Development of REBCO Twisted Stacked-Tape Cables for Magnet Application

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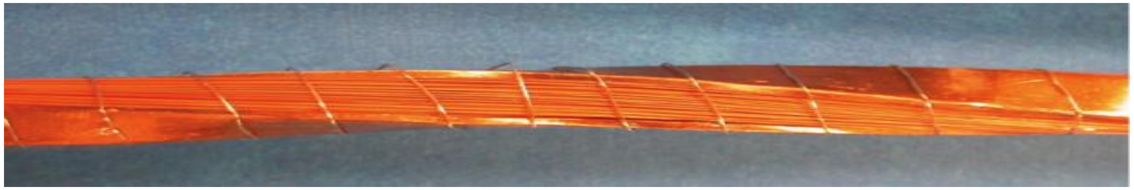
1st Workshop on Accelerator Magnets in HTS at DESY, Hamburg, Germany

Twisted Stacked-Tape Cable (TSTC)

What is it?



For example:

40 YBCO tapes (4 mm width, 0.1 mm thickness) are **stacked** between two 0.5 mm thick copper strips, and

loosely wrapped with a fine stainless steel wire 0.23 mm in diameter,

and then **twisted** together along their axis.

Outline

- Single tape torsion behavior
- Twisted-Stacked Tape Cable (TSTC) bending test in self field at 77 K
- Stacked-Tape Twist-Winding (STTW) for 3D magnet winding method
- High field tests at 4.2 K
  - Pentagon coil tests at NHMFL (up to 20 T)
  - Straight cable test at KIT (up to 12 T)

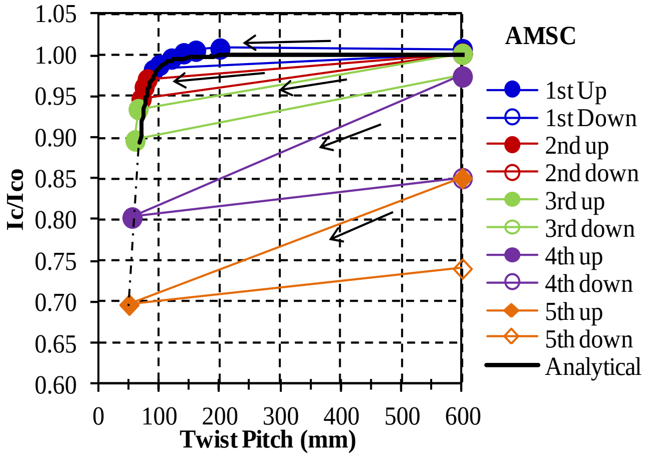
*Cable "**degradation**" compared with single tape*

- Possible Degradation explanation by non-uniform current distibution
- Large-scale TSTC conductor concept
- TSTC for Accelerator Magnet Application
- Conclusion and future work

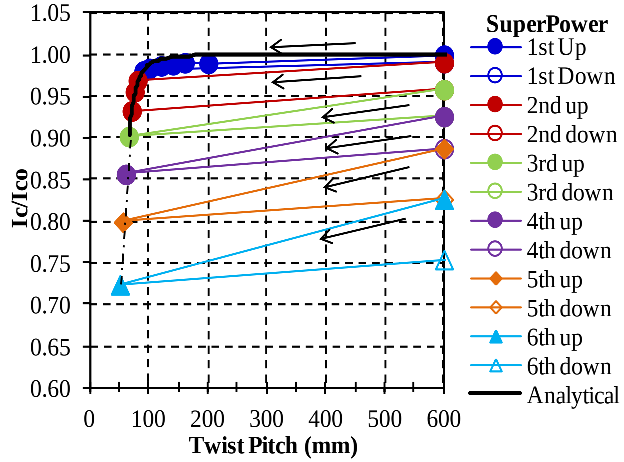
REBCO Single Tape Tests at 77 K

Critical Current vs. Twist Pitch

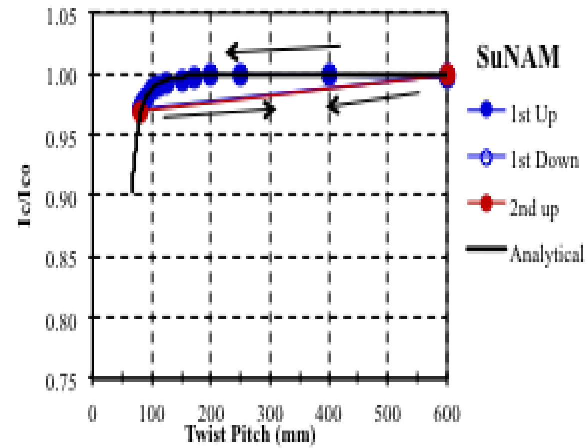
SuperPower



AMSC



SuNA

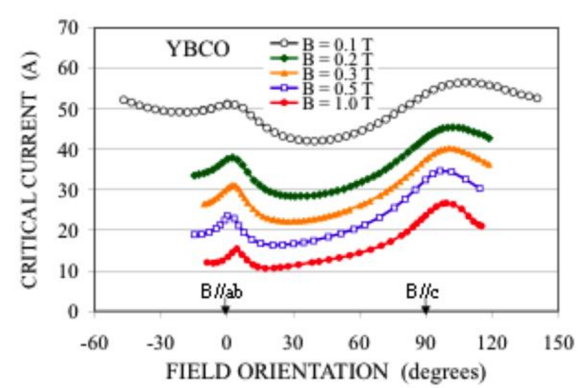


Characteristics* of REBCO Tapes Used

	SuperPower	AMSC	SuNAM
Tape Type	SCS4050-AP	344C	SCN04150
Processing	IBAD-MOCVD	RABiTS-MOD	IBAD (Sputter & E-beam)
Width (mm)	4.15	4.42	4.1
Thickness (μm)	94	208	150
Substrate material	Hastelloy C-276 (50 μm)	Ni-5at%W (50 μm)	Stainless steel (104 μm)
Cu stabilizer (μm)	40 (ElectroPlating)	100 Laminated	~50 (ElectroPlating)
Critical current at 77 K, Self field (A)	~105	~110	~240

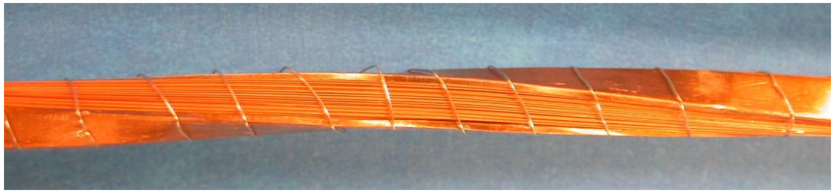
*Based on manufacturer's specification.

Field orientation (SuperPower AP tape)

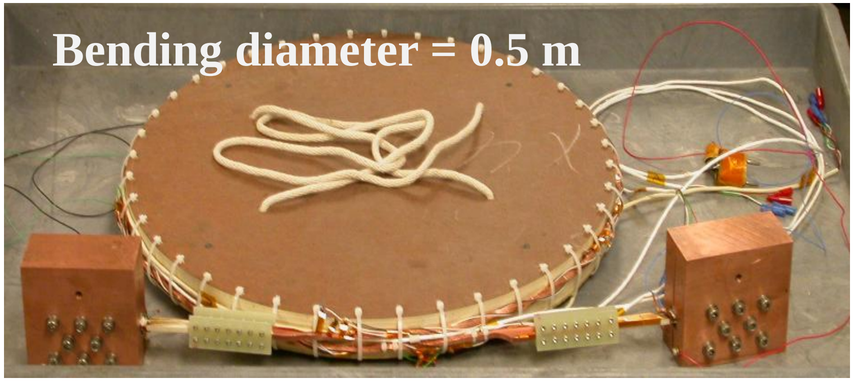


Cable Bending Tests at 77 K

2 m, 32 tapes YBCO Twisted Stacked Tape Cable (TSTC)with 200 mm twist pitch



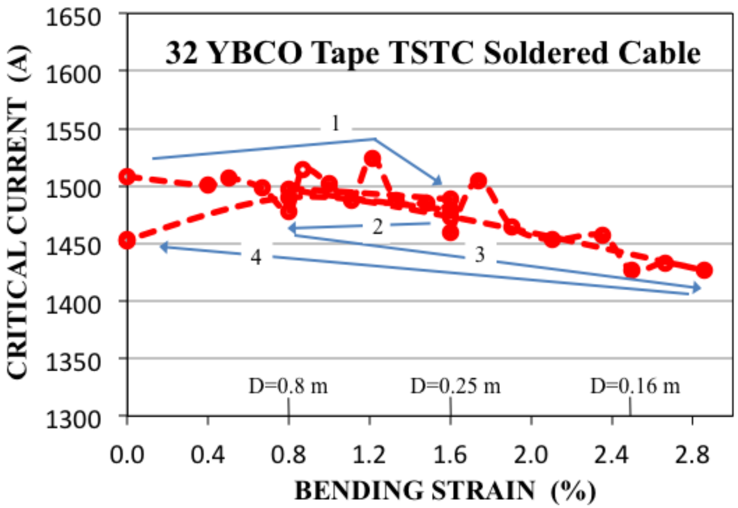
Cross-section: 4.8 mm x 4.8 mm
Twist pitch: 200 mm



2 m one turn coil

Cable degrades due to self-field.

After soldering the straight cable was mounted on side surfaces of various diameter disks.



I_c degradation due to bending

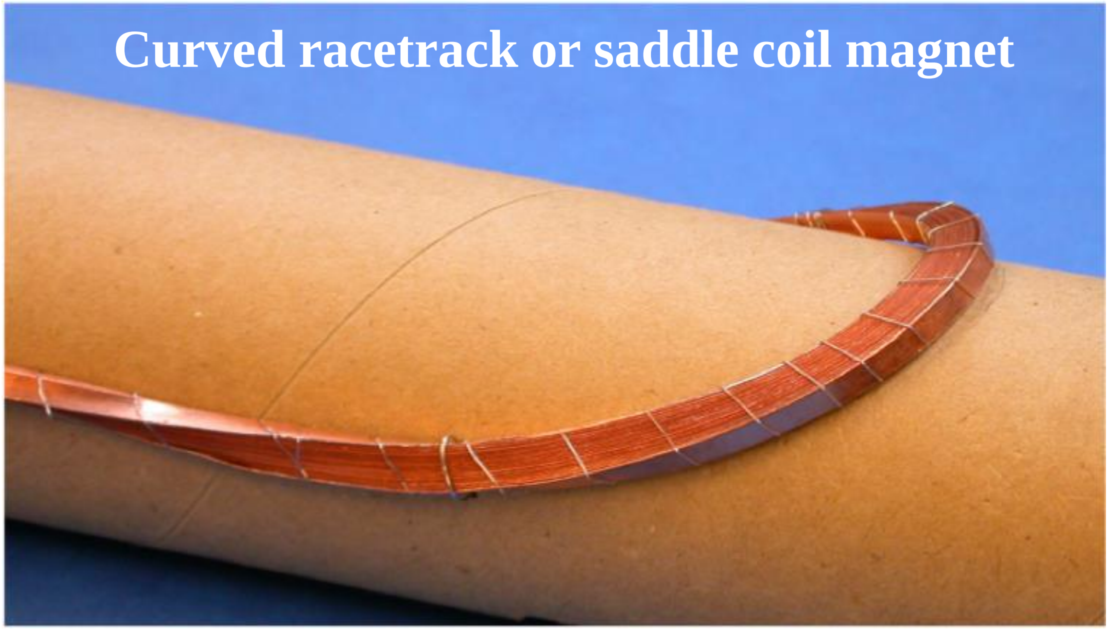
Bending Diameter	Degradation
250 mm	1.9 %
140 mm	5.4%
Straighten after bending tests	3.6%

TSTC conductor is bendable.

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

New REBCO tape magnet winding concept

Stacked tape cable is twisted during winding



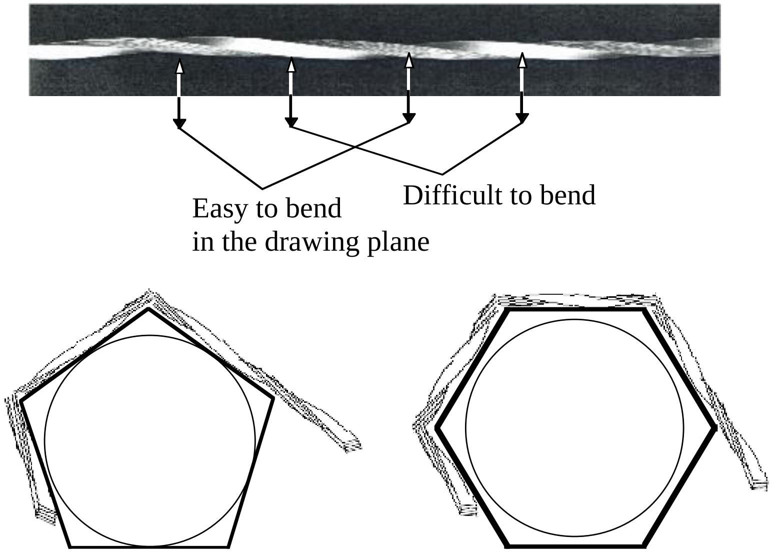
A U-turn portion of one turn coil demonstrating a curved saddle winding on a 50 mm diameter tube. The cable is composed of 50 YBCO tapes.

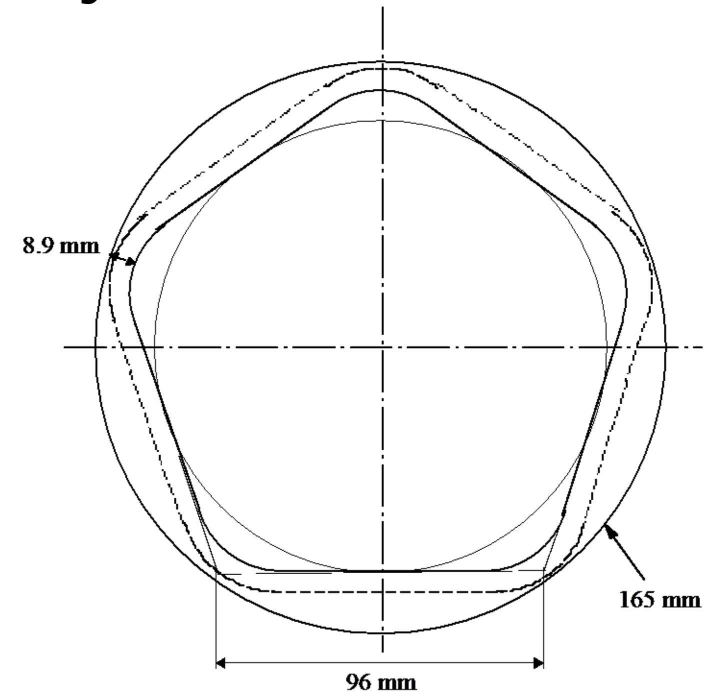
Applications

Small diameter magnet

3D HEP accelerator magnets, generator and motor magnets

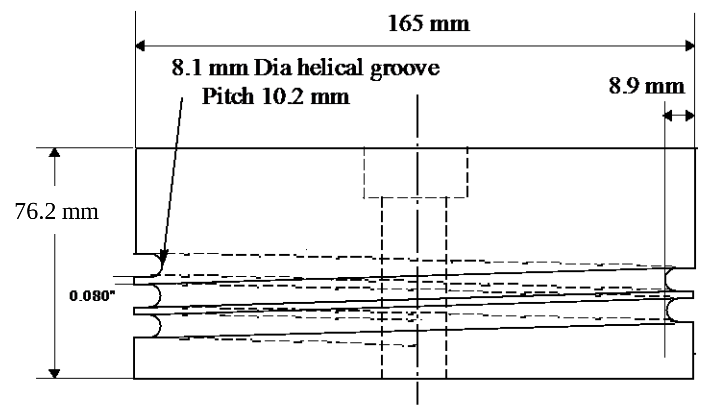
YBCO TSTC Small Coiled Sample for High Field Test Made by STTW





Straight length should be half of the cable twist-pitch or a multiple of it.

Pentagon Coil Tested at NHMFL



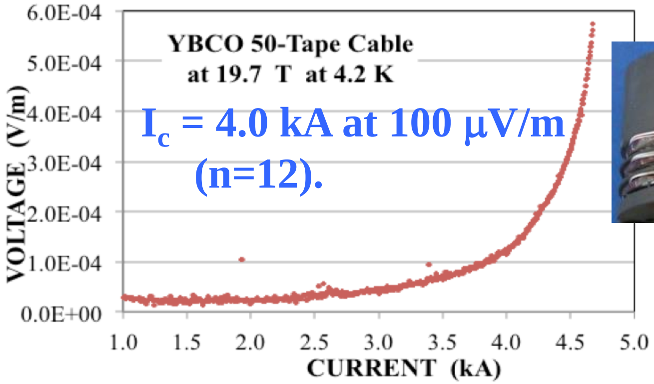
(a) 50 tape, 2.5 turn coil composed of YBCO cable wound on a 165 mm diameter pentagon cylinder. (b) Enlarged view of a 3D sharp bending section.

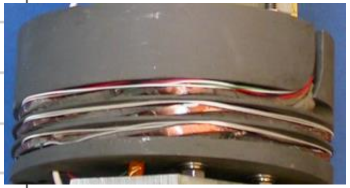
High Field Test at NHMFL

Two Pentagon Coils Tested at 20 T

50-Tape, 2.5 Turn, 2.32 m cable wound on pentagon shaped cylinder surface with about 200 mm twist-pitch. Tested at NHMFL using 20 T, 195 mm warm-bore Bitter magnet

1st Pentagon Coil

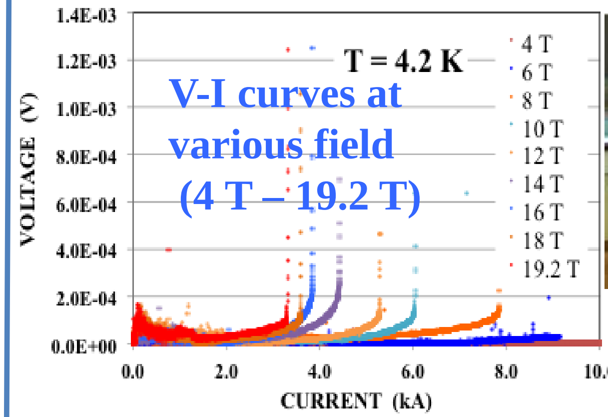


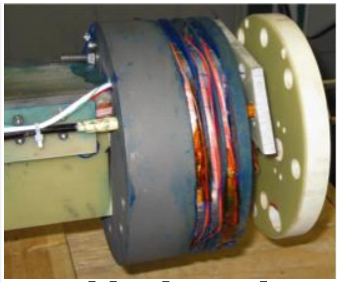


Soldered cable

Damaged by Lorentz load.

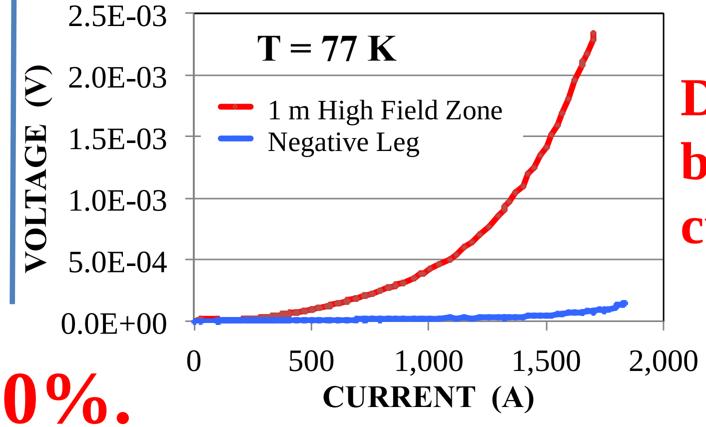
2nd Pentagon Coil





Cable channel filled with Stycast underneath conductor

Self-field test at 77 K after high field test



Degraded by over currents.

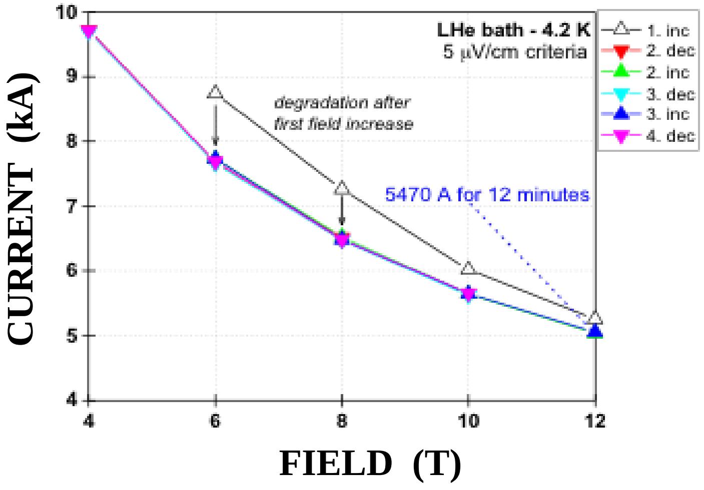
The degradation was about 50%.

High Field Test at KIT

40-Tape YBCO TSTC Conductor Tested at KIT

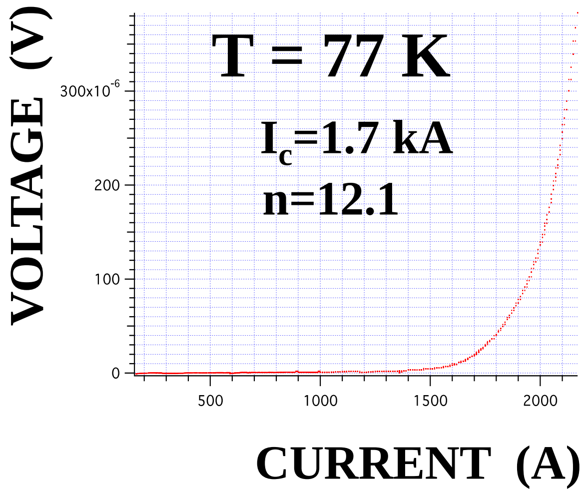
40-Tape, 1.16 m long, 200 mm twist-pitch cable in 9.5 mm OD solder-filled Cu tube tested using FBI at KIT, Germany (12 T, 10 kA, 4.2 K – 77 K)

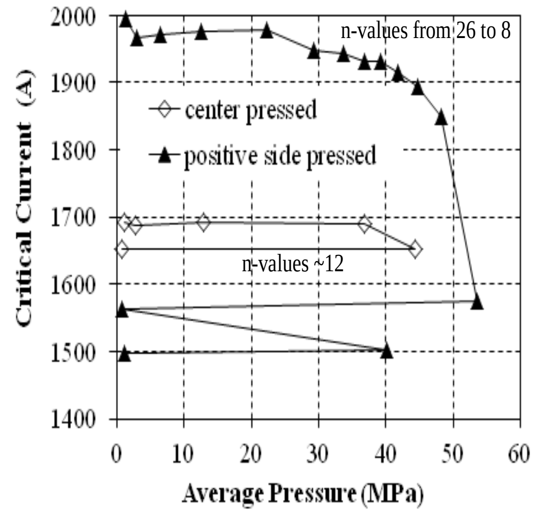
Critical current vs. Field tested at KIT.
C. Barth et al., presented at ASC 2012



No voltage change observed for 12 minuets at 5.47 kA at 12 T.

Transverse load test at 77 K after high field test at KIT



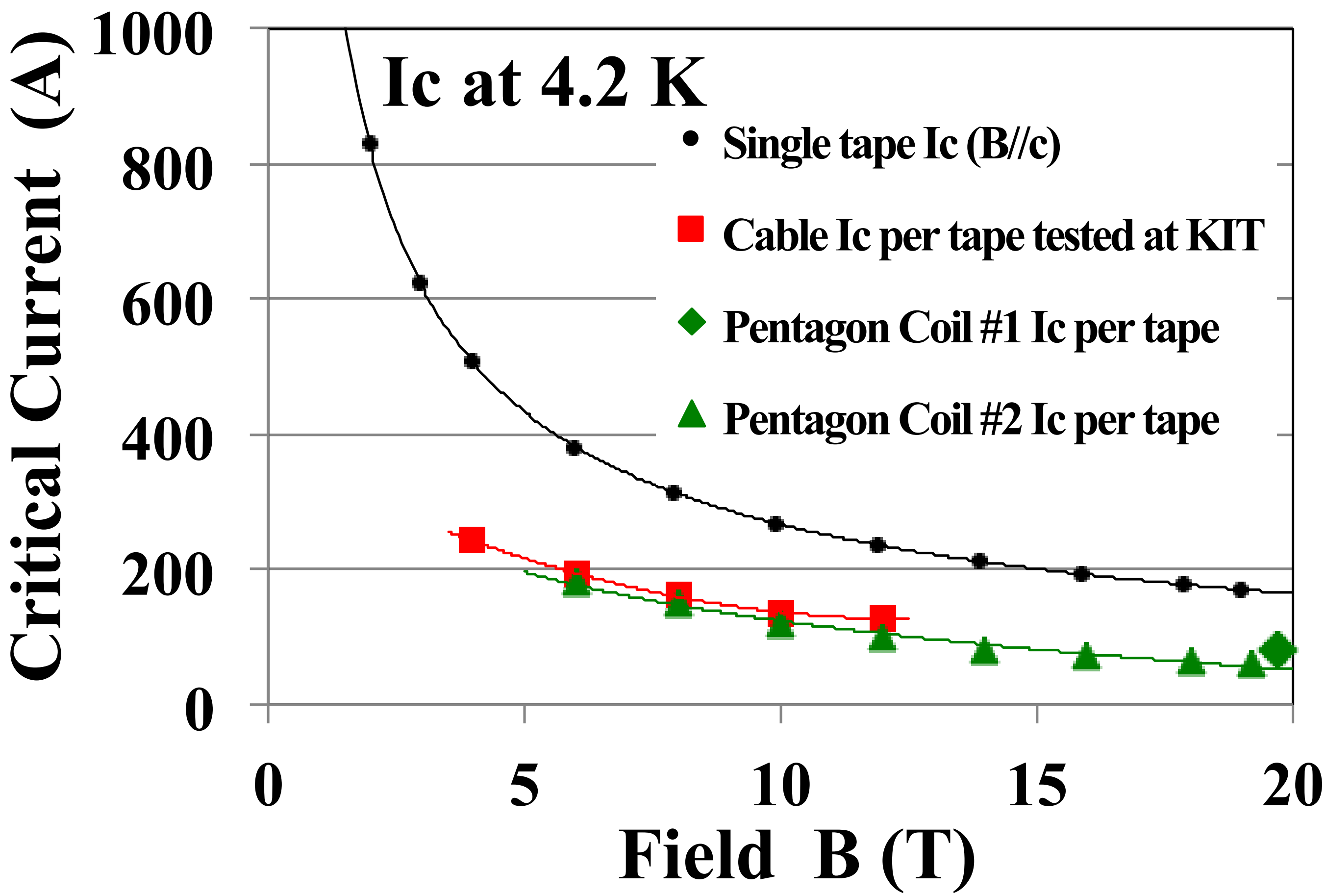


KIT tested section: 15% initial Ic, but less trans. load effect.
End section: No initial Ic degradation, but large load effect.

Lorentz force degradation was 10% - 15%.
Additional degradation of about 45% was NOT permanent.

Summary of TSTC Conductor Test Results at High Field

Critical current comparison of two pentagon coils tested at NHMFL and one straight-cable tested at KIT with single-tape data (B // c-axis).



Degradations were about 50% at high fields.
Partially Lorentz force degradation.
Mostly not a permanent degradation.

Degradation Origins ?

Permanent Degradation

Electromagnetic Lorentz force degradation:
10% - 15% for a 40-tape TSTC at 12 T.

Non-Permanent Degradation ?

About 45% was NOT permanent.

Mechanical

It may not be possible to mechanically produce 45% non-permanent degradation.

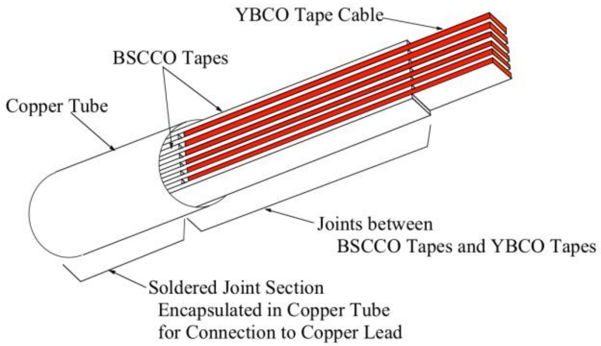
Electrical

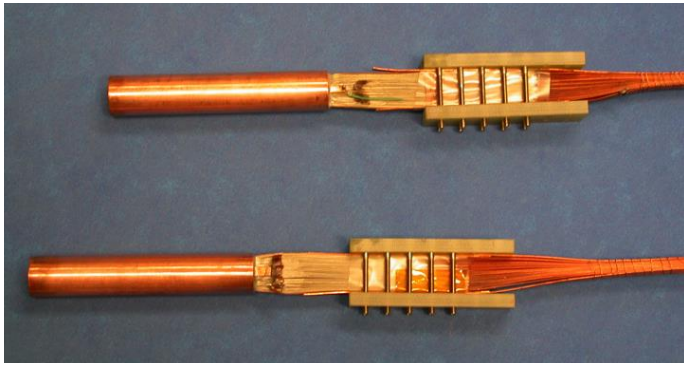
Possible loop current time constants are shorter than a few hundred seconds.

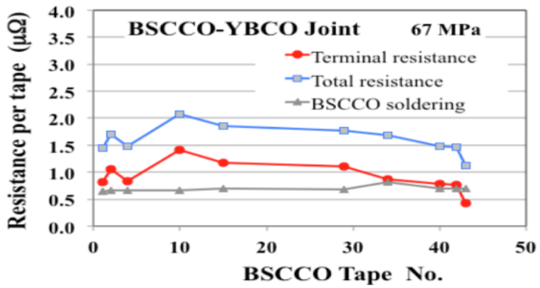
Non-uniform termination resistance causes non-uniform current distribution and degradation.

REBCO Cable Termination Methods

YBCO-BSCCO Termination

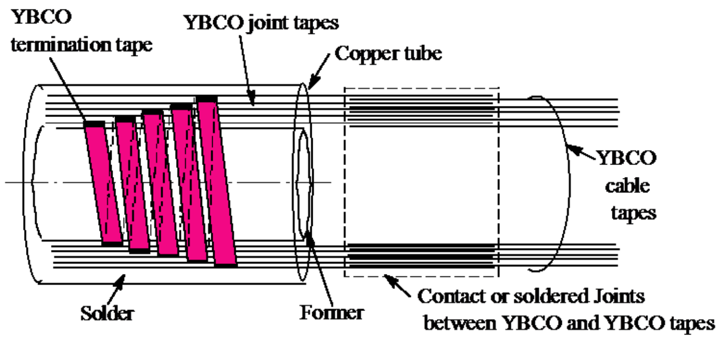


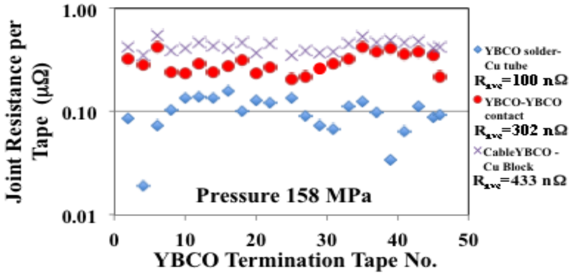




Tape termination resistance
Average 920 nΩ
Standard deviation 270 nΩ

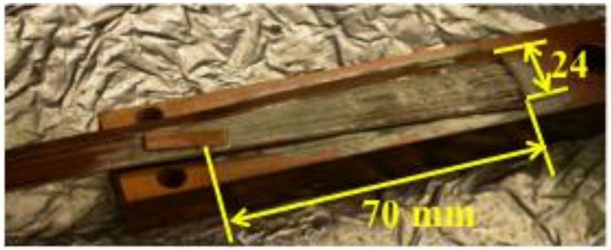
YBCO- YBCO Termination

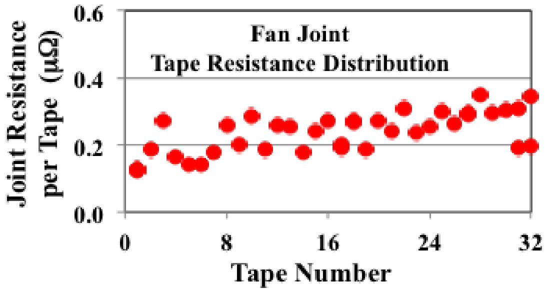




Tape joint resistance
Average 430 nΩ
Standard deviation 50 nΩ

Folding-Fan Soldered Termination

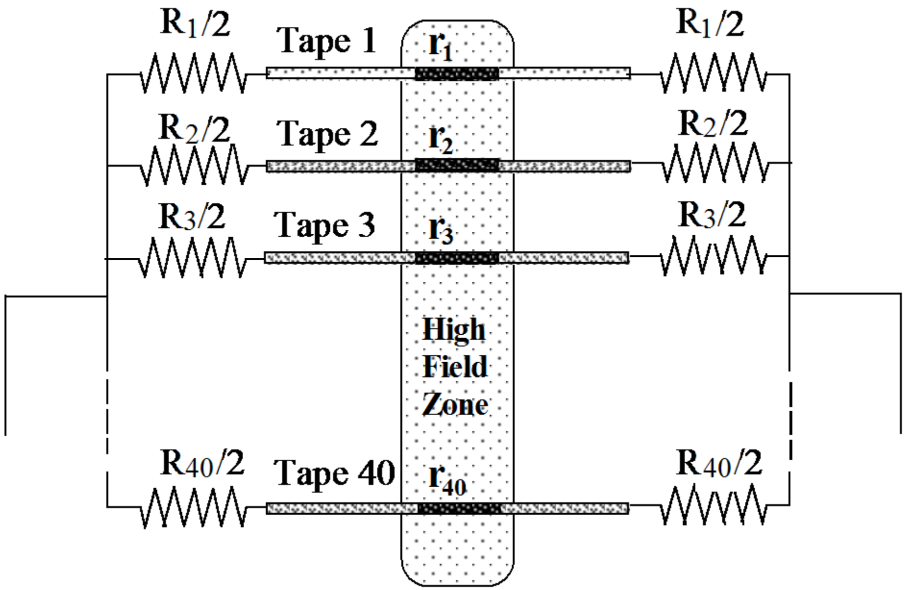




Tape joint resistance
Average 238 nΩ
Standard deviation 59 nΩ

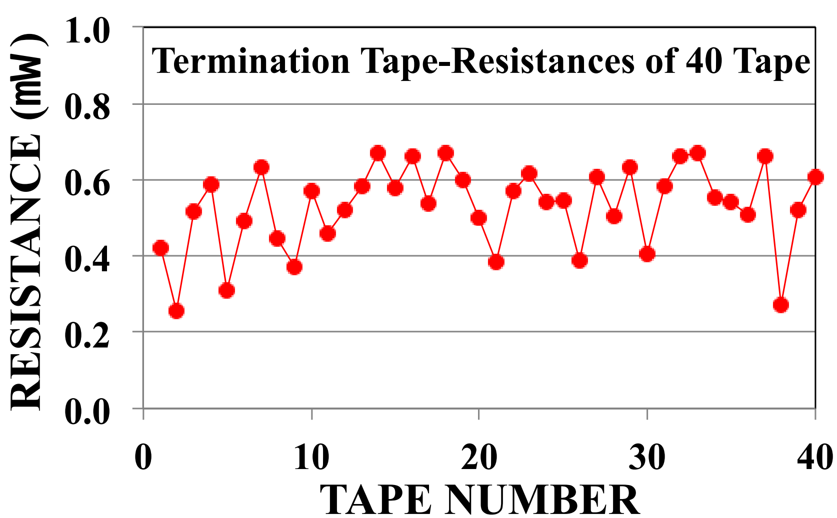
Current Distribution due to Termination Resistance

Pure-Resistance Model Circuit of 40-Tape Cable



- Apply a total current and analyze tape currents by iteration using Microsoft Excel®
- No current sharing between tapes

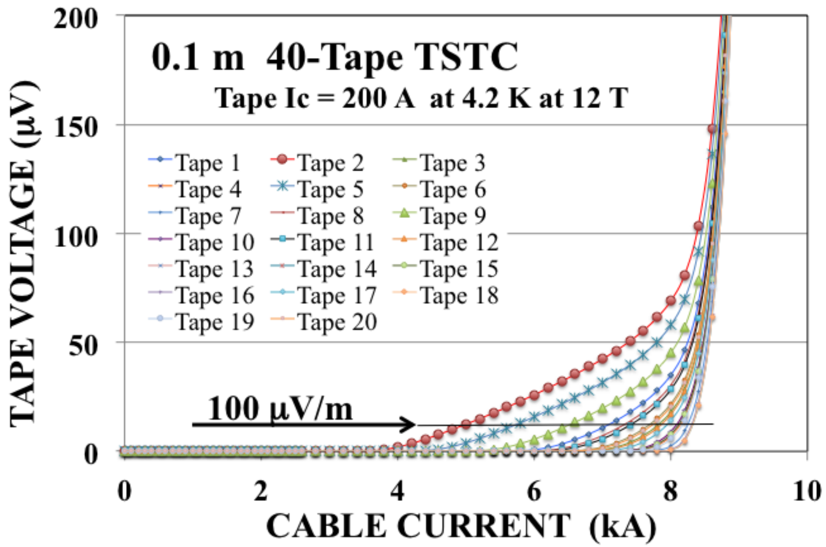
Estimated Termination Resistance Distribution used for Simulation



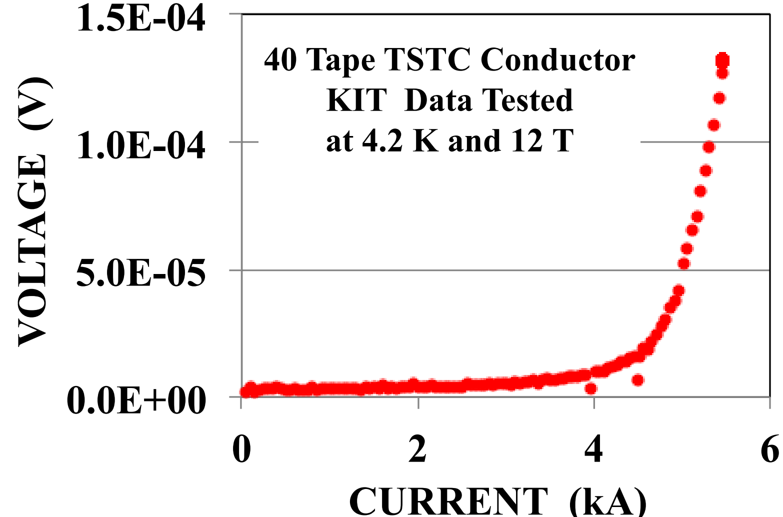
Termination tape-resistance statistic

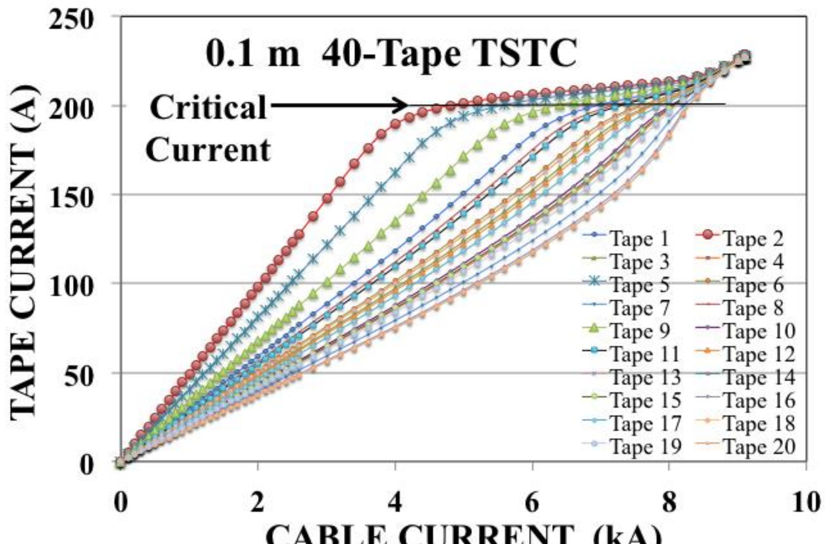
Average	Standard Deviation	Maximum	Minimum
529 nΩ	109 nΩ	672 nΩ	254 nΩ

Simulation Results for 1 m 40-Tape YBCO TSTC Conductor Tested at KIT



Test results measured at KIT



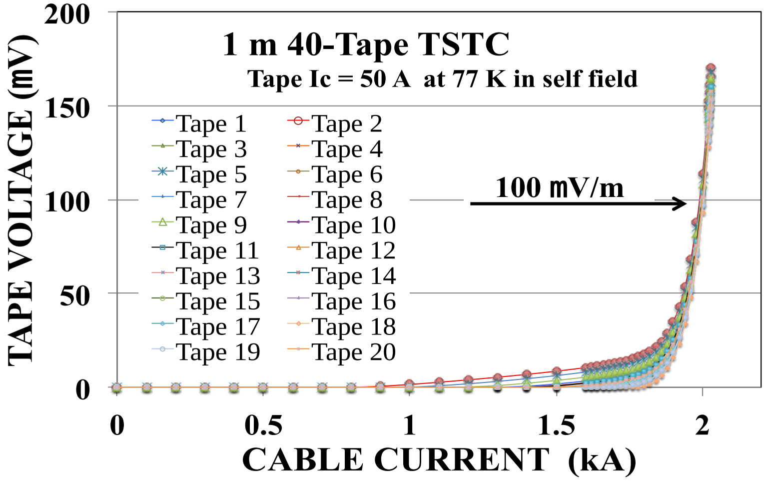


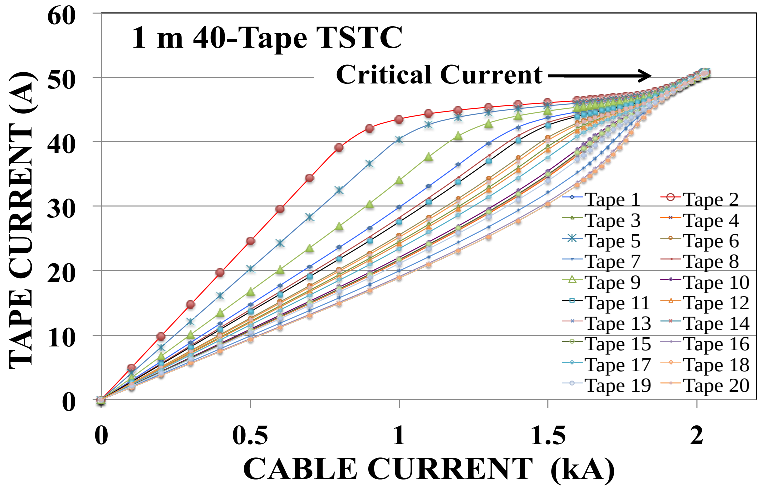
Figures show voltage and currents of 20-tapes among 40-tapes

Lower termination resistance tapes reach 100 μV/m at much lower current than the expected cable critical current.

Performance in Self Field and 5 m Cable

1 m 40-Tape Cable at 77 K (Self field)

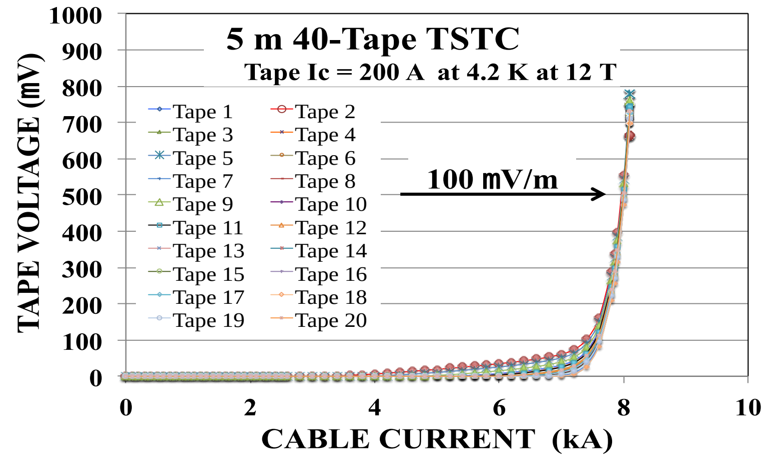


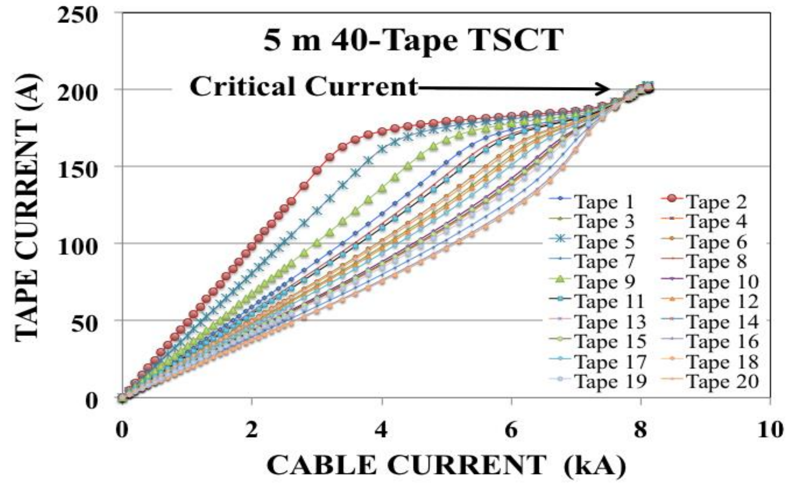


Termination resistance is not critical in self field at 77 K

(low current and long sample).

5 m 40-Tape Cable at 4.2 K and 12 T





Long cable is affected less by non-uniform termination resistances.

Large-Scale TSTC Conductor Concept

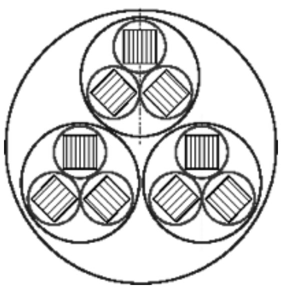
Basic conductor

Twisted stacked-tape cable in a round tube

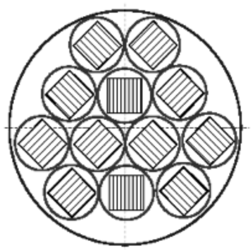
Cross-section and a twisted stacked-tape conductor

Multistage conductor

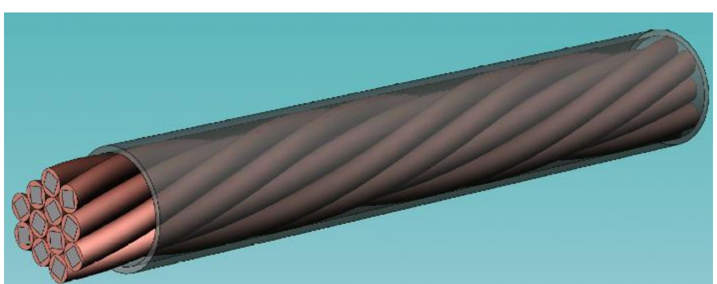
3x3 cable and 12 sub-cable conductors



3x3 cable



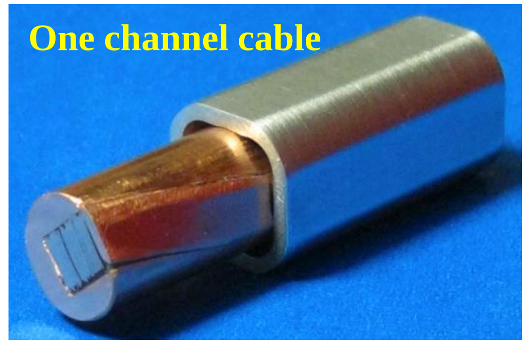
12 sub-cable



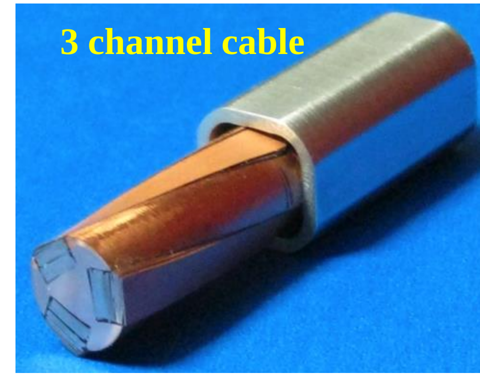
12 sub-cable conductor

CICC mockup of TSTC conductor

12 mm x 12 mm, copper diameter 9.5 mm

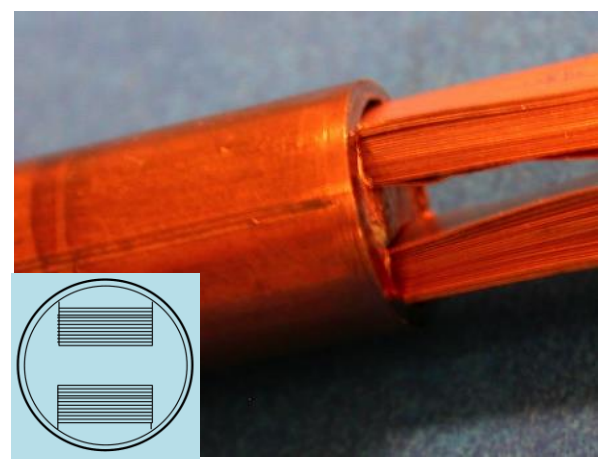


40 YBCO tapes



20 YBCO tapes in each helical groove (Total 60 tapes)

Supercon H-Channel TSTC Conductor



Self field degradation is reduced.

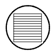
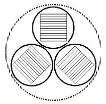
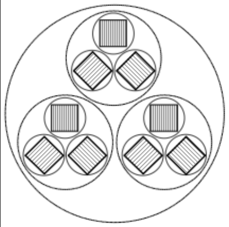
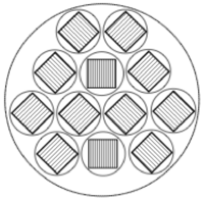
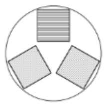
40 tape H-channel dual-stack cable

Large TSTC Conductor Current Capacity

Estimated currents and current densities of various conductors

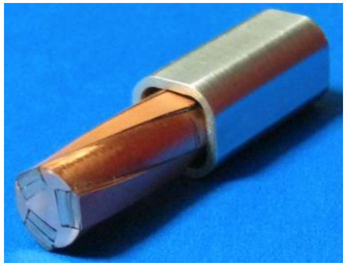
Basic cables composed of 40-tapes

Calculation based on SuperPower tape, the critical current (193 A) at 16 T and 4.2 K

Conductors	Current at 16 T, 4.2K (kA)	Current Density (A/mm^2)	Conductor Diameter (mm)	Conductor Cross-Section
Basic cable	7.7	273	6.0	
3 subcable	23.2	175	13	
3x3 cable	69.5	113	28	
12 subcable	92.7	205	24	
H-channel basic cable	7.7	109	9.5	
3-channel basic cable	23.2	151	14	

Multi-stage cables

H-channel cable

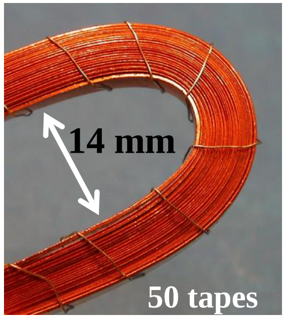


3-channel CICC cable

TSTC for Accelerator Magnet Application

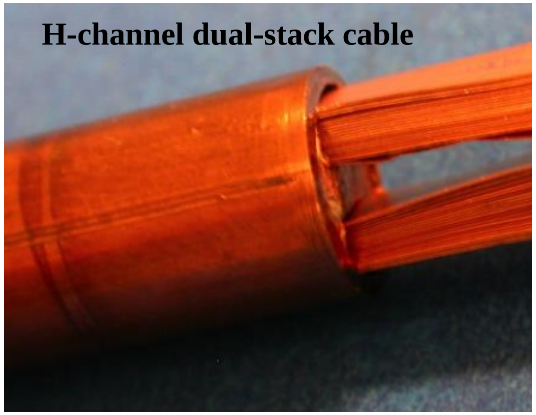
Possible Practical Basic Conductor

Small diameter 3D winding



STTW

Large diameter magnet



TSTC

4 mm width, 40-tape TSTC conductor
based on SuperPower AP Tape

- **Minimum twist pitch -**
  150 mm (100% I_c), 100 mm (98% I_c)
- **Electromagnetic force degradation -**
  ~15% degradation by 60 kN/m (5 kA x 12 T) or 15 MPa
  20 T magnet: 136 kN/m (6.8 kA x 20 T) or 34 MPa
  Degradation?
- **Critical current and current density**

Achieved	I_c	Overall J_e
TSTC tested at KIT 9.5 mm Dia. Cu sheathed	5 kA (B=12 T)	70 A/mm^2 (B=12 T)

Tape I_c = 235 A at B = 12 T, I_c = 170 A at B = 20 T

Potential	I_c	Overall J_e
TSTC		
9.5 mm Dia. Cu sheathed TSTC tested at KIT	9.4 kA (B=12 T) 6.8 kA (B=20 T)	**133 A/mm^2** (B=12 T) **96 A/mm^2** (B=20 T)
Single stack 6.0 mm Dia.	6.8 kA (B=20 T)	**241 A/mm^2** (B=20 T)
H-channel dual stack 9.0 mm Dia.	6.8 kA (B=20 T)	107 A/mm^2 (B=20 T)
STTW		
Stacked tapes sandwiched with two Cu strips 6.5 mm Dia.	6.8 kA (B=20 T)	**203 A/mm^2** (B=20 T)

Conclusions and Future Work

Twisted Stacked-Tape Cable (TSTC)

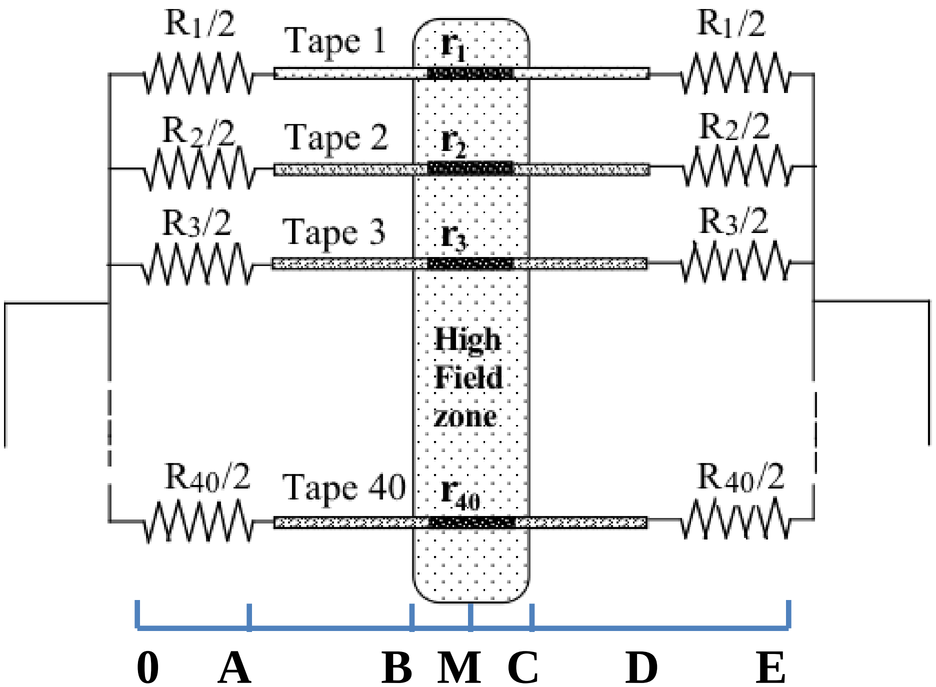
- Simple cabling method, high tape usage, good bendability, compact cable, high current density, scale-up for large cable fabrication
- Termination and joint:
  - YBCO-BSCCO, and YBCO-YBCO (demountable mechanical contact or soldered)
  - Fan solder termination
- Degradations:
  - Low field: Self-field degradation
  - High field: Electromagnetic force and non-uniform termination resistances

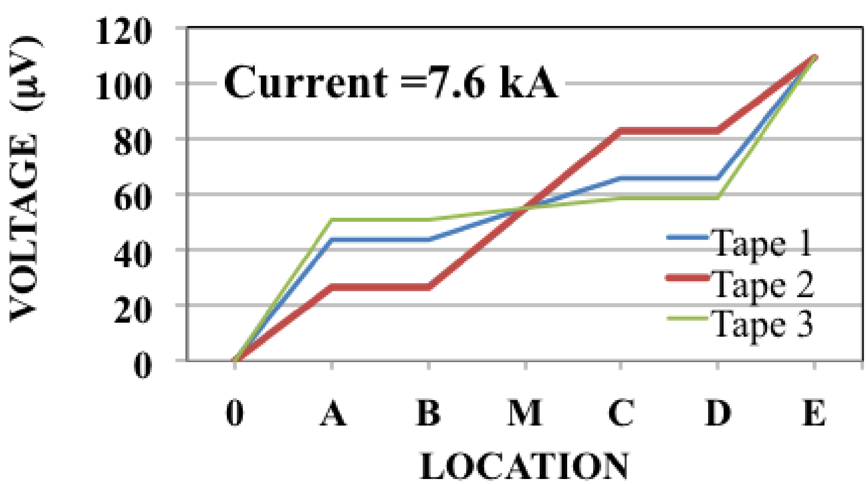
Future Work

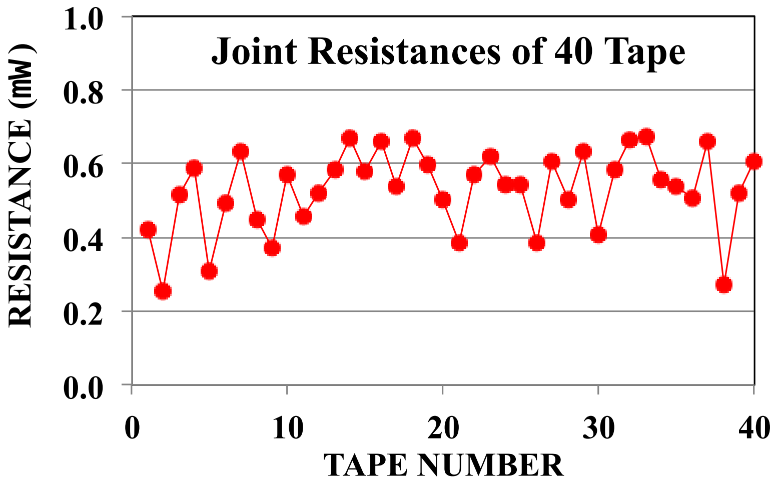
- Further degradation study: High field cable tests
- Stacked-Tape Twist-Winding (STTW) for 3D magnets
- Multiple-stage cable: Bendability and high field tolerance
- AC losses, screening (shielding) current, magnetization, transverse load

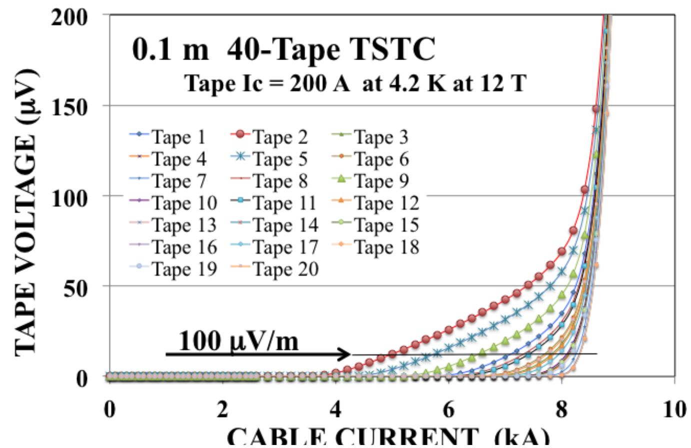
Thank you for your attention

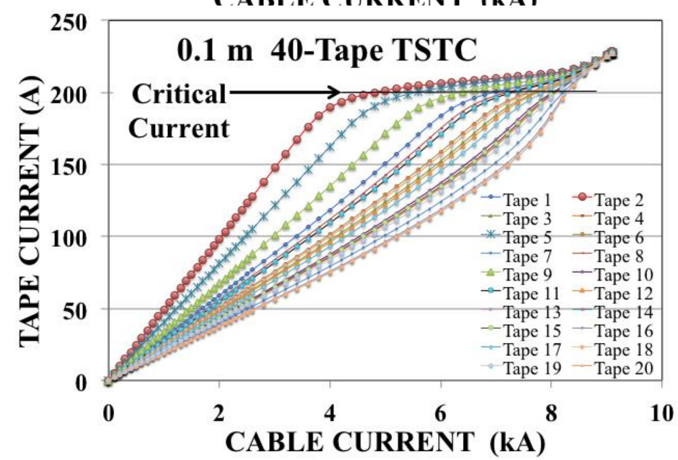
Tape voltages of Tapes #1, #2 and #3

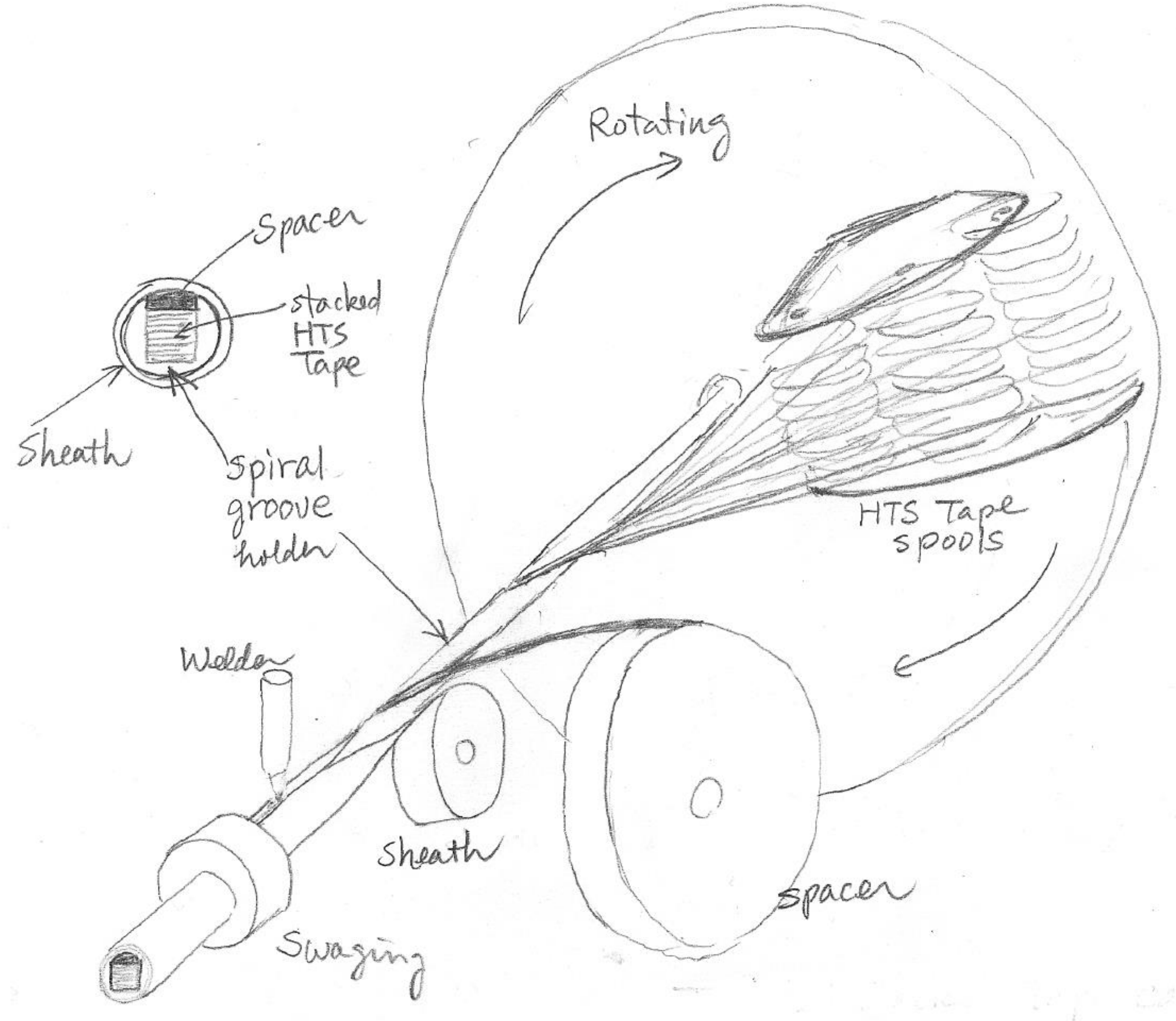




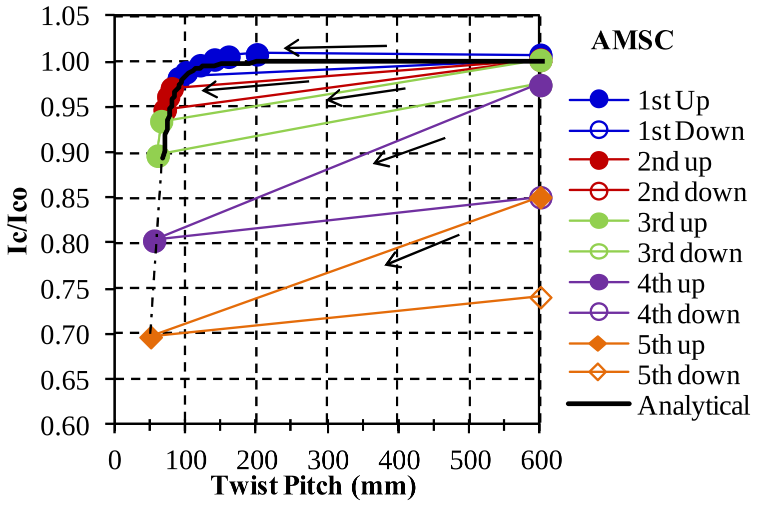


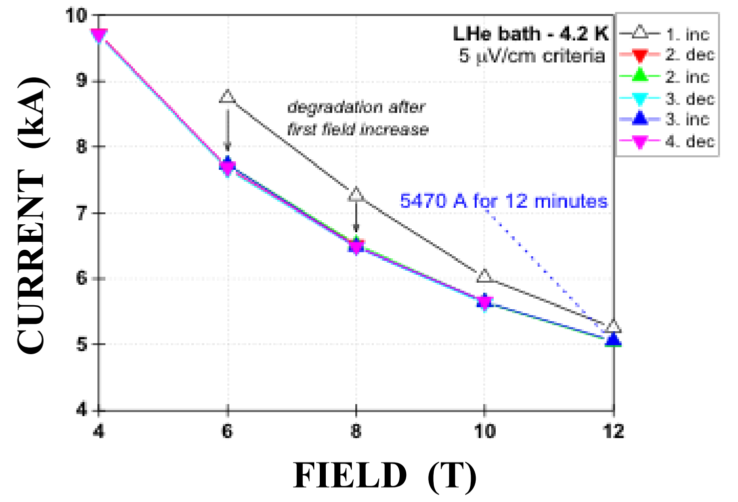


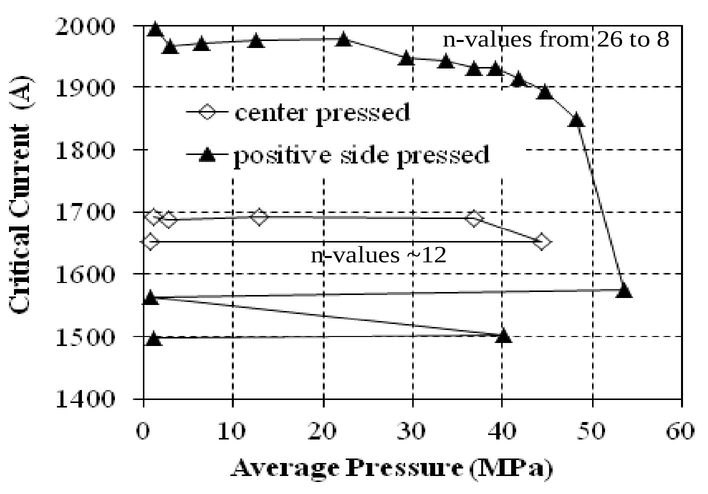


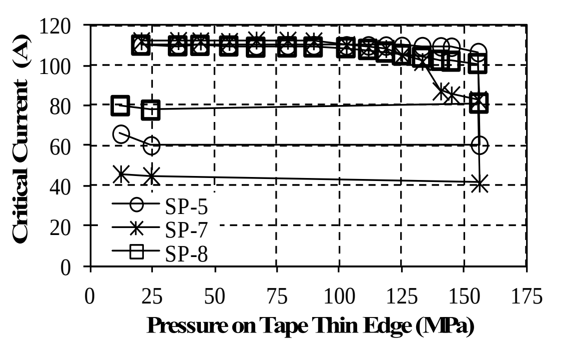


Twisted Stacked-Tape Cable Process


AMSC
1st Up
1st Down
2nd up
2nd down
3rd up
3rd down
4th up
4th down
5th up
5th down
Analytical
Ic/Ico
Twist Pitch (mm)


LHe bath - 4.2 K
5 μV/cm criteria
degradation after first field increase
5470 A for 12 minutes
1. inc
2. dec
2. inc
3. dec
3. inc
4. dec
CURRENT (kA)
FIELD (T)

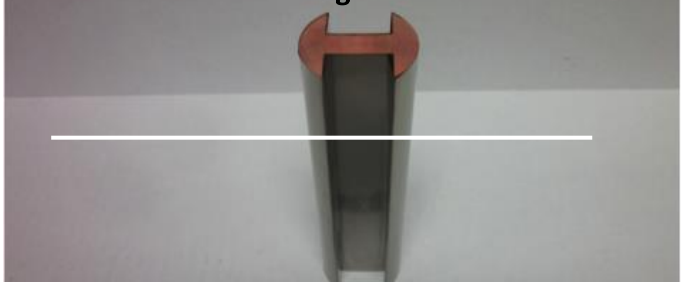

n-values from 26 to 8
center pressed
positive side pressed
n-values ~12
Critical Current (A)
Average Pressure (MPa)


SP-5
SP-7
SP-8
Critical Current (A)
Pressure on Tape Thin Edge (MPa)

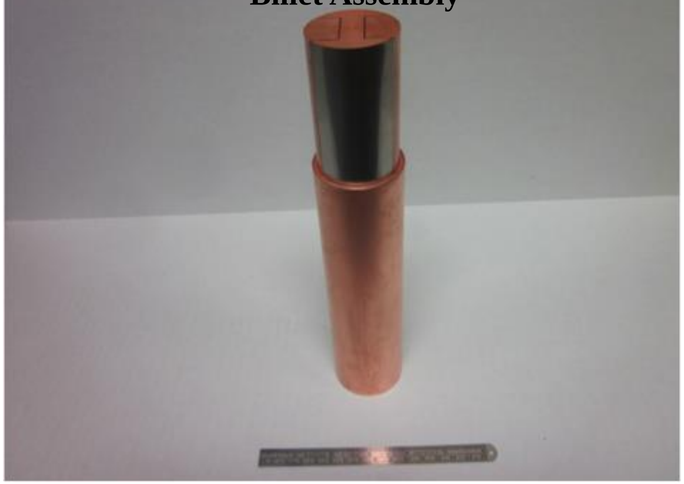
Scale-up Fabrication Method Development (2)

1.75” OD x 6” L Cu Rod after EDM Cutting of Channel Slots

Channel Wrapped in 0.005” Ti Foil Etching Barrier



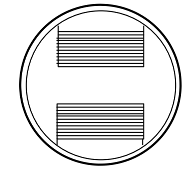
EDM Channel with Ti Etching Barrier in Billet Assembly



Supercon H-Channel TSTC Conductor

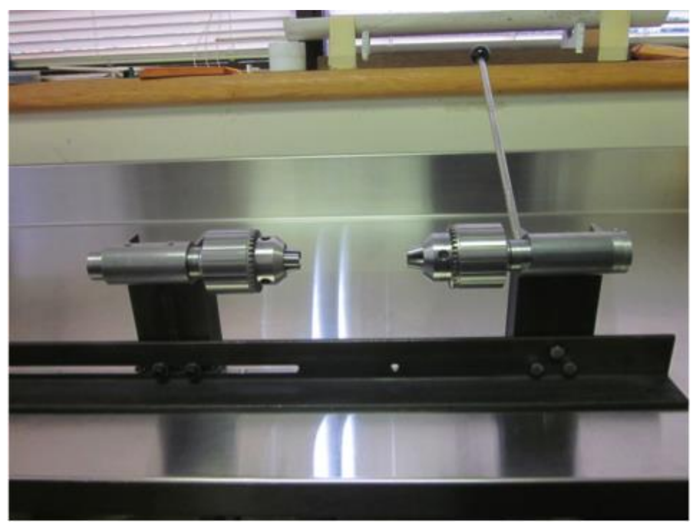
H-channel conductor with 40 tapes

1. Make H-channel slot from a billet (44.5 mm Dia. 152 mm length) by EDM.
2. Channel surfaces covered with 0.13 mm **Ti foil**.
3. Cover with a copper sheath, and draw down to 7.9 mm Dia. (4.8 m length).
4. **Twist** and remove the outer sheath and channel fillers by **Ti-etching**.
5. **Insert 20 YBCO tapes** in each channel.
6. Rod and tape assembly are inserted into a **copper sheath**, and draw the sheath to match to the H-channel diameter. Outer diameter is about 9.1 mm.



Cross-section of H-channel cable

40 tape H-channel cable



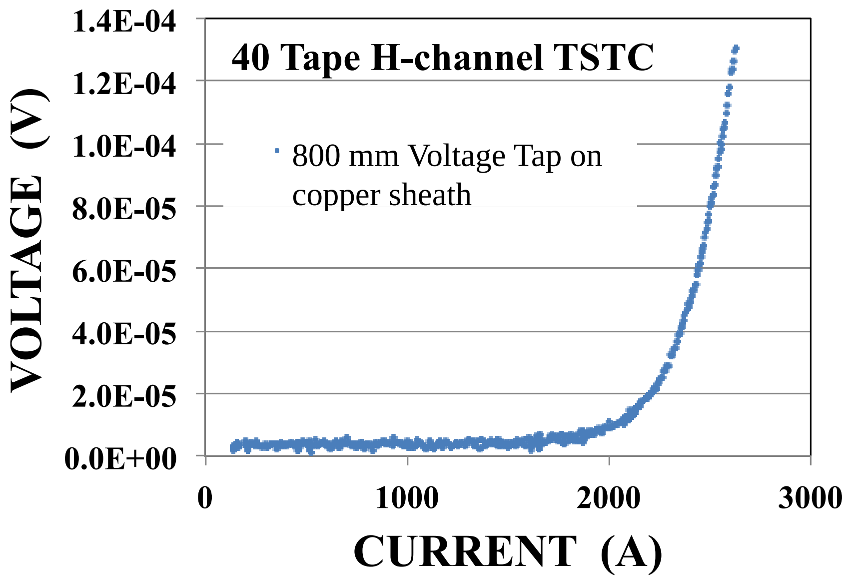
Twisting tool

The distance between chuck jaws is adjustable up to 800 mm.

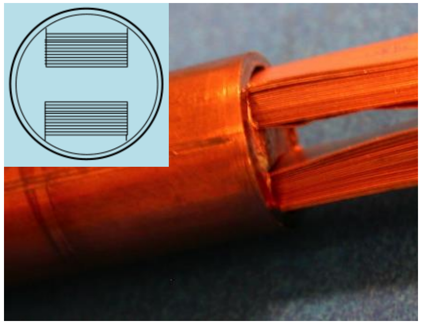
Scale-up Fabrication Method Development (2) cont'd

H-Channel Conductor

Critical Current Test Results at 77 K

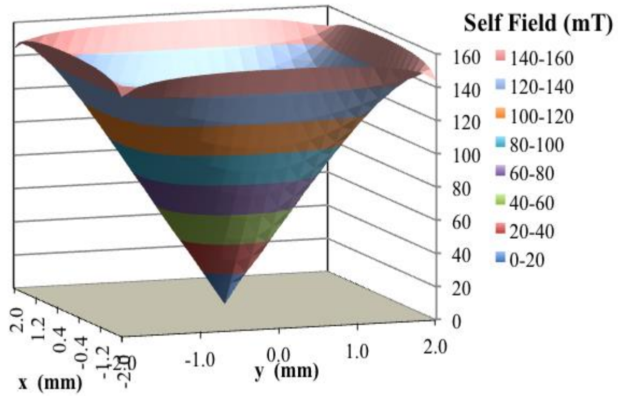


Supercon H-Channel TSTC Conductor

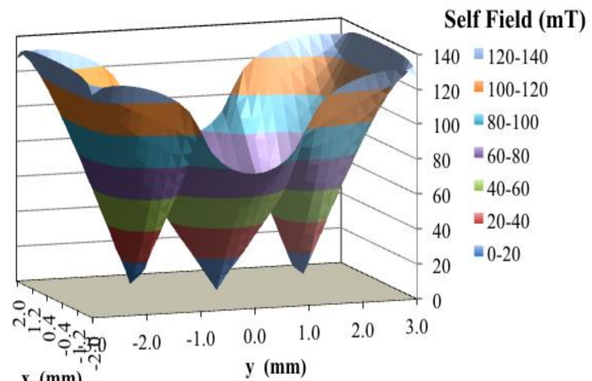


I_c = 2080 A at 10 μV/m,
2560 A at 100 μV/m (n=12)

Self-field distribution on cable cross-section



Single channel (4 mm x 4mm)



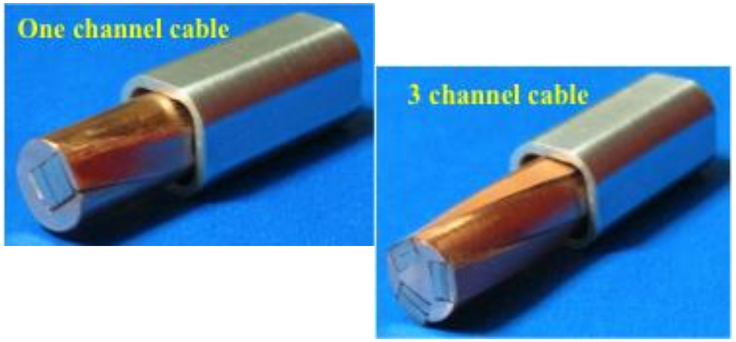
H-channel (Two of 2 mm x 4mm)

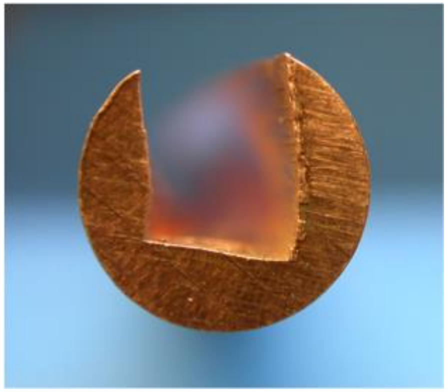
H-channel conductor reduces the self-field effect.

Scale-up Fabrication Method Development (1)

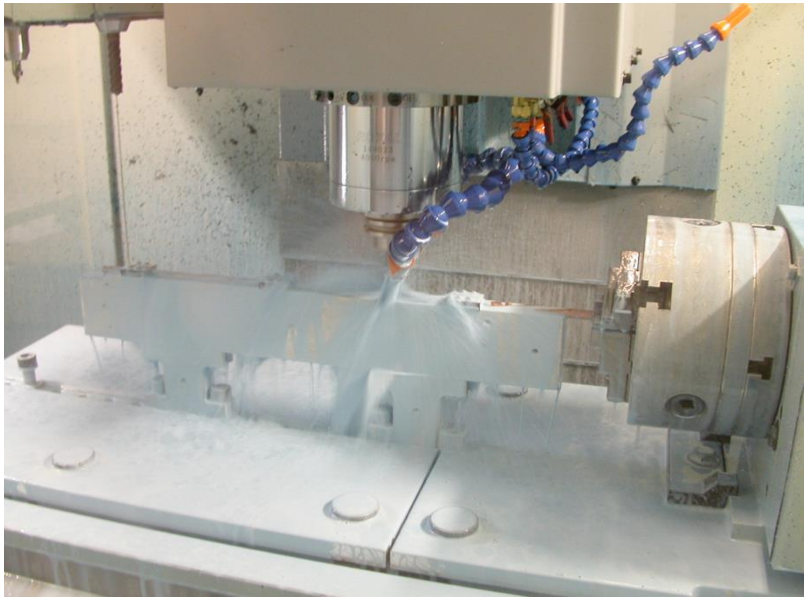
Machine Helical Groove in a copper rod

Fabricated one (upper) and three (lower) helical grooves of 508 mm length on 3/8” diameter copper rod.
The inserts show close-up view of the rods of one and three grooves, and the cross-sections.



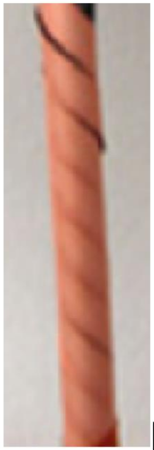
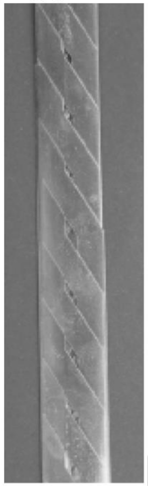


Cross-section of one-helical-groove machined on a 3/8” (9.5 mm) diameter copper rod.



Four axis CNC milling machine fabricating 20” long, three helical grooves on a 9.5 mm diameter copper rod.

HTS Tape Cabling Methods

	Helical winding on a round former		Stacking	
Cabling methods	Winding with a long pitch on a large diameter former.  [2]	Winding tightly with a short pitch on a small diameter former.  [10] **CORC** Conductor on Round Core	Roebel cabling of tapes cut in zigzag pattern.  [5] **RACC** Roebel Assembled Coated Conductor	Twisting stacked tapes.  [22] **TSTC** Twisted Stacked-Tape Cable
Calculated length ratio of cable to tape length	**94% - 97%** depending on former diameter and winding pitch	**40% - 90%** depending on former diameter and winding pitch	**40% - 89%** depending on the number of strands obtained from a original tape	**99%**

M. Takayasu, et al, *Supercond. Sci. Technol.* **25** 014011, 2012.

[2] J.F. Maguire, et al., *IEEE Trans. Appl. Supercond.* **17** 2034-2037, 2007.

[5] W. Goldacker , et al., *IEEE Trans. Appl. Supercond.* **17** 3396-3401, 2007.

[10] D.C. van der Laan, et al., *Supercond. Sci. Technol.* **24** 042001, 2011.

[22] M. Takayasu M, et al, *IEEE Trans. Appl. Supercond.* **21** 2341-2344, 2010.