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40-mm Bore HFM Cross-Section Design with 0.8 mm Strand Diameter Nb_3Sn Cable

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Abstract

The goal of the performed study was to find an optimal coil cross-section for a 40-mm bore high field dipole using a Nb_3Sn cable with 38 0.808-mm strands. Many coil cross-sections with acceptable parameters were obtained, two of them are reported. They will be compared with cross-sections using a Nb_3Sn cable with 28 1-mm strands and apertures of 50, 45 and 40 mm [1-5], in order to choose the cross-section for the First High Field Dipole Model to be built at FNAL.

INTRODUCTION

Two layers coil cross-section designs with 40-mm bore diameter were optimized by using ROXIE package [6]. It helps to minimize objective function (in present case – harmonic content) depending on design parameters (positioning and inclination angles for each block) by chosen optimization algorithm. Since, there are a lot of local minimums of objective function, there are a number of design parameters combinations which lead to acceptable field quality. The main task of optimization is to find the cross-section that satisfies both required magnetic field quality and good cables placement from the point of view of manufacturing and of force distribution.

CABLE PARAMETERS

The Nb_3Sn cable dimensions were similar to the cable adopted for LHC High Gradient Quadrupoles, consisting of 38 strands with 0.808-mm diameter.
The insulation was assumed to be epoxy impregnated S-2 glass. The thickness was choose based on measurements made at FNAL for a sleeve [7]: 0.12-mm azimuthal insulation (corresponding to about 8.5 MPa of pressure) and 0.13-mm radial insulation (no pressure applied).
Cable critical current was chosen according to FNAL specification #5520-ES-362049. Measurements of critical current performed at FNAL on IGC 1-mm strand short samples gave slightly lower results [8]. Improvements are on course at IGC. No cabling degradation has been taken into account. Cable parameters are given in Table1.

Cable height (bare) , mm	15.400
Cable inner width (bare), mm	1.3250
Cable outer width (bare), mm	1.5880
Radial insulation thickness, mm	0.13
Azimuthal insulation thickness, mm	0.12
Number of strands	38
Strand diameter (mm)	0.808
Cabling angle (degree)	16.0
Cu/SC ratio	0.85
Critical current density at 12 T & 4.2 K (A/mm^2)	1886
Critical current density at 13 T & 4.2 K (A/mm^2)	1435

Table 1: cable parameters

CROSS-SECTION DESIGN

Coil cross-sections were optimized using ROXIE5.2. 2*19 current filaments in each cable were used to compute field quality. Only two-layer designs were studied. The internal radius of the layers was 20 (inner) and 36.12 mm (outer). The yoke radius was 60 mm and a constant iron permeability of 1000 was used.

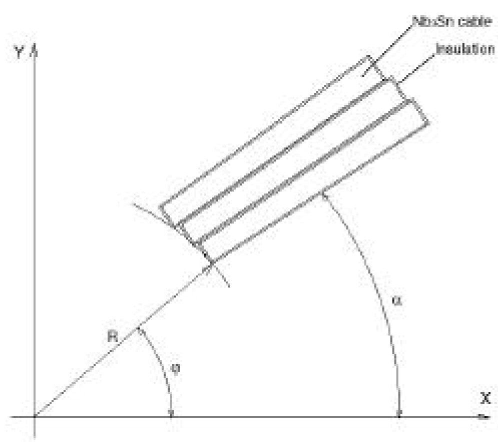

Fig. 1 Block design parameters

In Table 2 the design parameters are reported (see Figure 1 for inclination and position angle), in Table 3 the main characteristics of each design are presented. Central field and stored energy are computed at maximum current.
In Figures 2 and 3 the cross-sections of the two best designs are shown.

Variant #	Block #	Number of turns	Positioning angle φ, deg.	Inclination angle α, deg.
1	1	6	3.534	4.669
	2	6	25.398	25.013
	3	8	47.267	50.614
	4	7	1.000	0
	5	4	34.000	30.003
	6	2	58.995	76.998
2	1	6	1.297	0
	2	7	22.904	29.022
	3	6	42.565	49.776
	4	5	0.898	0
	5	5	25.000	24.794
	6	3	55.700	61.754

Table 2: Design parameters

Parameter	#1	#2
Number of turns	66	64
Central field at quench (T)	12.56	12.54
Quench Current (A)	15807	15445
NI/B (A/T)	83093	78799
Stored Energy (kJ/m)	303	301
Inductance (mH/m)	2.43	2.53
Pole width, mm	15.12	14.6
Harmonics, 10^-4		
b3	-0.000	-0.004
b5	0.002	0.026
b7	0.016	0.036
b9	0.024	-0.172
b11	0.037	0.167
b13	-0.030	-0.015

Table 3: Design characteristics

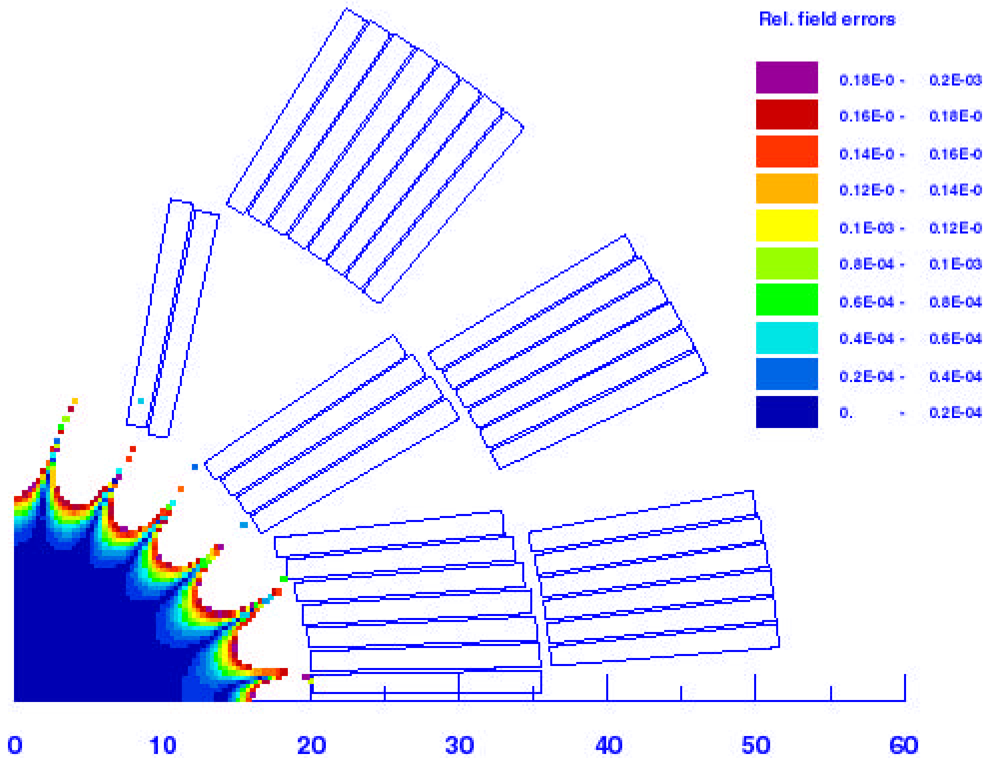

Fig. 2 Field quality diagram. Cross-section #1

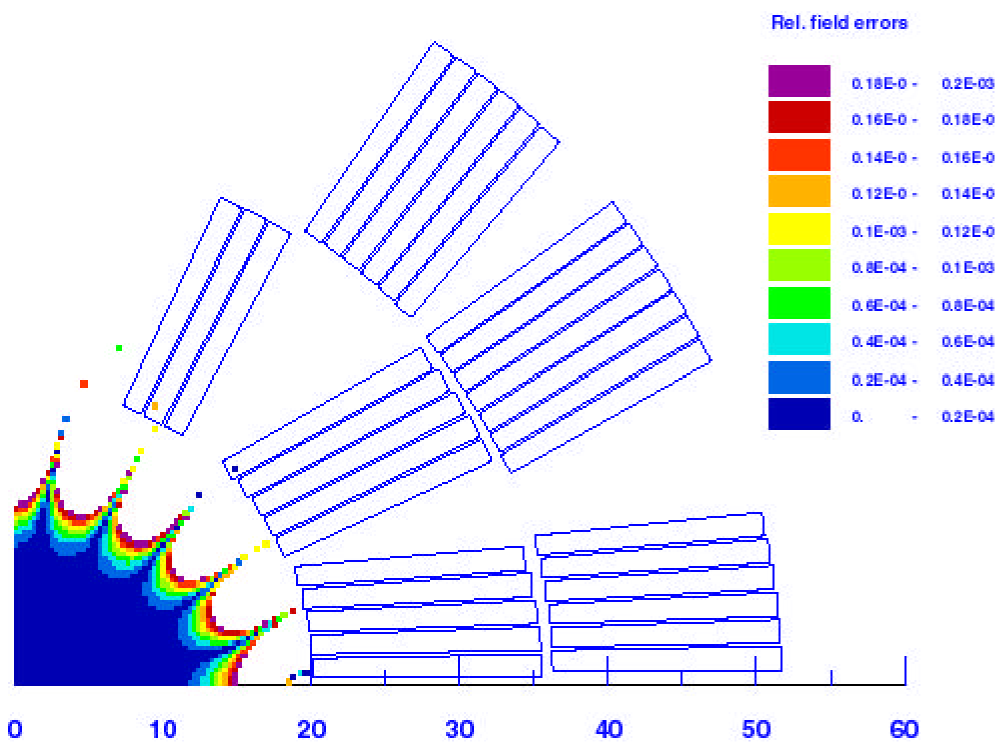

Fig. 3 Field quality diagram. Cross-section #2

MECHANICAL PARAMETERS

As it is mentioned in [2] there are some important parameters that allow comparing coil cross-sections from a mechanical point of view at this stage of the design.

The force component applied perpendicularly to the cable wide side contributes to the stress developed in the dipole midplane that can be a cause of critical current degradation. Moreover it is necessary to know this component to calculate the needed prestress $\boldsymbol{P_{pr}}$:

$$P_{pr} \geq \frac{\sum_{1}^{N}(nF_n)}{Nw},$$

where $\boldsymbol{N}$ is the number of turns per layer, $\boldsymbol{n}$ is the turn number from the midplane and $\boldsymbol{w}$ is cable width. It is easy to see that the pressure developed in the midplane due to Lorenz force

$$P_{L.F.} = \frac{1}{w}\sum_{1}^{N} F_n$$

is always larger then the required prestress.

Force component applied parallel to the cable wide side can lead to relative movement of strands in cable if corresponding stress exceeds friction or sheer strength. The sum of X-components of the force is another useful parameter to estimate the confinement force required. Table 4 summarizes force distribution for the two dipole cross-section design at quench current.

Parameter	#1		#2	
	Inner layer	Outer layer	Inner layer	Outer layer
$\boldsymbol{P_{pr}}$, MPa	47.9	66.5	48.8	58.8
$\boldsymbol{P_{L.F.}}$, MPa	71.7	95.5	65.3	84.0
$\sum F_x$, MN/m	1.85	1.32	1.87	1.16

Table 4: Total force, prestress and stress on the midplane.

CONCLUSION

As a result of optimization were found several HFD coil cross-sections with both acceptable field quality and cable arrangement in blocks. They may be used as a starting-point for the following study of iron yoke saturation and mechanical stress calculations.

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