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# Characteristics of a multilayer eddy-current-type ac magnetic coil with a cooling system

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This paper deals with the performance characteristics of a new ac high magnetic field generator based on the effect of eddy currents. We have proposed a new ac high magnetic field generator and have obtained magnetic fields up to 15 T at 60 Hz. The proposed structure consists of layers of exciting coils and conductors built in concentric circles. The eddy currents in the conductor flow close to the hole in the conductor. The magnetic flux induced by the eddy currents is concentrated within the hole, and an ac high magnetic field is produced. A procedure for estimating the optimum shape and number of layers required to increase the concentration effect, together with a design of the cooling system necessary for continuous operation, is presented.

## INTRODUCTION

Generally, there are two types of high magnetic field generators: the dc type with a superconductive coil and the pulse type using the discharge current of a condenser bank. On the other hand, a high ac magnetic field may be obtained in the gap between the ferromagnetic core of electromagnetic by using a commercial power source. However, because of the saturating effect of the core, it is difficult to make a high ac magnetic field. As a matter of fact, an ac magnetic field up to 3 T at a commercial frequency has not been realized.

We have previously presented the results of developing high-speed rotating-disk-type high magnetic field generators and as well as ac high magnetic field generators by using a stationary conducting plate which acts as a magnetic shield. In these devices eddy currents play a key role in the operation. In the former case, the magnetic flux induced by the asymmetrical eddy currents in the high-speed rotating disk plate under the dc magnetic field is concentrated in the slit. In the latter case, the magnetic flux induced by the ac eddy currents in the stationary conducting plate under the ac magnetic field is concentrated in the slit.

The traditional high magnetic field generator is one in which the high magnetic field is directly obtained by the excitation current in the coils, when the voltage is applied to the coils. But for our devices, the high magnetic field is indirectly generated by eddy currents, and it has many special features.

In addition to being efficient, the proposed method offers significantly higher ac high magnetic fields (about 20 T) than traditional methods. It is also possible to change the operating frequencies over a wide range (20–1000 Hz).

In this paper, the principal of a multilayer eddy-current-type ac high magnetic coil which offers excellent performance characteristics is described. The optimum shape is obtained by using numerical techniques discussed in the pa-

per. Characteristics of the device are discussed in detail, and the water-cooling system which is necessary for continuously operation is also described.

## H-SHAPE CYLINDER-TYPE COIL

Figure 1 shows an ac high magnetic field generator. In order to improve further the concentration effect, an H-shape cylinder-type coil for the magnetic shield is proposed. It has a structure which is made of solid copper with a hole located at the center. A slit is cut in the radial direction, and the exciting coil is wound around the shield.

The structure of the shield conductor without the slit is cylindrically symmetric. As the exciting current is applied, it can be assumed that eddy currents are induced cylindrically, as shown in Fig. 2. But it is clear that the eddy currents flow in the radial direction near the slit. In order to apply two-dimensional finite-element method (FEM), the  $r$ - $z$  plane away from the slit is the plane analyzed. On the  $r$ - $z$  plane, both the applied current and the eddy currents have only the  $\theta$ -direction component. For a  $\theta$ -direction current, the magnetic vector potential  $A$  also has only one component. We assume that the material parameters are constant and the

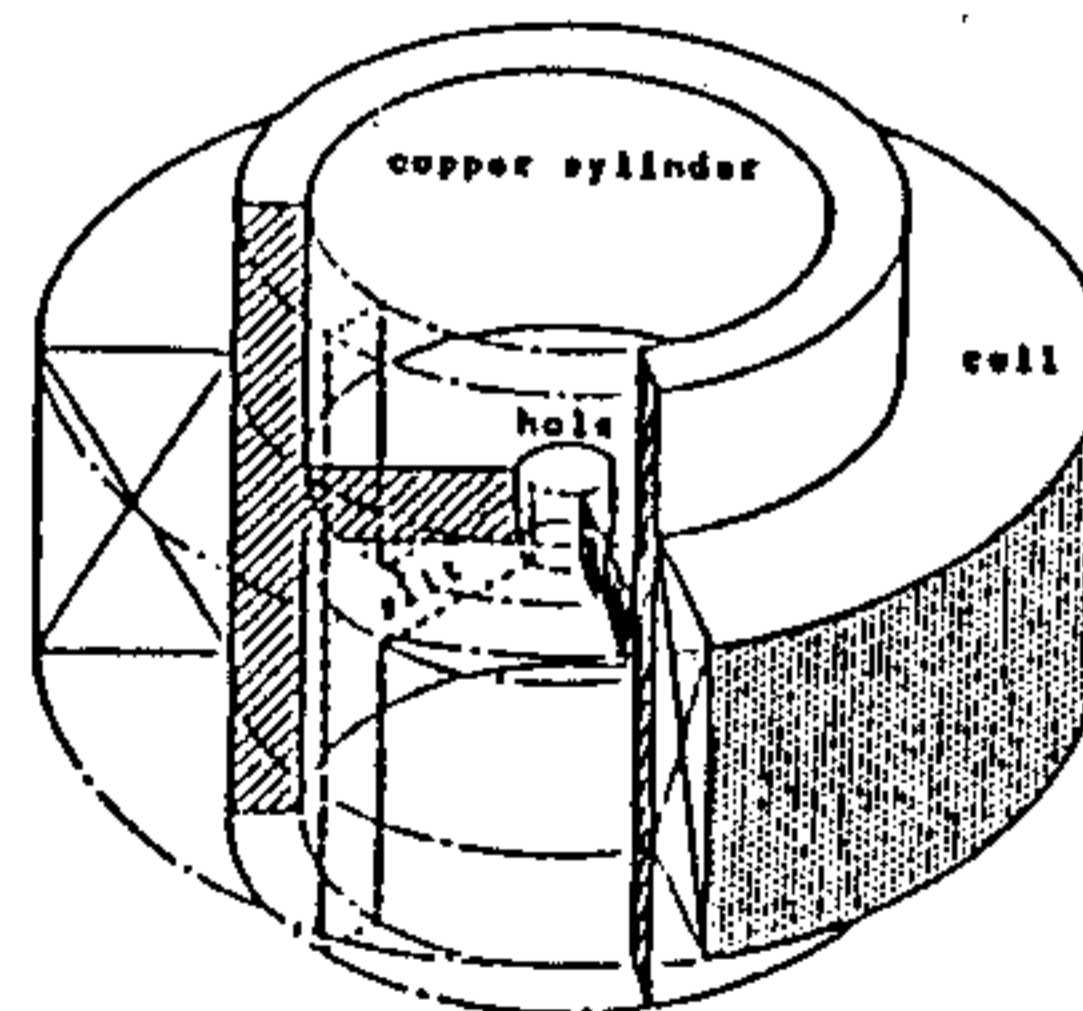


FIG. 1. H-shape cylinder-type coil.

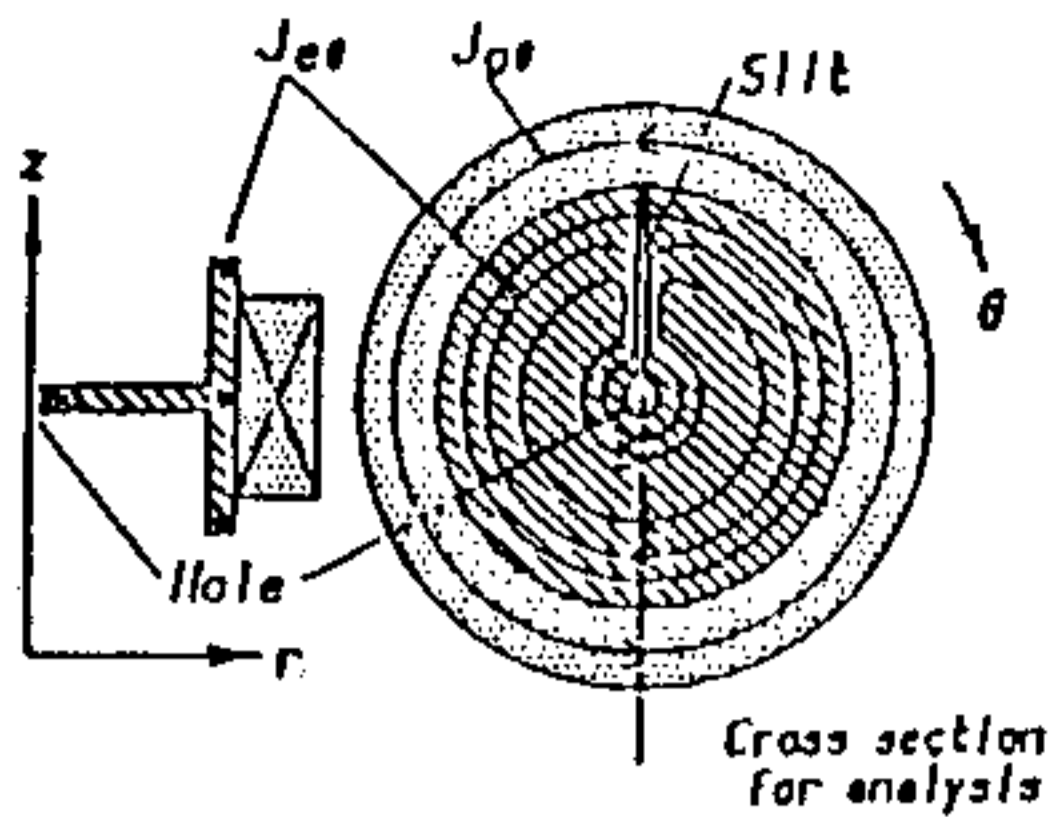


FIG. 2. Cross section for analysis.

variables vary sinusoidally with time. In the two-dimensional region, the  $\theta$ -direction vector potential  $A_\theta$  satisfies the equation

$$\nabla^2 A_\theta = \mu_0 J_{0\theta} - \mu_0 J_{e\theta}, \quad (1)$$

where  $J_{0\theta}$  is the applied current,  $J_{e\theta}$  is the eddy current,  $\omega$  is the angular frequency, and  $\sigma$  is the conductivity.

The eddy currents  $J_{e\theta}$  are expressed as

$$J_{e\theta} = j\omega\sigma A_\theta - \left(\frac{\sigma}{r}\right) \frac{\partial\phi}{\partial\theta}, \quad (2)$$

where  $\phi$  is a scalar potential. The component is constant in the  $r$ - $z$  plane. As the cylindrical shield has a slit isolated electrically, the total value of the  $\theta$ -direction eddy currents on the cross section of copper is equal to zero. Therefore, the eddy currents satisfy

$$\int J_{e\theta} dS = \int \left[ j\omega\sigma A_\theta - \left(\frac{\sigma}{r}\right) \frac{\partial\phi}{\partial\theta} \right] dS = 0, \quad (3)$$

where  $S$  is the  $r$ - $z$  cross section of the shield. Therefore, the value of  $\partial\phi/\partial\theta$  is expressed as

$$C_0 = \sigma \frac{\partial\phi}{\partial\theta} = - \int j\omega\sigma A_\theta dS / \left( \int \frac{1}{r} dS \right). \quad (4)$$

The peak value of an input voltage is given by

$$V = j\omega \int A_\theta dl + RI, \quad (5)$$

where  $R$  is the resistance of the coil. As an input voltage or an input current is applied, Eqs. (1), (3), and (4) are solved by using an iteration method.

In order to improve the magnetic concentration, we examined the shape of the shield conductor. It was found that it is better to set the cylinder height above that of the coil.

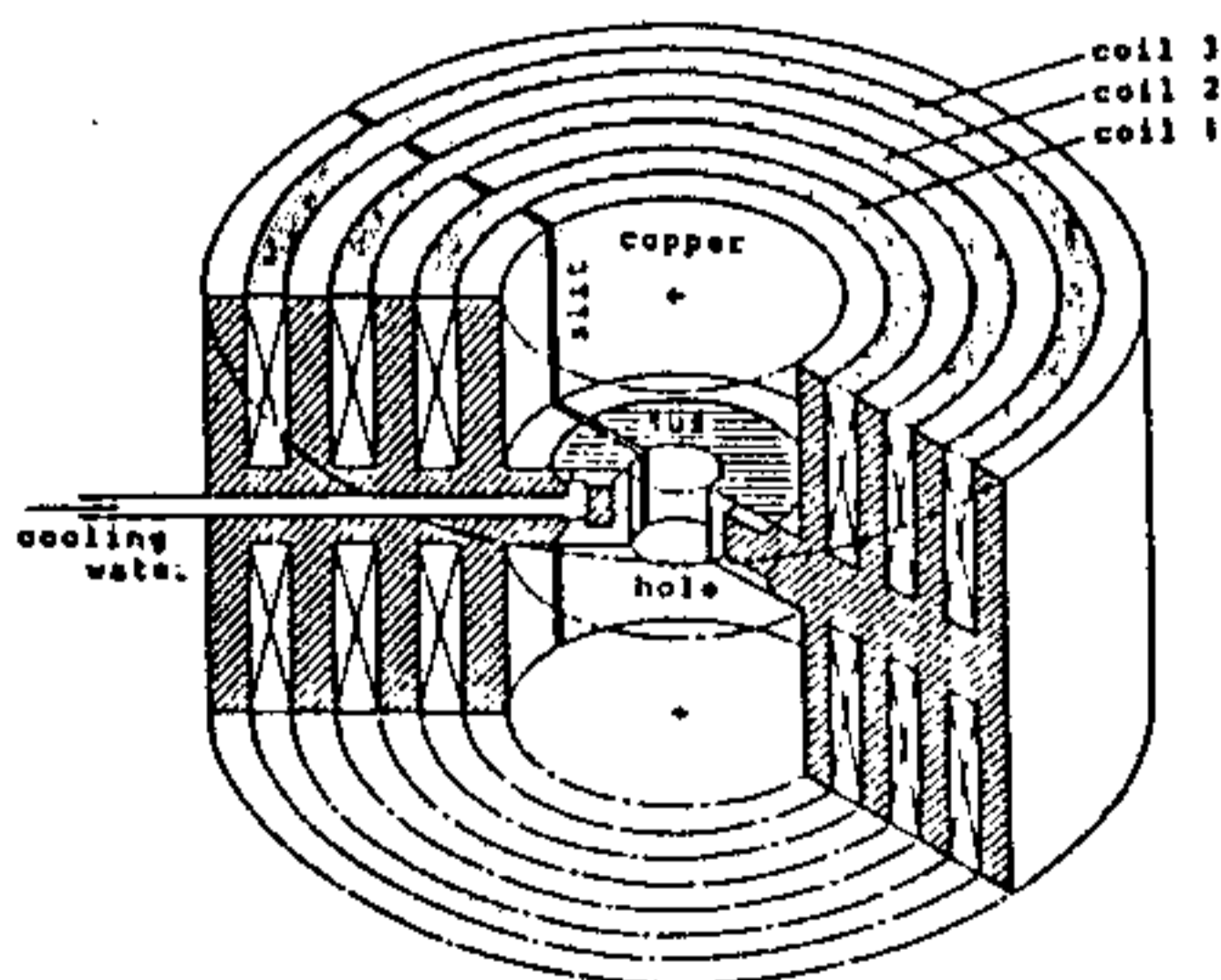


FIG. 3. Multilayer eddy-current-type coil with cooling system.

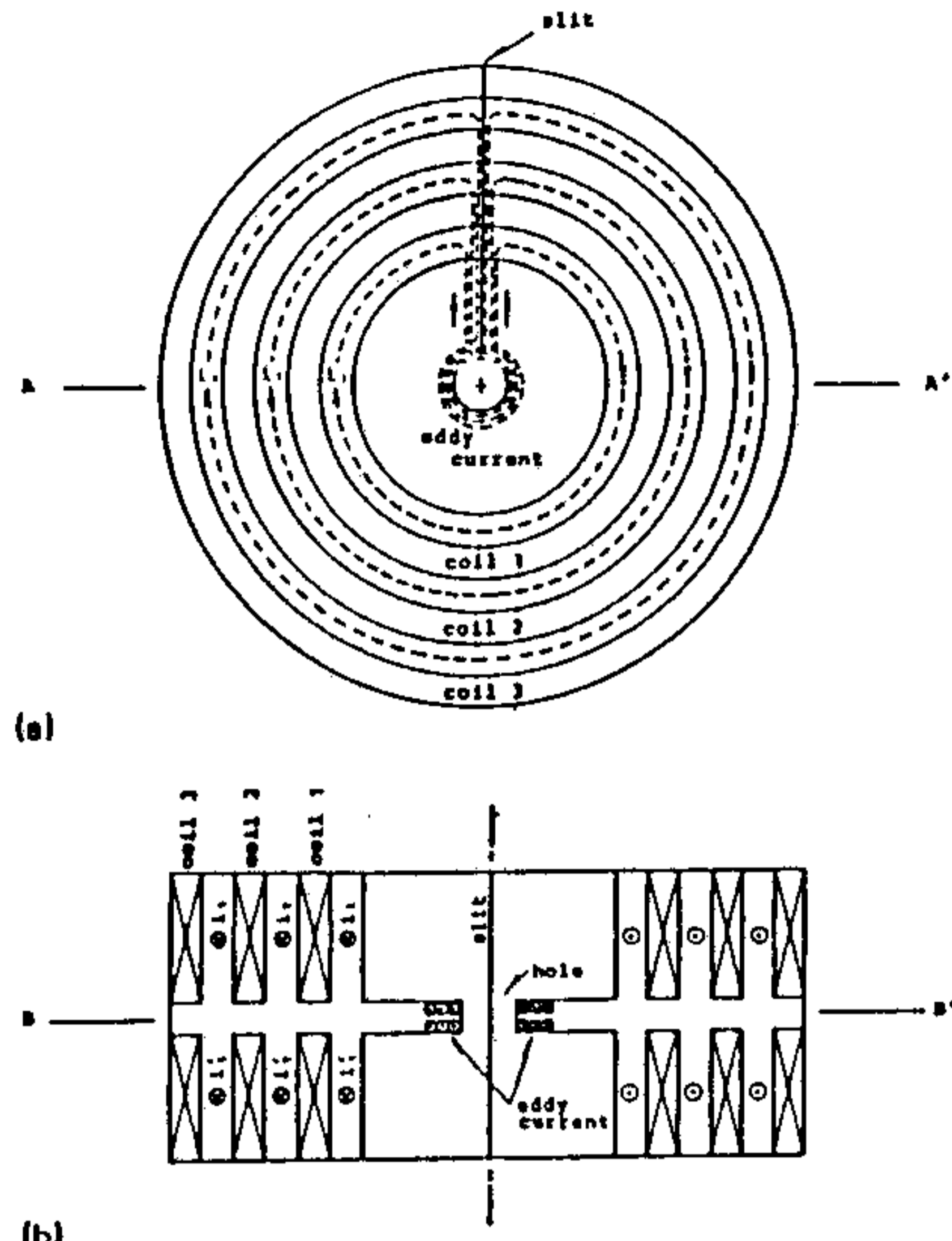


FIG. 4. Distribution of eddy currents of (a) plane and (b) cross section.

The thickness of the cylinder is related to the skin depth of copper. The skin depth is 8.4 mm at 60 Hz.

#### MULTILAYER EDDY-CURRENT-TYPE COIL

Figure 3 shows the multilayer eddy-current-type coil to improve the H-shape cylinder-type coil further. The figure shows the coil with three layers. In the multilayer excitation coil, the eddy currents induced by the leakage flux flow around the hole, thereby increasing the flux density in the hole.

Figure 4 shows the outline of the eddy-current distribution. As an exciting ac voltage is applied to the multilayer coil, the ac flux is induced in the perpendicular direction. The ac flux increases the eddy currents in the multilayer coil and the eddy currents flow around the hole.

The eddy currents at the lower cross section of the conductor also flow around the hole due to the slit. Therefore, the flux induced by the eddy currents is concentrated in the hole, resulting in a high magnetic field.

Figure 5 shows the equipotential distribution on the two-layer structure. The structure improves the concentra-

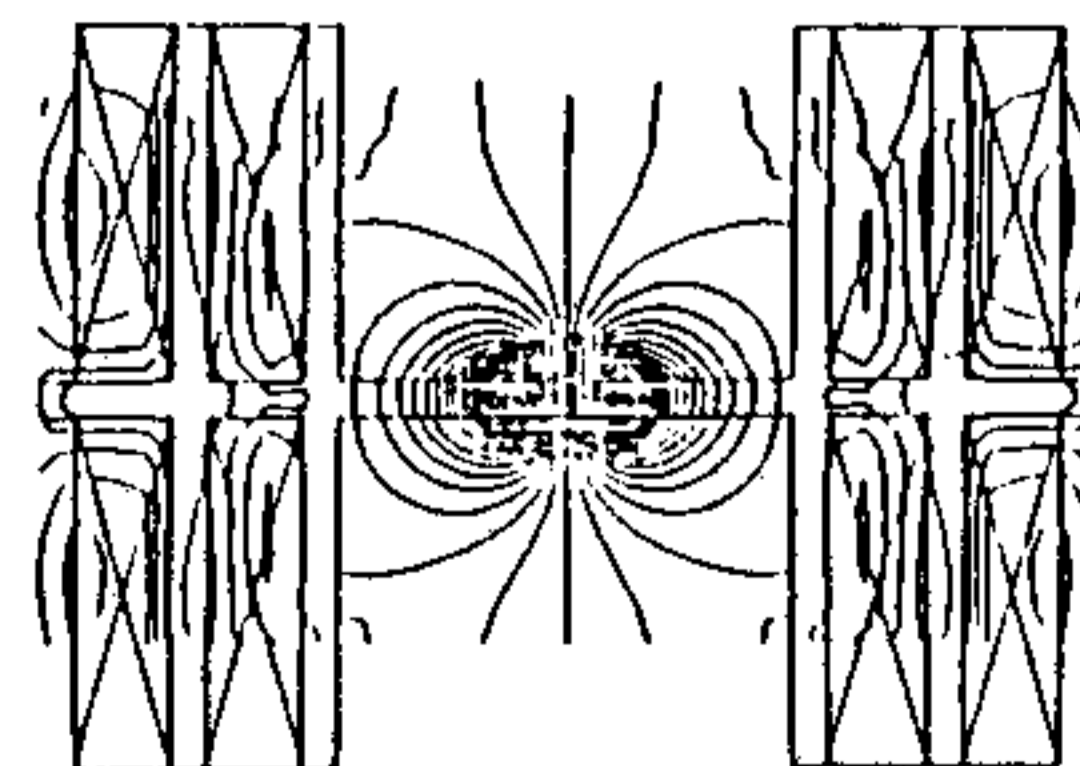


FIG. 5. Equivalent-potential lines.

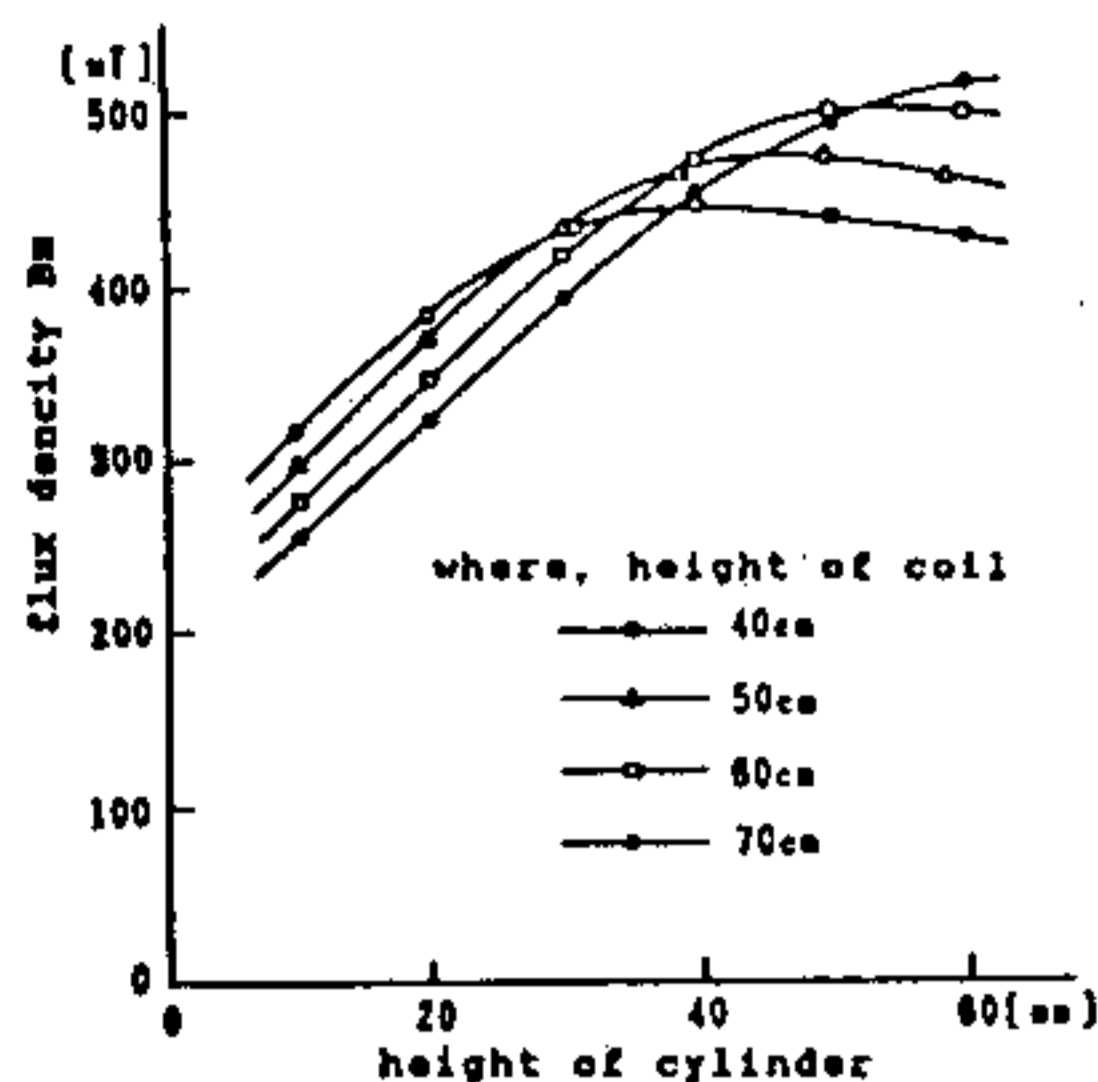


FIG. 6. Relation between the layer height and flux density.

tion effect significantly more than both the previous conductive plate and H-shape cylinder structure. In order to improve the flux concentration effect, we have examined the optimum condition of the multilayer type coil.

According to the numerical solutions, it is clear that three layers are adequate to increase the flux density. This also offers the convenience of being able to use a three-phase power source.

Figure 6 shows the relation between the cylinder height and flux density. It is shown that good results are obtained when the layer height is equal to that of the coil.

Figure 7 shows the experimental values. The solid line indicates the characteristics of the three-layer structure. When an ac input voltage of 1350 V at 60 Hz is applied, an ac flux density of 11.2 T is obtained. The value of the applied electrical power is 111 kW. The dotted line indicates the characteristics on the two conductive plates proposed previously. A flux density of 7.4 T is obtained when an ac voltage of 3400 V at 60 Hz is applied and the input power is 1697 kW.

It is clear that the concentration effect of the multilayer eddy-current-type coil can be improved considerably. To obtain a flux density of 15 T (estimated value), the applied voltage must be raised up to 2000 V. However, the conductor without a cooling system around the hole melted, due to the resulting high temperature, and was damaged by the Maxwell stress force, as shown in Fig. 8.

Therefore, for continuous operation a water-cooled device has been constructed as shown in Fig. 3. The device can

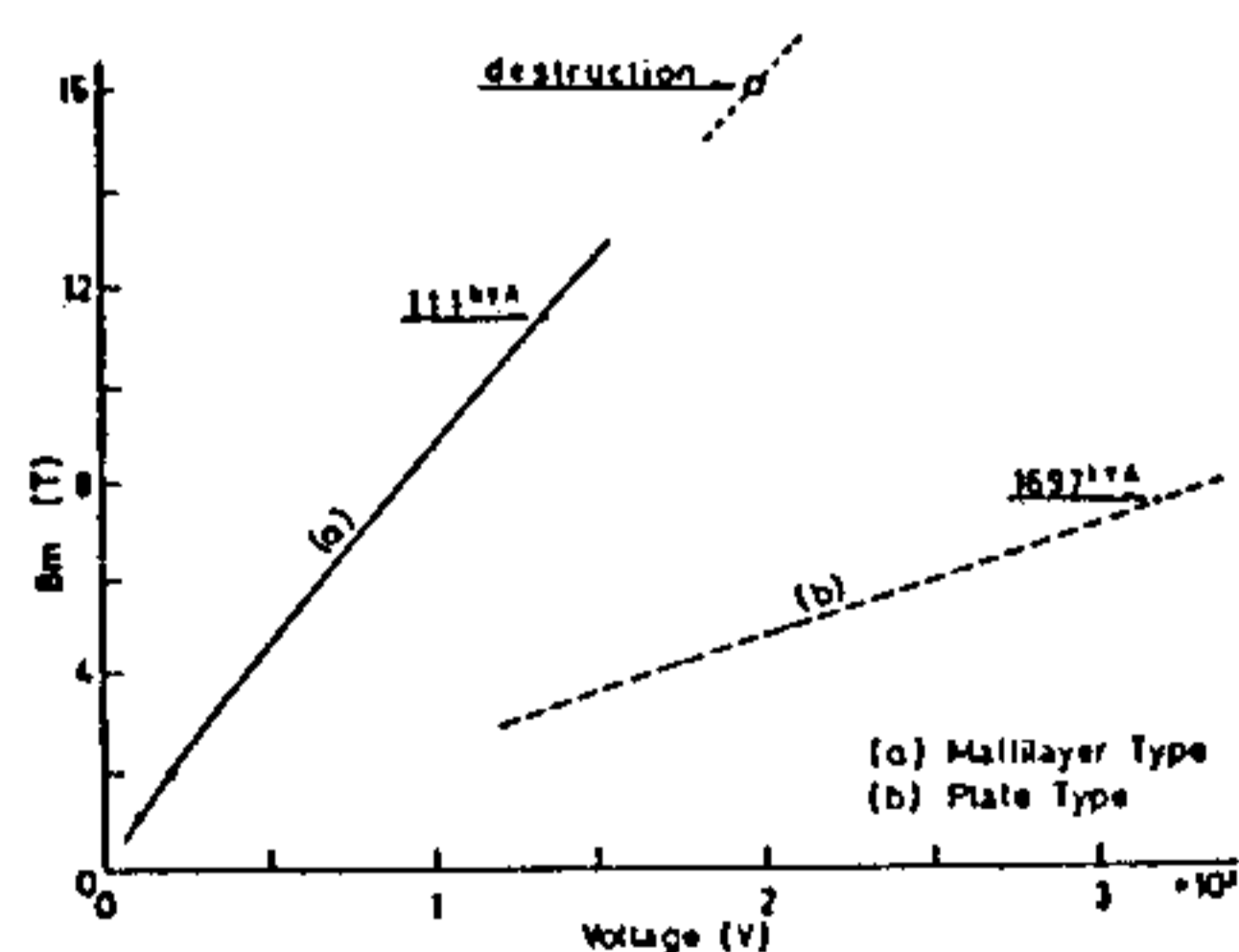


FIG. 7. Relation between the ac voltage and the maximum flux density (experiment).



FIG. 8. Melted and cleaved condition on the hole (2000 V/15 T).

work continuously, even when the applied voltage is raised up to 3000 V, and when an adequate supply of cooling water is provided.

## CONCLUSION

Our results may be summarized: (1) The ac high magnetic field generator incorporating the multilayer eddy-current-type coil has less leakage flux, which is efficient in concentrating the flux, and also offers good frequency characteristics. It can be used for generating high pulsed magnetic fields. (2) If a water cooling system is used, an ac high field of about 20 T can be generated continuously. (3) If a three-layer structure is used, it is convenient to use three-phase power. The result is higher efficiency.

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