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The BaBar superconducting coil: design, construction and test

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The BABAR Detector, located in the PEP-II B-Factory at the Stanford Linear Accelerator Center, includes a large 1.5 Tesla superconducting solenoid, 2.8 m bore and length 3.7 m. The two layer solenoid is wound with an aluminum stabilized conductor which is graded axially to produce a $\pm 3\%$ field uniformity in the tracking region. This paper summarizes the 3 year design, fabrication and testing program of the superconducting solenoid. The work was carried out by an international collaboration between INFN, LLNL and SLAC. The coil was constructed by Ansaldo Energia. Critical current measurements of the superconducting strand, cable and conductor, cool-down, operation with the thermo-siphon cooling, fast and slow discharges, and magnetic forces are discussed in detail.

1. 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 solenoid is cylinder just inside the flux return.

The Letter of Intent for the Study of CP Violation and Heavy Flavor Physics at PEP-II was presented by BaBar Collaboration on June 1994. At that time, the studies performed on detector resolution for decay $B^0 \rightarrow \pi^+\pi^-$ showed that, to achieve a good momentum resolution ($< 25 \text{ MeV}/c^2$) in the Drift Chamber without increasing the tracking volume, 1.5T magnetic field was needed. In addition the limited space allowed to the coil led to the choice of a superconducting magnet. The magnetic field was required to be uniform in the tracker volume. Combined radius of vertex detector,

tracker, particle identification system, electromagnetic calorimeter and suitable clearances led to 3 m inner bore. The tracking of the muons and K_L^0 's detection asked for a segmented iron flux return. The design was based on criteria developed and tested over the last 15 years with detector magnets employing aluminum-stabilized thin solenoids [2]. The double layer coil is internally wound on a 35 mm thick 5083 aluminum support mandrel. Cooling pipes welded to the outside diameter of the support mandrel form part of the thermo-siphon system. Electrical insulation consists of dry wrap fiberglass cloth and epoxy vacuum impregnation.

The final coil parameter are shown in Table 1.

The Technical Design Report was issued on March 1995 and reviewed the same month at SLAC.

Table 1
Main characteristics of BaBar solenoid (as built)

Central Induction	1.5T
Conductor peak field	2.3T
Winding structure	2 layers graded current density
Uniformity in the tracking region	$\pm 3\%$
Winding axial length	3512 mm <i>at R.T</i>
Winding mean radius	1530 mm <i>at R.T.</i>
Operating current	4596 A
Inductance	2.57 H
Stored Energy	27 MJ
Total turns	1067
Total length of conductor	10 300 m

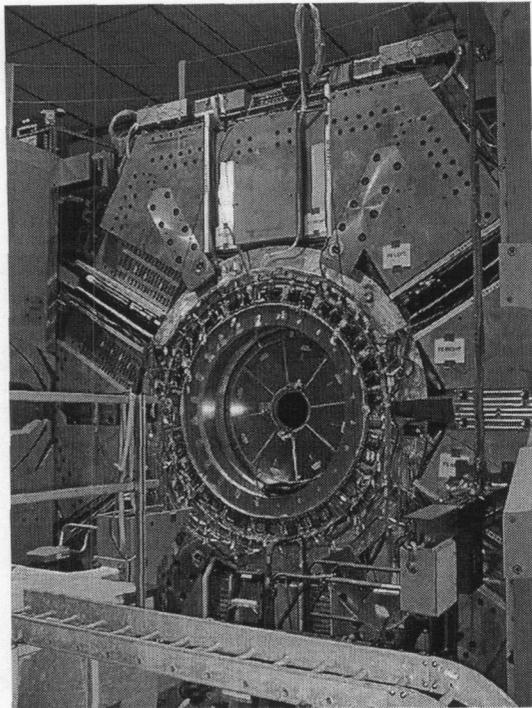


Figure 1. View of BABAR solenoid in the hexagonal (photo taken on September 1998)

The magnetic system was identified to be composed by:

- The solenoid
- The laminated barrel and end caps flux return , composed each by 20 steel plates of different thickness (after modified to 17 plates). A gap of 150mm between barrel and end caps allowed a path for detector wiring.
- The Q2 shield in the forward end door
- An iron shield in the backward end door.

The chosen option for the Particle Identification (DIRC) and the Q2 shielding led to a strong asymmetry in the iron flux return and then to axial offset force of about 45 ton (after optimization of the end plugs geometry). The constraints coming from the detector's needs led to choose a coil similar to CDF coil, involving soft Al stabilised conductor (A superconducting cable embedded in a ultrapure Aluminium matrix). The hoop strength is provided by an aluminium alloy cylinder

2 CONDUCTOR

The conductor (shown in fig.2) is composed of a superconducting Rutherford type cable embedded in a pure aluminum matrix through a co-extrusion process, which ensures good bonding between the aluminum and the superconductor. In order to have a field homogeneity of $\pm 3\%$ in the large volume specified by the *BaBar* experiment, the current density in the winding is graded: lower in the central region and higher at the ends. The gradation is obtained by using conductor of two different thickness: 8.4 mm for the central region and 5 mm for the ends. Both 20 mm wide conductors are composed of a 16 strand Rutherford cable stabilized by pure aluminum. Table 2 describes the strands, the Rutherford cable and the final conductor characteristics. The conductors were supplied by Europa Metalli (Fornaci di Barga -Italy). The co-extrusion processes were carried out at ALCATEL SWISS CABLE under assistance of ETH Zurich

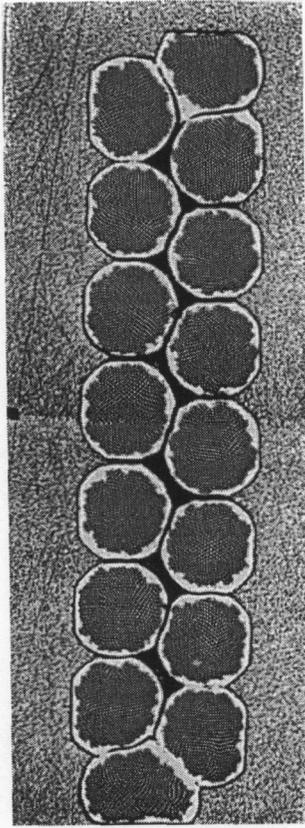


Figure 2. Cross section of the conductor

Critical current measurements were carried out on the Rutherford cables which were extracted from the pure aluminum matrix by chemical etching. The samples were arranged with the field normal to the wide face in order to reproduce the same field conditions experienced by the conductor inside the BaBar coil.

The short samples were measured in the facility MA.RI.S.A., using the transformer method [3]. For each short sample, critical current measurements were performed at different magnetic fields, as shown in Fig. 3. The critical field at 2.5 T was extrapolated from Fig. 2. The critical current for all lengths is greater than the specified value: $I_c(B = 2.5 \text{ T}; T = 4.2 \text{ K}) = 12680 \text{ A}$.

In sample #3 the superconducting to

normal transition was not observed, because the sample quenched before a significant voltage was measured. This was attributed to poor soldering of the sample within its holder. For this sample only, the quench current at different applied magnetic fields was measured.

The peak field in the BaBar coil preliminary design, a single layer winding, was $B_{\text{peak}} = 2.5 \text{ T}$. At this field the critical temperature for NbTi is $T_c = 8.27 \text{ K}$. The current sharing temperature for this single layer design is 6.79 K.

During the engineering design phase the coil configuration was modified from a single layer to a double layer design to increase the stability margin. This led to a reduction in the peak field of the thin conductor from 2.5 T to 2.3 T.

Considering the effective packing factor of the constructed coil, the nominal current was found to be $I_n = 4605 \text{ A}$. Since the field is higher in the inner layer, making this the more critical layer, the conductor margins were re-computed taking into account modifications to the peak field, critical current, and nominal current for these three sectors. The highest I_n / I_c ratio for the thick conductor was, $I_n / I_c = 0.33$. The lowest current sharing temperature is the forward thin conductor, $T_g = 7.28 \text{ K}$. As a result of changing to a 2-layer design the coil has more temperature margin than the original single layer coil.

A parameter of interest is the enthalpy variation from 4.5 K to 7.28 K:

$$E_{u.v.} = \int_{4.5}^{7.28} C_p(T) \delta T \quad (1)$$

where $C_p(T)$ is the specific heat (in J/Kg) and δ the density. By averaging the thermal properties among the four components of the winding, aluminum, copper, NbTi and fiberglass epoxy, we find $E_{u.v.} = 3635 \text{ J/m}^3$.

Table 2
Summary of specification for strands,
Rutherford and full conductor

Component	Characteristic	Value
Strand	NbTi	Nb 46.5 +/- 1.5 wt % Ti
	Filament size	< 40 μ m
	Cu/NbTi ratio	> 1.1
	Wire diameter	0.8 mm \pm 0.005
Rutherford	Transposition pitch	< 90 mm
	No. of strands	16
	Final size	1.4 x 6.4 mm ²
Conductor	Al-RRR	>1000
	Dim. (mm):	
	Thin conductor	(4.93 x 20) \pm 0.02
	Thick conductor	(8.49 x 20) \pm 0.02
	Rutherford-Al bonding	> 20 MPa
	Al/Cu/NbTi:	
	Thin conductor	23.5:1.1:1
	Thick conductor	42.4:1.1:1
	Edge curvature radius	> 0.2 mm
	Critical current @ T=4.2K B=2.5T	12680 A

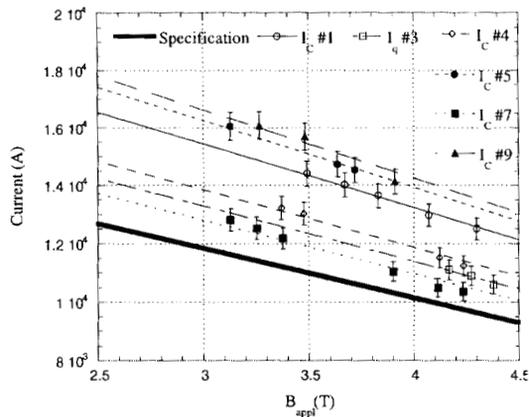


Figure 3 Critical current and quench currents vs. applied field [where applied field is external field plus the sample self field ($B_{sf} = 0.68$ Gauss/A)] performed on the six samples. The thick solid line represents the specification.

This enthalpy margin can be re-written in a more convenient way as energy per unit conductor length, resulting $E_{u.l.} = 0.36$ J/m for thin conductor and $E_{u.l.} = 0.65$ J/m for thick conductor. As comparison, ALEPH and CDF, two well known operational magnets, have an $E_{u.l.}$ 0.35 J/m and 0.1 J/m respectively.

3. CRYOGENICS

The coil is indirectly cooled at an operating temperature of 4.5 K using the thermo-siphon technique (Fig.4 shows the schematic of the cryogenic circuit). The liquid helium is circulated in channels welded to the support cylinder. The piping was designed for a steady-state cooling flow of 30 g/sec.

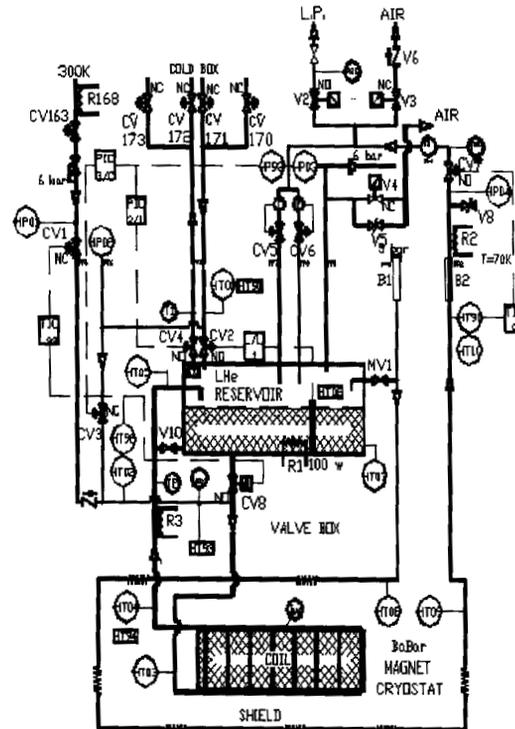


Figure 4. Cryogenic scheme

Cool-down and cryogenic supply to the coil and 40 K radiation shields is accomplished by a modified Linde TCF-200 liquefier/refrigerator. Liquid helium and cold gas from the liquefier/refrigerator and its 4000 l storage dewar is supplied to the coil and shields via 60 m long, coaxial, return gas screened, flexible transfer line. It is possible to cool down the coil by a mixture of warm and cold He gas or by supplying colder and colder gas through the refrigerator. The shields are cooled by part of gas coming back from coil. The actual cool-down at SLAC took about a week as shown in fig.5. The heat load measurement at 4.5 K was performed by closing the input valve to the 4000 l control dewar and by measuring the LHe consumption in that dewar. This test gives pessimistic information because the transfer line losses are included too.

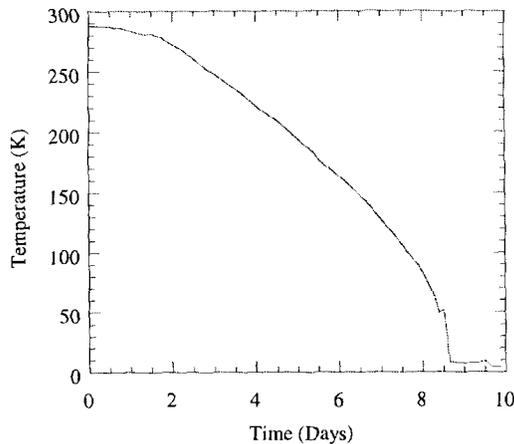


Figure5. Coil average temperature during cool-down

A total loss of 35 (+2, -3) W was measured., with no power in the coil. During the test, the mass flow rate in each lead was 70 NLP/m, this means a load of 4 W per lead. When coil was powered at 1.58 T the mass flow rate per lead (at a voltage across each lead of 40 mV) was 90 NLP/m corresponding to a heat load of 5 W per lead. Mixing these

data and considering that 3 W loss are due to the transfer line we concluded that heat load was between 19 W and 24 W + 14 l/h. This very low value of the loss is partially due to the shield temperature (45 K). The shields were cooled by cool helium gas coming from the LHe reservoir in the Valve Box.

The shield temperatures ranges between 37 and 49K with a mass flow rate of 0.35 g/s. The total loads at the shield is 87 W.

4. OPERATION

The coil current was incrementally increased to 4605 A. The central field measured with an Hall probe was 1.503 T. The operating current for 1.50 T was then determined to be 4596 A and the design current (1.05 times the nominal current) was determined to be 4825 A. On charging the coil at 1.00 A/s the inductive voltage across the coil was 2.573V. The measured inductance is 2.573 H, which is in good agreement with computation (2.56 H). The final step in the commissioning process was to charge the solenoid to the design current of 4826 A. The measured field at the design current was 1.58 T.

The coil is protected with the usual method of a resistor in parallel. If a quench is detected (50 mV unbalance signal between the two voltages in two layers), a breaker opens, closing the current in coil and dump resistor.

The peak voltage at the coil ends can be as high as 340V. Considering that the center tap of the dump resistor was shorted to ground, the maximum voltage to ground is 170 V. Fig. 6 shows current during a fast dump from 4600 A. The fast discharge from the nominal current causes a quench due the heating of the supporting cylinder (Quench Back).

The coil temperature increases to 37 K uniformly. In these conditions about 5 hours are needed to cool-down the coil again, fill the reservoir and be ready for re-charging.

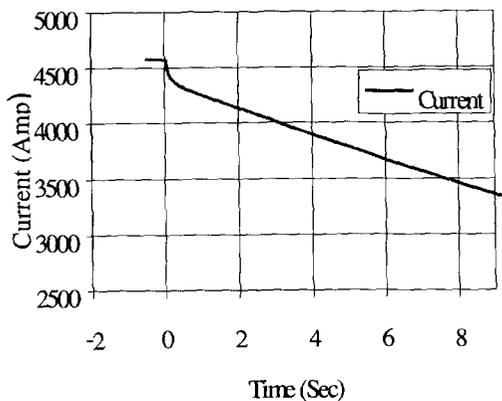


Figure 6. Coil current during fast dis-charge. Time $t=0$ is the breaker opening

6. MAGNETIC FORCES

The coil is placed inside a non-symmetric flux return yoke. This gives rise to axial offset forces. The net axial force is the difference of two large compressive forces of approximately 380 MT on the forward and backward ends of the coil. It is very sensitive to the axial location of the coil within the barrel; the gradient is approximately 1.5 MT/mm of axial displacement.

In order to have an offset force in one direction only (no inversion during the ramp up), the coil was positioned with 30 mm axial displacement in the forward direction. Fig. 7 shows the measured axial offset force as resulted from the strains in the three Inconel 718 tie rods placed at the backward side. These tie rods were designed to hold forces as high as 25 ton with a safety factor of 4. Forces on single tie rod and total force (sum of the three) are shown. The total force is forward directed and has a maximum of 8 ton at 3800 A. The three tie rods at the opposite side (forward) are not strained.

The force behavior vs. current is in agreement with a axial displacement of 33 mm in forward direction of the coil with respect to the iron (as resulted from ANSYS and MERMAID 2D computation [4]). The

average strain in the three tie rods is 500 μm corresponding to 0.3 mm displacement.

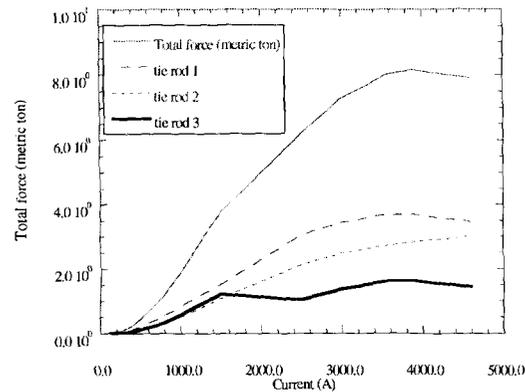


Figure 7. Axial forces in the solenoid backward end tie rods.

7. SUMMARY

The superconducting solenoid was successfully commissioned in March 1998, and following a detailed field map the solenoid was then warmed up for final assembly of the BABAR detector. In November 1998 the coil was put again in operation for cosmic ray run.

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