# SUPERCONDUCTING MAGNETS FOR DETECTORS

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SUMMARY

A Fermilab/KEK/University of Tskuba, Japan collaboration is designing a large superconducting solenoid for the Fermilab Collider Detector Facility (CDF). A review of the status of other superconducting solenoids built for colliding beams machines is presented and progress on the design of the CDF magnet is discussed. Two types of superconducting coils appear to be feasible; a bath-cooled cryostable design or an indirect cooled design using force flow helium. Advantages and disadvantages of each design are pointed out. Scaling up such coils to larger detectors is also discussed.

## History

Many of the large general purpose detectors used at colliding beam machines rely on gas ionization devices located in a magnetic field to measure the angles and momenta of charged secondaries produced in the collisions. For most systems the position measurement error of the ionization device limits the momentum resolution, resulting in a resolution that tends to degrade as the momenta of the secondaries increase. The resolution of such a system can be improved by increasing the track length in the magnetic field over which the particle trajectories are measured and, within limits, by increasing the magnetic field strength. As the center of mass energy of colliding beam machines has increased, there has been a continuing desire to construct magnets producing high fields over ever larger volumes. Although such magnets can take many forms (depending upon the type physics one wishes to emphasize), axial field solenoids have often been chosen to provide the magnetic field for large general purpose detectors. By aligning the solenoid axis with the beam axis, the magnetic field of the detector has only minimal impact on the circulating beams. In addition, the uniform fields provided by the solenoid simplify track reconstruction of complex events.

The characteristics of the SC solenoids built thus far for colliding beam machines are summarized in Table I.[1] The first such coil to be built was used in the PLUTO detector[2] built for the Doris electron-positron storage ring at DESY. The coil employed a multiple layer winding of copper stabilized NbTi superconductor immersed in a bath of liquid helium. Since no electromagnetic calorimetry is used outside the coil, no attempt was made to reduce the amount of material used in its construction. The coil was tested in 1972 and is still successfully being operated at PETRA. The solenoids built after PLUTO have had the additional constraint that their structures be as "transparent" as possible to secondaries produced in beam-beam collisions. This constraint is a result of both physics and economics. The physics often dictates that both electrons and photons be detected with good position and energy resolution. In addition the number of pions misidentified as electrons by the detector should be as small as possible. These goals are best achieved with a minimum of material located between the beam crossing point and the detector's EM calorimetry. Thus ideally the coil that provides the magnetic field for tracking chambers ought to be located outside the calorimetry. However, locating the coil outside the calorimetry requires that both it and the return yoke of the magnet be substantially larger and thus more expensive. In addition, access to the calorimetry is

TABLE I

SUPERCONDUCTING SOLENOIDS USED FOR COLLIDING BEAM PHYSICS

| MAGNET | PLUTO PETRA/DESY | ISR-I1 CERN | CELLO PETRA/DESY | TPC-LBL PEP/SLAC | CLEO CESR/CORNELL |
|---|---|---|---|---|---|
| Type | Pool-boiling cryostable | Pool-boiling cryostable | Force flow indirect cooled | Force flow indirect cooled | Force flow indirect cooled |
| Useful bore (m) | 1.4 | 1.38 | 1.5 | 2 | 2 |
| Winding length (m) | 1.2 | 1.8 | 3.4 | 3.4 | 3.15 |
| Design central field (T) | 2.2 | 1.5 | 1.5 | 1.5 | 1.5 |
| Tested Central field (T) | 2.2 | 1.5 | 1.3 | | 1.0 |
| Stored energy (MJ) at design field | 4.3 | 3.0 | 7.0 | 10.9 | 9.4 |
| Design Current (A) | 1270.0 | 2200.0 | 3400.0 | 2230.0 | 2200.0 |
| Tested Current Date | 1270.0 (1972) | 2200.0 (1976) | 3200.0 (1979) | 1200.0† (1980) | 1600.0 (1981) |
| Radiation Thickness (λ) | --- | 1.1 | 0.5 | 0.68 | 0.75 |

†TPC magnet was damaged during testing by an insulation breakdown. It is currently being rewound.

*Operated by Universities Research Association, Inc., under contract with U.S. Department of Energy.

severely limited by the coil. A reasonable compromise has been to locate the coil inside the calorimetry but construct it in such a way that it is as thin as possible both in terms of radiation and absorption lengths.

In practice this has meant using structural aluminum vacuum shells and radiation shields as well as using high purity aluminum instead of copper to stabilize the superconductor. The reasons for this last choice are apparent from Fig. 1. As can be seen, the electrical resistance of high purity aluminum at a temperature of 4K is substantially smaller than that of copper. There are, however, several complications encountered when using high purity aluminum in large coils. The two most important difficulties are its very low yield strength (∿ 1200 psi as compared to 7000-13000 psi for OFHC copper) and the fact that its resistivity can increase substantially if it is subjected to cyclic strains in excess of ∿ 0.3% (Fig. 2). In spite of these problems, aluminum's 8.9 cm radiation length vs. 1.4 cm for copper makes it very attractive as a stabilizer for "thin" solenoids.

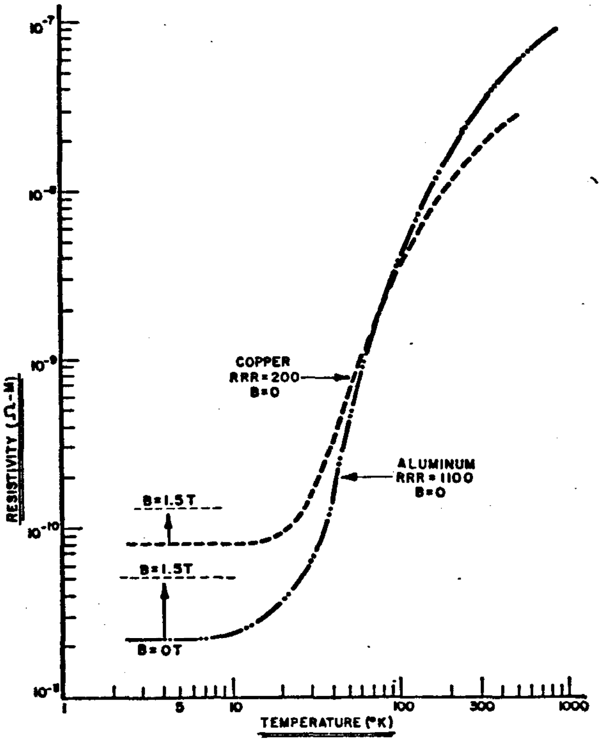


Fig. 1 Resistivity of Aluminum and copper. B = list lines include magnetoresistivity effects

The first such magnet built with this design criterion was one completed by Morpurgo in 1976 for the CCOR experiment at the CERN Intersection Storage Rings.[3] This coil like PLUTO's was cryostable and bath cooled. It was, however, unusual in that the bulk of the stabilizer for the conductor was provided by soldering a relatively small Cu-NbTi superconductor between two larger high purity aluminum strips[4] (see Fig. 3). The coil has a useful bore of 1.4 meters, is 1.8 meters long and produces a central field of 1.5 T. The six layer coil and cryostat correspond to 1.1 radiation lengths ($\lambda_R$). Except for minor problems with refrigeration and a failed epoxy fiberglass coil support member, the coil has operated very successfully for more than five years at the ISR. The magnet is operating at present at the ISR.

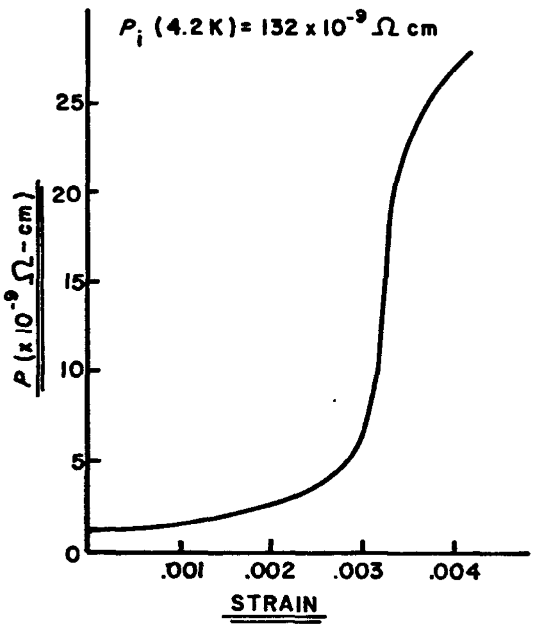


Fig. 2 Cyclic strain behavior of the resistivity of high purity aluminum. Ref.5

CONDUCTOR USED IN ISR SOLENOID

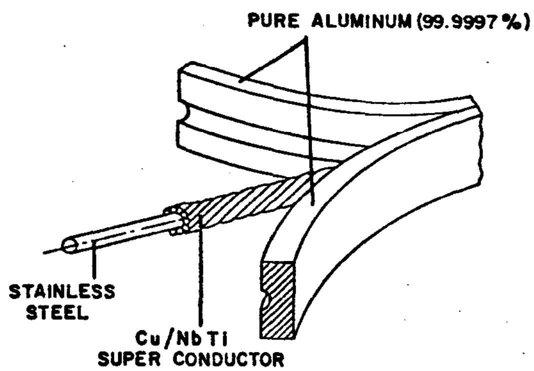


Fig. 3 Aluminum stabilized conductor

The next "thin" solenoid was built by CEN(Saclay)/ITP(Karlsruhe) collaboration for the CELLO detector at PETRA[6]. The coil has a design central field of 1.5 T, a 1.5 m useful bore, and is 3.4 m long. This coil employs a single layer coil cooled by helium force flowed in an external electrically insulated cooling pipe. Although its conductor also uses a Cu-NbTi superconductor soldered to a high purity aluminum strip, the design philosophy was quite different. Both the ISR and PLUTO solenoids were bath cooled cryostable magnets. In these magnets full cryostability implies that there is sufficient liquid helium in direct contact with the conductor such that if a "normal zone" is formed (e.g., by conductor motion, cracking epoxy, etc), then the ohmic heating generated in the conductor's stabilizer is less than the available cooling power to the helium bath. As a result, any conductor normal zone is rapidly cooled below the critical temperature $T_c$ of the superconductor and the conductor returns to the superconducting state. Thus so long as a fully cryostable coil is covered by liquid helium it cannot quench. The CELLO magnet on the other hand does not have helium directly in contact with the conductor. For stability, the design relies on the high thermal diffusivity and specific heat of the aluminum stabilizer to prevent small local heat pulses from quenching the coil. The coil is however designed to quench safely. During such a quench the high natural quench velocity in the aluminum shunt causes the energy deposited in the coil to be spread over a large region thus avoiding excessive conductor temperatures. The CELLO magnet was tested in 1979. A defect in the superconductor required the coil to be repaired by bypassing 6 turns. The magnet was subsequently tested successfully, however, the operating current of the coil was limited to a value corresponding to 1.3 T by spontaneous quenches presumably because of additional conductor defects. After initial refrigeration problems were solved, the magnet has run very successfully for two years, the last continuous run being 4500 hours without interruption.[7] This magnet is particularly impressive in that its total radiation thickness is 0.5 $\lambda_R$.

Two other indirectly cooled solenoids have been built. One is for the TPC detector built by LBL for PEP[8] and the second for the Cornell CLEO detector at CESR[9]. A cross section of the CLEO coil is shown in Fig. 4. Both magnets have a useful bores of 2 m and design central fields of 1.5 T. These coils differ from CELLO primarily in their method of quench protection. The SC winding is not shunted by aluminum stabilizer. Instead, both coils use a mandrel made of a low resistivity aluminum alloy to form a "shorted secondary". (The TPC magnet uses a second low resistivity "shorted secondary" wound on the mandrel underneath the superconductor.) These secondaries are designed to be well coupled inductively to the primary winding and have time constants that are comparable with the primary winding/dump resistor time constant. During a quench a portion of the primary current is rapidly transferred from the primary winding to the "shorted secondaries". Ohmic heating in the secondaries cause the SC primary to be become normal faster than it would through normal zone propagation alone. In addition the secondary circuit absorbs a substantial fraction of the stored energy avoiding high conductor temperatures in the primary winding. Both the TPC and CLEO coils have been tested. The Cornell coil was tested in 1981 up to 73% of its rated current, but the test was terminated by a power lead failure. Fortunately only external damage resulted, and the magnet was subsequently tested successfully to a field of 1.0 T and installed in the iron. Figure 5 shows the primary current vs. time for a quench in the CLEO magnet. The current in the primary is seen to drop quickly from its initial value of 1600 A to 1040 A as current is transferred to the magnet's bore tube. There are currently no plans to test the magnet up to its design field of 1.5 T. The magnet is in use at 1 T at CESR and the magnet's operation has stabilized such that during two months of recent operation the magnet quenched only once.[10] Unfortunately, the TPC solenoid was severly damaged during its initial testing in 1980 by an insulation breakdown.[11] However, the magnet's cryogenic and electrical performance were verified up to half the rated current before the failure. The coil is currently being rebuilt at LBL.

## CDF Solenoid

Next I would like to describe progress on the design of a superconducting solenoid for the Fermilab Collider Detector Facility. This will be the major detector used at the Fermilab collider to study $\bar{p}p$

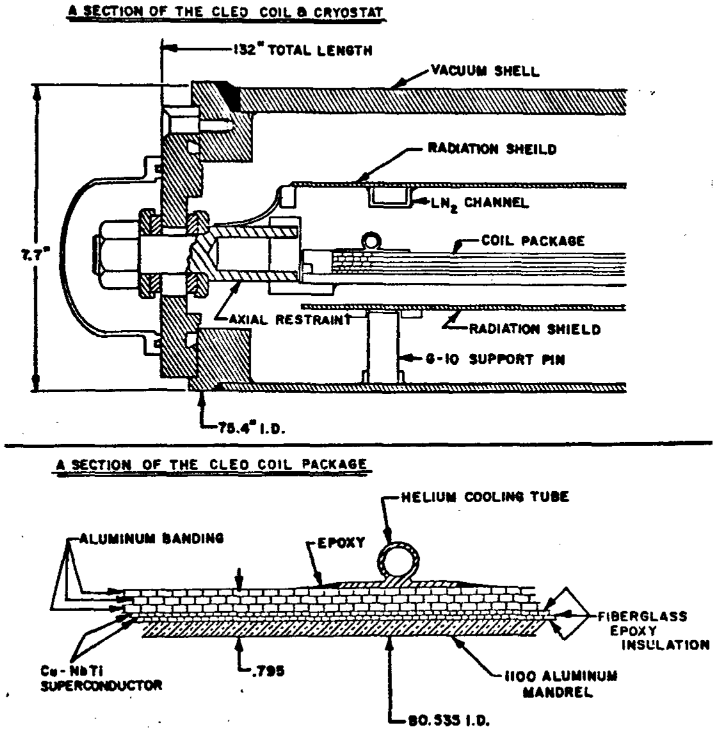


Fig. 4. Coil & cryostat of the CLEO indirect cooled cable.

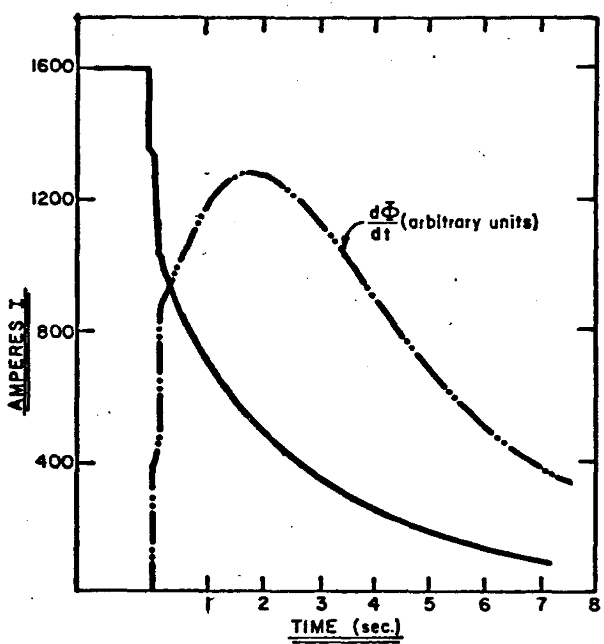


Fig. 5. Current vs. time during quench of CLEO magnet.

collisions at center of mass energies up to $\sqrt{s}$ = 2000 GeV. When the collider is operating, the detector will be located in an experimental hall at the BØ collision area. When the accelerator operates for fixed target physics, the detector will operate in a nearby (30 m) assembly building for testing and field mapping. The detector and its physics goals have been described elsewhere[12].

The central detector for CDF (shown in Figs. 6 and 7) employs a large axial magnetic field volume instrumented with a cylindrical drift chamber and a pair of intermediate tracking chambers. This system will determine the trajectories, signs and momenta of charged particles produced with polar angles between 10 and 170 degrees. The magnetic field volume required for tracking is approximately 4 m long and 3 m in diameter. To provide the desired $\Delta p_T/p_T \lesssim 15\%$ at 50 GeV/c using chambers with $\sim$ 200 μ resolution the field inside this volume should be 1.5 T and as uniform as is practical to simplify track finding and reconstruction.

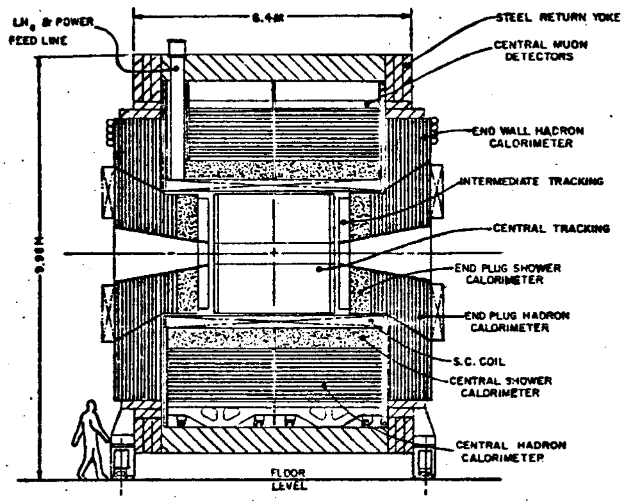


Fig. 6 CDF Central Detector (Side view)

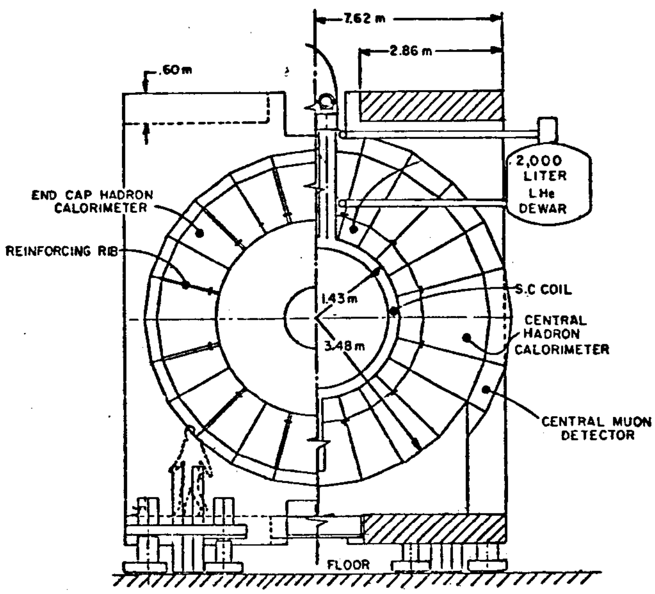


Fig. 7. CDF detector end view.

This field will be produced by a solenoid with a uniform linear current density of 1.2 x $10^6$ A/m surrounded by a partially calorimeterized iron return yoke. The coil itself will be approximately 3 m in diameter and 5 m long. Since both central electromagnetic and hadronic calorimetry are located outside the coil, the coil must be "thin" both in physical thickness and radiation and absorption lengths. In addition, because the magnet must be off during $\bar{p}$ accumulation, and the stored $\bar{p}$ beam lifetimes may be short initially, the magnet must be capable of being charged to full field quickly ($\sim$ 10 minutes).

We have investigated the feasibility of building a conventional water-cooled aluminum coil (see Figs. 8 and 9). While such coils could be built, the electrical power costs would be enormous, exceeding the capital cost of a comparable SC coil in $\sim$ 1 year. Therefore we have decided the coil will be superconducting. The short magnet charge time makes TPC or CLEO type coils with low resistance bore tubes unattractive since a 10 minute linear charge would produce over 1200 watts of eddy current heating in a low resistivity (1100-0 aluminum alloy) bore tube of our size. Thus we are currently considering two possible designs, a bath cooled coil[13] similar to Morpurgo's ISR magnet as well as an indirectly cooled CELLO type coil. A summary of the characteristics of a bath cooled solenoid for the CDF detector appears in Table II. The proposed conductor for this design is shown in Fig. 10. It consists of a Cu/NbTi superconductor coextruded with a high purity (RRR ≳ 1200) aluminum stabilizer. The coil would be a single layer of conductor wound on an insulated structural aluminum bobbin. Turn to turn insulation would be provided by epoxy fiberglass spacers, while the coil "bursting forces" would be contained by high strength aluminum banding wound over the conductor (see Fig. 11). This geometry permits 50% of the surface area of the conductor to be exposed to the He bath.

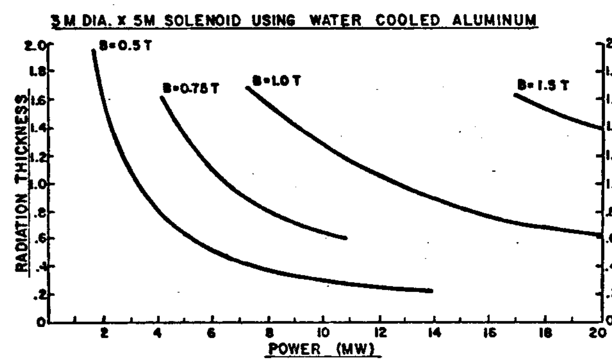


Fig. 8. DC power vs. radiation thickness for a conventional coil.

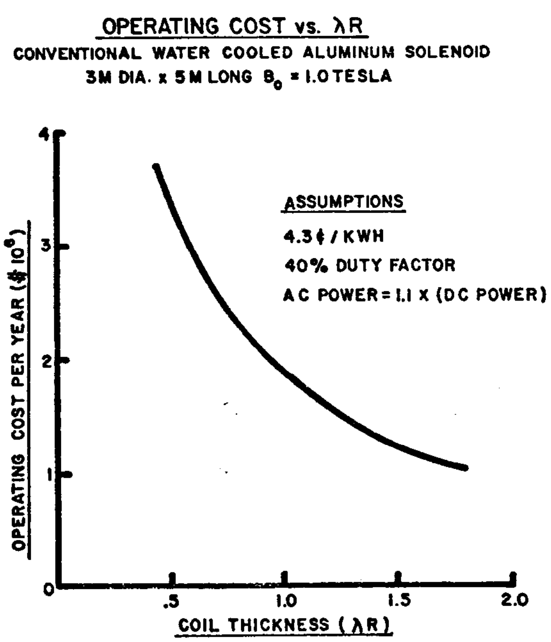


Fig. 9. Operating costs for conventional coil.

TABLE II

CDF POOL BOILING MAGNET PARAMETERS

| | |
|---|---|
| Useful Bore: | 2.86 m |
| Outer Diameter: | 3.35 m |
| Length: | 5.07 m |
| Central Field: | 1.5 T |
| Coil Diameter: | 2.99 m |
| Coil Length: | 4.79 m |
| Winding Scheme: | Single layer helix (870 turns) |
| Operating Current: | 6600 A |
| Stored Energy: | 31 MJ |
| $EJ^2$ | $2 \times 10^{23}$ $A\text{-}J/m^2$ |
| Inductance: | 1.38 H |
| Max. Discharge Voltage: | 30 V ($\tau$ = 300 sec)<br>202 V ($\tau$ = 45 sec) |
| Compressive Axial Force at Midplane: | 86 metric tons |
| Axial Decentering Force: | 15.2 metric tons/cm |
| Max. Radial Decentering Force: | 12.3 metric tons/cm |
| Est. LHe Consumption: | 56 L/h (40 W) |
| He Capacity of Cryostat: | ∿ 800 L |
| He Reservoir Capacity: | 1750 L |
| He Cryostat Pressure Rating: | 4.76 Atm |
| Est. $LN_2$ Consumption: | 11 L/h (500 W) |
| Cold Mass (Magnet) | 7200 kg |
| Est. Cooldown Time: | 300K to 80K $\leq$ ∿ 6 days<br>80K to 4.2K $\leq$ 2 days |
| Weight of Steel Yoke: | ∿ 1000 metric tons |
| Weight of Central Detector: | ∿ 2000 metric tons |

The coil would be fully cryostable according to the Stekly criterion[14] and thus should not be able to quench. Nevertheless, the cross sectional area of the stabilizer is sized very conservatively such that even if the coil should quench (e.g., low liquid helium level), then it could be discharged into an external dump resistor such that the maximum conductor temperatures would not exceed 250K.

The entire coil would be preloaded axially and radially to prevent conductor motion during excitation and enclosed in an outer aluminum shell. This shell would serve both as the He containment vessel and provide attachment points for supports. A cross section of this proposed coil is shown in Fig. 12. The coil would be supported to its vacuum shell by 30 metallic (Inconel 718) support members: 6 axial supports at one end and 12 tangentially attached radial supports at each end of the coil. Each support is $LN_2$ intercepted and equipped with spherical bearings to allow for differential thermal contraction of the coil during cooldown. The coil will be surrounded with superinsulation, $LN_2$ cooled radiation shields and an aluminum vacuum shell. The entire package is 25 cm thick and corresponds to 1.04 radiation lengths and 0.24 nuclear absorption lengths. The contributions of various components to the thickness of the coil are shown in Table III.

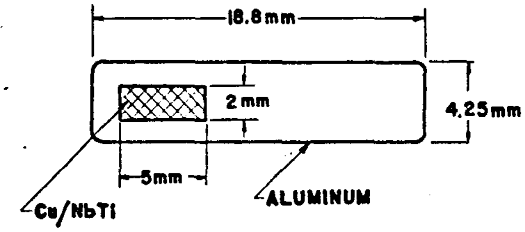


Fig.10. Proposed Cu/NbTi/Al conductor for CDF bath cooled coil.

| | |
|---|---|
| <u>Conductor</u> | |
| General | Cu/NbTi coextruded with high purity aluminum stabilizer |
| Overall dimensions: | 4.25 mm x 18.8 mm |
| Al:Cu:Nb-Ti area ratios: | 14:1:1 |
| Short sample current: | 13.2 kA at 2.0 T, 4.2 K |
| Bare conductor current density: | 8260 $A/cm^2$ |
| <u>Aluminum Stabilizer</u> | |
| Residual resistivity ratio: | $\geq$ 1200 |

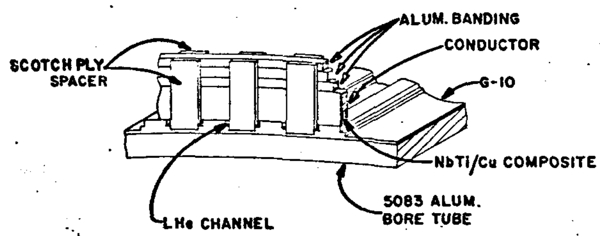


Fig. 11. Proposed CDF bath cooled coil geometry

| | |
|---|---|
| <u>Electrical Insulation:</u> | |
| On coil bobbin: | epoxy-fiberglass with channels |
| Turn to turn: | 0.050" (1.25 mm) epoxy fiberglass |

Liquid helium will be supplied to the coil from a dewar mounted on the magnet yoke through a vertical "power chimney" containing the gas cooled power leads. The estimated helium consumption for the magnet and its transfer lines is approximately 56 liters/hr (40 W).

An indirect cooled CELLO type design for the CDF coil is also being investigated. It is similar in many respects to the bath cooled design. The vacuum shell, supports, radiation shields, conductor and bore tube are nearly identical. The outer helium shell however is replaced by a serpentine LHe cooling tube attached to the coil banding. The banding would be electrically insulated from the conductor. In addition the turn to turn insulation would be thin polyamide-imide tape or similar material to enhance longitudinal quench propagation (see Fig. 13). The overall radiation length of this coil would be almost the same as the bath cooled coil since material removed by eliminating the outer He vessel and thinning the bore tube is partially compensated for by increasing the conductor's Al stabilizer (to keep

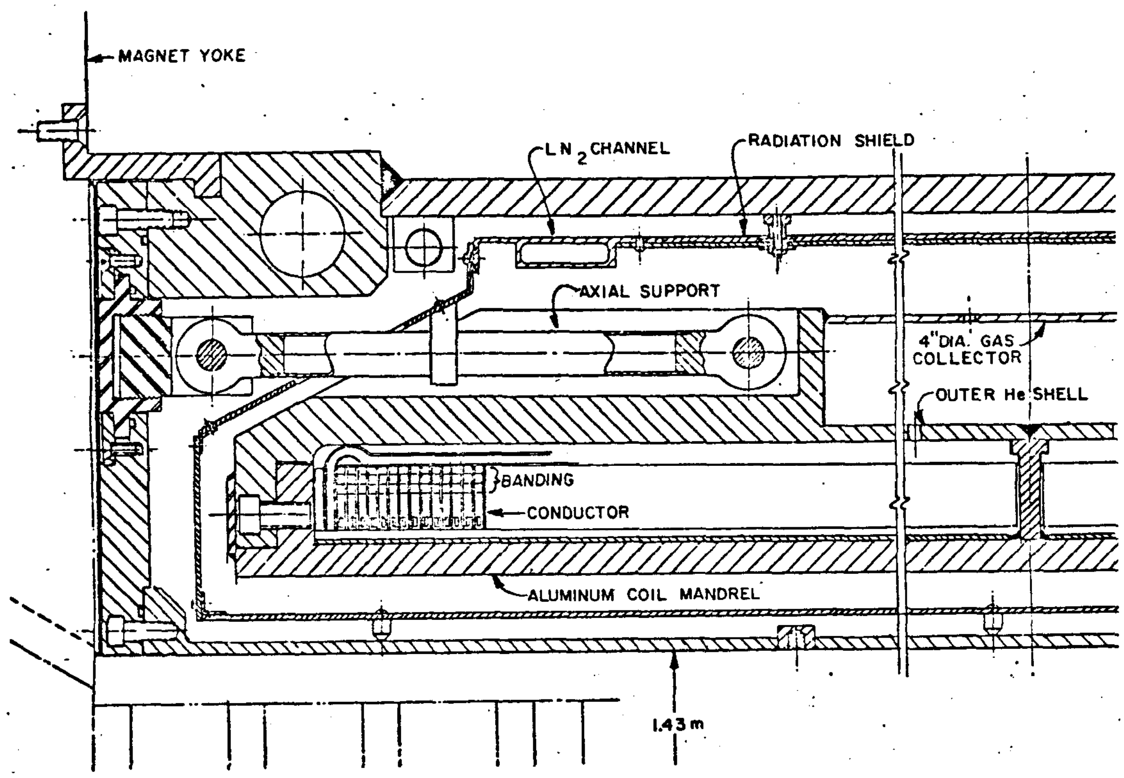


Fig. 12 Cross section of a bath cooled CDF coil

conductor temperature ≲ 100°K during a quench) and by the addition of the He cooling circuit. The physical thickness required is also about 25 cm.

To investigate the problems associated with such a magnet a 1 m diameter x 1 m long R&D solenoid was constructed and tested[15] in Japan by Hitachi Ltd. using conductor and banding techniques similar to that proposed for the full sized coil. The coil was successfully excited to 1.6 T (70% of short sample) without spontaneous quenches. Normal zone velocities for quenches induced by a heater were measured and are shown in Fig. 14. The estimated velocity of the normal zone along the conductor length (if we assume that the quench only spreads that way) is shown on the left ordinate axis. The effective velocity along the axis is shown on the right axis. These velocities have in turn been input to a computer quench simulation program and used to estimate the quench behavior of the 3 m diameter x 5 m by full sized coil.

TABLE III

3m DIAMETER x 5m LONG BATH COOLED SOLENOID

| Item | Material | cm | Radiation Length | Absorption Length |
|---|---|---|---|---|
| Inner vacuum shell | Aluminum | 0.64 | 0.071 | 0.0170 |
| Inner helium shell (coil bobbin) | Aluminum | 1.59 | 0.178 | 0.0426 |
| Conductor | Aluminum<br>Copper<br>NbTi | 1.7 | 0.232 | 0.04000 |
| Insulation | Epoxy/fiberglass | 0.6 + spacers | 0.046 | 0.019 |
| Banding | Aluminum | 1.5 | 0.169 | 0.0404 |
| Outer helium shell | Aluminum | 0.79 | 0.089 | 0.0213 |
| Radiation shields | Aluminum | 2 x 0.20 | 0.044 | 0.0106 |
| Outer vacuum shell | Aluminum | 1.90 | 0.214 | 0.0512 |
| TOTAL THICKNESS | | | 1.04 | 0.242 |

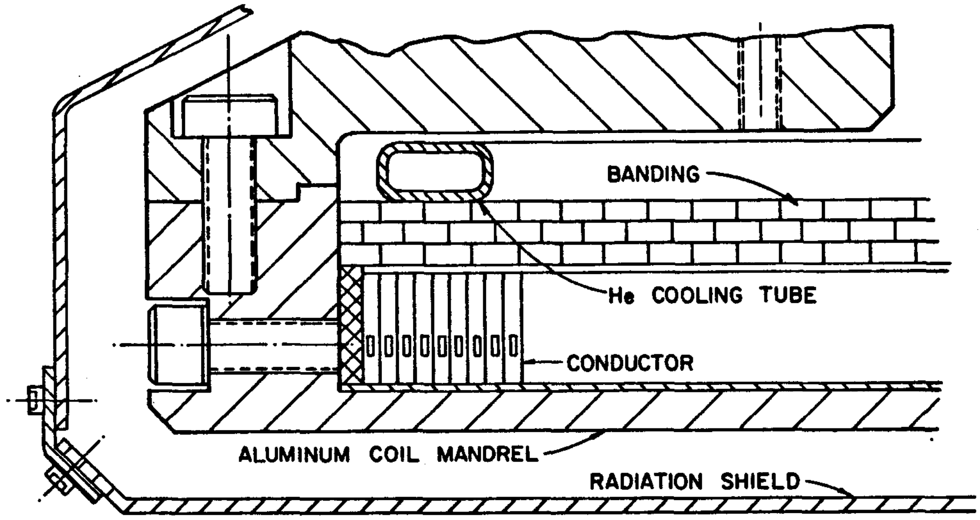


Fig. 13 Indirect cooled coil & cryostat

The results indicate that such a coil will quench safely with conductor temperature not exceeding 100K.

Both coil alternatives are still under examination. Some of the author's perceived advantages and disadvantages of each are summarized in Table IV. We plan to decide which coil to build and begin final engineering design and construction in May of 1982 with a goal of completing the coil for testing in 1984.

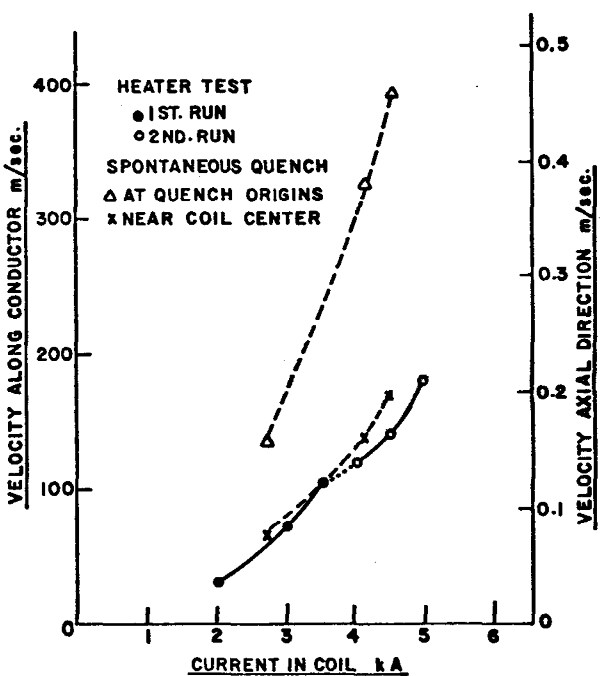


Fig. 14 Quench velocities in CDF R&D coil

TABLE IV

COMPARISON
BATH COOLED VS. INDIRECT COOLED COILS

| | BATH COOLED | INDIRECT COOLED |
|---|---|---|
| ADVATAGES | Coil can't quench<br>Coil insensitive to small conductor motions, cracking epoxy, etc.<br>Low voltage during coil discharge<br>He bath can absorb large amounts of eddy current heating during charge cycle<br>Insensitive to short refrigerator interruptions | Small amounts of helium in coil → no cryogenic safety problems<br>Coil cryogenics & leak checking simpler<br>Coil may be cheaper<br>Faster cooldown rate<br>Coil can be better electrically insulated |
| DISADVANTAGES | Large LHe reservoir in coil requires large vent pipes and safety reliefs<br>Helium cryostat more complicated and expensive<br>Leak checking harder<br>Cooldown takes longer | Coil can quench<br>Must avoid conductor motion, cracking epoxy, etc.<br>Small defects in superconductor can limit maximum current<br>Must avoid "hot spots" in coil (e.g., at support attachments)<br>Recovery from quench takes many hours<br>Higher voltages during quench → insulation more critical<br>More sensitive to eddy current heating during charge cycle<br>Short refrigerator interruption can quench coil |

## Larger Coils

Finally I would like to discuss briefly what the prospects are for scaling up magnets of the types I have described for future colliders. Table V contains a list of the world's currently approved accelerator projects as well as those that have been proposed recently. With the exception of the UNK and TEVATRON fixed target accelerators, all other approved or proposed machines are colliders. The increased center of mass energies at these machines will probably result in a several new large detectors being built that employ superconducting solenoids substantially larger than those built thus far. There are no fundamental reasons why the SC technology presently applied to solenoids at colliders cannot be extended to these larger coils. In addition, other new techniques such as cryostable force flow coils (perhaps using "cable in conduit" conductors similar to those developed for large fusion magnets) may be attractive for these large coils. It is interesting to consider what scaling laws apply that will allow us to extrapolate from existing coils to larger ones.

## Scaling Laws

### Momentum Resolution

For a solenoid whose volume is instrumented with a track detector with fixed position measurement error the resolution of the solenoid/tracking chamber system varies as

$$\frac{\Delta P_T}{P_T} \propto K \frac{P_T}{B_o R^2}$$

where P = transverse momentum
$B_o$ = solenoid field
R = radius of solenoid
K = constant (≃ 0.01 for 200 μ drift chambers)

Thus the most effective means of improving the detector resolution for high momentum particles is to increase the radius of the coil since the resolution depends inversely on the square of this quantity.

### Stored Energy of the Magnet

The stored energy of the solenoid is a useful parameter since the construction costs, quench protection, and thickness of SC solenoids all increase rapidly as the magnet's stored energy is increased. The stored energy is given by

$$E = \int \frac{B^2}{2\mu} dV$$

which for a solenoid with a non-saturated iron return yoke is approximately

$$E \doteq \frac{B^2}{2\mu_0} (\pi R^2 \ell)$$

where ℓ is the length of the coil. A useful number is that 1 $m^3$ of magnetic field volume at 1.5 T corresponds to about 0.9 MJ of stored magnetic energy in the coil.

TABLE V

WORLD ACCELERATOR PROJECTS

| | | | |
|---|---|---|---|
| APPROVED | | | |
| Europe | $p\bar{p}$ | CERN | 270 x 270 GeV $p\bar{p}$ |
| USA | ISABELLE | Brookhaven | 400 x 400 GeV pp |
| | TEVATRON | Fermilab | 1 TeV Fixed Target |
| | $p\bar{p}$ | Fermilab | 1 x 1 TeV $p\bar{p}$ |
| USSR | UNK. | Serpukhov | 400 GeV Fixed Target (3 TeV Fixed Target) |
| Japan | TRISTAN | KEK | 27 GeV $e^+e^-$ |
| Europe | LEP | CERN | 50 x 50 GeV $e^+e^-$ |
| PROPOSALS | | | |
| Europe | HERA | DESY | 30 GeV/820 GeV p |
| USA | SLC | SLAC | 50 x 50 GeV $e^+e^-$ |
| | CESR II | Cornell | 50 x 50 GeV $e^+e^-$ |
| | CHEER/ Columbia | Fermilab | 10 GeV e/1000 GeV p |
| Japan | TRISTAN | KEK | 27 GeV e/300 GeV p |

## Thickness of the Coil

For detectors with their EM calorimetry outside the coil, the coil thickness in radiation lengths is particularly important. Although the actual thickness depends on the details of a specific design, several useful scaling laws can nevertheless be applied. The main contributors to the coil thickness are the outer vacuum tank wall, the conductor banding and conductor stabilizer.

### Outer Vacuum Shells

The outer vacuum shell of an SC coil must withstand external atmospheric pressure and thus is subject to elastic buckling failure. If this shell is formed out of solid sheets of aluminum alloy, then it contributes a substantial fraction of the total coil thickness (see, e.g., Table III for the CDF coil). The collapse pressure of this shell is given by the Southwall equation

$$P_c \simeq 0.807 \left(\frac{1}{1-\nu^2}\right)^{3/4} \frac{E\, t^{2.5}}{\ell\, r^{1.5}}$$

where E is Young's modulus, ν in Poisson's ratio, and $P_c$ is the collapse pressure. The thickness required is given by

$$t = \frac{P_c^{2/5} R^{3/5} \ell^{2/5}}{0.918\, E^{2/5}} \left(\frac{1}{1-\nu^2}\right)^{3/10}$$

Note however that this thickness can be reduced in several ways. Reinforcing rings can be added periodically to reduce ℓ (the unsupported length); materials can be selected that have both high Young's modulus and long radiation lengths (e.g., Graphite epoxy) or honeycomb type structures can be used to increase the shell thickness while adding minimal material. Figure 15 shows the effects of support rings or honeycomb construction on the radiation thickness of the vacuum shell for the 3 m diameter CDF coil. It should be pointed out however that while such solutions are attractive in terms of radiation thickness, they require more physical space, and may be substantially more expensive than solid sheet vacuum shells.

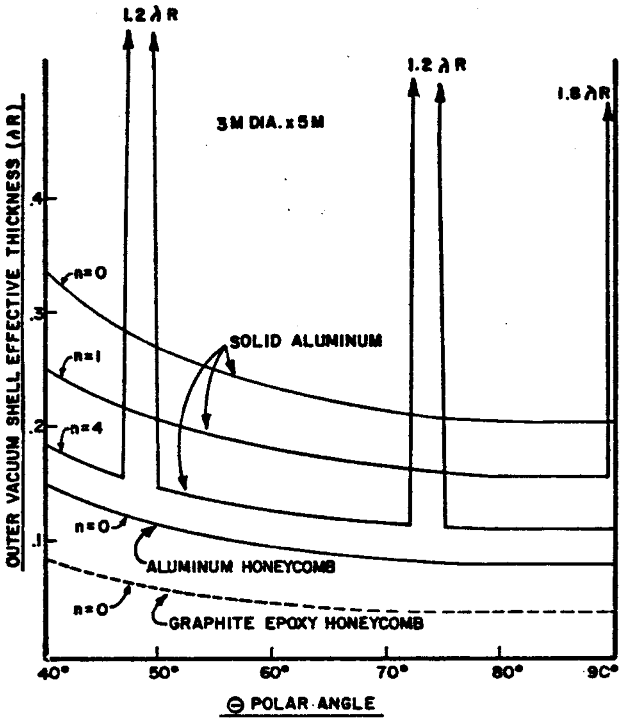


Fig. 15 Thickness vs. angle for various vacuum shell types n = no. of support rings used.

Conductor Banding

The conductor banding must contain the coil bursting forces. Its thickness is determined by the stress limit $\sigma_M$ in the banding material.

$$t \propto \frac{B^2 R}{\sigma_M}$$

thus the banding thickness will increase linearly with radius for large coils and as the square of the field.

Conductor Stabilizer

Similarly we can determine the thickness of the conductor's stabilizer if we make the pessimistic assumption that the conductor heats up adiabatically while the current is discharged into an external dump resistor r with time constant $\tau = L/r$ where the inductance $L = 2E/I^2$. If we further assume that maximum allowable voltage across the coil is limited to a value $U_M$ then one can demonstrate that the required thickness of the stabilizer is given by

$$t = \frac{B^2 R}{\mu_0} \left( \frac{\pi \ell}{2 \mu_0 U_M \, \eta \, F(\theta) I} \right)^{1/2}$$

where

$$F(\theta) = \int_0^\theta \frac{C(T)}{\rho(T)} \, dT$$

and

$\eta$ = the fraction of the conductor with respect to the whole package
$\theta$ = maximum hot spot temperature
$C$ = specific heat
$\rho$ = resistivity

Thus both the stabilizer and banding in the coil will increase in thickness $\propto B^2 R$ while the vacuum shell scales as $R^{3/5}$. As a result, the overall coil thickness for the large "thin" coil will increase nearly linearly with its radius. Indeed, as a result, several of the largest detectors proposed for LEP would have had coils that were too thick to permit the desired electromagnetic calorimeter resolution and $\pi/e$ separation. As a result, these detectors have been designed to put the EM calorimetry inside the coils.

Figure 16 shows one representative detector of those proposed for LEP[16]. It would use a 1.5 T SC solenoid instrumented with a time projection chamber. Its indirect cooled CELLO type coil would have a 5 m bore and be 6.4 m in length. Since the detectors EM calorimetry will be located inside the coil, the coil is relatively thick $\sim$ 0.5 nuclear absorption lengths. In addition to this coil several other high field SC solenoids with diameters 4-5.5 m and lengths of 6-7 m are being considered for LEP. Similarly, detectors using large SC solenoids have been proposed for Tristan, Isabelle, etc.

Conclusion

A number of SC solenoids have been built for colliders, and it seems likely that many more large SC solenoids will be built in the future. The solenoids built thus far have not, however, been free of construction and operational difficulties. Nevertheless, several large SC solenoids are now operating reliably at Colliders, and there is reason

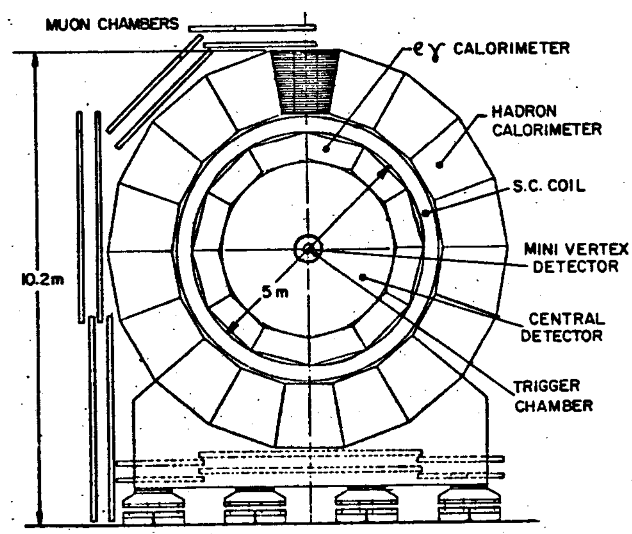


Fig. 16 Proposed LEP detector

to believe that new larger solenoids can be constructed using straight forward extrapolation of existing techniques. It seems likely that improvements in conductors, coil technology and refrigeration techniques will permit their reliable construction and operation.

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