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CONCEPTUAL DESIGN OF LARGE-BORE SUPERCONDUCTING QUADRUPOLES WITH ACTIVE MAGNETIC SHIELDING FOR THE AHF

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CONCEPTUAL DESIGN OF LARGE-BORE SUPERCONDUCTING QUADRUPOLES WITH ACTIVE MAGNETIC SHIELDING FOR THE AHF

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Abstract

The Advanced Hydrotest Facility, under study by LANL, utilizes large-bore superconducting quadrupole magnets. In the paper we discuss the conceptual design of such quadrupoles using active shielding. The magnets are specified to achieve gradients of up to 24T/m with a 28-cm warm bore and to have 0.01% field quality. Concepts for the magnet cryosystems and quench protection are also briefly discussed to confirm the reliability of the proposed design.

INTRODUCTION

The LANL Advanced Hydrotest Facility (AHF) [1] utilizes large-bore superconducting (SC) quadrupole magnets to image protons for radiography of fast events [2]. Since twelve imaging lines converge on the object to be radiographed [3], size limitations are an important consideration as is magnetic coupling between lines. The pre-conceptual magnetic analysis of warm, cold iron core magnets and active shield version was described in [4]. In this paper we investigate an active shielding version, which is very promising, approach for this application. The quadrupoles have two concentric windings connected in series and configured so that the outer winding fully eliminates the outer fringing magnetic field. This design also eliminates problems connected with a warm or cold ferromagnetic core. The active shielding eliminates fringing fields and Lorentz forces between adjacent quadrupoles, reduces magnet weight and cold mass.

Proton beam lines consist of several large-bore quadrupoles which can be connected in series using common current leads and LHe forced flow or each doublet of quadrupoles has separate current leads and pool boiling cryosystem. The first approach widely used in accelerators, the second one in MRI, SC spectrometers, etc. The brief discussion of both options with preliminary quench analysis is presented in this paper.

QUADRUPOLE DESIGN

Specification and Parameters

In order to meet the imaging system requirements for AHF, the focusing quadrupole magnets should satisfy the criteria presented in Table 1 [5]. In addition, due to the limited space, the magnets should generate a minimum fringe field outside to avoid interaction between magnets in the doublets and adjacent strings.

Table 1. Magnet parameters

Parameter	**Small-bore**	**Large-bore**
Operating gradient, T/m	24.15	13.18
Magnetic length, m	4.3	3.0
Reference radius R_{ref}, mm	113.4	241.3
Field quality at R_{ref}	$<10^{-4}$	$<10^{-4}$
Main coil inner radius, mm	170.0	322.0
Screen coil inner radius, mm	276.0	513.5
Iron screen inner radius, mm	345.0	595.0
Iron screen thickness, mm	10.0	10.0
Number of turns in the main coil	232	508
Number of turns in the shield coil	104	220
Coil area, cm^2	174.4	378.0
Operating current, kA	14.10	11.77
Quench gradient with NbTi, T/m	28.25	15.80
Quench current with NbTi, kA	16.49	14.11
Peak field in the coil, T	6.1	6.3
Inductance, mH/m	9.91	49.41
Nominal stored energy, kJ/m	985.4	3420.7
Max. field in the iron screen, T	0.4	0.2

Design Concept

The quadrupole design is based on the active shielding concept, where the return flux from the main winding is suppressed using another winding carrying an opposite current. The cross-sections of the small and large aperture quadrupoles based on this concept are shown in Fig.1 and Fig.2. This approach allows keeping the main part of magnetic flux within the cold mass preventing interaction between the cold mass and iron screen, inherent to the warm yoke concept. It also allows avoiding the iron saturations effects leading to the field distortions.

A simple estimation shows that limiting of the magnet current within reasonable boundaries of 15-20 kA leads to several hundred of turns in the windings for the given apertures and gradients. A traditional shell type coil with that number of turns would suffer from the stress accumulation in the midplane and large random field harmonics coming from the uncertainties of individual cable position within the shells. Thus it was imperative to split the shells into a number of mechanically decoupled blocks, providing the stress management and individual support for each block.

In order to accomplish this task, winding into the support structure approach was chosen. The winding mandrel is a cylinder with rectangular slots machined in longitudinal direction. For an easier stacking and prestressing inside the slots, the cable is to be wound in the "hard bend" way with the long edge tangential to the mandrel. In addition, to simplify the manufacturing, all slots in the mandrel should be oriented radially. After the coil is wound and cured, the mandrel serves as the mechanical support structure for the coil.

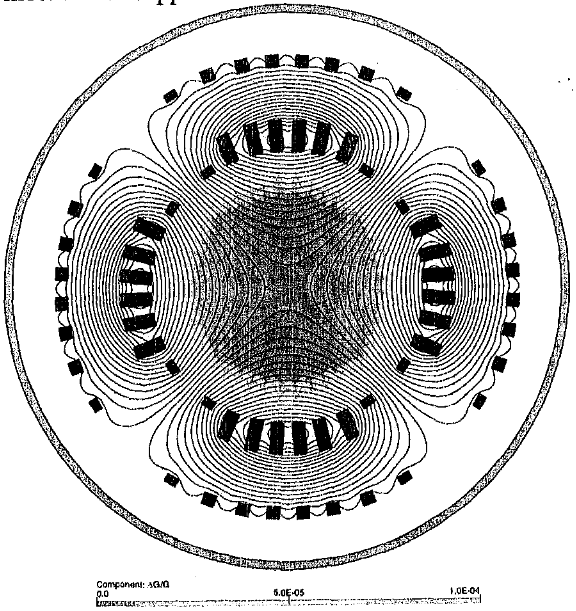

Fig. 1 Small-bore quadrupole field quality and flux lines

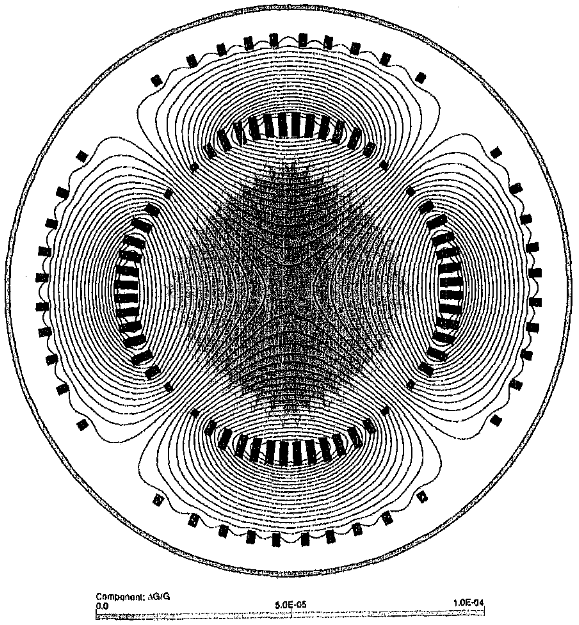

Fig. 2 Large-bore quadrupole field quality and flux lines

Apart from the traditional shell type magnet, the cable width in the proposed design concept does not drive the shell thickness and therefore the maximum gradient. It offers an opportunity of tuning the operating parameters by simply changing the number of cables in the blocks and neither the cable dimensions nor the number of layers. However, the cable width does drive the number of blocks and thus cost of the support structure, which should obviously be minimized. From this viewpoint, the maximum cable width acceptable for the cable winding in the hard-bend direction should be chosen. Simple bending experiments demonstrated that the Rutherford type cable with 28 strands, 1 mm in diameter can be hard-bent around ~50 mm round mandrel without the stability loss. Given that the cable mechanical stability will be additionally enhanced by the support from the mechanical structure during the coil winding, the number of strands was fixed at 32.

Superconducting Cable

Both magnets are based on the same 32-strand cable with either NbTi or Nb_3Sn strands. The strand and cable parameters are summarized in Table 2. The higher critical current density and lower Cu:nonCu ratio in Nb_3Sn strands allow replacing significant amount of SC strands in Nb_3Sn cable with pure Cu strands preserving the magnet maximum field gradient.

Table 2: Cable parameters

Parameter	**NbTi**	**Nb_3Sn**
Strand diameter, mm	1.000	
Number of strands	32	
Cable bare width, mm	16.214	
Cable bare thickness, mm	1.772	
Number of SC strands	32	8
Number of Cu strands	0	24
Copper to non-copper ratio	1.6	0.85
J_c(5T,4.2 K), A/mm^2	3000	-
J_c(12T,4.2 K), A/mm^2	-	2200

Field Quality

Field quality in an air core magnet with large number of conductor blocks can be rather easily optimized to values of two orders of magnitude better than specified field harmonics 10^{-4}. In Table 3 presented results of both quadrupoles optimization shown in Figs. 1-2. So, the manufacturing accuracy will define the final field quality.

Table 3: Field harmonics

n	**b_n, 10^{-4}**	
	Small-bore	**Large-bore**
6	-0.0012	-0.0002
10	0.0005	-0.0001
14	-0.0035	-0.0001
18	0.0005	0.0002

The random field harmonics were calculated as standard deviations among a large number of cases in assumption of +/-50 μm random block displacements from the nominal position. The results show that the small bore magnet with this tolerance on the block positions will meet the field quality requirements for individual harmonics with the probability of 68%. However, due to the larger number of blocks, the large bore magnet with the same positioning tolerances will meet the field quality requirements with 99% probability or one can relax the tolerances to +/-140 μm to get the same probability.

Quench Margin

The maximum field gradient was calculated for the quadrupoles made of NbTi and Nb_3Sn conductors. Conductor properties are shown in Table 2. Both large and small quadrupoles based on the NbTi conductor achieve the maximum operating gradients with 15-20% critical current margin. Using Nb_3Sn cable in these magnets allows enhancement of the operating gradients by a factor of 1.5 with the same Ic margin.

The radiation losses in magnet coils will produce an extra heat load of 0.3–1.0 mJ/g. Fig. 3 shows the quench limit for NbTi and Nb3Sn coils vs the magnet critical current margin. To provide magnet operation at 1.0 mJ/g heat deposition the critical current margin for above designs in case of NbTi coil has to be more than 25% and in case of Nb_3Sn coil only 10%.

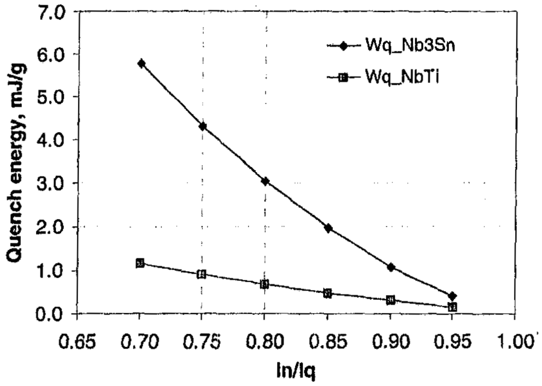

Fig. 3 Quench energy vs. coil critical current margin for NbTi and Nb3Sn quadrupoles.

Quench Protection

Magnets will be protected with an active quench protection system based on the internal quench heaters as it is used in modern SC accelerators. Analysis shows that at quench detection time of ~50 ms and 50% coil volume quenched by the heaters, the coil maximum temperature does not exceed 300 K and maximum voltage between the coil and ground during a quench is less than 100 V.

Cryosystem

Tom Peterson's proposal:Pat Kelley should briefly, describe the cryogenic system concept here, with reference to published papers for more details. I suggest emphasizing the difficult geometry--the lack of a nice, linear magnet arrangement--as one of the unique difficulties for this cryosystem design. Somewhere in this section, wherever it fits, he would like to add something like the following sentences:

One potential problem with pool-boiling combined with large heat loads is the large volumetric flow rate required for removing vapor generated in tight spaces, particularly with the flow driven by density gradients (natural circulation). Especially with spaces of less than 1 mm, which are not vertical, heat fluxes that can be removed by boiling and natural circulation start to drop off. Our extensive experience with magnets cooled by pool-boiling helium in vertical test dewars may not be relevant, since heat loads there are typically minimal and local heat fluxes are very low. In spite of the geometric difficulties presented by the radial magnet arrangement, forced flow cooling, which has been used successfully in long accelerator magnet strings such as Tevatron, HERA, and RHIC, might have to be developed for the AHF system as an integral part of the magnet design.

SUMMARY

The conceptual design of the AHF SC quadrupoles confirmed the feasibility of design based on the active shielding approach. The results, from this analysis, are:

- magnetic design is in an agreement with the specified field quality 10^{-4} ;
- quadrupoles windings can be made from NbTi or Nb_3Sn superconductor;
- proposed mechanical structure with stress management;
- quench protection system is visible;
- cryosystem is briefly discussed.

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