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***Abstract*— It has been shown that by superposing two solenoid-like thin windings, that are oppositely skewed (tilted) with respect to the bore axis, the combined current density on the surface is $\cos(\theta)$-like and the resulting magnetic field in the bore is a pure dipole field. Following a previous test of such a superconducting dipole magnet, a quadrupole magnet was designed and built using similar principles. This paper describes the design, construction and test of a 75 mm bore 600 mm long superconducting quadrupole made with NbTi wire. The simplicity of the design, void of typical wedges, end-spacers and coil assembly, is especially suitable for future high field insert coils using Nb_3Sn as well as HTS wires. The 3 mm thick coil reached 46 T/m but did not achieve its current plateau.**

***Index Terms*—NbTi, tilted helical solenoid, superconducting quadrupole.**

I. Introduction

THE original concept of using helical winding to wind quality accelerator superconducting magnets gained renewed interest in the past few years [1]–[8]. Part of it arose from work on high field magnets and the possibility of applying this method to insert coils. This appealing approach, partially void of the usual complexity associated with superconducting magnet technology, can achieve adequate field quality with significant reduction of manufacturing costs and complexity and apply to a number of different superconducting materials. Therefore Lawrence Berkeley National Laboratory (LBNL) demonstrated the practical potential use of such an approach by testing a small NbTi dipole magnet in 2005 [9]. Based on the magnet performance the concept has been extended to quadrupole magnets. This paper presents the design, assembly and test results.

II. Design and Analysis

A. Construction

Four layers of a NbTi wire were wound around a Kapton® insulated aluminum mandrel with each turn guided by four winding pins placed around the mandrel at 90 degrees with respect to each other and displaced axially to form a sinusoidal-like pattern as depicted in Fig. 1, Fig. 2, and Fig. 3. The stainless steel pins, 3.77 mm apart, have been inserted and glued into 4 sets of 110 pin-holes. Each turn followed a path that took it around the four pins with a forward pitch for each following turn. The theoretical path followed the relation:

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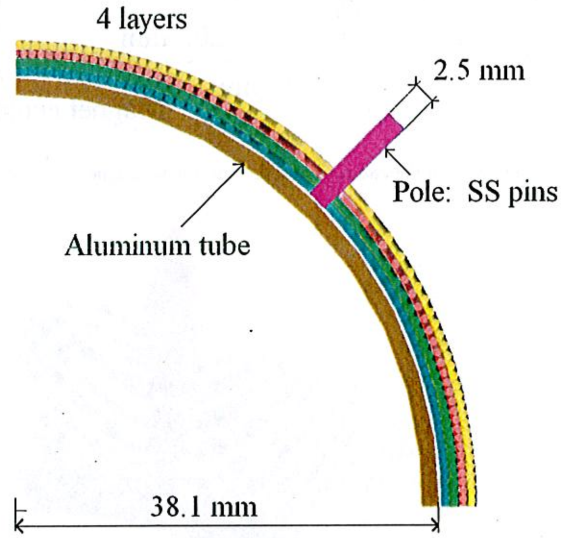

Fig. 1. Quadrupole cross-section with four layers of wire around a pole.

$$
\begin{aligned}
x(R,\theta) &= R\cos(\theta), \\
y(R,\theta) &= R\sin(\theta), \\
z(R,\theta) &= \frac{R}{\sqrt{2}\tan(\alpha)}\sin(2\theta) + \frac{\theta d^*}{2\pi\sin(\alpha)}
\end{aligned}
\tag{1}
$$

R is the winding radius, α is the mid-plane inclination angle between the wire and the Z axis and d^* is the wire diameter plus additional space between wires.

The solenoid field component cancels out by alternating current directions between layers. The net axial current, in the direction along the mandrel Z axis, forms an azimuthal distribution that approximates a $\cos(2\theta)$ current density distribution. However in this magnet the wire was wound between pins following a natural geodesic path; an approximation that did not follow the theoretical path of Eq. 1. Additional fiberglass sheets, used as filler materials, were added over the ends to fill the void arising from the tilted winding (see Fig. 4). S-glass wrapping over the four layers provided coil compaction and a layer of insulation to an outer aluminum shell. The coil placed between the inner mandrel, outer shell and additional end-caps was vacuum impregnated with epoxy. The only pre-

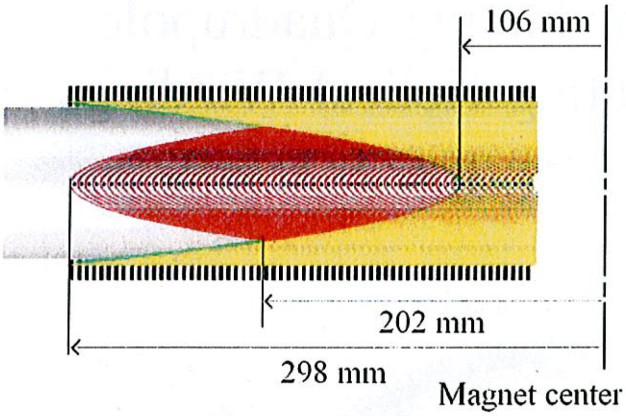

Fig. 2. Side view of the end region of the quadrupole magnet winding.

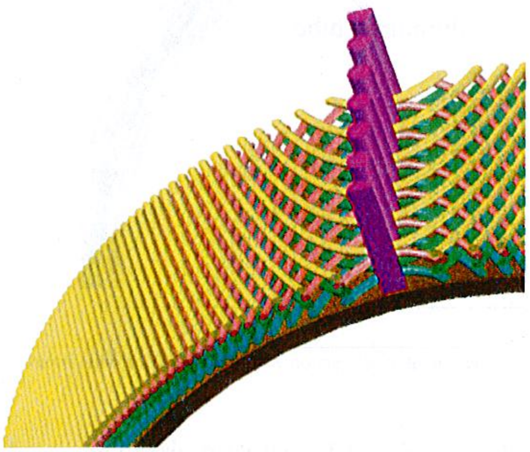

Fig. 3. View of layers wound around pins (poles).

stress applied to the coil was during cool-down as a result of thermal expansion differences between the outer Aluminum shell and the impregnated coil. The pre-stress is therefore likely to be insufficient to fully support the coil and minimize training. Table. I summarizes the magnet parameters.

B. Computations

We used four different ways to compute the field and gradient: three two-dimensional programs and one using the exact helical path as described in Eq. 1. The results are summarized in Table II. We have also calculated the expected harmonics. The first allowed harmonic b_6 is plotted in Fig. 6 at a radius equal to 17 mm corresponding to 45% of the bore radius.

1) Poisson - 2D Line-currents: Assuming a thin layer at radius $R = 40.45$ mm, we calculated the intersecting points between two layers of sinusoidal quadrupole windings. At a given Z, 25 intersecting points were recorded and their corresponding angle θ used to locate the line current to be used in the program POISSON. Each line-current carried a current equal to 1600 A corresponding to 4 layers each transporting 400 A (a flux plot is shown in Fig. 5).

TABLE I
MAGNET PARAMETERS

NbTi wire	
Diameter (wire plus insulation)	0.749 mm
Cu:Sc ratio	2.1:1
Filament diameter	55 μm
Number of filaments	54
Wire insulation	formvar®
Magnet	
End to end winding length	596 mm
Magnetic length	415 mm
Winding angle, α	17 °
Wire diameter + gap, d^*	1.1 mm
Total number of turns per layer	110
Total of layers	4
Bore radius	38.1 mm
Self-inductance	11 mH
Winding tension	13.3 N
Mechanical structure	
Inner Aluminum 2024 mandrel	OD: 76.2 mm, ID: 72.9 mm
Outer Aluminum 6061 shell	OD: 101.6 mm, ID: 88.9 mm
Shell length	686 mm
Winding space between shells	6.35 mm

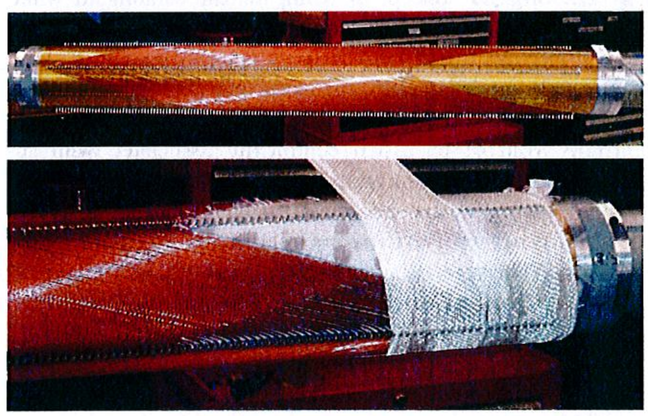

Fig. 4. Photos of the magnet before and during final glass wrapping.

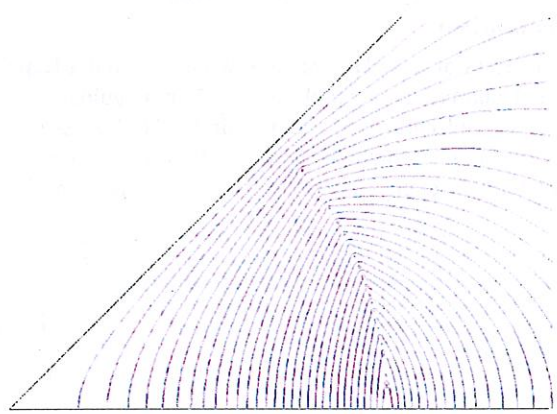

Fig. 5. POISSON 2D flux plot using line current distribution.

TABLE II

COMPARING CALCULATED AND MEASURED GRADIENTS.

Method	Type	Gradient (T/m)
POISSON 2D	Line currents at cos (2θ)	30.7
ANSYS 2D	thick shell cos (2θ) current density	31.1
Analytical 2D	thin shell cos (2θ) surface currents	31.4
Biot-Savart 3D	line currents along helical path	30.4
Measured	rotating coil	28.9

2) ANSYS - 2D thick shell: ANSYS was used to solve the magnetic field of a thick shell carrying a current density distribution proportional to $J_0 \cos(2\theta)$ where $J_0 = 666.6$ A/mm^2 corresponding to four layers carrying 400 A each.

3) Analytical - 2D thin layer approximation: Assuming an average radius R=40.45 mm and a coil thickness δR=3 mm we calculated the gradient G using the relation for a thin layer approximation:

$$G = \frac{\mu_0 J_0'}{2R} = \frac{\mu_0 I}{R^2} \tag{2}$$

where $J_0' = J_0 \delta R$ is the current density per unit length and I is the total amp-turn per pole.

4) Biot-Savart - 3D helical line-currents: We have used the Biot-Savart law to sum up the field contributions from segmented short line-current elements following a path according to Eq. 1.

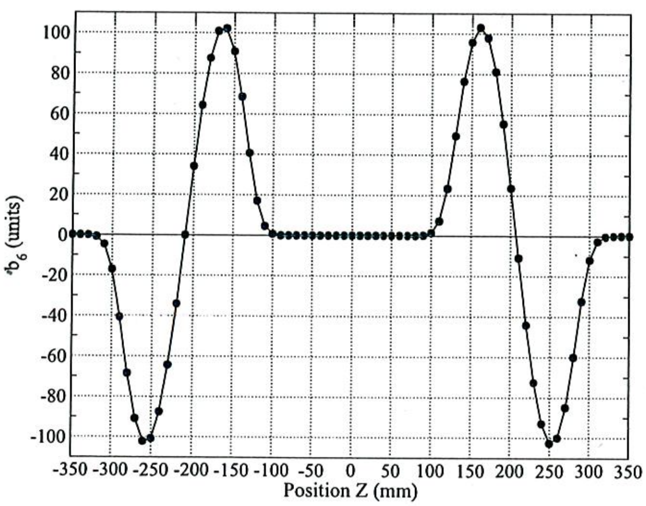

Fig. 6. Allowed harmonic b_6 calculated at a radius of 17 mm corresponding to 45% of the bore radius.

III. TEST RESULTS

The magnet was first tested at LBNL at 4.4 K. It was then shipped to CERN for additional tests at 4.4 K and 1.9 K. During the first thermal cycle, the magnet first quench was at 200 A reaching 432 A after 15 quenches as depicted in Fig. 7. During the second thermal cycle, the first quench was below 300 A but soon surpassed its first thermal cycle current and finally settled around 580 A. Subsequent tests at 1.9 K and 4.4 K raised the current to 609 A and 637 A, respectively, corresponding to 85% of its short-sample limit (750 A at 4.4 K) as depicted in Fig. 8. At 637 A, we calculated the field at the conductor to be 1.93 T. The long training could be attributed to: 1) lack of supporting structure and pre-stress, and 2) impregnated NbTi conductor. This magnet did not have voltage taps to locate the quench origin and strain gages to estimate the pre-stress.

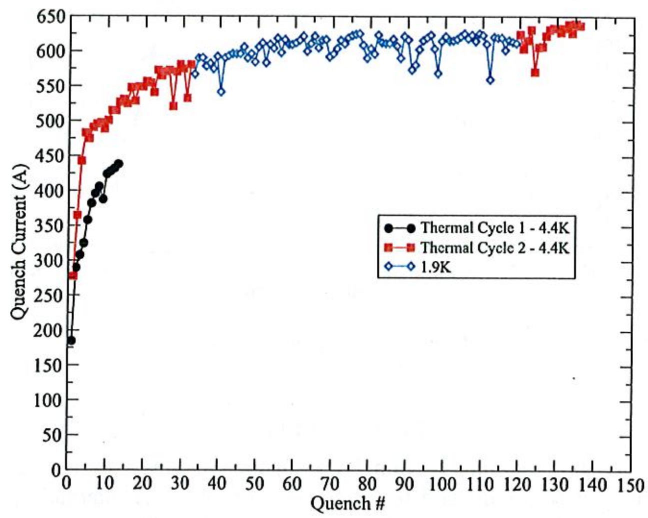

Fig. 7. Training curve.

A. Field measurements

During the first thermal cycle a transverse Hall probe was placed approximately at 27 mm off the magnet axis to measure the field. The sensor was rotated on its axis to capture the maximum magnetic flux density and was also used for z-scan measurements. Fig. 9 shows a comparison between calculation and experimental data. At CERN magnetic measurements were made using a rotating coil. The measured rotating coil gradient was used to normalize the Hall probe data. However, measured

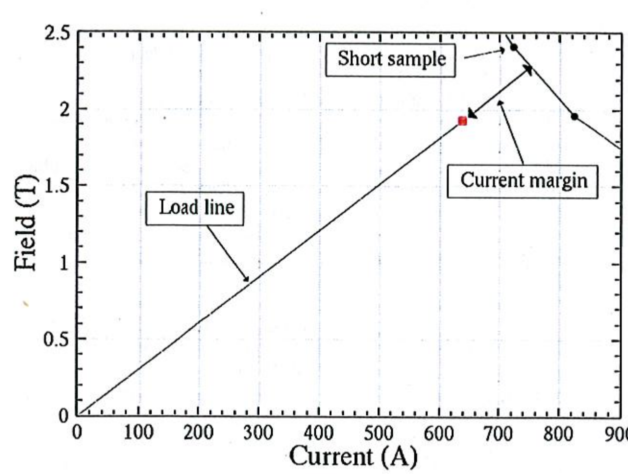

Fig. 8. Load line and expected short-sample limit.

harmonics were much higher than what could be explained by a sensitivity analysis and will have to be further investigated.

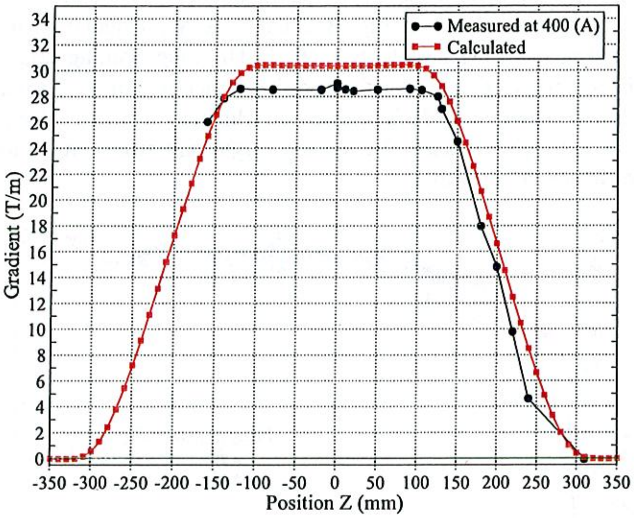

Fig. 9. Axial scan of measured and calculated gradient.

IV. Conclusion

A thin (3 mm) 76 mm bore superconducting quadrupole magnet was built and tested using four layers of alternating helical NbTi windings. The magnet reached 46 T/m at 85% of its short sample limit at 4.4 K. Excessive training is attributed to lack of structural support. Although the field quality issue remains open, the simplicity of the design, small number of parts and minimum assembly effort, are attractive features for Nb_3Sn and HTS coils.

Acknowledgment

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