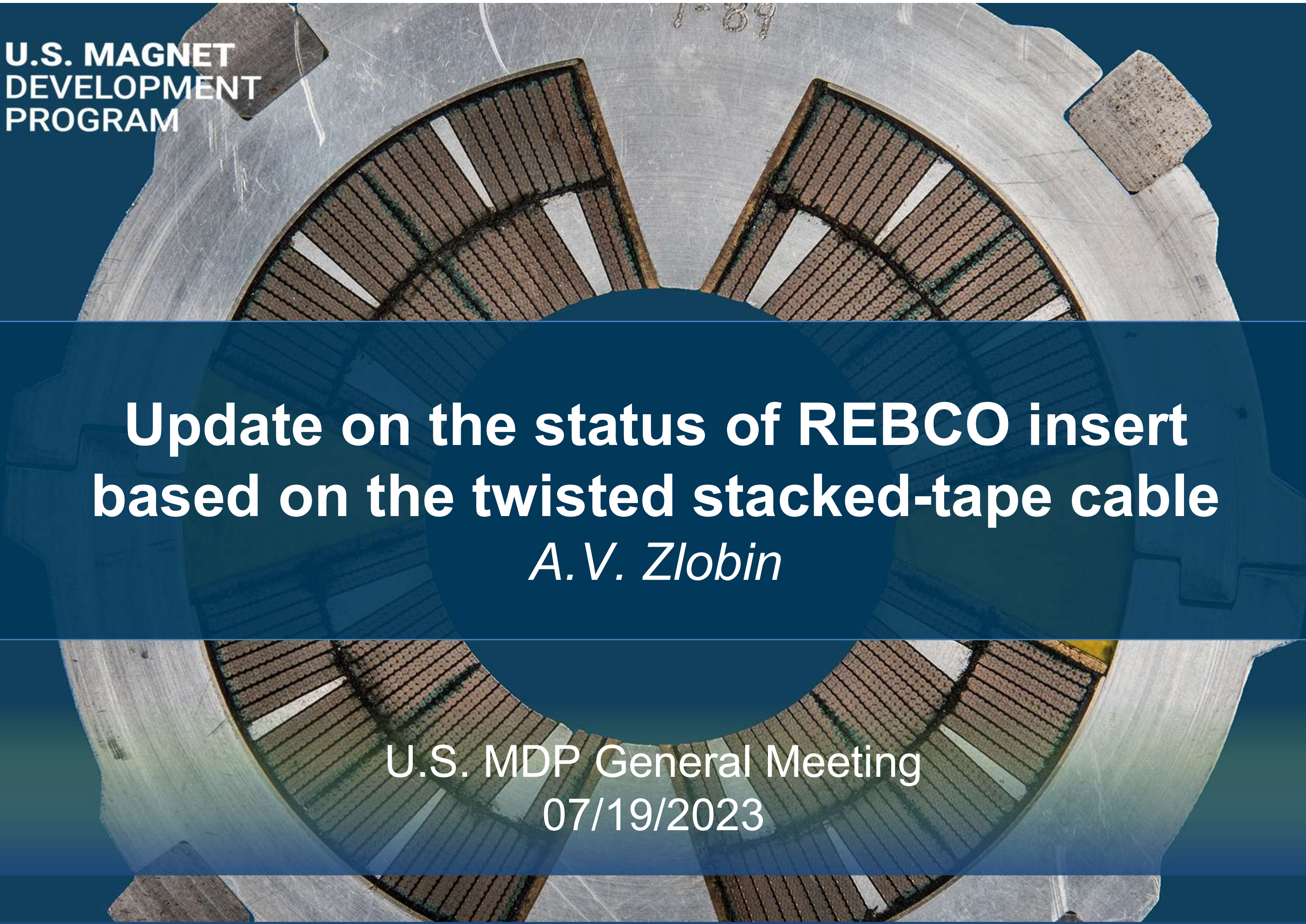
U.S. MAGNET DEVELOPMENT PROGRAM



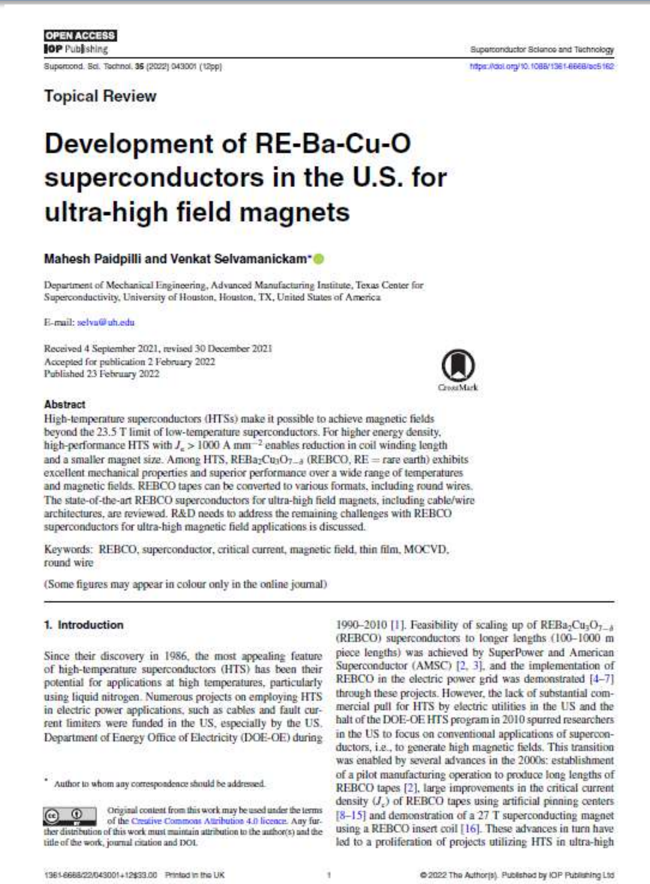
Update on the status of REBCO insert based on the twisted stacked-tape cable

A.V. Zlobin

U.S. MDP General Meeting
07/19/2023

U.S. MAGNET DEVELOPMENT PROGRAM

REBCO cables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Topical Review

Development of RE-Ba-Cu-O superconductors in the U.S. for ultra-high field magnets

Mahesh Paidpilli and Venkat Selvamanickam*

Department of Mechanical Engineering, Advanced Manufacturing Institute, Texas Center for Superconductivity, University of Houston, Houston, TX, United States of America

E-mail: selva@uh.edu

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Abstract
High-temperature superconductors (HTSs) make it possible to achieve magnetic fields beyond the 23.5 T limit of low-temperature superconductors. For higher energy density, high-performance HTS with $J_e > 1000$ A mm^{-2} enables reduction in coil winding length and a smaller magnet size. Among HTS, $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = rare earth) exhibits excellent mechanical properties and superior performance over a wide range of temperatures and magnetic fields. REBCO tapes can be converted to various formats, including round wires. The state-of-the-art REBCO superconductors for ultra-high field magnets, including cable/wire architectures, are reviewed. R&D needs to address the remaining challenges with REBCO superconductors for ultra-high magnetic field applications is discussed.

Keywords: REBCO, superconductor, critical current, magnetic field, thin film, MOCVD, round wire

(Some figures may appear in colour only in the online journal)

1. Introduction

Since their discovery in 1986, the most appealing feature of high-temperature superconductors (HTS) has been their potential for applications at high temperatures, particularly using liquid nitrogen. Numerous projects on employing HTS in electric power applications, such as cables and fault current limiters were funded in the US, especially by the US. Department of Energy Office of Electricity (DOE-OE) during 1990–2010 [1]. Feasibility of scaling up of $REBa_2Cu_3O_{7-\delta}$ (REBCO) superconductors to longer lengths (100–1000 m piece lengths) was achieved by SuperPower and American Superconductor (AMSC) [2, 3], and the implementation of REBCO in the electric power grid was demonstrated [4–7] through these projects. However, the lack of substantial commercial pull for HTS by electric utilities in the US and the halt of the DOE-OE HTS program in 2010 spurred researchers in the US to focus on conventional applications of superconductors, i.e., to generate high magnetic fields. This transition was enabled by several advances in the 2000s: establishment of a pilot manufacturing operation to produce long lengths of REBCO tapes [2], large improvements in the critical current density (J_c) of REBCO tapes using artificial pinning centers [8–15] and demonstration of a 27 T superconducting magnet using a REBCO insert coil [16]. These advances in turn have led to a proliferation of projects utilizing HTS in ultra-high

* Author to whom any correspondence should be addressed.

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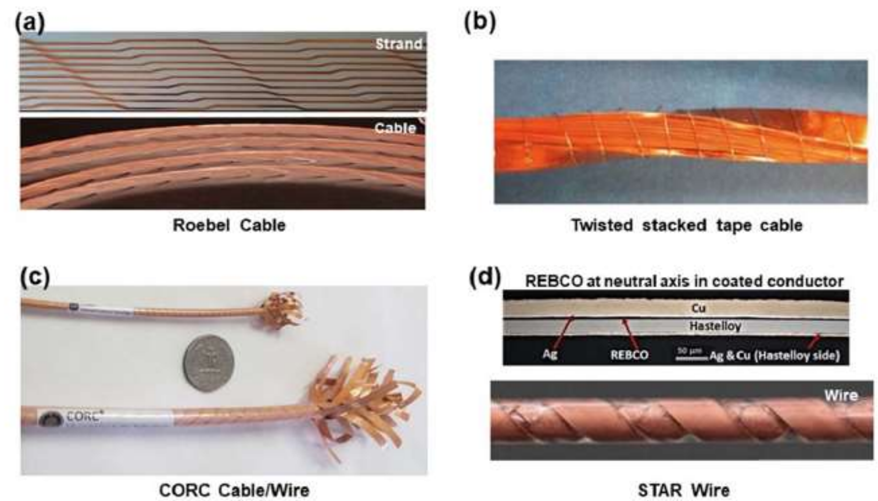


Figure 5. Photographs of (a) Roebel cable, (b) TSTC, (c) CORC cable/wire, and (d) STAR wire. Reprinted, with permission from [57–62]. Reproduced from [57]. © IOP Publishing Ltd. All rights reserved. Reproduced from [58]. © IOP Publishing Ltd. All rights reserved. Reproduced from [59]. © IOP Publishing Ltd. All rights reserved. © 2013, IEEE. Reprinted, with permission, from [60]. Reproduced from [61]. © IOP Publishing Ltd. All rights reserved. Reproduced from [62]. © IOP Publishing Ltd. All rights reserved.

- In EU HTS magnet R&D is based on Roebel cable
- US MDP is focusing on CORC and STAR
- Twisted Stacked-Tape (TST) cable was also proposed for HTS coils

U.S. DEPARTMENT OF ENERGY | Office of Science

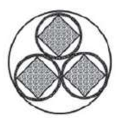
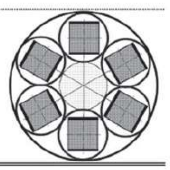
TST Cable designs & winding technologies

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017 6900105

Investigation of HTS Twisted Stacked-Tape Cable (TSTC) Conductor for High-Field, High-Current Fusion Magnets

Makoto Takayasu, Luisa Chiesa, Patrick D. Noyes, and Joseph V. Minervini

PERFORMANCES AT 17 T OF MULTISTAGE CABLES MADE OF SINGLE-STACKED-TAPE CONDUCTORS OF VARIOUS TAPE WIDTHS, BASED ON THE CRITICAL CURRENT OF 180 A AT 17 T AND 4.2 K FOR A 4 MM WIDTH, 0.1 MM THICKNESS REBCO TAPE

Conductor	Tape width (mm)	Tape current (A)	Number of Tapes	Critical Current (kA)	Cable Diameter (mm)	Conductor Cross-Section
Single-stage	4	180	40	7.2	7.4	
	6	270	60	16.2	11.1	
	12	540	120	64.8	22.2	
Triplet	4	180	120 (40 x 3)	22	16	
	6	270	180 (60 x 3)	49	24	
	12	540	360 (120 x 3)	194	48	
Hexa	4	180	240 (40 x 6)	43	23	
	6	270	360 (60 x 6)	97	35	

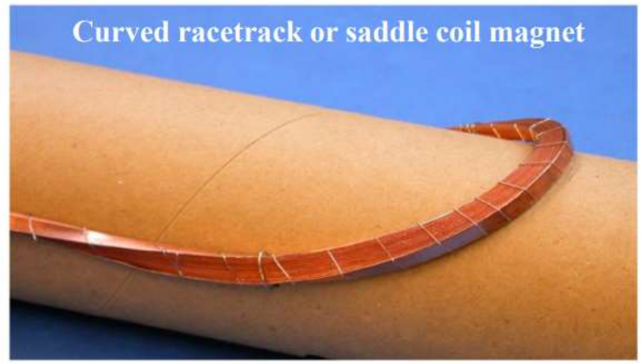
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA
Department of Mechanical Engineering, Tufts University,Medford, MA

2014WAMHTS-1_REBCO Twisted Stacked-Tape Cable_Takayasu

Stacked-Tape Twist-Winding (STTW) Method for 3D Magnets

New REBCO tape magnet winding concept

Stacked tape cable is twisted during winding



A U-turn portion of one turn coil demonstrating a curved saddle winding on a 50 mm diameter tube. The cable is composed of 50 YBCO tapes.

Applications

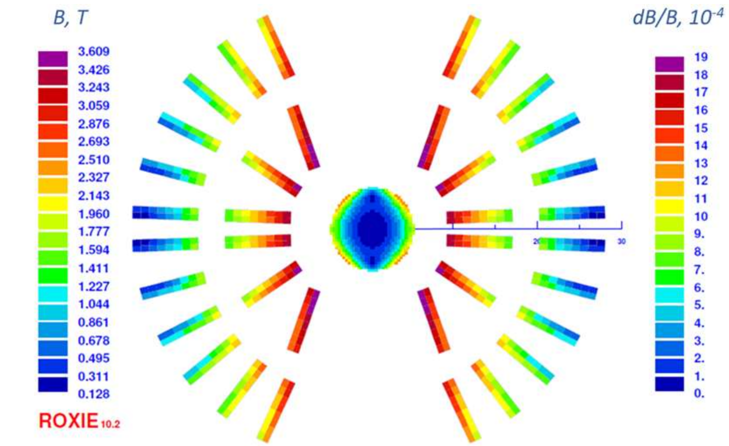
Small diameter magnet

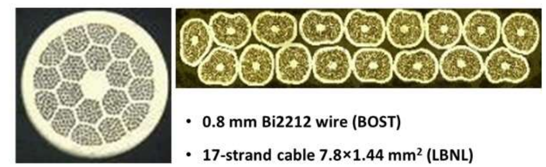
3D HEP accelerator magnets, generator and motor magnets

Bi2212 and REBCO SMCT insert coils

Coil parameters.

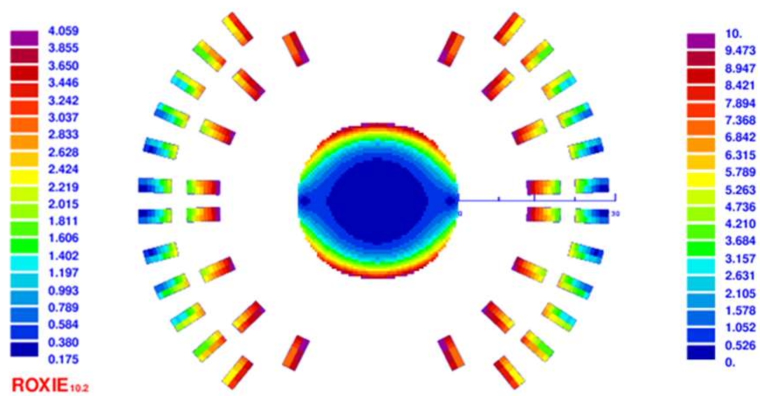
Parameter	Bi2212	REBCO
Number of layers	2	2
Number of turns	9 (3 IL+6 OL)	10 (4 IL+6 OL)
Coil ID-I/ID-O/OD, mm	9/20/59	19/25/59
Yoke R_{in}, mm	30	30
Yoke permeability	1000	1000
Coil B_{max}/I, T/kA	3.609/8	4.06/8
Coil B_o/I , T/kA	3.503/8	3.59/8
B_{max}/B_o	1.03	1.13
L. mH/m	0.200	0.345

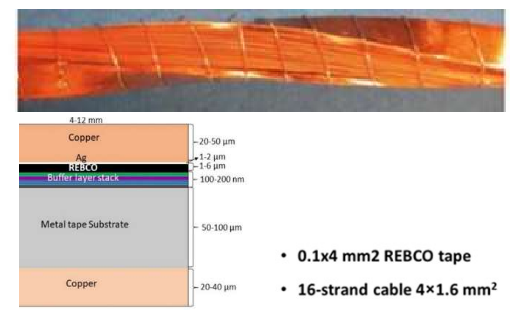




- 0.8 mm Bi2212 wire (BOST)
- 17-strand cable 7.8×1.44 mm² (LBNL)

Bi2212 round composite wire and Rutherford cable

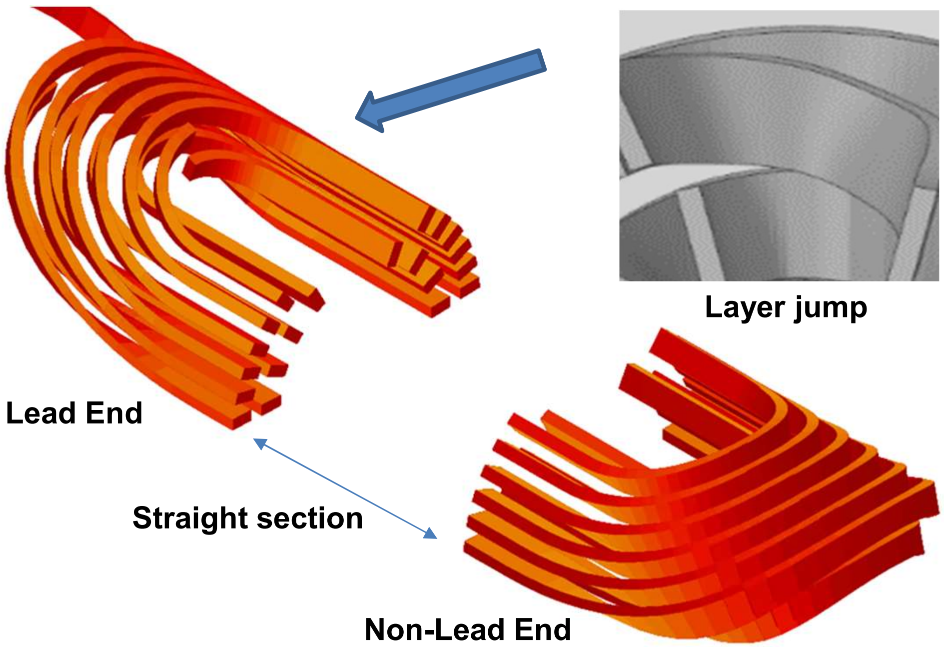


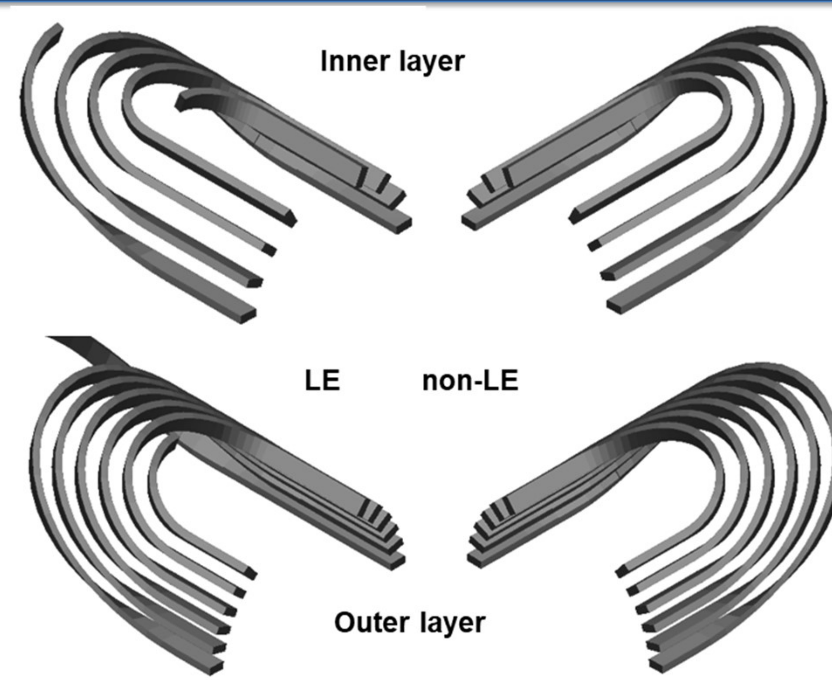


- 0.1x4 mm2 REBCO tape
- 16-strand cable 4×1.6 mm²

REBCO tape and twisted stacked-tape cable

TST Cable twist in coil

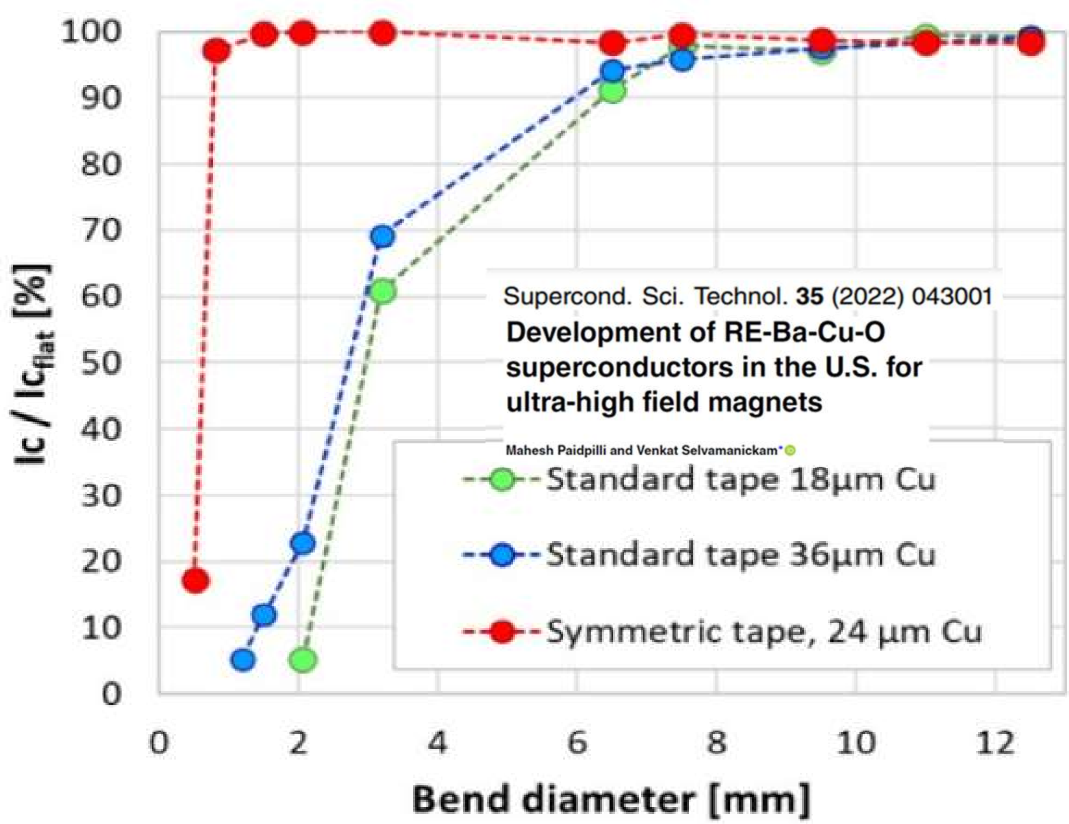


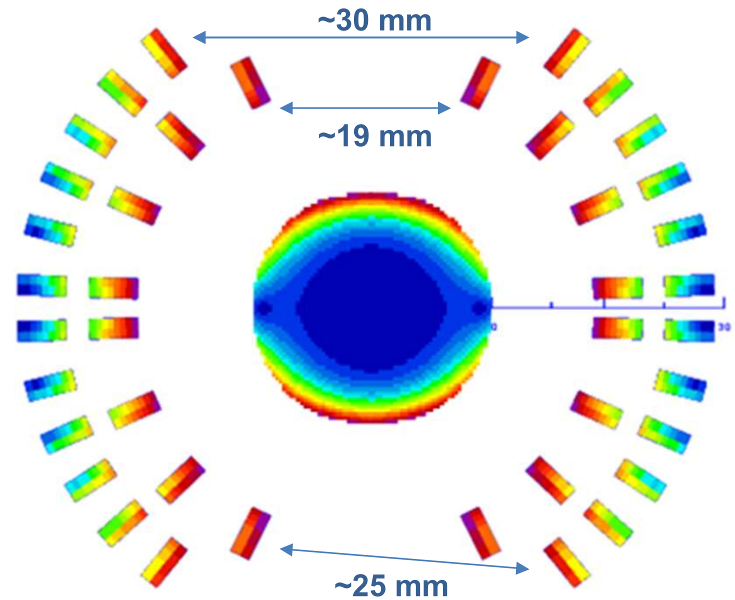


- **Coil ends and layer jump – cable easy-bend with small radius and twist.**
- **Coil straight section – cable twist by 180 degree or 0.5L_p.**

Question: What are the limits for R_b and L_p?

Conductor degradation due "easy" to bending





=> The minimal bending diameter is ~19 mm which is much larger than the degradation limits of ~8 mm

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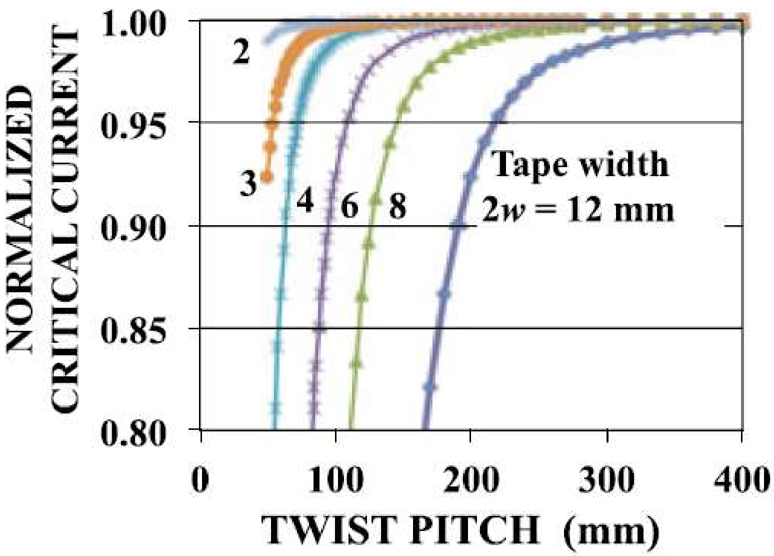
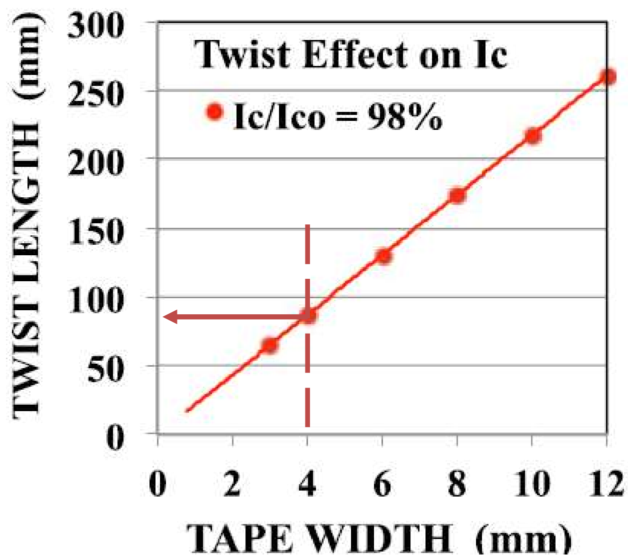
Conductor degradation due to cable twist

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017 6900305

Electrical and Mechanical Characteristics of HTS Twisted Stacked-Tape Cable Conductor

Makoto Takayasu, Luisa Chiesa, Leslie Bromberg, and Joseph V. Minervini





=> For 4 mm wide 0.1 mm thick tape L_t minimal is ~80 mm

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Coil parameter optimization

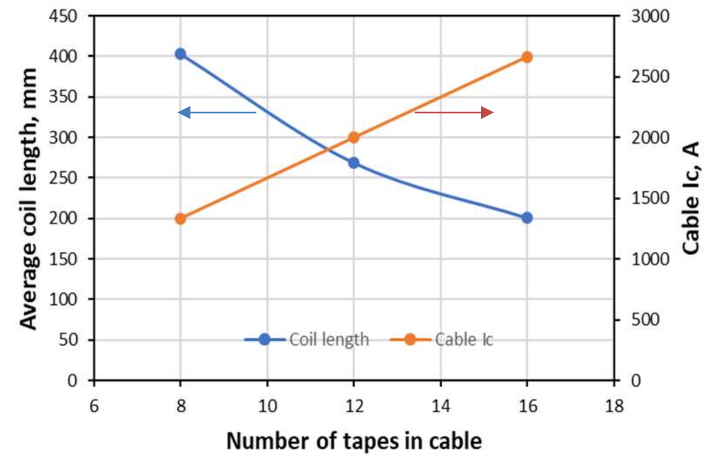
- ROXIE parameters for ends (angle, ellipticity) for all turn positions could be measured using Kapton tape
- Practice coil winding using the cable made of Kapton or copper tapes

- **=>For ~30 cm long coil $0.5L_p$~10 cm ($0.5L_p$_min~4 cm)**

~18 cm

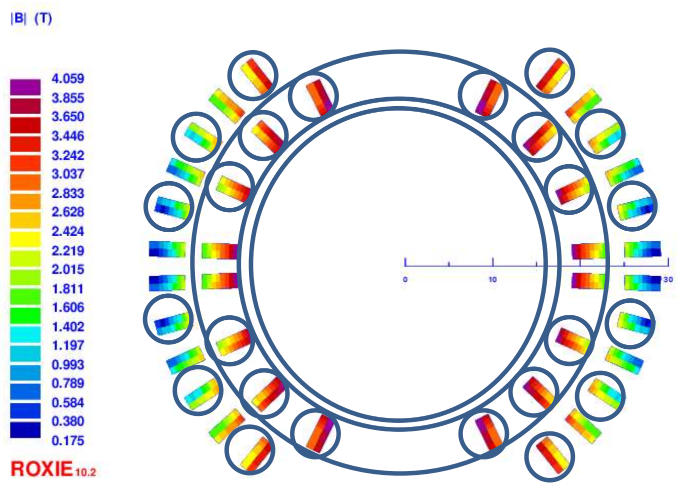
Cable and straight section lengths

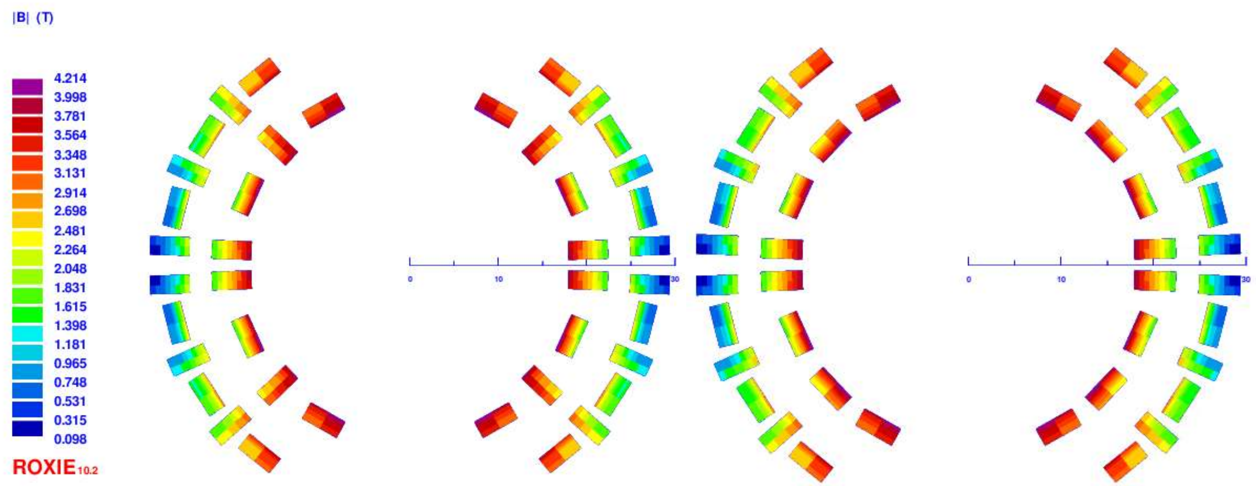
Spool	Tape length, m	Spool Ic, A	Cable length, m	Cable length, m	Coil length, m
			16 tapes	12 tapes	8 tapes
1	29	167	7.3	9.7	14.5
2	30	164	7.5	10.0	15.0
3	30	166	7.5	10.0	15.0
4	32	169	8.0	10.7	16.0



- 4 spools with test data provided by LBNL
  - thanks to X. Wang (LBNL)
- Cable piece length increases from ~7 m for 16 tapes to ~14 m for 8 tapes
- **With present coil ends only 12 or smaller number of tapes provide reasonable straight section length**

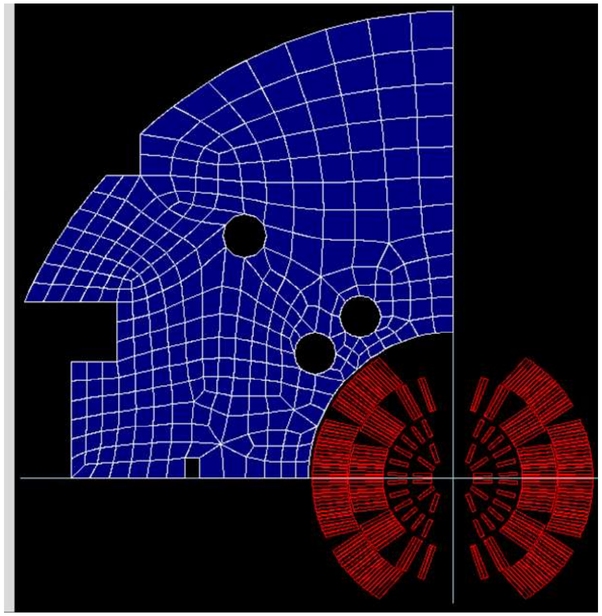
Turn twisting in coil straight section

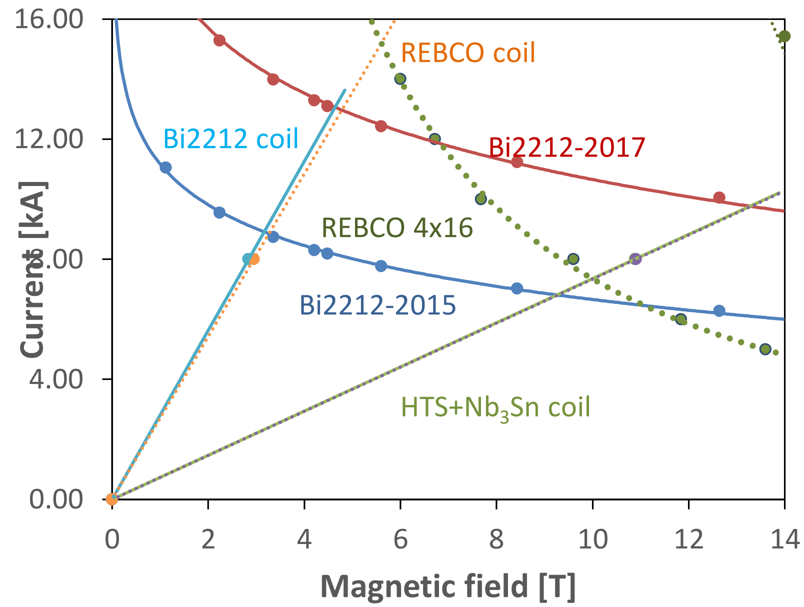


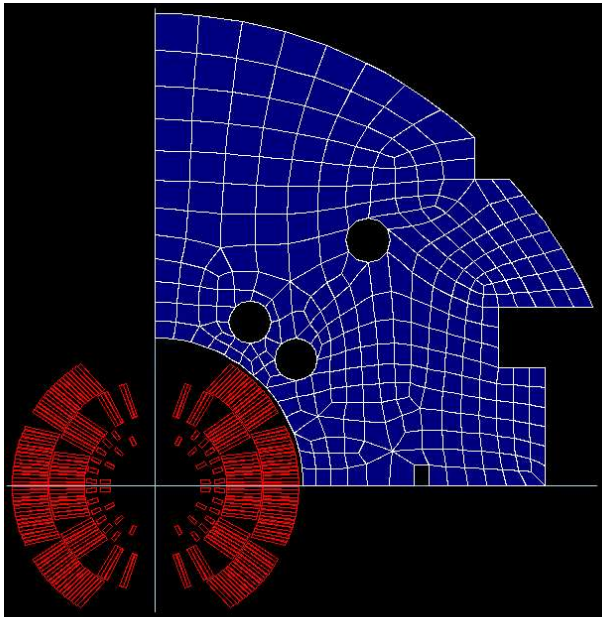


- **Due to turn twist in straight section, 2 possibilities for the present coil design**
  - every second turn can be twisted or
  - all inner-layer turns and every second outer-layer turns except midplane turns.
- **Even with all turns twisted in SS the cable twist pitch varies along the coil => uncompensated flux**

Bi2212 vs REBCO insert parameters

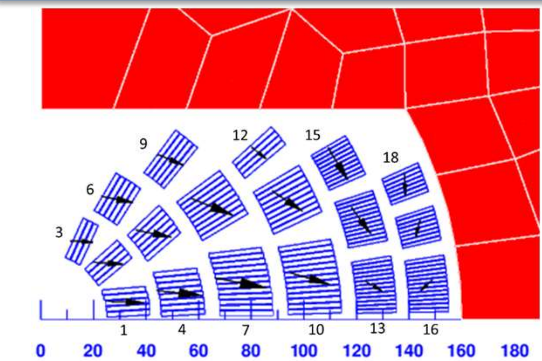






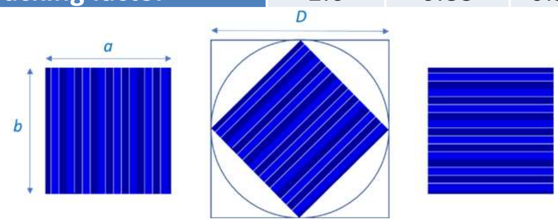
- The coils will be tested **first** separately and **then** as inserts into Nb_3Sn coils
- Load lines for Bi2212 and REBCO inserts (with 16 tape cable) are close

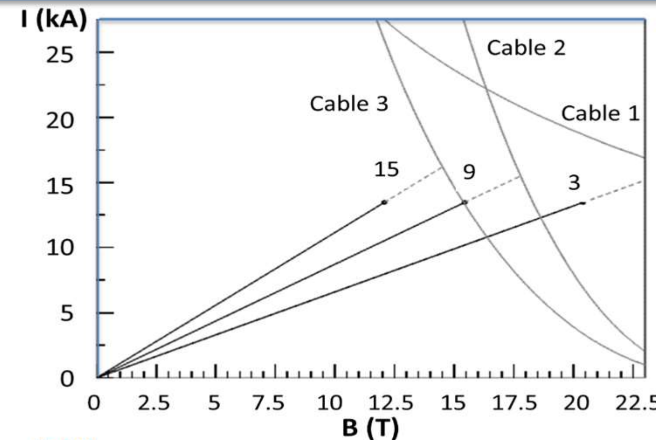
20 T hybrid dipoles with Bi2212 and REBCO coils

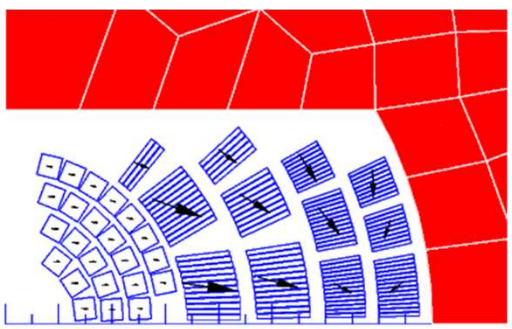


IPAC2023

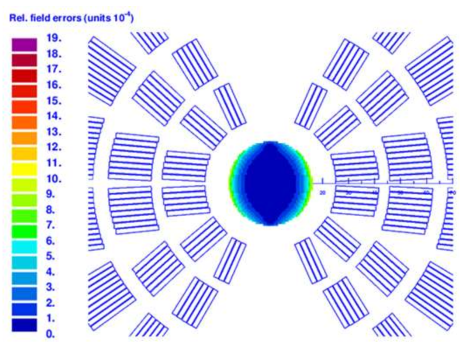
Parameter	REBCO	Bi2212	Nb_3Sn	Nb_3Sn
Strand size, mm	5×0.1	1.0	1.0	0.7
Number of strands	50	32	40	40
Cable width, mm	8	16.5	20.1	15.0
Cable small edge, mm	8	1.85	1.70	1.22
Cable large edge, mm	8	1.95	1.90	1.38
Cable packing factor	1.0	0.83	0.90	0.81

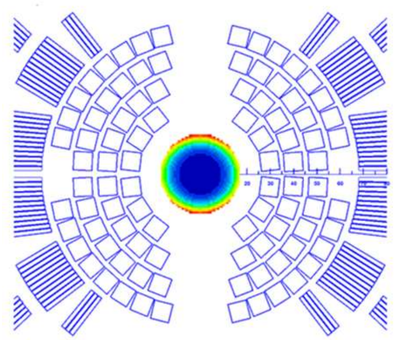


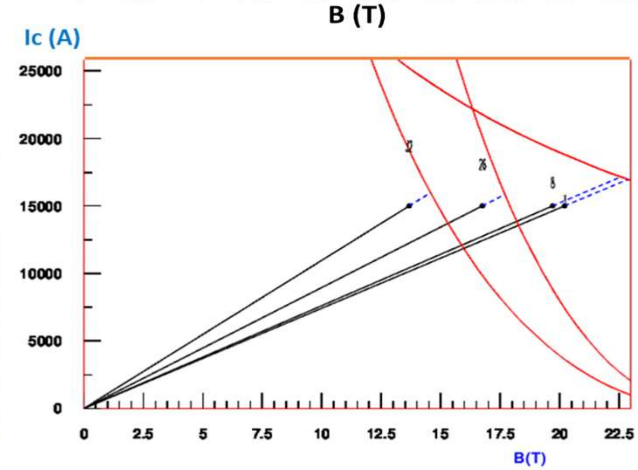




FERMILAB-TM-2807-TD
(in preparation)







Summary

- **2L design concepts of REBCO insert coil and SMCT coil support structure is being developed**
  - REBCO coil parameters with 16 tape cable are similar to Bi2212 coil which allows direct technology and performance comparison
  - coil support structure will be made of inexpensive LS-316 or bronze
- **Plastic model to optimize the cable insulation, coil design, SMCT structure and coil winding technology is useful**
  - copper tape of similar size is available and inexpensive
- **REBCO tape for the first insert provided by LBNL**
  - thanks to X. Wang (LBNL) for the tape and test data
- **Demonstration of this cost-effective approach could be done in FY23-FY24 in parallel with the Bi2212 insert coil task**
- **Possibility of using this technology for the 20 T hybrid dipole is being studied**