The Superconducting Magnet for the BABAR Detector of the PEP-II B Factory at SLAC

P.Fabbricatore, S.Farinon, R.Parodi , INFN, via Dodecaneso 33, I-16146 Genova, ITALY

E.Baynham, S.F. Carr, D.A Cragg, R.J.G. Greenhalgh , P.L. Sampson, Rutherford Appleton Laboratory , UK

T.G. O'Connor , O.Fackler, Lawrence Livermore National Laboratory, USA

B.Bell, W.Burgess, W.Craddock, R.F. Boyce, J. Krebs, N. Yu, SLAC, USA

J.L.Heck , Oak Ridge National Laboratory, USA

***Abstract*— An Aluminium stabilized, thin superconducting solenoid is required for the central field of 1.5 T for the BABAR detector. The winding is supported by an Aluminium alloy outer cylinder, which provides hoop strength to the coil. The coil has dimensions of 3 m in diameter and 3.7 m in length. The current density is graded to meet the field uniformity requirements of ± 2%. A hexagonal flux return, comprised of a barrel and two end doors provides the external flux path for the field. Additional material is required in the end caps to shield the flux from the beam line magnets. To accommodate the muon detectors, the barrel and end caps are segmented into 20 plates of different thickness. Special attention is given to the support of the coil and cryostat to account for seismic loading. The coil is indirectly cooled to 4.5K using the liquid helium thermo-siphon technique and cooling channels welded to the support cylinder. Automatic cooldown and cryogen supply to the coil and its 40K radiation shield is done by a helium liquefier/refrigerator via coaxial, return gas screened, flexible transfer lines.**

I. INTRODUCTION

The magnet for the BABAR experiment at PEP-II in SLAC [1] is a thin superconducting solenoid within a hexagonal flux return as shown in Fig. 1. The detector performances and the geometry considerations drove the design of the solenoid and the flux return. Studies of the meson decay $B^0 \rightarrow \pi^+\pi^-$ suggested that a magnetic field of 1.5 T is necessary to achieve a mass resolution of 21 MeV/c^2. The combined thickness of the vertex detector, drift chamber, particle identification and electromagnetic calorimeter set the solenoid inner diameter to about 3 m. A segmented geometry was chosen for the flux return for an efficient identification of $K_L{}^0$ and for distinguishing muons from pions. The total thickness of the steel layers in the barrel and end doors was determined both by the minimum steel required to avoid magnetic saturation and by the need for sufficient thickness to ensure that most of the pions interact in the steel.

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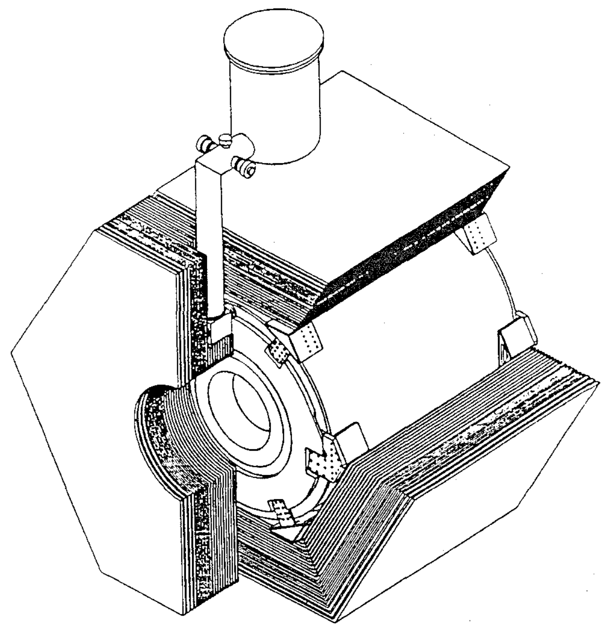

Fig.1 Schematic view of BABAR solenoid in the hexagonal yoke

The minimum steel thickness to prevent pion *punch-through* is 55 cm (equivalento to 3.6 λ_{int}).

The main requirements for the BABAR solenoid are:
i) Central induction of 1.5 T
ii) Field uniformity of ±2% in the tracking region, which approximately covers the axial range from -1483 mm backward to +1287 mm forward, with respect the magnetic centre; the radial limit is 800 mm.
iii) Nuclear interaction thickness of 0.25-0.4 λ_{int}.
iv) Cryostat limiting dimensions: IR 1400 mm; OR 1730 mm; Length 3850 mm
The requirements for the Iron Flux Return are:
i) Provide an external flux path for a 1.5 T field
ii) Provide 3 cm spacing between the steel plates for Instrumented Flux Return instrumentation
iii) Provide the gravitational and seismic load path for the barrel detector components to the concrete foundation
iv) Fit in the allowed experimental room
v) Movable end doors to allow access inside the barrel.

Design of the solenoid is based on the criteria developed in the last 15 years for the aluminium-stabilised thin solenoids. The first magnet of this class can be considered CELLO [2], built at Saclay for the Petra Collider at DESY. The common feature of these magnets consists in the use of indirectly cooled aluminium stabilised conductor. Cooling pipes are connected to the supporting structure, made of aluminium alloy. Magnet parameters (Table I) shown in the present paper are related to the design parameters as developed on March 1995.

II. Magnetic design

A.The model for magnetic analysis

Magnetic analysis is based on the 2D model shown in Fig. 2. The model includes: the coil, the laminated barrel and end caps flux return , each composed of 20 steel plates of different thickness, the magnetic shield of the PEPII quadrupole (Q2) in the forward end door and an iron shield in the backward end door. The model also includes a required gap of 150mm between barrel and end caps.
The backward shield is designed to accommodate a DIRC detector, which is supported by two steel rings, which are also included in the model. The main role of the backward shield is to symmetrize the magnetic field , to balance the magnetic force on the solenoid due to the Q2 shield and to improve the field uniformity in the backward region of the tracking chamber. With respect to the real magnet, having hexagonal structure, the main magnetic analysis was carried out for the plane intersecting the hexagon at the centre of two opposite sides.
The computations were carried out using a 2D magnetic finite element of ANSYS [3] (version ANSYS50a) , implemented on a Digital ALPHA-VAX and on HP730 stations.
The mesh for the magnetic analysis, was suited in order not to exceed 15000 plane elements, so that acceptable CPU time was achieved for calculations. This approach allowed the study of several magnetic configurations leading to an optimization of the field homogeneity.
The coil is meshed into 60 elements of rectangular shape. The radial thickness is 1 cm, in order to reproduce the thickness of the Rutherford cable. Coil dimensions are 4.5 K dimensions.

B. Central field and uniformity

The aim of the magnetic design was to obtain a magnetic field of 1.5T with uniformity of ±2% in the tracking region. The uniformity is obtained by grading the current density of the solenoid in three regions. A central region covering ±961 mm includes 310 turns and two end regions of length 774mm each includes 215 turns. The current density in the end regions is 1.7 times that of the central region. The central field of 1.5T is obtained at a current of 6833 A, with a total ampere turns of 5.0564 10^6. The three sections of the magnet are connected electrically in series. Table I summarizes the main characteristic of the solenoid.Figure 2 shows the graph of the field lines over the full detector region. Fig. 3 shows the field uniformity in the drift chamber region . The target uniformity of ±2% is obtained in the whole region of interest except at the backward edge, where the uniformity decreases to a minimum of - 3%. In the forward direction a better field uniformity is obtained due to the symmetry.

TABLE I

MAIN CHARACTERISTICS OF BABAR SOLENOID

Central Induction	1.5T
Conductor peak field	2.5T
Uniformity in the tracking region	± 2%
(r< 800mm -1483 mm < z < 1287 mm)	(3% at the backward edge)
Winding Length	3470 mm *warm* 3455 mm *cold*
Winding mean radius	1505 mm *warm* 1498.5 mm *cold*
Operating current	6833 A
Inductance	1.15 H
Stored Energy	27 MJ
The coil is made by two conductors forming 3 regions with different current density:	
1 Central region:	
length	1922 mm *warm* 1913.63 mm *cold*
Number of turns	310
2 Side regions:	
length	770.56mm *cold* 774 mm *warm*
Number of turns	215
Total turns	740
Total length of conductor	6998 m

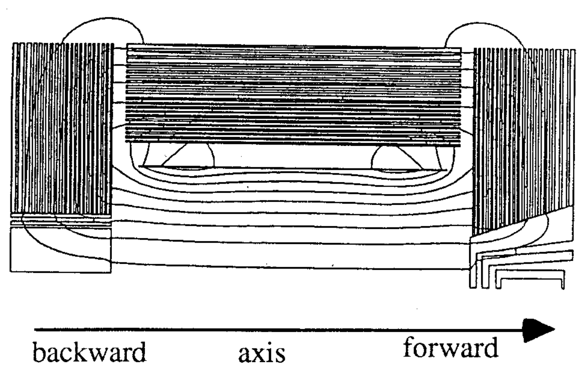

Fig.2 2D model of BABAR solenoid (with the iron yoke and the thin coil) and iso-lines of the potential vector.

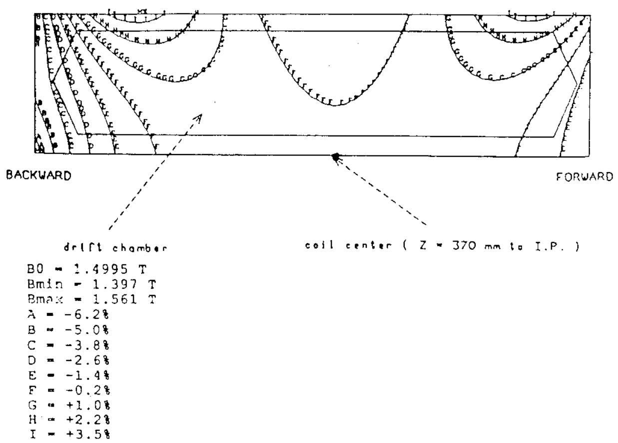

Fig.3 Curves of iso-field in the central zone of the solenoid. The drift chamber is outlined. The capilal letter are referred to different values of the field variation with respect the central field $\Delta B_0/B_0$

C. Magnetic loads

Computed axial and radial magnetic forces are shown in Fig. 4, where the forces at each element of the mesh are displayed as arrows. Regarding the solenoid, we can see that the general characteristics of these forces are:

i) The radial forces are higher at the end regions than at the central region.

ii) The axial forces are inward directed for the end regions and outward directed for the central region.

The radial pressure applied to the central region, with lower current density, is quite independent of position and equal to 0.85 MPa. The pressure at the end regions is much higher, ranging from 1.15 MPa to 1.52 MPa .As explained better in the next section, the conductor is stabilised with pure aluminium, which is not able to support such pressures due to its low yield strength (less than 15 MPa). It is then necessary to include a mechanical structure providing the hoop strength. This support is given by an outer aluminium alloy (5083 or 6061) cylinder, which limits the radial displacements to 1 mm.

The axial force is compressive at each end region and equal to 4.8 MN, while at the central region the force is outward directed for 1.6 MN, so that the coil is compressed with a total force of 3.2 MN. In order to support this force, the winding must be coupled to the cylinder. This is made by gluing winding and cylinder through an epoxy impregnation. The drawback of this solution is the generation of a shear stress at the bonding winding-cylinder of maximum 4.5 MPa, which however is well inside the capability of an epoxy adhesion.

III CONDUCTOR

The conductor is composed of a superconducting Rutherford cable embedded in a pure aluminum matrix through a co-extrusion process, which ensures a good bonding between aluminium and superconductor. Overall dimensions of the conductor are 3.2mm x 32mm, for the higher current density regions and 5.8mm x 32mm for the

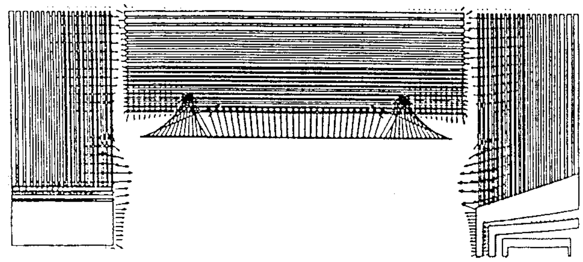

Fig.4 Magnetic loads applied to the iron yoke and to the thin solenoid

low current density region, placed in the central part of the coil. The Rutherford cable was designed starting from multifilamentary NbTi strands of 0.84 mm diameter. For the critical current determination we used the value of Jc=4500 A/mm2 at T=4.5 K and B=2.5 T, expected for the virgin strands on the basis of our measurements on similar strands. The cabling process causes a degradation of the critical current , measured to be 8 - 9%, whilst further 3 % degradation is due to the co-extrusion process. For safety reasons we assumed a total degradation of 20%. As result, the total superconducting cross section of 3.96 mm^2, shared by 20 strands of 159 filaments 40 μm diameter , should be able to carry 15200 A at 2.5 T and 4.5 K. Fig. 5 shows the load line intercepting the critical curve. The operating current is 45% of the critical current at the peak field giving a large safety margin. Winding requires a conductor length of 3 km for the central region and 2.0 km for each end region.

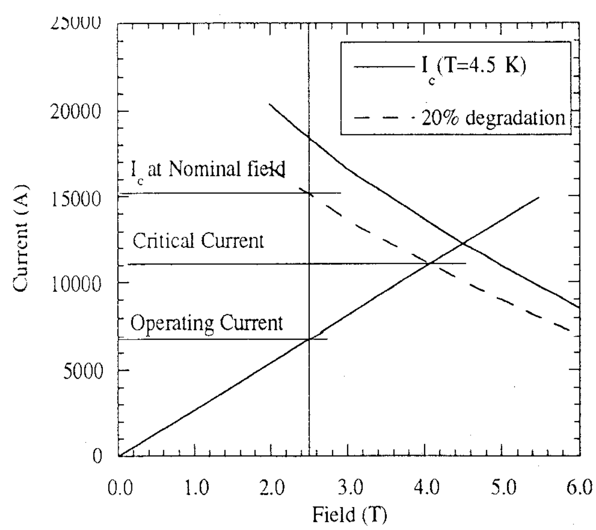

Fig.5 Critical curves (—at 4.5 K; - - with 20% respect to the previous curve) intecepting the load line of the peak field at the conductor.

IV. STABILITY AND QUENCH

Conductor stability has been estimated using modelling codes developed at RAL and INFN Genova [4] for the study of the LHC detector magnets. The two parameters defining stable or unstable conditions are the minimum propagating zone (MPZ) and the minimum energy to quench the magnet. Stability estimates are given in TABLE II for three different conductors with RRR 250,500 and 750 of aluminium. The table also includes quench propagation velocities computed using the stability model. The computations presented in the present paper do not take into account of current diffusion effect. In all cases the stability is computed for an input heat pulse duration of 100 ms. In order to understand whether the calculated stability margins are acceptable,we can consider that in the case of a complete turn, placed at the solenoid end, losses contact with the aluminium alloy cylinder (due to an epoxy failure) and move under the action of the magnetic load, a heat dissipation of 0.4 J occurs. The quench energy 1.6J computed for RRR=500 conductor is expected to be adequate for a coil such BABAR, which is designed to work at low stress level.

TABLE II

BABAR SOLENOID STABILITY

RRR--->	250	500	750
Quench Energy (J)	0.6	1.6	3.2
MPZ length (m)	0.3	0.6	0.9
MPZ characteristic time (s)	0.17	0.18	0.18
Longitudinal Propag. velocity (m/sec)	4.5	4.4	4.2
Transverse Propag. velocity (m/sec)	0.1	0.08	0.06

The quench analysis of the BABAR solenoid has been made using a code developed for the design of the solenoid for DELPHI experiment at LEP (CERN). The code models the thermal and inductive behaviour of the solenoid in order to take into account the effects of the quench back and the heat transfer to the support cylinder. The coil is assumed to be protected by a resistor of 70 mΩ electrically connected in parallel to the solenoid. As usually made for the magnet protecting systems , there is a breaker, which excludes the dc current power supply from the solenoid and parallel resistor during the quench. The quench is supposed starting at one end of the solenoid in the higher current density region. Three basic cases have been considered:

i) The circuit breaker opens with 2 seconds delay after a quench occurs at one end of the coil. In this case the quench back occurs after 1 second from breaker opening . The peak temperature in the coil and cylindrical shell is approximatively 45K.

ii)The breaker opens after 5 seconds. The peak temperature rise is increased to 60 K which is still acceptable.

iii) Breaker failure. The peak temperature in the coil rises to 210 K, which is however a safe value.

V. CRYOGENICS

The coil is indirectely cooled at an operating temperature of 4.5 K using the thermo-siphon technique. The liquid helium is circulated in channels welded to the support cylinder. The pipings are designed for a steady-state cooling flow of 30 g/sec.

Cooldown and cryogenic supply to the coil and 40 K radiation shields is accomplished by a modified Linde TCF-200 liquifier/refrigerator.

Liquid helium and cold gas from the liquifier/refrigerator and its 5000 l storage dewar is supplied to the coil and shields via 60 m long, coaxial, return gas screened, flexible transfer line.

VI. SUPPORTS

Inside the vacuum vessel, the cold mass is supported by six axial tie rods and eight radial tie rods. The axial tie rods are positioned at one end of the cold mass, equispaced around the circumference. They take axial forces, magnetic and seismic. The eight radial tie rods are positioned for each end at 45^{o} from the horizontal, aligned tangentially. They take the vertical and sideways forces, seismic and magnetic. The seismic loads are included considering a sideways force of 0.2g and vertical force of 1.6g. Combined loads gives forces as high as 37 t (compressive) for the axial rods and 25 t for the radial rods.

The cryostat is supported by the iron yoke, through four main support brackets which are fitted to the barrel. A solution was also studied to support the inner detector (50 t) to the iron yoke through the cryostat. In this case eigth subsidiary support brackets were needed because of the seismic load at the inner detector. Fig.1 shows a part of the designed external supporting system.

V. SUMMARY

The superconducting solenoid for the BABAR experiment at SLAC has been designed according to the concepts developed in the last 15 years for the indirecly cooled thin solenoids used in the High Energy Physics experiments. Nevertheless there are some aspects which are peculiar for this solenoid as the requirement for a supporting system able to support seismic loads.

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[3] ANSYS is a registered trademark of Swanson Analysis Sistems, Inc

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