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CONCEPTS FOR THE DESIGN OF MAGNETS AT TARGET LOCATIONS SUBJECTED TO VERY HIGH RADIATION LEVELS

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Summary

Magnets for advanced hadron facility secondary beam lines will be positioned close to targets at which nuclear radiation levels will be about 10^8 rad/h. New designs are proposed in which the magnet coils are remote from the beam apertures and are shielded from radiation by the poles or other non-magnetic shielding material. The magnet yokes and poles are integrated into the radiation shielding surrounding the targets. If necessary, the coils can be removed for servicing without exposing the parts of the magnet with very high residual radiation fields. It will also be unnecessary to have vacuum joints adjacent to the magnets because the parts of the magnet close to the beam tube should never have to be removed for maintenance.

Introduction

Targets at Kaon Factories or Advanced Hadron Facilities will be subjected to 100 μA of protons at 30-60 GeV. The radiation levels close to these targets will be approximately 10^8 rads/h and they will be surrounded by 2 m of steel and 5 m of concrete shielding.[1] Secondary beam lines emanating from these targets will require magnets to be buried in the shielding. These magnets will have to operate reliably for a period of many years because the radiation levels will require that any repair or maintenance procedure be carried out by remotely controlled tools. The anticipated radiation levels are at least an order of magnitude higher than those experienced at the present meson factories.

At TRIUMF[2] it is current practice to remove a faulty magnet to either a hot cell (remote manipulators) or a warm cell (semi remote operation) for repair. It is usual to allow a period of at least two weeks cool down after beam operation before we start the repair operation. It has been possible to make repairs on magnets with residual contact fields of 200 rads/h, but it is a slow and time consuming operation. It is necessary to break a remotely operated vacuum seal upstream and downstream of the magnet using long handled tools because the beam pipe is trapped within the magnet. Mineral insulated conductor quadrupoles of the design originated at Los Alamos are used.[3] These are narrow quadrupoles and they operate at a high current density and require multiple cooling circuits per coil.

At SIN the latest design uses half quadrupoles which can be removed from the beam line without breaking any vacuum seal.[4] These magnets also use mineral insulated conductors but they are indirectly cooled.

In both types of design the magnet coils are immediately adjacent to the beam tube and receive the highest radiation fields.

The 'Long Pole' Concept

At a workshop at TRIUMF it was realized that for the highest radiation levels the magnets and shielding should be considered as an integrated design rather than as separate components — after all both components are made largely from iron, and copper also makes an excellent radiation shield. It was suggested that the magnets should have long poles and coils remote from the beam tube. Such magnet might be magnetically inefficient but the space between the beam tube and the coils could be filled with a non-magnetic dense shielding material which would give good radiation shielding. If the coils are shielded from the highest radiation levels then they will be easier to repair if, for example, a water leak occurs. It was also decided to design magnets which did not require breaking a vacuum connection if they have to be removed from the beam line.

Dipoles

Figure 1 shows a cross section for a dipole magnet with a 10 cm air gap and a 2 T field. It would have an effective length of 2 m. The flux profile is shown in Fig. 2.

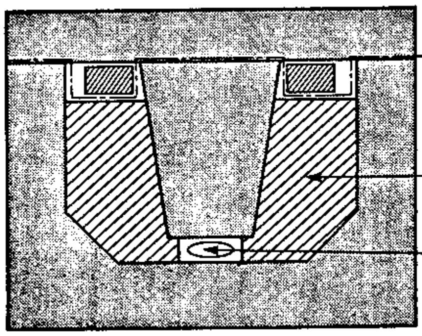

Fig. 1. Proposed dipole with long pole.

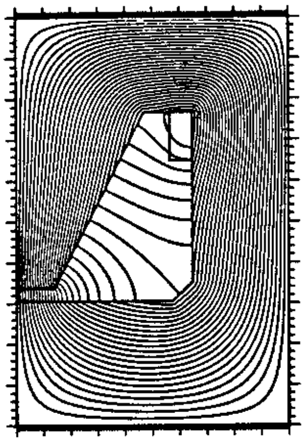

Fig. 2. Semi dipole field profiles.

The following features are easily realized:

- The coil is remote from the beam tube.
- The coil is shielded from high radiation by a non-magnetic shielding. In the magnet studied the coil is 1.4 m from the beam tube, enough to attenuate the radiation field by five orders of magnitude, which means that it might not be necessary to use inorganic coil insulation.
- The coil can be removed for servicing without

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exposing the beam tube or moving the lower part of the magnet.

- There is no need to break the beam line vacuum in order to service the coils.

The magnet is larger overall than a conventional design but the coil current density can be low to reduce the power requirements. The overall cost of such a magnet has to be considered together with the cost of the shielding material that it replaces.

Quadrupoles

It is not so straightforward to design a quadrupole to meet the requirements achieved by the dipole. This is because it is not desirable to have coils beneath the beam tube.

An obvious choice is a half quadrupole as shown in Fig. 3a. The coils are 2 m above the beam plane and it has all the features of the dipole described above. The disadvantage of a half quadrupole is that the beam optics designer is constrained to use a triplet at the start of each channel to make the beam transport achromatic. This may not always be convenient.

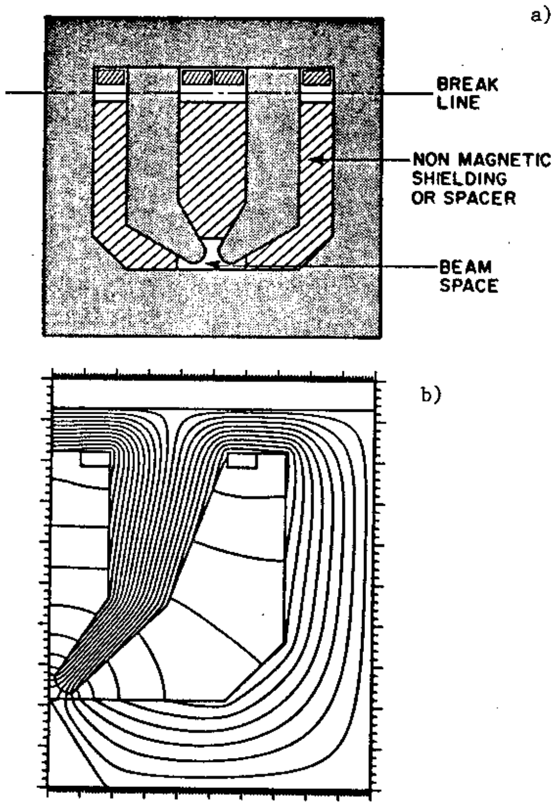

Fig. 3. a) Half quadrupole with long poles. b) Full long pole quadrupole field configuration.

A more convenient design is shown in Fig. 4 in which the coils have been placed on the side yokes rather than on the poles which are symmetrical. Attempts to design a magnet with either the two coils or the poles non-symmetrical always resulted in a high harmonic content of the field. The magnet of Fig. 4 achieves low harmonics but the side yokes should be moved further out to increase the amount of radiation shielding. In this particular design the magnet has a bore of 25 cm and a pole tip field of 0.8 T. The distance between the beam tube and the coil is 30 cm which is insufficient and a mineral insulated conductor would be essential. Also this design requires that a non-magnetic material be placed on the outside of the

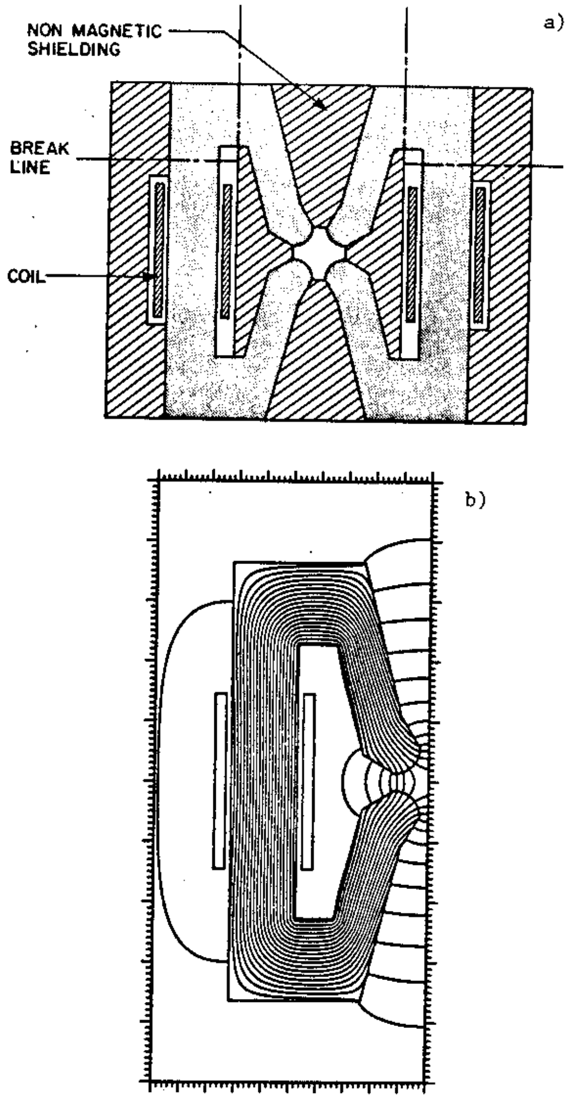

Fig. 4. Full long pole quadrupole with low harmonics.

magnet to prevent flux short circuiting through the surrounding steel shielding.

These magnets are considerably wider than the conventional narrow quadrupoles which we are presently using. This may cause problems when one looks at a proposed layout as shown in Fig. 5 but it should be possible to fold back the yokes to make the magnet three-dimensional as shown in Fig. 6.

Other Design Considerations

The nuclear heating adjacent to the beam tube is estimated to be 1 w/cm^3.[1] This means that for the dipole of Fig. 1 (with a pole width of 40 cm and length of 2 m) 160 kW must be removed from the 20 cm of each pole adjacent to the gap. To achieve this it will be necessary to have cooling passages 1 cm diameter in an array of approximately 15 cm to maintain temperature differentials in the iron at reasonable levels, e.g. below 100°C. The magnets described here will require that end plates be installed to prevent cross talk between the magnets because the poles are so remote from the working aperture.

Non-Magnetic Shielding

The radiation shielding can be any non-magnetic metal. Obviously it should be dense have a good

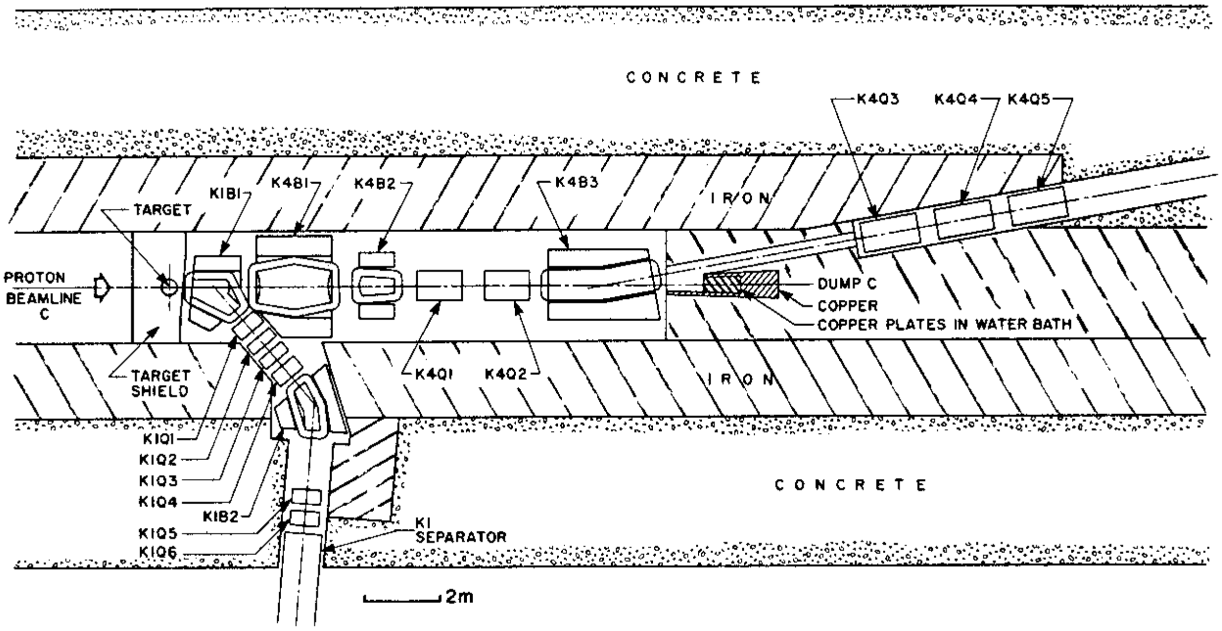

Fig. 5. Proposed target and magnet layout for the TRIUMF KAON Factory.

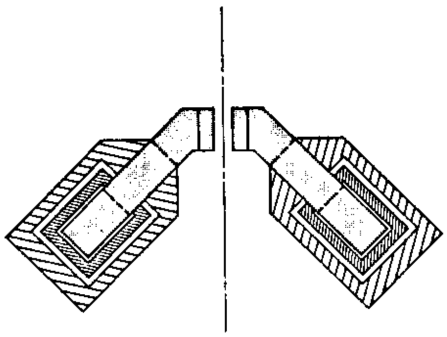

Fig. 6. Plan view folded quadrupole

thermal conductivity because it will need to be cooled and be as low cost as possible.

It will have to be machined to fit closely around the poles and in the quadrupoles it will be used as a spacer between the two halves of the magnet. A single piece which fits into one side of the dipole of Fig. 1 will weigh 20 tons so the cost of fabrication rather than the basic material cost will dominate.

A brief review of some obvious choices is shown in Table 1 together with some of the more relevant properties. As the density and thermal conductivity should be as high as possible and the cost as low as possible a figure of merit is also given. This is simply the product of density times thermal conductivity divided by the fabricated cost per pound. The fabricated cost value is a quick estimate only and needs to be established further.

From this table it is seen that copper is the most promising material probably as machined castings. Its coefficient of thermal expansion is $16.4\times10^{-6}/^\circ C$ which is closer to the value of 10.2×10^{-6} for iron and much better than the value of 29.3×10^{-6} for lead. Although lead is denser its poor thermal conductivity and low melting point would make it more difficult to cool.

Summary

A concept has been proposed which uses large magnets with long poles for areas of very high radiation levels. These magnets have

- Coils remote from the beam tube which is at the highest radiation level.
- Coils which are shielded from radiation by non-magnetic shielding.
- Coils which can be removed for servicing without breaking the beam line vacuum or exposing the high radiation regions of the magnet.
- Internal cooling passages to remove nuclear heat from the yokes and non-magnetic shield regions.
- End guard plates to prevent cross talk between adjacent elements.

Table 1.

Material	Density g/cc	Thermal conductivity G-cal/s/cm^2 c/cm	Fabricated cost/lb $/lb	F.M.
lead	11.34	0.083	4.00	0.24
copper	8.94	0.923	4.00	2.06
leaded brass	8.7	0.355	3.25 → 4.50	0.95 → 0.67
316 ss	7.9	0.069	7.50	0.07
iron (for comparison)	7.87	0.19	1.25	1.19

The disadvantages are that the magnets are larger than conventional magnets with the same specification which may cause problems when the design of channels rather than of single magnets is considered.

However, unless we adopt radically new designs the radiation levels anticipated at kaon factory targets will mean that a faulty magnet will become a throw-away component because it will become too radioactive to be repaired.

References

[1] Kaon Factory Proposal, TRIUMF 1985.
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[3] A. Harvey, "Radiation Hardened Magnets using Mineral-Insulated Conductors," in Proc. 4th Int. Conf. on Magnet Technology, Brookhaven, 1972; BNL Conf-720908, p. 456.
[4] D. George, R. Abela, D. Reuben, "Half Quadrupoles for use in a High Radiation Environment," in Proc. 9th Int. Conf. on Magnet Technology, Zurich, 1985, p. 184.