Current Sharing, Protection, Redundancy, and Contact Resistance in YBCO Coated Conductor Cable and Magnet Integration for Superconducting Particle Accelerators

M.D. Sumption (Sumption.3@osu.edu), M. Majoros, and E.W. Collings
CSMM, MSE, The Ohio State University
Columbus, OH 43210

Introduction

The discovery of the Higgs boson at the LHC has opened a new era for high energy particle physics. The smallness of the Higgs mass suggests that many new particles and interactions await discovery using a very high energy TeV-class collider [1]. In response very large circumference (~100 km) colliders with energies up to 100 TeV are presently under study. High temperature superconducting (HTS) materials, particularly in the form of cables, are increasingly of interest for the windings of high field insert magnets for the next generation of particle accelerators [2,3]. Such magnets must operate under demanding conditions, with exceedingly high current densities, Lorentz forces, and the potential for disturbances and larger scale faults. The systems must have good operational availability, and they must be robust. Faults and other disturbances must not cause a catastrophic failure within the magnets. For the LTS magnets which HTS magnets replace, certain elements of conductor design, magnet design, and protection system operation have been able to either avoid or minimize such risks, but this is well known to be much more difficult for HTS systems. This LOI focusses on current sharing, protection, redundancy, and contact resistance in YBCO coated conductor cables and how this impacts their integration and use in accelerator magnets.

Motivation

The Problem of Fault and Quench: The difficult issue of normal zone detection and protection is well known for HTS. For superconducting magnets in general, disturbances can lead to electro-magneto-thermal run away which can cause a quick and un-recoverable temperature rise above T_c, at which point the large magnet current densities can generate enough normal state heating to permanently destroy the conductor and magnet. For HTS magnet, the disturbance level must be much higher than for LTS, but certain classes of disturbances (including fault modes) can indeed trigger such run-away phenomena. Unfortunately the time it takes to detect the problem (a normal zone) is increased proportionally. Even then, the energy stored in the magnet much be safely dissipated and the typical modes used with LTS are much more challenging because of much higher T_c values for the HTS.

A number of innovative work-arounds have been explored, including early quench detection using fiber optic temperature sensors distributed throughout the cable (and thus in principle magnet) [4], and the use of no-insulation schemes, typically in the context of tape wound magnets [5][6]. No-insulation schemes work very well, but are most easily implemented for tape wound magnets which are segmented, the role of any no-insulation approach in cable wound magnets is not yet clear (e.g., intra or inter-cable?). This does overlap to some degree with the investigations of proper control of contact resistance within the HTS cable [7]-[9], well known to be critical from LTS cables. Other important factors that must be included include thermal sharing strand-to-strand, and local heat removal. Local heat removal is closely tied to magnet design, since the choice of whether or not to epoxy impregnate the magnet, which is also a critical for mechanical performance, hugely impacts local heat removal by preventing liquid cryogen influx within the winding. Fault, quench propagation, and protection are ultimately magnet level issues, and must be resolved at the same time and in conjunction with cable level studies.

The Need for Redundancy and Robustness: While the issues of fault, quench, and protection are significantly modified from LTS cables and magnets, they are not completely new. However, HTS conductors are both more anisotropic and heterogeneous in their mechanical properties. Thus, their integration into magnets and their mechanical response, both to mechanical constraint and Lorentz force body load are both more difficult to estimate (roughly, or by modelling and simulation), and more difficult to solve. There is likely to be a need for redundancy, and how to balance the need to add margin vs modify cable design for more robust response to mechanical and magnetic loading is not clear without more study.

The Role of Integration in Magnets: As noted above, studies of cables in isolation are needed, but these studies must be informed by a knowledge of the magnet environment. On the other hand, magnet studies alone cannot investigate a sufficiently wide range of possibilities. There is a need for studies and in particular, continued magnet/cable modelling and modelling inspired cable testing including cable mechanical design, magnet/cable cooling mode, and magnet/cable quench and protection.

Unresolved Questions and Programmatic Needs

1. The Need for Further Modelling Studies: Cable modelling is progressing (e.g., a small sampling is [10]-[14]) but more work is yet required. In particular, it is important to move beyond the physics of the cables to connect the materials science and the processing conditions that impact parameters critical to determine their actual performance. The studies need also to be projective, studying not what present cables do, but what new conditions and modes could do. The studies need to be both sufficiently detailed at the cable level to be meaningful, but then implemented in magnets design with a design for function, rather than replacement. The models need to be portable, and they need verification and benchmarking.

2. The Need for Further Experimental Cable Contact Resistance, Current Sharing, and Quench Studies: Cable measurement is being performed, with good result [15]-[21], but more work is yet required. Cable testing needs to be correlated with modelling and in some cases driven by it. One of the most critical issues however is the need to be able to perform the tests by various researchers and groups, at excitation levels and conditions which are relevant. This requires an investment in cable test facilities. But, it should not be a singular facility, but in fact a number of such test facilities at a range of scales is needed, discussed below.

3. The Need for Small/Medium Size Cable Studies at University Laboratories, in Collaboration with National Lab Partners: The measurement of HTS cables for accelerators is ongoing at a number of institutions, including CERN (Roebel and CORC™) [15,16], KIT (Roebel) [17], CAS-ACT (CORC™) [18], and at the NHMFL [19]. Other large scale facilities also exist which could in principle perform HTS cable measurements, but here and elsewhere, measurement and facility costs and scale present problems. The capital cost of the existing facilities is too large for university programs, but their input on this problem is important. Also, the size of samples needed for these tests themselves become costly. *While some larger scale facilities are in the planning stages for the US now, a set of smaller level university level capabilities are needed for cost, scale, as well as the additional approaches that university groups may bring to the problem.*

This is a particularly good avenue for workforce development and training since the topical area spans university-level and lab-scale work, and has both experimental and computational elements.

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