# **GUIDING OPTICS SYSTEM FOR LEBRA FEL USER FACILITY**

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### Abstract

The FEL guiding optics system for the LEBRA user's experimental facility was completed in 2003. The optical beam extracted from the Infrared FEL resonator has been guided through a long vacuum system to the user's experimental rooms, where a maximum of 17 aluminiumcoated mirrors have been used in the guiding optics. The maximum length of the optical line is approximately 50 m. The divergent FEL beam extracted from the resonator through a coupling hole has been converted into a parallel beam. An approximately identical diffraction pattern of a guide laser was observed at the output ports of the experimental facility. The guiding optics has two FEL monitoring ports, each containing a CaF<sub>2</sub> beam sampler and a total reflection mirror, which has advantages for simultaneous measurement of the power and the spectrum of the FEL during user's experiments. The transport efficiency of the guiding system depends on the FEL wavelength and the radius of the coupling hole in the resonator mirror.

## **INTRODUCTION**

Use of the infrared free-electron laser (FEL) for experiments in medical science and material science was started in 2003 at the Laboratory for Electron Beam Research and Application (LEBRA) of Nihon University. The FEL guiding optics completed prior to the beginning of user's experiments was designed to transport the FEL and its higher harmonic undulator radiations. The lights in the wavelength region of 0.2 to 6  $\mu$ m are extracted from the FEL resonator through a coupling hole in one of the resonator mirrors. After converted to a parallel beam, the lights are transported to user's experimental rooms using aluminium-coated plane mirrors. The top view of the LEBRA accelerator facility and the user's experimental facility is shown in Fig. 1.

This paper reports on the present status of the LEBRA FEL system and the optical guiding system for the FEL user facility.



Fig. 1. Top view of the LEBRA accelerator facility and the user's experimental facility.

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### THE FEL SYSTEM OF LEBRA

Table 1 shows the specifications of the infrared FEL system installed in LEBRA. A schematic layout of the system is shown in Fig. 2. The FEL guiding optics system in the accelerator room is also shown in Fig. 2. The planar FEL undulator consists of Halbach-type NdFeB permanent magnets [1]. The electron beam wiggles in a vertical direction in the undulator so that the focusing field of the undulator binds the electron beam orbit in a horizontal direction.

The highest electron energy is currently restricted to 100 MeV due to the maximum klystron output rf power. The minimum undulator gap width was reduced by 5 mm compared with the earlier design specification by replacing with a thinner undulator vacuum duct, which increased the maximum undulator *K*-value from 1.5 to 2. The wavelength of the FEL is variable in the range from 0.9 to 6.5  $\mu$ m, which is accomplished by adjusting the electron beam energy and the undulator gap width i.e. the undulator *K*-value [2].

The electron beam from the linac has a longitudinal bunch structure with a period of 105 mm corresponding to the accelerating rf of 2856 MHz. The separation D between the two resonator mirrors is 6.718 m, i.e. 64 times the free space wavelength of the microwave. The curvature radius R of the resonator mirrors was decided to be 4.0 m. Then the Rayleigh length  $L_{\rm R}$  of the FEL in the resonator, given by the relation [3]

$$L_{\rm R} = \sqrt{D(2R - D)/2},$$
 (1)

Table 1. Specifications of the LEBRA infrared FEL system.

Maximum electron beam energy	125	MeV
Maximum undulator K-value	2	
Micropulse beam current	> 20	А
Period of undulator field	48	mm
Number of periods	50	
FEL wavelength range	0.6 - 6	μm



Fig. 2. Schematic layout of the LEBRA FEL system and the FEL guiding optics system in the accelerator room.

is 1.47 m, which is slightly longer than the half of the undulator length. For the resonator mirrors, silver-coated copper mirrors with a diameter of 25 mm were manufactured at Rocky Mountain Instrument Co. (RMI). The nominal reflectance of the mirrors is greater than 99.3 % for the wavelength range from 1 to 20  $\mu$ m. The FEL power is extracted from the resonator through a small coupling hole on the center of the upstream mirror.

The radius a of the coupling hole at the mirror in current use is 0.15 mm. Provided that the FEL in the resonator is a Gaussian beam, the FEL beam radius w on the surface of the resonator mirror is given by

$$w = \sqrt{\frac{\lambda_{\rm L} L_{\rm R}}{\pi} \{1 + (D/2L_{\rm R})^2\}},$$
 (2)

where  $\lambda_L$  is the FEL wavelength. Then the coupling coefficient  $\kappa$  of the hole, defined as a ratio of the optical power contained in the cross section of the hole to the total power incident on the mirror, is given as

$$\kappa = 1 - \exp(-2a^2 / w^2)$$
. (3)

For the FEL wavelength of 0.9  $\mu$ m, obtained with the electron beam of 100 MeV and the *K*-value of 0.93, the coupling coefficient deduced from Eq. (3) is 0.017. Therefore the sum of the mirror loss and the external coupling loss for each round-trip of lights in the resonator is approximately 3.1 % of the total power.

Lasing by this system has been experimentally confirmed over the *K*-value range from 1 to 2, which suggests a broad variability of FEL wavelength at fixed electron energy. Lasing at 0.6  $\mu$ m is feasible with the present system by increasing the electron energy up to 125 MeV, though the estimated total loss in each round-trip increases to about 5 % due to a decrease of the mirror reflectance and an increase of the coupling loss.

#### THE BEAM EXPANDER SYSTEM

The FEL extracted from the resonator through the small coupling hole has a divergence angle due to a diffraction effect referred to as the Fraunhofer diffraction. For the first dark ring or the central core of the diffraction pattern that contains 84 % of the extracted optical power, the divergence angle  $\theta$  of the radius is approximated as [4]

$$\theta = \frac{3.833\lambda_{\rm L}}{2\pi a}.\tag{4}$$

For the 5 µm fundamental FEL, the coupling-hole radius of 0.15 mm causes the divergence of the core radius with  $\theta = 20$  mrad. The maximum distance between the FEL output mirror and the user's port is approximately 50 m. Therefore, a conversion optics system is necessary for efficient guiding of the light beam to user's experimental rooms. In the optical guiding system of LEBRA, the divergent beam has been converted to a parallel beam by means of a beam expander system consisting of an ellipsoidal mirror and a parabolic mirror. The expander mirror system was manufactured and aligned by CANON Inc..



Fig. 3. Geometrical configuration and ray trace of the beam expander system. The rear surface of the upstream mirror lies at the position equivalent to one of the focal points of the ellipsoidal mirror.

The geometrical configuration of the mirrors in the expander system is shown in Fig.3. The basic idea of the optics system is the same as which was installed in FEL-SUT MIR FEL beam line [5]. The FEL extracted through the coupling hole in the upstream mirror is reflected with the primary and the secondary plane mirrors, and then directed toward the ellipsoidal mirror. The optical path length between the coupling hole and the ellipsoidal mirror decided to be approximately 2.5 m so that the rear surface of the upstream mirror or the exit of the coupling hole is placed at the position equivalent to one of the focal points of the ellipsoidal mirror. Therefore the divergent light beam which comes out of the coupling hole is focused at another focal point of the ellipsoid.

As seen in Fig. 3, the ellipsoidal mirror and the parabolic mirror have been aligned to form a confocal configuration so that the light beam, once focused at the common focal point, is converted to a parallel beam by the parabolic mirror, where the focal length is 420 mm for both mirrors. These mirrors have a common central axis parallel to the FEL resonator axis. Then, the collimated beam obtained at the exit of the beam expander has approximately the same profile as that on the surface of the ellipsoidal mirror.

# PARALLEL BEAM TRANSPORT AND FEL MONITOR SYSTEM

As seen in Fig. 2 the output parallel beam from the expander chamber is sent to the next room through a rectangular chicane section. This section was installed to suppress the leakage of gamma rays and neutrons to the

next room through the vacuum duct in the shielding wall. Concrete, lead and plastic blocks surrounding the fourth mirror chamber in the chicane section effectively shield the direct radiations from the electron beam dump.

The parallel beam is guided to nine separate experimental rooms by switching the beam line with retractable plane mirrors. The guiding system in the user's facility was installed in the pit under the floor. Every switching section is equipped with a total reflection mirror (aluminium coated) and a partial reflection mirror ( $CaF_2$  plate), which allows for parallel experiments in the different rooms.

For the purpose of monitoring and control of the FEL lasing during user's experiments, two monitor chambers have been inserted in the midstream of the guiding system. Each chamber contains a  $CaF_2$  beam sampler and a total reflection mirror for alternate monitoring of high intensity fundamental FEL and higher harmonics during user's experiments, or low intensity spontaneous emission during electron beam adjustments.

The FEL monitor chambers and associated optics placed in the large experimental hall are shown in Fig. 4. The output from the upstream side chamber has been used for the measurement of the FEL macropulse waveform by means of an InSb detector. The output from another chamber has been used for the measurement of the FEL macropulse energy and the spectra of higher harmonics. Use of separate beams in simultaneous measurement of different FEL properties requires no wide-band half mirror. Also, it allows easy alignment of the devices on the optical base.

The wavelength of the fundamental FEL has not been measured directly in the wavelength range longer than 1.6  $\mu$ m due to the restricted range of the array detector and the spectrometer in LEBRA. Instead, the spectra of the higher harmonics in the visible region have been used to extrapolate the wavelength of the fundamental FEL.



Fig. 4. The picture of the FEL monitor chambers and associated optics on the optical base. Each chamber contains a  $CaF_2$  beam sampler and a total reflection mirror for an alternative use.

# CONSIDERATIONS ON THE POWER LOSS IN THE GUIDING SYSTEM

The radius of the plane mirrors used in the guiding system downstream from the beam expander is 50 mm, which results in an effective radius of 35 mm due to the reflection angle set at 45 °. The minimum inner radius of the vacuum duct is about 25 mm. Therefore, the aperture of the vacuum duct is the main restriction for the transport efficiency of the FEL power except for the mirror reflectance.

The profile of the parallel light beam transported to the user's facility is primarily determined by the wavelength of the light, the radius of the coupling hole in the upstream mirror, and the distance between the coupling hole and the ellipsoidal mirror. From Eq. (4) the core radius  $a_A$  of the diffraction pattern at the ellipsoidal mirror is given by

$$a_{\rm A} = \frac{3.833\lambda_{\rm L}d}{2\pi a},\tag{5}$$

where d (= 2.5 m) is the distance between the coupling hole and the ellipsoidal mirror. The radius is assumed to be conserved in the travel to the experimental rooms.

The guiding system was originally designed to use a resonator mirror with a coupling hole of 0.5 mm radius for the lasing in the wavelength range of 5  $\mu$ m or longer, where the core radius is greater than 15 mm but still less than the inner radius of the vacuum duct. On the other hand, the mirror with the coupling hole of 0.15 mm radius in current use was intended for use in lasing at the wavelengths shorter than 2  $\mu$ m by taking into account the coupling coefficient. For this mirror, the core radii of the FELs with the wavelength of 2, 3, 4 and 5  $\mu$ m are approximately 20, 30, 40 and 50 mm, respectively.

Thus, the use of the current mirror for lasing in the wavelength range longer than 3  $\mu$ m results in a large

power loss due to the eclipse caused by the aperture of the vacuum duct.

The current FEL system takes at least 1 day to replace the mirror. However, a more efficient optical beam transport and a relatively high coupling coefficient by an optimised mirror will allow for the use of considerably higher FEL power at the user's experimental rooms for longer wavelength FELs.

### **SUMMARY**

The FEL in the wavelength range from 0.9 to  $6.5 \,\mu m$  has been lased with the LEBRA infrared FEL system. The divergent beam extracted through a small coupling hole in the FEL resonator mirror has been converted into a parallel beam with the beam expander system consisting of an ellipsoidal mirror and a parabolic mirror. The transport efficiency for long-wavelength FELs is low due to the large radius of the parallel beam. However, the efficiency in the long wavelength region can be improved by replacing the current mirror with a resonator mirror which has a larger coupling hole.

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