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Experimental results and Finite Element Analysis of single REBCO tape and TSTC conductor for high field magnets

L. Chiesa, N. Allen, F. Pierro, Z. Zhao and M. Takayasu

Tufts University | School of Engineering

MIT | PSFC Plasma Science and Fusion Center

CCA2016
Coated Conductors for Applications 2016
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Luisa.Chiesa@tufts.edu

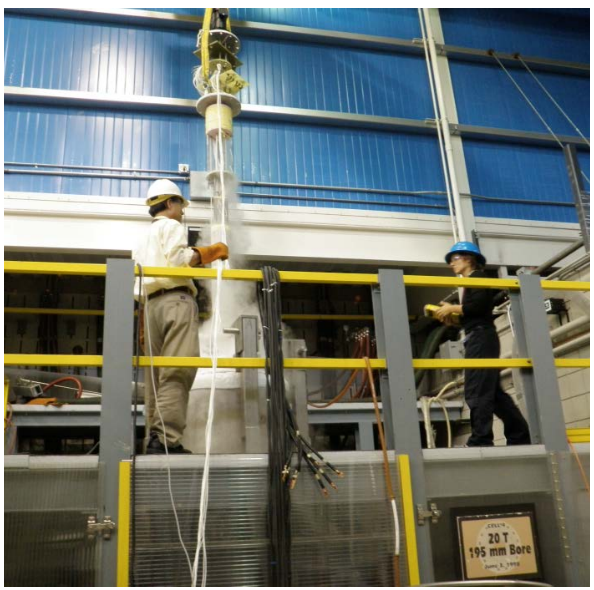
Outline

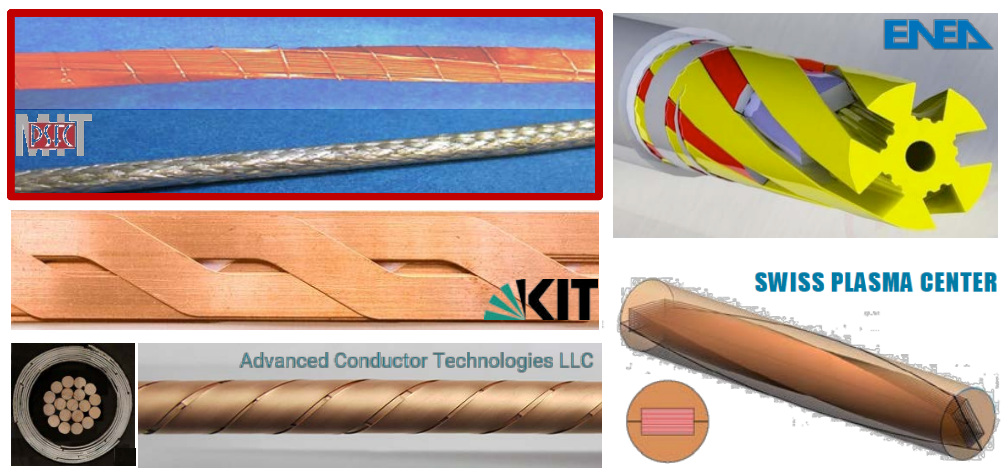
- Research activities and their importance
- Experiments on single tapes and TSTC conductors
- Modeling work on tapes and cables
  - Torsion, Bending and Lorentz load
- Next high field TSTC experiment
- TSTC conductor scale-up
- Joints and AC losses
- Future directions and conclusions

Introduction

Complementary research activities of Tufts and MIT-PSFC:

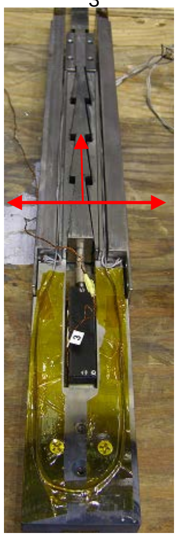
- Characterization of the electrical and mechanical behaviors of HTS materials under loads relevant to magnets using *custom-made experimental devices* and *finite element analysis* (FEA) techniques in support of design and fabrication of the next generation high-field HTS magnets.
- *Development, fabrication and high-field, high-current experiments of the Twisted Stacked-Tape Cable* (TSTC).



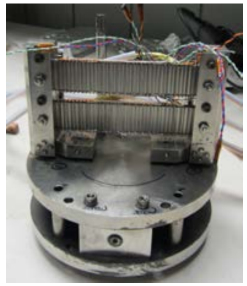


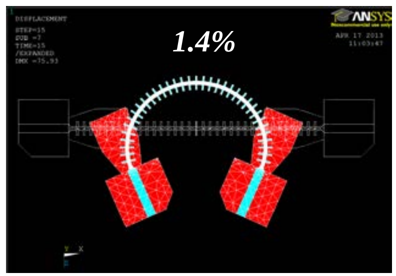
What do we do?

Transverse load Nb_3Sn

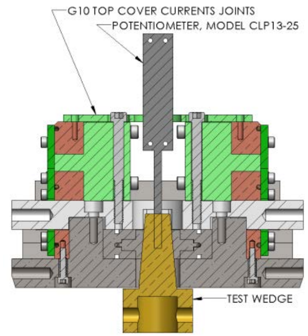


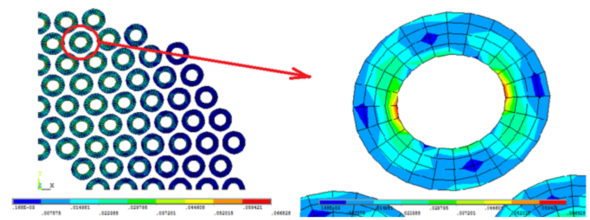
Pure bending Nb_3Sn



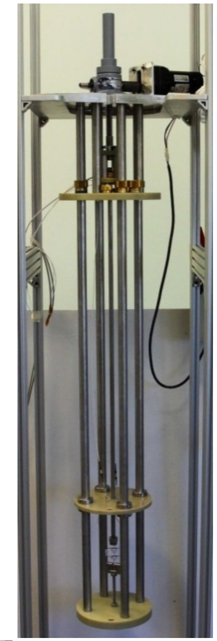


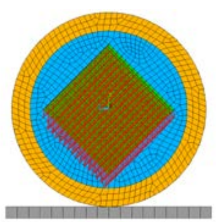
Transverse load Nb_3Sn

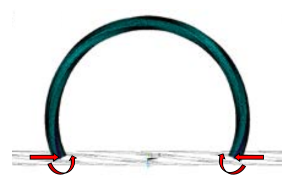


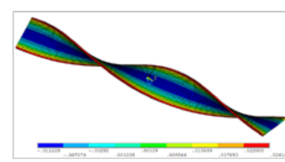


Electromechanical characterization HTS









HTS Conductor Electro-Magnetic load

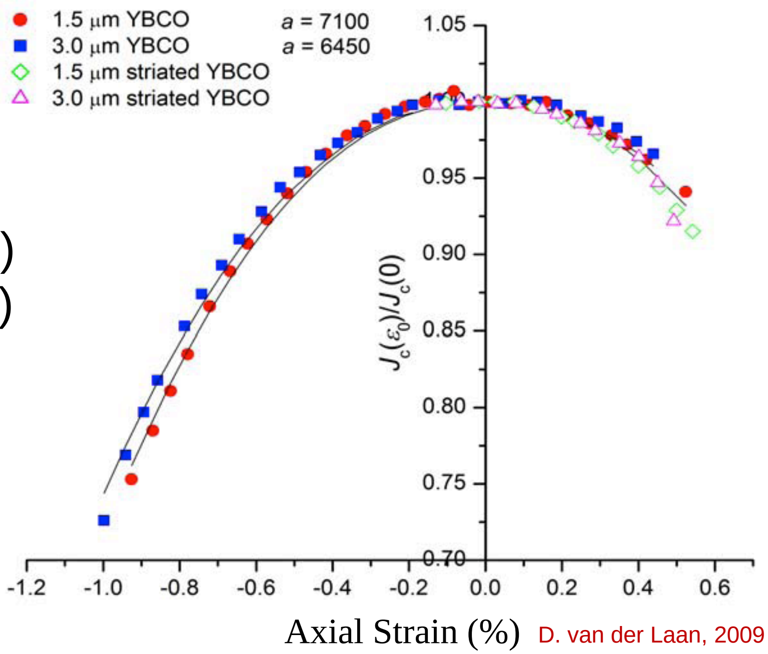
HTS Conductor bending

Torsion-Tension HTS

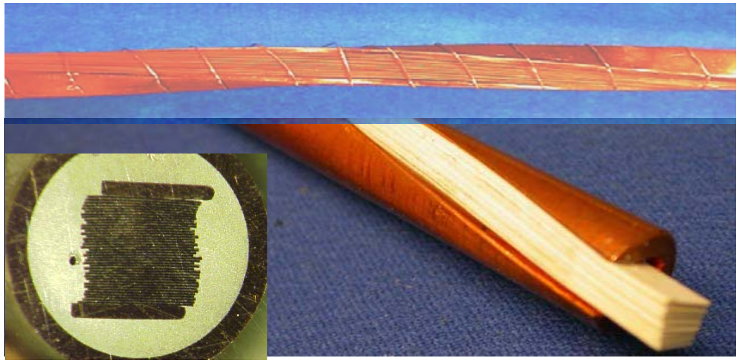
Our approach

The *critical current* of a superconductor is a function of *load* (stress & strain). For high field magnet applications the conductor will experience a variety of different loads during *cable and magnet fabrication, thermal cool down, and magnet operation:*

- *Axial* (different rates of thermal contraction)
- *Torsion* (twisting during cable fabrication)
- *Bending* (winding of magnet coils)
- *Transverse compression* (electromagnetic forces)
- *Combined tension-torsion* (magnetic hoop stress)



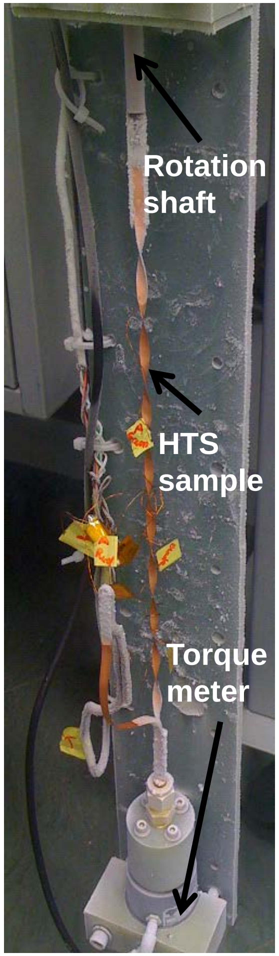
D. van der Laan, 2009



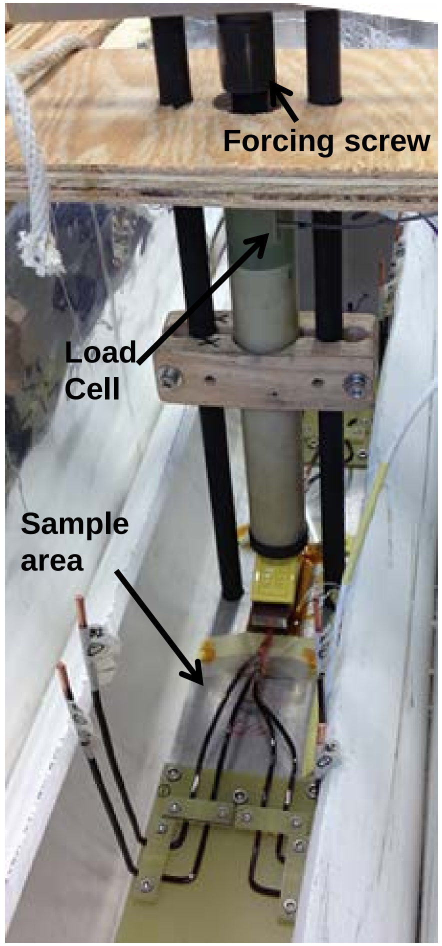
We are particularly interested in ***HTS TSTC conductor*** to be used in the next generation high-field magnets.
Our work allowed us to identify key features of TSTC for twisting, bending and transverse load.

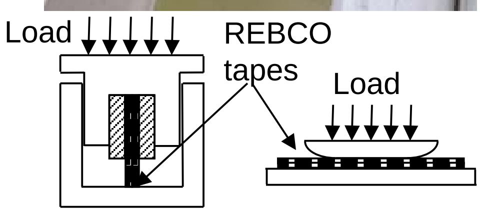
Experiments on REBCO tapes

I. Pure Torsion

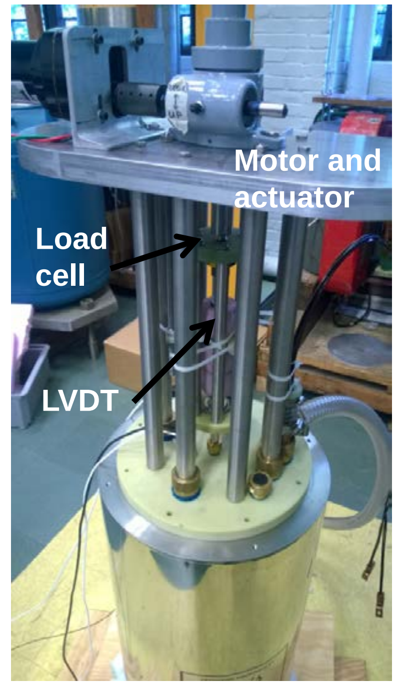


II. Mechanical Transverse Compression

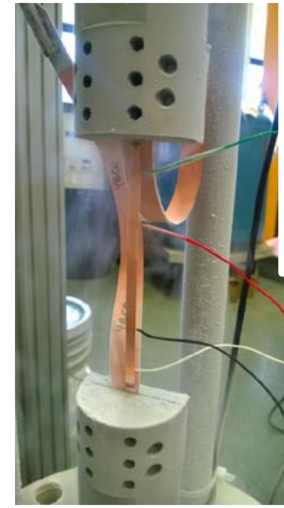


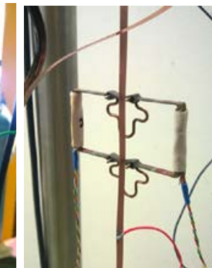


III. Tension

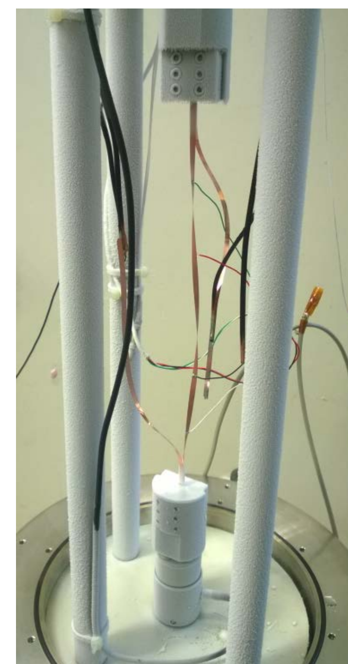


a. Tension



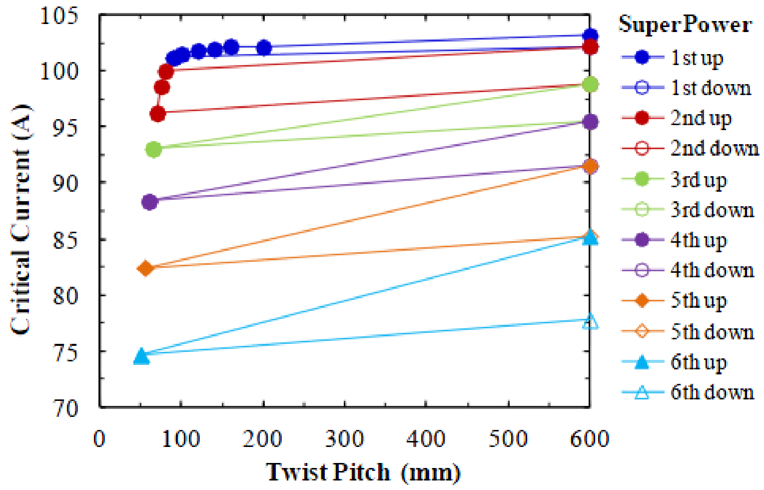


b. Tension-Torsion

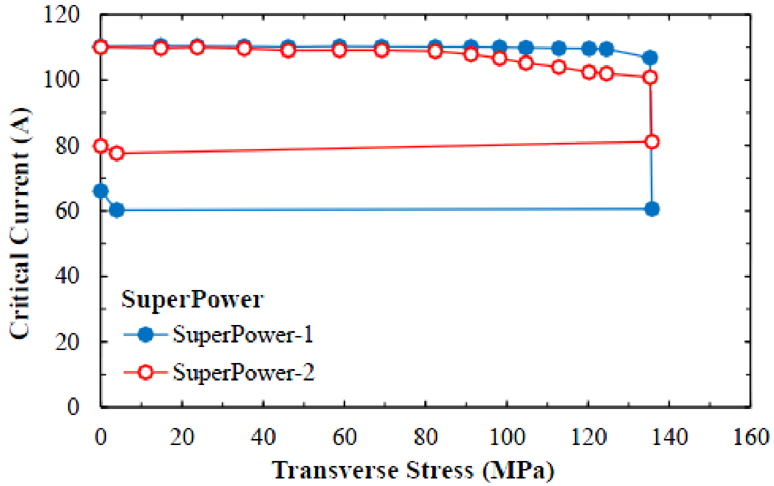


Experiments on REBCO tapes

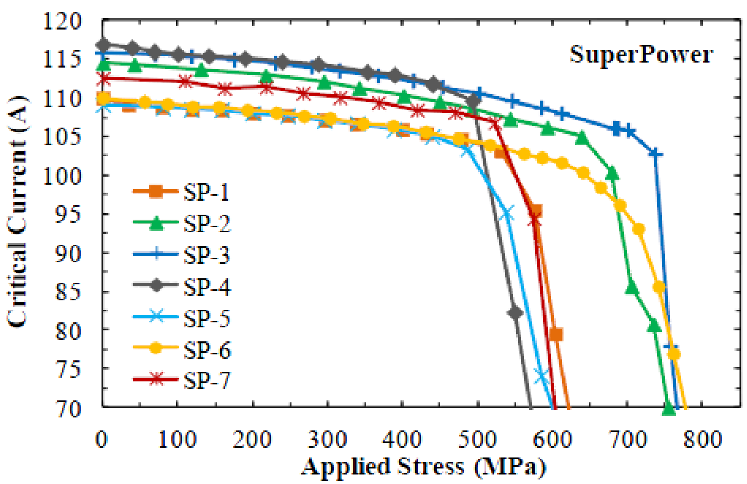
I. Pure Torsion



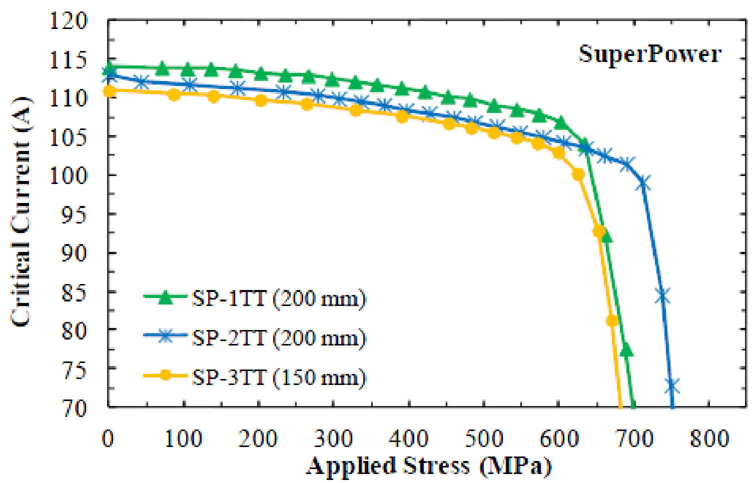
II. Mechanical Transverse Compression (Thin Edge)



III.a Tension



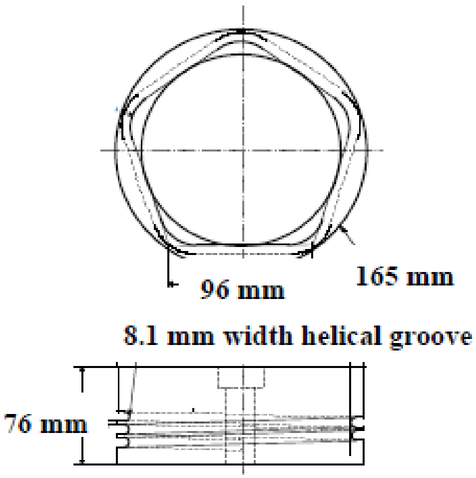
III.b Tension-Torsion



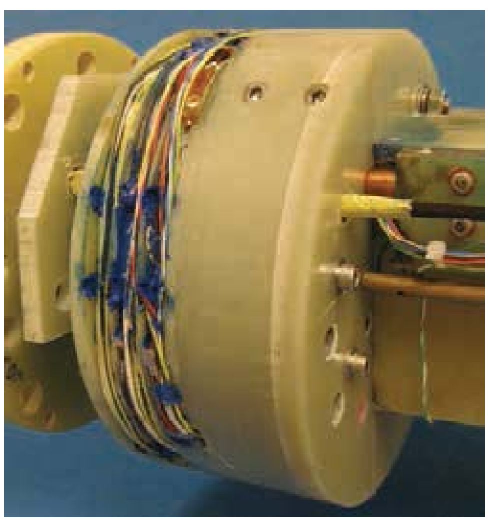
Experiments on TSTC conductors

Pentagon Stacked-Tape Twist-Wind (STTW) Sample

40-Tape, 2.6 Turn, 2.6 m cable ~200 mm twist pitch
REBCO tape: SuperPower 4 mm width, 0.1 mm thick, 120 A at 77 K



Stacked-tape cable **twisted during winding** in a groove covered with **braided copper**.



Soldered, and then filled with **Stycast** around the braided copper.

Sample current DC power supply of 10 kA

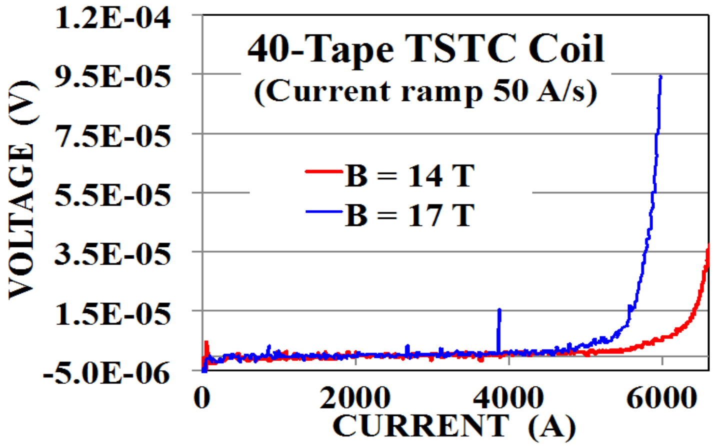
(seven small power supplies in parallel)

17 T Bitter magnet

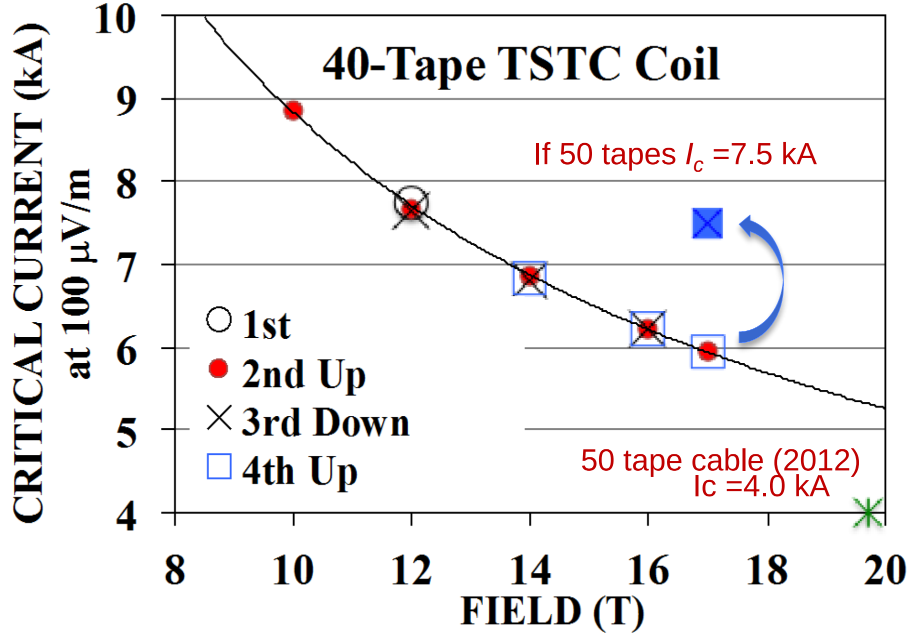
Takayasu ASC2016, 3LPo1H-04

Experiments on TSTC conductors

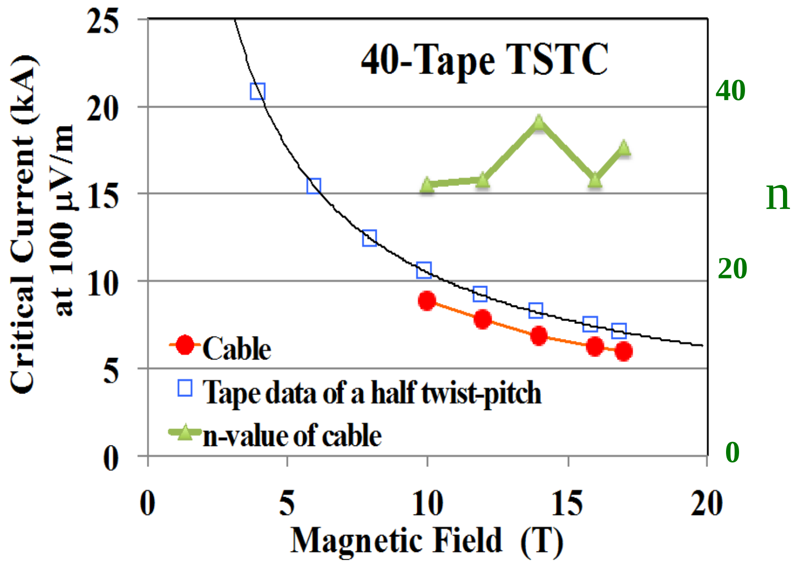
I-V curves



B - I_c results

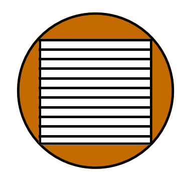


Comparison with tape data



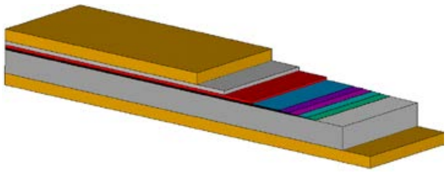
- The degradation compared to single tape data was **16%** [16%, between 10 T and 17 T]
- High n-value
- **No cyclic load effect** (102 kN/m)

J_e (8.1 mm Dia.) = 117 A/mm²
J_e(4 mmx4mm) = 375 A/mm²
J_e(5.7 mm Dia.) = 239 A/mm²

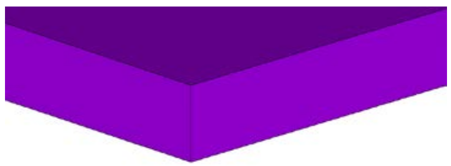


Modeling

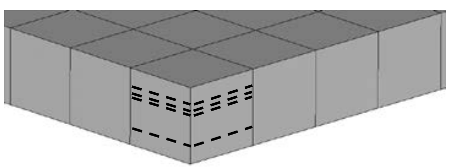
Structural *finite element analysis* ANSYS



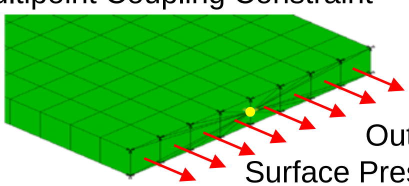
Single homogenous volume



One element in thickness

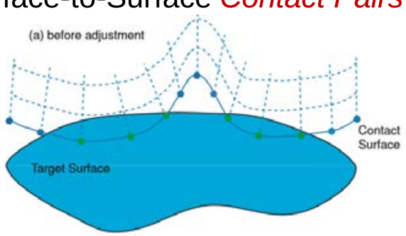


Multipoint Coupling Constraint

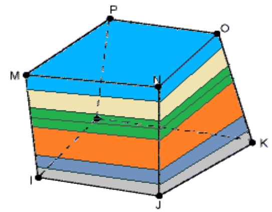


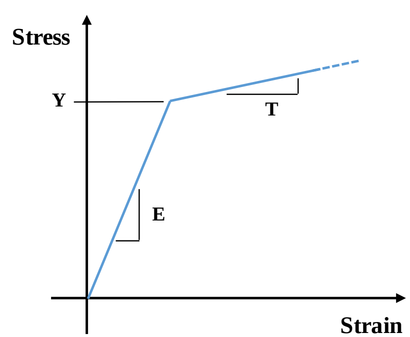
Outward Surface Pressure

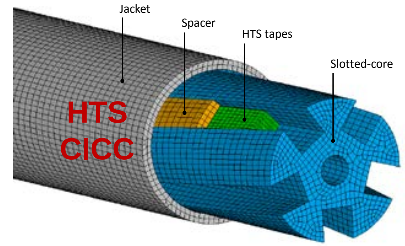
Surface-to-Surface *Contact Pairs*

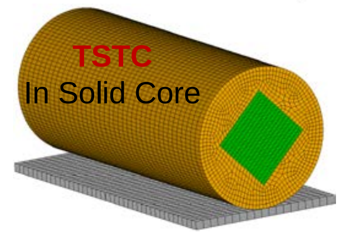


SOLSH190 – 3D 8-node structural *solid-shell element* with layered capabilities









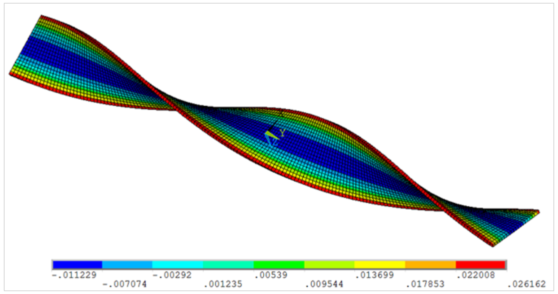
Bilinear Material Properties

	Material	**E** (GPa)	**Y** (MPa)	**T** (GPa)
Substrate	Hastelloy® C-276	180	**1225**	7.5
	Stainless Steel	190	**850**	10.0
	Ni-5AT.%W	120	**225**	3.75
Copper	Electroplated	85	350	4.0
	Rolled	120	455	4.5
Silver		90	225	22.0
REBCO/Buffer		150	---	---
Aluminum		80	235	15.0
Copper		120	400	4.5
Solder (Sn60/Pb40)		30	40	0.1

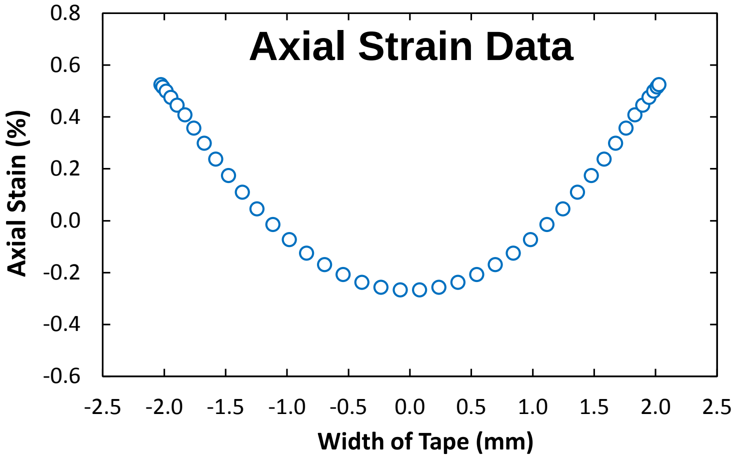
Predicting I_c using FEA strain results

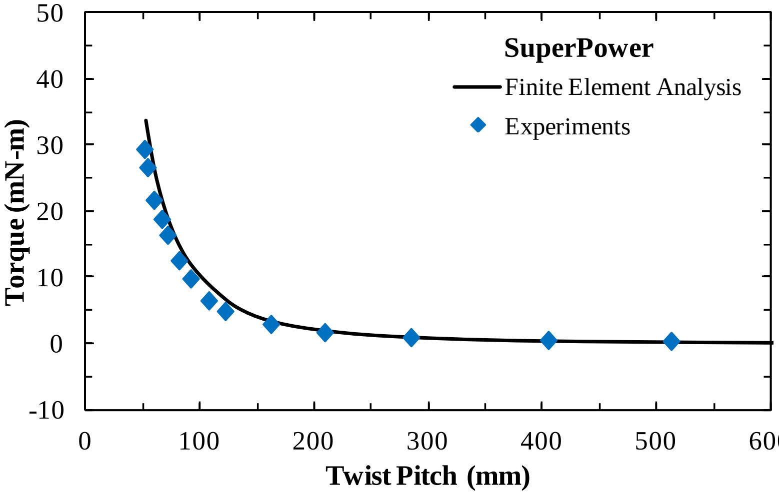
We can estimate *critical current* of tape using *axial strain* through width of tape

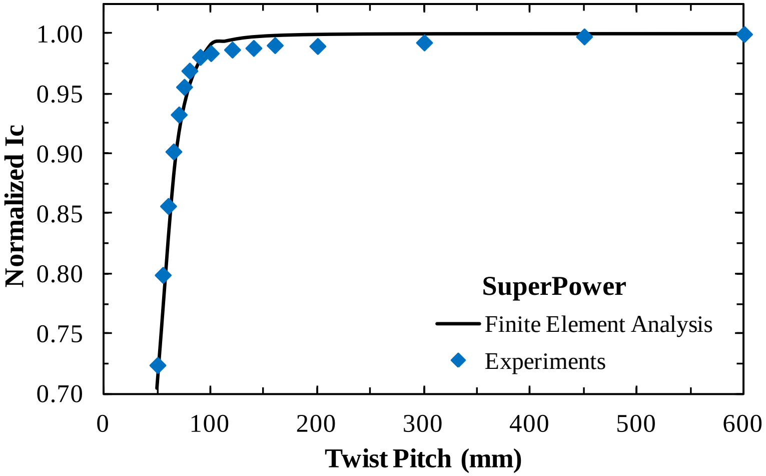
Numerical Model



Axial Strain Data







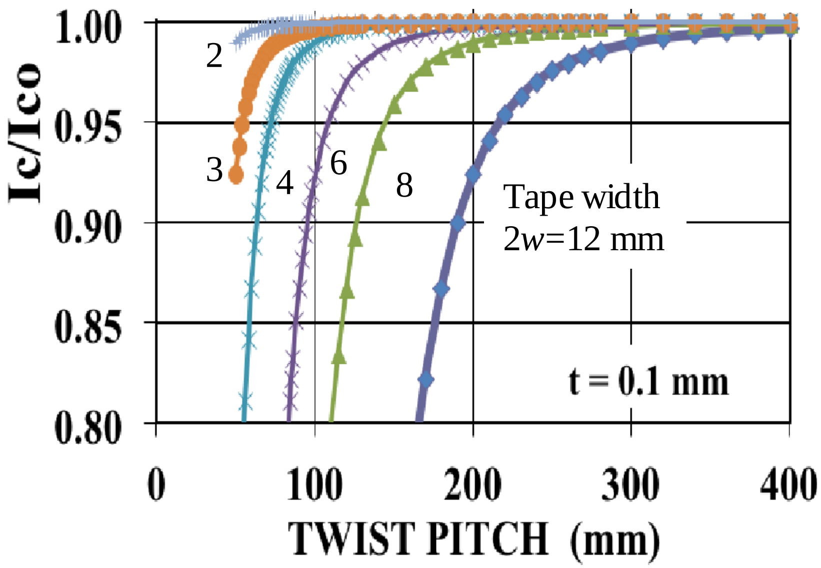
Analytical Relationship

$$I_c = t_s \int_{-\frac{w}{2}}^{\frac{w}{2}} j_c(\varepsilon_x)\,dx \qquad j_c(\varepsilon) = I_c(\varepsilon)/(t_s w)$$

$$I_c/I_{co} = 0.057713 \times 10^{12}\, \varepsilon_{b\theta}^{6} - 0.03979215 \times 10^{10}\, \varepsilon_{b\theta}^{5} - 0.2090279 \times 10^{8}\, \varepsilon_{b\theta}^{4} + 0.02385557 \times 10^{6}\, \varepsilon_{b\theta}^{3} - 0.1668065 \times 10^{4}\, \varepsilon_{b\theta}^{2} - 0.003\,662115 \times 10^{2}\, \varepsilon_{b\theta} + 1.0$$

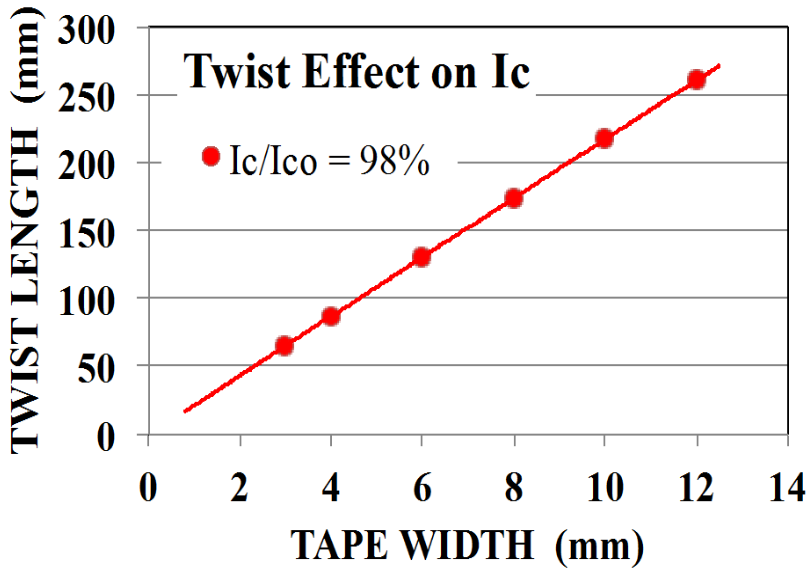
Experimental Data
D. van der Laan, 2009

Twisting of tapes with different widths



I_c Degradation due to Twisting
(analytical evaluation)

$$\varepsilon_x = \frac{\theta^2}{2}\left(x^2 - \frac{w^2}{3}\right)$$



Tape-Width Dependence
(analytical evaluation)

Twist-pitch L_p (I_c/I_{co} =0.98) ≈ 22 · 2*w* (mm)
2*w* tape width

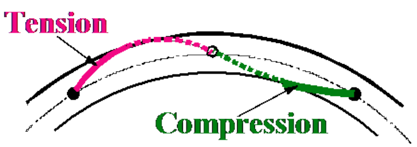
Takayasu ASC2016, 2LPo2D-03

Bending behavior

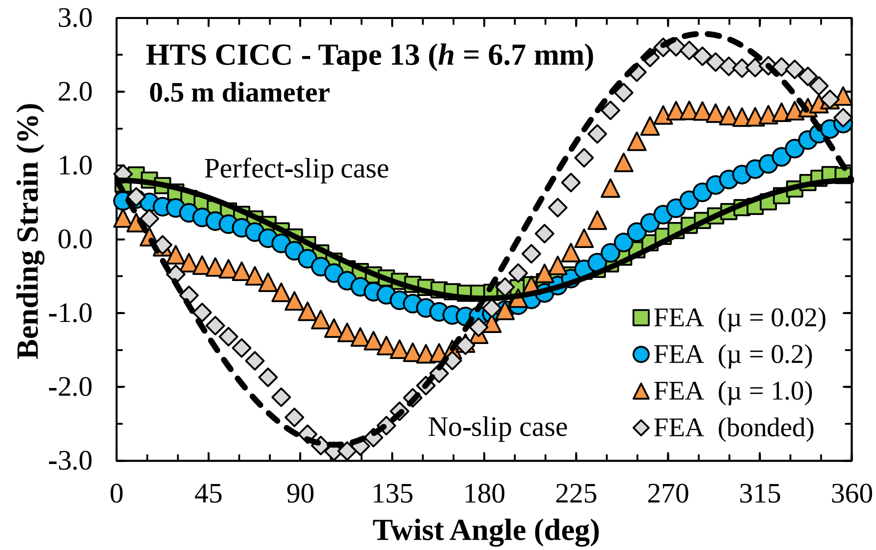
No-slip model

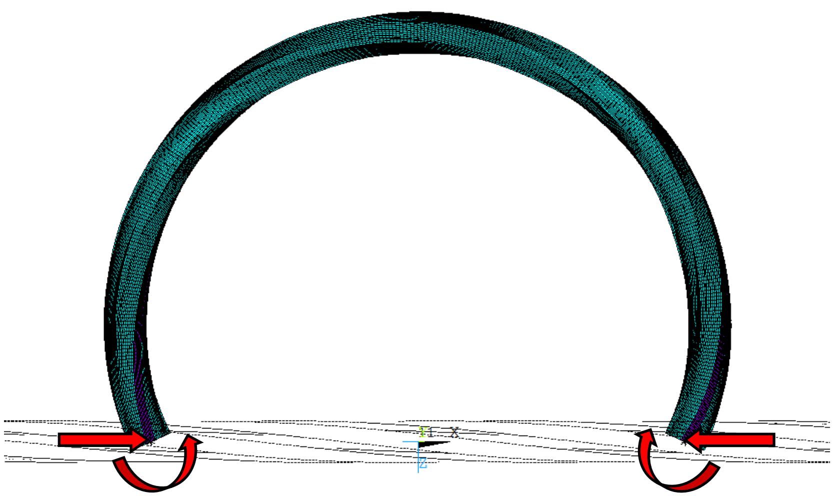
$$\varepsilon_b = \frac{\left(\frac{x}{\cos\alpha}\right)\sin\theta + h\cos\theta}{r_o}\cos\alpha$$

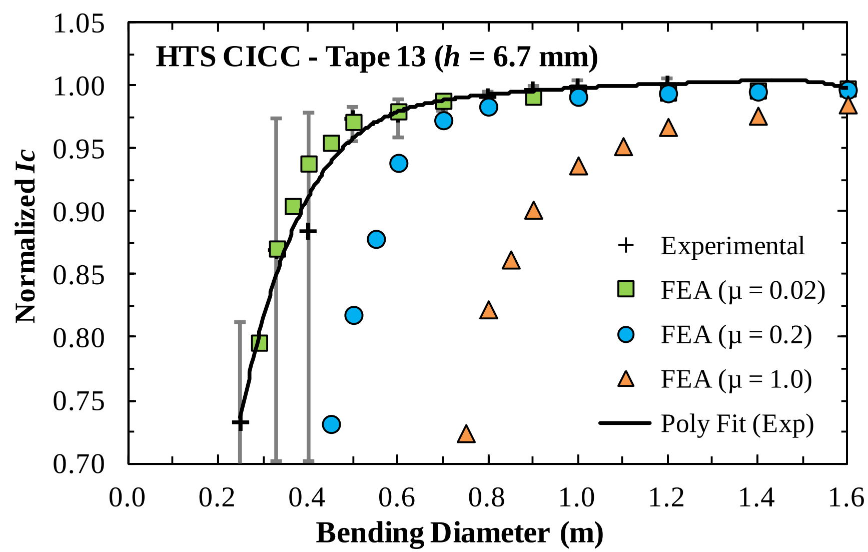
Perfect-slip model (PSM)



$$\varepsilon_b = \frac{x\sin\theta}{r_o}$$

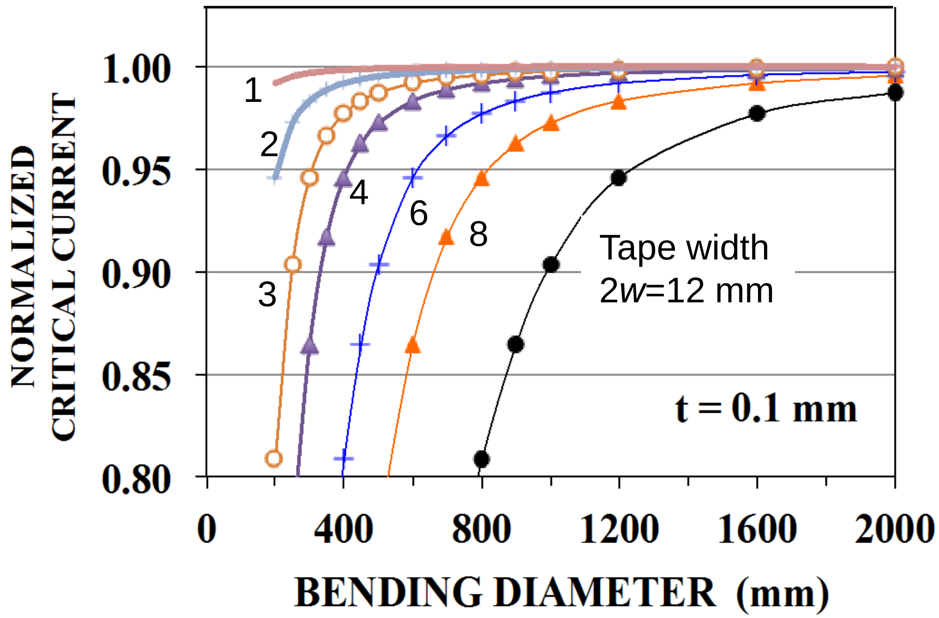




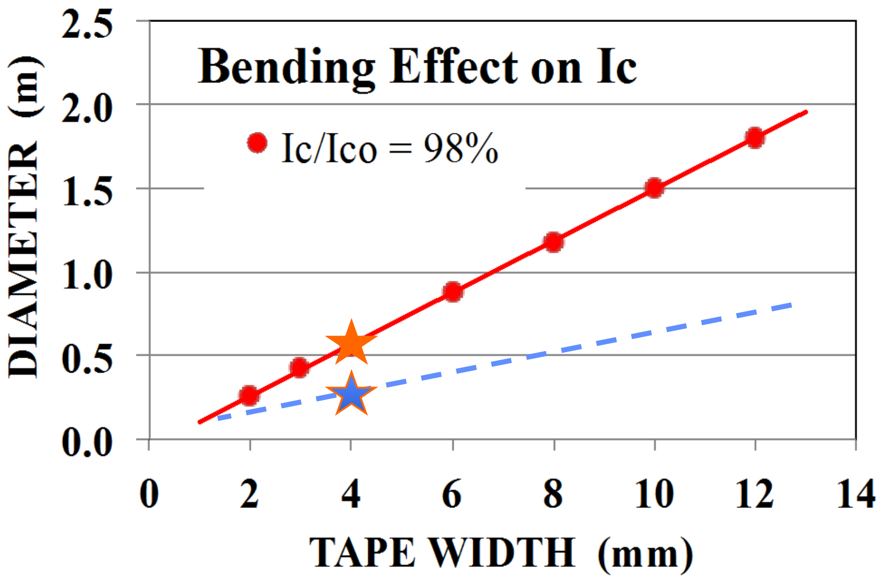


Takayasu, CEC-ICMC, 2015
De Marzi, MT24, 2015

Bending diameters for different tapes width



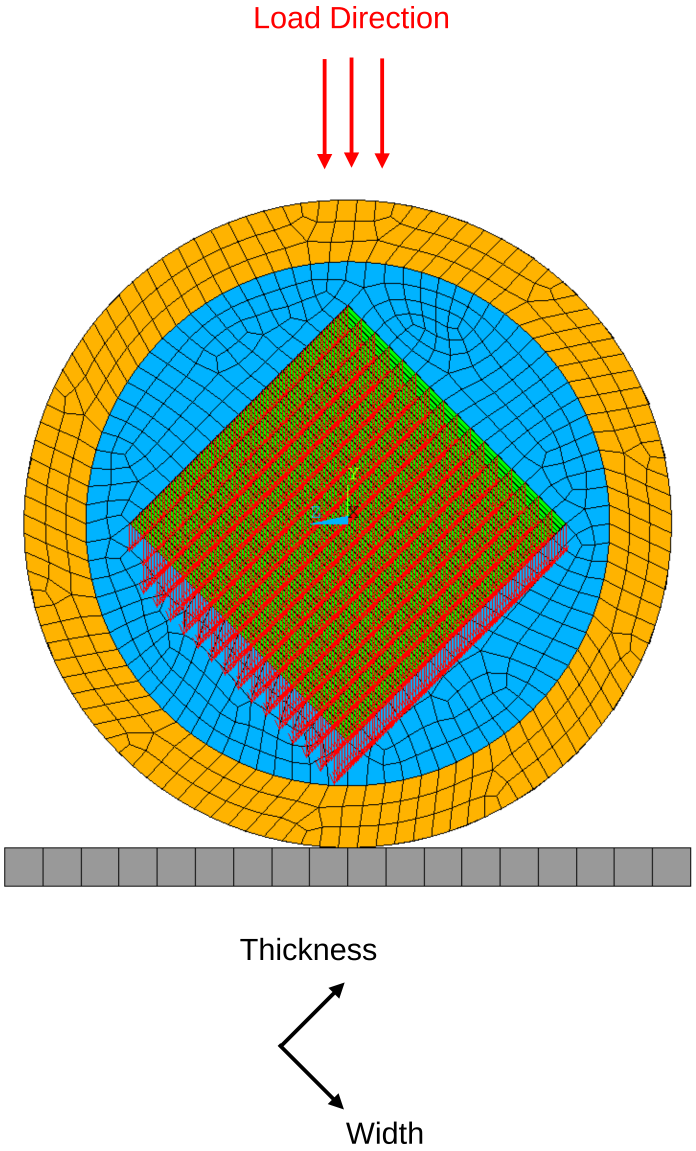
I_c degradation due to bending based on Perfect-Slip Model
(analytical evaluation)



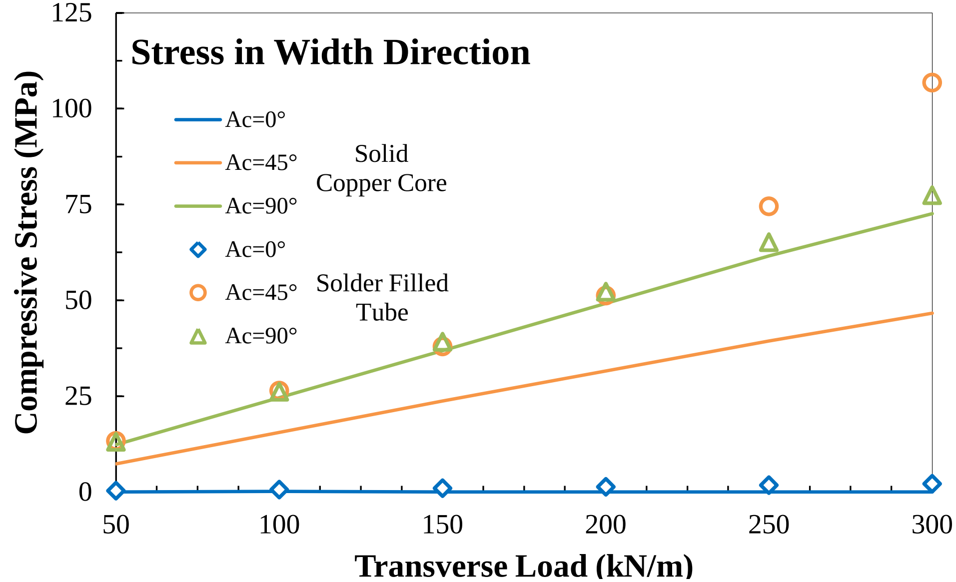
Bending Diameter vs. Tape Width
(analytical evaluation)

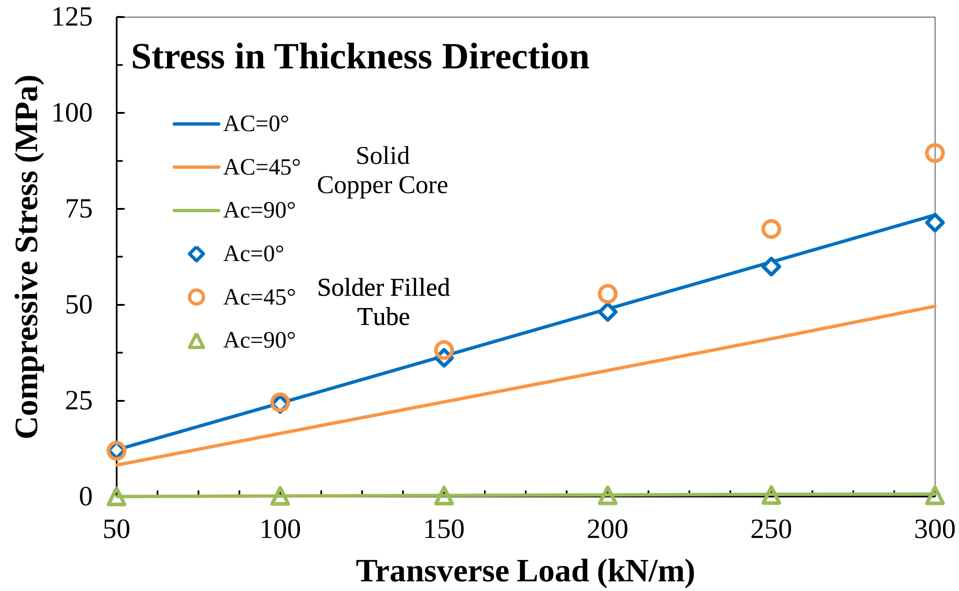
Bending diameter r_o $(0.98\ I_c/I_{co}) \approx 150 \cdot 2w$ (mm)
$2w$ tape width

Predicting support structure for large EM loads



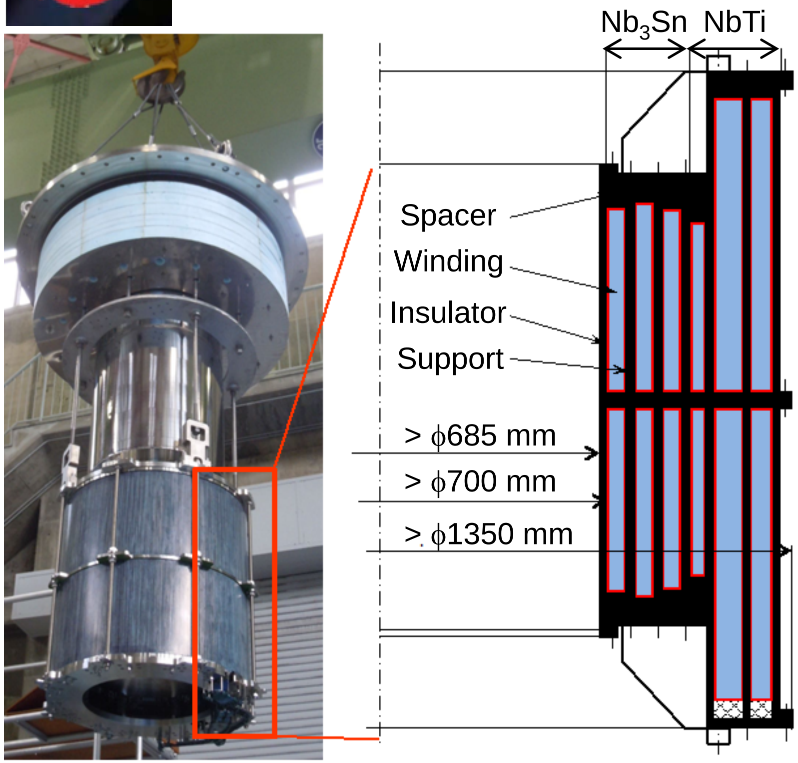
Stress is maximum value of 95% of the elements (stress concentrations were excluded)



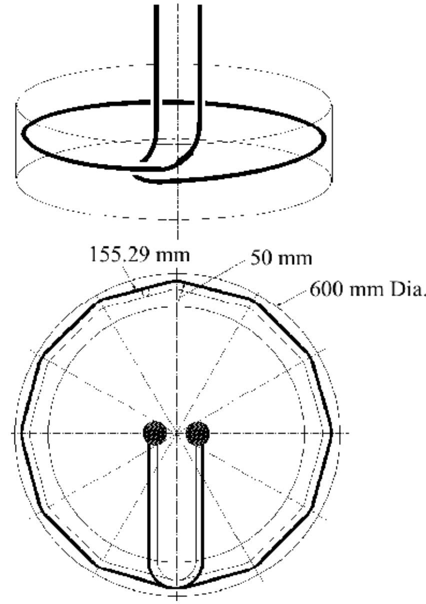


Allen, ASC2016 2LPo2D-04

Next TSTC experiment at high fields-NIFS



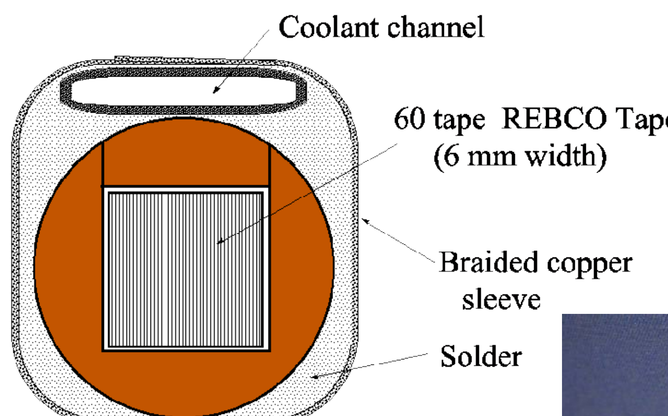
S. Imagawa



One turn coil sample
Dodecagon shape

Max. Field: 13 T
Bore: ϕ700 mm
Sample Current: 50 kA
Temperature: 4-50 K

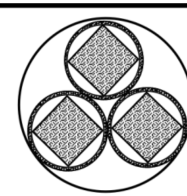
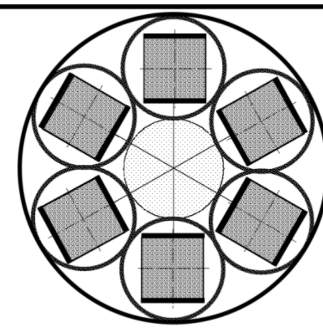
Conductor cross section

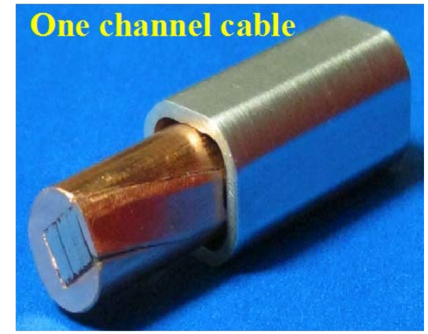


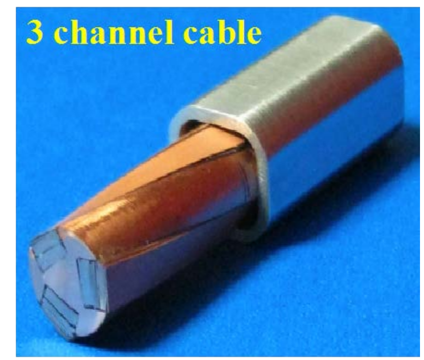
N. Yanagi, et al., 3rd *HTS4Fusion*, ENEA/Tratos, September, 2015.

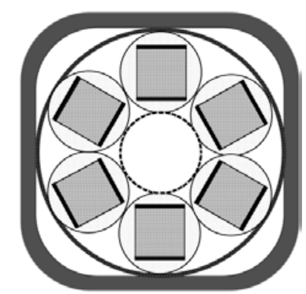
Possible cable configurations

Based on SuperPower SCS4050-AP (2012), 4 mm width, 0.1 mm thickness REBCO tape.
Tape critical current : 180 A at 17 T and 4.2 K.

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	



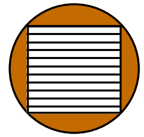




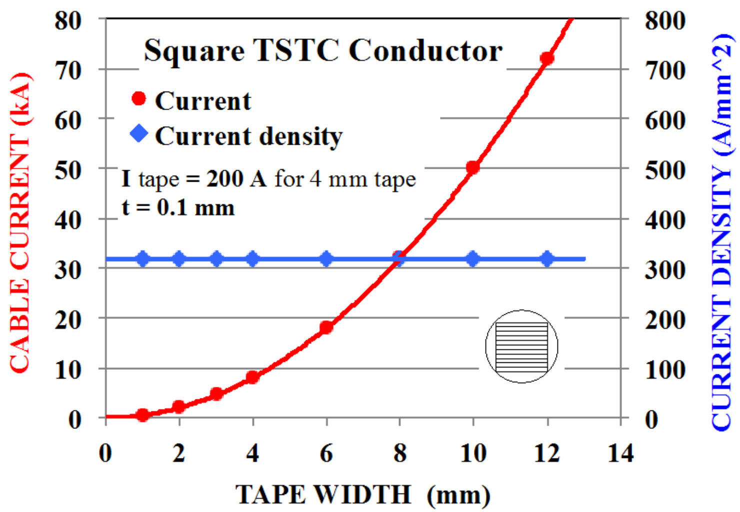
4 mm Tape Hexa CICC
(26 mm x 26 mm)

Current and current density vs. width, thickness

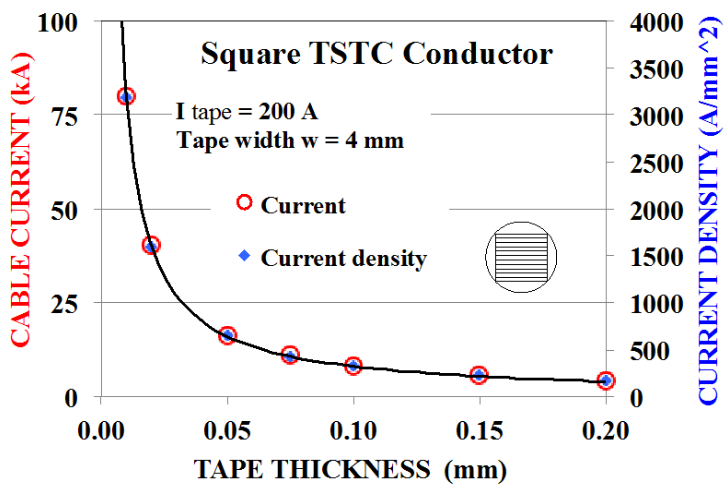
Square TSTC Conductor
Stabilizer space 36% of total cross-section



Evaluation based on
4 mm width, 0.1 mm REBCO tape
Critical current : 200 A



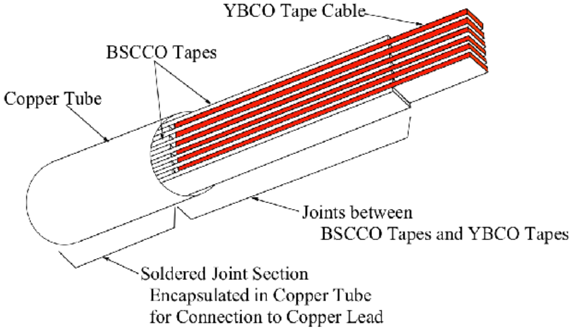
Tape-Width Dependence
Tape thickness = 0.1 mm

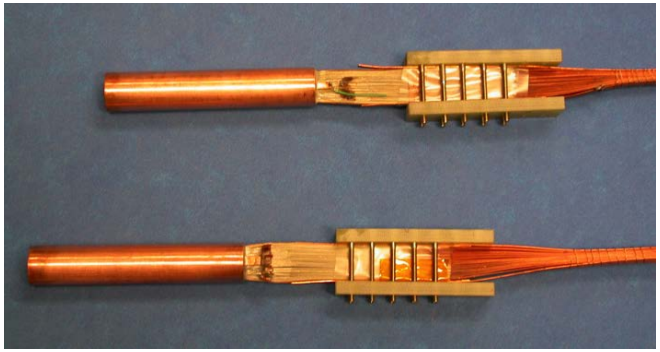


Tape-Thickness Dependence
Tape width = 4 mm

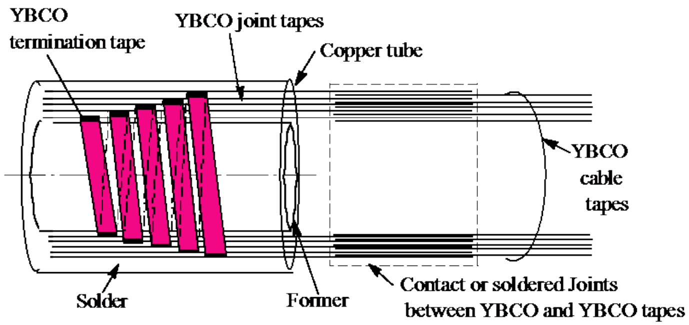
Joints

I. YBCO - BSCCO Termination

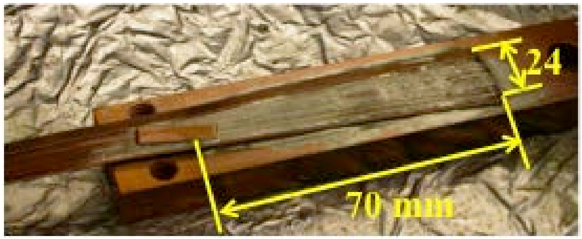




II. YBCO - YBCO Termination



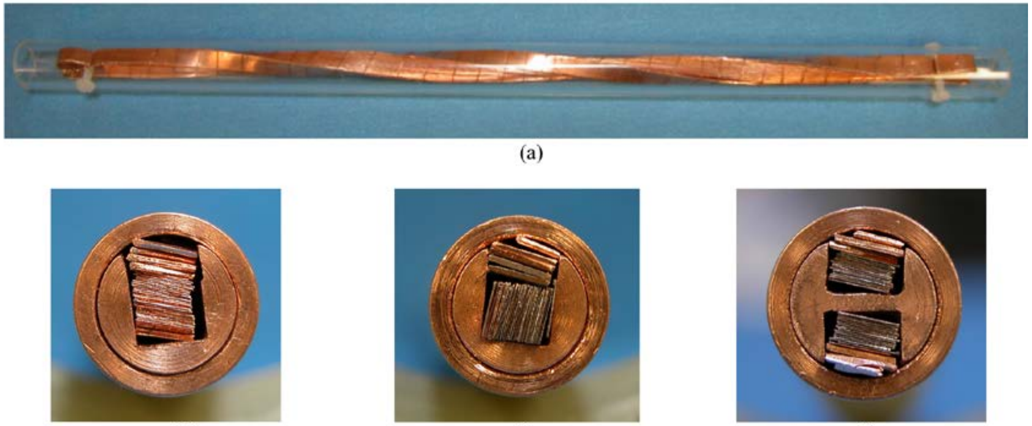
III. Folding-Fan Soldered Termination



AC losses characterization

Ohio State University
Prof. Mike Sumption

Various TSTC conductors (30 SuNAM tapes)


(a) (b) (c) (d)

SuNAM (SCN04150-140819-01)
4.1 mm width
150 μm thickness
Non-magnetic stainless-steel substrate (>80 μm)

Tape critical current 200 A at 77 K in self-field (manufacturer's data).

Conductor length: 203 mm

Twist pitch: **200 mm**

Fabricated AC loss test samples of various TSTC conductors (sent to OSU).
(a) Stacked tapes **twisted between copper strips**, encapsulated with a 0.5" OD plexiglass tube.
(b) Tapes **stacked horizontally** in a single helical groove of OFHC rod enclosed in an OFHC sheath (0.5" OD).
(c) Tapes **stacked vertically** in a single helical groove of OFHC rod enclosed in an OFHC sheath (0.5" OD).
(d) Stacked tapes in **two helical grooves** of OFHC rod enclosed in an OFHC sheath (0.5" OD).

These samples after tests will be soldered and sent back to OSU for the soldered sample tests, in order to investigate solder effects on AC losses.

Future directions and conclusions

- Continue EM studies of cables and use future experiments to validate modeling
- Use modeling to optimize design of HTS cable options for high field magnets
- Continue study of joints for HTS cables
- Comprehensive structural and electromagnetic modeling
- CICC fabrication development for a long conductor
- More experiments on cables at high field and 4.2 K are necessary!!! ($$$)

- Our ***expertise*** is the *electromechanical characterization* of *REBCO* (single tape and TSTC) using *experiments and finite element analysis*.
- The work provides critical information to design and fabricate cables and magnets for HEP/Fusion that are structurally and electromagnetically sound.

THANK YOU

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