Oral Presentation 3LO2-5 HTS, Magnets and Cables, EUCAS 2017

Transposed high current cables made with strong Bi2212 superconductor wire

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President and CEO

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Acknowledgements & Collaborators

Development network

-Plasma Science & Fusion Laboratory at MIT (Cabling line)

- Profs Yuki Iwaza and John Voccio (Ic testing)

-Francis Bitter Magnet Laboratory at MIT (Ic testing)

-Applied Superconductivity Center at Florida State University (Wire dev't, testing)

Funding

-DOE Phase 1 SBIR DE-SC0017709 (Just started)

-DOE Phase 2 SBIR DE-SC0011334 (Just finished)

-Solid Material Solutions, LLC

Objectives

- **Strong round & rectangular HTS wires**
  - Like proven LTS – Nb3Sn wires, but with superior Je(B, T) and still affordable
  - Built on unique Bi2212 properties, with our strengthening, dev’t expertise
    - Reaction to achieve high Je does not require tape shape
  - As low-cost / m as 1G tape, but with lower $/kAm price due to higher Je(4.2K)
- **Transposed cables for robust, low loss coils with these wires**
  - Like proven LTS – Nb3Sn cable designs
  - But with superior Je(B,T) while meeting all other requirements

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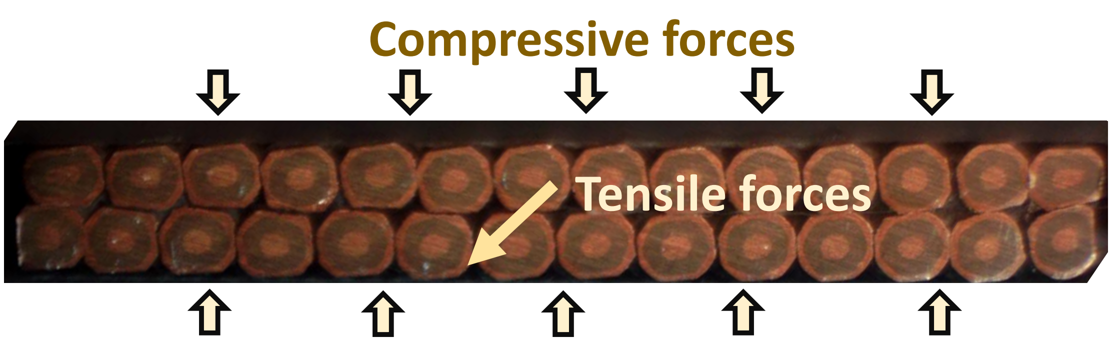
  - Like proven LTS – Nb3Sn cable designs
  - But with superior Je(B,T) while meeting all other requirements
- **HEP design targeted**
  - The LTS Rutherford round wire cable type below (CERN)
  - Compression, tension tolerant as needed



Applications

→Particle Accelerator	→Fusion Development
Physics – quadrupole, saddle / racetrack Proton therapy – large solenoid	Tokomak central solenoid → Ramped field, large coil
(SMES / Transformer)	(Generator / Motor)

Strong Wire? Attach Reinforcement

- **Why? Silver cannot be modified** to attain required stress tolerance
  - **Modulus too low,** ~ 80 GPa versus > 150 GPa needed
  - **Annealed by reaction** so even weaker than just from low modulus
- **Why rectangular initially? Easier to produce, prove approach basics**
  - **Plus better cabling density** is likely without much deformation
  - **And, lower contact pressures,** with much fewer internal damage issues
- **Round development? Now ongoing with cabling starting soon**

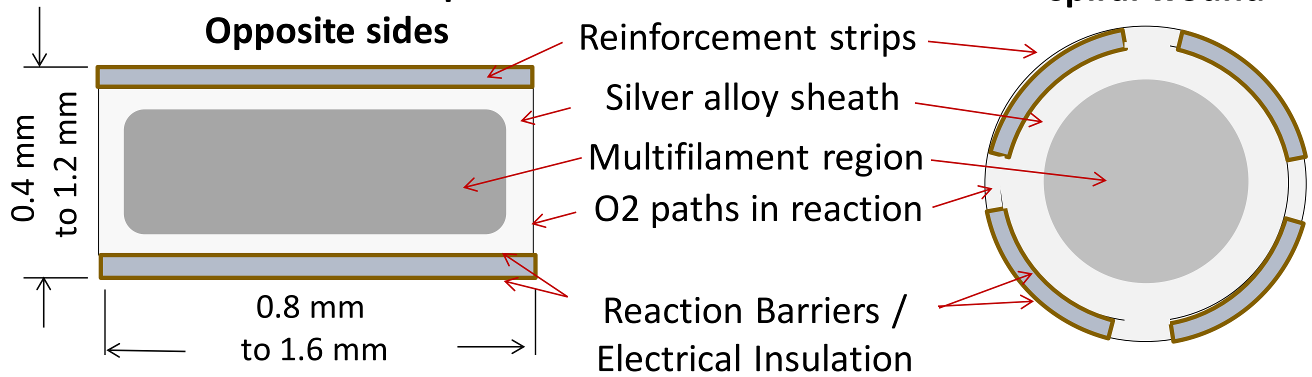
Strong Bi2212 Wire Designs

Rectangular (ReSRW)

Surface bonded strips on Opposite sides

Round (RoSRW)

Surface bonded strips, spiral wound



Edge view, Rectangular

Spiral On round

Reinforcement	strips bonded to some surfaces
Rectangular	square to ~ 2:1
Round	0.8 mm – 1.6 mm diameter
Strip dimensions	as needed, 10% - 50% by area
Stress tolerance	250 to ~600 MPa
Use modes	Wind & React, React & Wind

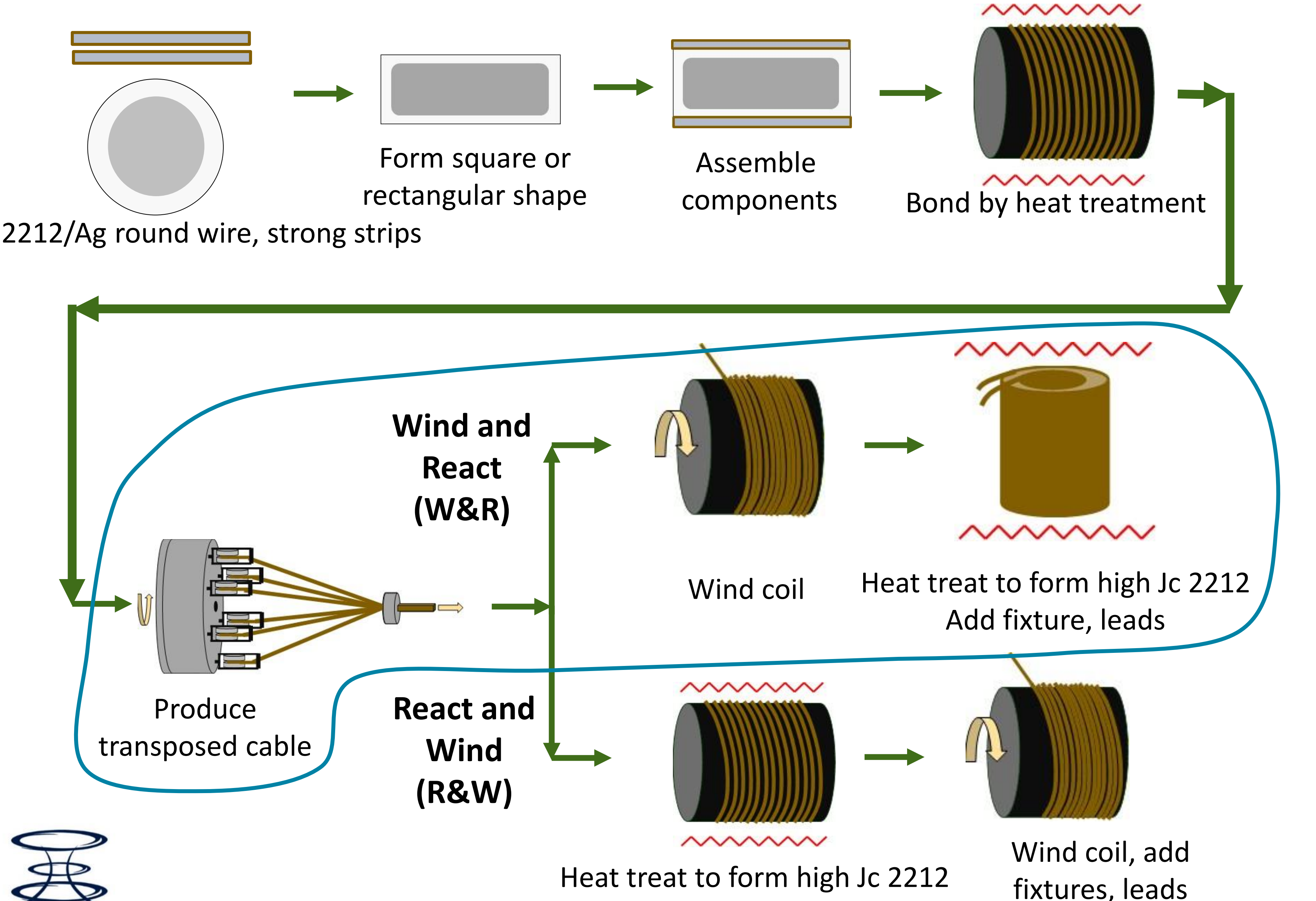
This approach enables:

- ❑ high Je Bi2212 to form by oxygen exchange between the 2212/Ag core and atmosphere during reaction
- ❑ needed strength and prevention of contact damage
- ❑ many design variations
- ❑ straightforward, scalable, low cost production

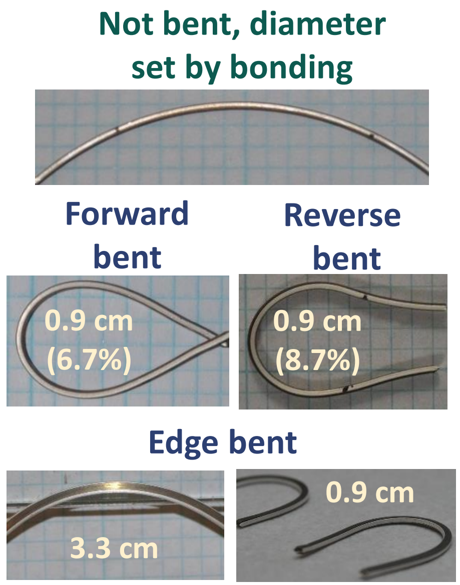
ReSRW with core wider than strips

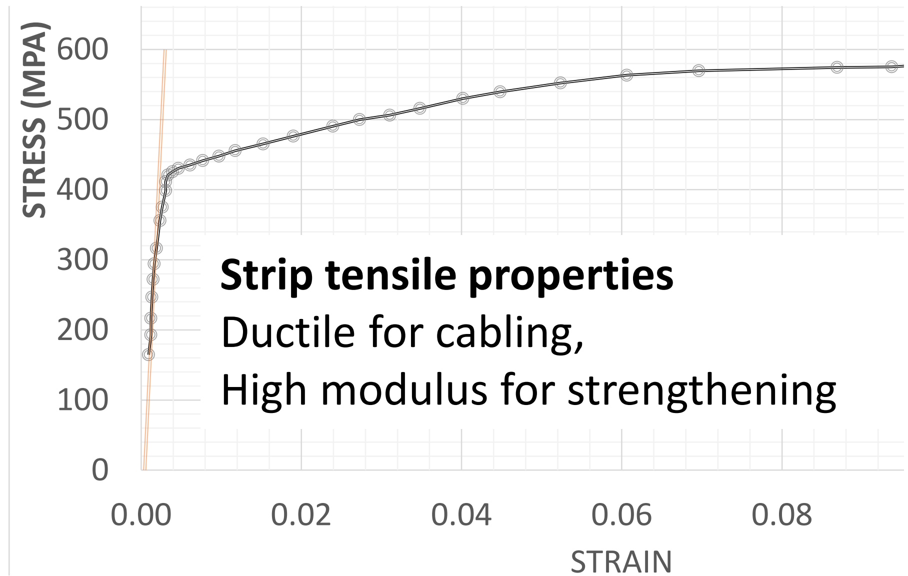
Long ReSRW on cabling reel

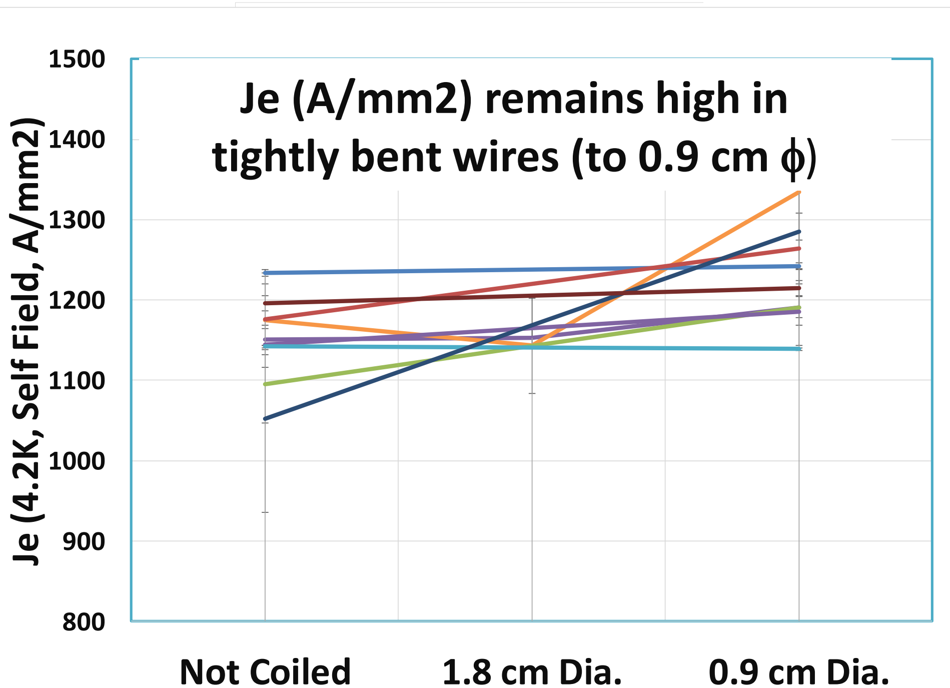
1st Process: Rectangular Wire → Cable → Coil



Wire Suitability for Cabling Before Reaction





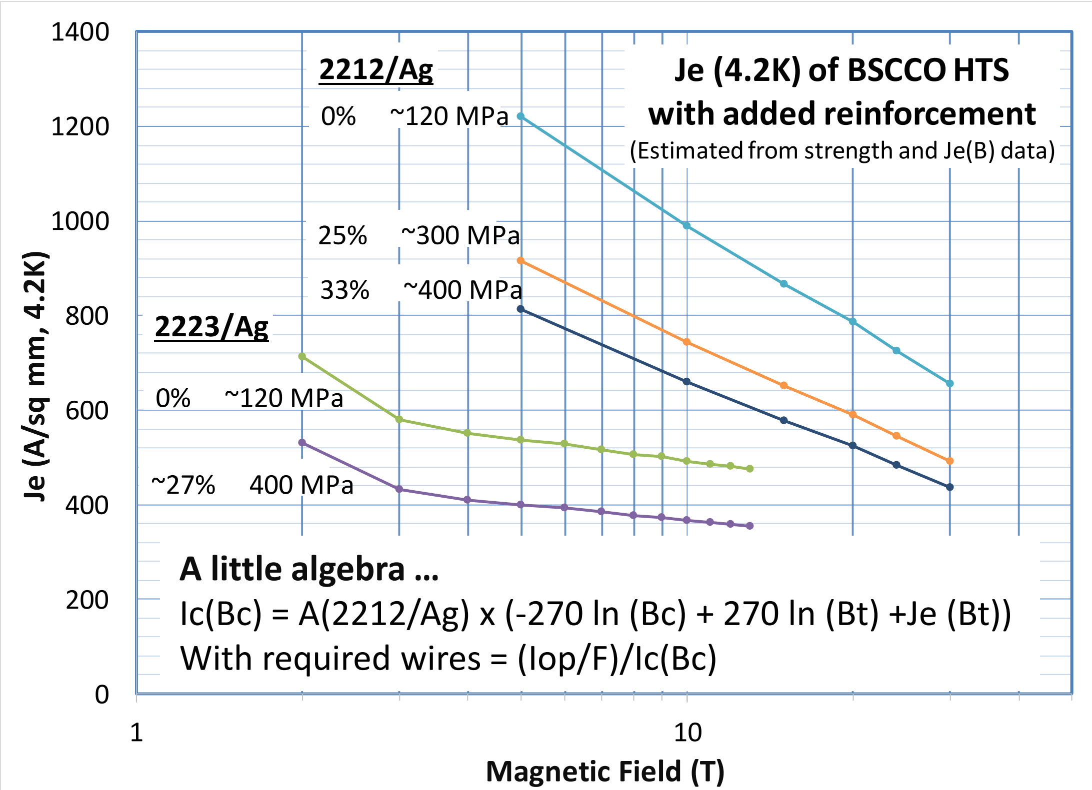


Tests indicate

- Sufficient ductility
- Adhesion for retained integrity
- Good Je even with 1 atm reaction
- No leakage or other defect

→ Great news for cabling!

Analysis of Je for wires needed, dimensions



Je Present Status (2212/Ag)

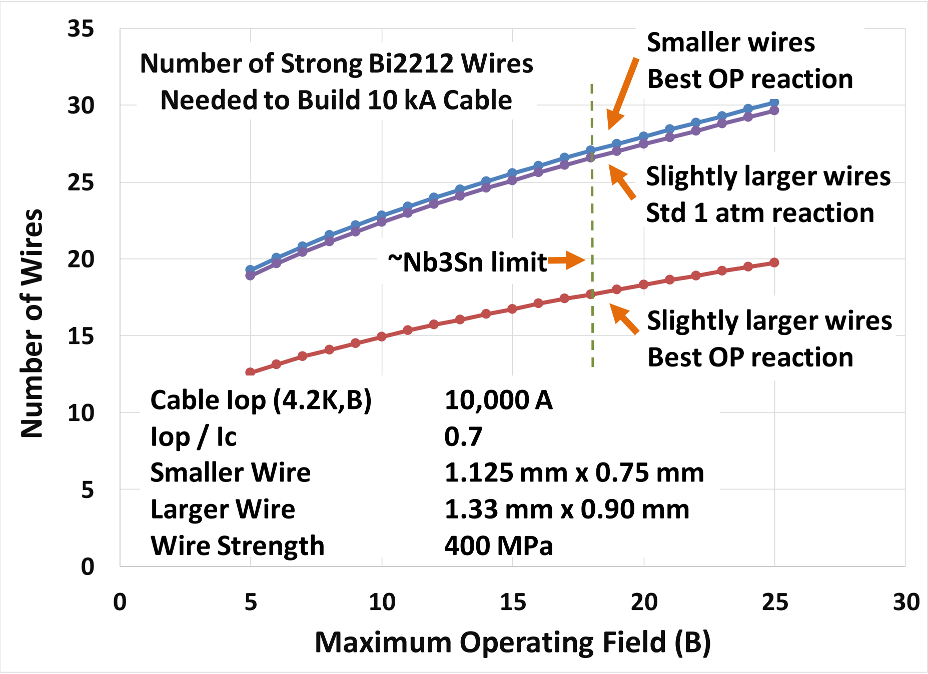
Wire State	Reaction	Je(4K, 5T) (A/mm2)
Drawn round	1 atm	~350
SMS roll densified	1 atm	700-800
Drawn or densified	50 atm	1200

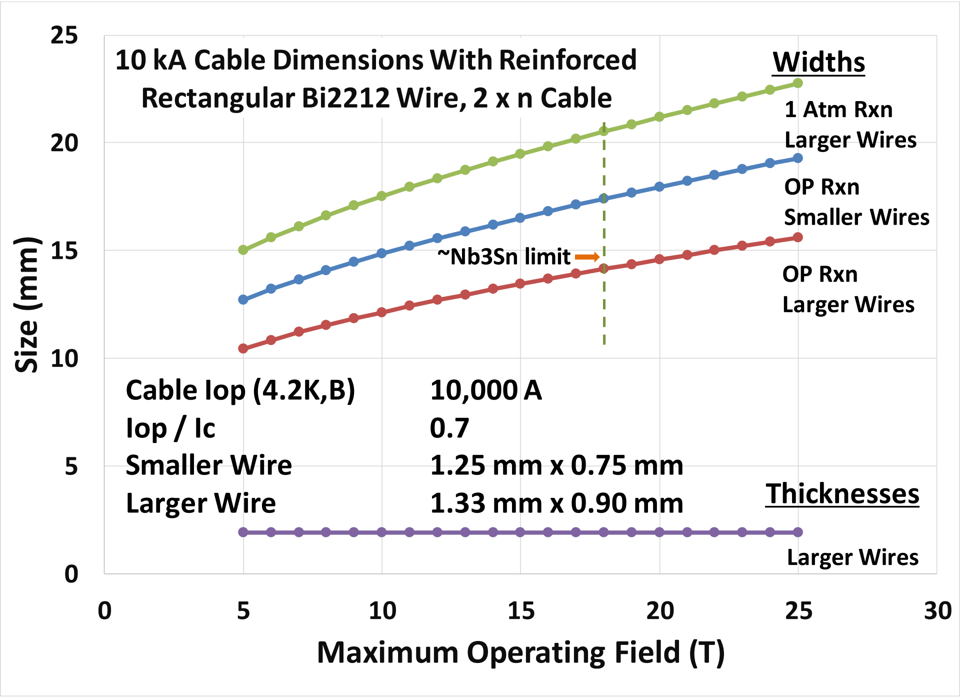
→ Je increased by mechanical densification
→ Je increased even more by gas pressure

Key points Je scaling well behaved with field and Jc
Analysis completed for 10 kA cable dimensions, # of wires

For ideal build like this →

Cable design analysis: baseline result

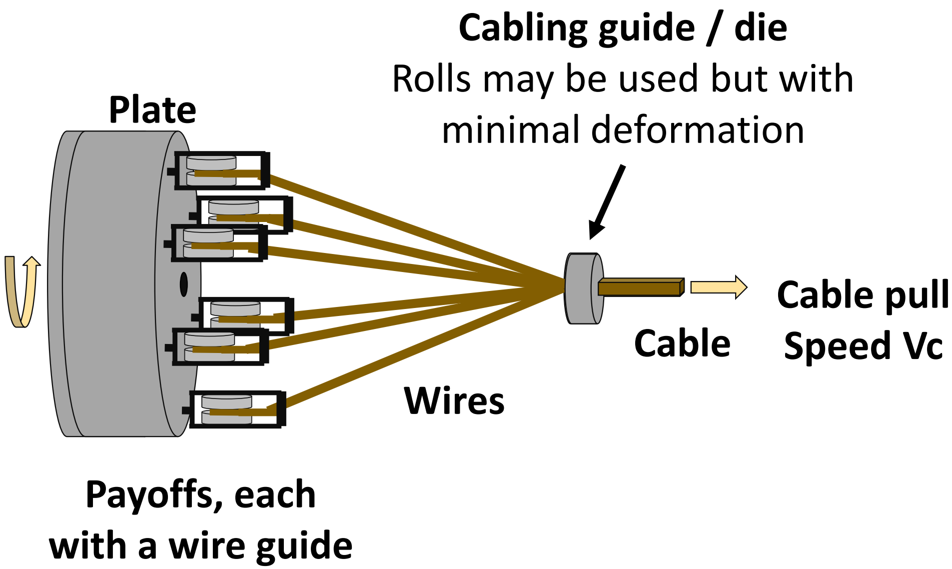




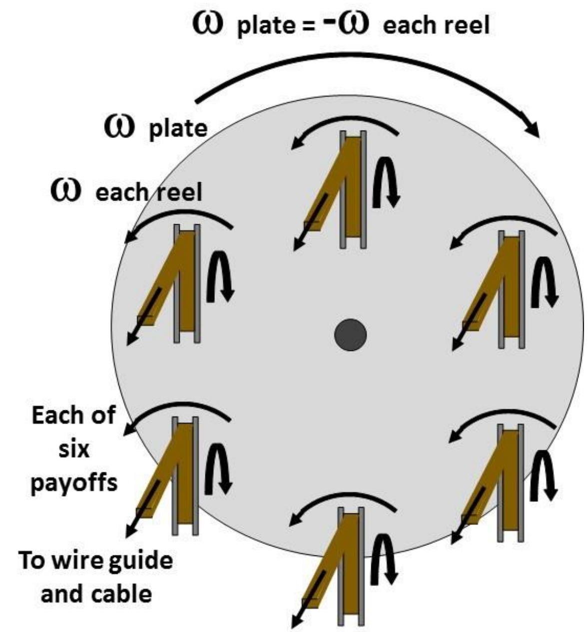
Result	Dimensions like Nb3Sn 10 kA cables	
For 25 T, 10 kA	1.9 mm x 25 mm for 1 atm reacted	30 wires
	1.9 mm x 16 mm for 50 atm reacted	20 wires

Cabling mode: without wire rotation, wrapping

Side view: illustration of planetary cabling



Front view: plate & payoff reels



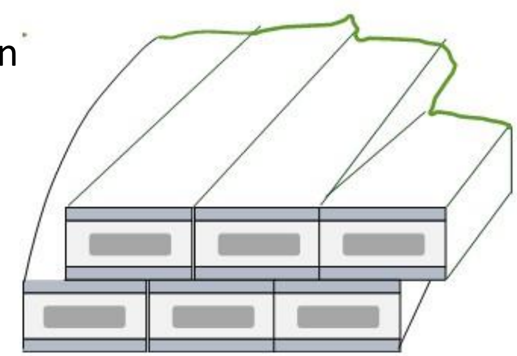
Pitch ~ Vc / ω

Plate rotates opposite to and at same rate as each reel

(used for some round wire Nb3Sn cables to minimize local strains)

- **Denser pack** with less deformation
- **No wire to wire sintering**
- **Large contact areas** with hard coating avoids local indent damage

Wire and cable surfaces ~ parallel



Cabling Set up and Procedure Development

Cabling line

- At the Plasma Science & Fusion Center (PSFC) of MIT

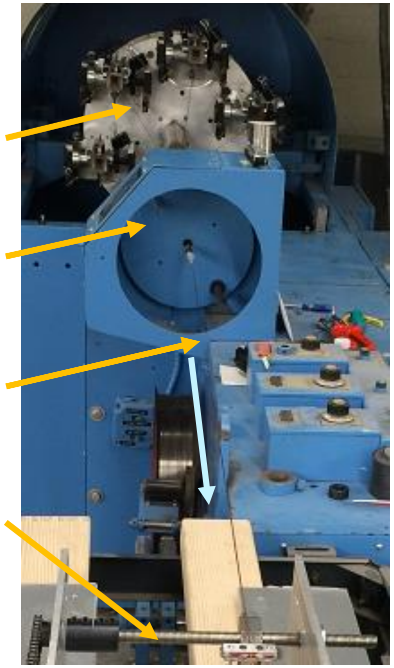
Set up

- Designed and applied our guides and tooling
- Added our cable pull mechanism and take up

Procedures and process

- Developed procedures with rectangular copper wire
- Produced, tested copper cables with different designs

Photo of cabling line



Cross section of copper analog cable

- Packing factor here is ~ 85% within the cable

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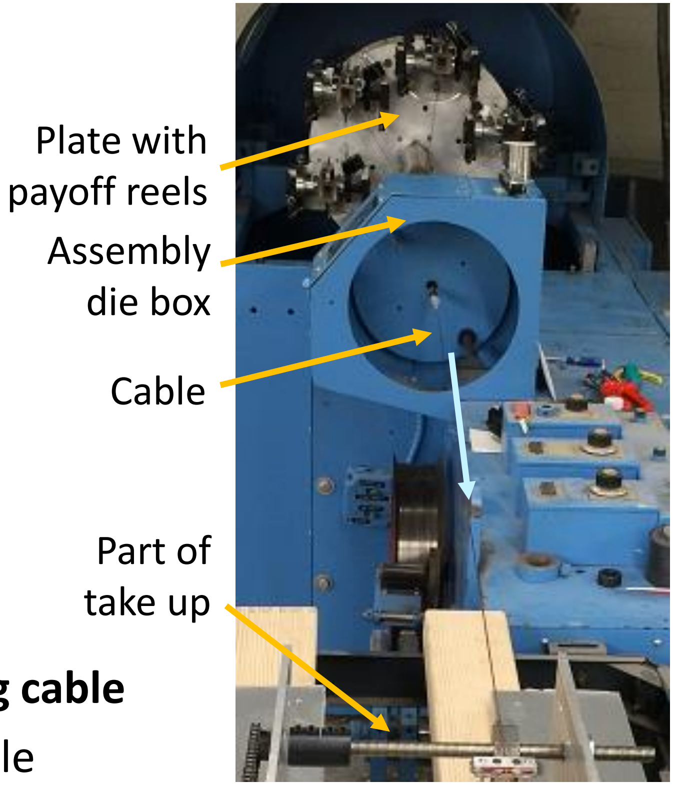
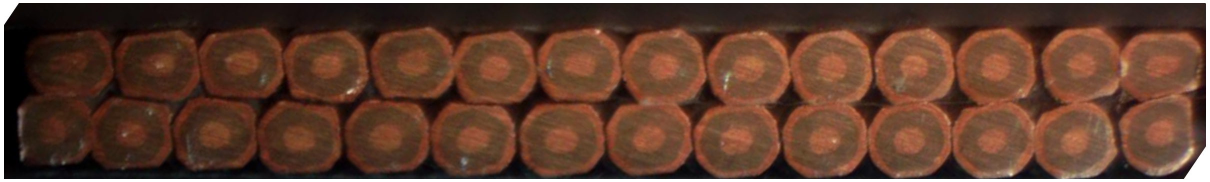


Cross section of copper analog cable

- Packing ~ 85% within this cable

Typical local deformation from consolidation rolling with round wire



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Bi2212 Wire Transposed Cabling Feasibility

Cable exiting assembly die

→ stable in < 2 pitch lengths

Copper

Copper

Copper

ReSRW - 2

ReSRW - 3

<u>ReSRW Wire Used</u>

Dimensions	1.02 mm x 0.78 mm
Strips	0.9 mm x 0.1 mm
Strip content	24 % (~300 MPa)

<u>Cabling</u>	**3 cables so far**
# wires	6
Pitch setting	4.5 cm
Wire tensions	14 N

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Result: Uniform Bi2212 Cables, No Damage

Cable 2
Cable 3

3 mm

Top View

Side View

<u>Cable Inspection</u>	
Pitch	~ 4.7 cm measured, and uniform
Layup	Wires retained ~parallel orientation to cable surface planes
Condition	No sign of damage, cables very stiff
Width	3.1 mm
Thickness	2.3 mm
Packing fraction	~67%
<u>Cable bend tests</u>	**To 4.5 cm**
Bend Limit	At ~ 5 cm

Approach qualified and works

→ Wire handles process

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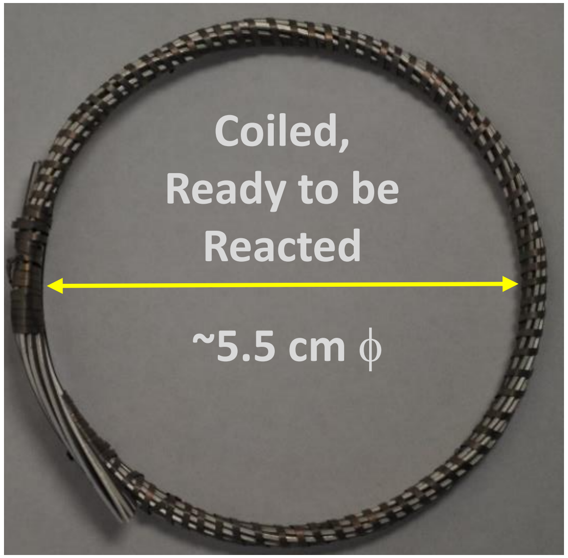
Fabricated first mini cabled coils w/o damage



<u>**Coil production and tests**</u>	
Coiling	Wound 3 mini coils
Wind method	By hand, ends free, some rebound
Diameters	5.5 cm
Control samples	Wire pieces cut from cable ends
Cable condition	Wrapped with strip for reaction
Reaction	At standard 1 atm
Inspection	No sign of damage, reacted coils very stiff

Coil winding & reaction responses good

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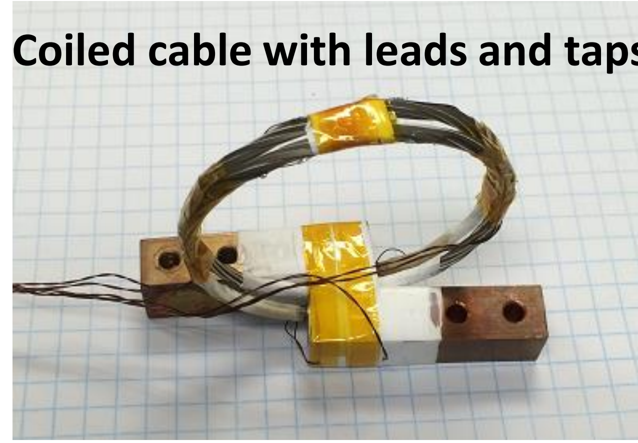
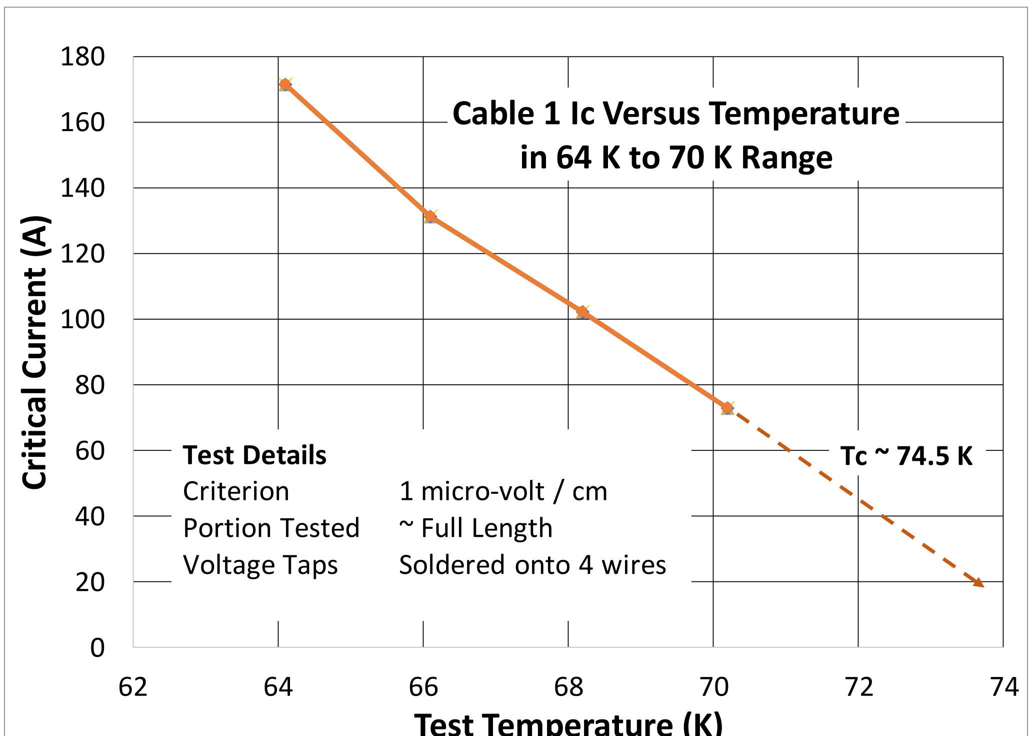
Ic tests so far: for wires (4K), coils (64K-70K)

Wire Ic's (4K, self field)	End pieces tested
average Ic, cable 2	940 A
Ic std dev, cable 2	2 %
Projected cable Ic(4K, 5T)	2 kA by scaling wire Ic's
Tested cable Ic(64K-70K)	170 A at 64K ~full length
Cable Ic tests at 4K in-field	Pending


Coiled cable with leads and taps



Ic data so far promising

But, additional data required

Looking to complete in-field 4.2K Ic tests

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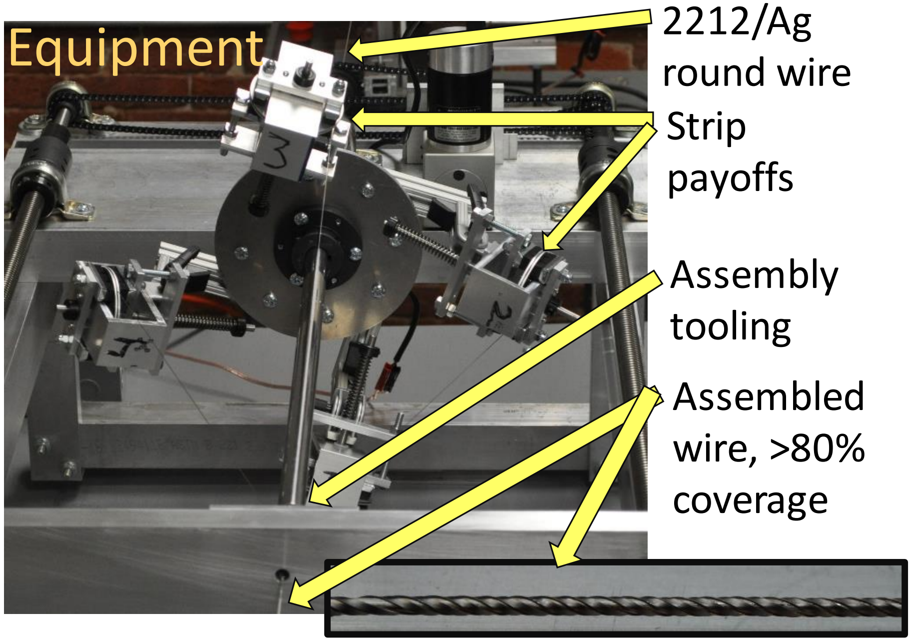
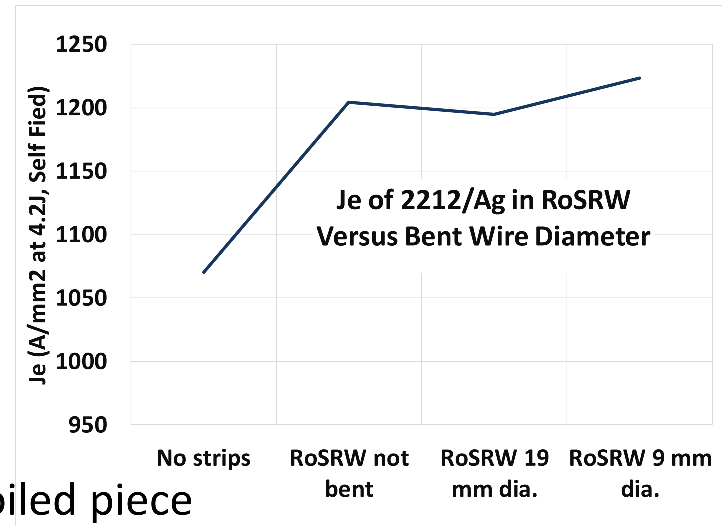
Now About RoSRW Cable Development

- ❑ Built and qualified equipment
- ❑ Developing design, process
- ❑ Testing Ic/Je, properties for cabling



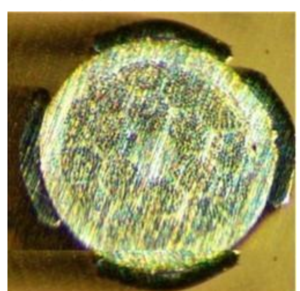
Ic testing

9 mm ϕ then reacted



Reacted wire

Cross-section



Coiled piece

Wire properties seem suitable for cabling

Next Steps

- Complete Ic (4K) testing of first cables
- Produce and test cables with more wires, longer lengths
- Build strong round wire cables and test – first one by Dec. 2017
- Achieve 10 kA (~15 T) design like CERN cable – first one Q1 2018
- Complete dev't & testing: LBNL, CERN, PSFC, NHMFL, others
- Integrate cable development with coil program(s)

Messages…

We demonstrated feasibility of making transposed cables with strong Bi2212 rectangular wire

Adapted and qualified cabling equipment and procedures

6-wire pay off (for now) | Planetary layup | Capable of long lengths

Produced first cables with 1 mm wide wires in pre-reacted condition

Okay packing (~67%) | 4.7 cm pitch | Wire integrity retained

Tested bending, then wound & reacted 5.5 cm diameter mini coils

Coil-able to 5 cm dia. | Cable integrity retained | No defects observed

Ic tests underway

Cabled wire Ic's(4K) ~940 A/mm2 | Projected cable Ic(4.2K, 15T) ~ 1.5 kA

Preparing strong round & rectangular wire cables for dev't & testing

→ Very promising first results

For achieving strong, LTS-like 10 kA transposed HTS cable

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THANK YOU
Alexander Otto (PhD)
Linda Saraco
Solid Material Solutions, LLC