NB_3SN ACCELERATOR MAGNET TECHNOLOGY R&D AT FERMILAB*

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Abstract

Accelerator magnets based on Nb_3Sn supercondutor are being developed at Fermilab. Six nearly identical 1-m long dipole models and several mirror configurations were built and tested demonstrating magnet performance parameters and their reproducibility. The technology scale up program has started by building and testing long dipole coils. The results of this work are reported in the paper.

INTRODUCTION

Nb_3Sn accelerator magnets allow magnet operation above 10 T and drastically increase the coil temperature margin relative to NbTi magnets. Magnets with such parameters are needed for the LHC IR upgrade, critical components of ILC, MSR and MC magnet systems.

Fermilab is developing Nb_3Sn accelerator magnets using shell-type dipole coils and the react-and-wind method. The R&D program includes the demonstration of main magnet parameters (maximum field, quench performance, field quality) and their reproducibility using a series of short models, and then the demonstration of technology scale up using relatively long coils. As a part of the first phase of technology development, more than fifteen 1-m long coils were fabricated and tested in six short dipole models and several dipole mirror models. The last three dipoles and two mirrors reached their design fields of 10-11 T. All six short dipole models demonstrated good, well-understood and reproducible field quality. The technology scale up phase started with building 2-m and 4-m long dipole coils and testing them in a mirror configuration. The status and results of the Nb_3Sn accelerator magnet R&D at Fermilab are reported.

MAGNET DESIGN AND TECHNOLOGY

The design and parameters of Fermilab's HFDA dipole series are described in [1]. These magnets are designed for a nominal field of 10-12 T at 4.5 K temperature. The design is based on a two-layer shell-type coil with 43.5 mm bore and a cold iron yoke. Fig. 1 shows the cross-section of the HFDA coil and cold mass.

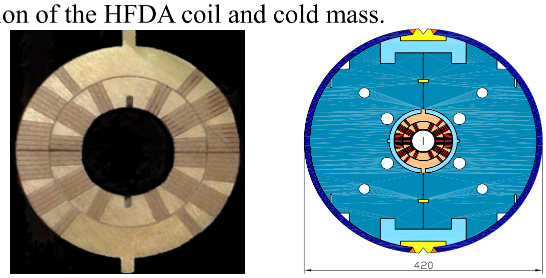

Figure 1: HFDA coil and magnet cross-sections.

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The coils were wound using keystoned Rutherford-type cable made of 28 (recently 27) Nb_3Sn strands, each 1 mm in diameter. The cable used in HFDA02-03 coils had 25 μm thick stainless steel core to control the strand crossover resistance while the cable used in HFDA04-07 coils was without a core.

The strand for the first three models HFDA02-04 was produced using the Modified Jelly Roll (MJR) process. The strand for the last three models HFDA05-07 was made using the Powder-in-Tube (PIT) process. The MJR strand had higher critical current density J_c(12T, 4.2K)~2-2.2 kA/mm^2 and larger filament size d_{eff}~100-110 μm whereas PIT strand had lower J_c~1.6-1.8 kA/mm^2 and smaller d_{eff}~50-60 μm [2]. A new improved strand based on Restack Rod Process (RRP) was recently developed by Oxford Superconductor Technologies [3]. This strand provides highest Jc (<3 kA/mm^2) and has a larger number of sub-elements with smaller size (~70 μm). This strand was chosen as the baseline conductor and was already used in two 1-m coils.

The coil fabrication technology is based on the wind-and-react method when superconducting Nb_3Sn phase is formed after winding during coil high-temperature heat treatment. This technique requires using special high-temperature insulation and metallic coil components. A significant improvement of the Nb_3Sn coil fabrication technology was achieved at Fermilab by using a ceramic binder [4]. To improve insulation properties after reaction, the Nb_3Sn coil is vacuum impregnated with epoxy.

SHORT MODEL R&D

Quench Performance

Six short dipole models were fabricated and tested in liquid helium at 4.5 K and lower temperatures. The first three models HFDA02-04, made of the MJR strand, were limited by flux jumps in superconductor and reached only half of their design field [4]. Fig. 2 summarizes the quench performance of the last models HFDA05-07.

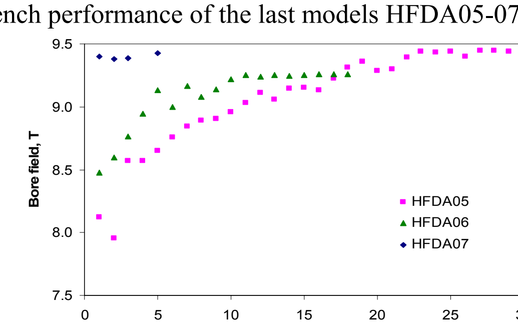

Figure 2: Magnet training at 4.5 K.

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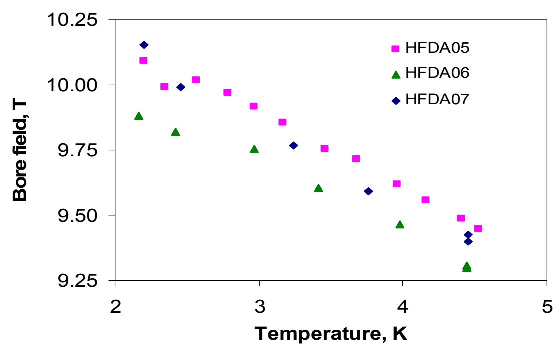

Figure 3: Maximum bore field vs. coil temperature.

All the three magnets, made of the more stable PIT strand, reached the maximum bore field of 9.3-9.4 T at 4.5 K. The reached field level was limited by the low critical current density of the PIT strand. Reducing the coil temperature to 2.2 K (and respectively increasing the superconductor J_c) the maximum bore field in all the three models increased to ~10 T (see Fig. 3).

The ramp rate dependences of magnet quench field normalized to the maximum quench field reached during training at 4.5 K and dI/dt=20 A/s for HFDA05-07 are shown in Fig. 4. Measured ramp rate dependences are well reproducible for all the magnets. The shape of ramp rate dependences at low current ramp rates suggests that it is dominated by the eddy current losses in the cable. At current ramp rates higher than 200 A/s the quench field drops dramatically due to high AC losses and limited cable cooling conditions in the coil.

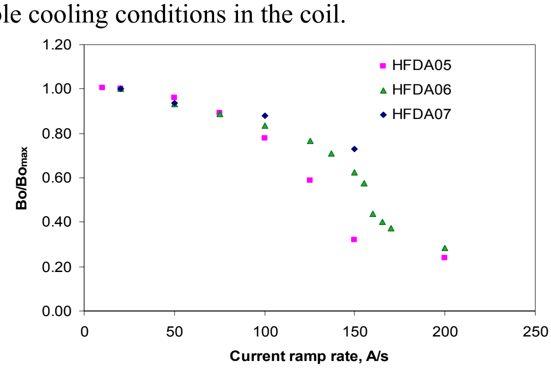

Figure 4: Ramp rate sensitivity of magnet quench field.

Field Quality

The field harmonics were measured at 4.5 K. They are reported at R_{ref}=10 mm. The HFDA02-07 geometrical harmonics determined as the average values between the current up and down ramps at 3 kA are shown in Table 1.

Table 1: HFDA02-07 geometrical field harmonics, 10^{-4}.

n	Average		St. deviation	
	a_n	b_n	a_n	b_n
2	-0.37	-0.15	7.3	4.1
3	0.55	2.06	0.6	4.3
4	-0.73	-0.06	0.9	0.7
5	0.17	0.60	0.1	0.9
6	-0.04	0.00	0.2	0.2
7	0.01	0.20	0.1	0.2
9	-0.02	-0.05	0.1	0.1

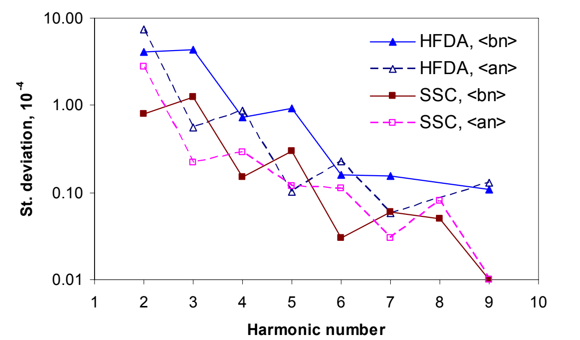

Figure 5: Comparison of normal $<b_n>$ and skew $<a_n>$ random errors in Nb_3Sn (HFDA) and NbTi (SSC) dipoles.

The average values of the low order harmonics in HFDA models are rather small, below one unit, except for the normal sextupole. Standard deviations of the normal and skew gradient and the normal sextupole are also relatively large with respect to the other harmonics.

The standard deviations of normal and skew harmonics measured in six HFDA models are plotted in Fig. 5 and compared with the results for the first six 40-mm SSC dipole models based on the traditional NbTi technology [5]. The variation of skew harmonics in Nb_3Sn models is quite close to the level of NbTi technology. The variation of normal harmonics is larger since it includes not only the coil component errors but also the adjustments of coil pre-stress shims. The reproducibility of both normal and skew harmonics will be improved.

The coil magnetization effect in dipole magnets is most pronounced in the normal sextupole. The results of its measurement in HFDA02-07 models are shown in Fig. 6 where the width Δb_3 of normal sextupole loop at Bo=2 T is plotted as a function of the current ramp rate.

The HFDA02-04 models demonstrate a very small and thus reproducible eddy current effect. Analysis shows that it is due to large crossover resistances in the cable with the stainless steel core and the high resistance of the strand matrix (RRR~10). The Δb_3 in HFDA05-07 models rapidly changes with the ramp rate. The negative slope of the Δb_3 ramp rate dependences indicates that the effect is determined by the eddy currents in the cable rather than in the strands in spite of the high conductivity of the copper matrix in PIT strands (RRR>50). The above results suggest that the eddy current magnetization effect can be reduced using cored cables and well-twisted strands.

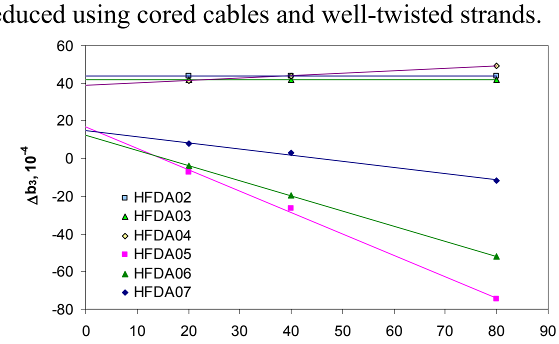

Figure 6: Ramp rate sensitivity of the normal sextupole.

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The sextupole loop width Δb_3 extrapolated to dI/dt=0 represents the persistent current part of coil magnetization proportional to $J_c \cdot d_{eff}$. The persistent current effect is reproducible in HFDA models made of the same strands. The sextupole hysteretic loops in HFDA02-04 were larger than in HFDA05-07 due to higher J_c and larger d_{eff} in MJR strands. This also led to the substantial variations of sextupole at low fields in these models related to the flux jumps in superconductor [6]. The large persistent current effect and its variations in Nb_3Sn accelerator magnets can be reduced by using strands with small sub-element size. The main component can also be compensated using a simple passive correction based on thin iron strips [7].

The effect of iron yoke saturation on the magnet transfer function and field quality in HFDA design was measured in HFDA05-07, which reached the field level of 10 T. The measured reduction of the magnet transfer function is in a good agreement with the calculations. It was also confirmed that the iron saturation effect in sextupole was effectively suppressed at high fields using special correction holes in the yoke.

TECHNOLOGY SCALE UP

After successful testing of several 1-m long dipole coils, a Nb_3Sn technology scale-up program has been launched. The goal of this program is to expand the developed Nb_3Sn coil technology based on the wind-and-react method to long coils. The key issues to be addressed by this program include the long Nb_3Sn coil winding, curing, reaction, impregnation, handling, and magnet assembly. The long coil testing is an essential part of the program due to brittle nature of Nb_3Sn superconductor.

The scale-up is performed in two steps starting with a 2-m long coil made of PIT Nb_3Sn strand which has demonstrated the good stability and reproducible performance. This will be followed by 4-m long coil made of advanced RRP Nb_3Sn strand [3].

Reference 1-m long coils made of PIT and RRP strands were fabricated and tested in the mirror configuration. The mirror model with a 2-m long PIT coil was also fabricated (Fig. 7) and tested. Training curves of the 1-m long PIT (HFDM03) and RRP (HFDM06) mirror models and the 2-m long PIT mirror model (LM01) at 4.5 K are shown in Fig. 8. The PIT mirror models reached their short sample limit and the field level of 10 T. Comparison of LM01 and HFDM03 quench performance shows that they are practically identical demonstrating that the goal of the first step of scale up program has been achieved.

Figure 7: 2-m long mirror LM02 with PIT coil.

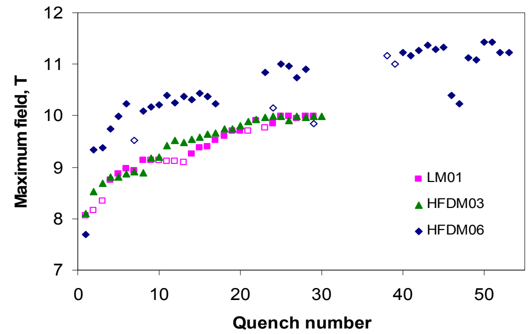

Figure 8: Mirror models training summary at 4.5 K. Open markers represent power supply trips.

The RRP mirror model with new strand reached 97% of its short sample limit and the maximum field of 11 T. Now this result has to be reproduced by the 4-m long RRP coil. To improve the magnet training performance the coil pre-stress in the 4-m long mirror will be adjusted for the higher field level expected in this model.

CONCLUSION

Six nearly identical 1-m long Nb_3Sn dipoles and several dipole mirror models were fabricated and tested at Fermilab. The design field of 10-11 T, limited by the conductor critical current density, was reached in the last three dipole and two mirror models. The quench performance and field quality data confirm the good reproducibility and robustness of the developed magnet design and technology. The scale up program of the Nb_3Sn accelerator magnet technology was started with successful testing of a 2-m long coil. The fabrication of a 4-m long coil is well underway. It will be assembled into a mirror configuration and tested in September 2007.

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