FERMILAB-BUILT SSC COLLIDER DIPOLES USING LOW TEMPERATURE CURING INSULATION SYSTEMS WITH AND WITHOUT GLASS TAPE

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Abstract-- Polyimide with epoxy impregnated glass tape was used in Fermilab baseline design of several SSC Collider dipole magnets which were used in the SSC Accelerator Systems String Test (ASST). Later in the magnet R&D program several magnets were built using conductor insulation in which adhesive that cures at 140^0 C was coated directly on the polyimide film. Some alternate materials for coil end parts and coil winding were also tested. The data taken during the tests of these magnets are compared with results from 10-stack studies of the two insulation systems and design expectations and correlated with changes in assembly methods.

I. INTRODUCTION

Fermilab built and tested several long (15 meter) and model (1.5 meter) collider dipole magnets for the SSC project, based on the baseline design of ASST. The mechanical design of the 2D cross section is discussed in detail in [1,2]. The return yoke of all 50 mm aperture SSC dipoles built at FNAL were vertically split. This gives support to the horizontal mid-plane under all conditions and the collar deflections are minimized under Lorentz (IxB) force [1]. The inner (outer) coils are made of 30(36) strand NbTi cable with six micron filament diameter. Several extensions to the baseline design were incorporated into last 5 short and last 4 prototype SSC dipoles. The primary purpose of these magnets was to study the effect of alternate insulation schemes, various coil end part designs and variation in manufacturing parameter on the performance of magnets under cryogenic conditions. The choice of alternate parts was considered to find ways that are more conducive for mass production of SSC magnets and to demonstrate the alternatives to present manufacturing techniques without altering the existing design. Some important factors in the selection of all polyimide insulation and changes in other magnet parameters, included their effect on the coil crossection, magnetic field, quench and mechanical behavior of the magnet. A strong insulation is needed on the coils to avoid turn to turn shorts. Fermilab magnet program for SSC used polyimide, with and without glass tape, in combination with adhesives which cured at low temperatures as compared to the melting polyimide insulation system of CDM baseline design. By using lower curing temperature, for the coils, it is possible to avoid the eddy current heating related to ramp rate sensitivity of these magnets. So, an insulation system with lower curing temperature is desirable. As a backup, some insulation schemes without glass tape were tested in last nine magnets built at Fermilab. Polyimide is more homogeneous so it is easier to handle for mass production of coils. The elimination of glass tape makes the coil smaller. So, another conductor turn, could be added to the coil which could increase the current density and thus the field. Cryorad adhesive has a high resistance to radiation. It was tested in two model magnets. Several materials and techniques were studied for mass production of coil end parts [Table I]. This paper outlines some of the advantages and disadvantages of the above variations. The mechanical behavior of magnets using all polyimide insulation is correlated with changes in the magnet design and assembly methods.

II. INSULATION SYSTEMS

In Fermilab baseline design the collars are designed to position the conductors as determined by the magnetic field without the use of pole shims [2]. Due to thin polyimide the desired coil size, after curing, carefully calculated pole shims and brass shims on all copper wedges had to be applied. The preload in the coil is created by the oversize pressure of the coil against the collar. Therefore the measured relationship between the coil and shim size with that of prestress was used

TABLE I. Salient Features of Later Model Collider Dipoles Built by Fermilab
RTM=molded keys and saddles; 1 = Spaulding part; 2 = Amoco Torlon 5030 with 30%glass fiber part; 3 = Cryorad part;

Magnet	End Parts	Pole Shim (mm) Inner/Outer	Coil Insulation Inner / Outer
DSA 330	G-10CR+RTM-(1)	0 / +0.25	2H+butt LT one side / 2H+2LT one side--scotch 2290 adhesive
DSA 332	G-10CR-as ASST	0 / +0.51	2H+butt LT one side / 2H+2LT one side
DSA 333	G-10CR+RTM-(2)	+0.09 / +0.2	2H+butt LT both side / 2H+2LT both side
			Apical film with Cryorad adhesive; cured at 140-145^{0}C
DSA 331	G-10CR-as ASST	Lo Inner+0.13 / 0	3NP one side / 2NP one side+2NP one side
DSA 334	G-10CR+RTM-(3)	0 / +0.20	2NP+butt NP both side / 2NP+2NP both side
DCA 320	G-10CR-as ASST	0 / +0.13	2H+butt LT one side / 2H+2LT one side-scotch 2290 adhesive
DCA 321	G-10CR-as ASST	0 / +0.13	2H+butt LT one side / 2H+2LT one side
DCA 322	G-10CR-as ASST	0 / 0	2NP+butt NP both side / 2NP+2NP both side-2290 adhesive
DCA 323	G-10CR-as ASST	0 / 0	2NP+butt NP both side / 2NP+2NP both side

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to determine the correct molded coil size [6]. The coil size was carefully made to have the same characteristics as Fermilab baseline design magnets.

Polyimide Insulation System With and Without Glass Tape

The polyimide insulation system with glass tape consists of a layer of 0.025mm x 9.5mm Kapton type H film overlapped by 50% surrounded by one layer of 0.1mm x 9.5mm glass tape impregnated with B-stage epoxy. The coils were cured at 135^0C. It was successfully used on Fermilab built ASST magnets which showed very little training [5,8,7].

Low temperature curing insulation system without glass tape was used with different combinations of end parts and shimming on last 9 magnets [Table I,3]. The insulation variations used on these magnets included polyimide only and its equivalent (Apical) cable insulation films of thickness 0.025 mm x 9.525 mm(0.001 in x 0.375 in). The variation in thickness of polyimide films of different kinds is not significant, but presence of glass tape in insulation scheme has a large effect on curing pressure. The thickness of glass tape is 3.5 mil/layer which correspond to 2.6 times of Kapton. In the absence of glass tape as part of the insulation, the coil size becomes smaller for a given pressure. The observed effect of creeping of all polyimide insulation is about twice as normal "Kapton with glass" insulation, and it is comparable to the 10-stack data [5]. Studies show that the thermal contraction and creeping of all polyimide is higher as compared to other insulation systems that were tested [7]. So, there is a large dynamic range for the cured coil size.

The loss in coil pressure after curing (coil creep) can be reduced by using lower number of polyimide insulation layers. Due to thinner insulation, the coils were smaller radially and in azimuth. The poles were shimmed using adhesive backed polyimide, and copper field wedges were shimmed with thick brass to make up the difference in coil size [3]. Despite the use of thinner insulation, the incidents of turn to turn shorts in magnets with all polyimide insulation were not any greater than magnets with polyimide and glass tape insulation.

III. END PARTS

Several processes and materials were considered for end parts of the magnets for their cost effectiveness, ease in production, uniformity and quality, their strength and radiation resistance. Fermilab baseline design for magnet ends uses a collet clamping system, consisting of a metal can which clamps four azimuthal G-10CR insulating blocks around the coil to provide prestress for the end region [2]. Several materials were molded into end parts except the collets. The details on combination of end parts used on model magnets using all polyimide are given elsewhere [3, Table I].

Resin transfer molding (RTM), compound transfer molding (CTM) and injection molding processes were investigated for use in end parts. The keys and saddles on some magnets [Table I] and test coils [8] were made using RTM. It turns out that end parts made with RTM with fiber glass preform are stronger than CTM parts because in RTM the fibers are aligned in a direction to give maximum strength. Although G-10CR has the highest flexural strength and despite the production complexity of machining G-10CR end parts the tooling is least expensive for this process, molding process is a better way of mass producing the end parts than machining them [8] particularly when a large number of magnets are to be manufactured.

DSA333 end parts were machined out of Torlon injection molded tubes. The quench behavior of this magnet indicates that the bonding between the end parts and the coils might not have been ideal. The epoxy used to bond the end parts with coil seemed to cure very well but its behavior at cryogenic temperatures is not well understood.

Aluminum is a material of choice for the outer end cans. It is cheaper to make and it has a higher coefficient of thermal contraction which allows it to shrink more at cryogenic temperatures.

IV. COLD TEST DATA

Fermilab-built magnets are instrumented with voltage taps for quench localization. The strain gages located in the collars measure azimuthal stress between the collars and the coils. Four end force gages were used to measure the coil pressure on end plate due to differential thermal contraction during cooldown and the Lorentz force due to magnet excitation.
Tests at liquid helium temperatures were performed on both long and short dipoles. Model magnets were tested in a 3.6 m vertical dewar and long magnets were cryostated. The strain gages on all magnets measured absolute stress at 4K [2,3]. Coil pressures were monitored throughout the cooldown and magnet excitation. The desired prestress was achieved on all magnets. This was possible, by careful handling of the process, even when the glass tape was eliminated from the insulation system. If a layer of thick polyimide was used instead, a large pressure drop could have occurred upon cooldown due to high thermal shrinkage of insulation. The prestress loss due to cooldown is a fraction of a collared coil's initial (295K) pressure [3,7]. The change of pressure due to thermal contraction during cooldown were higher for the inner coils (Fig. 1) than for the outer coils (3,7). There were some unusual behaviors which can be attributed to manufacturing processes.

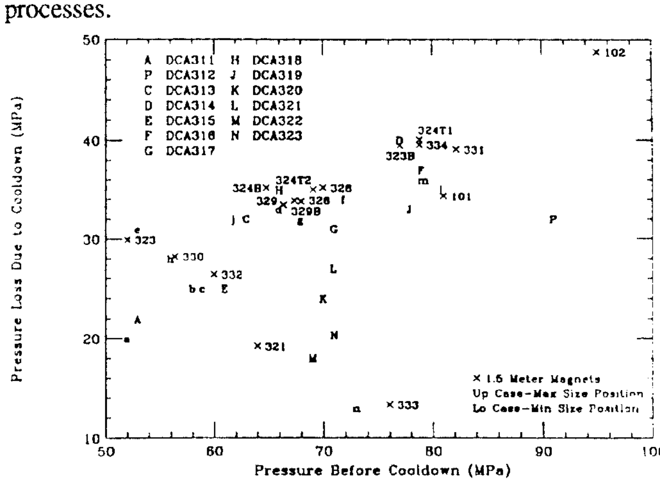

Figure 1: Prestress loss due to cooldown vs coil pressure before cooldown for Fermilab built magnets for the SSC.

V. EXCITATION BEHAVIOR

The absolute loss in inner coil pressure of Fermilab model and prototype magnets at 7 kA is shown in Fig. 2 The magnets with higher prestress tend to lose more pressure during magnet excitation. The pressure loss characteristics were maintained in all magnets due to cooldown and excitation [3]. Any unusual excitation behavior, such as DCA311, can be easily observed. DCA311 shows higher than average loss upon excitation, although the prestress is not very high. This unusual change in inner coil pressure, with excitation, is attributed to the diminishing support of the collars from the yoke.This is because the yoke laminations on DCA311 were chevroned due to loose packing.

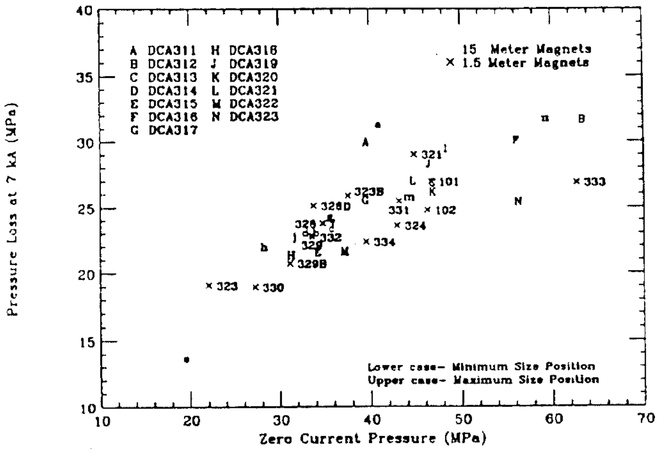

Figure 2: Absolute pressure loss in inner coils as a function of initial coil pressure

The pole stress on all magnets remains positive, during excitation, and there is no sign of unloading [3,5,9] at 7 kA. By maintaining the coil crossection for all magnets, there does not seem to be any noticeable difference in their excitation behavior due to different types of insulation.

The magnet is partially supported in the axial direction at each end by sets of four bullet load slugs with strain gages. The end force measured, by the bullet gages, increases in proportion to current squared. Fig. 3 shows the total end force experienced by the long and short magnets during excitation. The longitudinal force in the end is expected to increase by approximately 10-15 % of the total electromagnetic force when the magnet is at 6.6T [9]. The total end force is estimated at 3 kN / $(kA)^2$. This is a small fraction of the total electromagnetic force in the coil, as most of the axial force is transferred to the shell through friction between collar and yoke. End force is highly dependent on the collar-yoke

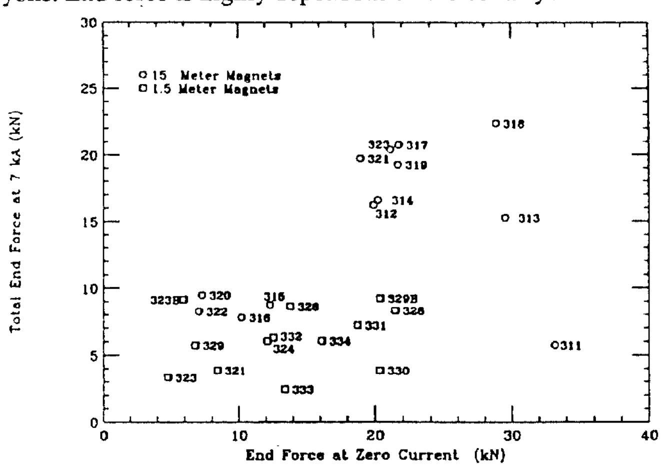

Figure 3: End force at 7kA vs initial end force at zero current.

interaction. Any unusual response is obvious, e.g., DCA311 shows very little end force, at 7 kA, than expected because of smaller collar-yoke interaction as explained earlier. Bullet gage preloads changed over thermal cycle in some magnets, but these changes did not affect the quench performance of Fermilab vertically split yoke magnets, as they have tight collar-yoke interaction.

VI. CONCLUSION

Quench performance of some of the magnets was not so stable [9]. This could have been due to too many shims, insulation itself or it could also be associated with manufacturing process. A slight modification in manufacturing process can affect the magnet performance, as observed in some magnets with two piece pole end key [3]. Magnets with all polyimide film insulation need to be studied more to fully understand their behavior. We have shown that "thinner insulation without glass tape" with low curing temperature can be used successfully in SSC collider dipoles. One of the magnets of this series DCA322 (all polyimide) was tested at 1.8K at about 9.5 Tesla, showing the Fermilab design to be robust. This gives a confidence in the mechanical design and the choice of insulation for Fermilab built magnets. This is very promising for SSC's future and a success of 2D design. Thermal contraction and coil relaxation is an important design issue for magnets with all polyimide insulation with no glass tape. It is important to use as little insulation as possible without risking turn to turn breakdowns.

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