IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

TEST DIPOLE MAGNETS FOR THE TRISTAN SUPERCONDUCTING PROTON RING

S. Mitsunobu, K. Hosoyama, A. Yamamoto, J. Kishiro, T. Kohriki, T. Kubo, H. Hirabayashi and Y. Kimura
National Laboratory for High Energy Physics, Oho-machi, Tsukuba-gun, Ibaraki-ken, 305, Japan

Abstract

Two test dipole magnets have been constructed for the TRISTAN superconducting proton ring. The magnet is a warm bore and warm iron type. The inner coil diameter is 14 cm and the coil length is 1.1 m. The Fermilab type collaring coil structure is adopted for its strong mechanical properties at high stressed conditions. The coil is wound in double shells with keystoned compacted cables of 27 NbTi strands. After 21 training cycles, the first magnet has been excited successfully up to 5.1 T in the central field, and the second magnet has been excited also up to 5.25 T after 12 quenches.

Introduction

An accelerator facility, TRISTAN is proposed at KEK for collisions between high energy electron and proton beams[1]. To attain collision energies as high as possible, the proton beams are accelerated and stored in a superconducting magnet ring. The present design requires a bending field of 4.5 T to obtain the nominal proton energy of 300 GeV. A magnet with rather large bore is required due to large beam size at injection and sagitta in magnet. We started developing large bore and high field magnet since two years ago.

The electron-proton collider requires 288 dipole magnets which have a field homogenity of $\pm 1 \times 10^{-4}$ within holizontal aperture of 90 mm in diameter and magnetic length of 4.84 meters.

Magnet Design and Construction

As the first step of developing of superconducting accelerator magnets, we have designed a warm iron and warm bore magnet, named TRISTAN Test Dipole, which has the inner coil diameter of 140 mm and coil length of 1.1 m. In early stage of the designing work, we studied mechanical properties and turn to turn insulation at highly compressed conditions of compacted strand cables. The cable has been used for the superconducting dipoles which will be installed in the beam line of the 12 GeV P.S.[2]. To obtain high enough prestress on a soft coils of compacted strand cables, the coil has to be compressed in large amount. Then we adopted the Fermilab type collaring structure for its strong mechanical properties at highly compressed conditions. The cross section of the magnet is illustrated in Fig. 1 and its principal parameters are listed in Table 1.

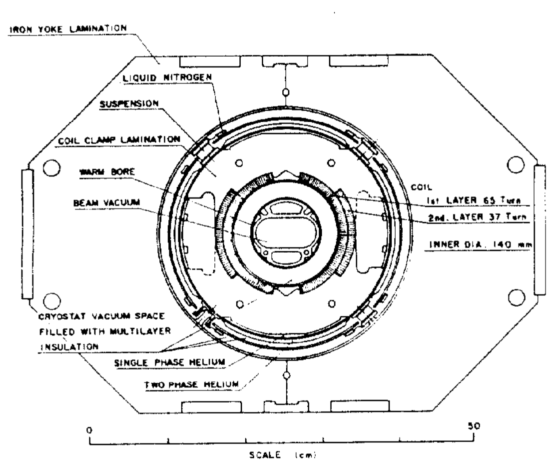

Fig. 1 TRISTAN Test Dipole Cross Section

Table 1 Parameters of TRISTAN Test Dipole

Coil Inner Diameter	140 mm
Warm Bore Diameter	90 mm
Coil Length	1100 mm
Magnetic Length	850 mm
Central Field	5 T
Current at 5 T	4870 A
Stored Energy	300 KJ
Inductance	25 mH
Bursting Force	2.2 ton/cm

The coil was wound in double shells using Rutherfored type compacted strand cable, which is the NbTi keystoned flat cable containing 27 strands of 0.71 mm in diameter. The cable is supplied by Furukawa Electric Co. Ltd., and has critical current of 5,500 A at 5.5 T and 4.2 °K. Table 2. summarizes its parameters. The cable is insulated with 25 μ thick Kapton tape. The inner coil was wound on a mandrel and cured in a 500 tons hydraulic press at 130 °C for 8 hours. We found that the total thickness of insulator, 175 μ, was reduced to about 90 μ after curing process. In the similar way, outer coil was wound allowing helium channels between two shells of the conductors.

Transversal magnetic forces working on the coil at full excitation of 5 T are calculated to be 0.68 tons/cm azimuthally and 2.2 tons/cm horizontally. To obtain azimuthal prestress of 4 kg/mm^2 at 4.2 °K, we chose the oversizing value of the inner and outer coil to be 1.5 mm and 0.8 mm, respectively.

The coil was lapped with Mylar film for ground insulation and clamped with 316 L stainless steel collar stacks in the hydraulic press. The radial thickness of the stainless steel collar is about 4.5 cm. The elliptical deformation of the coil at 5 T was estimated to be less than 0.1 mm.

Table 2 Parameters of Superconducting Cable

Single Wire Diameter		0.71 mm
Nb-Ti Filament Diameter		9 μm
Number of Filaments per Wire		2300
Twist Pitch		10 mm
Copper/Super Ratio		1.8
Cross Section (Keystoned)		
	Width	9.49 mm
	Thickness	1.23 to 1.42 mm
Number of Wires per Cable		27
Stranding Pitch		85 mm
Packing Factor		86 %
Critical Current at 5.5 T		5500 A

Magnet Test

The dipole coils assembled with the iron core (Fig. 2) was tested in the vertical cryostat. It took about 30 hours to cooldown the magnet, which has the total mass of 1.6 tons, from room temperature to 4.2 °K.

0018-9499/81/0600-3266$00.75©1981 IEEE

In the experiment, we used a BOC TurBOCool 100 refrigerator.

The magnet was excited by use of a transister power supply of 6 V and 5,000 A. When the superconducting coils of the magnet went to normal, almost all the stored energy ($\approx$ 300 KJ) was dissipated in the magnet coil in a resistive state, because we did not use the energy recovery system. Resultant vaporized helium gas was collected in a recovery gas bag through a pnumaticaly opened valve.

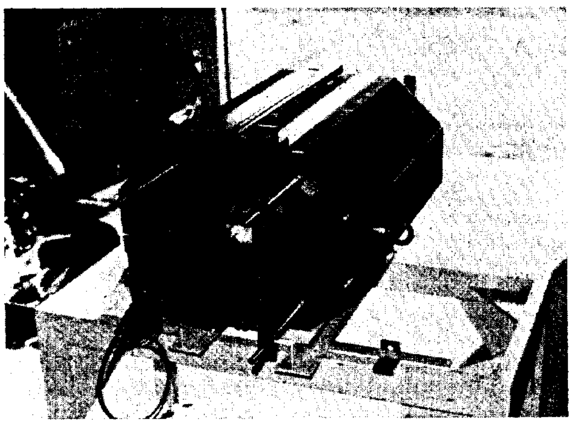

Fig. 2 Assembled Test Magnet before Installation in the Vertical Cryostat

Training

The results of the magnet training experiment are plotted in Fig. 3. The load line of the second magnet and critical data of the cable are shown in Fig. 4.

In July 1980, the first test dipole was excited up to 4.2 T after 15 quenches. The training began from 3.1 T. After scheduled interruption for 6 weeks, the second excitation was tried and 5.1 T was attained after 6 more quenches at 4.2 °K. The transition from super to normal is detected by measuring the voltage difference between the upper and the lower halves of the coil. This observation tells us which coil goes to normal.

The second magnet test was completed in December 1980. It reached its critical current 5,200 A (5.25 T central field) after 12 quenches. Though we did not notice any difference between the upper and the lower coil in the process of the manufacturing, the first 7 quenches up to 4.5 T occured in the upper half coil.

In the case of the second magnet, we made the following modifications in the construction process and the insulation of the cable.

i) The quantity of B-stage epoxy impregnated in the fiber glass tape was reduced from 30 % to 20 % in weight percent.
ii) The coil was wound more tightly and skillfully, especially at the coil end part.
iii) The capacity of the hydraulic press for collaring was increased from 500 tons to 750 tons to get higher prestress in the second magnet coil.

The magnets were usually excited with ramp rate of 5,000 A/400 sec. For the second magnet higher ramp rate of 5,000 A/40 sec was tried and field strength of 5.25 T was achieved without any quench.

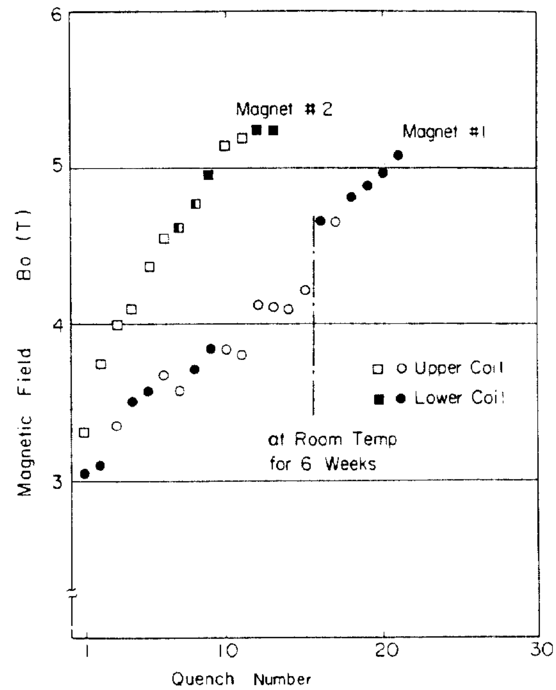

Fig. 3 Training Curves of the 1st and 2nd Magnet

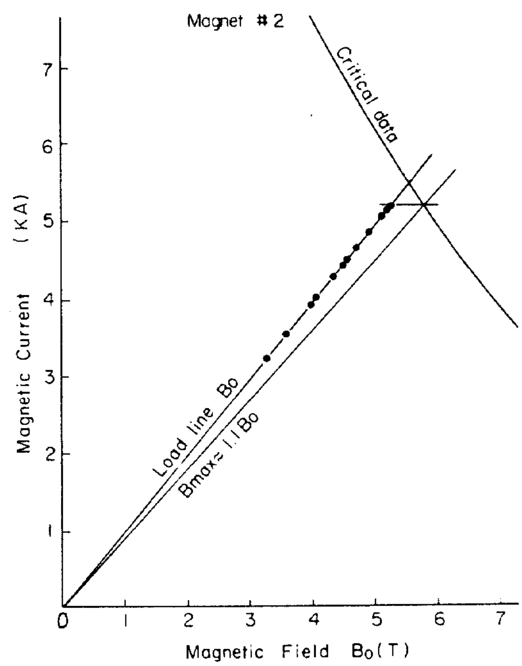

Fig. 4 Load Line and Critical Data

Field Measurements

The magnetic field was measured with a Hall probe and a rotating coil. The length of the rotating coil is 60 cm. The coil was continuously rotated by a synchronous moter. The induced signal was analyzed with a spectrum analyzer (Hewlett-Packard 3582A), which was triggered by a rotary encoder signal.[3)]

As is well known, the field in the median plane, B, is expressed as

$$B = B_0(1 + b_1X + b_2X^2 + b_3X^3 + b_4X^4 + \ldots),$$

where the coefficients b_2, b_4, ... represent sextupole, decapole, ... component, respectively. In Table 3, the measured values of b_2, b_4, b_6, b_8 and b_{10} are compared with the calculated results. The differences between the measured harmonic coefficients and calculated ones are small except for the sextupole component. We used computer programe "LINDA" to estimate the field uniformity and field distribution in the iron core. Our polygonal approximation of the current distribution was not accurate enough, therefore, considerable amounts of sextupole and decapole component appeared.

The reconstructed field distribution of the magnet is depicted in Fig. 5. Figure 6 shows the excitation dependences of b_2 and b_4, for the second magnet. At low fields, b_2 and b_4 show usual hysteretic behavior due to the intrinsic superconductor magnetization[4]. Above 2 T all harmonic components become almost constant except for b_2. The coefficient b_2 slightly changes with the field strength above 2 T, but this dependence does not seem to be explained by the coil deformation.

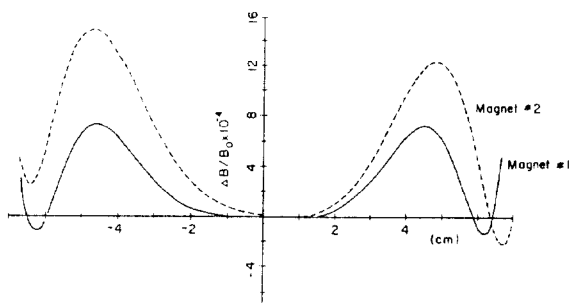

Fig. 5 Field Reconstruction from Harmonic Components

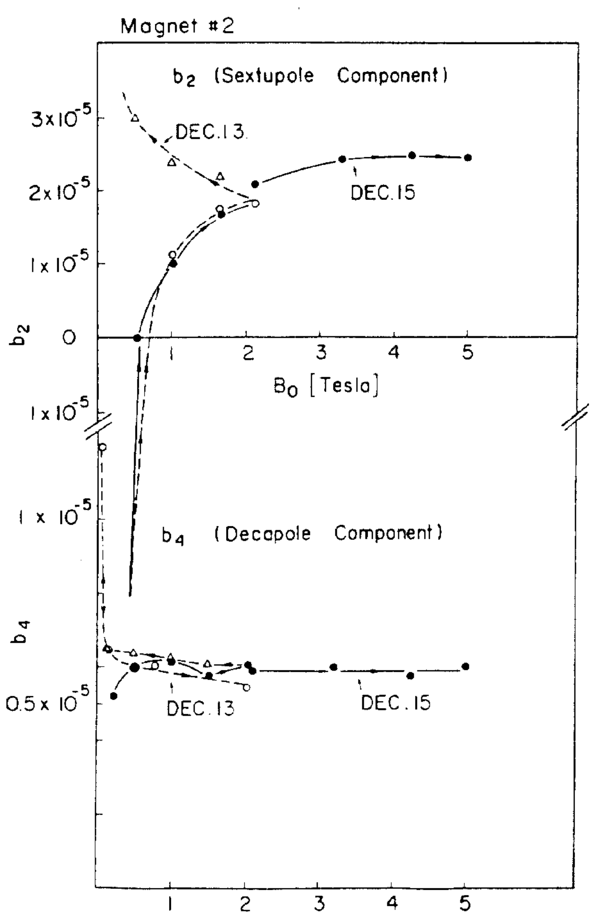

Fig. 6 Sextupole and Decapole Components of 2nd Magnet

Table 3 Multipole Coefficients at 4 Tesla

	Magnet #1	Magnet #2	Calculated
$b_2(cm^{-2})$	$-8.3x10^{-6}$	$2.3x10^{-5}$	$7.7x10^{-5}$
$b_4(cm^{-4})$	$5.1x10^{-6}$	$5.1x10^{-6}$	$5.6x10^{-6}$
$b_6(cm^{-6})$	$-8.2x10^{-8}$	$-8.7x10^{-8}$	$-7.6x10^{-8}$
$b_8(cm^{-8})$	$-5.2x10^{-9}$	$-4.9x10^{-9}$	$-5.4x10^{-9}$
$b_{10}(cm^{-10})$	$1.0x10^{-10}$	$9.3x10^{-11}$	$1.1x10^{-10}$

Conclusion

The present experiences in the construction and tests of the two dipoles lead us to the following conclusions.

i) Although the present coil experiences high transversal stress more than 13 kg/mm^2 during the curing and collaring processes, the magnets are excited up to its critical current without degradation of the wires.
ii) For the second magnet, the training was obviously reduced with use of much higher prestress. It seems that the collaring technique is also usefull for construction of the superconducting dipole with bore diameter as large as 140 mm.
iii) The coil creeping by thermal cycling and repeating excitation should be studied further, because the prestress of 13 kg/mm^2 at room temperature is much higher than the elastic limit of copper matrix.
iv) Some improvements in coil current configuration in the double shells should be made to satisfy the required specifications for TRISTAN ring magnet.
v) Studies of beam induced quenching should be made with use of high energy proton beam.

Aknowledgements

The authors wish to express their gratitude to Prof. T. Nishikawa and Prof. T. Kamei for their continual encouragement and support to this work. Almost all assembling of our dipole magnets were made by the staffs of machine shop at KEK, and we wish to thank Mrs. T. Hongo, Y. Sakakibara, A. Terashima, Y. Kobayashi and H. Inoue for their contributions. We would like to aknowledge the Fermilab people for offering their information on the magnet technology.

Reference

1. Y. Kimura, "TRISTAN", Invited Paper at XIth International Conference on High Energy Accelerators, CERN, July 7-11, 1980

2. H. Hirabayashi, To be published in IEEE, Trans. Proc. 1980 Applied Superconductivity Conference, Santa Fe, Sept. 29 - Oct. 2. 1980

3. D. A. Gross, M. Wake, R. Yamada, D. Blatchley and M. E. Price, IEEE Trans. Mag-15, 137 (1979)

4. W. B. Sampson, P. F. Dahl, A. D. Mcinturff, K. E. Robins and E. J. Blser, IEEE Trans. Mag-15, 114 (1979).