MISALINGMENT TOLERANCE OF A HOLE-COUPLING OPTICAL RESONATOR FOR JAERI ERL-FEL

R. Nagai, R. Hajima, N. Kikuzawa, E. Minehara, N. Nishimori, M. Sawamura,
JAERI, Tokai, Ibaraki, Japan

Abstract

The misalignment tolerance of a hole-coupling optical resonator for the JAERI ERL-FEL is estimated with a wavelength of 22 μm by a Fox-Li procedure simulation code. To ensure the high-power and stable FEL operation, the misalignment tolerance has to be clear, because the FEL power depends on the misalignment of the optical resonator. It is found that the misalignment tolerance of the hole-coupling mirror is less than the non-coupling mirror and the offset effect of the non-coupling mirror is compensable the mirror tilting. The misalignment tolerance is sufficiently large for the FEL power fluctuation of 1%.

INTRODUCTION

An R&D program aimed at a 10-kW class free-electron laser based on a superconducting energy recovery linac (ERL-FEL) is in progress at the Japan Atomic Energy Research Institute (JAERI) [1]. To use the FEL light for various applications, the FEL power should be stable. The FEL power stability is depends on the electron beam stability and the misalignment tolerance of the optical resonator. To be stabilized the electron beam, the RF system and electron gun of the JAERI ERL was improved [2, 3]. In this paper, the misalignment tolerance of the optical resonator of the JAERI ERL-FEL is presented.

The optical resonator of the JAERI ERL-FEL consists of gold-coated end mirrors and a center-hole output coupler [4]. This allows wide broadband operation [5] and ultrashort optical pulse generation [6]. To ensure high-power and stable FEL operation, the misalignment tolerance should be larger than the setting error of the optical resonator and the vibration of the floor. The misalignment tolerance with a wavelength of 22 μm is estimated using a Fox-Li procedure simulation code [4].

MISALIGNEMT TOLERANCE

The FEL extraction efficiency is inversely proportional to the square root of round-trip loss and the square root of interaction mode volume of the optical resonator [7]. The output efficiency of the optical resonator is defined as $\eta_{out}=\alpha_{out}/\alpha_{loss}$, where α_{out} is the output ratio, α_{loss} is the round-trip loss. The FEL power is then represented by the following equation:

$$P_{fel} \propto \frac{\alpha_{out}}{\alpha_{loss}{}^{3/2} \cdot V^{1/2}}, \tag{1}$$

where V is the interaction mode volume. The round-trip loss includes the output ratio, the reflective loss at the end mirrors, and the additional diffractive loss. Because the misalignment of the optical resonator introduces additional diffractive loss and expansion of the interaction mode volume, the FEL power is fluctuated by the misalignment. The FEL power is calculated by the Fox-Li simulation code. The FEL power is normalized by the FEL power of perfect aligned optical resonator. The misalignment tolerance for the FEL power fluctuation of 1% is estimated by calculation the normalized FEL power of the misaligned optical resonator.

Model of the Optical Resonator

The estimation model of the optical resonator consists of two end mirrors, four apertures, and a center-hole output coupler as shown in Fig. 1. The end mirror reflectivity is 99.4 %. The four apertures represent the undulator duct and bending magnet ducts. The optical guide and gain guide effect of the electron beam are not taken into account. The parameters of the estimation model are listed in Table 1.

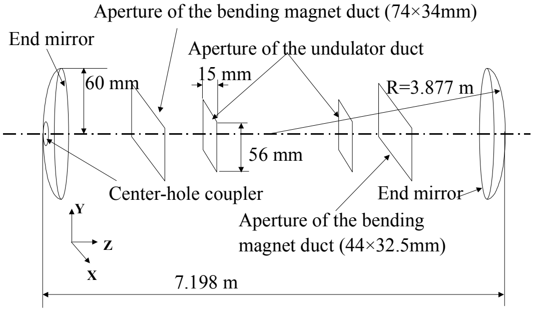

Fig. 1: Model of the optical resonator

Table 1: Parameters of the optical resonator

Length of the resonator	7.198 m
Length of the undulator duct	2 m
Rayleigh range	1 m
Radius of the end mirror	60 mm
Reflectivity of the end mirror	99.4 %
Radius of the center-hole coupler	1 mm

Tilt Tolerance of the Misalignment

To estimate tilt tolerance of the misalignment, the output ratio, the additional diffractive loss, and the interaction mode volume are calculated with the tilt misaligned optical resonator. The additional diffractive loss and the output ratio are shown in Fig. 2. The tilting directions are in yz and zx plane (see Fig. 1). M1 and M2 represent the hole-coupling mirror and the non-coupling mirror, respectively. The output ratio decreases with an increase of the tilt misalignment. In the tilt of less than 190 μrad, the additional diffractive loss decreases with an increase in the tilt misalignment due to the decrease of the scattering at the edge of the center-hole coupler. In the tilt of larger than 190 μrad, the additional diffractive loss increases with an increase in the tilt misalignment due to the increase of the scattering at the aperture of the undulator duct. The interaction mode volume is approximately flat in this range of tilt misalignment. The mode degeneracy due to the tilt misalignment is therefore sufficiently small for the FEL interaction.

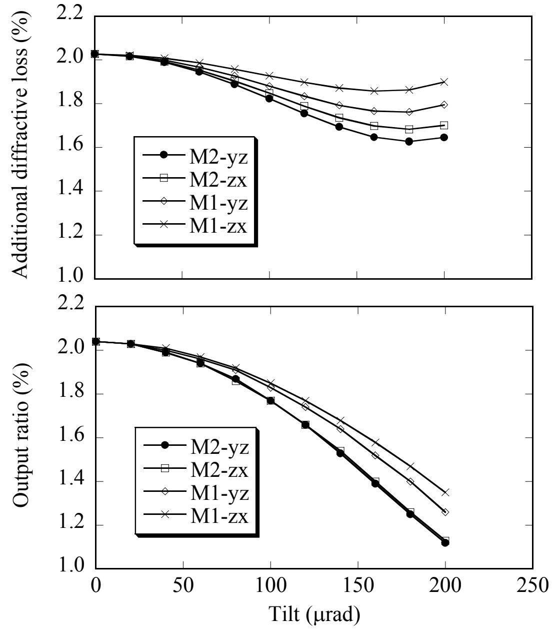

Fig. 2: Additional diffractive loss (upper) and output ratio (lower) for the tilt misaligned optical resonator

The normalized FEL power with the tilt misalignment is shown in Fig. 3. The tilt tolerance for the FEL power fluctuation of 1% is about 100 μrad for both end mirrors.

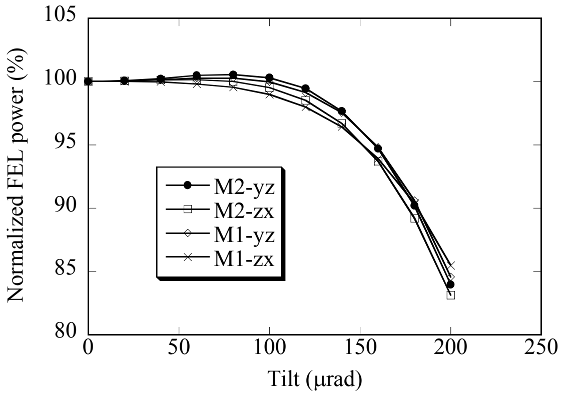

Fig.3: Normalized FEL power for the tilt misaligned optical resonator

The tilt tolerance of a symmetrical optical resonator is given by

$$\Delta\Theta_M << \left(\frac{2\lambda}{\pi d}\right)^{1/2} (1-g)^{1/4} (1+g)^{3/4}, \qquad (2)$$

where λ is the wavelength, d is the optical resonator length, and g=1-d/R (R is the curvature radius of the end mirror) is the stability parameter [8]. For JAERI ERL-FEL, the tilt tolerance is $\Delta\Theta_M$<<378μrad. This value is consistent with the estimation of the tilt tolerance.

Offset Tolerance of the Misalignment

To estimate offset tolerance of the misalignment, the output ratio, the additional diffractive loss, and the interaction mode volume are calculated with the offset misaligned optical resonator. The additional diffractive loss and the output ratio are shown in Fig. 4. The offset directions are in x and y direction (see Fig. 1). The output ratio decreases with an increase of the offset misalignment. In the offset of less than 0.8 mm, the additional diffractive loss decreases with an increase in the tilt misalignment due to the decrease of the scattering at the edge of the center-hole coupler. In the offset of larger than 0.8 mm, the additional diffractive loss increases with an increase in the tilt misalignment due to the increase of the scattering at the aperture of the undulator duct. The interaction mode volume is approximately flat in this range of tilt misalignment. The mode degeneracy due to the tilt misalignment is therefore sufficiently small for the FEL interaction.

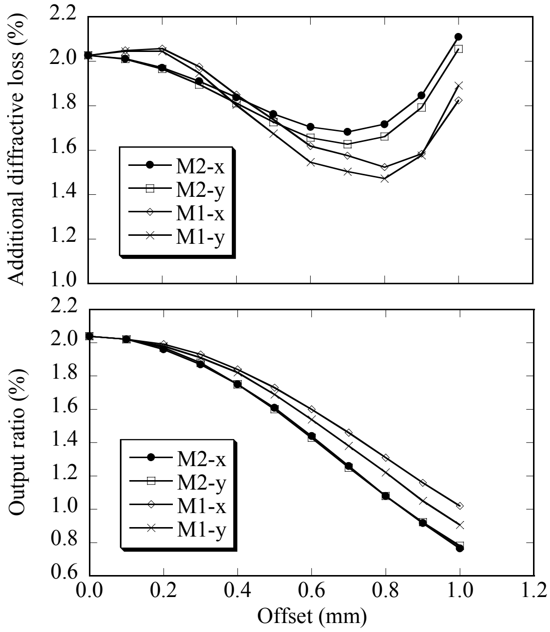

Fig. 4: Additional diffractive loss (upper) and output ratio (lower) for the offset misaligned optical resonator

The normalized FEL power with the offset misalignment is shown in Fig. 5. The offset tolerance for the FEL power fluctuation of 1% is about 0.1 mm and 0.4 mm for M1 and M2, respectively. In the tilt misalignment and the offset misalignment of the M2, the center-hole coupler is aligned with the resonator axis. In the offset misalignment of M1, the center-hole is offset from the resonator axis. M1 is therefore more sensitive than M2 for the offset misalignment.

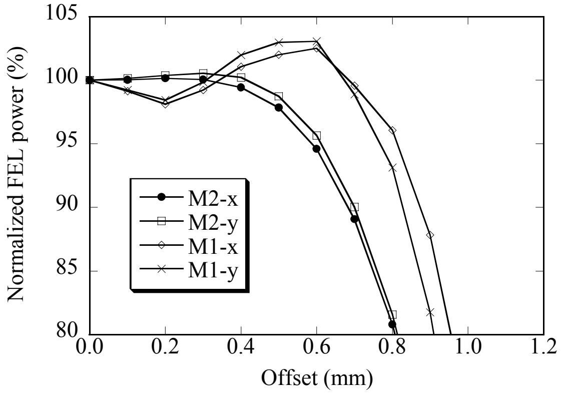

Fig. 5: Normalized FEL power for the offset misaligned optical resonator

Because the optical resonator of the JAERI ERL-FEL is near-concentric configuration, the relationship of the tilt tolerance and the offset tolerance is given by

$$\Delta_M \approx R \cdot \Delta\Theta_M \, . \quad (3)$$

In the case of M2, the offset tolerance of 0.4 mm corresponds to the tilt tolerance of 100 μrad.

Offset Effect Compensation by the Mirror Tilting

As mentioned above, the offset misalignment is similar to the tilt misalignment in the near-concentric optical resonator. Therefore, the offset effect compensation by the mirror tilting is possible. To estimate offset effect compensation of M2, the normalized FEL power is calculated with the offset and tile misaligned optical resonator. As shown in Fig. 6, the offset effect of M2 is compensable tilting the mirror with the offset of up to 1 mm.

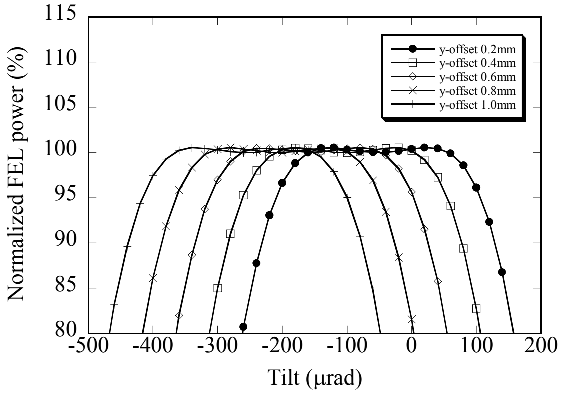

Fig. 6: Offset effect compensation by the mirror tilting for the non-coupling mirror

Because the offset effect of M1 is irregular due to the offset effect of the center-hole as shown in Fig. 5, the offset effect compensation is not expected. To investigate offset and tile misalignment effect of M1, the normalized FEL power is calculated with the offset and tilt misaligned optical resonator. The normalized FEL power is enhanced by the suitable offset and tilt misalignment as shown in Fig. 7. The flat top range of the normalized FEL power decreases with an increase of the offset misalignment. The offset and tile tolerance for the FEL power fluctuation of 1% are 0.1 mm and 40 μrad, respectively.

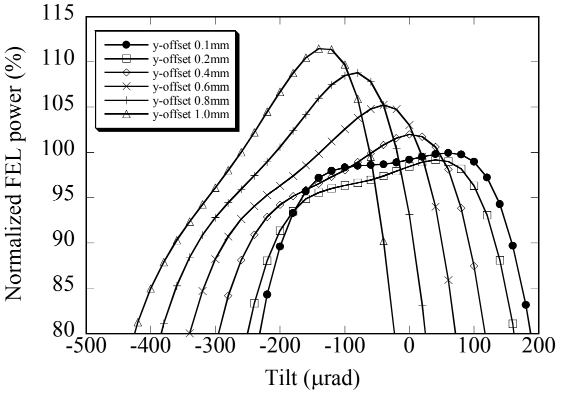

Fig. 7: Offset effect compensation by mirror tilting for the hole-coupling mirror

CONCLUSION

The misalignment tolerance of a hole-coupling optical resonator for the JAERI ERL-FEL is estimated with a wavelength of 22 μm by a Fox-Li procedure simulation code. The offset and tilt tolerance for the FEL power fluctuation of 1% are 0.1 mm and 40 μrad, respectively. The vibration of the floor is less than 1 μm. The accuracy of the He-Ne alignment system of the optical resonator is less than 20 μrad. The offset and tilt tolerance of the optical resonator is therefore sufficiently large for the FEL power fluctuation of less than 1%.

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