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# Optimization of permanent linear wiggler for free electron laser by using the 3-D finite element method

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# OPTIMIZATION OF PERMANENT LINEAR WIGGLER FOR FREE ELECTRON LASER BY USING THE 3-D FINITE ELEMENT METHOD

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## ABSTRACT

The optimal configuration of magnets of a linear wiggler, which produces the flux focussing and wiggling of an electron beam, has been investigated in order to improve the performance of a device for producing free electron lasers.

The effects of the distribution of magnetization, the structure and the magnet height on the flux distribution in the wiggler are examined. The optimal configuration of the wiggler is obtained by numerical analysis.


## 1. INTRODUCTION

Research and development of a high power wiggler which produces a strong free electron laser[1] are now carried out in National Laboratory for High Energy Physics in Japan. The role of the wiggler is to wiggle an electron beam so as to produce the free electron laser. External quadrupole magnets[2] are used in the conventional wiggler in order to focus an electron beam[3]. As pointed out by E.T. Scharleman[4], however, the power efficiency of the laser is seriously reduced by the external quadrupole magnets. If both roles (focussing and wiggling) of the wiggler and the quadrupole magnet are played by the wiggler itself, the power efficiency of the laser will be considerably improved. Moreover, the device for producing the free electron laser becomes compact and can be produced economically. However, such a wiggler which focusses and wiggles the electron beam has not been designed until now. On the other hand, recently the technique for analyzing 3-D magnetic fields has progressed rapidly. Hence, the optimal configulation of magnets of the wiggler is investigated using the numerical method.

In this paper, the magnetic field in the wiggler is analyzed using the 3-D finite element method. The effects of the distribution of magnetization, the structure and the magnet height on the flux distribution are investigated to approach the optimal flux distribution.

## 2. FLUX DISTRIBUTION IN THE CONVENTIONAL WIGGLER

Figure 1 shows a conventional wiggler[5]. The gap length is normalized to unity. Figure 2 shows the sectional view in the x-y plane.

In order to focus the beam in both x- and y-directions, the y-component By of the flux density along the x- and y-axes should satisfy the following equation[4,8]:

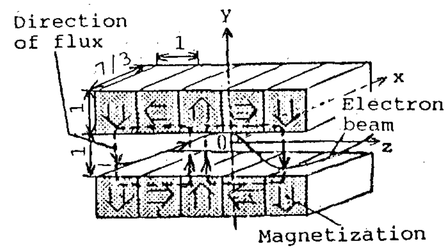
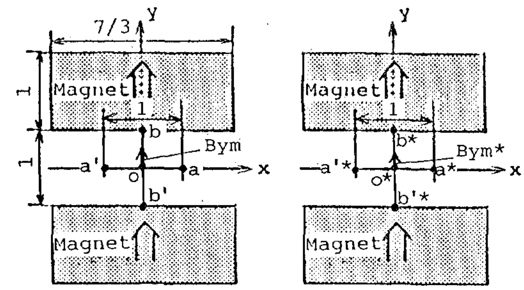



Fig.1. Wiggler.




(a) z=0 (b) z=0.5

Fig.2. Cross section.

$$By=Bym\left(1+\frac{k^2}{2}x^2\right)\left(1+\frac{k^2}{2}y^2\right)\cos\sqrt{2}kz \qquad (1)$$

where, k is a wave number[3], and is equal to 1.11. Bym is the amplitude of By at the origin. When the configuration of magnets is changed, Bym varies as denoted in Section 3. In order to strongly wiggle the beam, Bym should be as large as possible.

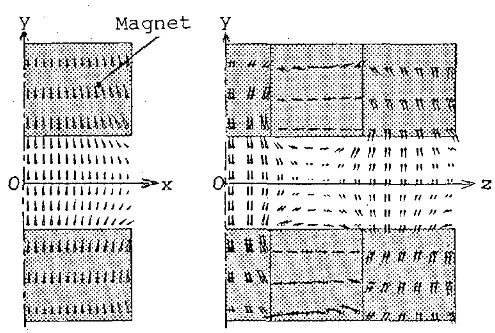
The magnetic field in the wiggler shown in Fig.1 is calculated using the 3-D finite element method. The magnetic scalar potential is chosen as the unknown variable[7]. As the magnets are made of samarium cobalt or NdFeB[6], the magnetizing curve of the magnet can be assumed to be linear. Then, the magnetization can be normalized to unity.

Figure 3 shows the distributions of the flux density vector. The electron beam is wiggled in the x-z plane by the y-component of the flux. The distributions of By on the lines o-a and o-b at z=0 shown in Fig.2(a), and those on the lines o*-a* and o*-b* at z=0.5 shown in Fig.2(b) are denoted by the solid and broken lines in Fig.4. By in Fig.4(a) is normalized by Bym, and that in Fig.4(b) is normalized by Bym*. Where, Bym* is the amplitude of By at x=y=0 and z=0.5. The ideal distributions of By given by Eq.(1) are denoted by (Δ). The ideal distribution on the line o-a (o*-a*) is equal to that on the line o-b (o*-b*) as denoted in Eq.(1). Figure 4 shows that the distributions of By in the conventional wiggler are very much different from those of the ideal distributions. That is, By at the points (a and a*) in Fig.2 are too small compared with the ideal ones.

## 3. OPTIMIZATION OF FLUX DISTRIBUTION

### 3.1 Adjustment of magnetization[9]

If the magnetization of the magnets near the




(a) x-y plane (b) z-y plane

Fig.3. Distributions of flux density vector.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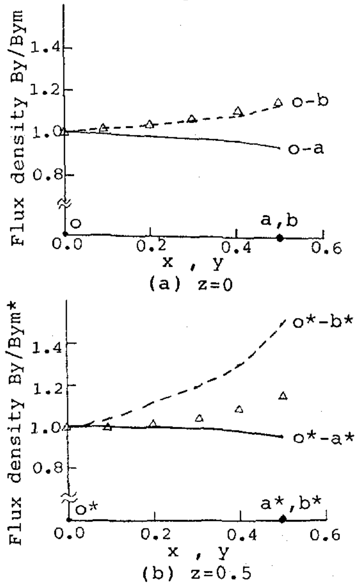
points (a and a*) increases, By at those points may also be increased. Then, each magnet in Fig.1 is divided into three parts with different magnetizations M1 and M2 as shown in Fig.5, and M1 and M2 are chosen so that the flux distribution approaches to the ideal one. The solid and broken lines in Fig.6 show the distributions of By in the case of M1=0.7 and M2=1.0. By on the lines o-a and o*-a* are increased a little by setting M1<M2. However, By on the line o*-b* is increased too much, and Bym and Bym* are decreased compared with those in Fig.4 as shown in Table 1.




Δ:ideal distributions

Fig.4. Distributions of By (coventional wiggler, M=1).

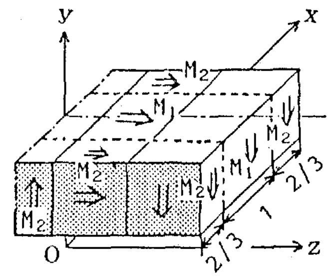



Fig.5. Adjustment of magnetization.

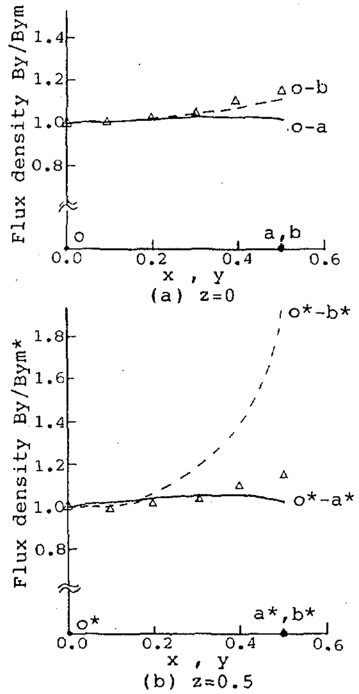



Fig.6. Distributions of By (adjustment of magnetization M1=0.7, M2=1.0).

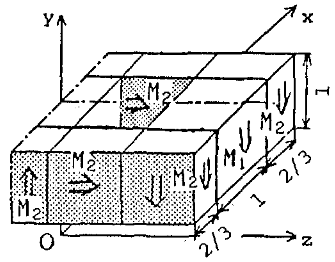



Fig.7. Missing block structure.

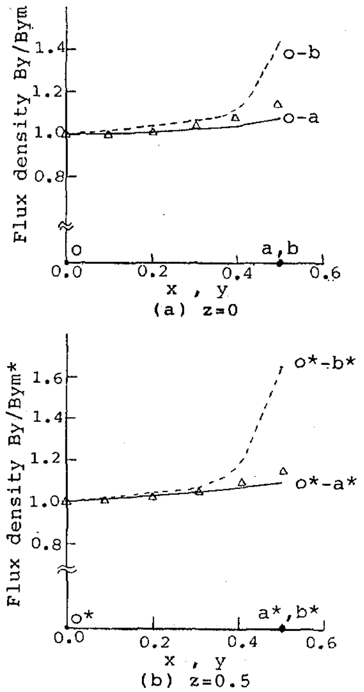



Fig.8. Distributions of By (missing block structure, M1=0.7, M2=1.0).

### 3.2 Missing block structure[9]

In order to decrease By on the line o*-b*, a part of the magnet near the center, of which the direction of magnetization coincides with the z-axis and adjacent to the point (b*), is extracted as shown in Fig.7. Figure 8 shows the distributions of By. By on the lines o-a and o*-a* approach the ideal ones. However, By at the points (b and b*) are larger than those of the ideal ones. Bym and Bym* are decreased due to the extraction of a part of the magnet as shown in Table 1.

### 3.3 Change of magnet height

In order to increase Bym and Bym* more than the case of Fig.7, the height of each magnet block is increased by dh to the inside of the gap as shown in Fig.9. Figures 10 and 11 show the distributions of By in the cases of dh=1/6 and 1/3. Bym and Bym* are increased more than the case of Fig.7 as shown in Table 1. From a viewpoint of the distribution of By, the case of dh=1/6 is optimal.

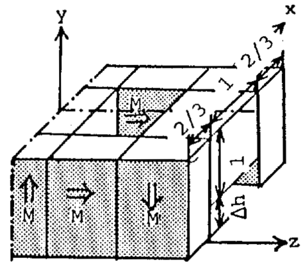



Fig.9. Change of magnet height.

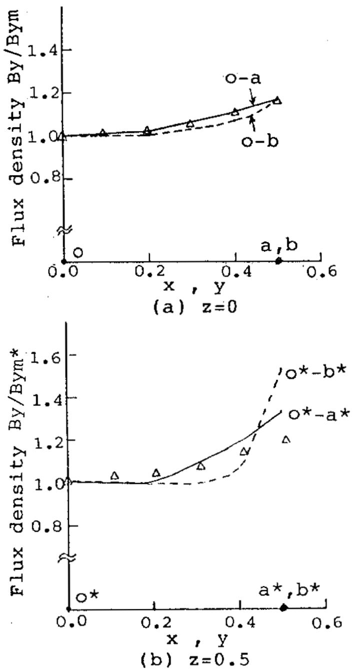



Fig.10. Distributions of By (change of magnet height, M=1, Δh=1/6).

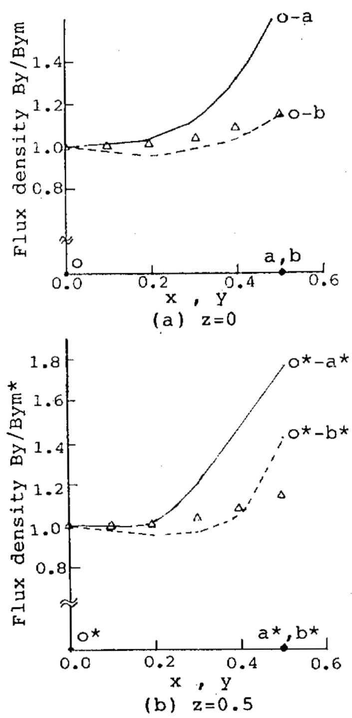



Fig.11. Distributions of By (change of magnet height, M=1, Δh=1/3).

Table 1 Comparison of flux density in each wiggler.

| Types of wiggler | Bym | Bym* |
|---|---|---|
| Conventional wiggler(Fig.1) | 0.62 | 0.47 |
| Adjustment of magnetization (Fig.5) ($M_1$=0.7,$M_2$=1.0) | 0.50 | 0.38 |
| Missing block structure(Fig.7) | 0.36 | 0.24 |
| Change of magnet height (Fig.9) (Δh=1/6) | 0.46 | 0.30 |

## 4. CONCLUSIONS

By numerical simulation, the optimal configuration of magnets of the linear wiggler is obtained by changing the distribution of magnetization, the structure and the magnet height.

The flux distribution may also be controlled by the iron shimming. Using the inverse method[10], the optimal configulation of the wiggler magnets may be directly obtained. The investigation of the optimal iron shimming and the optimal design using the inverse method will be reported in the future.

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