Title

Development of a modeling toolbox for CORC cable performance evaluation

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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date:
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In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions. It is to be forwarded to the DOE Office of Scientific and Technical Information upon completion or termination of the CRADA, as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Lawrence Berkeley National Laboratory and

CRADA number: Award AWD00005440, FP00011919

CRADA Title: Short Title: FY20 INFUSE CRADA_SUPERPOWER. Long Title: Development of a modeling toolbox for CORC cable performance evaluation

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Joint Work Statement Funding Table showing DOE funding commitment:

DOE Funding to LBNL	$192,000
Participant Funding to LBNL	
Participant In-Kind Contribution Value	$50,000
Total of all Contributions	

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

(Publications must include journal name, volume, issue, Digital Object Identifier)

- Invited Talk: C. Messe "A Special Purpose Finite-Element Framework for High-Temperature Superconductor Applications", HTS2022 – 8th International Workshop on Numerical Modeling of High Temperature Superconductors, 14th-16th June 2022, Nancy, France.
    - Christian Messe. A Special Purpose Finite-Element Framework for High-Temperature Superconductor Applications. Kévin Berger (Université de Lorraine - GREEN), Jun 2022, Nancy, France. ⟨hal-03791404⟩

- Poster Presentation: C. Messe "Current Sharing for Mixed h-a and h-phi Finite Element Formulations Applied to CORC® Cables", ASC22 – Applied Superconductivity Conference, 23rd-28th October 2022, Honolulu, HI

- Poster Presentation: L. Brower et. Al: "Field Quality Studies of HTS Magnets for Fixed-Field Proton Therapy Gantries" ASC22 – Applied Superconductivity Conference, 23rd-28th October 2022, Honolulu, HI

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:
N/A

Executive Summary of CRADA Work:
One critical, yet currently unknown aspect in the development process of CORC® cables is how current sharing around defects impact the overall performance of a cable design. Within the scope of this project, a simulation framework has been developed that is specialized on the quenching behavior and temperature rise around cable defects.

From a simulation point of view, the challenges in modeling these phenomena lie in the coupled multi-field nature of the problem, the highly nonlinear behavior of the materials involved, the abstraction of thin structures in 3D space, as well as the ill-conditioned, nonsymmetric, non-positive definite structure of the system matrices that are generated when a finite-element approach is used.

After a diligent review of state-of-the art literature of this field, we found the novel "mixed finite-element formulations" to be the most promising methods to reach our goals. These new modeling approaches promise to be significantly more efficient than the methods industry uses today. The theoretical fundamentals have been summarized and documented in a unified notation into a textbook-like living document.

Since these models have just been developed over the last five years, they are not fully available in commercial software yet. In order to make these models available for our daily-use design workflow, we developed a custom finite element codebase that includes both the h-a and the h-phi (aka h-v) formulation for solid elements. The code supports first and second order elements for two and three dimensions.

Two characteristics specific to the numerical simulation of CORC cables are the thin-shell modeling approach and the problem of current sharing between overlapping tapes. A thin shell approach that utilizes the mixed finite element formulation was only published in literature in December 2021. To the best of our knowledge, no current sharing model and no quenching model for a mixed thin-shell formulation has been published to date.

In order to be able to simulate quenching with the use of thin shells with mixed finite-element formulations, the theoretical foundations for a thermally coupled thin-shell approach have been developed and are now being implemented.

Once a sufficient level of code maturity has been reached, we will be able to simulate the full electromagnetic, transient behavior of the CORC current sharing process, which is critical for the understanding of cable behavior during magnet tests, as well as to guide further optimization of the cable architecture.

Summary of Research Results:
The general design of the code as well as selected benchmark examples will be presented later this month at the 8th International Workshop on Numerical Modeling of High Temperature Superconductors in Nancy, France. We are currently investigating options to share our code with other researchers.

An adaptive Picard-iteration method was developed that is able to handle the previously mentioned strongly nonlinear material laws with a reasonable computational effort. Preliminary tests indicate that this method is significantly more stable than the Newton-Raphson method that is typically used to solve this kind of nonlinearity-problem. In a novel hybrid approach, we solve the model with the more stable Picard-iteration first and swap to the faster Newton-Raphson method once the numerical error falls below a predefined threshold. We find these first results very promising and hope to conduct further studies to improve our understanding of this novel approach.

A characteristic typical to mixed finite-element formulations is that the system matrices are neither symmetric nor positive definite. The zeros on the main diagonal add an additional amount of complexity to the solving procedure. We are working with the Computational Division of Berkeley Lab to incorporate the STRUMPACK solver that is developed in-house into our code. At this point, the API has been finished and first test problems have been solved. The advantage of having a modern large-scale matrix solver in-house is that we can optimize for speed on a more advanced level compared to a third-party solver. First results are promising; more work is needed on this field.

For the current sharing between overlapping tapes in the CORC cable, a novel method has been developed that utilizes the boundary terms of the weak form of the Ampére-Maxwell equation. The progress on the current sharing model will be presented in the upcoming Applied Superconductivity Conference 2022 in Honolulu, HI, later this year.

In the upcoming development steps, the thermally coupled thin shell model will be finalized in a two-dimensional model and a simple benchmark problem will be defined. In a second step, the model will be extended with the previously mentioned current sharing model. Next, the thin shell model will be △expanded into three-dimensional space.

Additional geometry algorithms will need to be developed to extend the current sharing model to three dimensions. More efforts will be put into optimizing the interaction with the STRUMPACK library to maximize performance. In a later stage of the problem, forced convection models will be implemented that model the fluid-structure interaction between the cable and a cryogenic fluid such as nitrogen or helium.