DEVELOPMENT OF THE SSC TRIM COIL BEAM TUBE ASSEMBLY*

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Introduction

The Superconducting Super Collider uses ≈9600 dipole magnets. The magnets have been carefully designed to exhibit minimal magnetic field harmonics. However, because of superconductor magnetization effects, iron saturation and conductor/coil positioning errors, certain harmonic errors are possible and must be corrected by use of multipole correctors called trim coils. For the most efficient use of axial space in the magnet, and lowest possible current, a distributed internal correction coil design is planned. The trim coil assembly is secured to the beam tube, a UHV tube with special strength, size, conductivity and vacuum.

The following report details the SSC trim coil/beam tube assembly specifications, history, and ongoing development.

Required Specifications

The original design of the SSC trim coil is composed of a sextupole corrector which is distributed along the outside of the beam tube. The number of turns is maximized to decrease the required current in the trim coil. The absolute position of each conductor is controlled to ±0.05 mm along the length of the ≈17 m beam tube. This positioning tolerance was especially challenging because there was no conventional way to mass produce long complex multiturn coils using wire only ≈.2 mm in diameter to such precision. The variations due to accumulated tolerances of the wire position produce coil blocks of unequal conductor density and the required symmetry of the coil is lost.

To obtain the required precision with a method suitable for production, a technique developed by the Kolmorgan Corporation was adopted. In that technique, copper wires are placed directly onto an adhesive coated G-10 circuit board by an accurate, fast, fully automated process. We felt that we could exploit this established technology to produce complex coil patterns for the SSC.

This technique was adapted to produce a flat coil pattern on a flexible substrate that could be bent around the outside of the beam tube. The edges of the pattern must meet precisely because a varying gap or coil asymmetry would produce unwanted field harmonics. The coil is secured to the beam tube; the substrate must be slit to a precise size to fit the beam tube, which has an outside diameter tolerance of ±.02 mm over the entire 17 meter length.

The trim coil's substrate must withstand cryogenic temperatures and tolerate high radiation levels. The beam tube must be made from a high strength material of the required size which would not exhibit high eddy current loading during magnet quenches and which has an extremely low and uniform permeability. It must have an extremely pure layer of copper on its inside surface. The copper coating must have excellent adhesion to the beam tube without contaminates to poison the UHV. The copper must be uniformly applied over the full 17 meters.

Superconductor

The minimum current requirement for the SSC trim coil is 5 amps at the full 6.6 Tesla dipole field. From previous experience with CBA trim coils, a safety factor of at least 3 was considered prudent for the trim coil peak operating current. The critical current of the trim coil design was originally set ≥15 amps at 6.0 Tesla.

The bare wire diameter is .0082 ± .0002"; it is .0095 ± .0005" including the insulation. Monofilament wire with ≈1.65 to 1 copper to superconductor ratio with a current density of ≥2000 amps/mm^2 was selected. The monofilament was selected because it welded better to the multiwire substrate than did multifilament wire.

Beam Tube

The magnetic field length of each SSC dipole has been set at 16.7 meters. The overall length of the beam tube is ≈17 meters. The tube O.D. is 1.360 + .001-.000". The design of the beam tube was based on a maximum pressure of 20 atmospheres or ≈300 psi at quench. The initial wall thickness was set at .035 + .005-.000". Concern over Lorentz loading from eddy currents in the copper plating and increasing quench pressure dictated an increase in the wall thickness to .044 ± .004".

Various materials were considered for the beam tube, including stainless steels, such as 304LN, 304L and 316L. For 300 series stainless steel, any unannealed mechanical work hardening results in non uniform magnetic permeability; a uniform permeability of ≤1.005 at 4.5 K is required. Armco Corporation produces high nitrogen content alloys called the nitronic series. Two alloys, Nitronic 40 and 33, both have higher yield strengths and lower permeability than 300 series alloys. The Nitronic alloys do not have large changes in permeability caused by cold working.

Trent Tube of East Troy, Wisconsin with experience in very long Nitronic 40 welded tubing, was chosen to produce tubes.

Welded tubing was initially thought unacceptable because of UHV problems and ferrite content in the welds. In working closely with Trent and the BNL Material Science Group, we developed a weld, draw and anneal schedule which yielded a variation in permeability throughout the tube undetectable by a ferrite scope at 20 C. Recent magnetic measurements of completed SSC magnets show no adverse effects of the weld on magnetic field quality. The final choice of alloy was based on the fact that N33 was only available in billet form whereas N40 (ASM #21-6-9) was supplied as sheet, ready for the welding process. The major disadvantage of the Nitronic alloys are that they cannot be vacuum electron beam welded since the nitrogen will come out of solution in the weld puddle, producing porous and brittle welds.

When the tube is produced, a final cold overdraw and roll straightening is required to assure the tube's outer diameter to ±0.02 mm and straightness of 1 mm/2 meters.

The Development Program

Contracts were established with the Kolmorgan subsidary, Multiwire, to develop the wiring of superconductor using

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semistandard equipment, for the development of a cryogenically stable substrate, and to build the first .5 meter and 4.5 meter trim coils. Short sextupole trim coils ≈.5 meters long were wound and tested successfully using various assembly techniques.

A special substrate transport system was designed and built at BNL to expand the wiring capacity of one axis of the Multiwire wiring machine. 4.5 meter coils were wired and delivered to BNL using the new tooling. Since final assembly tooling was not available for the 4.5 m magnets, we removed the FEP backing on the substrate and used an epoxy impregnated glass wick to bond the trim coil to the beam tube. This assembly, unfortunately, resulted in an unsymmetrical coil with a substrate edge gap varying between .050" and .070". This error was observed in the magnetic field measurements. The operation of the coils was successful, however, with currents reaching ≈15 amps at 6.2 Tesla. The assembly tooling was completed in time for the 17 m magnet trims where the edge gap did close, showing a dramatic improvement in field quality.[1]

The Multiwire Process and Trim Coil Assembly

The Multiwire process was first developed by Mr. Page Burr in 1969 for the routing of copper wire on circuit boards. It was an alternative to printed circuit techniques. Our superconductor is insulated with a .0005" radial build up of polyimid "ML" insulation with a 1000 volt turn-to-turn breakdown. A very thin layer ≈.0002" thick of High Bond adhesive coats the insulation. The insulated wire is stored in a spool above a wiring head. A small motor on the wiring head drives the wire at a precise speed between a stylus and the circuit board adhesive. The stylus is vibrated at ≈25 KHz. The kinetic energy imparted to the wire while under the stylus causes the High Bond coating to chemically react with the circuit board adhesive, called RC205. The pressure and elevation of the head controls the depth of the wire into the RC205. Wiring speeds are between 8 to 15 meters per minute. In the past, Multiwire had produced various types of complex wiring patterns. The standard wiring machines have the capacity to wire a circuit board or coil pattern of 24" x 24".

A special substrate is required. It has to be cryogenically stable, it has to bond to the Kapton-insulated beam tube without distorting the wire positions, and it has to provide good bonding strength for the wires during the wiring, handling and assembly. The strength and electrical insulation are supplied by a .003" thick Kapton sheet. A .001" thick FEP teflon coating on one side provides the means of binding to the bore tube. The other side contains a .002-.003" matt of fiberglass bonded to the Kapton with a .002" layer of RC205 adhesive. On top the fiberglass matt is a layer of .005" RC205 for receiving the wires. The matt prevents the adhesive from cracking at LN2 temperature. The total substrate thickness is only ≈.014". This material is processed in 6" strips by the Sheldahl Co. of Northfield, Wisconsin.

After manufacture, the material is shipped to the Mellon Co. of Cranston, Rhode Island and slit to a width of 4.346 + .002 -.000" with a straightness of .005" over 24 inches.

Once slit and inspected, the substrate is shipped for precision punching by the Schneider and Marquard Co., Newton, New Jersey. Two sets of holes are punched at one inch increments along the length of the substrate. Location slots are punched along the substrate at 18 inch increments. The slots and holes are designed to allow any combination of odd or even harmonics from quadrupole to 14-pole correction coils. Present correction elements include an 8 meter long 19 turn sextupole, 5 meter long 12 turn decapole and 4 meter long 14 turn octupole.

After the substrate is punched, the material is sent to Multiwire. The hole and slot pattern is registered to the wiring head with the use of precision sprockets on the substrate transporter, which is mounted on the bed of the Multiwire wiring machine. The superconductor is applied to the substrate in a preprogrammed wire pattern (see multiwire flat pattern layout, Figure 1). After the wiring is finished, a protective .001" Kapton cover sheet is applied over the coil.

Once the wired substrate is received and inspected at Brookhaven, it is placed on a 60 ft. surface plate and the position of the location slots are checked and transferred to the beam tube. The beam tube has previously been wrapped and heat sealed with .001" FEP dispersion coated Kapton film to achieve a precise diameter. Precision locating fixtures have been used to apply location pins made from RX-630 to the wrapped beam tube. The pins transfer the precise and very flat plane of the surface plate to the beam tube.

Special tooling is used to roll out and secure the wired substrate onto the beam tube. The location slots in the substrate fit snugly onto one row of location pins bonded to the beam tube. The substrate is wrapped around the beam tube and then securely wrapped with a double layer of FEP-impregnated Kevlar yarn. A final 50% overlap wrap of FEP-coated Kapton film is applied over the Kevlar. The Kapton assures a >5 KV breakdown between the trim and main coils.

The entire assembly is passed through a radiant oven to heat seal the various components of the assembly together. The location pins protrude through the top Kapton layer. Using the previously mentioned fixtures, locating keys are applied to the location pins and glued into position on 18 inch increments, on both sides of the tube. Bumper strips of G-10 are glued onto the Kapton outer wrap. These are used to space the beam tube inside the main coil at assembly.

The assembly is inspected and electrically tested for proper resistance, continuity, inductance and highpot breakdown (see the section drawing of the beam tube assembly, Figure 2).

Copper Plating

For the efficient transmission of beam image currents in the SSC, the beam tube must have a highly conductive surface applied to its inner diameter. This surface must have minimum photodesorption outgassing so that under the bombardment of synchrotron radiation the UHV of $\approx 10^{-10}$ Torr may be maintained to maximize the beam life. A high purity copper plating was selectd to form the conductive surface. During magnet quenching, eddy currents will be induced in the copper surface. Resulting high forces will tend to shear the coating off the tube wall. The copper's adhesive strength to the beam tube must be higher than the copper's yield strength. In addition, the surface must be smooth and void of high vapor pressure materials which outgas into the UHV.

Over the past two years, BNL has worked closely with the PCK Company to develop a copper plating that matches the above requirements. Beam tubes up to 18 feet in length have been plated, using a technique developed at PCK. This technique includes a non-consumable anode suspended in the beam tube, a copper bus applied to the outside of the beam tube and anode terminations protruding through manifolds at the tube ends. The anode is made up of a copper core inside a titanium tube with a thin layer of platinum on its surface.

A cleaning solution followed by a water rinse is first pumped through the beam tube. A solution of sulfuric acid is then pumped through the tube while a DC current is used to activate the inside surface. The activation solution is followed by a copper sulfate solution. Using various current densities, copper is applied to the stainless steel and built up to a uniform coating of .0025 ± .0005" along the entire length of the tube. After the copper is plated, a rinse is performed, followed by vacuum drying. The resulting copper surface has a uni-axial grain structure having the minimum number of grain boundaries. Resistivity ratios at zero field and 4.2K have been measured to be ≥900.[2] Photodesorption outgassing rates have been measured to be less than 5 $\times 10^{-9}$ Torr-liters/cm^2/sec. Photodesorption experiments have shown that the clean plated surface has a lower outgassing rate than stainless steel.[3]

Radiation Experiments

Concerns were raised about the effects of radiation on the beam tube assembly materials: Kapton, Kevlar, Glass, RC205 adhesive, and FEP Teflon. FEP was originally chosen as the main bonding agent of the trim assembly. Teflons in general are not recommended for use in high radiation environments. They have a low resistance to radiation as compared to other thermal plastics, rubbers, or polymers.

FEP-coated Kapton was chosen because it could be held to extremely close tolerance (±.0001") and as a standard Dupont product, it was readily available. This allowed close diameter tolerances which could not be achieved by use of epoxy as a bonding agent. FEP also had good bond strength at cryogenic temperatures.

A study at Brookhaven concluded that Teflon's radiation resistance is good if it is not irridiated in the presence of oxygen. Cryogenic temperatures also improve radiation resistance.[4] Since the SSC magnet offers this environment, it was decided that the benefits outweighted the risks. Alternate adhesives were also investigated; for instance, RC205 has various components of epoxy and rubbers, but the composite as a whole had no published radiation effects data.

Using the Brookhaven Linac Isotope Producer (BLIP) various component materials of the trim assembly were irradiated. The exposures were preformed at 3.5 and 20 μ amp-hours of proton beam current of energy $\approx$193 Mev. Although of relatively low energy, the ionization attributable to the proton beam is similar to a long-term exposure in the SSC machine. No effect on the Kapton substrate material other then a slight stiffening was found. Significant degration in the strength of G-10 at the higher bombardment was observed; the sample turned black and lost over 90% of its mechanical strength. Some degradation in RX630 was found but not enough to preclude its use. Initial observations showed an actual improvement in FEP bond strength but under high bombardments, the FEP became brittle. The peel strength of the superconductor from the RC205 adhesive did not change appreciably. However the interstitial bond strength of the RC205, glass and Kapton laminate deteriorated to a point that alternative adhesives must be investigated. The Kevlar yarn remained intact; however, under the higher bombardment, some loss of bond strength was noticed.

Future Developments

Work has begun on the evaluation of alternative adhesives that could be used in the trim coil assembly. An improved epoxy-based wire adhesive called PK102 will be tested for its radiation resistance. Different adhesives such as Tefzel are being investigated for the eventual replacement of the FEP Teflon.

Glass and carbon fiber yarns are being evaluated as alternatives to Kevlar. Alternative materials and designs are being evaluated to replace the G-10 bumpers on the outside of the trim coil assembly. Further work will continue to optimize the trim coil design to precisely match the SSC field requirements where needed.

Work is continuing on the development of a facility to plate beam tubes up to 17 meters in length.

Armco Nitronic 33 alloy stainless steel will be investigated as a lower cost, lower permeabilty alternative to the present Nitronic 40. New tooling will be developed at BNL to improve the trim coil/beam tube assembly tolerances. This tooling will also substantially reduce assembly time and cost.

Work will continue to emphasize industrial involvement in the development and improvement of the trim coil components and will seek to optimize procedures for the mass production of assemblies.

Technical Spinoffs

The first spin-off of this technology was the production of precisely made detector wire patterns for an IBM/BNL collaboration on a monopole detection experiment. Also, General Electric is working with Multiwire to develop a less expensive and more precise alternative for the production of superconductor trim coils for nuclear magnetic resonance imaging equipment. The Multiwire technique of precision wire placement can be applied to experimental instrumentation such as lumped correctors, measuring coils, and drift chambers for the SSC and other accelerators.

Conclusions

Over the past three years Brookhaven has been involved in a program which has led to the successful development of a precision field correction coil/beam tube assembly for the SSC. The initial results show that the assembly fulfills the various requirements of the SSC accelerator design in the areas of field strength, quality, copper plating, photodesorption, and assembly procedures.

Work is still needed to improve the radiation resistance of constituent materials. Efforts are under way to optimize and refine the materials and production techniques as well as quality control procedures to assure the efficient and trouble free operation of the 9600+ trim coil beam tube assemblies for the SSC project.

References

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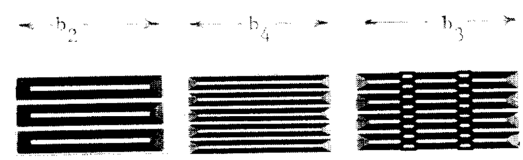

Figure 1. Multiwire Flat Pattern Layout.

TYPICAL SECTION OF THE SSC
BEAM TUBE ASSEMBLY

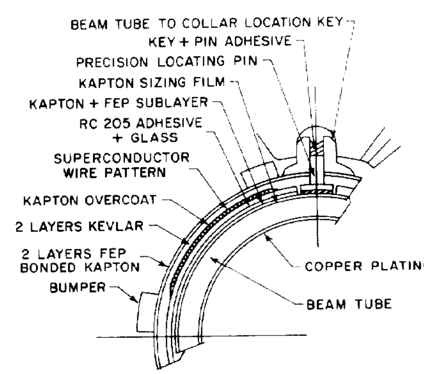

Figure 2. Beam Tube Assembly