun the axial magnetic field increases from zero at the cathode with a gradient of 0.1T/m. The stability of 1×10^{-2} for anode and grid voltage is requirted to provide the phase variation of lower than $\pm3°$ between the gun micropulse and the original 476 MHz from the subharmonic cavity.

The gun current pulse measured by a ns-BCT and an oscilloscope of 1 GHz is in agreement with the result of the code prediction.

3.2 The subharmonic buncher

The SB is a stainless steel re-entrant cavity operating at 476 MHz, the 1/6 of the main accelerating structure frequency. It is chosen so that the 1ns beam pulse from the gun extends roughly within a $\pm90°$ phase spread in the SB. The SB is made of stainless steel instead of copper in order to rechieve a relatively low Q (around 3000), which reduces the influence of beam induced fields, and equipped with a plunger compensating for detuning due to the beamloading. The detuning depends on the frequency and current of the micropulses. The dynamics calculations show that the optimum operating peak voltage over the SB gap is ~30 kV while the drift distance from the midplanes of the SB to the first cell of the fundamental buncher is ~70 cm. The transit time factor for 100 keV electron traversing a gap of 20mm is ~0.9.

An obvious disadvantage of using stainless steel is that the amount of rf power required is larger than those for a copper cavity. The SB is fed by a 25kW transmitter. By adjusting the amplitude and phase of the gap voltage in association with tuning the plunger position, one can match the SB with any beam loading.

3.3 The fundamental buncher

The fundamental buncher (FB) is a tapered phase velocity traveling wave structure buncher with 12 cells in the $2\pi/3$ mode at 2856MHz. The phase velocity and peak electric field of every cell are listed in Table 2 for an input power of 20MW. The FB is designed to compress the bunch length from 60ps to 6ps while accelerating the electrons to 3.5 MeV. A further reduction of the bunch length to 4ps is expected to take place in the Acc1. We have adopted the beam to this relativistic energy and small phase spread in as short a distance as possible, in order to minimize the influence of space charge and rf radial electric field on the emittance growth.

Table 2 The parameters of FB

Cell No.	β_w	β_g	E_z/MV·m^{-1}	α/m^{-1}	R_s/MΩ
1	0.77	0.03241	9.62	0.07881	29.36
2	0.81	0.02775	11.19	0.08847	35.50
3	0.83	0.02489	12.22	0.09685	38.91
4	0.86	0.02306	13.10	0.10180	42.81
5	0.88	0.02214	13.59	0.10421	45.22
6~12	1.0	0.02234	14.33	0.09401	56.14

The FB will use the full output of a 20MW klystron to get a relatively high field gradients needed. The residual power of 18MW at the exit of FB will be fed to the Acc1 and Acc2 via a variable power divider. This is ensured by the special buncher design which reduces the phase spread smoothly, i.e., particle phase trajectories do not intersect for a wide range of input phase. The output, therefore, has the unambiguous phase -energy relationship needed to give further phase compression in the Acc1.

3.4 The solenoids

The radial growth of the beam due to space charge and rf radial electric field in the SB, the FB and Acc1 are constrained by a set of solenoids from the exit of gun to the end of the Acc1. The PARMELA code simulation was done from the gun to the end of Acc1 in order to predict the optimized axial magnetic field profile.[3] The typical beam quality, average beam energy is 33.3 MeV and peak current is ~50A at the exit of Acc1. The code was run on with ~1000 simulated particles and 5 degrees of 2856 MHz time steps.

3.5 The others

A homemade HK-1 type klystron with peak power of 30 MW is chosen as the rf power sources while a new modulator was designed to power the klystrons with a macropulse length of 6~8μs. The unflatness of the top of the output voltage pulse for the modulator affects seriously the energy spread of electron beam. A high stability modulator with ±0.5% pulse top ripple has been developed to meet the requirement of SFEL.

The output current of the ns grid gun is measured by a ns-beam current transformer (BCT) and a wall current monitor. The BCTs wth μs response diagnose the current of macropulse along the accelerators. Using the profile monitor (PM) the beam position and profile can be determined. The PM also allows to measure the emittance of the beam at the exit of the FB and Acc1 using a quadrupole and the three-gradients method.

4 Beam transport

The electron beam leaving the injector or Acc1 or Acc2 is guided through a 90° bending section into the wiggler. In order to maintain beam quality the major considerations in designing the bending section are as follows:

a. It is symmetric in arrangement. This makes it doubly achromatic (first and second order) to maintain the constant emittance of beam.

b. In the middle of the bending section, the beam image is widened due to the dispersion, and inserting an analyzing slit for energy spread filtering, if desired.

c. Great care should be taken to minimize aberrations and higher order effects for getting as completely isochronism and achromatism as possible.

d. The beam size and the waist position inside the wiggler is tuned by adjusting the quadrupoles, two of which are in bending section and the other two after the last dipole, i.e., in the optical cavity.

5 The cavity and wiggler

The optical cavity is composed of two spherical mirrors in a quasi -confocal arrangement. The twice cavity length round trip cavity must be a multiple of the electron microbunch-bunch distance, namely $2L = md$, where m is an integral number, d is the distance between the micropulses of electron beam. Both the mirrors of the cavity are made of gold-plated copper with the same radius of curvature. The output coupler is a rotating ZnSe plate at near Brewster's angle. The beam waist occurs at center of wiggler. The mirrors will be tilted and moved in automatic control along the optical axis for resonator tuning. The wiggler consists of a pair of linear arrays of $SmCo_5$ permanent magnets or hybrid construction with Nd-Fe-B blocks with variable gap. The design of the wiggler and the cavity are under way.

6 The status and schedule

The installation of the high brightness injector and the waveguide system were started in April 1995. Whole components were installed until the end of 1995. Tests of electron gun, the control system and microwave power system were started in January 1996. The commissioning of the injector was started in December 1996. The expertise on the electron gun and SB was made out on the end of 1996. The Acc1 and Acc2 are available. The injector mode and the injection + Acc1 mode would operate by the end of 1998.

In the meanwhile the following systems were completed.

(1) The accelerator column and microwave power system for 45 MeV linac. The rf frequence stability of 10^{-7}/day has been reached.

(2) The cooling water and constant temperature water system. The constant temperature for the accelerator column and subharmonic cavity was held in 45±0.1°C.

(3) The control system for linac and beam diagnosis system. The control system consists of the synchronous trigger, the interlock and the equipments monitoring-controlling, the beam diagnosis system including beam current transformer (ns and μs), wall current monitor (sub-ns), profile with fluorescent screen and emittance and energy-spread diagnosis.

(4) The FEL experiment region of 1000 m^2: accelerator hall, four FEL-laboratories and five accelerator-technic laboratories.

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