CONCEPTUAL DESIGN FOR THE SECOND PHASE PROJECT OF THE JAERI FEL FACILITY

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Abstract

Free electron laser (FEL) facility in far infrared region (phase I) is now under construction at JAERI. As a second phase of the FEL project it is planed to lase at wave length range from near infrared to ultraviolet. The accelerator consists of the superconducting injection and main linacs. In order to achieve lasing at ultraviolet region, it is intended to recirculate the electron beam three times to increase the energy. The preliminary design of the FEL project is presented.

INTRODUCTION

The free electron laser facility, which is presently under construction at our institute comprises a conventional electron gun, a bunching section, and superconducting pre and main accelerators. For the moment there are existing the electron gun and the bunching section. The superconducting accelerators will be completed in the coming year and then the lasing experiment at far infrared region (wave length $\lambda \sim 40\ \mu$m) will be performed. In the second phase of the FEL project, whose construction will start in 1994, we envisage to shorten the wave length to near infrared region ($\lambda \sim 2\ \mu$m) by means of adding to the main accelerating cavities. In order to reach ultraviolet ($\lambda \sim 0.3\ \mu$m) lasing, the recirculation of the electron beam is contemplated. It is desirable for various applications to increase the output power of the FEL, so that the constant wave operation of the facility is intended. The superconducting cavity is suitable for this purpose on account of the low energy dissipation in the cavity.

Since the excellent beam quality is demanded of a driver for FEL experiments, the possibility of upgrading the present design of the facility is investigated. In this paper we report on the outline of the FEL project, especially on the study about the layout of the beam transport.

ELECTRON BEAM REQUIREMENTS

The radiated light wave from the electron traversing the undulator magnet contains not only a single mode but also higher harmonics due to the *figure eight motion* in the undulator. The small-signal gain corresponding to h-th harmonic wave is given by[1]

$$G_h = -16\sqrt{2}\pi^2\lambda_h^{3/2}\lambda_w^{1/2}\frac{K_w^2}{(1+K_w^2)^{3/2}}\frac{I_p}{I_A\Sigma}N_w^3 f(\nu_h) \times h^{5/2}\left[J_{\frac{h-1}{2}}(h\xi) - J_{\frac{h+1}{2}}(h\xi)\right]^2 , \quad (1)$$

where λ_h is the wave length of h-th harmonics, λ_w the undulator period, K_w the averaged undulator parameter, I_p the electron peak current, I_A the Alfvén current, Σ the cross sectional area between the electron and the light beams, N_w the number of the period of the undulator, and

$$\xi = \frac{K_w^2}{2(1+K_w^2)} ,$$
$$\nu_h = 4\pi h N_w \frac{\gamma-\gamma_h}{\gamma_h} ,$$
$$f(x) = \frac{d}{dx}\left(\frac{\sin(x/2)}{x/2}\right)^2$$

Here γ_h is the electron energy corresponding to the h-th harmonic resonance of the FEL oscillation. The wave length λ_h is related to the energy λ_h by the formula

$$\lambda_h = \frac{\lambda_w}{2h\gamma_h}(1+K_w^2) . \quad (2)$$

In general the fundamental harmonic wave ($h = 1$) is utilized for FEL since the mode gives the largest gain among the harmonics. The gain function $f(x)$ oscillates and attains a maximum at $\nu \approx 2.6$. To obtain sufficient gain, the width of the energy spread $\Delta\gamma/\gamma$ should be less than $1/(2hN_w)$. Therefore we can not make N_w so large.

In the case $K_w \geq 2$, the small signal gains of the higher harmonic waves become comparable to the fundamental one. The small signal gain is however at maximum for $K_w \approx 1.1$, so that the energy loss fed to the higher harmonic waves would not become an issue for the wiggler which has the undulator parameter

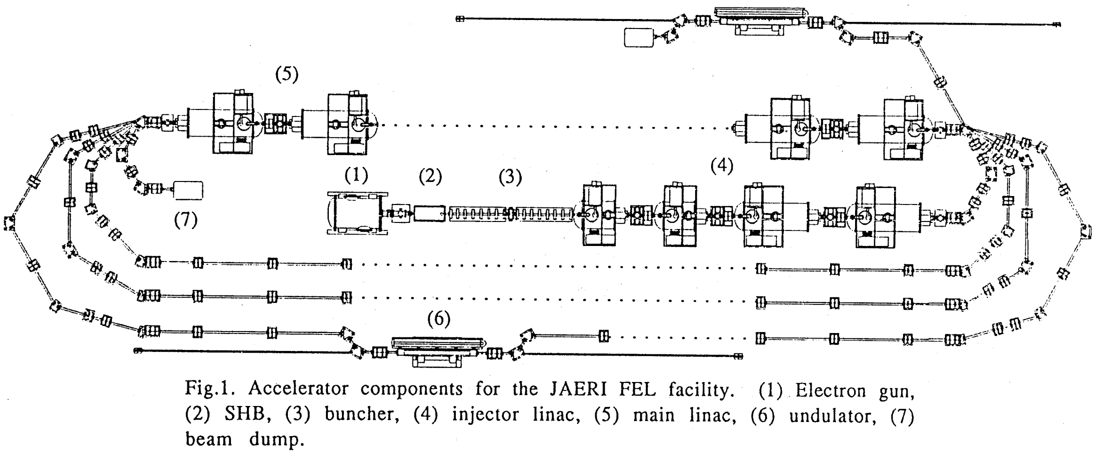


Fig.1. Accelerator components for the JAERI FEL facility. (1) Electron gun, (2) SHB, (3) buncher, (4) injector linac, (5) main linac, (6) undulator, (7) beam dump.

below the value maximizing the gain.

The characteristic parameters of the undulator — the period, the number of the periods and the undulator parameter — are planed to be 3 cm, 100 and 1, respectively.

As seen in Eq.(1), the small signal gain decreases as the wave length becomes shorter. The higher quality of the electron beam is required for the lasing at the shorter wave length. Taking practical restrictions into account, the quality values for an electron beam entering an undulator are chosen to obtain a gain as large as possible. The fundamental parameters of the electron beam for the second phase of the JAERI FEL project are listed in Table 1.

Table 1
Quality values for an electron beam entering an undulator

Recirculation	on	off
Light wave length	0.3 μm	2 μm
Energy	160 MeV	60 MeV
Emittance	10 π mm mrad	
Peak current	10 A	
Energy spread	0.1 %	

DESCRIPTION OF THE ACCELERATOR

The layout of the second phase of the JAERI FEL facility is shown in Fig.1. To save the accelerating structures and the RF power of the facility, the recyclotron design will be adopted. The injection linac is placed in the middle of the recyclotron. The beam passing through the undulator is guided to the main linac for recovering the beam energy. The undulator outside of the recyclotron will be used for lasing by means of the electron beam just coming out the injection linac.

The injector linac has the same compositions as that of the first phase; a Pierce electron gun, a sub-harmonic buncher (SHB), a buncher, two pre-accelerators and two standard accelerating structures. The pre-accelerators are identical with the standard structures except for having only one cell instead of five. In Ref.[2] one can find the present status of the injection system of the JAERI FEL facility.

For the electron beam raising the FEL oscillation the higher current, the smaller emittance and the lower energy spread are desirable. For these requests, the characteristics of the electron gun are fixed as summarized in Table 2. The performance of the electron gun is established in the present injector[2]. While in the first phase of the FEL project the linac is in pulsed operation with a macro pulse of 1 msec wide at intervals of 0.1 sec, the CW operation is expected in the second phase.

Table 2
Characteristics of electron gun

Applied voltage	250 kV
Peak current	100 mA
Pulse length	4 nsec
Repetition rate of pulse	10.4 MHz

As stated in the previous section, the energy dispersion of the electron beam should be less than 0.1 %. If the pulsed beam has a finite length compared with the RF wave, the RF field changes within the bunch. This induces the energy dispersion of the beam. To prevent such an enlargement of the energy spread, the pulsed beam should fit within a few degrees of the RF phase. The velocity bunching is then made by a SHB (83.3 MHz) and a buncher (499.8 MHz). The SHB gives the energy modulation of about 100 kV to the pulsed beam. After a long drift ($\sim 6m$), particle overtaking occurs and the beam is compressed of a factor of 100. This is profitable for obtaining a high peak current.

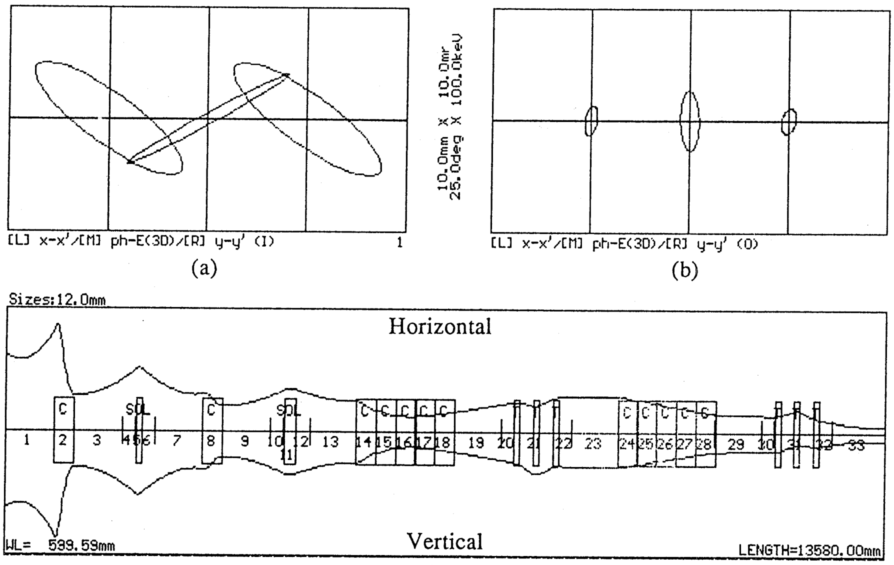
The pre-accelerating cavities play the role of capture section. Just at the injector linac, the energy dispersion of the beam is about 1%. This makes the beam transport in the bending system tractable.

The main linac consists of ten standard accelerating structures. At the design field gradient 4 MV/m, the main linac accelerates the beam with the energy of around 50 MeV per one path. The details of the super conducting cavities are reported in this symposium[3].

BEAM TRANSPORT

Due to the large amount of the charge density, space charge effects would not be negligible in the long drift of the low energy beam. Therefore using the beam dynamics program *TRACE-3D*[4], we investigate the beam transport in the FEL facility of the parameters fixed above.

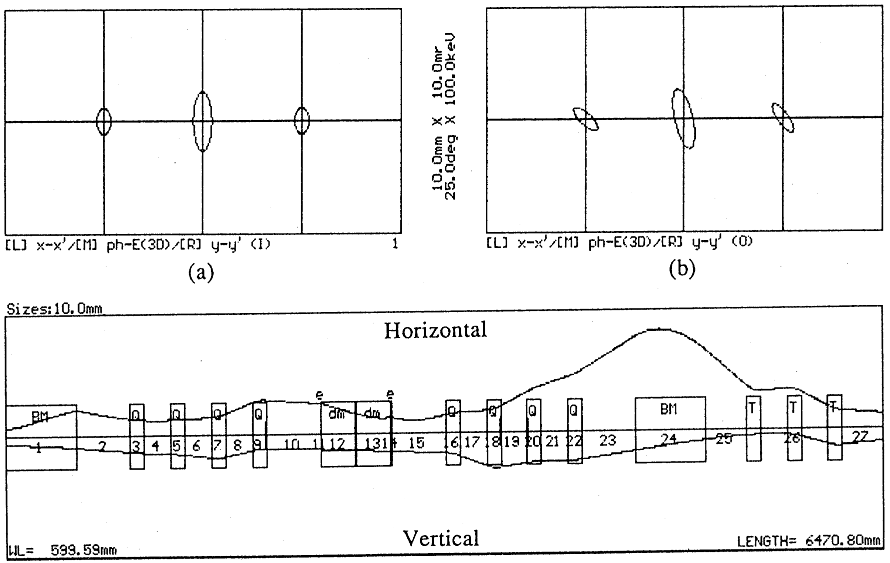
The superconducting cavities need the long field free distance ($\sim$ 750 mm) from the entrance to the accelerating gap,



(a) (b)

(c)

Fig.2. (a) and (b) Beam ellipses at the entrance and the exit of the injector linac respectively. (c) Beam envelopes in the injector linac.



(a) (b)

(c)

Fig.3. (a) and (b) Beam ellipses at the entrance and the exit of the 180° bending system respectively. (c) Beam envelopes in the injector linac.

where the influence of space charge is most violent. Figure 2 shows the variation of the beam envelope in the accelerating structures of the injection system. It implies that if we transport the beam through the injector with loose transverse focusing we can control the beam expansion caused by the space charge.

The 180° bending systems used for the beam recirculation should possess the properties of being both achromatic and isochronous in order to transport the beam without destroying the transverse or longitudinal dimensions of the bunch. Furthermore in order not to disturb the lasing process, it is important that overlapping between the electron and the light beams does not change over time. For this reason the achromaticity and the isochronicity are necessary for the FEL facility at any cost. The achromaticity means that the horizontal motion is independent of the energy of the particle. The isochronous condition is realized if the path length of a particle is proportional to the velocity of the particle.

An achromatic system for the first 180° bending in the circulation is shown in Fig.3. The system comprises three 60° bending magnet, two pairs of doublet quadrupole magnets. The bending system is almost achromatic; the resultant R matrix of the system satisfies

$$R_{16} = 0.0006 \ , \qquad R_{26} = 0.0002 \ .$$

It is found that a pair of doublet q-magnets is suited for making the bending system achromatic without severe restrictions.

The design of the rest of the beam transport line is now under progress.

DISCUSSIONS

In the simulation by means of *TRACE 3-D*, we can not estimate the degradation of the emittance due to the influence of space charge. It is said that space charge induces the emittance growth in a drifting beam of a finite length[5]. If the emittance growth becomes a serious problem for an ultraviolet FEL, we might consider to replace the conventional injector with the one free from a long drift distance, such as photo-electric injector[6].

To obtain a shorter light wave length, it is better to move the two standard cavities of the injector to the main linac. In that case the electron beam should be injected into the main linac in an almost straight line.

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