Magnetization, Drift, and Energy Loss in HTS Cables 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]. These are potential replacement for LTSC cables, either NbTi or Nb_3Sn. There are a number of issues with the use of these cables as replacements for LTSC, including a cost which remains far too high, mechanical anisotropy and heterogeneity of the conductors, unresolved problems with current sharing, quench detection, and protection, and large magnetization induced field errors and their decay. However, they have now the high currents at high magnetic fields required for serious engineering designs, and their as-of-yet unharnessed high field properties have the potential to revolutionize accelerator magnets and accelerators. This LOI focusses on the magnetization, field errors, and dynamic effects related to their use in accelerator magnets.

Motivation

Particle accelerators use dipole magnets to steer the particle beam, as well as quadrupoles and higher order magnets to focus the beam. If the conductors used to wind these magnets did not have a magnetic (or superconducting) response, the only field errors would be due to geometric (winding) errors. However, superconductors, especially HTS conductors, have a significant magnetic response [3], which leads to magnetization-induced field errors which tend to de-focus the particle beams. The magnetization has several components, including hysteretic ("persistent currents"), eddy currents and coupling currents ($\propto dB/dt$), and current loading modifications to these main contributions. These effects are typically most important at the injection field because at this relatively low field the magnetization values are largest. The field errors, measured in units (1 part in 10^4) are relatively low for NbTi based accelerator magnets (~ 3), about 10 X larger for Nb3Sn magnets (~ 30) [4], and may be 10 X larger still for HTS systems (~ 300?), although this is unknown and will depend upon the HTS design and, assuming it is an insert in an LTS magnet, what fraction of boost the HTS magnet is responsible for. What is known is that HTS conductors, both Bi:2212 based and more so YBCO coated conductor based, have significantly larger magnetization, and to first order field errors are $\propto$ magnetization/unit current.

It is important to note that the potential field errors of HTS insert magnets are highly dependent on design; designs which use YBCO conductor in field parallel only orientations may minimize field errors [5], but most present HTS magnet inserts will need to take magnetization-induced field errors into account, and this is certainly true for any magnets using CORC or Amperes cables, any cables in canted $\cos\theta$ magnets, and many designs of $\cos\theta$ magnets.

Unresolved Questions

1. Magnetization Prediction for Accelerator Design: Magnetization is a key parameter needed for the proper design of accelerator quality HTS magnet inserts. For Rutherford cables made from round NbTi or Nb3Sn strands, relatively easy measurements of small segments of strand can be fairly well scaled to the cable level. While supplementary cable level measurements are important, relatively good predictions can be made in simple ways. This has not been possible for cables YBCO coated conductor, although recent work has begun to establish principles for doing simple scaling [6-9]. The work has required direct "benchmarking" measurements of various coated conductor type accelerator cables [6-8], as well as the development of analytic scaling models which can be used in numerical software [9]. While it is in principle possible to use direct computer simulation to achieve FEM results for a given applied field condition, such work is onerous if it must be completed at every field for various points in a magnet winding in order to compute a field error as a function of magnet excitation. On the other hand, simple methods which use strong approximations for the conductor give low fidelity results. In particular they miss the modification of magnetic response via shifted *M-H* response with modified penetration fields. What is needed is a synergetic set of analytic and FEM models with benchmarks to both conductor and magnet. Some work has been done in this area such work should be continued in order to develop ***robust kernals which can be injected into FEM software to make predictions about HTS cables which have not yet been made – prospective cable design studies for accurate error prediction.*** Some initial work has made measurements for a number of cables using different techniques [6-9], developed analytic models [9], and has inserted this into block-dipole magnet designs to predict field errors. However, much more work is required here, and in particular the jump from 2-D block dipole application to 3D canted $\cos\theta$ design. We note that Bi:2212 strands, even though they are round, have complicating factors which require their direct measurement as well. In addition, it is important to explore the influence of field errors at accelerator operation points besides injection, because of the persistence of magnetization to high fields.

2. Magnetization Drift Prediction for Accelerator Design: The effect of drift on error fields for NbTi magnets is well known, and arises from an interaction of hysteretic currents and cable level coupling currents. This effect is even less desirable than simple field error, since it changes with time in a non-linear way. HTS, both YBCO and Bi:2212 based may inherit this problem as well, but they have a drift problem all their own. Flux creep leads to a kind of intrinsic drift, which has now been measured for HTS accelerator style cables [7]. This will lead to field errors, both substantial and undesirable, which should be understood, and may be controlled, with the right pre-injection cycle, or at least minimized with proper design. So far, this work has only progressed to the measurement of the effect. However, what is needed is the ***development of useful and simple models*** (models for creep in simple tapes and wires exist, but will need modification for cables) ***which can be ported over to FEM software and used to make field error predictions for accelerator magnets, allowing us to predict time dependent field errors in HTS magnets.***

3. Energy Loss limits for HTS magnet systems: While superconductors are "lossless" when in DC mode, and for NbTi and Nb3Sn, losses are small enough to be unimportant, the losses in HTS are sufficiently larger that they must be estimated, mostly to make sure we avoid temperature rise during field ramping, depending upon the thermal conductivity of the composite winding. ***It is important to perform such calculations, estimating losses for realistic conditions.***

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.

References

1. "High Energy Colliders", Report of the Particle Physics Project Prioritization Panel (P5), May 2014, p. 43
2. X. Wang, S. A. Gourlay, and S. O. Prestemon, "Dipole Magnets above 20 Tesla: Research Needs for a Path via High-Temperature Superconducting REBCO Conductors", *Instruments* 2019, 3(4), 62; https://doi.org/10.3390/instruments3040062
3. M. Majoros, M.D. Sumption, E.W. Collings and D. C. van der Laan, "Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables", *Supercond. Sci. Technol.* 27 (2014) 125008 (12pp); doi:10.1088/0953-2048/27/12/125008.
4. X. Wang, G. Ambrosio, G. Chlachidze, E.W. Collings, D.R. Dietderich, J. DiMarco, H. Felice, A.K. Ghosh, A. Godeke, S.A. Gourlay, M. Marchevsky, S.O. Prestemon, G. Sabbi, M.D. Sumption, G.V. Velev, X. Xu, and A.V. Zlobin, "Validation of Finite-Element Models of Persistent-Current Effects in Nb3Sn Accelerator Magnets", IEEE Trans. Appl. Supercond. 25 4003006 (6 pp) (2015)
5. L. Rossi, A. Badel, H. Bajas, et al., "The EuCARD2 Future Magnets Program for Particle Accelerator High-Field Dipoles: Review of Results and Next Steps", *IEEE Trans. Appl. Supercond.* 28 (2018) 4001810.
6. C. Kovacs, M. Majoros, M.D. Sumption, E.W. Collings, "Magnetization Measurements of CORC and Roebel Type YBCO Cables for Accelerators Using a ±3-T Dipole Magnetometer", *IEEE Trans. Appl. Supercond.29* (2019) 8200905
7. C. S. Myers, M. D. Sumption, and E. W. Collings, "Magnetization and Creep in YBCO Tape and CORC Cables for Particle Accelerators: Value and Modification Via Pre-injection Cycle", *IEEE Trans. Appl. Supercond. 29* (2019) 8201405.
8. C. S. Myers, M. D. Sumption, and E. W. Collings, "Magnetization and Flux Penetration of YBCO CORC Cable Segments at the Injection Fields of Accelerator Magnets", *IEEE Trans. Appl. Supercond.* 29 (2019) 4701105
9. C.S. Myers, X. Wang, M.D. Sumption, and E.W. Collings, manuscript in preparation.