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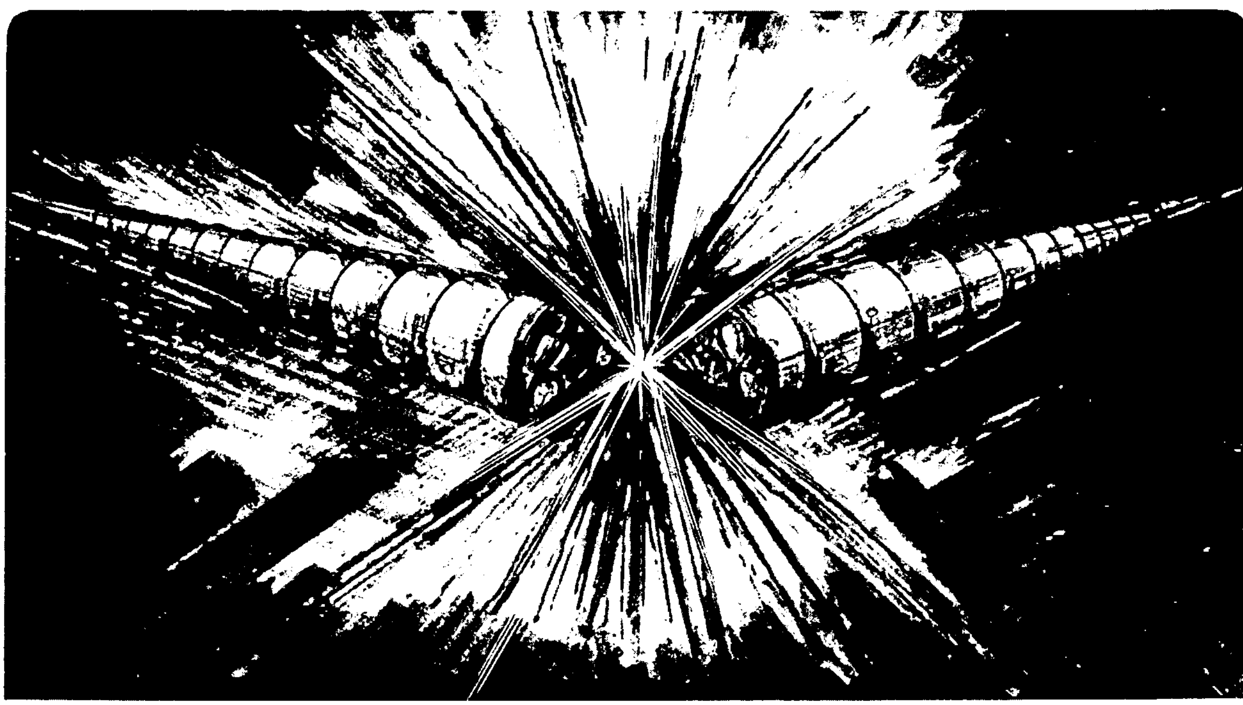

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DESIGN OF THE Nb_3Sn DIPOLE D20

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Abstract-- The design of a 50 mm bore superconducting Nb_3Sn dipole with a short sample field of 13 T at 4.3 K and a current of 5500 A/turn is presented. The magnet is composed by two double pancake layers. The inner cable has 37 strands with a strand diameter of 0.75 mm and a Cu/Sc ratio of 0.4; the outer cable has 47 strands with a diameter of 0.48 mm and a Cu/Sc ratio of 1.15. In order to obtain a high transfer function and low saturation effects on the multipoles, the stainless steel collar is elliptical and the iron yoke is "close in". The thin collar itself provides only a minimum prestress and the full prestress of 100 MPa is given by a 25 mm welded stainless steel shell or by winding a wire around the yoke. Aluminum spacers are used as assembly tools and as a means to control the gap size in the vertically split iron yoke. This paper presents the magnetic design and the calculated stress and strain distribution in structure and coils. A 1 m model called D20 is to be built and tested at LBL.

I. INTRODUCTION

The superconducting dipole D20 (Figures 1-2) has 2 layers of Nb_3Sn coils each wound in a double pancake. The cable parameters are shown in Table 1. The inner cable has 37 strands with strand diameter of 0.75 mm and a Cu/Sc ratio of 0.4. The outer cable has 47 strands with a diameter of 0.48 mm and a Cu/Sc ratio of 1.15. The inner wire has been designed so that it can be used in a higher field magnet. The coils will be fabricated using the "wind and react" technology and vacuum impregnated with epoxy. The reaction process for Nb_3Sn requires keeping the coils in an oven at 700 °C for a week. The cables will be insulated with a Mica-Alumina Silica 1/2 lapped tape 0.12 mm thick. This magnet has a structure very similar to the superconducting NbTi dipole D19, built and tested at LBL, that reached at 1.8 K the field of 10.06 T [1–4]. In D20 as in D19, the yoke is "close in" to have a higher transfer function. The elliptical yoke is used to minimize the effect of the iron saturation on the sextupole component of the magnetic field.

The D20 model will have a circular iron yoke for convenience; however for an application such a colliding beam accelerator, a twin-bore configuration, which is more efficient in use of iron, would be used.

The two double pancake layers of coils will be collared with an elliptical collar 9 mm thick at the middle plane. The collars are composed by two symmetric pieces assembled in pack of 90 laminations, each thick 1.37 mm. The straight section and the ends are to be collared. After collaring with a prestress of 15 MPa, the yoke will be put in place and a stainless steel shell 25 mm thick will be welded while the magnet is in a press. The press load required to weld the 1 m long magnet is 10 MN [5]. An alternate procedure is to wind a rectangular wire around the yoke with a tension of 500 N until the desired prestress and winding thickness are reached. The winding layer has to have a high radial stiffness in order to get the right closing force on the yoke gap after cooldown. The design coil prestress of 110 MPa on the inner layer and 90 MPa on the outer layer prevents the coils separation from the collar when the magnet is energized at 13 T.

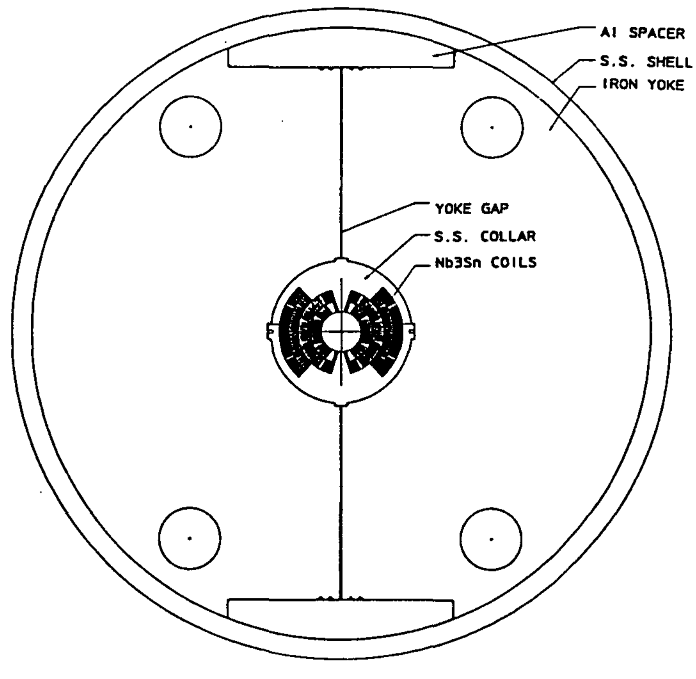

Figure 1: D20 magnet cross section

II. MAGNETIC DESIGN

The goal of the magnetic design is to design a magnet with a short sample field of 13 T, 50 mm bore diameter, 50 mm maximum winding thickness and 9 mm collar thickness. The field goal was chosen to extend the technology of accelerator magnets to high field superconductors such as Nb_3Sn; in addition to development of cables with sufficient current density, D20 provides an opportunity to test such cables in a realistic application.

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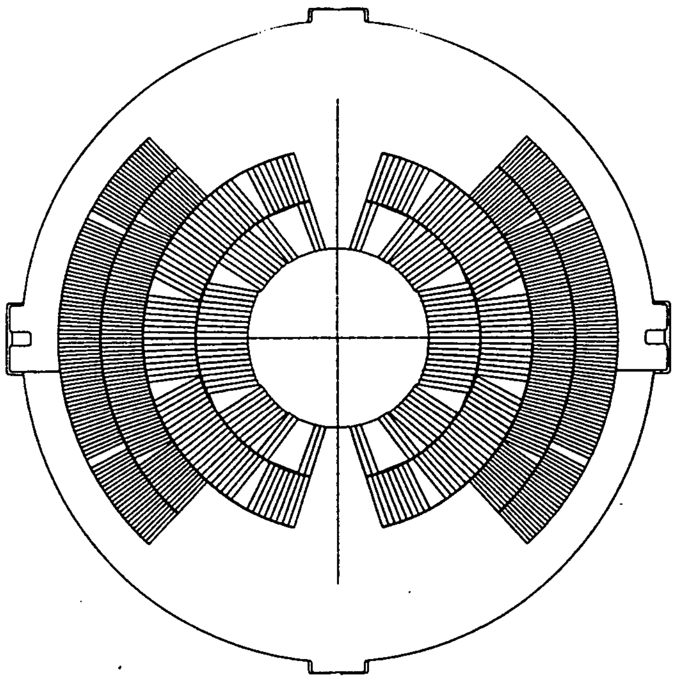

Figure 2: D20 coil cross section

The magnetic design has been done using three successive iterations:

- infinite permeability circular yoke, circular sector coils, no wedges;
- infinite permeability circular yoke, stacked turns and wedges;
- finite permeability elliptical yoke, stacked turns and wedges.

In the first design phase, the coils were modeled as circular sectors without wedges and the number of strands, the strand diameter and Cu/Sc ratio were optimized for both layers. This step has led to the design choice of two double pancake layers because the two single layer solution required the use of stiff cables and also low Cu/Sc ratio due to limitations in maufacturing high current density strands. In this phase a higher field dipole that would use the same D20 inner layer wire was also considered. The design has been performed with a in-house program that computes analytically the magnetic field and the multipoles, and with the optimization program MINUIT [6]. The objectives of the optimization were to get the highest possible central field, low sextupole and decapole coefficients, two layers with the same current margin, two cables with the same current and the same current density in the copper, and low cable stiffness. The resulting magnet configuration has a short sample field of 14.3 T with a current of 6280 A/turn. The cable characteristics are shown in Table 1.

In the second design phase the collar is circular and 9 mm thick, and the yoke has infinite permeability. The cables have been stacked laying the center of the outer edge on a circumference. Design variables were the number of blocks, the number of turns in each block and the dimensions of the wedges. The goal was to get the highest central field, keep the multipole coefficients low, get wedges not too sharp and have the turns as radial as possible. With these approximations the short sample central field achieved is 13.15 T with a current of 5000 A/turn; it is lower than the previous current because of the wedges. The short sample field is limited by the outer layer.

Table 1. D20 Cable Parameters

D20	Inner Cable	Outer Cable
Strand No.	37	47
Strand diameter (mm)	0.75	0.48
Cable width (mm)	14.1	11.52
Keystone Angle (°)	1.11	0.87
Mid-thickness (mm)	1.60	1.11
Cu/Sc ratio	0.4	1.15
A_{sc}/turn (mm^2)	11.676	3.956
A_{cu}/turn (mm^2)	4.670	4.549

The third design phase considers the real iron permeability and determines the collar elliptical profile and the yoke outer radius. This analysis, performed using the finite element program ANSYS [7] and a routine [8] to compute the multipole coefficients developed at LBL, concerns mainly the sextupole variation with the current. At low current the sextupole depends on the collar ellipticity; at high current as the yoke approaches saturation, the flux leaks out of the yoke and the sextupole drops rapidly. The goal has been to reduce the change in sextupole from low field to the operating field. The yoke outer radius was set to 381 mm and the ellipticity to 1.02. After having found the optimal collar ellipticity, the cross section was adjusted in order to have zero sextupole at low current. The main dimensions of D20 are shown in Table 2. In Figure 3 are shown the load lines of the magnet and the short sample curves. The transfer function at the short sample field is 2.22×10^{-3} and it is 14% lower than at low current. The sextupole variation from low current to the field of 13 T is 1.8 units (Figure 4).

Table 2. D20 Main Dimensions

D20	
Bore Diameter (mm)	50
Inner Layer Outer Radius (mm)	53.5
Outer Layer Outer Radius (mm)	77.1
Elliptical Collar (mm)	87.1 × 89.1
Yoke Outer Radius (mm)	381
Shell Thickness (mm)	25

The maximum field at the conductor at the field of 13 T and at the short sample are shown in Table 3. The short sample field is 13.35 T at 6000 A/turn. It is higher than the one predicted with the infinite permeability analysis because with the real permeability the yoke contributes less on the outer coil field than to the central field. The real permeability yoke increases not only the short sample current but also the short sample field. The Lorentz forces acting on the coils at 13 T are shown in Table 4. The stored energy at 13 T is 820 kJ/m.

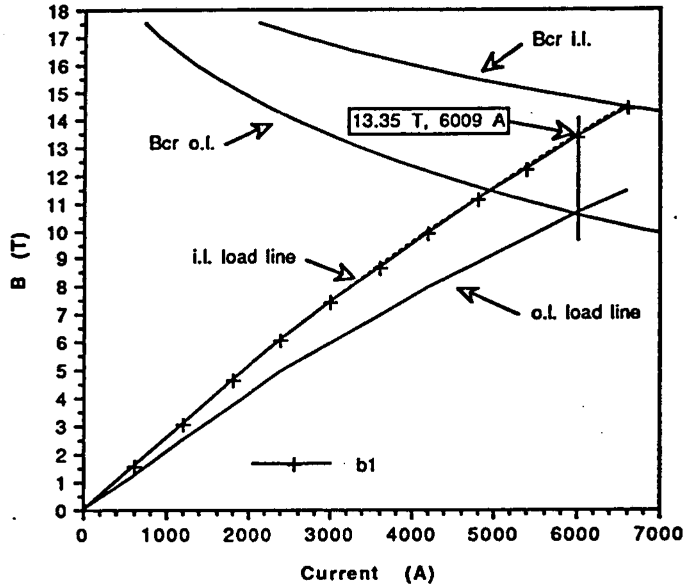

Figure 3: Load lines and short sample curves

Table 3. D20 Magnetic Parameters

D20 @ 4.35 K	Central Field (T)	I. Layer Field (T)	O. Layer Field (T)
5815 A	13	13.03	10.31
6009 A Short Sample	13.35	13.4	10.59

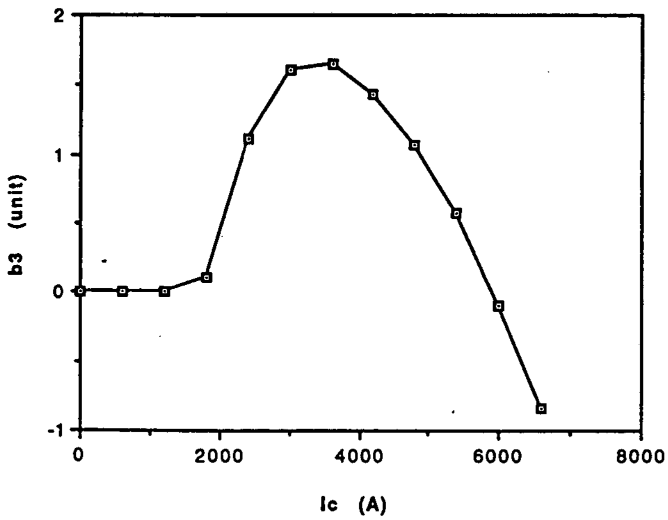

Figure 4: Sextupole variation

The critical field for the Nb_3Sn material was computed as [9]:

$$J_c(B,T,\varepsilon)=C(\varepsilon)\,(B_{c2}(T,\varepsilon))^{-1/2}\,(1-t^2)^2\,b^{-1/2}\,(1-b)^2$$

$$B_{c2}(T,\varepsilon)=B_{c20}\,(1-t^2)\,[1-0.31\,t^2\,(1-1.77\ln t)]$$

$$t=T/T_{c0}(\varepsilon),\quad b=B/B_{c2}(T,\varepsilon),\quad C(\varepsilon)=C_0\,(1-a\,|\varepsilon|^u)^{1/2}$$

$$B_{c20}(\varepsilon)=B_{c20m}\,(1-a\,|\varepsilon|^u),\quad T_{c0}(\varepsilon)=T_{c0m}\,(1-a\,|\varepsilon|^u)^{1/w}$$

with

$T_{c0m}=18.3$, $B_{c20m}=26.047$, $C_0=19299$, $a=900$, $\varepsilon=-0.003$, $u=1.7$, $w=3$, $T=4.3$ K.

The critical current used in the cable specifications and the cables current density at the short sample are shown in Table 5.

Table 4. Lorentz Forces on a D20 Quadrant

D20 @ 13 T	
F_x (N/mm)	4800
F_y (N/mm)	-2361
F_z (N)	205000

Table 5. D20 Current Density Data

D20 @ 13.35 T I = 6009 A/turn	Inner Cable	Outer Cable
J_c(4.35 K) (A/mm²)	745 @ 13.5 T	1550 @ 10.5 T
J_{cu} (A/mm²)	1286	1320
J_{sc} (A/mm²)	515	1519
$J_{overall}$ (A/mm²)	265	469

III. MECHANICAL DESIGN

The mechanical structure of this magnet is very similar in priciple to the D19 superconducting dipole built and tested at LBL. The collar is only 9 mm thick on the mid plane and cannot provide the full design prestress. The full prestress of 110 MPa on the inner layer and 90 MPa on the outer layer is obtained by welding the 316L shell in a press. This prestress is needed to avoid the separation of the coils from the collar when the magnet is energized to 13 T. The vertically split yoke has a tapered gap that measures 0.56-0.76 mm and the yoke outer radius is 381 mm. The aluminum spacer is 280 mm long with a clearance of 0.25 mm with the yoke. This clearance allows the compression of the collar and the coils to reach the design prestress after assembly. During the cooldown the aluminum spacer shrinks and allows the gap to close tightly. During the cooldown the coils lose in average 11 MPa prestress. When the magnet is energized at 13 T the Lorentz forces partially unload the yoke gap without opening it. This makes the structure very stiff.

Instead of using the 25 mm welded shell, it is possible to wind a rectangular wire around the yoke until the necessary coils prestress is reached. This method has the advantage of being easier and more controllable than the weld process for the D20 model and does not require a high press load.

The mechanical analysis has been performed with ANSYS Rev. 4.4A on a SUN SparcStation II. The finite element model contains 5500 nodes and 6500 elements with a maximum wave front of 330 and converges in 5 iterations. The assumptions adopted in the mechanical analysis are the following: all the materials are homogeneous, isotropic and linearly elastic; the coils have no hysteresis; there is no sliding between the coils and the copper wedges; there is no friction; plane stress analysis is valid. The coil Young's modulus considered in this analysis is 17 GPa. Three load cases have been examined: full magnet at room temperature, full magnet cooled down at 4 K, full magnet cooled down and energized at 13 T.

The mechanical behaviour of D20 at 13 T is summarized in Table 6. The room temperature coil prestress is mantained during the cooldown. At the mid plane the Lorentz forces increase the prestress on the inner coil by 7 MPa and on the outer coil by 41 MPa. At the coil poles, the Lorentz forces decrease the inner coil prestress 71 MPa and the outer coil prestress of 59 MPa. When the magnet is energized there is a 22 MPa residual compression at the pole and thus no separation and possibility of motion that might cause training. The diagrams of the azimuthal stress at the pole and the middle plane of the inner layer are shown in Figures 5-6. At room temperature the aluminum spacer is loaded and during cooldown it shrinks considerably, unloading completely. During the magnet energization at 13 T, the yoke gap is partially unloaded but it does not open, thus keeping the coil displacements low. At 13 T, the radial displacement of the collar is 63 µm at the mid plane and 58 µm at the pole. The stainless steel collar, at the mid plane near the keyway, has a radial displacement of 63 with the Lorentz forces.

Table 6. D20 Mechanical Parameters

D20 w/ shell	magnet at 300 K	magnet at 4.3 K	magnet at 4.3K - 13T
$\sigma_{m.p.\ i.c.}$ (MPa)	107	93	100
$\sigma_{m.p.\ o.c.}$ (MPa)	90	81	122
$\sigma_{top\ i.c.}$ (MPa)	109	96	25
$\sigma_{top.\ o.c.}$ (MPa)	90	81	22
$F_{half\ gap}$ (N/mm)	0	2826	1240
$F_{Al\ bar}$ (N/mm)	516	0	0
σ_{shell} (MPa)	280	405	406

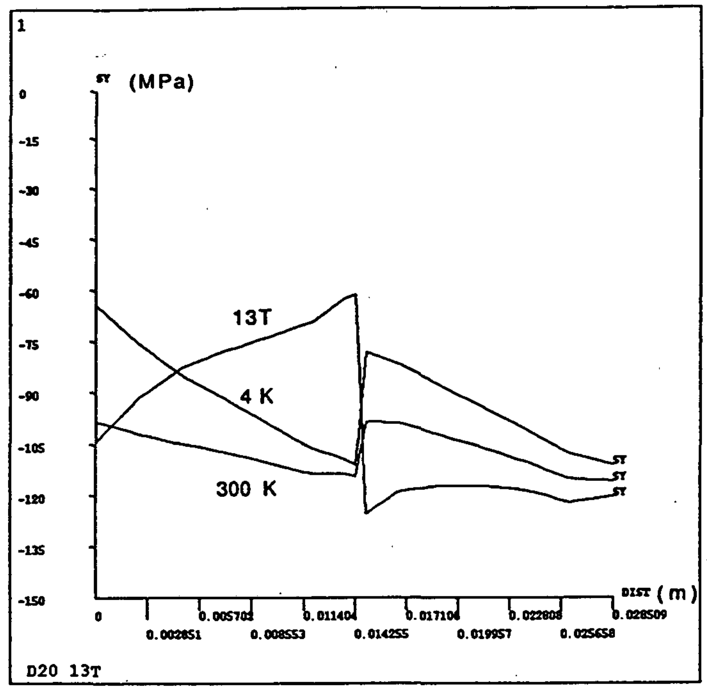

Figure 5: Azimuthal stress at the inner layer mid plane

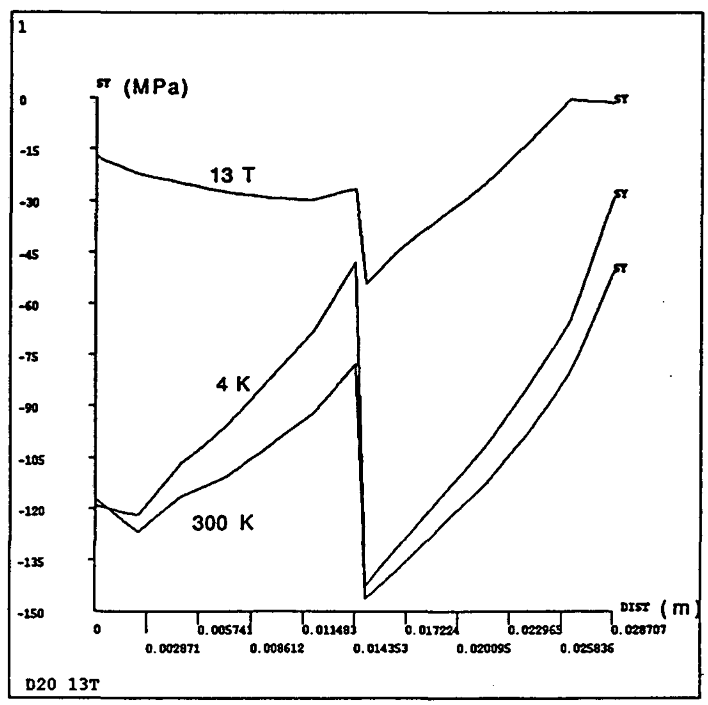

Figure 6: Azimuthal stress at the inner layer pole

IV. CABLE DEGRADATION

The assumed total degradation fot the cable is 10% [10] at the azimuthal stress of 140 MPa. Assuming that the degradation is a linear function of the stress, it is possible to compute the margin in each point of the coils. Figures 7-8 show the azimuthal stress and the magnetic field at 13 T. The azimuthal stress indicates that the inner layer will have a total degradation of 10% and the outer layer 3%. Considering the degradation the short sample field is 13.31 T at 5988 A (Figure 9). The point limiting the short sample remains the outer layer pole turn.

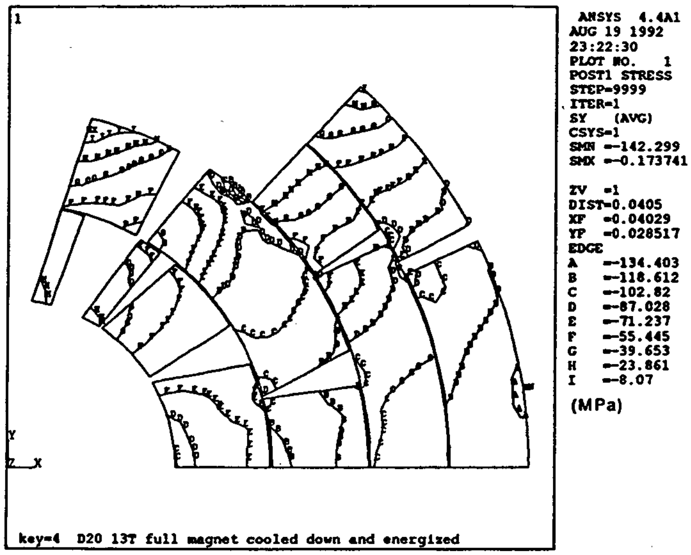

Figure 7: Azimuthal stress in the coils at 13 T

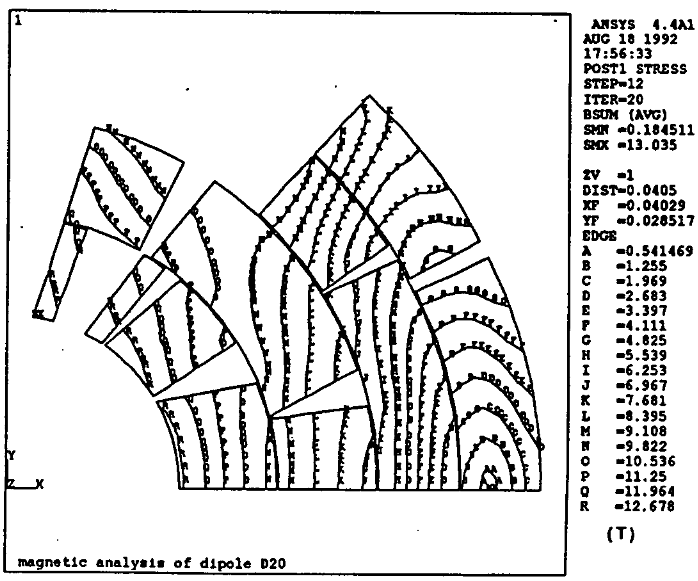

Figure 8: Magnetic field in the coils at 13 T

V. CONCLUSIONS

At this time the cables are being manufactured by IGC and Teledyne Wah Chang. The short sample performance, the degradation and the Young's modulus will be measured. The magnet has been designed to withstand the Lorentz forces at 13 T. This report shows also that the cable degradation of 10% under transverse pressure of 140 MPa should lower the short sample performance of the magnet from 13.35 T to 13.31 T at 4.35 K. A test is being performed to evaluate to feasability of replacing the welded shell with a wire-wound steel structure.

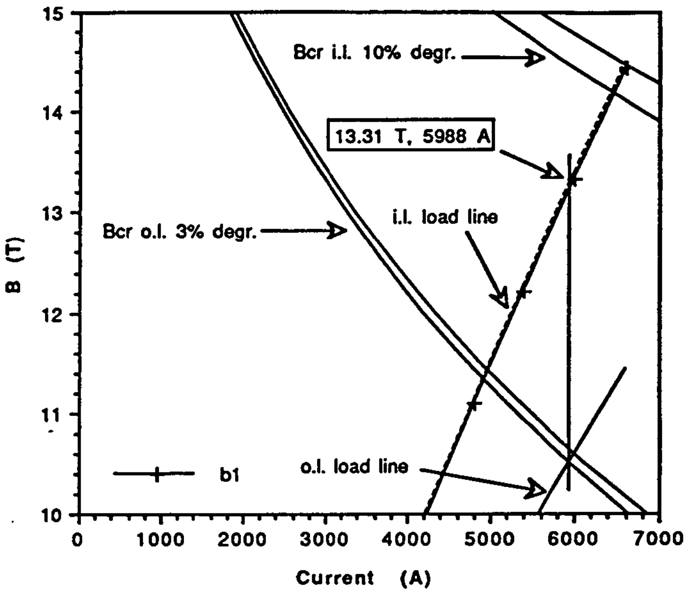

Figure 9: Load lines and degradation short sample curves

REFERENCES

[1] S. Caspi, A 50 mm Dipole for the SSC - DE-1, Lawrence Berkeley Laboratory, SC-MAG-283.

[2] S. Caspi, Expected Short Sample Performance of Dipole D19, Lawrence Berkeley Laboratory, SC-MAG-366.

[3] D. Dell'Orco, Finite Element Analysis of Elliptical Dipole Magnet D19, Lawrence Berkeley Laboratory, SC-MAG-329.

[4] D. Dell'Orco, S. Caspi, J. O'Neill, A. Lietzke, R. Scanlan, C.E. Taylor, A. Wandesforde, A 50 mm Bore Superconducting Dipole with a Unique Yoke Structure, Applied Superconductivity Conference, Chicago 1992.

[5] D. Dell'Orco, D19 Dipole Magnet Welding Test Report, Lawrence Berkeley Laboratory, SC-MAG 396.

[6] F. James, M. Roos, MINUIT - Function Minimization and Error Analysis, CERN Computer Center, Geneva, Switzerland.

[7] J. A. Swanson, G. De Salvo, ANSYS Users Manual, Swanson Analysis Systems Inc. P.O. Box 65, Houston, PA 15342.

[8] D. Dell'Orco, Y. Chen, Magnetic Field Quality Analysis Using ANSYS, Lawrence Berkeley Laboratory, SC-MAG-302.

[9] L.T. Summers, M.W. Guinan, J.R. Miller, P.A. Hahn, A Model for the Prediction of Nb_3Sn Critical Current as Function of Field, Temperature, Strain, and Radiation Damage, 1990 IEEE Trans. on Magnetics.

[10] J.M. van Oort, R. Scanlan, H.W. Weijers, S. Wessel, H.H.J. ten Kate, The Reduction of the Critical Current in Nb_3Sn Cables under Transverse Loads, 1992 Applied Superconductvity Conference, Chicago, Il.