U.S. MAGNET DEVELOPMENT PROGRAM

REBCO accelerator magnet development: status and plans

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U.S. DEPARTMENT OF ENERGY | Office of Science

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The REBCO session

- This talk
  - The MDP REBCO component: goals and plans
  - Status at LBNL and allied conductor programs
  - Things could be done but don’t have the resources for
  - Conductor needs
- Second talk by R. Gupta
  - Major SBIR effort on REBCO accelerator magnets and hybrid test
- Discussion
  - Priorities for magnet development
  - Community and international collaboration

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REBCO can make significant progress in the next 2 years

Quote from an important stake holder…

"In the area of future high field accelerator magnets, REBCO has the interesting combination of

- the very best high field performance of any conductor we have today,
- probably the greatest challenges for engineering accelerator magnets,
- and the least amount of effort directed toward this particular application."

The goal for the MDP REBCO component

- Develop the magnet technology for REBCO
  - To be prepared when the conductors are available
- Demonstrate the feasibility of REBCO accelerator magnets
  - Produce an insert with a self-field > 5 T and measure the field quality
  - Test the true capability of REBCO insert in background field
- Establish a magnet platform to develop conductor, diagnostics and analysis tools to push the limits of REBCO

The REBCO component addresses the following 5 driving questions

Cost	⑧	Can we build practical and affordable accelerator magnets with HTS conductor(s)?
Conductor	⑩	What are the near and long-term goals for HTS conductor development? What performance parameters in HTS conductors are most critical for high field accelerator magnets?
Performance	②	What are the drivers and required operation margin for HTS accelerator magnets?
	③	What are the mechanical limits and possible stress management approaches for 20 T LTS/HTS magnets?
	④	What are the limitations on means to safely protect HTS magnets?

With proper performance and cost, one day all magnets with be HTS

Technical approach is well integrated with MDP Technology and CPRD Areas

- Develop REBCO magnet technology
  - Magnet design for specific conductor (round wire, tape stack)
  - Fabrication (winding strain, impregnation)
  - Protection against Lorentz and thermal stress/strain during cooldown and quench

- Measure, understand and predict magnet performance
  - Develop and validate analysis tools
  - Explore the true performance of REBCO insert in background field
  - Integrated with the Technology Development Area

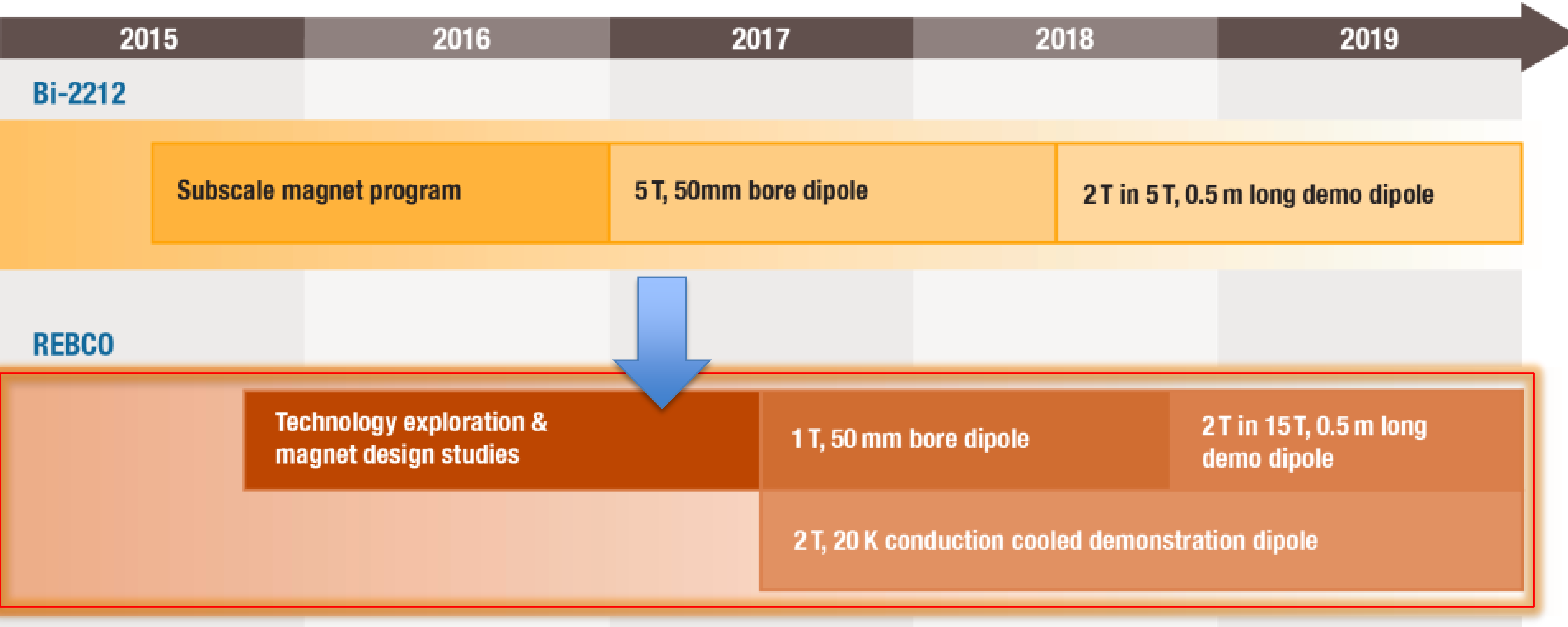
- Feed back to conductor development based on magnet performance/needs
  - Integrated with the CPRD Area

Technical challenges to be addressed

Magnet conductors: performance and cost

- Magnet design
- Coil winding
- Degradation-free Impregnation
- Materials and fabrication of magnet structures
- Modeling and analysis
- Test and diagnostics
- Quench detection and protection
- Field quality

We are still on track for the REBCO plan

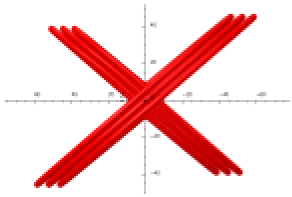


… but we can move faster given more resources

FY17: demonstrate a 1 Tesla CORC® dipole (C1)

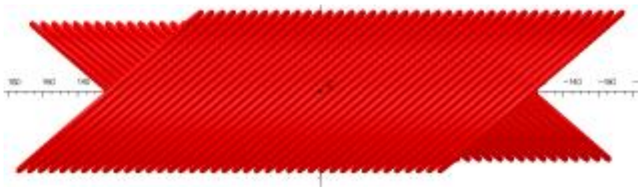
- Demonstrate the feasibility using readily available conductors
- C1: 2-layer, 70 mm ID, 40 turns, 1 Tesla dipole field, 4.2 K

C0: 3-turn mini coil



- Prove the principle
- Develop technology and infrastructure
- Pending one test

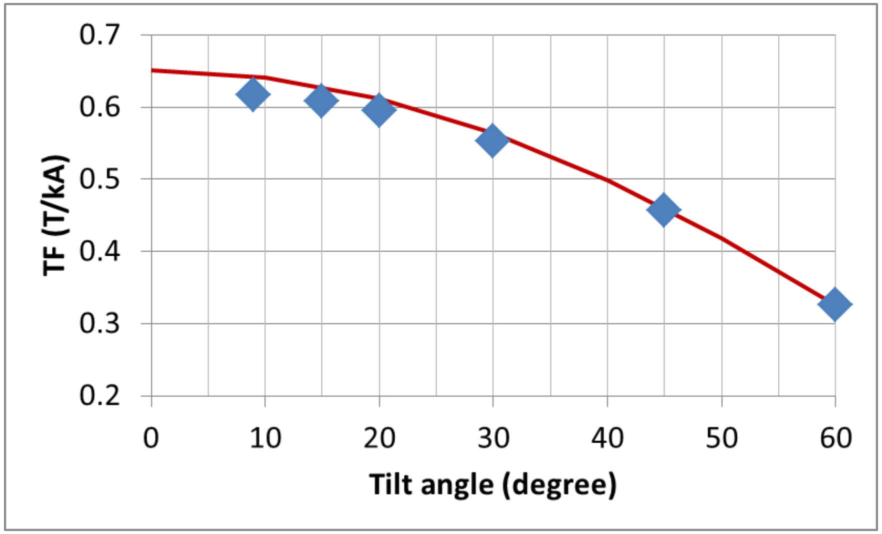
C1: 40-turn coil

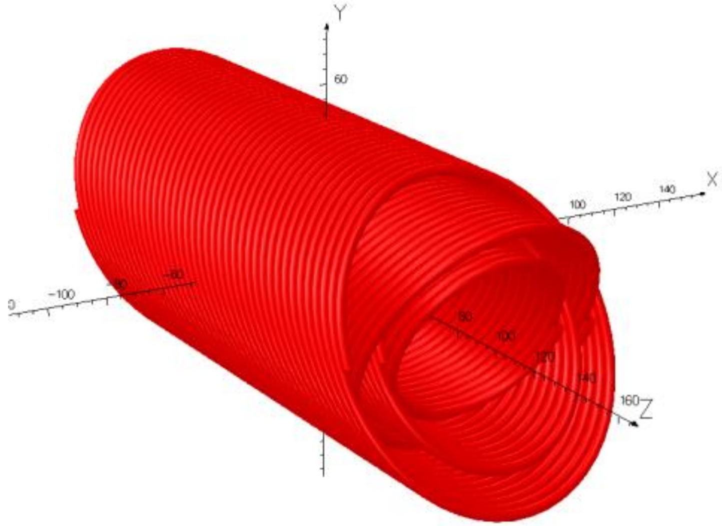


- Demonstrate 1 T
- Measure field quality
- Feed back to conductor development

FY18: develop a 2 Tesla CORC® dipole insert (C2)

- Demonstrate 2 T (stand alone, 4.2 K) with next-generation conductors
- C2: 4-layer, 50 mm ID, <100 mm OD





Push the conductor performance

- Double the I_c at 3 T, 4.2 K
- Reduce the minimum bending radius from 25 to 15 mm
- Can reach 3 Tesla if we achieve both

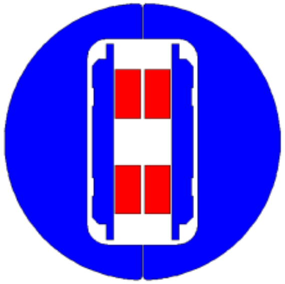
A global community for potential collaboration

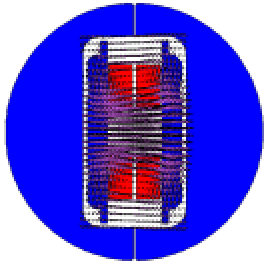
Institutions	Conductor	Coil geometry
CERN	Roebel	Aligned block
CEA/Saclay	Roebel	Cosθ
	Tape stack	Racetrack
U. Geneva, Bruker	Single tapes	Solenoid
KEK, Kyoto U., Toshiba	Single tapes	Cosθ
IHEP	Single tapes	Racetrack
ASC/NHMFL/FSU	Single tapes with and without insulation	Solenoid
BNL/PBL	Single tapes	Common coil
LBNL	CORC®	Canted cosθ

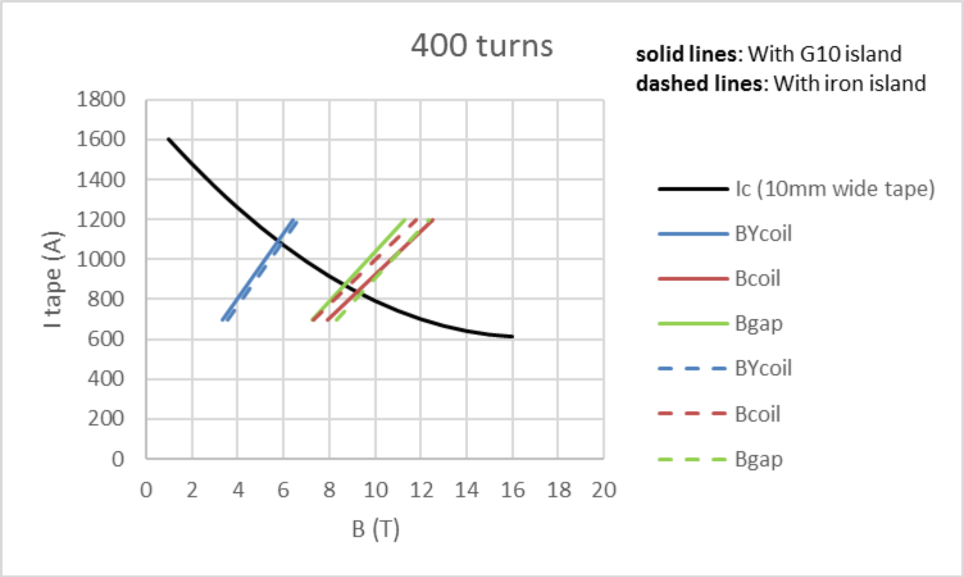
We also have 15+ tape/conductor vendors worldwide

Racetrack coil study with potential collaboration with IHEP, China

- Institute of High Energy Physics proposed to collaborate on REBCO coil technology by providing conductors
- 10 T dipole field with two racetrack coils using 1 km conductor

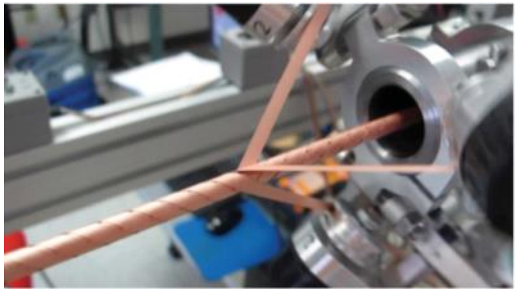






Analysis performed by Laura Garcia Fajardo

Development of the first 3-turn CORC® coil (C0)

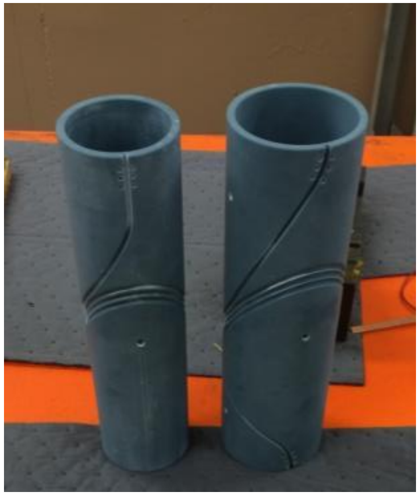


- 8 layers of SuperPower tape with 2 tapes/layer, 2 mm wide, 30 µm thick substrate
- Expected self-field I_c at 4.2 K: 4300 A
- Wire diameter: 3.09 mm
- Total sample length: 2.3 m

Image courtesy by J. Weiss and D. van der Laan

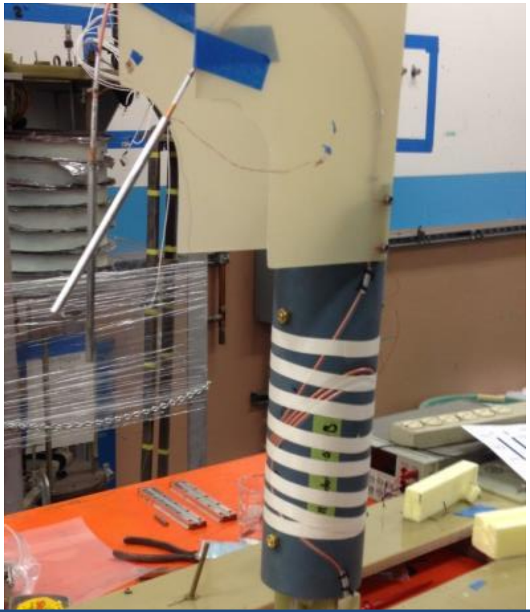
Fabrication of C0 (3-turn proof-of-principle coil)

3D printed mandrels

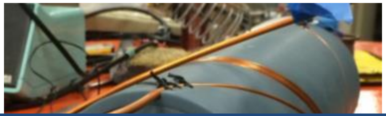


Coil winding

Assembly before test

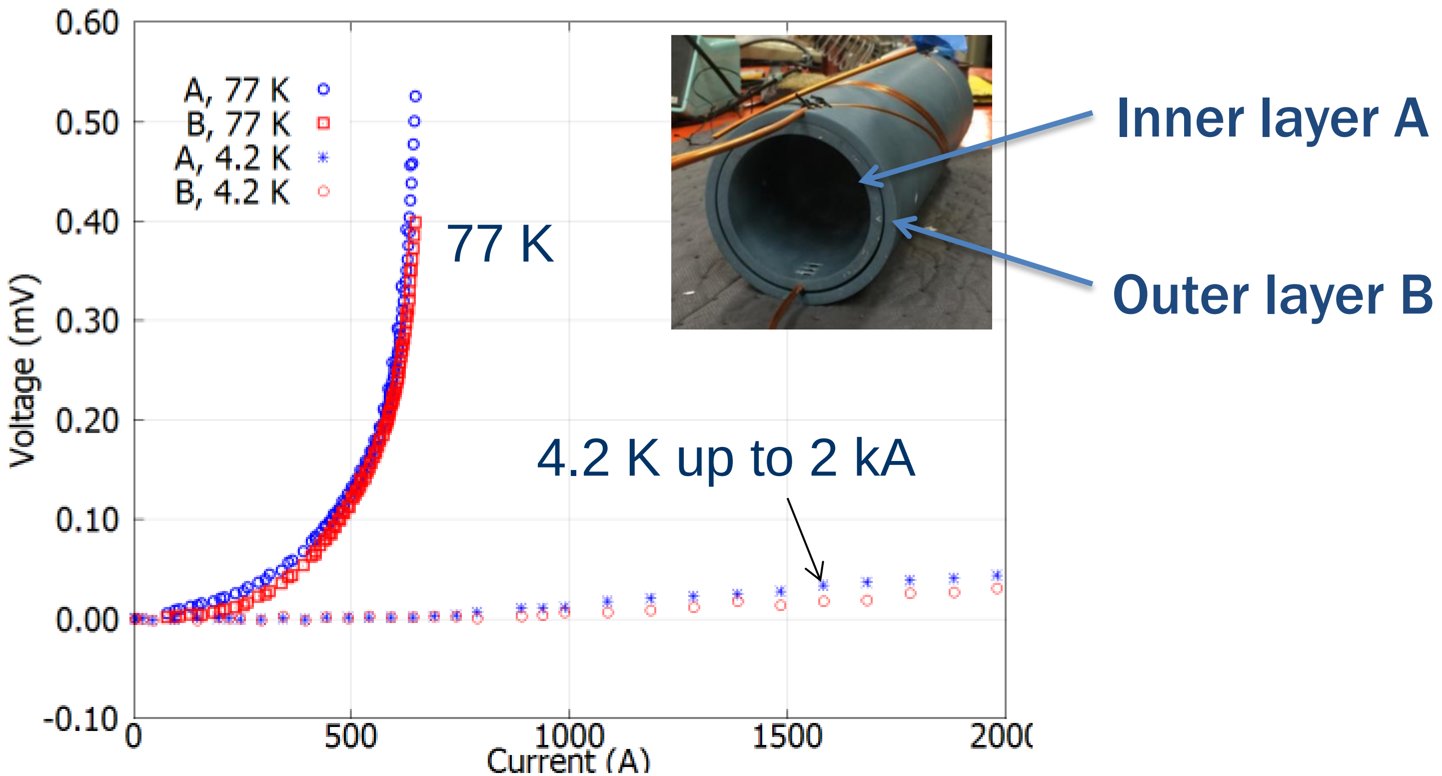


Assembling two layers



Made possible by Hugh Higley, Bill Ghiorso, Andy Lin and collaboration with Advanced Conductor Technologies supported by HEP SBIR

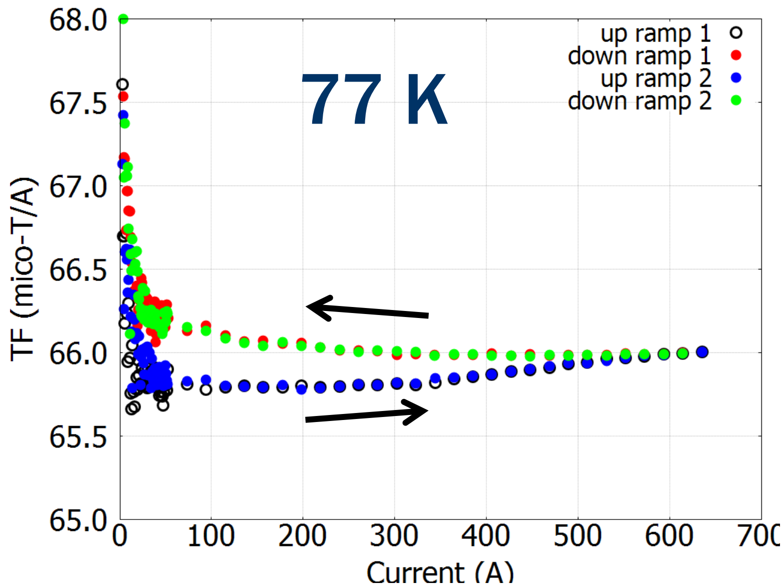
Test of CO at 77 and 4.2 K (limited by a 2 kA power supply so far)

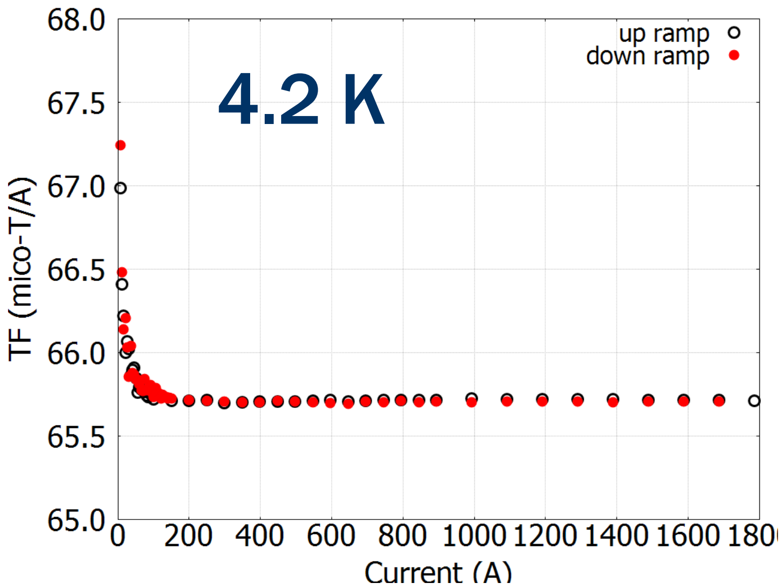


- The voltage of each layer indicates higher I_c at 4.2 K (expecting 4.2 kA)
- In preparation to test with the other power supply (20 kA)

Hysteresis due to magnetization is less pronounced at 4.2 K (preliminary)

- The persistent current effect is a big concern for HTS magnets

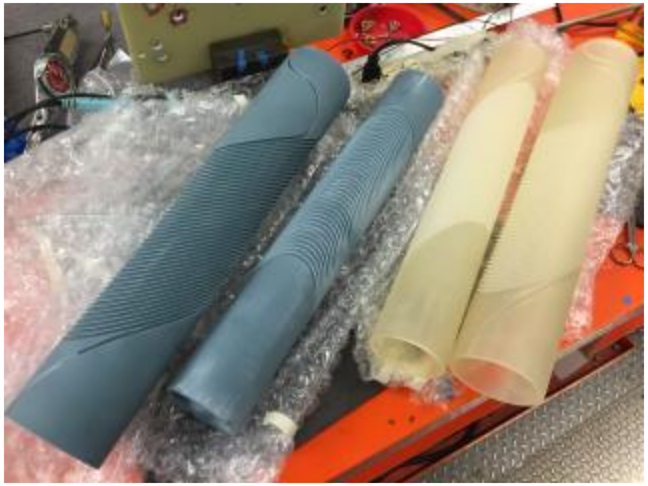




- Good news but requires confirmation in the coming tests

Next steps for REBCO magnets in FY17

- Test C0 (3-turn coil) with a different power supply to confirm the transition at 4.2 K
- Wind and test C1 (40-turn, 1 Tesla dipole coil)
  - Conductor and mandrels are in hand



Status of allied conductor programs

- Status of the R&D programs on REBCO tape and conductor relevant for accelerator magnets
  - Advanced Conductor Technologies, LLC
  - University of Houston
  - MIT Plasma Science and Fusion Center

- The MDP can significantly leverage the effort of these outstanding programs

CORC® wires from Advanced Conductor Technologies

30 µm substrate thickness enabled the introduction of CORC® wires

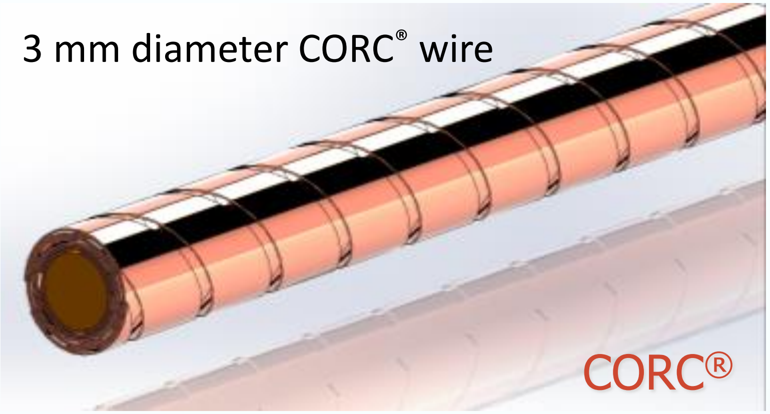
- Wire size 3-4.5 mm
- J_e > 300 A/mm^2 at 4.2 K, 20 T
- Bending radius <25 mm

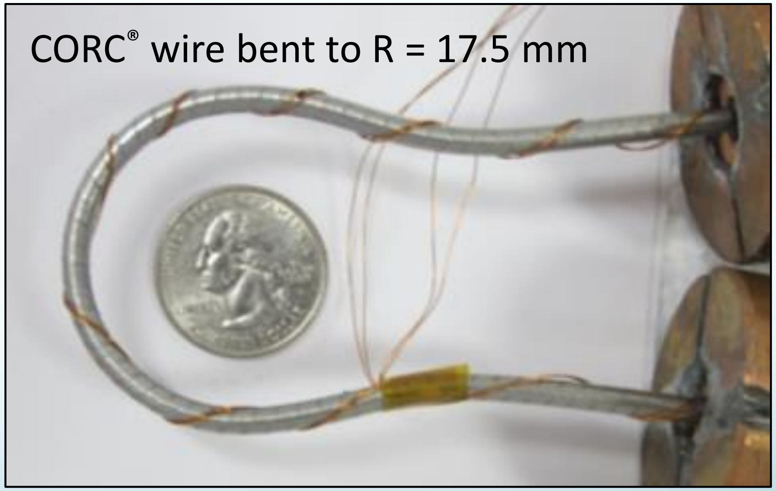
Applications

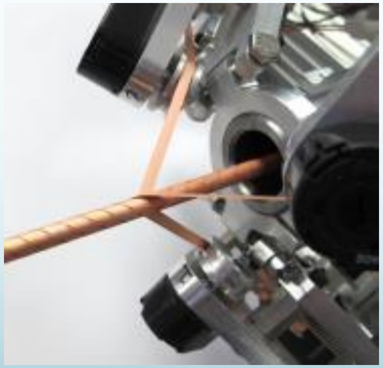
- Accelerator magnets
- Fusion magnets
- High power density transmission

CORC® cable and wire production (2016)

- Total length of 120 meters
- Commercial CORC® wire length 50 m
- Commercial CORC® cable length 20 m





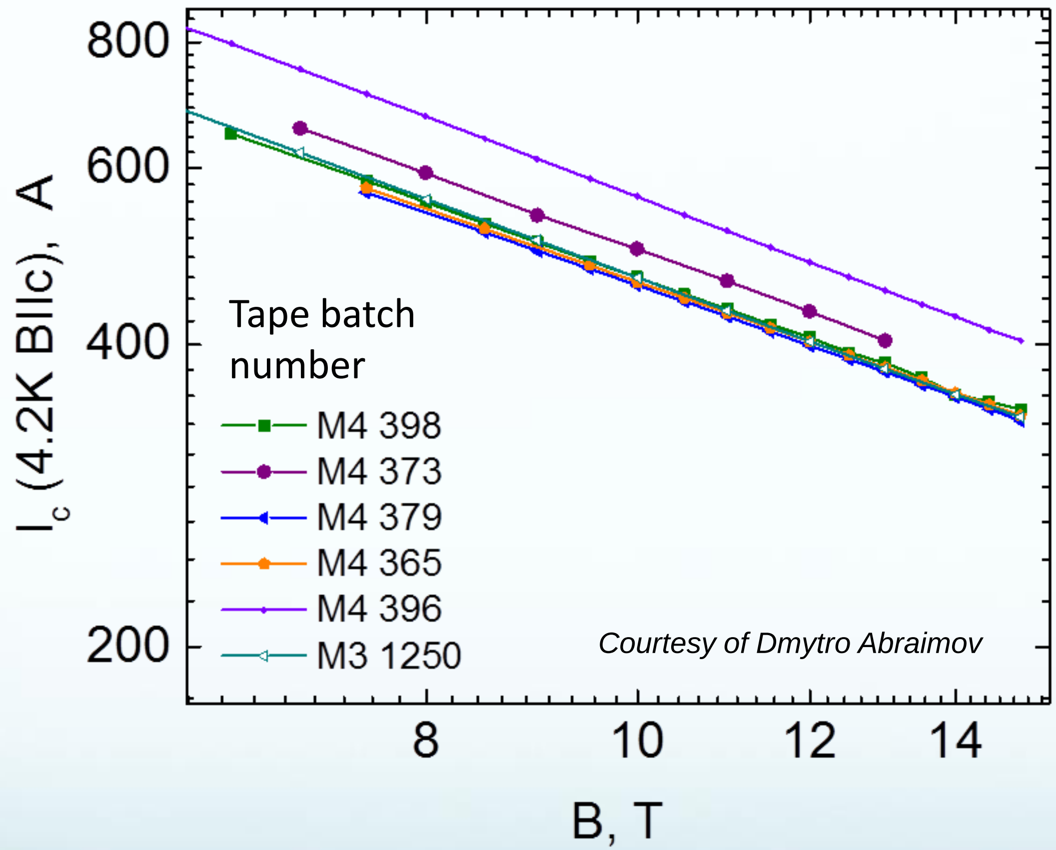


Advanced Conductor Technologies LLC
www.advancedconductor.com

Danko van der Laan, Jeremy Weiss

Increased pinning in SuperPower tapes

High-field performance at 4.2 K of 2016 production tapes from SuperPower

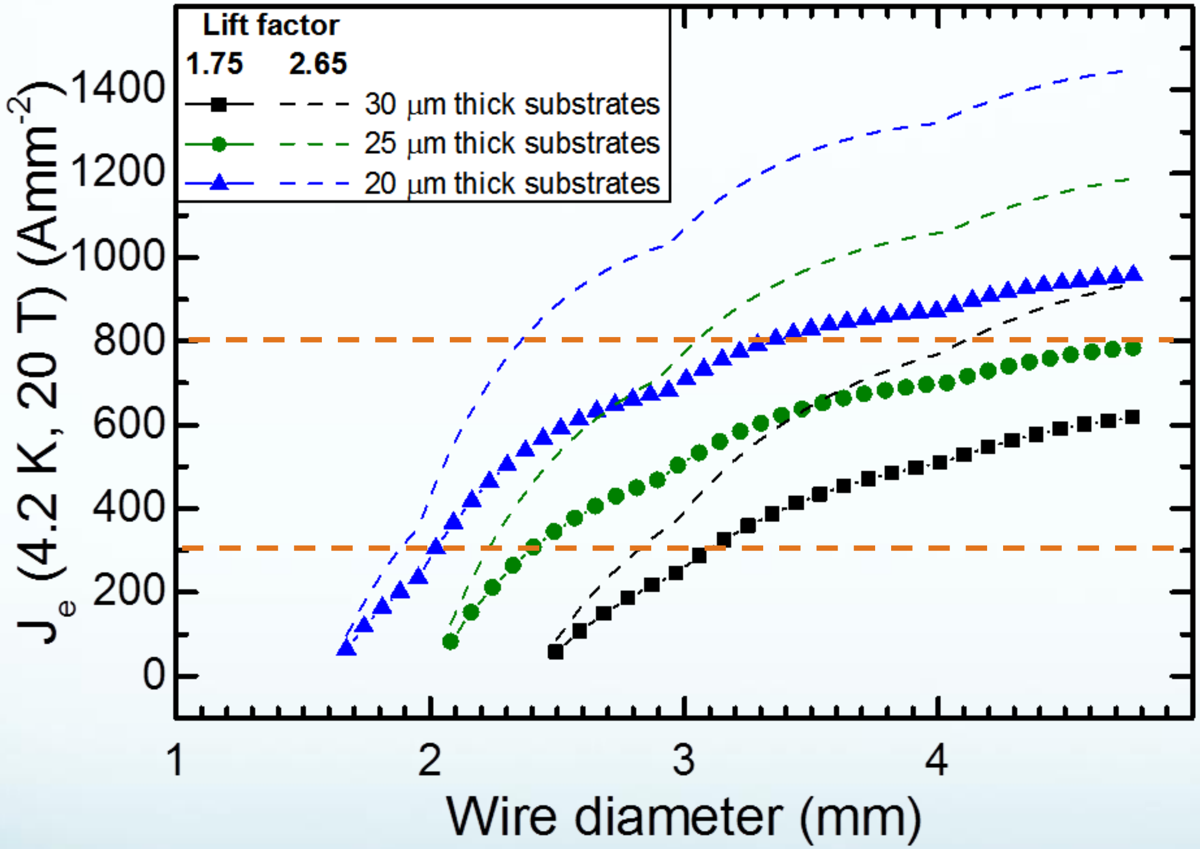


Lift factors (I_c(4.2 K, 20 T) / I_c (77 K, SF)) increased from 1.3-1.6 to 1.75-2.65!

Danko van der Laan, Jeremy Weiss

Increasing J_e of CORC® wires through thinner substrates

Advanced Conductor Technologies is working with SuperPower to further decrease the substrate thickness to 20-25 μm

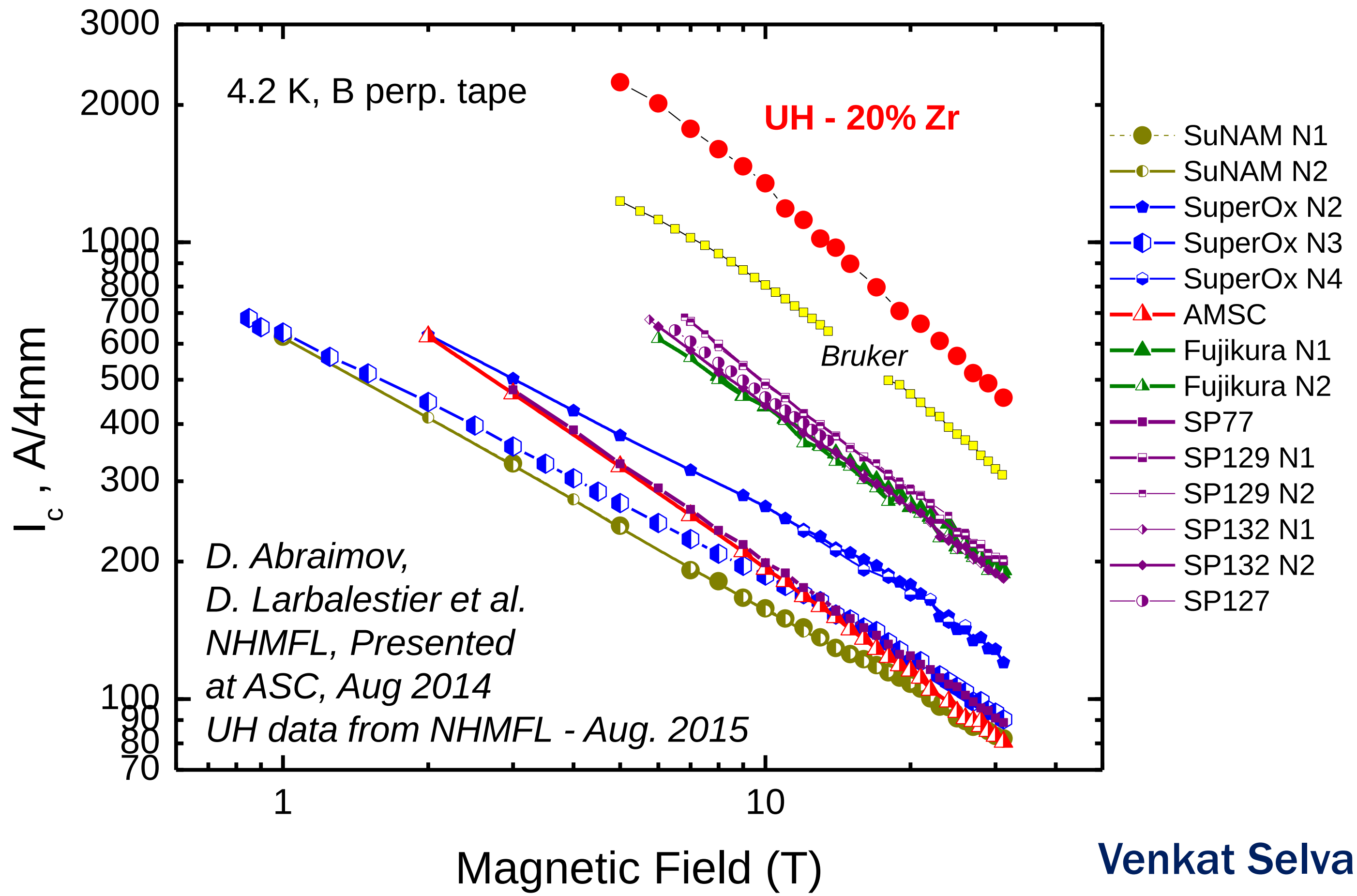


J_e(20 T) of a 3.5 mm CORC® wire likely to increase from 300 A/mm^2 to 1,000 A/mm^2 when combining lift factor of 2.65 with 20 μm thick substrates

Danko van der Laan, Jeremy Weiss

UNIVERSITY of HOUSTON

Superior performance of 20%Zr-added REBCO tapes in high fields at 4.2 K

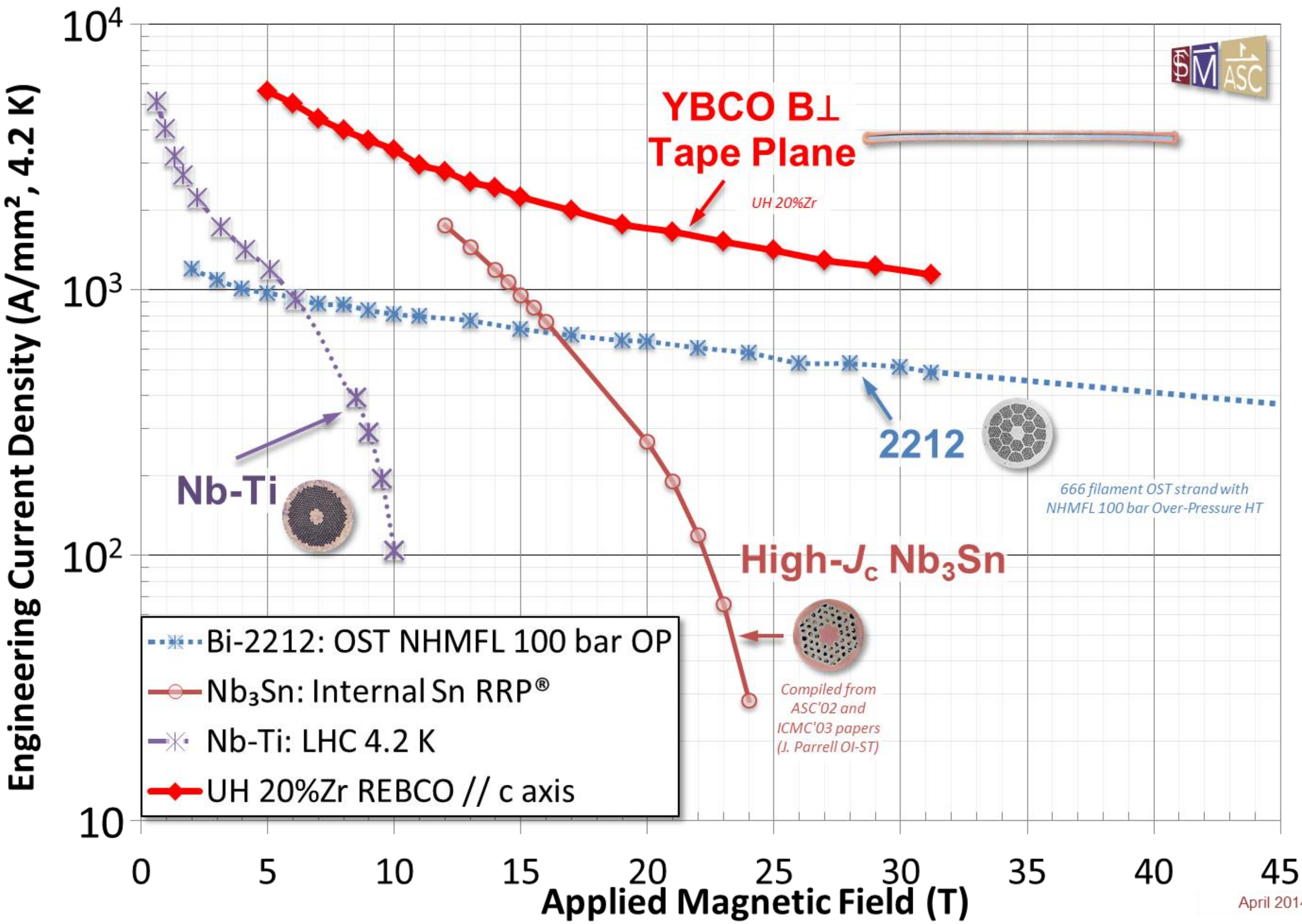


Venkat Selvamanickam

At 4.2 K, 21 T, I_c = 663 A/4mm, J_e = 1658 A/mm^2

UNIVERSITY of HOUSTON

15%Zr & 20%Zr tape performance at 4.2K better than all wires even in field perpendicular to tape

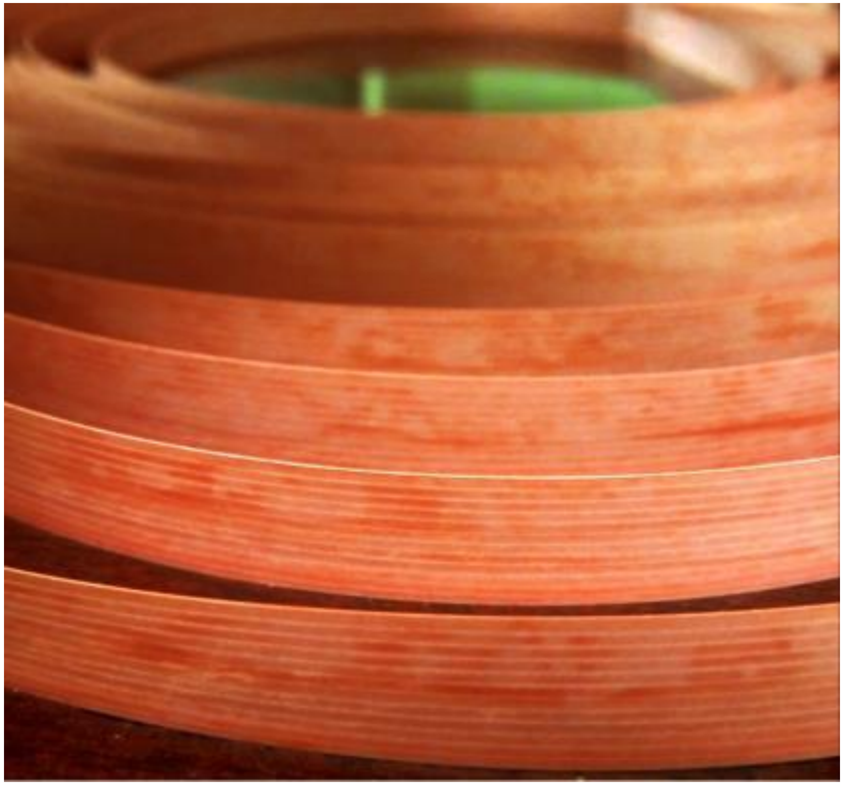


J_e of 20% Zr
2.3X Nb_3Sn
@ 15 T
6.4X Nb_3Sn
@ 20 T

J_e of 20% Zr
3.1X Bi-2212
@ 15 T
2.7X Bi-2212
@ 20 T

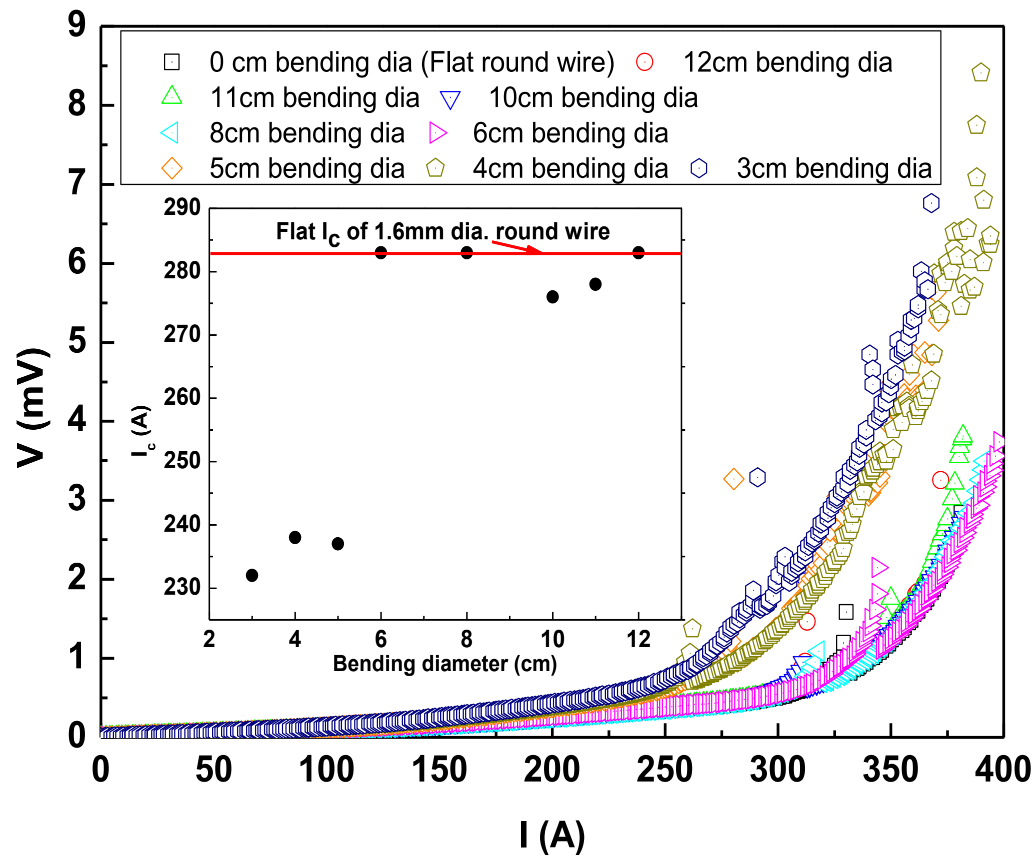
Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm
UH data on 15%Zr tapes from *APL Materials* **2,** 046111 (2014)

Fully-stabilized multifilamentary REBCO tapes produced in long lengths



Excellent mechanical properties of round ultra-small diameter REBCO wire

3 cm bending diameter



Twisted Stacked-Tape Cable (TSTC)

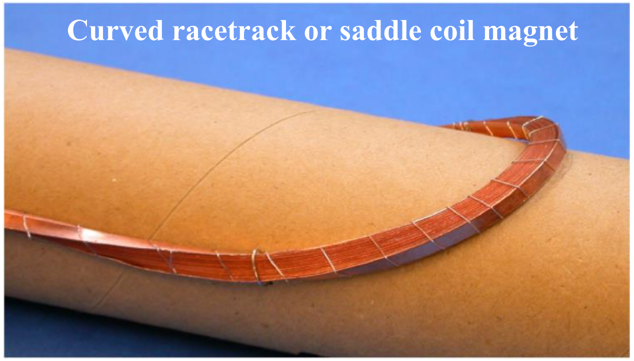
For example:

1. REBCO tapes are **stacked** between two thick copper strips.

2. The stacked-tapes with the copper strips are loosely **wrapped** with a fine stainless steel wire.

3. Then the stacked-tape cable is **twisted**.

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



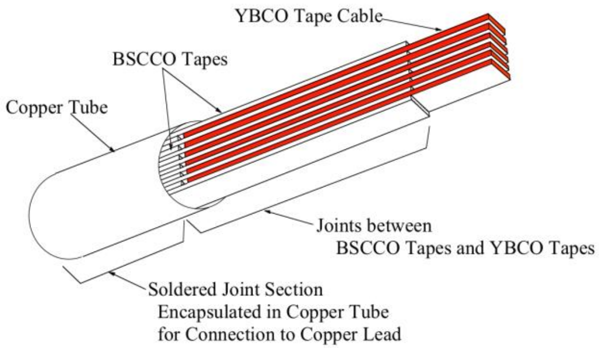
A curved saddle winding of 50 YBCO tapes on a 50 mm diameter tube.

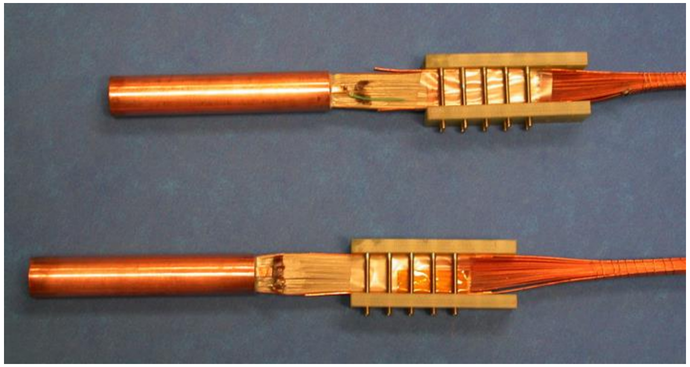
Stacked tape cable is twisted during winding.

3D accelerator magnets,
generator and motor magnets

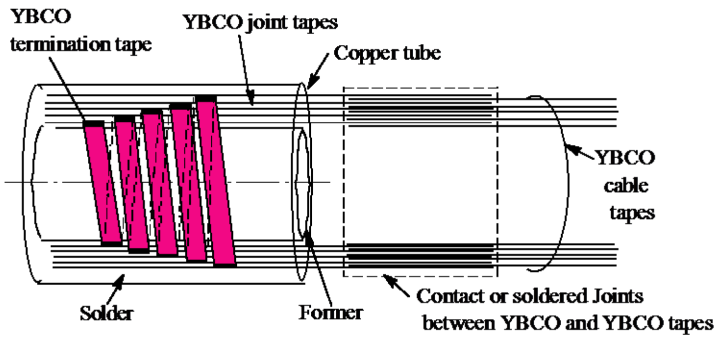
REBCO Cable Termination Methods Developed

YBCO - BSCCO Termination

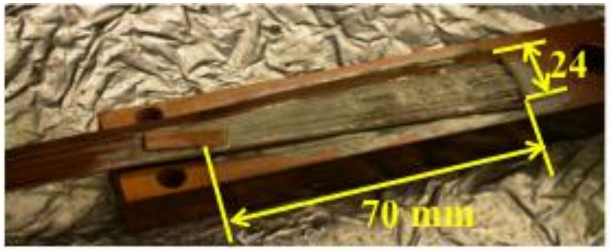




YBCO - YBCO Termination



Folding-Fan Soldered Termination



Things we could do but don’t have resources for

- Make REBCO program technically limited
  - We now test every 3 months. Not good enough – should be testing every 3 weeks.
  - “(REBCO) Magnet is held back by conductor cost”.
  - Another problem is we need 1 FTE technician for next 2 years

  (< 0.25 FTE now)

- LTS/HTS hybrid test infrastructure (long lead-time item)
  - Critical to understand the true capability of HTS inserts
  - Get ready for the needs of special magnets

- Conduction cooled REBCO coil

REBCO conductors in 5 years besides lower cost

- A high-current, flexible and stable conductor for REBCO insert
  - High J_e: > 600 A/mm^2, 4.2 K, 20 T
  - Small bending radius: < 15 mm
  - Compact: diameter < 3.5 mm
  - Effective current sharing between tapes inside the conductor

- Increase the J_e in commercial tapes to 3000 A/mm^2 at 4.2 K, B//c, 20 T
  - They approach 1000 A/mm^2. J_e of UH research samples reached 1800 A/mm^2.

- Place the REBCO layer close to the neutral plane of the tape
  - Thinner substrate is one option: from 30 micron to 20 or less
  - Any other options?

REBCO Conductor procurement needs for FY17 and FY18

- CORC® wire for the 2-layer and 4-layer CCT designs
  - 100 m between May and December 2017 ($300 k)
  - 25 m per piece, 4 pieces
  - Diameter < 3.5 mm
  - Minimum bending radius < 25 mm

- REBCO tapes for tape stack CCT dipole and racetrack magnet (FY18)
  - 100 m per piece, 5 pieces ($40 k)
  - 4 mm wide

- Dummy Roebel cables for alternative magnet design (FY17)
  - 10 m ($6 k)

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Sample opportunities for SBIR collaboration

- QA for long length conductor
  - Measure I_c uniformity for long conductors (100 m) before winding
- Low loss joints between conductors
  - Low resistance: 1 – 10 nΩ. Easy to make without significant heating
- Impregnation, structural material and fabrication
  - Epoxy and impregnation that will not degrade the conductors
  - High strength mandrel with a CTE compatible with conductors
  - Efficient fabrication (machining and/or printing)

Dedicated talks on quench detection and protection

- This afternoon during the Technology Development Session

14:35 **Diagnostics: current status and future directions** *35'*
Speakers: Maxim Martchevskii (LBNL), Stoyan Stoynev (FNAL)

15:50 **Rayleigh-scattering Interrogated Optical Fibers for HTS Quench Detection & Other Sensing Needs** *25'*
Speaker: Justin Schwartz (NCSU)

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Discussion points

- Priorities for the MDP REBCO effort
  - Near term, next 1 – 2 years
  - Mid term, next 3 – 5 years
    - Move the conduction cooled option from near term to mid term

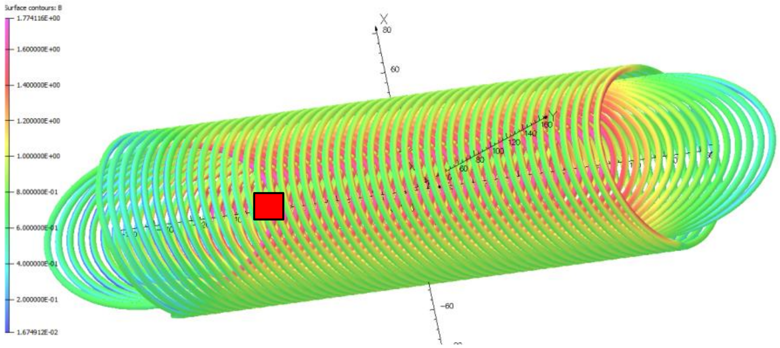
- How to form a community effort?
  - SBIR and universities programs are important to leverage
  - International collaboration: who, what, when, how?

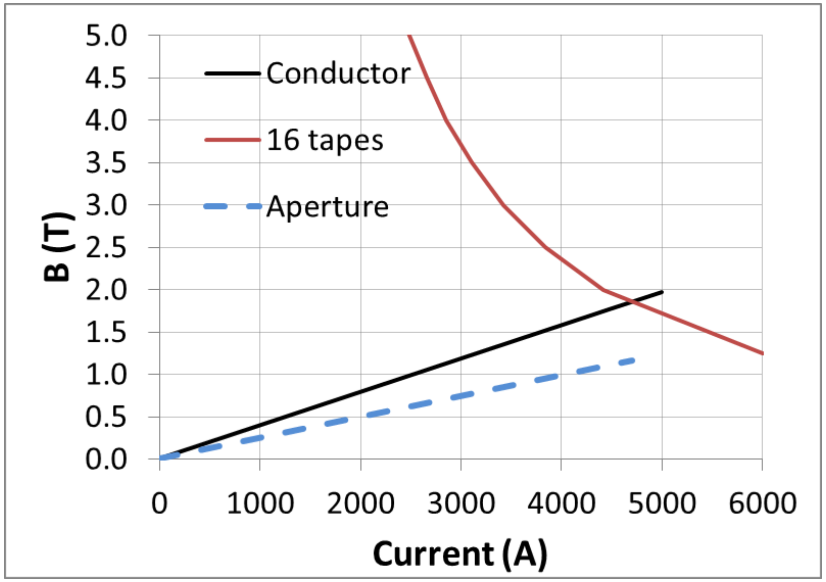
Summary

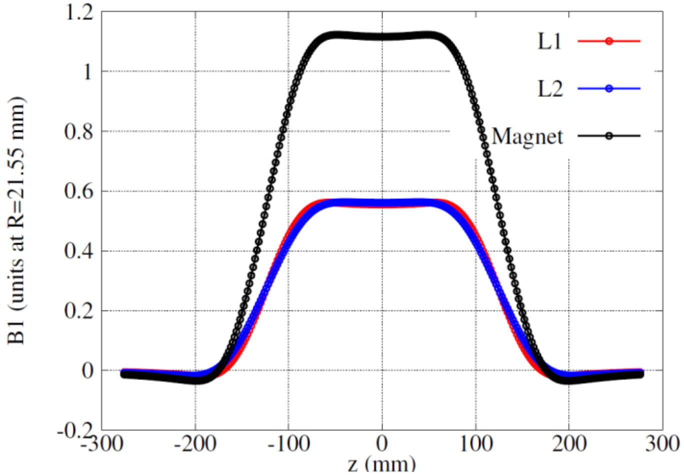
- The MDP REBCO component can generate significant impact in the next 2 years
  - Demonstrate the feasibility of REBCO magnet technology
  - Use magnet performance to guide conductor optimization

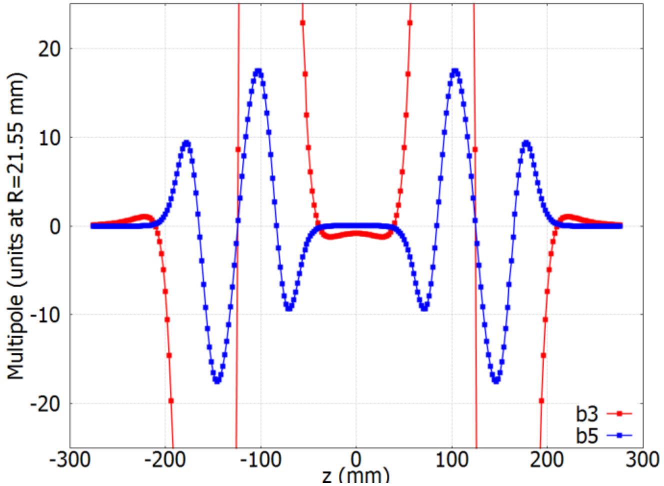
- We need faster progress to seize the opportunity
  - Need 1 FTE technical staff for the next 2 years (we have < 0.25 FTE now)
  - Build the conductor inventory to explore the magnet technology
  - Start preparing the LTS/HTS hybrid test infrastructure

C1: 1 T dipole field at 4.2 K









Load line for C2