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# **Combined ac Corrector Magnets**

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## Abstract

Conceptual designs have been made for two types of multipole corrector magnets for use in TRIUMF's proposed KAON Booster ring which operates at 50 Hz. The lack of space in the synchrotron lattice makes it attractive to combine dipole, quadrupole and sextupole correctors in the same yoke structure.

A conventional constant current density winding design is compared with an alternative magnet with twelve poles and windings distributed in slots and at the pole faces. The problem of induced voltages in the windings is discussed.

# I. INTRODUCTION

TRIUMF's Kaon Factory Booster ring design calls for extended families of corrector magnets which operate at 50 Hz. A suggestion to combine dipole and quadrupole correctors was made in 1989 [1] and a preliminary design presented. Further work was carried out in 1992 to add a sextupole field to such a magnet. This paper presents two designs for a combined dipole, quadrupole and sextupole magnet. Each type of field requires independant current control.

The first design presented is for a magnet with a cylindrical yoke and constant current density windings and the second is for a 12 pole magnet with interpole and pole face windings.

#### II. REQUIRED FIELD PARAMETERS

It was decided to investigate a magnet with the parameters listed in Table 1 which would cover the magnets in the arcs specified with sextupole fields which would be the most demanding. Production magnets would be made with variations e.g. some magnets would have skew quadrupole windings but not dipole windings.

Table 1	Parameters	of Study	Magnets

Minimum bore radius	62.0	mm
Good field radius	52.0	mm
Magnetic length	0.3	m
Dipole field	$0.027~\pm~3.1~\%$	Т
Quadrupole field	$0.865~\pm~2.3~\%$	T/m
Sextupole field	$17.3 \pm 1.1 \ \%$	$T/m^2$

# III. CYLINDRICAL YOKE MAGNET WITH CONSTANT CURRENT DENSITY WINDINGS

The section shown in Fig. 1a is a conceptual design based on [2] which meets the criteria of Table 1. The winding configuration was chosen to make the most efficient use

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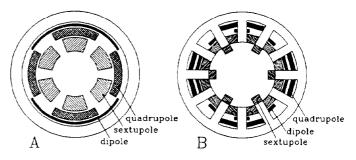


Fig. 1. Magnet Cross Sections: a) Cylindrical Yoke, constant current density windings; b) Multipole with interpole and pole face windings.

of space as the windings requiring the most ampere turns are placed closest to the inner diameter. A radial space of 0.5 cm was maintained between each set of coils and the steel yoke to allow for coil formers which would be nested together in the magnet assembly. The sextupole coil inner radius has a 0.8 cm allowance over the 6.2 cm inner radius specified. Because the steel yoke enhances the fields of the individual coils and its inner radius is not initially known several iterations of the design equations are needed to determine the coil radii. The magnet parameters are given in Table 2.

Table 2 Cylindrical yoke magnet parameters.

Winding	Inner	Outer	Current	Coil
_	Radius	Radius	Density	Angle
	cm	cm	$A/cm^2$	Degrees
Dipole	14.25	14.75	415	60
Quadrupole	11.5	13.75	475	30
Sextupole	7.0	11.0	460	20
Steel Yoke	15.25	18.25	-	
Magnet Bore	_	6.2	-	

Calculations from the formulae given in [2] and the POISSON code show that the magnet will produce the specified fields. The field quality requirements are also exceeded although the dipole does have an N=5 component of about 1% and an N=7 component of about 0.2%. It would be possible to reduce these if necessary by modifying the winding configurations [3]. The harmonics are essentially unchanged when the windings are excited individually and simultaneously.

It has been assumed that each component of the magnet would have the same effective length, but in view of the differing coil radii this may not be exactly true. Before a magnet was designed in detail this would be checked using the TOSCA code and if necessary the operating currents would be adjusted. The yoke flux density is low, being about 3.2 kG maximum. The windings would be made from square hollow copper conductor 0.162 in. square x 0.090 in. ID (4.1 mmsquare x 2.29 mm ID) each winding would operate at approximately 100 A peak. The coolant temperature rise was limited to 20 C to allow a margin for eddy current losses caused by transverse fields in the conductor material. These losses are estimated at 5.6 Watts/m for this conductor in a transverse field of 3 kG. At this level the losses are similar to the coil resistive losses.

The power supply requirements, Table 3, are estimated from resistive losses and stored energies. Operating margins and any allowance for core losses have not been included. The operating frequency is 50 Hz.

Table 3. Biased power supply requirements.

	A rms	V rms	VA rms
Dipole	60.32	15.7	947
Quadrupole	61.85	101.5	6278
Sextupole	63.2	56.6	3577

Each coil would be cooled with a single cooling circuit except for the quadrupole which might need two circuits per coil because of pressure drop considerations.

# IV. A 12 POLE MAGNET WITH INTERPOLE AND POLE TIP WINDINGS

An alternative multipole design is shown in Fig. 1b,with parameters listed in Table 4. It is similar in concept to dc magnets used at Daresbury as multipoles in the SRS, but with ac excitation as provided by the programmed quadrupoles in the earlier synchrotron NINA at the same laboratory [4-7].

The sextupole field is superposed on the basic 12 pole geometry with only alternate poles excited. The quadrupole coils each surround two poles with four poles unused. Each dipole coil couples to six poles with a distributed winding that grades the ampere-turns according to the angle of the pole. The magnet bore is larger than specified to obtain adequate field quality for the quadrupole harmonic. The pole face windings on the unused sextupole poles are necessary to offset the field distortion caused by these poles.

Table	4.	12	pole	magnet	parameters.
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-	-	
Clear bore radius		8.5 cm
Pole tip radius		11.0 cm
Pole width		2.8 cm
Pole height		$7.5~\mathrm{cm}$
Yoke radial thickne	ss	$3.5~{ m cm}$
Outer radius		$22.0~{ m cm}$
Dipole	Number of Turns	30
	Peak Current	81.4 A
	RMS Current	49.8 A
Quadrupole	Number of Turns	<b>38</b>
•	Peak Current	109.6 A
	RMS Current	67.1 A
Sextupole	Number of Turns	55
1	Peak Current	114.7 A
	RMS Current	70.3 A

The windings use the same conductor at similar current densities as the previous design. Except for the pole tip windings the conductors are in low field regions between the poles so eddy current losses will not be large.

The maximum flux density in the poles and yoke with all coils excited is 1.1 T.

The minimum power supply ratings for each component estimated for the inductive component only, are given in Table 5.

Table 5. 12 pole magnet power supply requirements.

	Dipole	Quadrupole	Sextupole
AC RMS Current (A)	27.78	38.75	40.55
RMS Voltage (V)	14.92	129.0	155.8
kVA Rating (kVÁ)	0.43	5.0	6.32

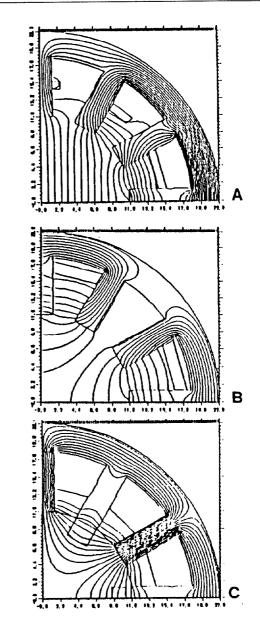


Fig. 2. Multipole Magnet Flux Contours: a) Dipole; b) Quadrupole; c) Sextupole.

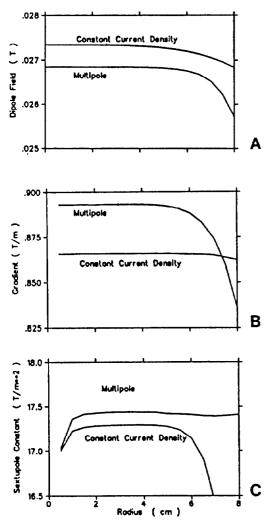


Fig 3. Field Profiles vs Radius: a) Dipole; b) Quadrupole; c) Sextupole.

Figure 2 shows the flux distributions for quarter sections of the magnet with individual coils energised.

The field profiles along the horizontal axis are shown for both magnets in Fig. 3. The apparent drop in value of the sextupole constant at small radii is not real, but is caused by the method of calculation.

### V. HARMONIC PICKUP BETWEEN COILS

The various coils will act as pickup coils to the driven coils of a different harmonic.

Let the pickup coil have harmonic m and the driving coil n, with a phase difference between them of  $\psi$ . Then the pickup coil response is given by

$$S_m = a_m \cos(m\theta + \psi) \tag{1}$$

and for the driving voltage

$$B_n = b_n \cos(n\theta) \tag{2}$$

The voltage output of the pickup coil is the product of eq. (1) and eq. (2). Over  $2 \pi$  the integrated output is

$$V = \int_0^{2\pi} a_m b_n \cos(m\theta + \psi) \cos(n\theta) d\theta \qquad (3)$$

and if  $m \neq n$  V = 0

but if n = m  $V = \pi a_m b_n \cos \psi$ 

Therefore in principle each coil will only pickup from it's own harmonic. However if the coils are not perfectly made, any imperfection harmonic will be picked up.

This conclusion was confirmed by using the PE2D code and by measurements on a small scale simple models.

### VI. MANUFACTURING CONSIDERATIONS

Both magnet designs are similar in size and complexity and the choice between them will be made on a cost basis. Detailed engineering designs have not been made. It is anticipated that the coils will be preformed and cast in sub-assemblies that will be assembled together. The length constraint is such that saddle end coils will be specified and it will be necessary to assemble the yokes around them. The laminations for the cylindrical magnet will be made from two overlapping halves and there may have to be six laminations to form the multipole geometry.

# VII. CONCLUSIONS

We believe that both designs are feasible. They are similar in size and operating current densities and both meet the field criteria specified. The multipole design has a better sextupole and dipole profile but a poorer quadrupole. The power supply kVA rating for the constant current density design is a factor of two lower than for the multipole design mainly due to the smaller radii of the windings.

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