Title
Progress Toward 10 Telsa Accelerator Dipoles

Permalink
https://escholarship.org/uc/item/7qb9g9k4

Author
Hassenzahl, W.

Publication Date
1983-04-01

LBL-16607

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

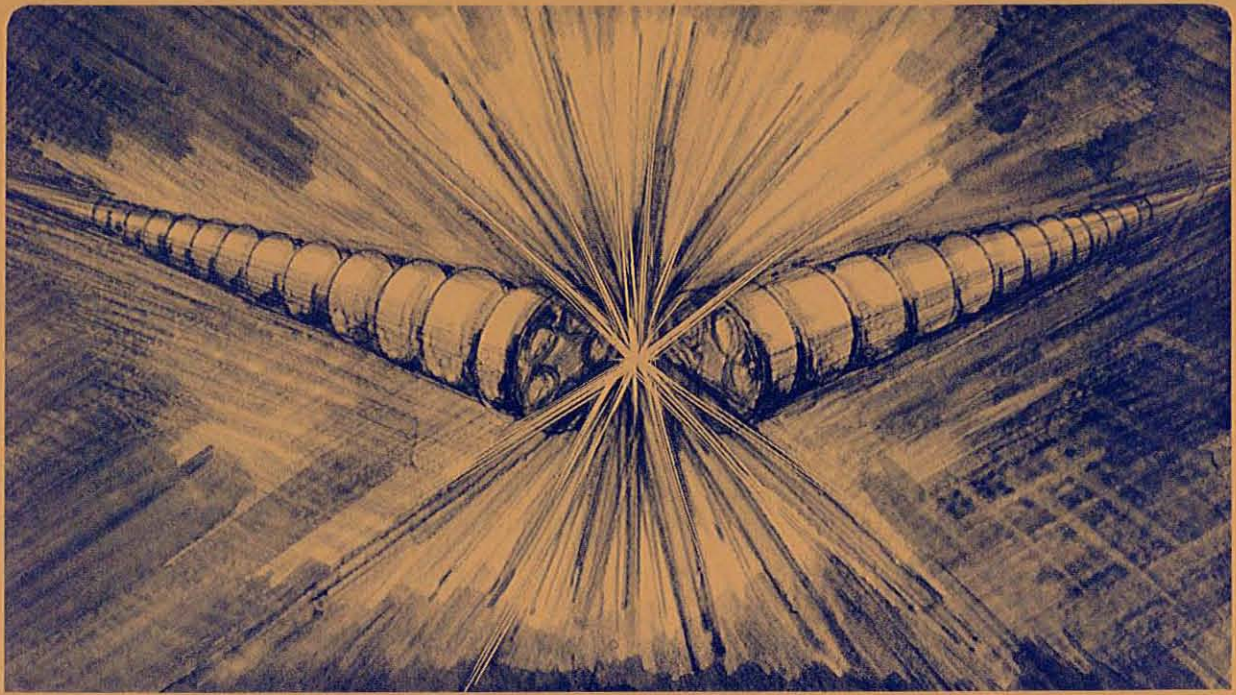
Accelerator & Fusion Research Division

Presented at the Eighth International Conference
on Magnet Technology, Grenoble, France,
September 5-9, 1983

PROGRESS TOWARD 10 TESLA ACCELERATOR DIPOLES

W. Hassenzahl, G. Gilbert, C. Taylor,
and R. Meuser

August 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Resumé - Un champ central de 9,1 T a été accomplit par un dipole Nb-Ti dans helium II sous pression atmospheric de 1,8 K. Trois dipoles Nb-Ti, sans fer, ont accomplis des champs centrals de 8,0, 8,6, and 9,1 T -- tous sont a les courant critiques d'echantillon court à 1,8 K. Dans helium I, a 4,3 K, les champs centrals sont redues par 1,5 jusqu'à 2,0 T.

Aimants specials de dix tesla ont été dessines pour Nb-Ti a 1.8 K et Nb_3Sn á 4.2 K. Ces dessins se sont basés sur petites apertures, entre 40 et 45 mm, densítés de courants trés elevés, plus hautes que 1000 A/mm^2 dans le supraconducteur, et un rapport tres bas entre le cuivre et le supra, environ 1. Dessins de couches et de blocs ont été developés qui utilisent "Rutherford Cable".

On a fait des cycles de champs des aimants Nb-Ti de 0 jusqu'a 6 T a une vitesse jusqu'à 1 T/s. Les pertes cyclic a 1 T/s sont 36 W (pour un aimant de longeur 1 m). A 0,2 T/s les pertes sont seulement 2 W.

Le progress dans notre program par utiliser Nb_3Sn et NbTi dans les aimants de 10 T seront discutés.

Abstract - A 9.1 T central field has been achieved in a Nb-Ti dipole operating in pressurized helium II at 1.8 K. Three different Nb-Ti dipoles, without iron yokes, have achieved central fields of 8.0, 8.6, and 9.1 T -- all short sample performance for the conductors at 1.8 K. In helium I, at 4.3 K, the maximum central fields are from 1.5 to 2.0 T lower.

Ten-tesla magnets have been designed for both Nb-Ti operating at 1.8 K and Nb_3Sn operating at 4.2 K. They are based on a very small beam aperture, (40 to 45 mm), very high current density in the superconductors (over 1000 A/mm^2), and a very low ratio of stabilizing copper to superconductor (about 1). Both layer and block designs have been developed that utilize Rutherford Cable.

Magnet cycling from 0 to 6 T has been carried out for field change rate up to 1 T/s; the cyclic heating at 1 T/s is 36 W per meter. At a more representative rate of 0.2 T/s the heating rate is only 2 W/m.

Progress in our program to use Nb_3Sn and NbTi superconductor, in 10 T accelerator magnets will also be discussed.

INTRODUCTION

Existing high-energy proton accelerators[1] have reached a size that appears to be a limit of machines using conventional magnets, and the first accelerator using superconducting magnets, the Fermilab Energy Doubler[2], is just beginning to operate. Because superconducting magnets allow both size and operating costs to be reduced they appear to be the clear choice for future high-energy synchrotrons[3,4], unless some other acceleration technology is developed.

The optimum field and the bore of the superconducting magnets destined for future machines are not certain. The choice of these parameters will be based on tradeoffs among many factors. Lower fields mean larger accelerators, which increases the cost of tunneling and conventional services. The volume of superconductor increases faster than the design field, however, and at very high field, greater than about 11 T, the current carrying capacities of conductors available at present become too small for consideration. Synchrotron radiation increases as the local field to the fourth power and for a 20 TeV accelerator, may limit the field to about 10 T because of the increased refrigeration load. Though the economic optimum may be somewhat lower, a likely upper limit imposed by these consideration is about 10 T which was set as an ultimate design goal for the magnets we are developing at the Lawrence Berkeley Laboratory.

The design bore of an accelerator is determined by cost, field quality, alignment accuracy, and the ease with which the beam can be steered. Recent experience at Fermilab indicates that a 75 mm inner winding diameter is satisfactory for synchrotron operation. We have used 58.5 mm for our recent magnet development program and see no fundamental limitation down to about 40 mm. Special consideration must be given to the ends of small magnets however, due to difficulty in bending conductors around the small radius at the pole.

CONDUCTOR

Two commercial superconductors: an alloy of niobium and titanium (Nb–Ti), and a compound of niobium and tin (Nb_3Sn), can be used in the field range near 10 T for accelerator dipoles. The approximate field limits for these materials are shown in Table I, and some critical current densities are given in Fig. 1.

Table I

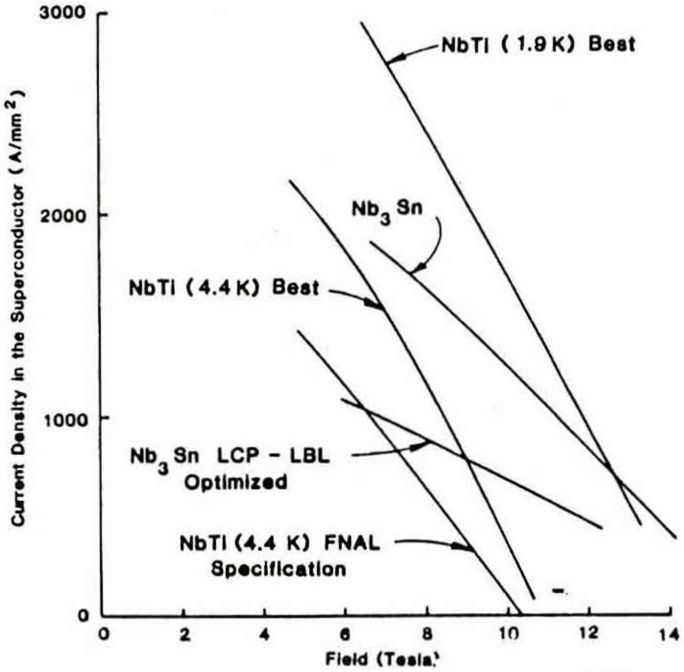
Maximum Design Field for Superconducting Accelerator Dipoles

Material	Temperature	Maximum Field
Nb–Ti	4.3 K	8 T
Nb–Ti	1.8 K	10 T
Nb_3Sn	4.3 K	10 T

The conductor used in the Nb–Ti magnets constructed at LBL has had a relatively low copper to supercondcutor ratio, between 0.86 and 1.5. By reducing this ratio as the field increases, the current density in the windings can be maintained at a high value, which keeps the total superconductor requirement down. The current density in the stabilizing copper, which affects stability and protection, changes very little. A copper-to-superconductor ratio of about 1.0 has been selected for our future developmental magnets.

Recently a multifilamentary Nb_3Sn conductor having a high critical current density has been developed[5,6] that uses a tin rich region, and does not have a bronze matrix initially. This avoids the costly annealing that is characteristic of bronze process Nb_3Sn. The characteristics of material manufactured by IGC and recently tested by LBL are equal to the best critical current densities shown in Fig. 1, or about 1500 A/mm^2 at 9 T.

If Nb–Ti is to be used in magnets with fields above about 8 T, the operating temperature must be reduced below 4.3 K, the temperature of liquid helium in equlibrium with helium gas at atmospheric pressure. A recent and effective development in cryogenics has been the operation of magnets at 1.8 K in liquid helium at atmospheric pressure, which has been straightforward, considerably simpler, and more reliable than many expected. The experience of laboratories that work with magnets in this temperature range has been that the anticipated problem of superleaks has not materialized because good seals (in particular, heliarc welds) for liquid helium are also superfluid tight.



XBL 8210-3095

Fig. 1. - Critical current densities in commercially available supercondcutors. The top curve for Nb_3Sn corresponds to Nb_3Sn tape and some recently developed high-internal Sn material.

MAGNETS

During the past year we have built and tested three Nb-Ti dipoles. Two are of the layer design, as shown in Fig. 2, and one is of the block design, as shown in Fig. 3. Details of magnet design and some test results have been described elsewhere[6,7,8,9]. The characteristics of these magnets are summarized in Table II. The Nb-Ti dipoles tested generally reach about 30% higher fields at 1.8 K than at 4.3 K.

Table II

Summary of Small-Bore, Nb-Ti Accelerator Dipoles Designed and Tested at LBL

Magnet Name	Design	Field (T)		Cu:Sc Ratio	Training
		4.3K	1.8K		
D-9A	4 layer	5.9	8.0	1.5	No
D-9B	4 layer	7.1	8.6	1.0-1.3	Yes
D-10B	8 pancakes	7.0	9.1	0.9	Yes

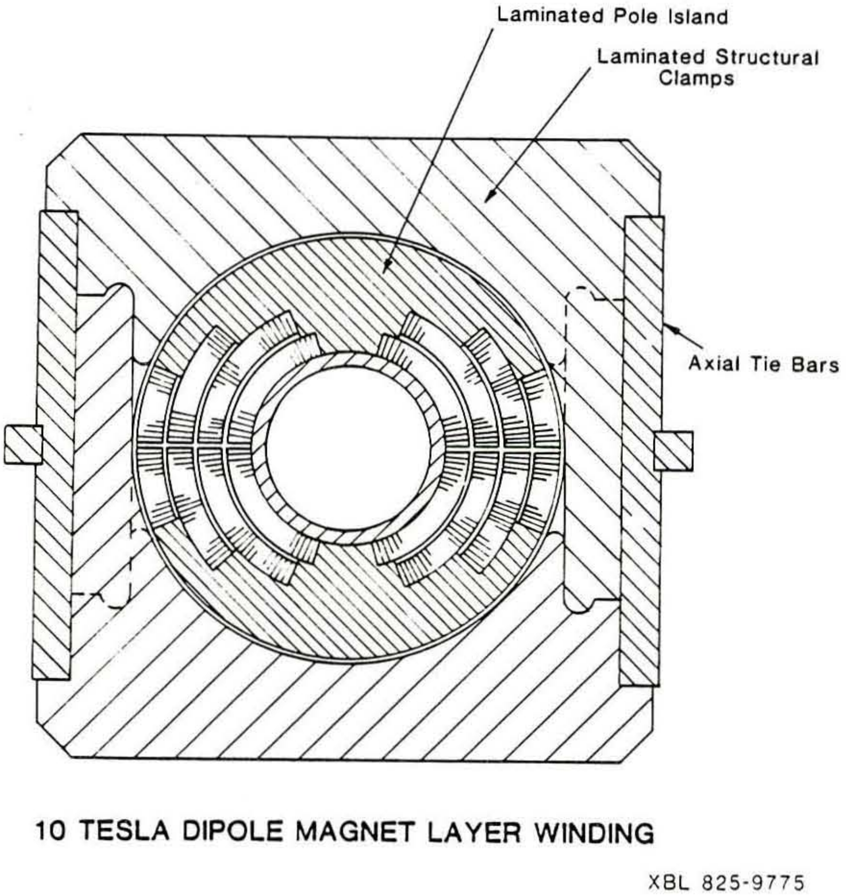


Fig. 2 - Cross section of D-9A, a typical 4 layer or 4 shell dipole.

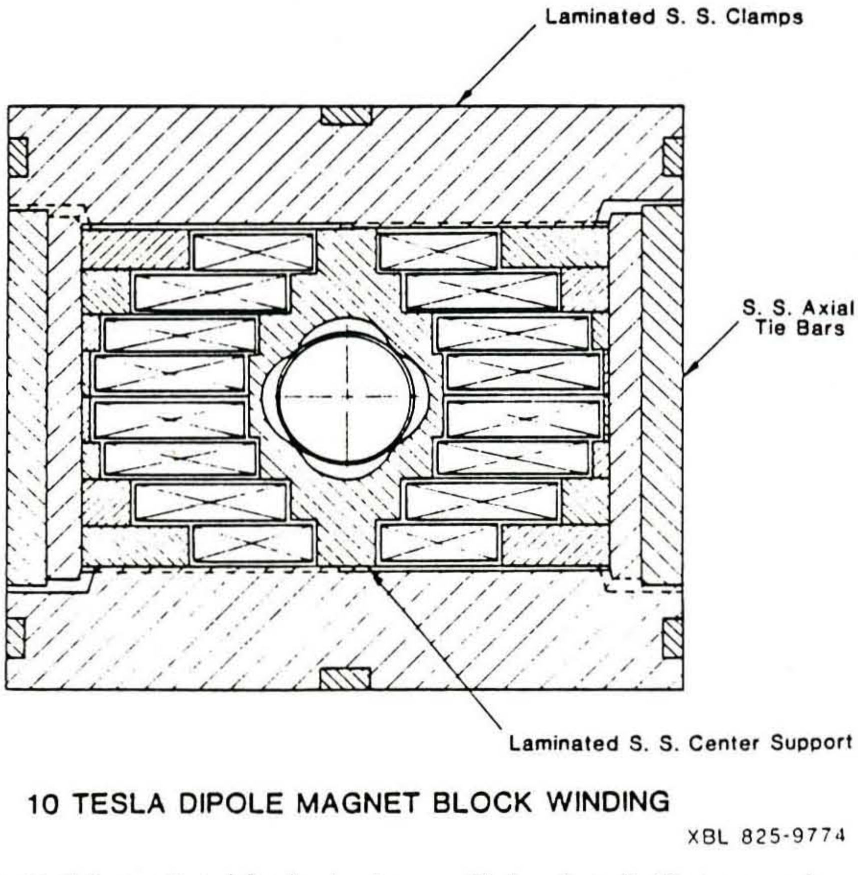


Fig. 3 - Cross section of a block design coil having 8 flat pancakes.

In the layer design the coil winding can support an inward radial load in the straight section and, when clamped under the maximum stress, remains separated from the stainless steel bore-tube by about 0.5 mm. A layer of 1-mm-thick nylon monofilament is wound over each layer to (1) provide a pre-compression before the subsequent layers are applied, (2) aid the external rings in supplying the final preload, and (3) provide a path for helium to flow circumferentially around the coil. The ends of the coil, which are not self supporting, contact the bore-tube and are under both a radial load and some circumferential load due to the nylon banding and external rings.

The ends of the coil layers are staggered, with the outer coils shorter, to reduce the maximum field at the innermost turn of the first layer. The high-field region is in the straight section of layer one. Neglecting end effects, the maximum field rise in the straight section of layer 1 is about 3% on the first turn.

The D-9A dipole performed better than any other first coil in a series that we have constructed. At 4.3 K the first quench was at 80% of short sample currents, and the second was at 100%. The performance in He II at 1.8 K was similar, with the first two quenches at 90% and 100% of short sample, 7.2 and 8.0 T, respectively. During the second test of this coil, which is now underway, we hope to learn if relaxation of prestress in the non-metallic portions windings will affect performance.

In the block or pancake coil, the coil sections are wound from heavy rectangular cable in flat pancake or race-track pairs. The particular geometry was chosen to enable heavy Nb_3Sn cable to be wound into a small-aperture dipole.

To test the new geometry for fabrication practicality and also to test the magnet for training and other pertinent behavior, we built D-10B using Nb-Ti cable.

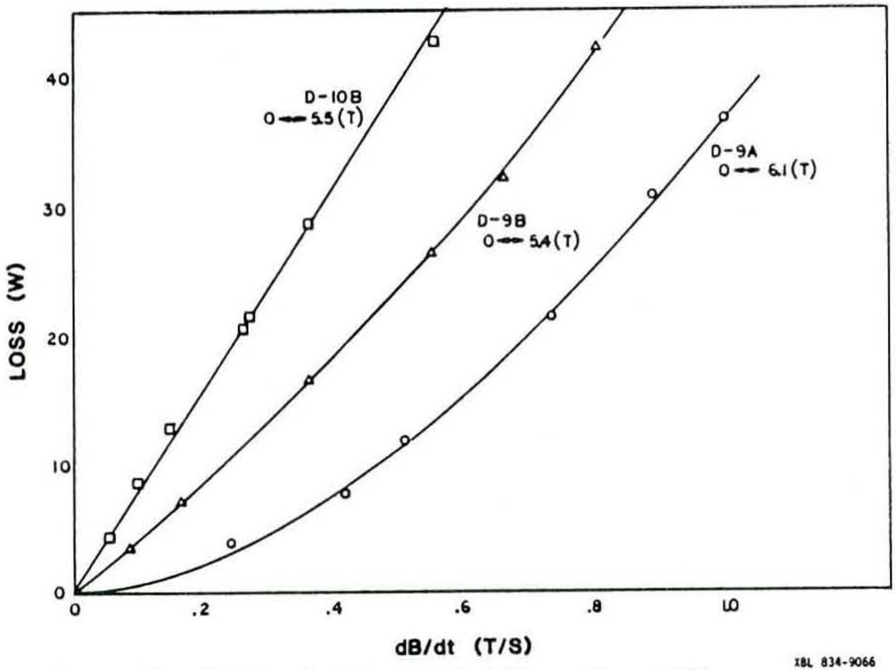
The first quench in D-10B at 4.3 K was about 80% of its short-sample, or some 5.5 T central field. The training was moderately slow, some 25 quenches to short sample. It is not clear whether this slow training is due to a superconductor stability problem, which might result from a low copper-to-superconductor ratio, to structural and pre-stress problems, or to conductor or manufacturing defects in one pancake pair. Most quenches occured in the pancake pair 3 and 4 of the bottom half. The maximum central field reached at 4.3 K is 7.0 T, and we believe it to be short-sample performance because the same current is reached before and after operation at higher currents in He II. Also, the character of the quenches, which is quite reproducible, is that of conductor operating at short sample. Some training also occurred in He II, in which a peak field of 9.1 T was reached.

Cyclic Losses

In He II one can measure the heat generated by magnet cycling by monitoring the bath temperature movements. And by observing simultaneously the voltage and current in the coil. The losses as a function of field change rate for magnets D-9A, D-9B and D-10B are shown on Fig. 4.

Inspection of the three curves shows that the D-10B behavior is linear, which means the loss is hysteretic in nature, occurring in the superconductor itself. The D-9A behavior is mostly quadratic on top of a small linear term, showing that most of the loss is eddy or coupling type in the cable with a small component due to the linear or hysteretic portion. The D-9B loss lies between the other two.

We can estimate the ratios of the hysteretic type losses to be found in the three magnets based on the material constants for the superconducting cables in magnets, as listed in Table III. The ratios of the linear slopes are in good agreement with those expected from the material constants, i.e., 1.00; 2.83; 7.44, as shown in the equations below Table III.



XBL 834-9066

Fig. 4 – Losses in coils D-9A, D-9B and D-10B. The differences can be ascribed to different filament sizes and different quantities of conductor in the coil.

Table III

	D-10B	D-9A	D-9B[a] Layers 1+2	D-9B[a] Layers 3+4
Cable Length (m)	394	370	215	163
No. Strands	27	23	21	23
Dia. Strands (mm)	.80	.67	.75	.67
Cu: S.C.	0.85	1.5	1.06	1.3
No. Filaments	409	2100	620	500
Filament Dia. (μm)	29.36	9.39	21.3	20.1
Vol. Cable (cm^3)	5.45×10^3	3.09×10^3	2.06×10^3	1.37×10^3
Vol. S.C. (cm^3)	2.95×10^3	1.24×10^3	1.00×10^3	0.59×10^3

a. For D-9B use $V_{S.C.} = 1.59\times10^3 cm^3$ and $d = 20.7$ μm.

$$\frac{L_{D-10B}}{L_{D-9A}} = \frac{(\mathrm{Vol\ S.C.})_{D-10B}}{(\mathrm{Vol\ S.C.})_{D-9A}} \frac{d_{D-10B}}{d_{D-9A}} = 7.44$$

$$\frac{L_{D-9B}}{L_{D-9A}} = \frac{(\mathrm{Vol\ S.C.})_{D-9B}}{(\mathrm{Vol\ S.C.})_{D-9A}} \frac{d_{D-9B}}{d_{D-9A}} = 2.83$$

The dominant factor in intra-cable coupling loss is the contact resistance at the strand cross-over points. As pressure on the cable increases this contact resistance decreases and the quadratic type losses increase. The observed coupling losses in Fig. 4 are qualitatively in agreement with the precompression applied during manufacture. Magnet D-9A had the most compressive pre-stress, D-9B less, and D-10B the least.

FUTURE PROGRAM

We are in the process of constructing two additional dipoles having nominal 50 mm cold bores. One is a four-layer design called D-9C and is similar to the two magnets, D-9A and D-9B. The differences are mainly in the conductor, which is graded. The conductor strands in the two cables used in D-9C are from the same billet and have a 1.0 copper-to-superconductor ratio. The cable for layers 1 and 2 has 21 strands of 0.79 mm (0.0318") and that for layers 3 and 4 has 27 strands of 0.67 mm (0.023") conductor. The current density in the outer two layers is 60 higher than in the inner two layers. Special fabrication fixtures for winding this coil are complete, and half of one layer has been wound.

The D-10A coil is a wind-and-react Nb_3Sn coil made of 8 pancake layers. It is similar in cross section to D-10B, which was described above and shown in cross section in Fig. 2. The conductor is wrapped with a glass insulation that can withstand the abrasion of winding and the ~700°C reaction temperature.

The conductor for D-10A is a 11 strand Nb_3Sn, Rutherford cable supplied by the Intermagnetic General Company. Each strand is 1.7 mm (0.068") diameter and has 2 to 3 μm diameter filaments.

The first half of D-10A and the outer two layers of D-9C have been fabricated. Both D-9C and D-10A should be completed and tested, including magnetic field measurements, in 1983. In addition, because it now appears that the next high energy proton accelerator in the U.S. may operate at a lower field we are turning our attention to graded 2-layer, 40 mm bore dipoles.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the help of the following members of the superconducting group's staff in designing, fabricating and testing these coils: C. Peters, J. Rechen, R. Wolgast, S. Caspi, A. Borden, R. Schafer, J. O'Neill, R. Hannaford, L. Parsons, T. Young, D. Kemp, and R. Althaus.

REFERENCES

1. The Fermilab Staff presented by P.V. Livdahl, "Operating Results from Fermilab," IEEE Trans. on Nucl. Science, Vol. NS-22, No. 3, June 1975, pp. 929-935.

2. H. Edwards, "Fermilab Tevatron," Proceedings 12th International Conference on High-Energy Accelerators, Fermilab, August 1983.

3. G. Horlitz and S. Wolff, "Performance of 1-m long/100 mm bore Superconducting Dipole Prototypes for HERA," IEEE Trans. on Magnetics, Vol. MAG-19, No. 3, May 1983, pp. 1343-1347.

4. N.I. Andreyev, V.I, Balbekov, E.A. Bulatov, Yu.P. Dmitrevskiy, V.I. Dolzhenkov, K.F. Gertsev, V.I. Gridasov, K.P. Myznikov, V.V. Sytnik, N.M. Tarakanov, L.M. Vasiliev, V.A. Vasiliev, and V.V. Yelistratov, "Development and Study of the UNK Superconducting Dipole Models," to be published in the Proceedings of the XII International Particle Accelerator Conference, Fermilab, August 1983.

5. R.E. Schwall, G.V. Ozeryansky, D.W. Hazelton, S.F. Cogan, and R.M. Rose, "Properties and Performance of High Current Density Sn-Core Process MF Nb_3Sn," IEEE Trans. on Magnets, Vol. MAG-19, No. 3, May 1983, pp. 1135-1138.

6. W.K, McDonald, C.W. Curtis, R.M. Scanlan, D.C. Larbalestier, K. Marken, and D.B. Smathers, "Manufacture and Performance of Nb_3Sn Conductors Fabricated by the MJR Method," ibid, pp. 1124–1127.

7. W.V. Hassenzahl, C. Peters, W. Gilbert, C. Taylor, and R. Meuser, "A Four Layer, Two-Inch-Bore, Superconducting Dipole Magnet," IEEE Trans. on Magnets, Vol. MAG-19, No. 3, May 1983, pp. 1389–1393.

8. W.V. Hassenzahl, S. Caspi, W. Gilbert, C. Peters, J. Rechen, and C. Taylor, "A Layer-Wound, 8.7-Tesla Superconducting Dipole Magnet," IEEE Trans. Nucl. Sci., Vol. NS-30, No. 4, Aug. 1983, pp. 3396-3398.

9. W. Gilbert, S. Caspi, W. Hassenzahl, R. Meuser, C. Peters, J. Rechen, R. Schafer, C. Taylor and R. Wolgast, "A 9.1 T Iron-Free Nb-Ti Dipole Magnet with Pancake Windings," ibid, pp. 2578–2580.

10. W.V. Hassenzahl, W. Gilbert, C. Taylor, and R. Meuser, "LBL Program on 1-meter-long, 50-mm Diameter Bore, Dipoles with Fields Greater than 8 Tesla," to be published in the Proceedings of the XII International Conference on Particle Accelerators, Fermilab, August 1983.