SUPERPOWER'S SECOND GENERATION HTS CONDUCTOR DESIGN FOR STABILITY AND LOW AC LOSSES

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ABSTRACT

SuperPower is developing a conductor design for improved mechanical properties, quench stability, and low ac losses. Coated conductors are typically 12 mm wide with a few microns of silver overlayer. SuperPower's design modifies such base conductor designs into geometries more suited for practical applications. Wide conductors are slit into 4 mm wide tapes, in particular for cable applications, but also to reduce ac losses. After slitting, the conductor is stabilized with approximately 20 microns of surround copper stabilizer, completely encapsulating the conductor and providing a hermetic seal. Other advantages of the surround copper stabilizer configuration are rounded edges for dielectric integration and superior over-current handling capability (9X critical current with 300 ms wide pulses). Prototype 1 m cables made by Sumitomo Electric using this practical conductor showed total ac losses under 0.4 W/kA-m. To further reduce ac losses, especially for high frequency applications of the military, SuperPower's conductor design involves striating the current-carrying layers by a photolithography process. Several racetrack coils made with our practical coated conductors have been provided to Rockwell Automation for use in a demonstration motor. Recent results of our practical coated conductor will be discussed.

KEYWORDS: HTS Conductors, Stability, ac Losses, Coils
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INTRODUCTION

SuperPower is developing a conductor design for improved mechanical properties, quench stability, and low ac losses. Coated conductors are typically 12 mm wide with a few microns of silver overlayer. SuperPower's design modifies such base conductor designs into geometries more suited for practical applications. This work coincides with SuperPower's scaleup efforts towards commercialization. Three objectives of this scaleup are i) the production of high performance second generation (2G) conductors via high throughput processes (namely IBAD MgO and MOCVD) to full fledged manufacturing; ii) the development of in-line and off-line QC tools and procedures for high-yield manufacturing and iii) the development of practical conductor configurations to meet specific customer requirements. These configurations provide for high engineering current density (J_e), low ac losses, quench stability and improved mechanical properties. Techniques to attain these targets include thin tapes, variable width including narrow tapes, intrinsic copper stabilizer, patterned (filamentized) conductors and an ability for the conductors to be twisted.

SUPERPWER'S 2G CONDUCTOR

MOCVD-based YBCO conductors have been produced by SuperPower in lengths over 200 m with end-to-end critical current exceeding 100 A/cm. Also, a 70 m long segment of MOCVD-based conductor has been demonstrated with a critical current of 200 A/cm. Further, a critical current uniformity of 2% has been achieved over 100 m lengths of MOCVD-based conductor. SuperPower has demonstrated A current configuration used in the production of SuperPower's 2G conductor is shown below in FIGURE 1. This configuration is based on IBAD MgO based buffers for high throughput. At present, linear tape speeds exceeding 10 m/h have been demonstrated using 12 mm wide tapes. This is equivalent to 30 m/h for 4 mm wide conductor. The main components of the conductor are i) the underlying substrate that provides the mechanical strength of the tape; ii) the buffer stack that provides the aligned template for growth of the superconductor; iii) the superconductor itself and iv) the stabilizer that provides electrical stability to the conductor and typically surrounds the entire assembly.

High Je Conductor Configuration

In a typical conductor configuration, the substrate thickness dominates the overall thickness of the conductor, followed by the thickness of the stabilizer material. As such, these two components have a high impact on the overall engineering current density that can be achieved in the conductor. While the stabilizer thickness is driven by the conductor operating parameters, the substrate thickness is less application driven. Previously, 100 micron thick substrates were utilized in the conductor construction. These conductors used IBAD YSZ in the buffer stack and were subject to a transverse bowing issue when the thickness was reduced to thinner levels. Recently, with the adoption of IBAD MgO in the buffer stack, this bowing issue is no longer present and the thickness of the Hastelloy HC-276 substrate has been reduced to 50 microns. This has reduced the overall thickness of

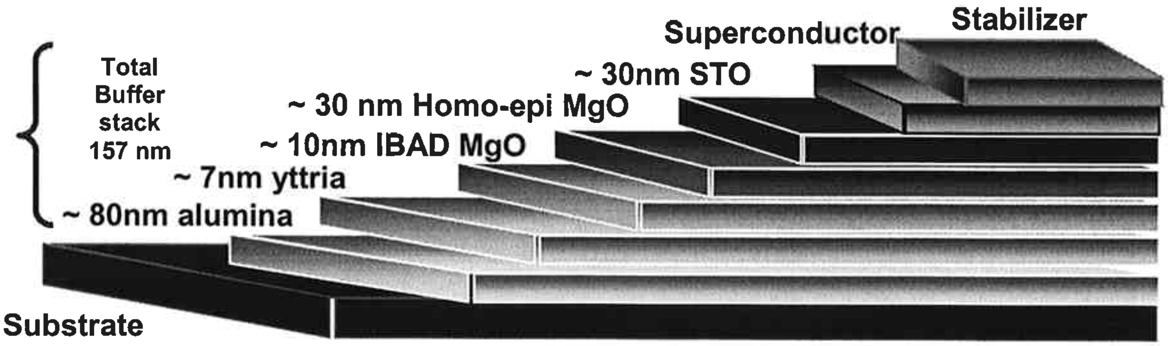

FIGURE 1. General configuration of SuperPower's 2G conductor.

the conductor from ~ 145 microns (including a 40 micron stabilizer thickness) to ~ 95 microns. This increases the J_e of the conductor by ~ 50%. A comparison of conductor performance for various configurations is given in TABLE 1 and FIGURE 2. As shown in TABLE 1, a critical current of 142 A/cm corresponding to a Je exceeding 25 kA/cm2 has been achieved over 25 m lengths of IBAD MgO-MOCVD-based conductor. Also, in short samples, a very high Je of 71 kA/cm2 has been demonstrated using a thicker (3 micron) HTS film. Figure 2 displays the in-field performance of Jc of this sample. It can be seen from the figure and Table 1 that a Je of 18.8 kA/cm2 has been achieved at 65 K and 3 T, which exceeds the goals set by the Title III program even for 2008.

Conductor Width

The ideal width of a conductor is often driven by the application. For example, for HTS cables, a width of ~ 4mm is often specified. Other applications, such as an HTS transformer low voltage winding, may require a wide tape to accommodate high operating currents. Tape width can also impact the ac losses of an HTS conductor, with narrower tapes usually being favored. Current processing at SuperPower uses 12 mm wide tapes as the base conductor. These base tapes are then slit to width, usually before the application

TABLE 1: Comparison of different conductor configurations showing high conductor Je for thick YBCO and thin substrates.

Substrate (μm)	Buffer	YBCO Thickness (μm)	Length (m)	Temp. (K)	Field (T)	Ic (A/cm)	Je (kA/cm^2)
100	YSZ	1.1	10	77	0	200	19.2
50	MgO	1.1	25	77	0	142	25.8
50	MgO	3.0	0.01	77	0	400	71.4
50	MgO	3.0	0.01	75	1	61	11
50	MgO	3.0	0.01	65	1	185	33
50	MgO	3.0	0.01	65	3	105	18.8

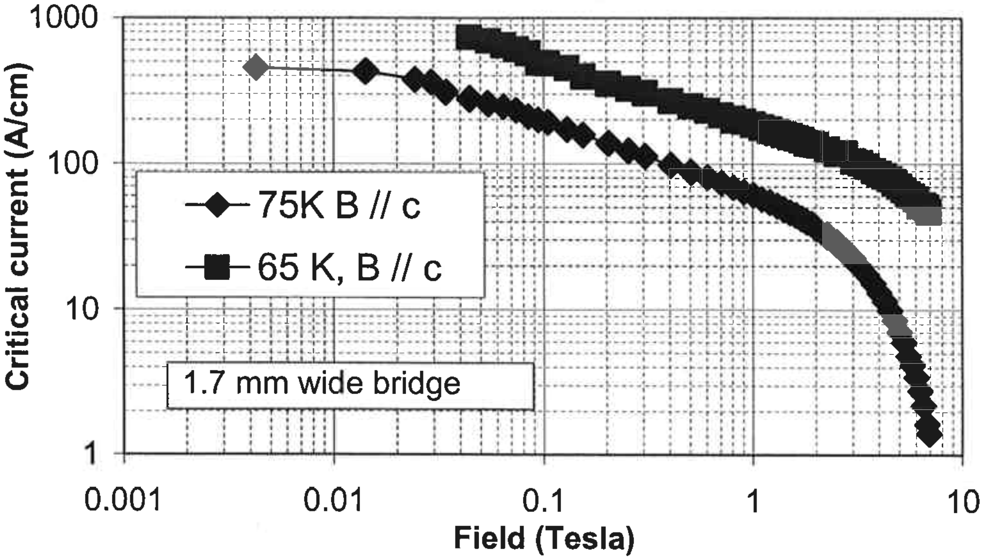

FIGURE 2: Critical current vs. field performance for 2G conductor (50 μm substrate, MgO buffer, 3 μm YBCO). Measurements made by LANL across a 1.7 mm wide bridge.

of the copper stabilizer. From a 12 mm tape, three 4 mm tapes are slit with no direct scrap and minimal I_c reduction due to limited damage at the slit edge. These losses average ~15% for 100 micron substrates and are reduced to ~ 7% for 50 micron substrate material. After slitting, the conductor is then plated with copper stabilizer. Data on the reduction in I_c is shown in FIGURE 3 for 25 m tapes and includes any reduction associated with the electroplating process.

Copper Stabilization

In order to provide proper stabilization to the 2G conductor, SuperPower has implemented a "Surround Copper" stabilizer design. In this approach, copper is electroplated after slitting in a single step around all sides of the 2G base conductor. This fully encases and provides protection to the underlying structure. One advantage of this approach is that the edges outer edges of the conductor are encased and fully rounded (FIGURE 4) which will be of benefit in high voltage applications. The surround copper stabilizer has been successfully implemented and tested to date on several hundred meters of conductor.

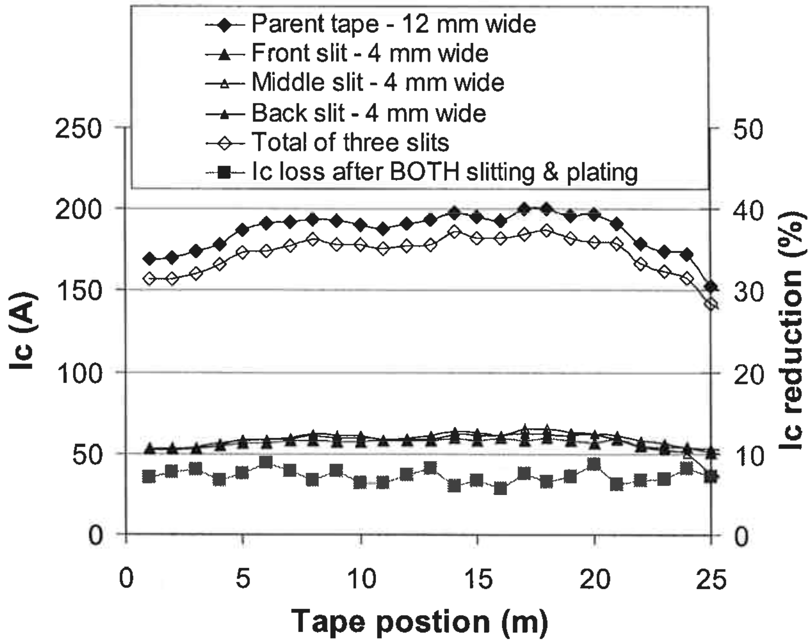

FIGURE 3: Impact of slitting process on a 12 mm wide tape slit into 3 x 4 mm wide tapes. Ic loss (including impact of copper plating) averages ~ 7 %.

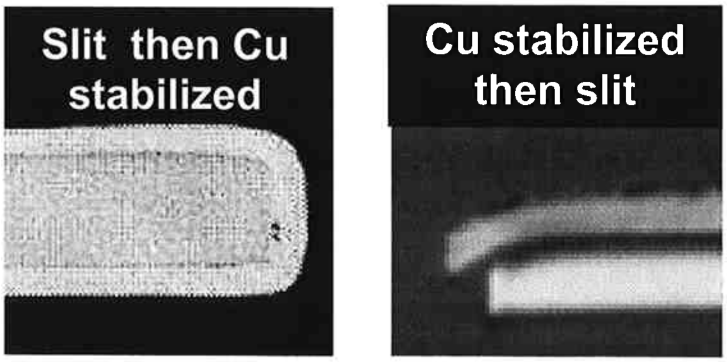

FIGURE 4: Edge comparison of i) a fully rounded edge on a 2G conductor with surround copper stabilization applied after slitting (left) and ii) sharp edge of a plated and then slit 2G conductor.

A major function of the surround copper stabilizer is to provide parallel normal conductor within the 2G structure in order to handle over-current situations that would typically result in damage to the conductor if the stabilizing material were not present. Tests have shown that with a surround copper thickness of 38 microns, over-current levels of 9 times I_c (300 ms pulses) and 3.5 times I_c (1 sec pulses) can be handled by the conductors without burnout and minimal I_c degradation. Results of these tests are shown in FIGURE 5.

Mechanical Properties

The mechanical strength of 2G conductors is highly dependent on the substrate material's mechanical properties and the effect of pre-strain that it and the stabilizer impose on the superconducting layer. An advantage of IBAD-based conductors is the ability to use high strength and high modulus materials such as Hastelloy HC-276 as the substrate. Critical strains of 0.48 % have been measured [1] on IBAD based tapes with surround copper stabilizer. In addition, critical tensile stresses of >350 MPa have been measured on these tapes. This value is more than twice than what has been measured [2] on RABiTS based conductors.

One advantage of the move to 50 micron based conductors is the improvement in bend properties that the conductor can withstand. The minimum bend diameter, with the YBCO layer in either tension and compression, has been reduced from ~ 24 mm for 100 micron substrate materials to below 11 mm for 50 micron substrate tape. These results were measured by bending the tape at RT over different diameter mandrels and measuring at 77 K in LN_2 while still being held on the mandrels. Ic retention of 95 % is used to determine the critical bend diameter.

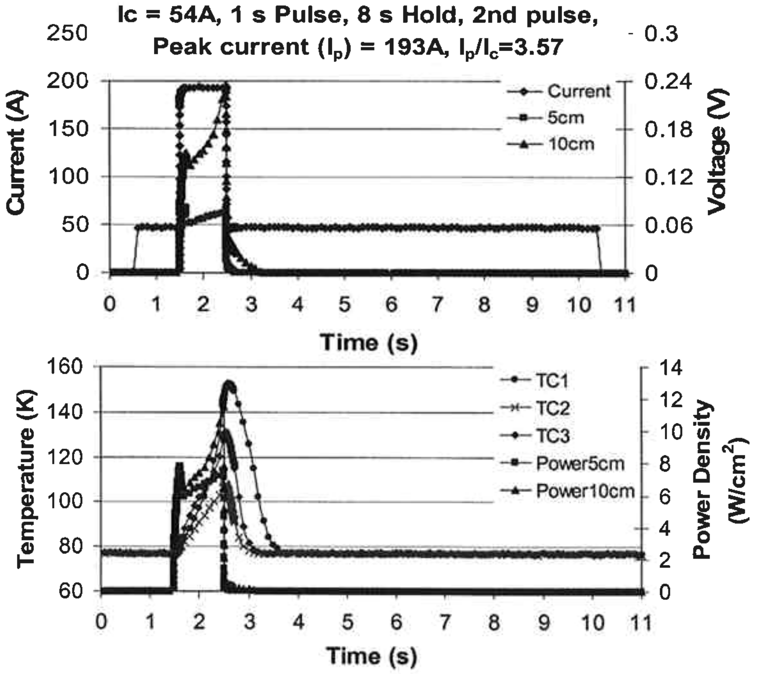

FIGURE 5: Results of 1 sec pulse over-current tests conducted at MIT on 4 mm wide 2G conductor. Current levels as high as ~ 3.5 times I_c were achieved without damage to the conductor.

AC Losses

IBAD based conductors offer clear advantages for achieving low ac losses in practical applications. The IBAD based conductors utilize non-magnetic substrates so that they are not subject to ferromagnetic losses during operation. Eddy current losses in the tapes are minimized by using highly resistive (~ 125 micro-ohm cm) substrates. Another advantage is the small grain size of the superconductor that results from an IBAD based tape. The small grain size, on the order of < 1 micron, permits the patterning of conductors into fine filaments to help reduce hysteretic losses.

To take advantage of the small grain size, SuperPower has developed striated conductors, using photolithography techniques to develop the patterns in the conductors. This is a high throughput process, much faster than alternative laser patterning techniques. During the process, the pattern is etched through both the stabilizer and HTS layers. Various patterning schemes are being evaluated to optimize the tradeoff between ac loss reduction and drop in I_c that occurs with the removal of superconducting materials. An example of a striated conductor is shown below in FIGURE 6. Measurements at LANL [3] of the ac loss in LN2 have indicated that up to a factor of 100 reduction is possible (FIGURE 7) provided that the filaments are fully decoupled.

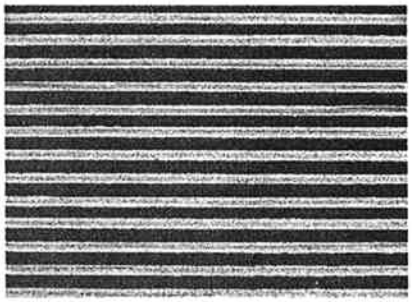

FIGURE 6: Striated (filamentized) 2G conductor with 100 μm wide HTS + stabilizer lines (light) and with 100 μm widespacing.

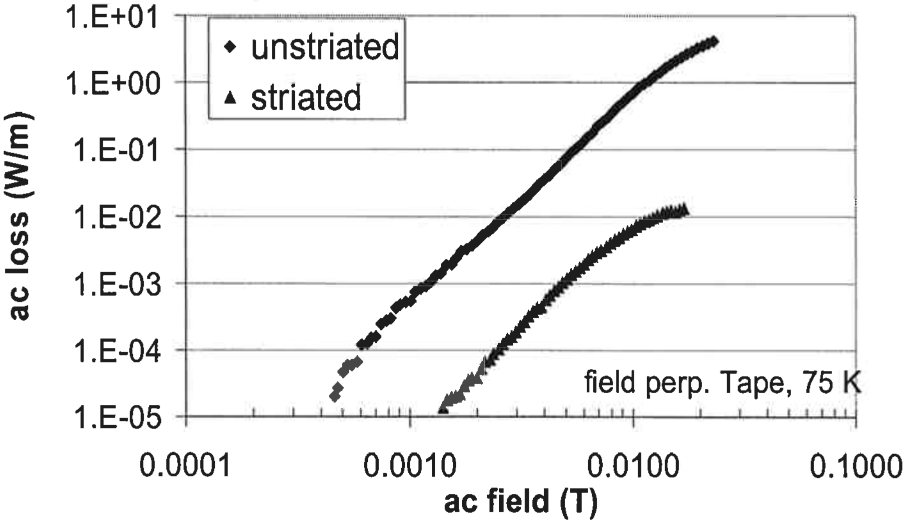

FIGURE 7: LANL measurements [3] showing the impact of striations on the ac loss in a 2G conductor, when fully decoupled.

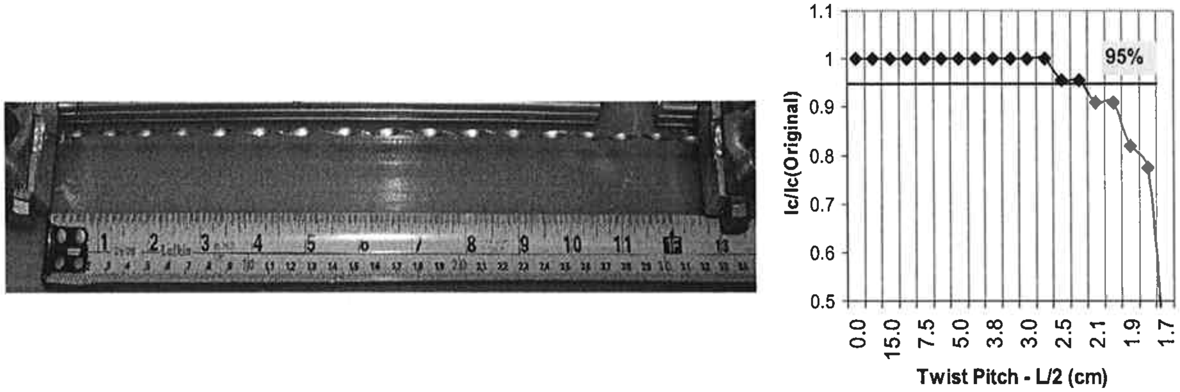

FIGURE 8: Photo of twisted 2 mm wide 2G conductor. 95 % Ic retention was maintained at a 4.6 cm twist pitch.

In order to take full advantage of the potential ac loss reduction in striated conductors, twisting experiments have been conducted on the 2G tapes. Unstriated conductors from 4 mm wide down to 1 mm wide have been successfully twisted (see Figure 8). Ic retention of 95% has been achieved with twist pitches as low as 4.2 cm with a 50 micron substrate, 1 mm wide conductor. Multi-strand prototypes consisting of multiple 1 mm wide tapes twisted in parallel have also been demonstrated opening up the possibility of new 2G wire configurations. Twisted 2G tapes with striations are planned for the near future.

APPLICATIONS

HTS Cables with SuperPower 2G Conductor

Working with our partner Sumitomo Electric Incorporated (SEI), two demonstration cables have been fabricated [4, 5] from SuperPower 2G conductor (FIGURE 9). The first of these 1 m test cables was fabricated in 2004 by SEI. The cable consisted of 48 x 2G tapes wound in 4 layers on either a 16 mm diameter FRP or metal former and did not contain a shielding layer. The recent test cable used a total 88 x 2G tapes (with surround copper) wound in 4 conductor layers and 2 shield layers. The test measurements for these coils are summarized in TABLE 2.

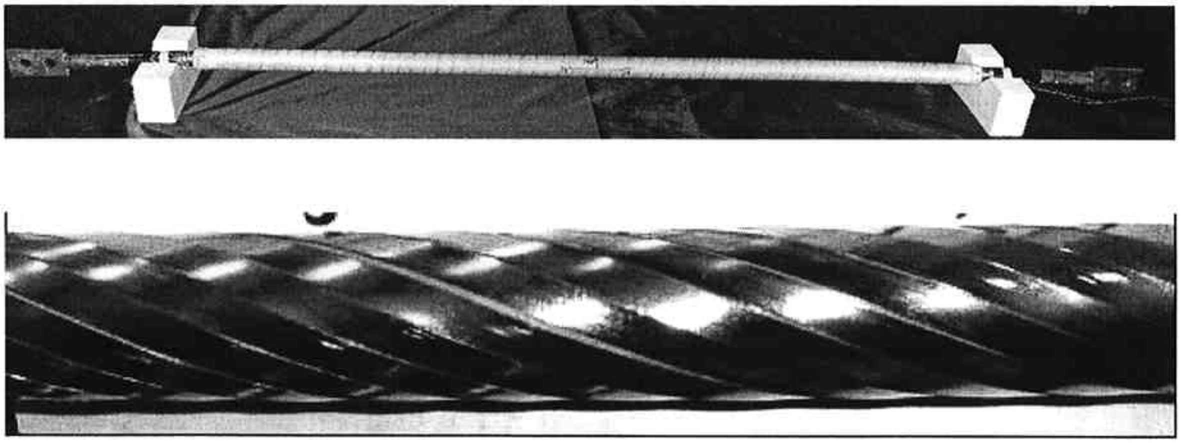

FIGURE 9: Photo of the 1 m long 2G cable fabricated in 2004 by SEI using conductor supplied by SP (top). Closeup of the 2005 cable without insulation showing the surround copper stabilized tapes (bottom).

TABLE 2: Summary of test results on the two 1 m cables fabricated by SEI from SP 2G conductor.

Cable feature	06/04 cable	07/05 cable
# conductor layers	4	4
# shield layers	0	2
Total # of 2G tapes used	48	88
Cable I_c (A)	2150	2350 (cond.) 2240 (shield)
AC loss in conductor + copper former (W/m) @ 1000 A_{rms}	0.4	0.16
Total (cond. + shield) ac loss (W/m) @ 1000 A_{rms}	n.a.	0.34

Rotating Machinery Prototypes

Working with our partner Rockwell Automation, racetrack coils have been fabricated by SuperPower (FIGURE 10a) and used at ~ 77 K in a 3.73 kW (5 hp) motor assembly FIGURE 10b). Four coils supplied in 2004 resulted in the assembly operating at ~ 0.9 kW (1.2 hp) acting as a generator [6]. Four newer coils with surround copper stabilization and improved coil design were supplied in 2005. Using these coils, the motor assembly operated at 5.6 kW (7.5 hp) at 1800 rpm [7]. In the latest set, each coil each had 25 turns and used ~ 7 m of 12 m wide conductor.

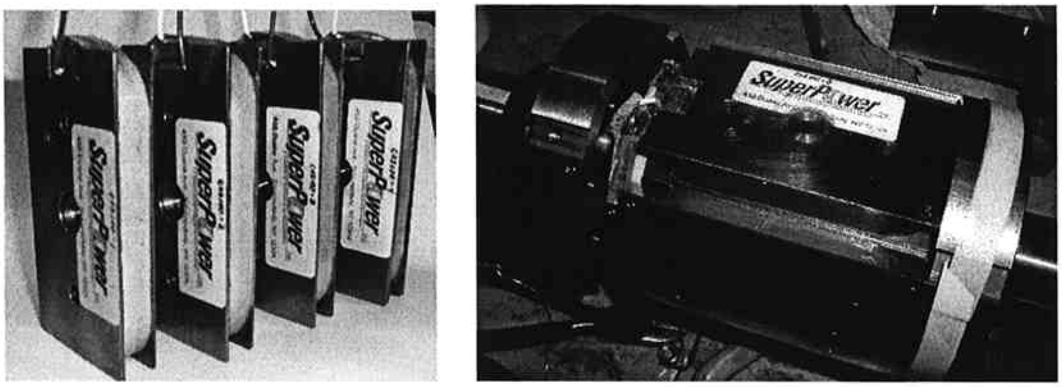

FIGURE 10 a) Four of the racetrack coils supplied to Rockwell Automation by SuperPower using 2G conductor. b) Racetrack coils mounted on the 3.7 kW (5 hp) rotor assembly.

Demonstration Coils

Recently, a double pancake coil was constructed using 20 m of 12 mm wide, 100 micron substrate 2G conductor. With a 12.7 mm (0.5 inch) inner diameter, this coil generated a central field of 0.4 T ($I_c = 56$ A) operating at 77K and 0.87 T ($I_c = 123$ A) at 64 K at a coil constant of ~0.0071 T/A that match modeled predictions. One aspect of 2G coil design that should be recognized is the impact of intermediate angle I_c vs. B properties of the 2G tape on coil performance. As shown in Figure 11 for a typical 2G conductor, the I_c vs. field angle properties of the 2G tape are at a minimum between ~ 15 to 60 degrees. The 0 degree angle is aligned with the flat surface (// a, b plane) of the tape, 90 degree angle perpendicular to the face of the tape (// c). Looking at the field angle within the upper right quadrant of the coil (Figure 12), a significant fraction of the coil (~ 40%) falls within this critical field angle region. With the central field of the coil at 0.87 T, the peak field within this region is ~ 0.7 T. This compares with ~ 0.9 T for fields at 0 degrees (// a, b) and ~ 0.3 T for fields at 90 degrees (// c). A load line plot of H//a/b, H//c and H//15-60 degrees

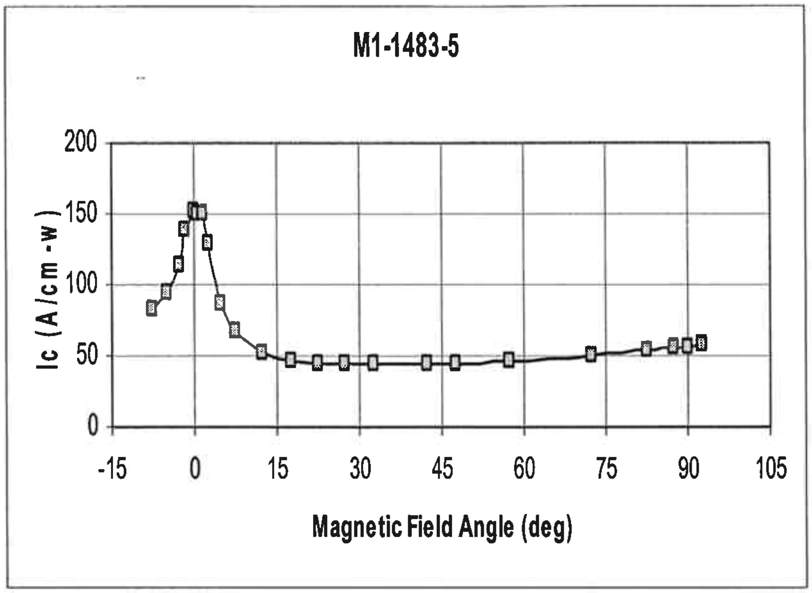

FIGURE 11: Ic (A/cm width) of 2G tape vs. magnetic field angle at a field of 0.6 T. Note minimum in 15 to 60 degree region.

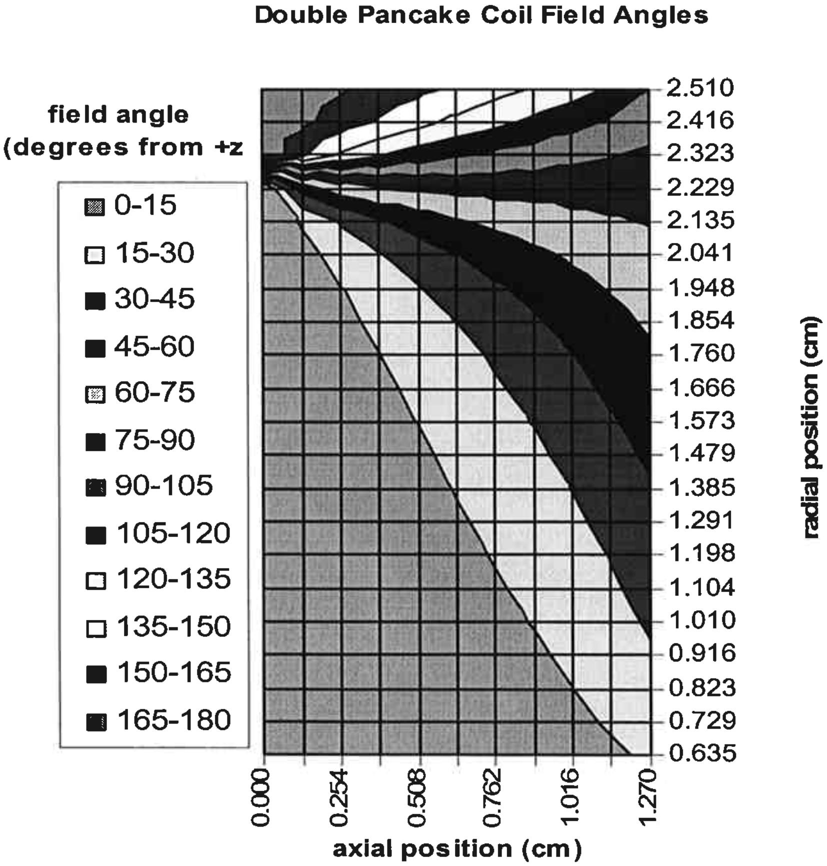

Figure 12: Plot of field angle vs. position in upper right quadrant of double pancake coil. Note extent of the 15 – 60 degree (and 120-165 degree) regions that occupy ~ 40% of the coil space. The maximum field in this region is ~ 0.7 T (B_o = 0.87 T) located in the bottom right hand corner at ~ 15 degrees.

performance indicates that the intermediate angle field limits the coil performance and has a fair match with the measured results of the coil (123 A). While the 2G performance is clearly superior to 1G performance at these fields and temperatures, these results indicate that a more complicated field analysis and matching to the 2G conductor performance is required in order to properly model the use of the 2G materials in the various applications envisioned for the future.

SUMMARY

Second generation conductor is becoming available in sufficient length and properties to begin addressing applications. High engineering current densities are being obtained with new thin substrate materials while slitting provides the flexibility for matching tape widths with application requirements. The adoption of "surround copper" stabilizations provides dielectric friendly round edge geometry and permits customization of copper thickness to meet different quench and stability requirements. Mechanical properties are adequate for most applications. Low ac loss designs and techniques are evolving to minimize the impact on the associated system cryogenics. 2G coil and device design and fabrication techniques are developing with successful prototypes demonstrated.

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