PROTOTYPE MAGNET DESIGNS AND LOSS MEASUREMENTS FOR THE DUAL FREQUENCY BOOSTER SYNCHROTRON FOR TRIUMF's KAON FACTORY

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Abstract

The prototype design choices and calculations for the Booster synchrotron magnets are presented. The dipoles will be excited with a dual frequency excitation, rising at 33.3 Hz and falling at 100 Hz. The ac component is superimposed onto a dc bias to give a peak field of 1.05 T and a minimum of 0.277 T. The quadrupoles will be excited in a similar manner. The methods of calculating the magnet ac losses are described. The majority of the discussion is for the dipoles because the design of these magnets is further advanced. Some preliminary results of core loss and conductor eddy current measurements are presented.

Introduction

TRIUMF's KAON factory will require some 1250 magnets for beam transfer, three storage rings, two synchrotrons, the beam switchyard and experimental facilities. Approximately 420 of these will be ac magnets. Alternating current magnets have not been required at TRIUMF prior to the KAON era, so we have not built up any reserve of experience for this type of magnet.

In our PDS (Project Definition Study) year we have decided to concentrate our efforts on the Booster ring magnets which are the most challenging in that they are cycled at 50 Hz with a dual frequency excitation. We plan to build a full-size dipole and a quadrupole and make detailed measurements so that we can verify our design criteria and calibrate our calculations. In parallel with the magnet design we are making measurements of steel losses with our biassed dc excitation and conductor eddy current losses at both sinusoidal and dual frequency excitations.

The magnet input specifications are listed in Table I for both dipole and quadrupole magnets and the required excitation curve for the dipoles is shown in Fig. 1.
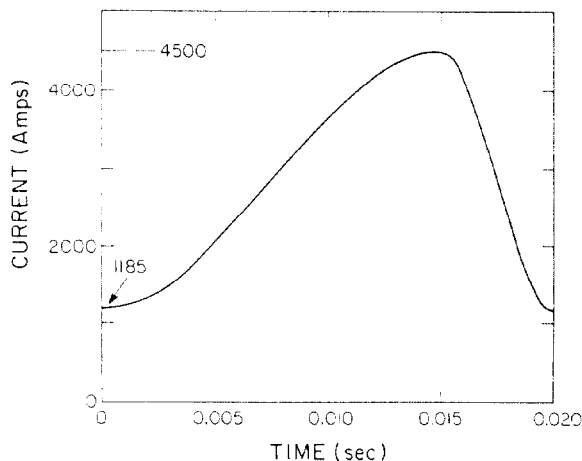

Fig. 1. Booster dipole excitation.

Dipole Profile

The pole profile and magnet and field profiles were established using the POISSON codes. We have investigated grain-oriented and non-oriented steels and looked at their effects on the field uniformity. By avoiding corner saturation it is predicted that the field within ±5 cm of the centreline will be within 1 part in 10^4 of the desired values at both injection and extraction. The two profiles are shown in Figs. 2(a) and 2(b). The maximum flux density in the yoke was set at 1.25 T as a result of a recommendation at a Magnet Design Workshop.[1] This turned out to be the best value for minimizing the total core losses.

Choice of Dipole Steel and Estimate of Core Losses

It was decided at the start to use a single piece lamination to reduce handling in the magnet assembly and to avoid the side air gaps, which introduce uncertanties into the final magnet. Such a lamination does not lend itself to the use of a grain-oriented steel because significant sections of the magnetic flux are perpendicular to the grain, and the advantage of the grain orientation is reduced. We chose 26 gauge M17 steel (0.0185 in., 0.47 mm). The estimated core losses for the 3 m long prototype are 4.92 kW and 3.91 kW for the M17 and M6 steels, respectively. The total magnet losses are 58.5 kW so the extra cost of the grain-oriented steel is not considered to be justified.

Table I. Booster synchrotron input parameters.

Physics		
Energy range	450–3000 MeV	
Field rise frequency	33.3 Hz	
Field fall frequency	100.0 Hz	
	Dipole	**Quadrupole**
Maximum pole tip field	1.05 T	0.70 T
Minimum pole tip field	0.277 T	0.175 T
Effective length	3.18 m	0.8 m
Pole gap	10.68 cm	13.2 cm
Field uniformity	$B/B_0 \leq 1 \times 10^{-4}$	$C_n/C_2 < 2 \times 10^{-3}$
Good field width	±5.0 cm	6.6 cm
Number required	25	48
Power Supply		
Maximum current	5000 A	1600 A
Maximum voltage/magnet (peak)	3 kV	0.4 kV
Maximum inductance	5.75 mH	1 mH
Number magnets/PS cell	5	24
Maximum voltage/PS cell (peak)	15 kV	10 kV

Fig. 2(a) Pole geometry.

FIELD BOUNDARY
CHANGE FROM
INJECTION TO
EXTRACTION
LESS THAN
1 PART IN 10^5

Fig. 2(b). Magnet end profile.
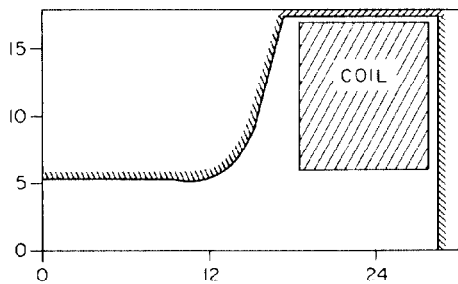
The core loss estimates must take the excitation into account and we calculate them by splitting the total loss into the hysteresis and eddy current components. We assume that the hysteresis loss is a function of the peak field. For our design this is 1.25 T. We also recognize that the steel does not undergo complete hysteresis loops and consider that 34% of the full hysteresis loss is appropriate for our excitation curve. We then assume that the eddy current losses are a function only of the ac field component, in our case 0.46 T. The frequency terms have to be adjusted as most manufacturers data is at either 50 or 60 Hz. The method of doing this is fully described in Ref. 2. For our 26 gauge M17 steel we estimate that the core losses will be 0.23 W/lb for our excitation. For comparison, at 1.25 T and 60 Hz full wave excitation the losses would be $\approx$1.0 W/lb.

The laminations will be parallel to each other and will be assembled on a curved bed. They will be epoxied together and stainless steel plates will be welded to the outside for rigidity and supports. There will be slots at intervals to accommodate coil clamps and cooling arrays to remove core losses.

Dipole Conductors

The magnet winding design is dominated by the power supply requirement of maximum voltage in the cell arrangement. The physical size of the magnet and not the field amplitude determines the inductance and hence the maximum number of turns allowable. We are limited to a maximum of 20 turns per magnet. This immediately sets the required current and approximate conductor size. The choice of conductors is limited to two types:

a) hollow square copper conductors in parallel
b) stranded cooled conductor of the type used at KEK[3]

We have chosen each turn to be twelve square hollow conductors put into a 1 wide × 12 high array, Fig. 3(a). This arrangement has the advantage that by suitable connection at the magnet exterior circulating eddy currents induced by the
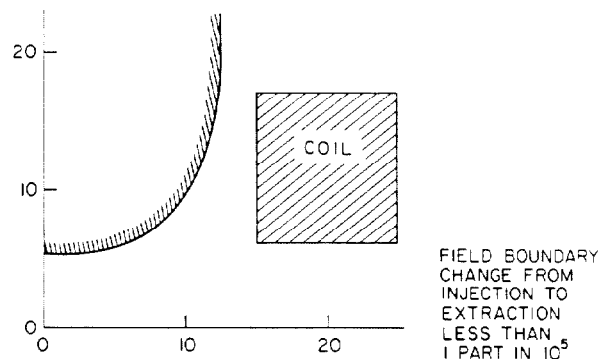
horizontal field components cancel and with only one conductor width transposition for vertical field components is not required. We also chose this conductor because its fabrication is quick and straightforward. Its eddy current losses are, however, higher than for the stranded cable, Fig. 3(b). The rms alternating field over the coil region was found to be 0.08 T and the calculated coil losses for both designs are compared in Table II.

Table II. Comparative magnet losses for different conductors (kW).

	Stranded cable	Square hollow array
dc resistive loss	42.0	36.8
ac resistive loss	7.1	6.3
ac eddy current loss	1.8	15.4
Total	50.9	58.5

If stranded cable with a larger strand size were specified, then the total losses per magnet could be reduced to 39.5 kW at the expense of a larger coil slot. The stranded type of cable should have a stainless steel cooling tube; otherwise the losses in the cooling tube itself must be added to the conductor losses.

The ten-turn coil array of 1×12 square conductors will be made by winding 12 ten-turn single layer pancake coils, installing them into a single coil array and making the end connections externally. Each layer will be individually cooled.

Quadrupoles

The quadrupole design will follow the same principles as given for the dipole. The proposed design is similar in size to an existing HERA magnet. We intend to purchase sufficient laminations, slightly modified, to make up the quadrupole and
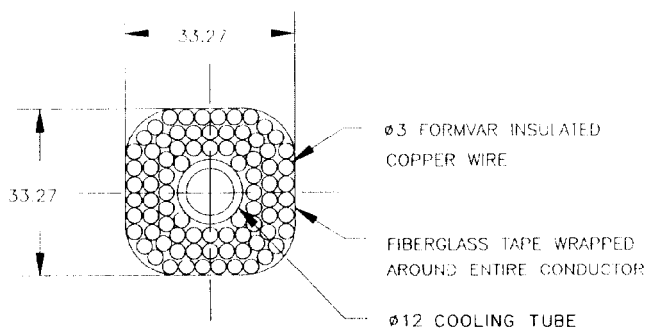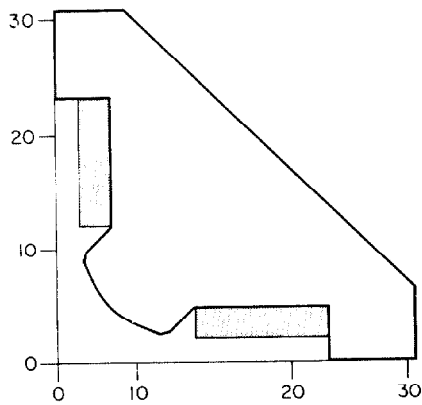

Fig. 3(a). 1×12 square hollow array.

Ø3 FORMVAR INSULATED
COPPER WIRE

FIBERGLASS TAPE WRAPPED
AROUND ENTIRE CONDUCTOR

Ø12 COOLING TUBE

Fig. 3(b). Cooled, stranded conductor.

391

Fig. 4. Quadrupole quarter section.

Fig. 5. Core losses with dc bias M22 steel, ac field 0.4 T.

avoid the cost of a completely new tool. The proposed coil is to be an indirectly cooled array of rectangular conductors. The quarter section is shown in Fig. 4.

Loss Measurements

We have assembled an Epstein coil array and have started a series of core loss measurements with both sinusoidal and dual frequency excitation superimposed onto a dc bias field. These measurements will be compared with our estimating method given earlier. Some preliminary results are shown for an M22 steel (Fig. 5); from this data an estimate can be obtained for a waveform similar to ours. Tests are continuing on both grain-oriented and non-oriented steels.

Also we have installed square hollow conductors in a dipole magnet and measured the eddy current losses by cooling water flow and temperature rise. For 0.5 in. square hollow conductor the measured loss agreed within 5% of the calculated values at 100 and 33.3 Hz, with a field level of 600 G. A stranded cable sample with a copper cooling tube did not give such a good agreement but the field level was too low for an accurate determination. The tests on both types of conductors are continuing.
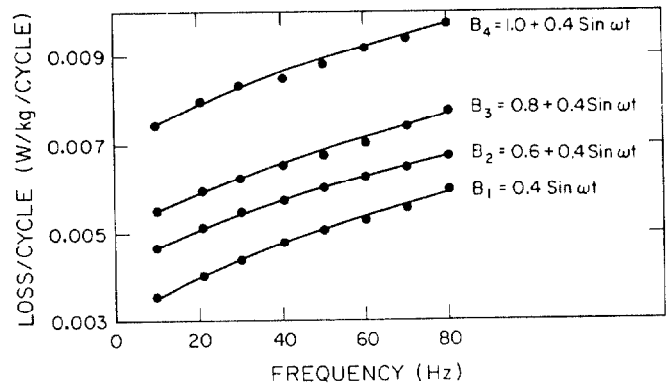
Conclusion

The main design choices for the prototype magnet design have been summarized. The dipole magnet drawings are nearing completion and will be put out to bid shortly. Both magnets have a completion date of October of this year so that we can complete our measurements by December 1989.

References

[1] Proceedings, KAON PDS Magnet Design Workshop, A.J. Otter and A. Strathdee, editors, TRIUMF report TRI-89-1 (1989).

[2] P. Schwandt, Estimation of specific core losses in dc-biassed laminated magnets, TRIUMF internal report TRI-DN-89-K22.

[3] H. Sasaki, T. Adachi, H. Someya and I. Sakai, A dc biassed rapid-cycling magnet system operating in a dual frequency mode, in Proc. KAON PDS Magnet Design Workshop, op. cit., p. 33.