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MASTER

TEST AND EVALUATION OF CONDUCTORS FOR SUPERCONDUCTING MAGNETIC ENERGY STORAGE[†]

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ABSTRACT

We have constructed pancake coils of a monolithic conductor and several different types of braid and cable, using a variety of insulating tapes and bonding resins. The coils were tested to quench in self-field at currents up to 2700 amperes. Results are presented for the training behavior of the various coils as compared to short-sample tests. A conductor composed of several braids or cables in parallel, which will be suitable for the in situ fabrication of large magnets is described.

I. INTRODUCTION

The U.S. program in Superconducting Magnetic Energy Storage (SMES) will eventually result in the construction of magnets which will store approximately 10⁴ MWh (3.6×10^{13} Joules) of energy for the purpose of diurnal load leveling on the national electric power grid. There are also specialized uses for magnets which store approximately 10 MWh of energy but which may be charged and discharged in minutes. Preliminary studies of such large magnets indicate a need for conductors which can carry a current of the order of 50 kA with modest ac losses. To achieve predictable performance of a large magnet with our present, limited experience requires that the conductor be cryostabilized. Economic considerations suggest a configuration with extended heat transfer area to minimize the volume of stabilizer, and the possible use of aluminum as stabilizer. The conductor must be such that the magnet coils can be wound in place underground, in a limited working space. For convenience in performing this operation the conductor should be produced in minimum lengths of roughly 1000 meters. No existing conductors satisfy all of these criteria. There are many development paths which can be followed. In this paper we report on our first steps along several of these paths which are based on present conductor technology.

a) We have obtained and tested a monolithic conductor containing copper-nickel to reduce ac losses. Several such conductors could be combined with additional stabilizer to form the desired conductor package.

b) We have tested braids and cables, similar to those proposed for superconducting accelerators. Several of these conductors may be combined with all-copper conductors to form the final conductor package.

II. CONDUCTORS AND TESTING

Three types of wire have been evaluated:

- 1) Triple matrix monolith, produced by AIRCO, matrix ratio 6:4:1, CuNi:Cu:NbTi. Wire 5.0 x 5.0 mm containing 22,800 filaments, 12.3 μ m diameter. Conductor twist pitch 50 mm.
- 2) Triple matrix conductor produced and cabled by MCA, matrix ratio 1:3:1, CuNi:Cu:NbTi. Each strand is 0.89 mm diameter and contains 2700 filaments, 6.2 μ m diameter. The final cable is 1.5 x 6.0 mm and consists of 13 strands, stabrite (Sn, 6% Ag) coated. The strand twist pitch is 7 mm and the cable twist pitch is 55 mm.
- 3) Triple matrix wire produced by AIRCO and braided by BNL, matrix ratio 0.33:1.25:1, CuNi:Cu:NbTi. Each strand is 0.30 mm diameter and contains 517 filaments,

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10 μ m diameter. The strand twist pitch is 8.3 mm. These strands were braided into two separate conductors:

a) The so-called ISA-IV braid. This is a fully locked and compacted braid, 16.9 x 0.64 mm, containing 97 strands, with a transposition length of 114 mm. It was filled with In (7%Pb)solder;

b) A braid which we refer to as SMES 50/49, consisting of 50 strands of this wire and 49 strands of #28 Cu wire. The braid was formed by twisting 3 wires together and then braiding 33 of these triples. The finished braid was 18.2 x 0.71 mm and was stabrite filled.

There were two principal objectives of the preliminary evaluation program: 1) to evaluate particular combinations of conductor, insulation, and winding configurations for their mechanical suitability relevant to winding very large solenoids in place, thereby anticipating problem areas for each configuration and defining needed development work in winding technology; and 2) to determine training behavior of coils of the various combinations.

The monolithic conductor was wound into 6 double pancakes, each containing 41 turns. The cable was wound into a 61-turn double pancake, while the braids were wound into 5 single pancakes, each containing 60 to 65 turns. All the coils were 25 cm i.d. and were insulated turn-to-turn with barber-pole wrapped fiberglass tape impregnated with a variety of B-stage epoxy resins or a urethane resin. The resin differences had no noticeable effect on magnet performance, although they did affect the ease of fabricating the coils. Pancake-pancake insulation was provided by a pad of glass cloth. All leads and joint structures were properly supported by filled epoxy and mechanical supports. Coil stacks were preloaded axially to ensure a residual preload after cooling in liquid helium. Radial preload could not be measured but was certainly not large compared to the magneto-mechanical stresses.

Three runs to determine training behavior were made at 4 K. The first run involved the six monolithic double pancakes. The second run used the three ISA-IV braid pancakes to establish a background field for the cable pancake. The third run used the ISA-IV braid pancakes and the two SMES 50/49 braid pancakes. In all cases the coil assembly could store about 100 kJ at the expected critical current.

III. RESULTS AND DISCUSSION

III-1. Monolith

Figure 1 shows the first eight quenches along the load line for the central coil of the monolithic coil stack, although we did not determine which coil quenched. In later runs of the same coil set we determined that the high field coil was, in fact, the first to quench.

It is difficult to know what to make of this result. The short sample data showed the wire to be resistive at all currents; however, some or all of this resistance is due to the joints. In Fig. 1 we have indicated the short sample curve for $\rho = 1 \times 10^{-10}$ Ω -cm as well as for quench. Both the high resistivity and the large span between this value and quench are highly unusual.

There are a number of reasons why we might have expected rather poor results for this conductor.

a) Several processing defects led to poor internal bonding in the conductor as well as an uneven, poorly bonded, outer CuNi jacket.

Fig. 1. Training behavior of monolithic conductor pancake coils. Solid curve: short sample quench current; open circles: short sample current at $\rho = 10^{-10} \Omega\text{-cm}$. Quenches are indicated by numbers along the load line which is for the coil with the highest field.

b) The large amount of CuNi made the conductor extremely difficult to wind. The conductor was much too elastic to form neatly into place during the winding operation. If we were to use such a conductor again, we would have to consider plastically deforming it to the desired shape in a separate operation.

c) The conductor tended to twist about its longitudinal axis and thus could not be wound into mechanically sound coils. While this effect was enhanced by the square cross section, it is doubtful we could have eliminated this twist in any practically obtainable cross section. An attempt to remove this twist in a separate plastic deformation process was not successful. This characteristic of any twisted conductor makes a twisted, triple matrix monolith an unattractive winding candidate.

III-2. Cable and Braid

The training history of the cable pancake is shown in Fig. 2. The first quench was at 78% of the ultimate current and the coil very quickly trained to a value of $\rho \approx 10^{-12} \Omega\text{-cm}$. Figure 2 also shows that the ISA-IV braid pancakes should not limit the current in the experiment. We were able to confirm electronically that the cable pancake was the one which quenched. Figure 3 shows the training behavior of the coils formed from SMES 50/49 braid. The first quench was at 80% of ultimate, with the coil quickly training to a current corresponding to a resistivity of 2 to $3 \times 10^{-12} \Omega\text{-cm}$. We were rather pleased with this result since the braid was not formed or compacted nearly as neatly as the ISA-IV braid. The differing mechanical properties of the mixed matrix and pure Cu wire led to the formation of loops and out-of-position strands in the twisting and braiding operations. These loose strands were easily cut if the braid was fully compacted.

III. CONCLUSIONS AND FUTURE PLANS

Modest sized pancake coils of both cable and braids perform as well as previous experience with dipoles and quadrupoles would indicate. These conductors were easily formed into pancake coils which were almost perfect mechanically. We feel this winding perfection plays a large part in their excellent performance. A coil which is structurally unsound will be prone to motion of conductors and other components and thus to a long training period.

Fig. 2. Training behavior of coil stack constructed of MCA cable (solid lines) and ISA-IV braid (broken lines). The broken curve is based on the measured short sample current for the individual strands at $\rho = 10^{-12} \Omega\text{-cm}$. The solid line is the measured short sample current for the cable at $\rho = 10^{-11} \Omega\text{-cm}$, corrected for conductor self-field. The open circles are the measured, uncorrected short sample quench currents for the cable.

Fig. 3. Training behavior for the coil stack constructed of SMES 50/49 braid and ISA-IV braid. Quenches which occurred in the pancakes made of SMES 50/49 braid are indicated along the load line for these coils.

The monolith does not show promise of forming such sound coils, particularly under the adverse field conditions expected during the construction of large coils. Further, monoliths are more difficult and expensive to produce in low-loss configurations and are not amenable to fabrication in conveniently long lengths. Thus we consider monolith based conductors to be second choice to either braids or cables. We had originally intended to extend this study by comparing identical coils made of cables with and without solder filling and by making a more definitive comparison of epoxy vs urethane bonding resins. However, results obtained at other laboratories on rather smaller solenoids as well as dipoles indicate there is little difference between any of these choices. We thus are planning to use our next cable samples in a test of a more advanced conductor configuration.

As a first attempt at a high current conductor, we propose to package several of these flexible conductors, braids or cables, in parallel, with internal cooling passages and additional copper added to attain cryosta-

bility. A possible 30 kA version of such a conductor, based on a wide cable, is shown in Fig. 4. All the superconductor is contained in the central element, with the outer conductor containing only copper or aluminum. A corrugated copper honeycomb structure provides internal cooling channels, greatly reducing the amount of copper necessary, and also provides an electrical path for current transfer from the central element to the outer stabilizer. The two advantages of having all the superconductor in the central element are 1) lower ac losses, and 2) lower fabrication costs. Small samples of this type of conductor have been fabricated by hand. These samples appear to be mechanically sound, and based on known heat transfer to liquid helium should be cryostable conductors as wound into a large coil.

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Fig. 4. Concept of a 30 kA, cryostable conductor consisting of a central cable or braid element which has a high superconductor content, and several parallel cables or braids made entirely of copper or aluminum. Conductors made in this way should be relatively inexpensive to fabricate, should have low ac losses, and, because of the large surface area exposed to helium should require a relatively small cross section of normal conductor as a stabilizer.