MODIFICATION OF LINDA TO TREAT THE GRAIN ORIENTATION EFFECT

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Summary

An approximate method of dealing the grain orientation effect has been investigated. This has been applied to the field computation of the main ring quadrupole magnet of KEK-PS.

Introduction

In the previous paper,[1] we have discussed the merit of using the oriented low carbon steel as the core material of the main ring quadrupole magnet for the KEK-PS. The field computation has been carried out by using the magnetostatic program, but the effect of the grain orientation was dealt only in a tricky manner by considering as if the core is made of the non-oriented steel with the B-μ relation appropriate to the rolling direction (we call this the L-direction) or the direction perpendicular to the rolling (C-direction)[2].

In the present study, we have tried to introduce the grain orientation effect into the field calculation more precisely by taking into account the directional dependence of the B-μ characteristics. For this purpose, we have modified the program LINDA.

In this paper, we will show the approximate method adopted here of treating the orientation effect and discuss the results of the computation.

Method of Computation

The direction of easy magnetization of iron ([100] axis) can be highly oriented to the rolling direction with a small angular spread in the specially processed steel. In the usual grain oriented steel with the Goss texture, the [110] and [111] axes lie in the plane of the lamination and coincide with the transverse and the 55° directions, respectively. If such grain oriented laminations are used for the magnet core, the field quality in the magnet gap should be influenced by the variation in the magnetic susceptibility with the crystallographic direction.

In general, if the anisotropy in the susceptibility is present, the permeability μ must be treated as a tensor quantity. This means that the directions of the magnetic field intensity H and the magnetization I do not coincide. For the oriented low carbon steel which is used as the core material of the main ring quadrupole magnet, there is no measurement on the transverse magnetization (the component of magnetization perpendicular to the direction of the magnetic field intensity), so that we can not treat the permeability in the tensor form.

We have investigated an approximate method of dealing with the orientation effect, instead of the tensor form. Fig. 1 shows the reluctivity as the function of the flux density B and the angle made by the direction of the magnetic flux line and the rolling direction θ, which was obtained by the Epstein test. From these curves, the magnetic flux density B at any angle and field intensity can be expressed by the quantities $B_L(H)$ and $B_C(H)$ in the following form;

$$B = (B_L(H)\cos^2\theta + B_C(H)\sin^2\theta)\, f(\theta, H) \qquad (1)$$

where $B_L(H)$ and $B_C(H)$ mean the B-H relations in the rolling direction and the transverse direction, respectively. f is an analytic function of θ and H, which is determined to reproduce the experimental B-H relations.

B and θ in each mesh rectangle are determined by solving the set of finite difference equations for the magnetic vector potential.[3] The values of B_L, B_C and $f(\theta)$ are stored in the program, as functions of the magnetic field intensity H. Then, the value of the reluctivity for each mesh rectangle is found from Eq.(1) by interpolation. Using new values of the reluctivity, the basic finite difference equations are solved repeatedly.

Results of Quadrupole Magnet

The parameters of the quadrupole magnet are given in Table I and the cross sectional view of the magnet is shown in Fig. 2.

The rolling direction of the grain oriented steel was selected to be perpendicular to the horizontal mid-plane, because the higher saturation is expected in the pole tip on the horizontal axis, say about 19 kG at the maximum excitation. We call the magnet of this type the vertically oriented one.

Table I - Parameters of Quadrupole Magnet

Max. gradient	1.8	kG/cm
Max. current	1.65	kA
Useful aperture		
vertical	56	mm
horizontal	140	mm
Turns/Pole	12	
Radius of inscribed circle	50	mm
Core dimension		
width	490	mm
height	620	mm
length	600	mm

The computed magnetic field gradient along x and y axes is shown in Fig. 3, which also contains that of the horizontally oriented magnet (the rolling direction being parallel to the horizontal mid-plane) and the non-oriented magnet.

In the case of the non-oriented magnet, the magnetic properties of decarbonized steel compiled in the original program were used. As seen from the figure, the improvement in the field gradient on the horizontal axis is remarkable when the rolling direction is perpendicular to that axis, while the field gradient on the vertical axis does not deteriorate in either case. These results are also anticipated from the map of flux lines and equipotential lines, as shown in Fig. 4. The saturation around the minimum gap on the horizontal axis is more serious in the horizontally oriented case than in the vertically oriented case, in spite of almost the same mmf drop. The figures attached to the equipotential lines denote the mmf drop measured in percent from the symmetrical axes of the magnet. The mmf drop at the pole surface gives the increase in ampere turns. The reason why the mmf drop become larger in the grain oriented cases compared to the non-oriented case is that the flux is almost parallel to the direction of the worst magnetic properties at the pole base where the flux density is relatively high. If the rolling direction is arranged to make 45 degrees with the horizontal axis, the mmf drop becomes very small but the deterioration of the field gradient, especially on the horizontal axis, is larger than the horizontally oriented case.

Three quadrupole magnet models, the vertically oriented, the horizontally oriented and non-oriented, were fabricated. Preliminary results of the field measurement show the fairly good agreement with the computations.

Acknowledgement

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References

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2. T. Doke, et al, "Use of Oriented Low Carbon Steel as Core Material of Gradient Magnets for a Strong Focusing Proton Synchrotron", Nucl. Inst. Meth. 83 (1970) 300.

3. J.H. Dorst, "Magnet Design Applications of the Magnetostatic Computer Program called SIBYL" Proc. of 1st Intl. Conf. on Magnet Technology, Stanford, 1965, p. 182.

4. The B-H curves of the grain oriented steel 'OPSM' are provided by Nippon Steel Corporation.

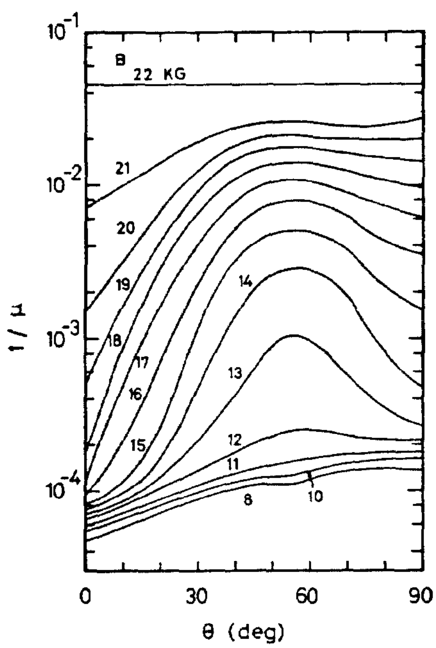

Fig. 1. Reluctivity ($1/\mu$) curves of the oriented decarbonized low silicon steel[4] as a function of θ.

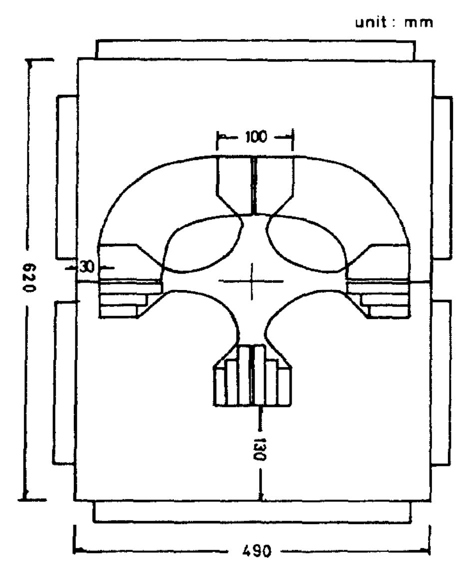

Fig. 2. Cross sectional view of the quadrupole magnet.

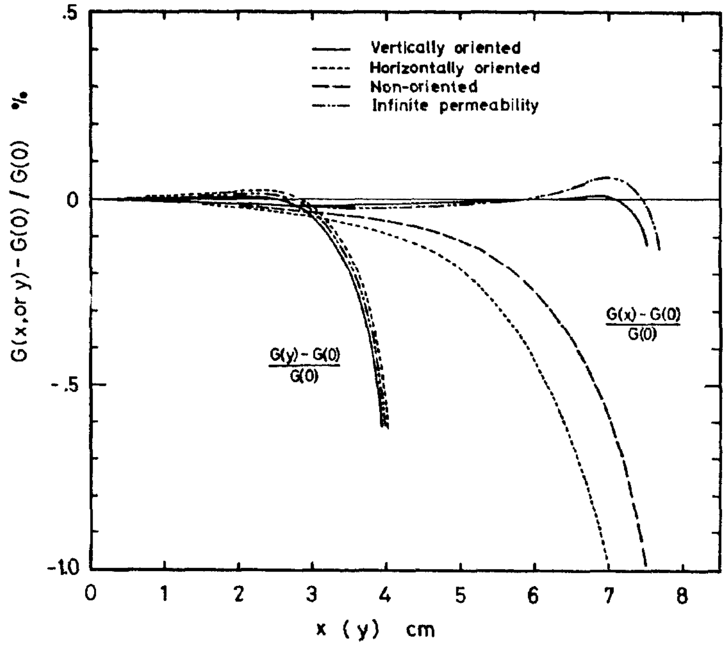

Fig. 3. Computed field gradient distribution on x and y axes as a function of distance from the magnet center, at the maximum excitation. G(x) and G(y) mean the field gradients on the x and y axes. G(o) is the field gradient at the magnet center. Field gradients for infinite permeable iron are also shown.

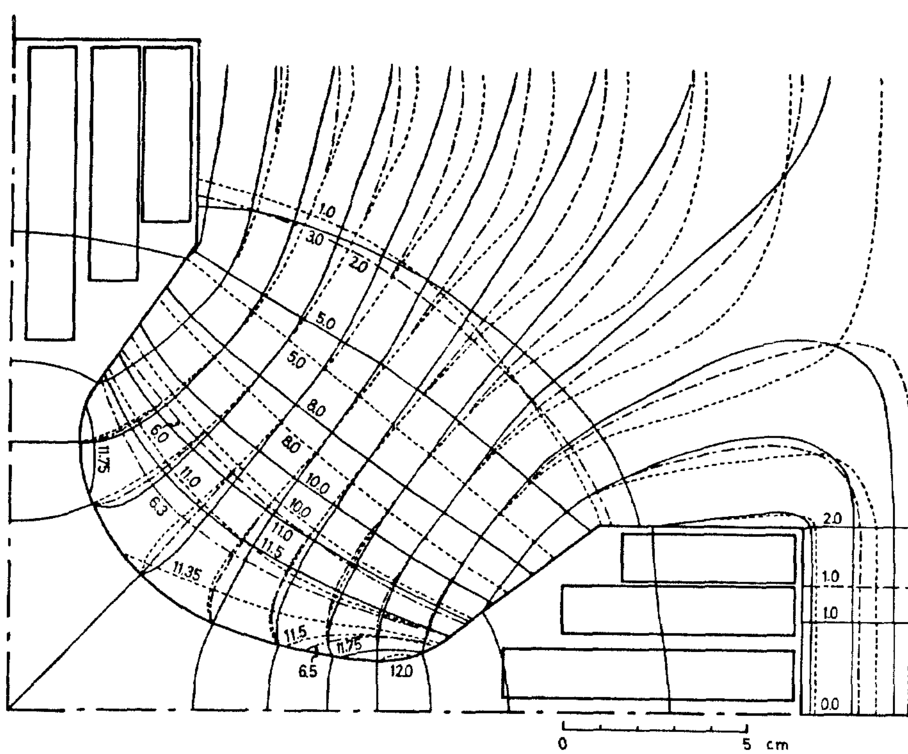

Fig. 4. Flux and equipotential lines inside the pole. Equipotential lines are assigned with percentage drop of mmf. Solid lines: vertically oriented case. Dotted lines: horizontally oriented case. Dash-dotted lines: non-oriented case.