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QUENCH PERFORMANCE AND FIELD QUALITY OF THE 15 T Nb_3Sn DIPOLE DEMONSTRATOR MDPCT1 IN THE FIRST TEST RUN*

A.V. Zlobin†, E.Z. Barzi, J.R. Carmichael, G. Chlachidze, J. DiMarco, V.V. Kashikhin, S. Krave, I. Novitski, C.R. Orozco, S. Stoynev, T. Strauss, M.A. Tartaglia, D. Turrioni,
Fermilab, Batavia, IL, USA

Abstract

Fermilab has developed and fabricated a 15 T Nb_3Sn dipole demonstrator for a post-LHC hadron collider. In June 2019, the magnet was tested and reached a world record field of 14.1 T at 4.5 K. The 15 T dipole demonstrator design and the first results of magnet cold tests including quench performance and field quality are presented and discussed.

INTRODUCTION

Fermilab in the framework of the U.S. Magnet Development Program (US-MDP) [1] has designed and fabricated a 15 T Nb_3Sn dipole demonstrator for a post-LHC hadron collider (HC). The main objectives of this work are demonstration of the field level, suitable for a future HC, and study of the high-field magnet performance, including quench performance, operation margins, field quality, and quench protection.

The 15 T dipole demonstrator, called also MDPCT1, is using optimized "cos-theta" coils and a cold iron yoke [2, 3]. An innovative mechanical structure based on strong aluminum I-clamps and a thick stainless-steel skin was developed to preload brittle Nb_3Sn coils and support large Lorentz forces. The maximum field for this design is limited by 15 T due to mechanical considerations. The first magnet assembly was done with lower coil pre-load to achieve 14 T and minimize the risk of coil damage during assembly.

This paper presents the MDPCT1 design and its parameters and reports the results of magnet training and magnetic measurements in the first test run.

MAGNET DESIGN AND PARAMETERS

The design concept of the 15 T Nb_3Sn dipole demonstrator and the details of magnet fabrication are presented in [2, 3]. The magnet design consists of a 60-mm aperture 4-layer shell-type coil, graded between the inner and outer layers, a cold iron yoke, a thick stainless steel shell, and a coil axial support structure.

The cable in the two innermost coil layers has 28 strands 1.0 mm in diameter, whereas the cable in the two outermost layers has 40 strands 0.7 mm in diameter. Both cables were fabricated at Fermilab using RRP Nb_3Sn composite wires produced by Bruker-OST. The 0.7 mm RRP-108/127 wire and the 1.0 mm RRP-150/169 wire have 41 and 52 µm subelements respectively to reduce the persistent current effect and improve cable stability with respect to flux jumps. The 0.025-mm thick and 11-mm wide stainless steel core is used in both cables to suppress the inter-strand eddy currents induced by the varying magnetic field in coils. The cables were insulated with two layers of 0.075-mm thick and 12.7-mm wide E-glass tape.

After winding, heat treatment at high temperatures in Argon to create superconducting Nb_3Sn phase, and impregnation with epoxy resin, the magnet coils were wrapped with four layers of 0.125-mm thick Kapton film and two 316L stainless steel sheets, each 2-mm thick, and placed inside the vertically-split iron yoke. The yoke is made of 1020 iron laminations with 587-mm outer diameter, connected by strong 7075-T6 aluminum I-clamps, and surrounded by a 12.5-mm thick 316 stainless-steel skin. The coils were supported axially by two 50-mm thick end plates made of 304L stainless steel connected by 8 stainless steel rods 30 mm in diameter.

The coil pre-stress at room temperature is provided by the mid-plane and coil-yoke shims, the yoke-clamp interference, and the yoke-skin shims. During and after magnet cooling-down, pre-stress is controlled by the size of the vertical gap between the yoke blocks. The transverse mechanical rigidity of the structure is provided by the rigidity of the iron laminations, aluminum clamps and skin.

Figure 1 shows the view of MDPCT1 from the magnet non-lead end.

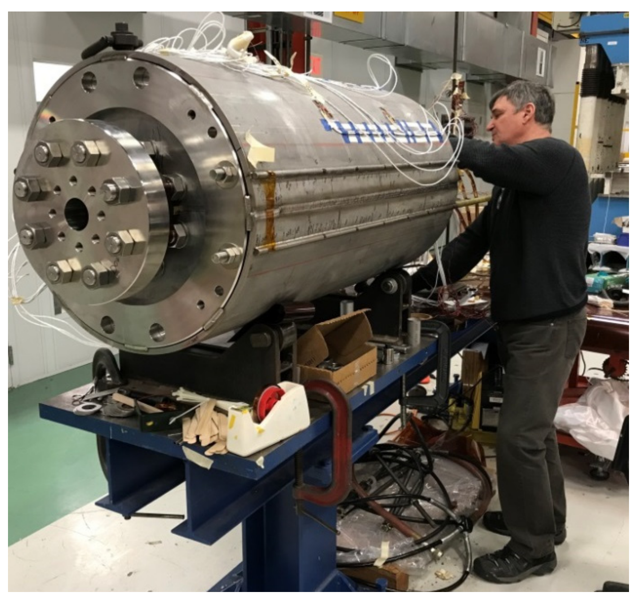

Figure 1: 15 T dipole demonstrator MDPCT1.

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† zlobin@fnal.gov

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The magnet parameters are summarized in Table 1. The magnet short sample fields at 1.9 and 4.5 K were calculated based on the test data of the coil witness samples.

Table 1: MDPCT1 Parameters

Parameter	Value
Magnet aperture, mm	60
Magnet outer diameter, mm	612
Geometrical length including splice box, m	1.46
Total magnet weight, kg	2390
Short sample bore field at 4.5 K $B_{ssl}(4.5K)$, T	15.16
Short sample bore field at 1.9 K $B_{ssl}(1.9K)$, T	16.84
Design bore field B_{des}, T	15.0

MAGNET TEST

MDPCT1 was tested at Fermilab's Vertical Magnet Test Facility in June 2019. The magnet test program in this test run was focused on the magnet training and magnetic measurements. The magnet training was performed at 1.9 K to the target field of 14 T, and the final quench was made at 4.5 K. The magnetic field measurements were executed in the field range up to ~14 T using 26 mm and 130 mm long, and 28 mm wide 16-layer Printed Circuit Board (PCB) probes [4]. The representative probe rotational speed was ~1 Hz.

The induction of magnetic field B in the accelerator magnet aperture is represented in terms of harmonic coefficients defined in the series expansion

$$B_y + iB_x = B_1 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1},$$

where B_x and B_y are the horizontal and vertical field components in the Cartesian coordinate system, b_n and a_n are the $2n$-pole normal and skew harmonic coefficients at the reference radius R_{ref}=17 mm. The right-handed coordinate system is defined with the z-axis at the center of the magnet aperture and pointing from return to lead end.

RESULTS AND DISCUSSION

Quench performance

The MDPCT1 quench history is plotted in Fig. 2. The magnet training started at 1.9 K. The first quench was detected at the magnet bore field of ~11.5 T. After four quenches the field in the magnet aperture exceeded 13 T and the training rate slowed down. The target field of 14 T for this test was achieved after eleven quenches, and then the magnet reached its quench plateau. The magnet was warmed up to 4.5 K and quenched again at the bore field of 14.1 T. This was the highest field reached in this test run. All the quenches were detected in the two outermost layers of both coils, except for quenches #12 and #15, which started in the innermost layer of one coil.

Quench bore field at 1.9 K and 4.5 K normalized on the short sample bore field B_{ssl} and on the design bore field B_{des}=15 T vs. the quench number is shown in Fig. 3. The magnet training started at ~67% of the B_{ssl} at 1.9 K, and the maximum bore field at 1.9 K was on the level of 84% of the B_{ssl}. At 4.5 K the magnet reached 93% of its B_{ssl} at this temperature. With respect to the magnet design field of 15T, the magnet training started at 75% and reached 94% of B_{des} value.

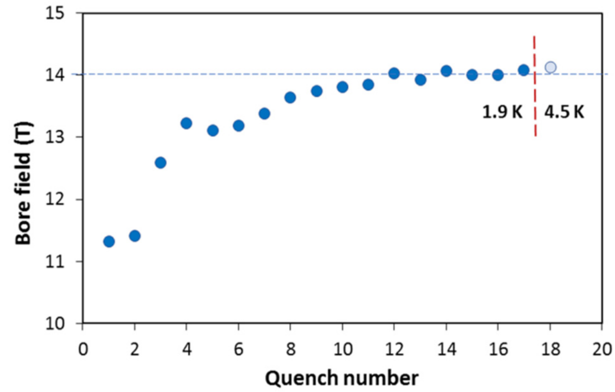

Figure 2: Magnet quench bore field vs. the quench number at 1.9 and 4.5 K.

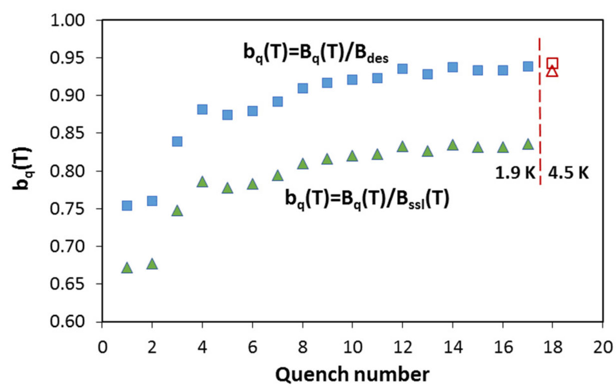

Figure 3: Normalized quench bore field vs. the quench number.

Magnet Transfer Function

Figure 4 shows the measured magnet transfer function (TF=B/I) vs. the magnet bore field. Due to the closeness of the iron to the coil, the iron saturation effect starts at B~2.5 T in the magnet aperture. At the bore field of ~14 T the magnet TF reduces from 1.778 to 1.452 T/kA or by 22.5%. At the low fields, the TF shows visible hysteresis due to the magnetization of the superconducting coils.

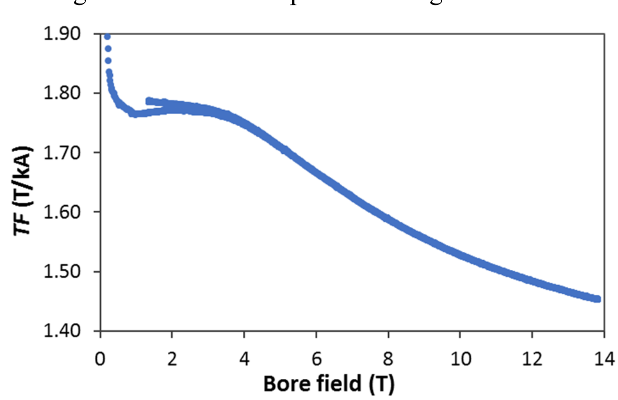

Figure 4: Transfer function TF vs. the magnet bore field.

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Field Harmonics

Figures 5-6 show the low-order allowed field harmonics b_3 and b_5 vs. the magnet bore field. The large hysteresis in b_3 and b_5 is due to the large coil magnetization related to the large superconducting filament size and high critical current density of the Nb_3Sn strands used in the magnet. Some small hysteresis was also seen in a_2 and a_3, which is likely due to a small difference of the radial sizes of top and bottom outer coils. The normal sextupole b_3 also shows a quite large iron saturation effect. Both effects are consistent with the theoretical predictions [3, 5] for the iron and superconductor magnetic properties that were used, and the magnet yoke geometry. The observed large coil magnetization and iron saturation effects can be reduced by special passive correction schemes discussed in [5].

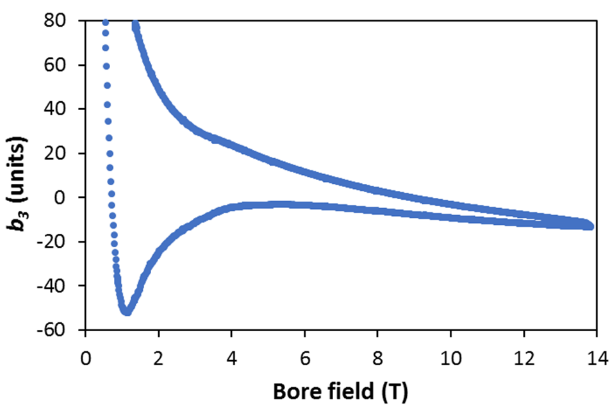

Figure 5: Normal sextupole b_3 vs. the magnet bore field.

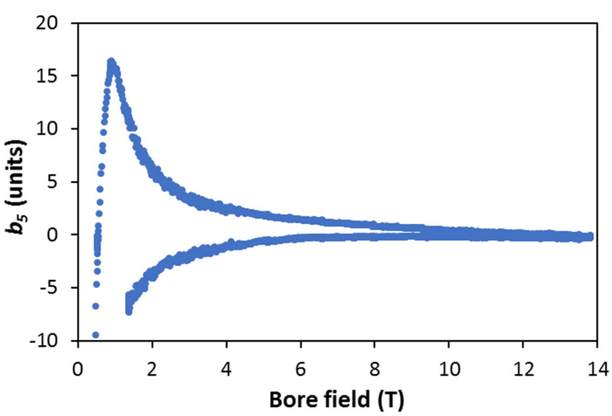

Figure 6: Normal decapole b_5 vs. the magnet bore field.

The geometrical harmonics, averaged over the probe length for MDPCT1, are presented in Table 2. They were obtained by averaging the values of measured harmonics during the field ramps up and down. It was done at the bore field of 2.5 T before the iron saturation effect starts impacting the field harmonics.

Table 2: Geometrical Harmonics (R_{ref}=17 mm)

n	2	3	4	5	6	7	8	9
b_n	2.0	10.3	0.6	0.9	0.1	1.2	0.1	0.3
a_n	-2.4	-4.4	0.0	-0.1	-0.1	0.1	-0.1	0.2

The design geometrical harmonics in the magnet straight section were minimized by optimizing the coil cross-section [3]. The measured quadrupole b_2 and a_2 and sextupole b_3 and a_3 geometrical components are relatively large due to the deviations of the "as-built" coil geometry from the design cross-section and coil alignment error inside the yoke.

CONCLUSION

Fermilab has developed and tested a 15 T Nb_3Sn dipole demonstrator MDPCT1 for a post-LHC hadron collider. Although the maximum field for this design is limited by 15 T due to mechanical considerations, the magnet was assembled with lower coil pre-load to achieve 14 T and minimize the risk of coil damage during assembly. In the first test in June 2019 the magnet after short training reached 14.1 T at 4.5 K or 94% of its design limit. It is the new world record for accelerator magnets. The magnet training was stopped at this point. It will continue in the second test run after increasing the azimuthal pre-stress and improving the axial support of magnet coils.

Magnet *TF* and low-order field harmonics were measured using rotating coils in the field range up to ~14 T. The measurements included geometrical components and contributions from the coil magnetization and iron yoke saturation effects. All the measured geometrical harmonics, except for a_2, a_3, b_2, b_3, are small, on the level of 1 unit or less. The coil magnetization effect in MDPCT1 at low fields is large due to the high critical current density and relatively large sub-element size in the contemporary Nb_3Sn strands. The iron yoke saturation effect in MDPCT1 starts at fields above 2.5 T and is also large. The eddy current effect in the cable on the *TF* and field harmonics in MDPCT1 was suppressed by using a stainless-steel core inside the cables.

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