

*Oral Presentation at MT25 Thu-Mo-Or31*

# Compact high field coils made with strong, rectangular Bi2212 wire

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# Acknowledgements & Collaborators

- **Applied Superconductivity Center (ASC)  
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- **Frances Bitter Magnet Laboratory (FBML at MIT)**

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# Objectives



- Strong rectangular Bi2212 wire (ReSRW) in commercial coils
  - Suitable for wind and react, compact coil production and utilization
- **Know how enabling magnet manufactures to fabricate coils with our wires – that are developed for specific kinds of compact coils**

## For Wind and React:

### Wire

Similar to LTS – Nb3Sn	Higher Je(B,T)	Shape for correct Ic / Iop, winding	Ductile for winding Strong reacted	High quality, no defects, uniform	Long, scalable, as needed
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### Compact Coil

Exceed LTS, copper limits	Small bore	Uniform winding placement	Good layer step-ups Effective insulation	Low lead $\Omega$ / SC joints as needed	No defects, Added features
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**Affordable**

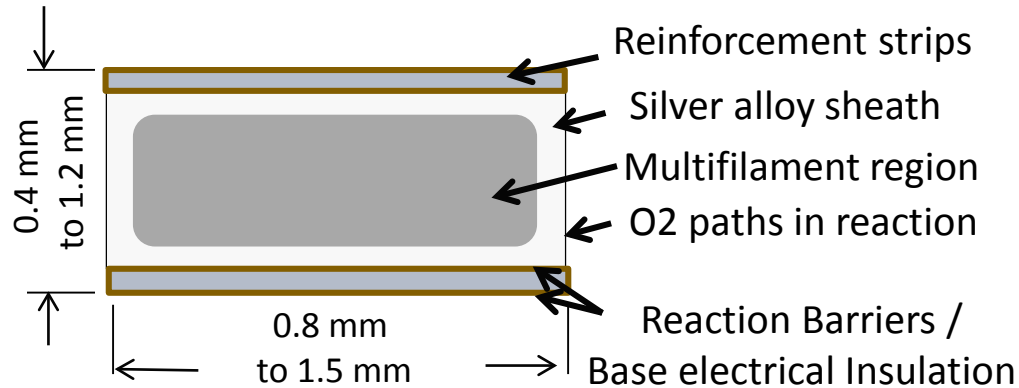
**Scalable**

**Reliable**

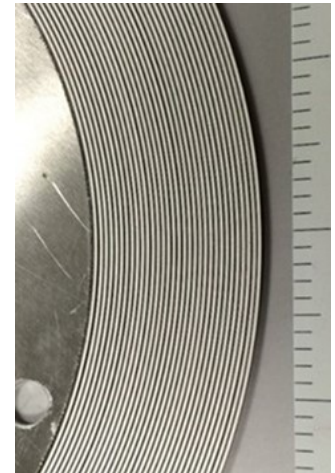
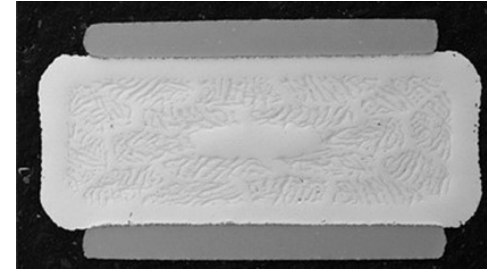


# Strong Bi2212 Rectangular Wire Design

## Surface bonded strips on opposite sides



## Example: strips narrower than 2212/Ag

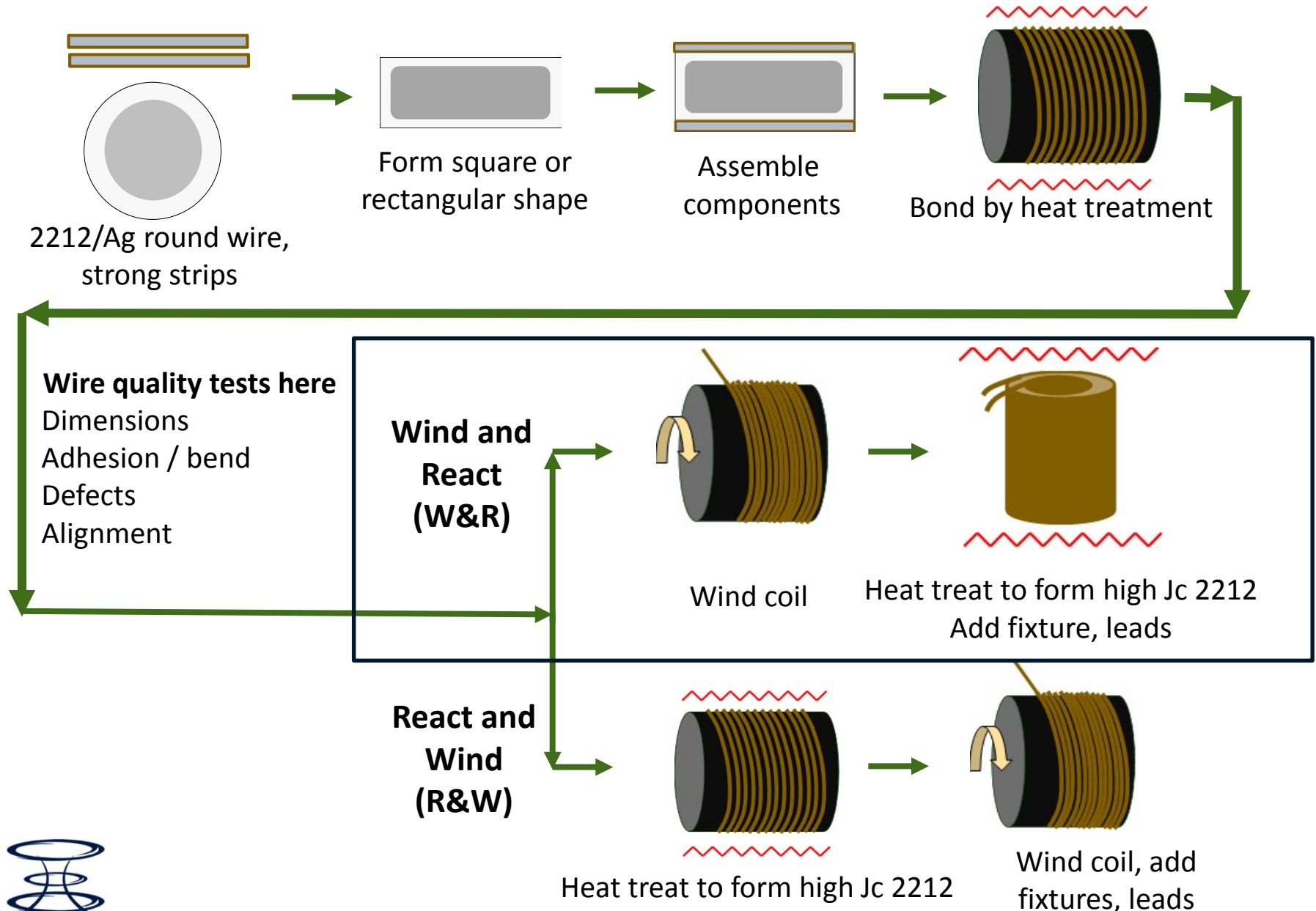


Wire on shipping reel

<b>Design</b>	strips bonded to some surfaces
<b>Rectangular</b>	square to ~ 2:1
<b>Standard widths</b>	1 mm, 1.4 mm and 1.6 mm
<b>Strip dimensions</b>	as needed, 10% - 50% by area
<b>Stress tolerance</b>	250 to ~600 Mpa
<b>Production</b>	Scaled to supply coil development



# Process: Wire $\rightarrow$ Coil



# ReSRW React & Wind Versus Wind & React

Or, Why Wind & React is the Better Choice for Many Coil Designs

## In R&W:

Part of strain budget always used up making wire into component

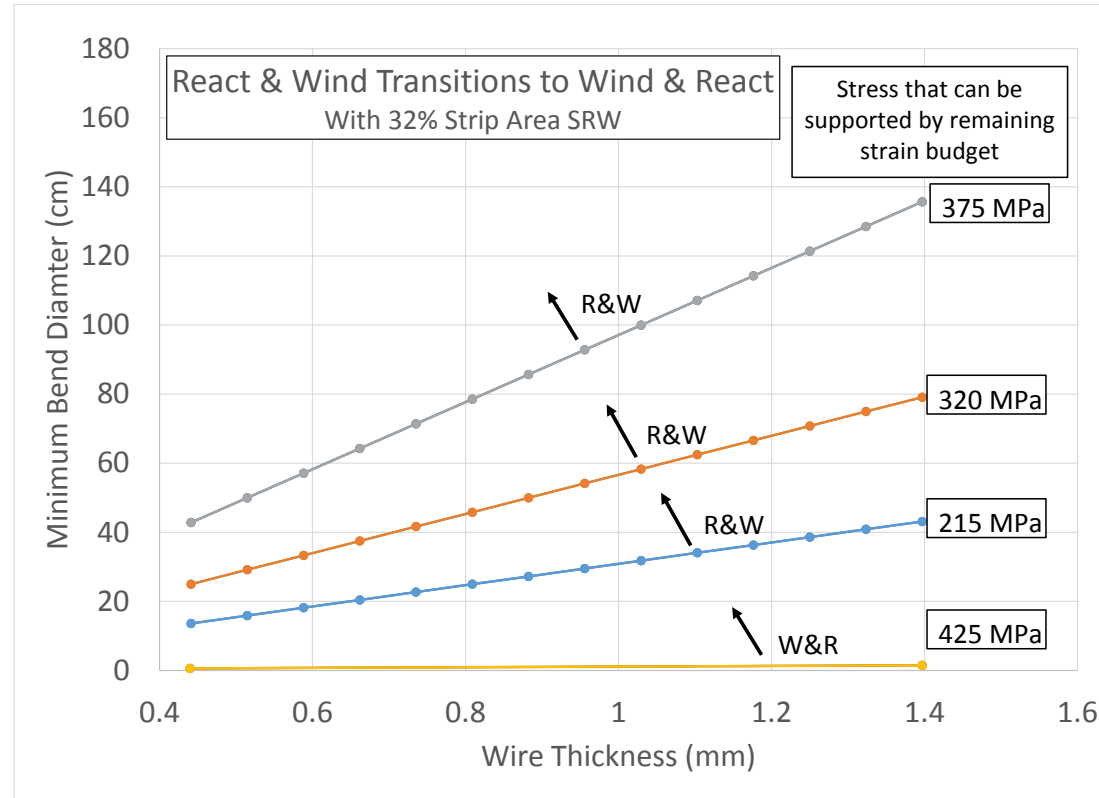
Remaining strain to critical strain is available to support hoop stress

Thinner wire uses up less of its strain budget when bent to a diameter

## In W&R:

The high Jc Bi2212 is formed at the net component shape

This leaves entire strain budget available to support tensile stress



Modeling based on measured tensile stress strain and bend properties of both as-bonded and reacted 2212 SRW

Larger diameter coils could be made by R&W, where bore diameter, field and wire thickness play key roles in determining the trade offs between W&R and R&W

# W&R Know-How Development Plan

- Define initial target, vital specifications (input from coil builders)
- Design wire and learn to make / test
- Set up / adapt coil fabrication capability
- Make and test selected prototype wire designs
- Make and test selected coil type(s)
- Feedback learning to modify wire, coil fabrication techniques
- Compile learning into “how to” technology package

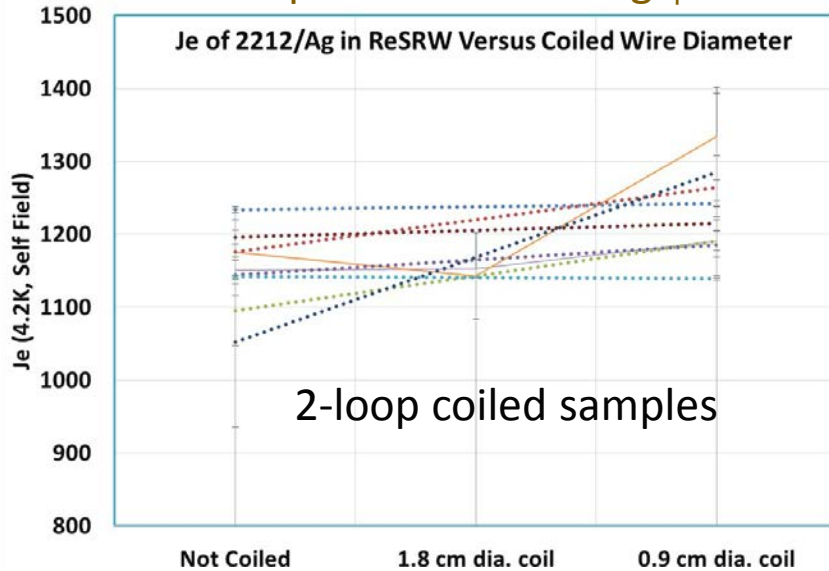
# **Strong Rectangular Wire Developments for Coiling**



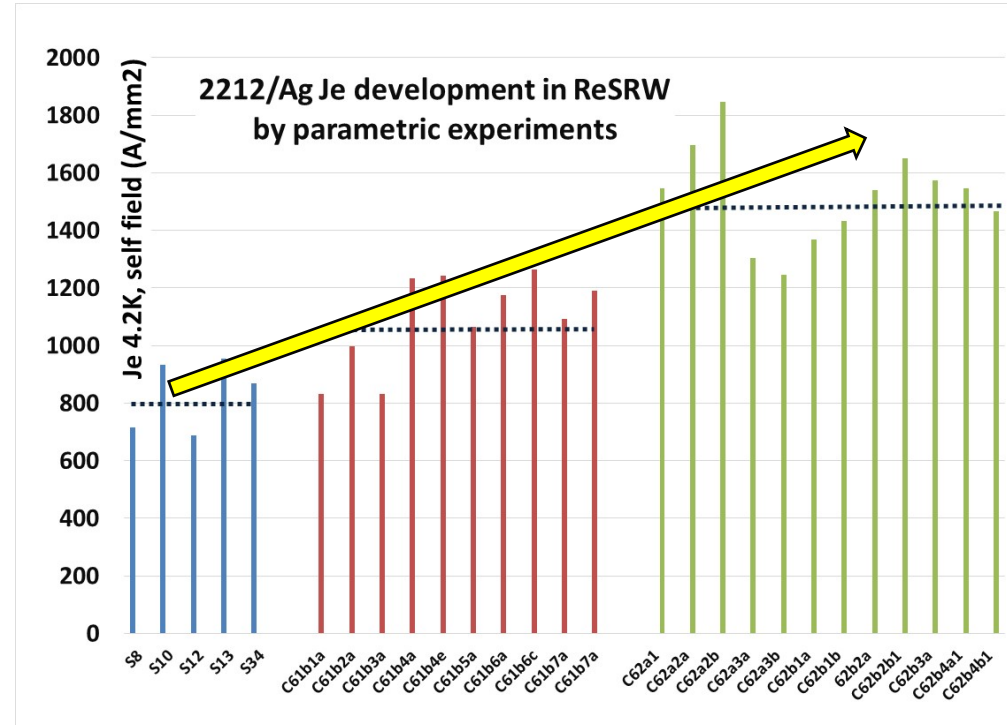


# Je / Ic Related Development

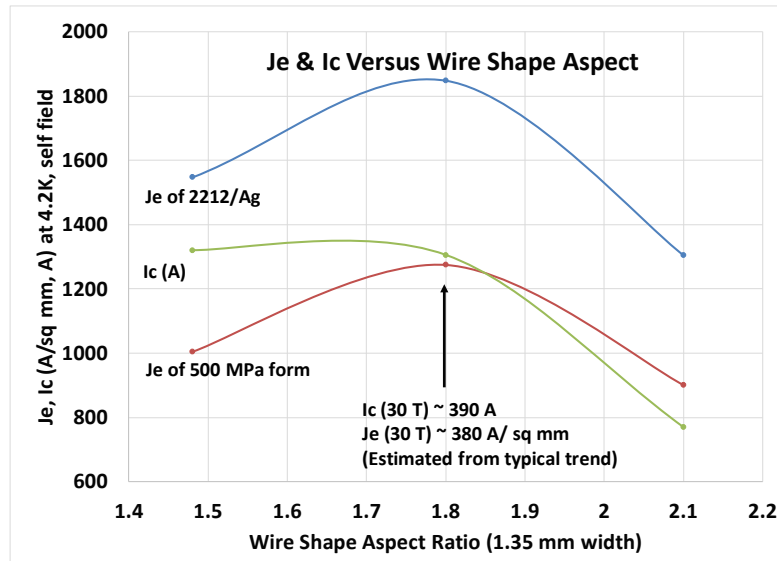
Effect of pre-reacted coiling  $\phi$  on Je



Effect of parametric variations on Je



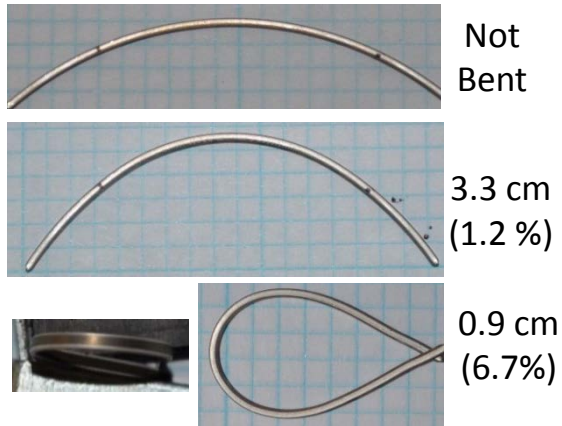
Effect of shape on Je with std reaction



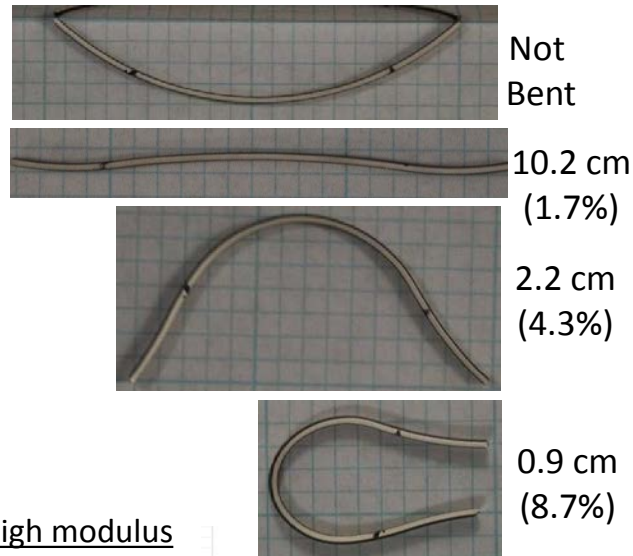
- ❑ Optimum shape is at ~1.75
- ❑ No Je decrease even bent to 0.9 cm
- ❑ Process for ~2-fold higher Je found by parametric studies at 1 atm

# Bonded ReSRW: Superb to <1 cm diameter bend

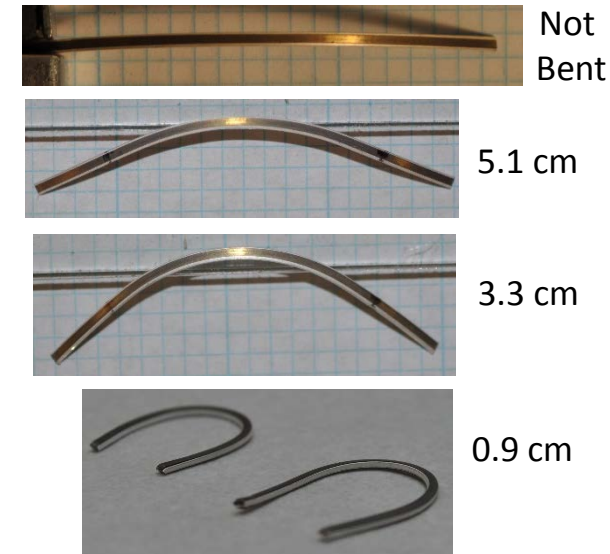
## Forward bend



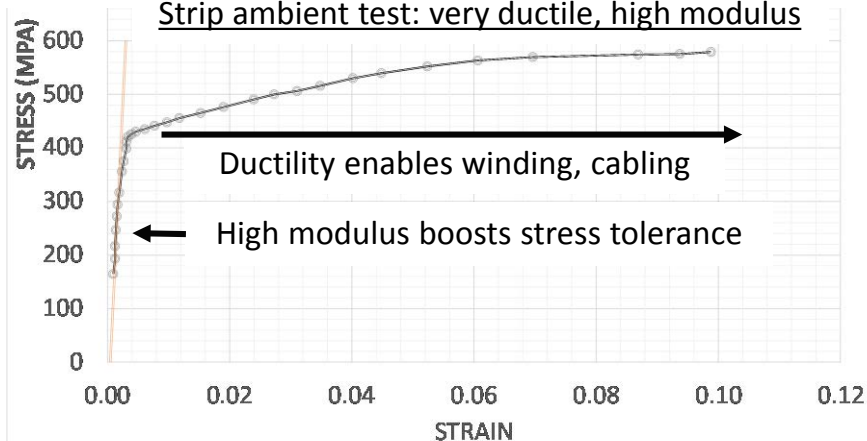
## Reverse bend



## Edge bend



Strip ambient test: very ductile, high modulus



## Starting State

- Mandrel bonded
- 7.3 cm wire set



→ Bonded wire takes tight forward, reverse & edge bends, to > 8% strain

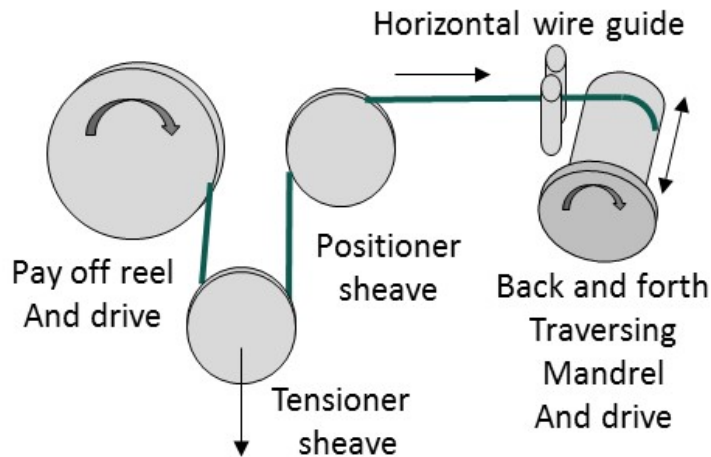
→ **Great news for handling, cabling, wind-and-react coiling**

# **Wind and React Coil Fabrication Know How Development**

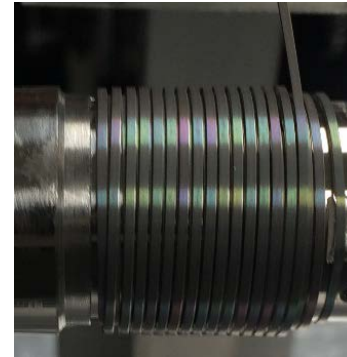


# Equipment and Development Approach

## Schematic of winding equipment



## Winding



0.9 x 0.8 mm wire

## Ready for reaction



## Established Equipment and Capability

- Precision reversing level wind mechanism and wire guides
- Precision controlled tension payoff
- Wire end fixturing & ramp based layer step up
- Mandrel design – currently “disposable” 304 SS

## Test Bed Coil Approach

- 12.5, 22.0 & 31.8 mm inner  $\phi$  test coils
- 2- and 4- layers mainline,  
more layers in studies
- No added insulation at this stage
- Evaluating thin options to 1000 V BDV

## Development Approach

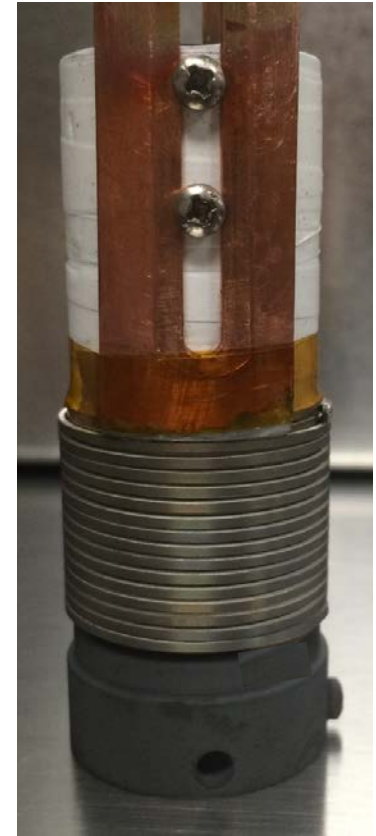
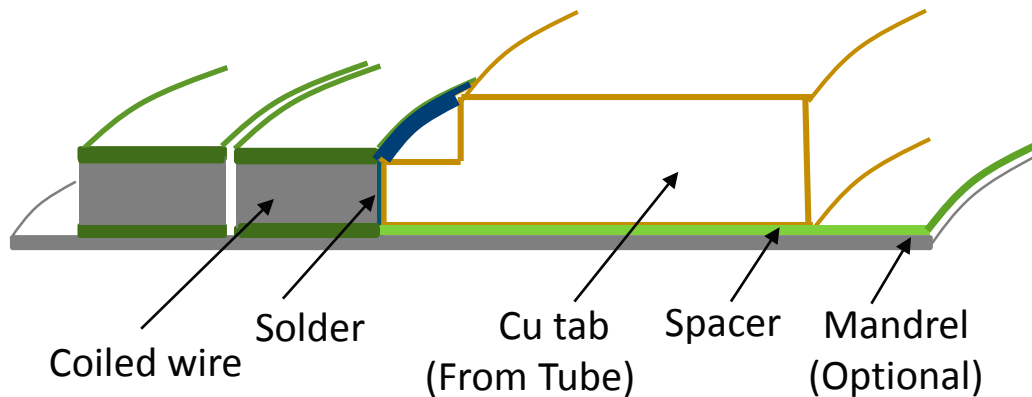
Develop initial coiling, W&R procedures  
Produced & tested 2 – and 4-layer coils  
Came up with modifications  
Tested by winding more 2 and 4 layer coils

# Terminations & Preparing for Energizing / Ic Test

**Q: How can we attach current leads?** low resistance, practical and dimensionally controlled connection to ReSRW since top and bottom have resistive metal attached?

**A: Edge tab current lead / peeled back strip methods:** allows practical low resistance connection to curved Ag edge

**Cu edge current lead tab  
and its connection  
to coiled wire**



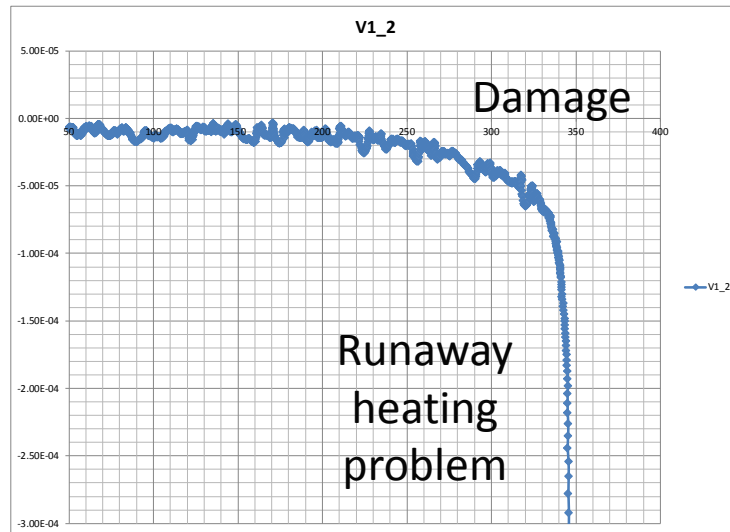
5 voltage leads also attached after current leads attached





# Illustration of problems addressed

One of several in first batch of 4-layer coils made, tested



Coil as Ic tested



V-leads

Cu current-leads  
Soldered to wires

Connected to much  
larger leads into cryostat

Coil disassembled



Layer 1  
No defects

Layer 2  
Few defects

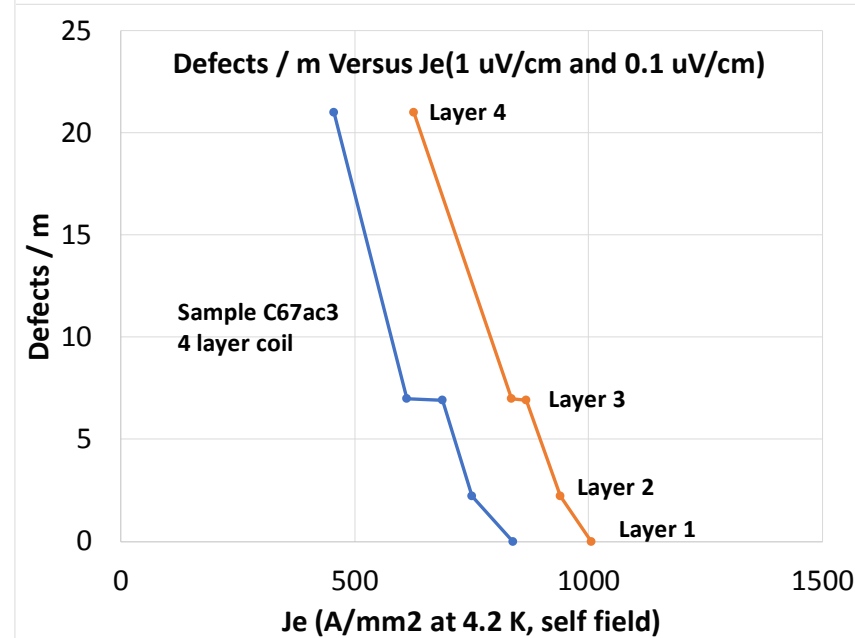
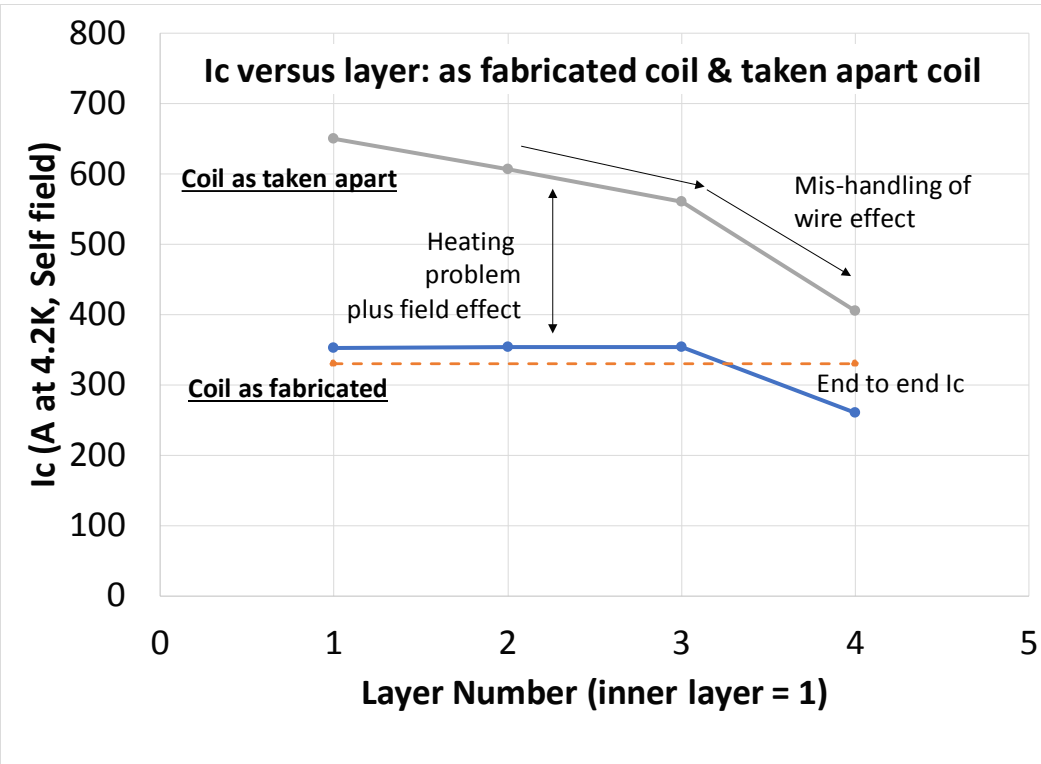
Layer 3  
More defects

**Layer 4: Most defects**

- ❑ Tested layer Ic in situ as fabricated
- ❑ Re-tested Ic of each separated layer, with HTS current leads



# Root Cause and Advancements



## Coil heating

Developed HTS current lead approach

## Wire Handling

Developed better guides – no contact with < 12 cm diameter surfaces

Reduced number of handling and respooling steps

Improved layer transition ramp approach

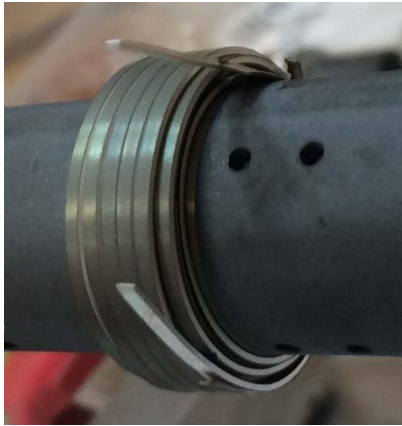
Optimized tensions

Improved strip bonding and adhesion uniformity



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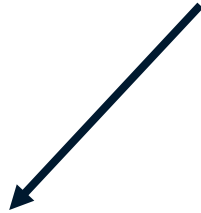
# Coil Terminations With HTS Leads



Test Coil  
Reacted



Bi2212/Ag ends  
prepped for  
soldered leads



Cu tab soldered to Bi2212/Ag,  
HTS (2G) lead soldered to Cu



Outer tabs  
soldered to heavy  
duty Cu leads  
leading to power  
supply



Coil with Cu-  
HTS current  
leads attached

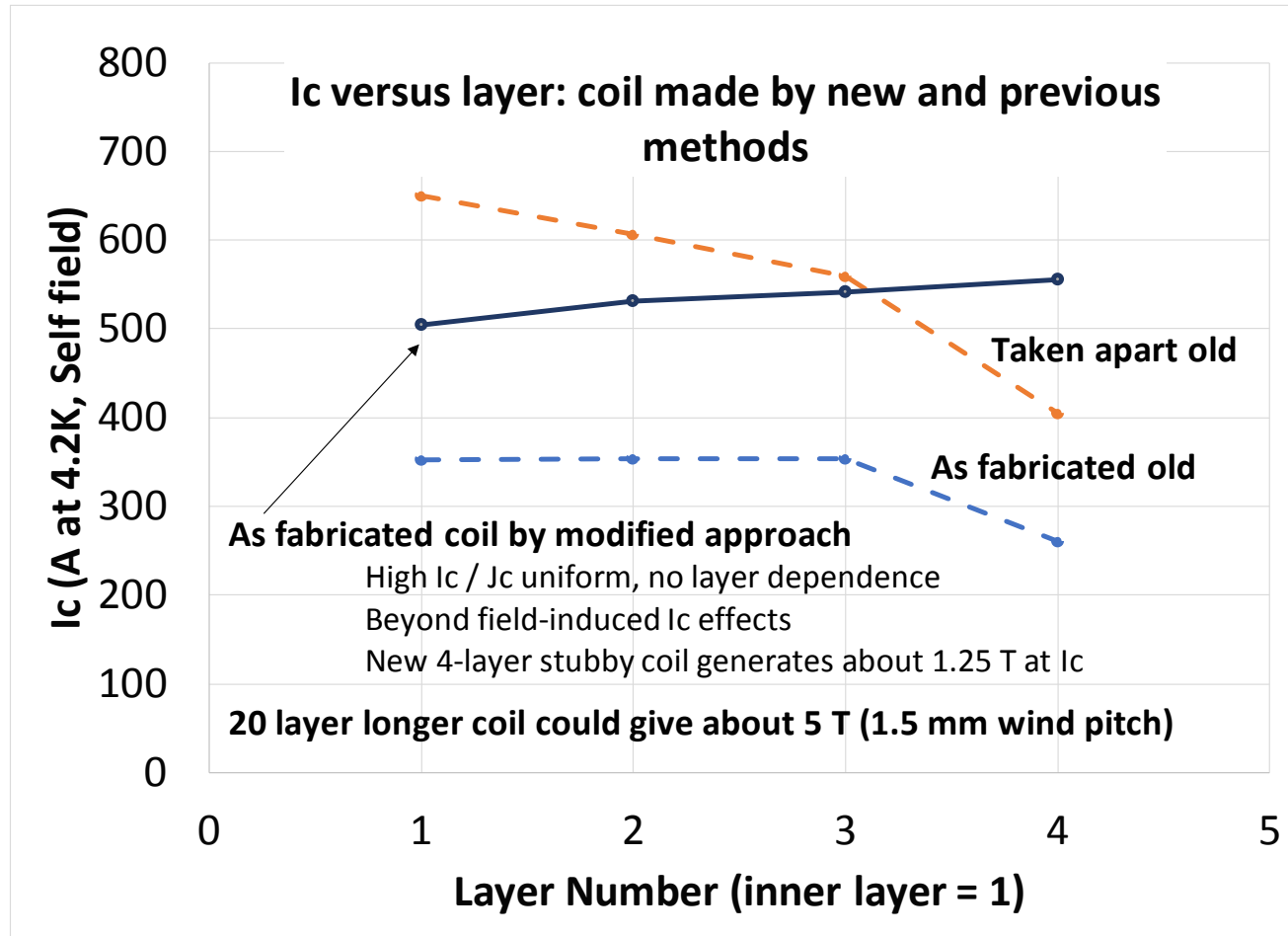


Voltage taps  
attached next





# Benefits of Modifications



## Status

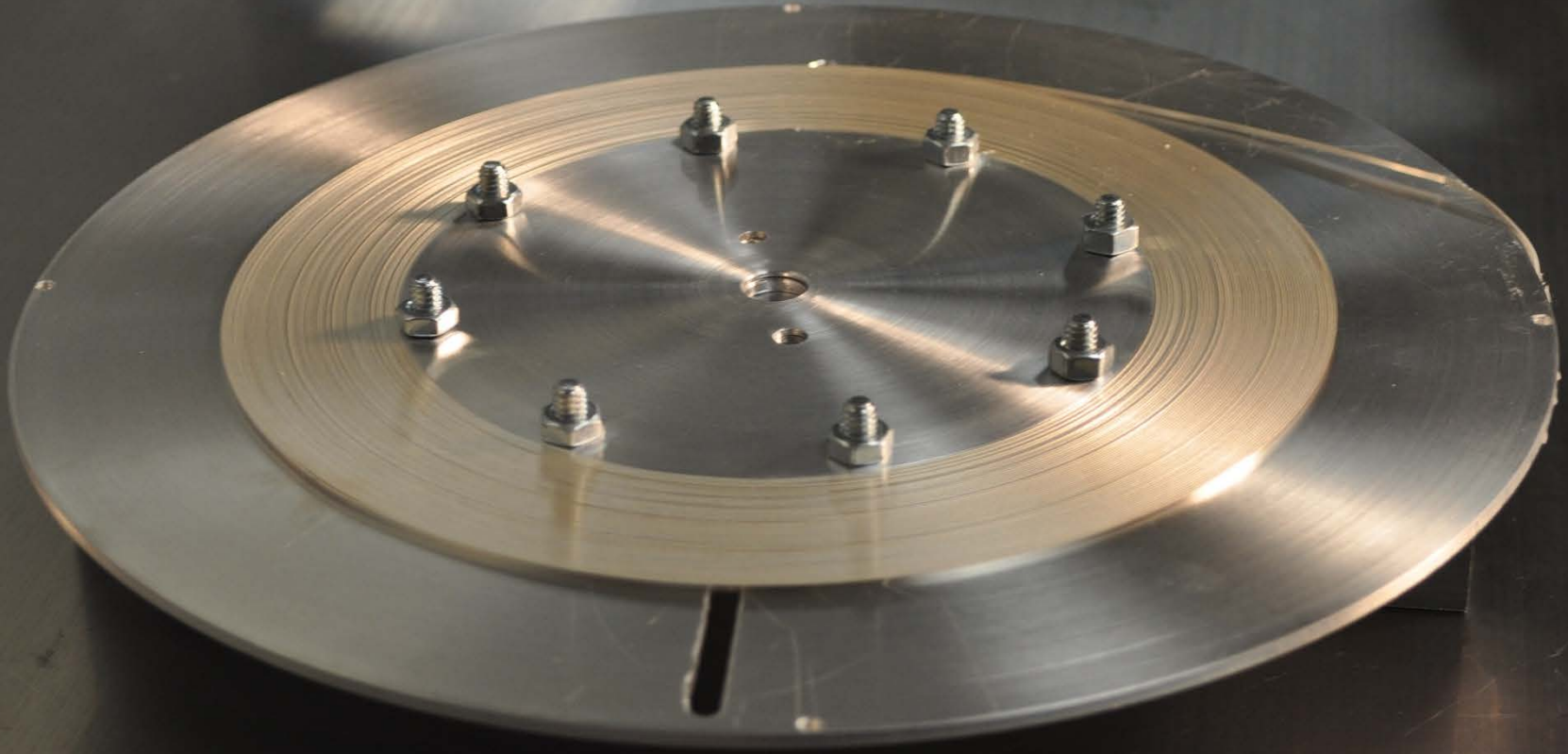
- ❑ Can now build coils without  $I_c$  variation except for field dependence
- ❑ Work with collaborators is vital for additional development
- ❑ OP processing and developments by FSU have demonstrated that similar 2212/Ag Je's are achieved with RESRW as with bare wire (~1.2 kA/mm<sup>2</sup> 4K, 5T)

# Summary

- ☐ **Key fabrication know-how for W&R coils with ReSRW is developed**
  - High density layer winding technique with ReSRW works
  - Wire bending to >4% winding strain works: ductility, bonding
  - Much better current lead connection method developed
  - Upgrades developed, validated to avoid Ic reductions
  - Ready for next stage with strong rectangular Bi2212 wire

to develop larger scale and full scale compact coils
- ☐ **Prepared to provide ReSRW and know how for coil / application development**
- ☐ **Recently addressed 2212/Ag base wire supply concerns are being successfully addressed**

# THANK YOU



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**Linda Saraco**

**Solid Material Solutions, LLC**

