DESIGN OF AN AC MAGNETIC BIASING CIRCUIT FOR THE KAON FACTORY BOOSTER RF CAVITY.

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ABSTRACT
The resonant frequency of an rf cavity to be used in the booster ring of the TRIUMF KAON factory, is determined by the state of magnetization of a set of 6 rings of G810 aluminium doped yttrium-iron garnet ferrite. The design of an ac magnet which performs the required magnetization is presented. The results of the ac magnet code PE2D to predict eddy current induced power losses walls of the rf circuit, support structure and the G810 cooling jacket are presented.

INTRODUCTION
TRIUMF is presently completing the project definition stage of its proposed KAON factory. Acceleration of the beam in the booster ring will be accomplished using perpendicular biased yttrium-aluminum iron garnet type ferrite tuners [1] as opposed to the more conventional parallel biased Ni Zn ferrites [2]. The G810 ferrite is operated in saturation and offers higher magnetic Q's and lower power losses than conventional ferrites.

A dc prototype was constructed at LAMPF and is shown schematically in Fig. 1. A toroidal magnet surrounds six ferrite rings. The axis of the structure is the beam axis. Beryllium oxide (BeO) cooling rings are placed between the ferrite. The BeO rings are in turn cooled at their outer radius by a copper cooling jacket.

An ac prototype based on the LAMPF dc tuner was designed at TRIUMF and is presently being constructed with an expected delivery date of October 1989. This paper describes some of the design considerations concerned with the ac version of the dc prototype.

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FIGURE 1. LAMPF DC Prototype Ferrite Biasing Circuit.

AC BIASING MAGNET
Since the magnet will operate under an alternating current waveform the circular yoke of the dc prototype was replaced by a laminated structure as shown in Fig. 2. The complete circular geometry was replaced with 12 rectangular laminated blocks. The blocks were then tapered by cutting and grinding to form the structure shown in the diagram. Grinding is performed in such a way that adjacent laminations are not shorted together. To save on the cost of dies, each lamination is made from three separate pieces.
This involves only two die types, one having the geometry of the pole and the other a simple rectangular shape which forms the return yoke.

The lamination thickness required to minimize eddy current loss in the yoke is given by evaluating the skin depth $\delta$ given by:

$$
\delta = \sqrt{\frac{2}{\omega \sigma \mu}}
$$

Where:
- $\omega$ = angular frequency
- $\sigma$ = electrical conductivity
- $\mu = \mu_r \mu_0$ = permeability of the material.

The waveform shape which biases the ferrite rings is a dual frequency function with a dc offset and is shown in Fig. 3. The waveform rises at 50Hz in 15ms and resets in 5ms at 100Hz.

The skin depth evaluated for the 100 Hz component, using $\sigma = 1.02 \times 10^7$ (\Omega m)$^{-1}$ and $\mu_r = 1000$ is 0.498mm. The magnet yoke therefore is made using 0.0148 inch (0.37 mm) laminations of M6 steel.

The magnet laminations are glued together in blocks using an epoxy resin. This will provide some resistance to vibrations as well as providing the required inter lamination resistance.

The magnet sectors thus formed will be held together by an aluminium clamping plate and a set of tie rods. The sectored design provides room for the entrance and exit of the stranded cable which requires a large bend radius and further provides easy access for the water jacket cooling lines. Furthermore this design will be useful for prototyping purposes.
which will likely involve dismantling the unit several times and for the installation of thermocouples and other diagnostic equipment.

**Magnet Coil**

The dc prototype used a coil with 140 turns. In order to reduce the inductance to a reasonable level this number had to be reduced substantially. Further in order to reduce eddy current losses, each of the turns of the coil would need to be made from many filaments insulated from each other and powered in parallel.

The ac prototype coil geometry consists of 12 turns of a stranded cable made available to us by LAMPF for evaluation. Shown in Fig. 4., the cable consists of 82 strands of #9 heavy formvar insulated magnet wire surrounding a 0.368 inch (9.35 mm) I.D, 0.499 inch (12.67 mm) O.D copper tube [3]. The cable is wrapped with a 4.0 inch (101.6 mm) wide, 0.005 inch (0.13 mm) thick, fiberglass tape, double lapped.

To prevent the risk of shorts due to the vibration of individual strands, and to provide insulation against the high voltages to ground, it was decided to vacuum impregnate the voids between the individual filaments as well as the coil structure itself.

*FIGURE 4. Cross Section of LAMPF Stranded Conductor.*

**RADIO FREQUENCY CAVITY**

The radio frequency cavity surrounds the ferrite and BeO rings and extends radially inward toward the cone shaped center conductor as shown in Fig. 5. The cavity can be considered as consisting of four parts: the end walls which are two large disks, the outer conductor which is a large cylinder and the center conductor which is a tapered conical shape.

To reduce eddy current losses, the end walls and outer conductor of the cavity were made from 0.020 inch (0.5 mm) stainless steel “membrane”. These walls are then plated with copper to a thickness of 0.0005 inch (0.0127 mm).

The center conductor is a machined stainless steel tube 0.078 inches (2.00 mm) thick and plated with copper on the outside to a thickness again of 0.0005 inches. The center conductor was made of thicker material than the rest of the circuit since it has to withstand vacuum loading.

The ferrite rings are held in place in the rf circuit using a ceramic ring and a support structure consisting of two stainless steel rings connected by an array of spokes as discussed below.

**MINIMIZING EDDY CURRENT LOSSES**

It is desirable in designing the magnetic circuit, radio frequency cavity and cavity support structure to minimize the power losses due to induced eddy currents whenever possible. In the case of the magnetic circuit this involved laminating the yoke and using a stranded cable for the coil.

For the radio frequency circuit some simple analyses help guide the design process. Consider the outer ring of the RF membrane support structure. Let the ring have an inner diameter $r_i$, outer diameter $r_o$ and be of thickness $h$.

Consider the ring as a series of annuli. The emf induced in the ring by the field is given by:

$$ e = -\frac{d\phi}{dt} $$

$$ = \pi r^2 \dot{B} $$

Where $r$ is the radial position of the annulus.

The resistance $dR$ of the strip is given by:

$$ dR = \frac{2\pi}{\sigma h dr} $$

Where $\sigma$ is the conductivity of the strip.

The mean power due to eddy currents is:

$$ \overline{P} = \frac{1}{2} \frac{e^2}{R} $$

It can be shown that:

$$ \dot{B} = \omega B_0 $$

Upon integration:

$$ P = \pi \frac{1}{16} (2\pi f B_0)^2 \sigma [r_o^4 - r_i^4] $$

If the ring is broken at opposite ends of a diameter the large eddy current buildup is avoided. The situation reduces to the eddy current losses in a long conductor of linear length $2\pi r_{mean}$. Consider the case in which a solid linear conductor is divided into elemental strips in the direction $x$, the thickness of the strips is again $h$. 


The emf which drives the eddy currents is given by:

\[ e = -\frac{d\phi}{dt} \]  
\[ = A\dot{B} = 2x\dot{B} \]  

The ratio of power losses with the break to those without is given by:

\[ \frac{P_{\text{break}}}{P_{\text{complete}}} = \frac{2(r_o - r_i)^2}{3(r_o^2 + r_i^2)} \]  

In the case of the membrane outer support ring the breaking of the complete ring results in a reduction of 900 times in eddy current losses. For the inner ring the reduction is a factor of 80 times. Consequently whenever a complete circular geometry can be broken a reduction in the eddy current losses will occur. This concept was extended to the large disc shaped rf membrane at the end of the rf cavity. Since the rf currents flow radially a large number of radial slots can be used to reduce eddy current losses with little disturbance to the rf currents. Consequently 48 radial slots are machined into the rf membrane. The inner and outer rings of the ferrite support structure were connected together via 48 slotted spokes as shown in Fig. 6., as a further extension of the basic methodology for reducing eddy currents.

The water jacket consists of a cylinder of copper...
FIGURE 6 Ferrite Ring and RF circuit Support Structure.

6.25 inch (159 mm) long and 0.629 inch (16 mm) thick. It has a series of water channels machined longitudinally in the walls of the cylinder. The jacket has the potential to generate very large eddy current losses and several insulating breaks are required to minimize this effect.

MODELLING WITH PE2D

The essential elements of the radio frequency cavity were entered into the magnet code PE2D. The geometry is shown in Fig. 7.

The program has the capability to run magnetostatic, steady state (sinusoidal driving current), and transient driving current cases. Also shown in Fig. 7 is a flux plot when the code is run in the magnetostatic mode.

The field results from the magnetostatic case were used in analytical calculations shown above to verify the magnitude of the results from PE2D since it is imperative to include the break in the support structure and rf circuit into the PE2D geometry.

It was not practical using PE2D, to include 0.0005 inches of copper on the 0.5 mm stainless steel radio frequency circuit. If one take the relative thicknesses of the copper and stainless steel into consideration, and the relative magnitude of the conductivities, it is possible to show in an analytical calculation the effect of the two metals together [4]. In the case of that part of radio frequency circuit which has the form of a slotted disk, the result is an increase of eddy current losses of 1.89 times that calculated for the stainless steel alone. For the part of the radio frequency circuit which has the form of a cylinder, there is a negligible addition to the eddy current losses due to copper plating.

The inner conical rf conductor was modelled as a circular cylinder of radius equal to the mean radius of the tube. The code was run in its transient driving waveform mode, using the waveform shown in Fig. 3. The eddy current induced power losses were evaluated at 10 intervals throughout the driving waveform cycle. The average of these losses for each part of the structure is presented in Table 1.

TABLE 1 Eddy current losses for ac geometry

<table>
<thead>
<tr>
<th>Section</th>
<th>Eddy Current losses (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Conductor</td>
<td>40</td>
</tr>
<tr>
<td>Outer Conductor</td>
<td>460</td>
</tr>
<tr>
<td>Disk Membrane</td>
<td>1890</td>
</tr>
<tr>
<td>Inner Support Ring</td>
<td>40</td>
</tr>
<tr>
<td>Outer Support Ring</td>
<td>20</td>
</tr>
<tr>
<td>BeO Cooling Jacket</td>
<td>1100</td>
</tr>
<tr>
<td>Total eddy current losses</td>
<td>3550</td>
</tr>
</tbody>
</table>
SUMMARY

An ac version of a ferrite biased tuner has been designed at TRIUMF Assembly of the complete tuner is scheduled for October 1989. The eddy current losses in the support structure, radio frequency circuit and BeO cooling jacket have been evaluated using PE2D to be 3550 W total.

REFERENCES


2. "Status of RF Development Work on a ferrite tuned amplifier cavity for the TRIUMF to KAON factory" IEEE Particle accelerator Conference Vancouver 1985 p2951
