4th Workshop on
Accelerator Magnets in HTS
WAMHTS-4

Recent developments on HTS Slotted-Core Cable-In-Conduit Conductor

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Fusion and Technology for Nuclear Safety and Security Department (FSN)

Summary

- Introduction:
  - HTS high current cables from the ENEA-Tratos Cavi collaboration: **slotted-core** and **round strand**

- *Al*-slotted core cable:
  - Performance of 5 slot sub-size slotted-core samples:
    - Electric experiments;
    - Thermo-hydraulic tests;
    - Bending tests: layout of samples, experiments and analytical model

- Conclusions and Perspectives

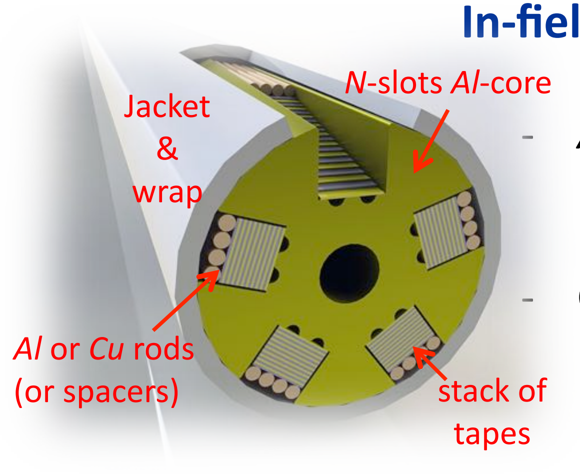
HTS cables @ ENEA

Fundamental design driver: ***industrial process feasibility***

Exploited technologies: ***Aluminum – extrusion***; ***Twisted-stacked tape***

Multi-strand *Al*-slotted Core HTS CICC

In-field applications



- *Al*-stabilized slotted core for HTS tape stacks;
- Coolant channels;

HTS cables @ ENEA

Fundamental design driver: ***industrial process feasibility***

Exploited technologies: ***Aluminum – extrusion***; ***Twisted-stacked tape***

Multi-strand *Al*-slotted Core HTS CICC

-field applications

- *Al*-stabilized slotted core for HTS tape stacks;
- Coolant channels;

5 slot Al-core for 4 mm wide tapes

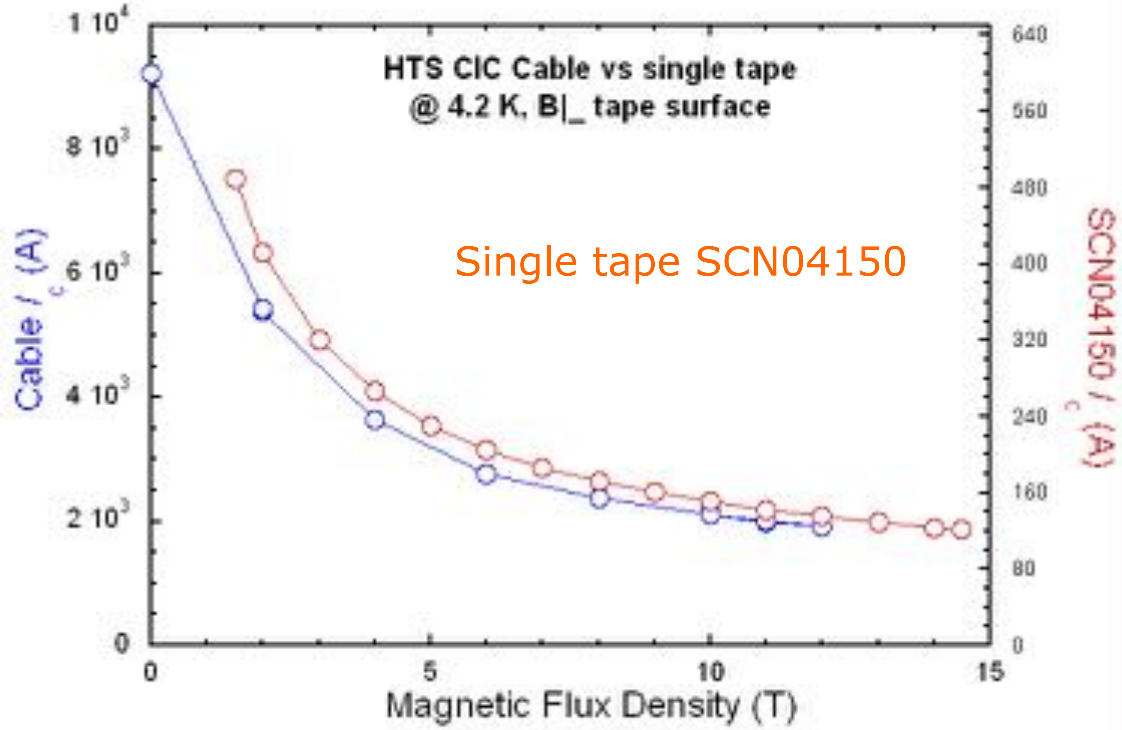
3 slot Al-core for 12 mm wide tapes

Al-stabilized twisted stack of 2G tapes Round strand (Macro-Strand, MAST)

fabrication process still to be improved

Tests at FBI Facility (KIT)

ASC14 – A. Augieri – Charlotte (NC), August 2014



- 1 stack of 18 Tape: ***SuNAM-SCN04150*** (I_c ≈ 225 A *sf*, 77K);
- Straight stack;
- Cable length: 120 cm

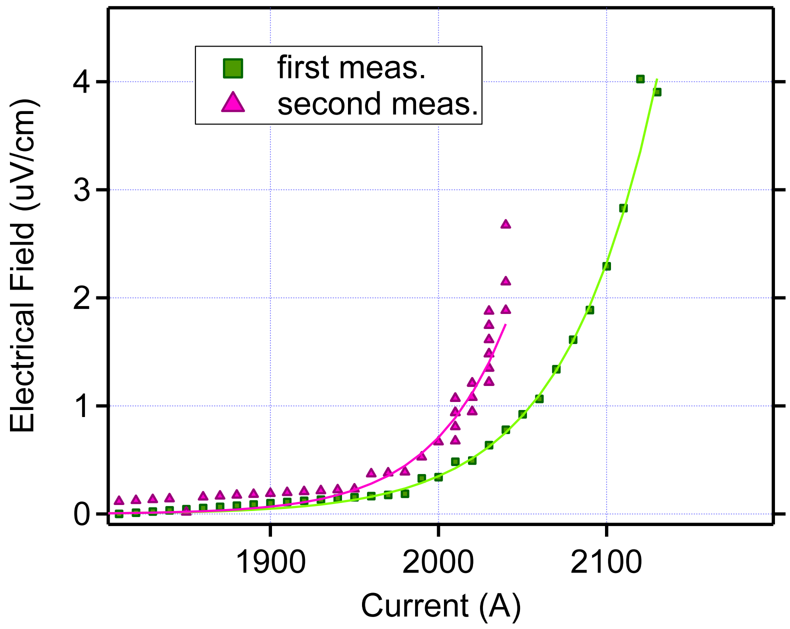
- I_c (*s.f.*) = 9.3 kA
- I_c (10 T) = 2.2 kA
- n – index = 15 - 21 independently from B

- No I_c degradation after multiple runs @10 T and 11 T
- In high field region: cable I_c reproduces single tape I_c(B)

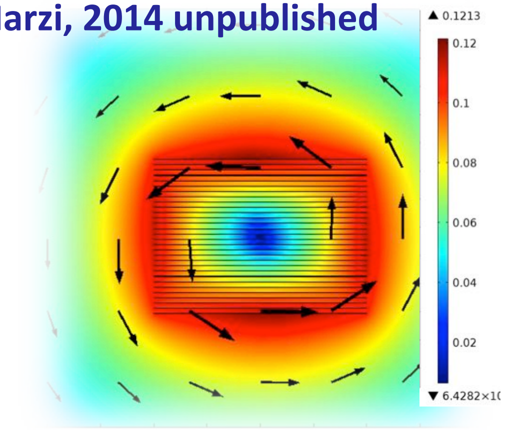
Outputs of Tests at FBI

Good prediction capabilities: Magneto-static FEM Model

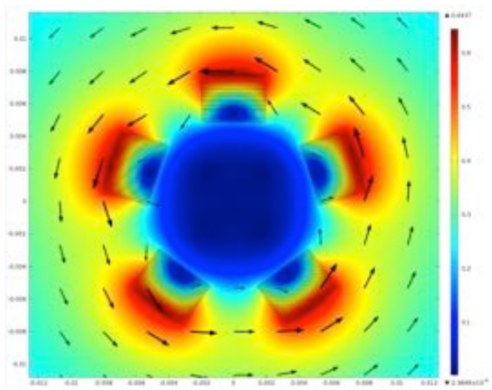
Termination feasibility: Cu insert for staggered stack end



G. De Marzi, 2014 unpublished



@ s.f., LN2	Measured	Computed
$I_{c,\ 1\ stack}$ - SUNAM	≈ 2049 A	= 2139 A



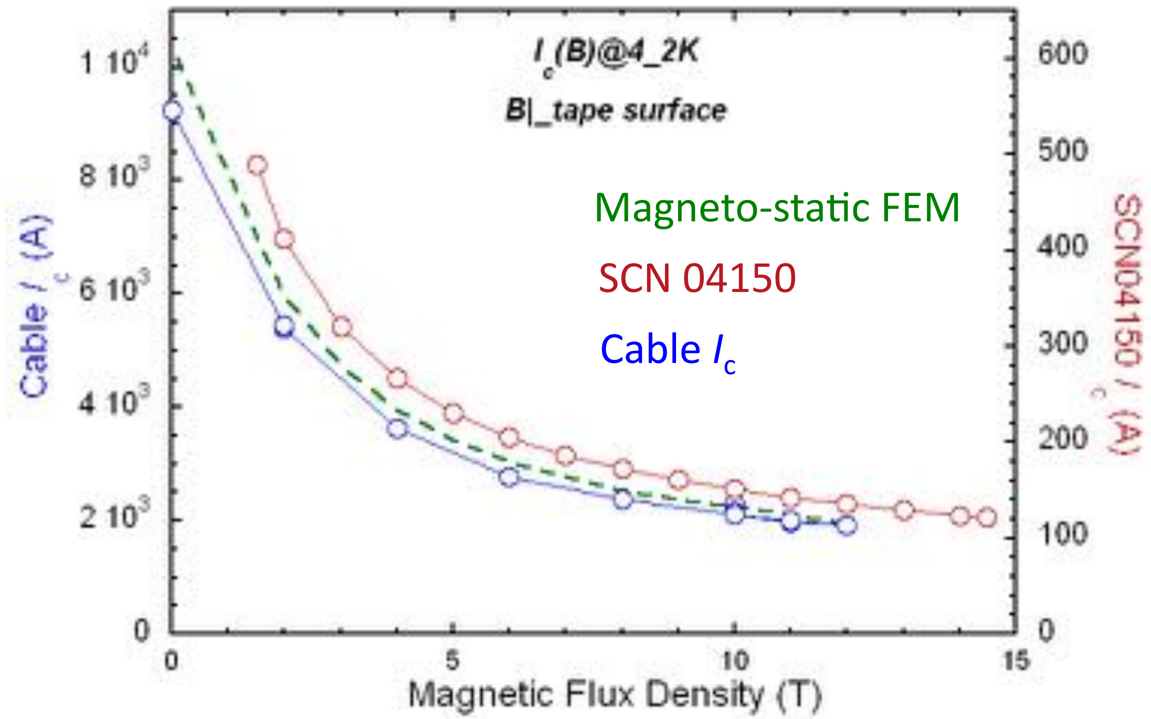
Prediction for fully equipped (5 stacks, 96 tapes) cable assuming the actual tape $I_c(B, \theta)$ @ 77 K:

$I_{c,cable}$ **≈ 9.7 kA @ s.f., LN2**

Outputs of Tests at FBI

Good prediction capabilities: Magneto-static FEM Model

G. De Marzi, 2014 unpublished



@ 12T, 4.2K	Measured
$I_{c,\ 1\ stack}$ - SUNAM	≈ 1952 A

Model prediction for fully equipped (5 stacks) cable (**@ 12T, 4.2K**):

$I_{c,cable}$ ≈ **10 kA (SUNAM SCN04150)**

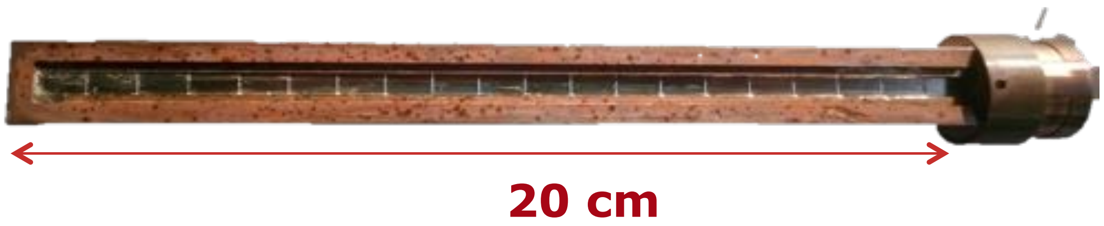
> 20 kA (SPI SCS4050-AP)

J_e ≈ 70 A/mm^2
(without Jacket)

Outputs of Tests at FBI

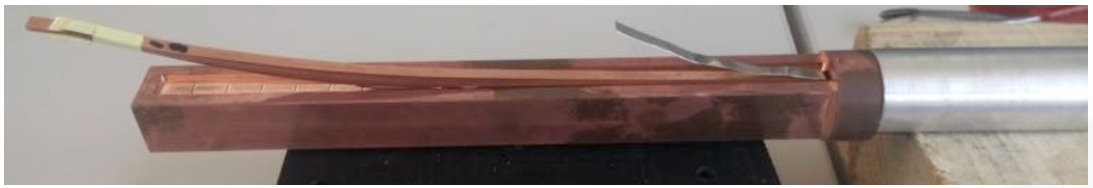
Good prediction capabilities: Magneto-static FEM Model

Termination feasibility: Cu insert for staggered stack end



Expected Resistance for a full cable (5 stacks): ≈ 10 - 20 nΩ

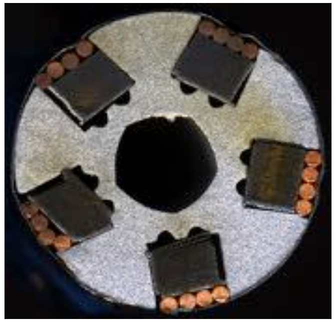
- Stack end soldered at T< 210 °C to Cu plate with Pb-Sn by applying low load (≈ 0.5 atm)
- R ≈ 0.5 μΩ cm^2 at LHe on single tape



Thermal-hydraulic test @ Sultan

Sample for hydraulic tests

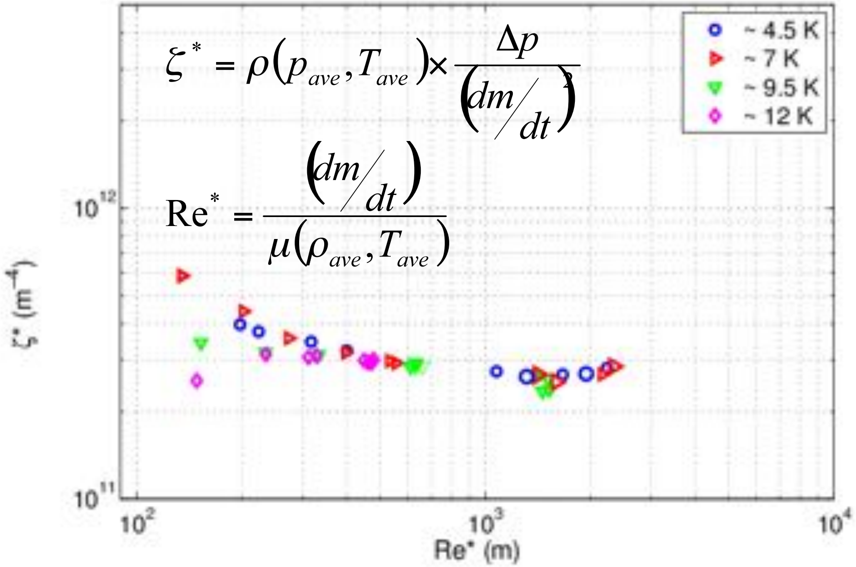
L. Savoldi et al. IEEE TAS (2016)



2 m long CIC sample

All slots filled with 20 SS tapes

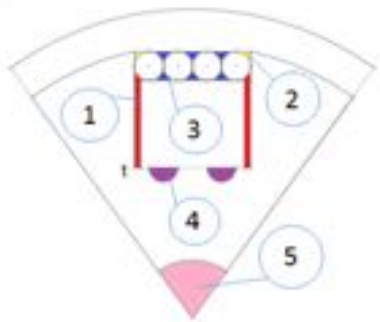
Twist pitch: 500 mm

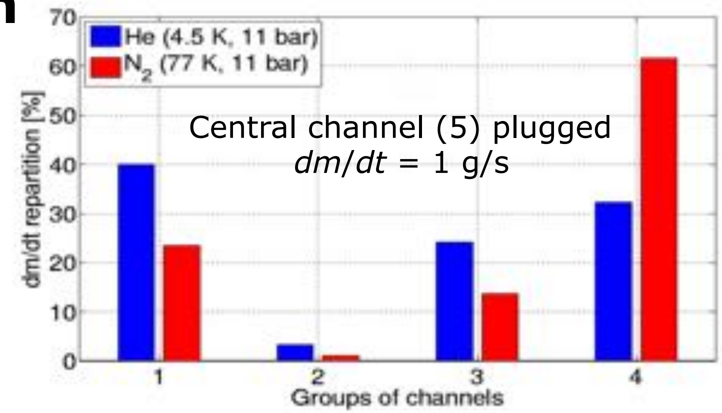


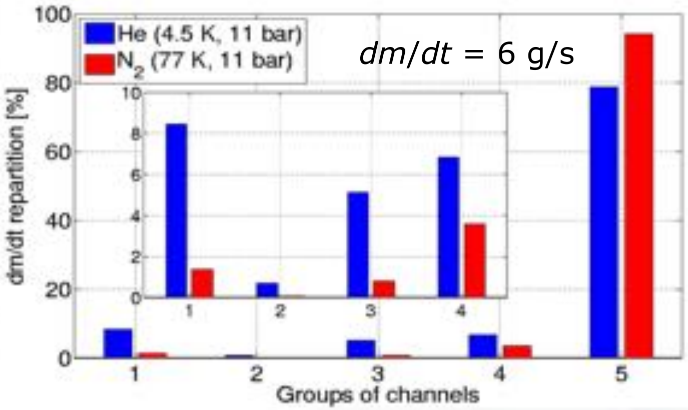
Hydraulic characteristic of the cable measured in different conditions (dm/dt, T_{in})

Input for the **4C code** to evaluate /optimize flow repartition by parametric analyses:

Flow repartition







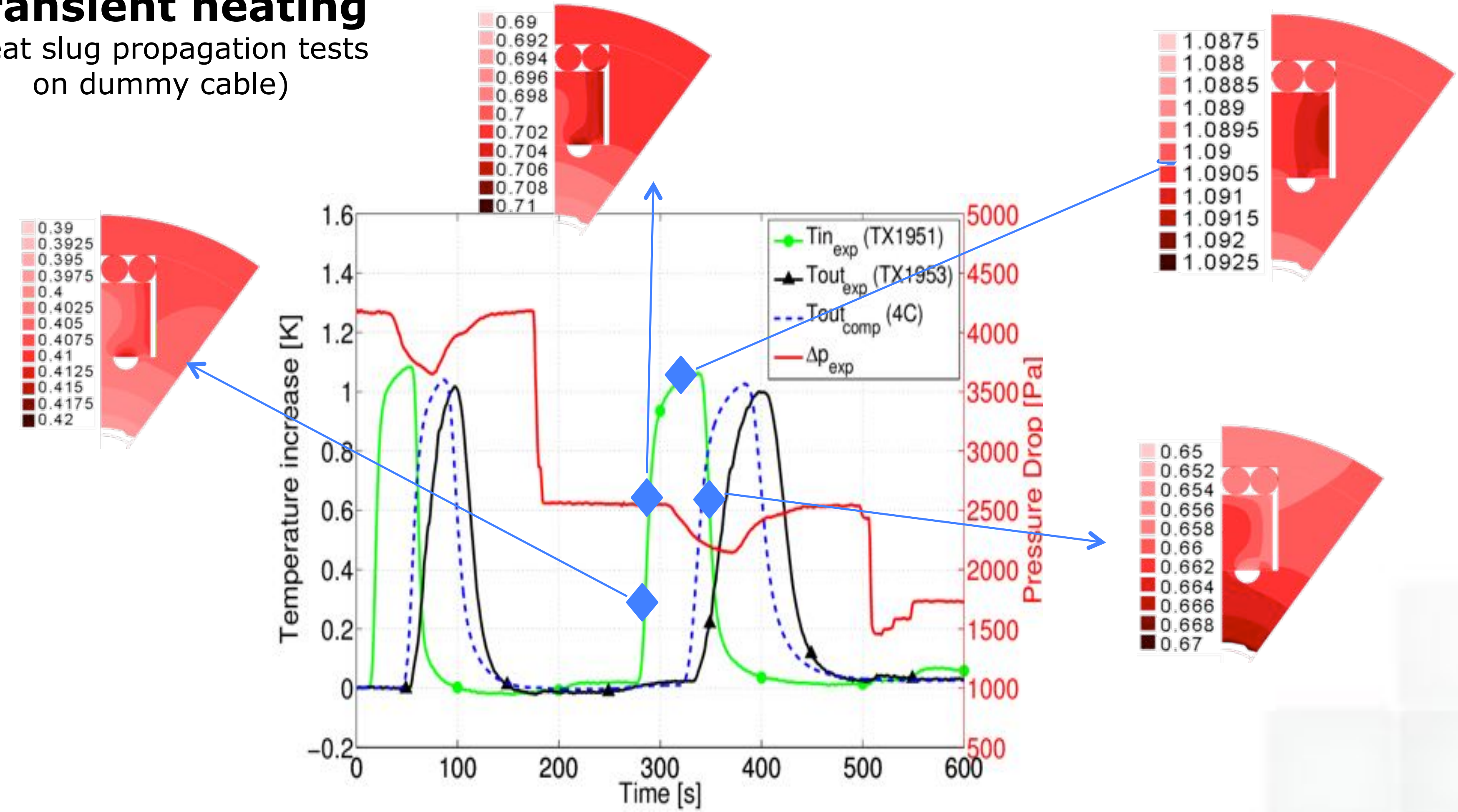
Thermal-hydraulic test @ Sultan

Cooling capability

L. Savoldi *et al.*
IEEE TAS (2016)

Transient heating

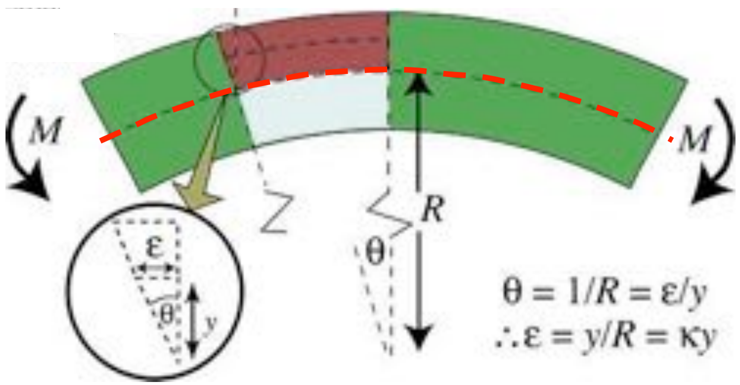
(heat slug propagation tests
on dummy cable)



T uniform within 30 mK (high heat diffusion across Al)

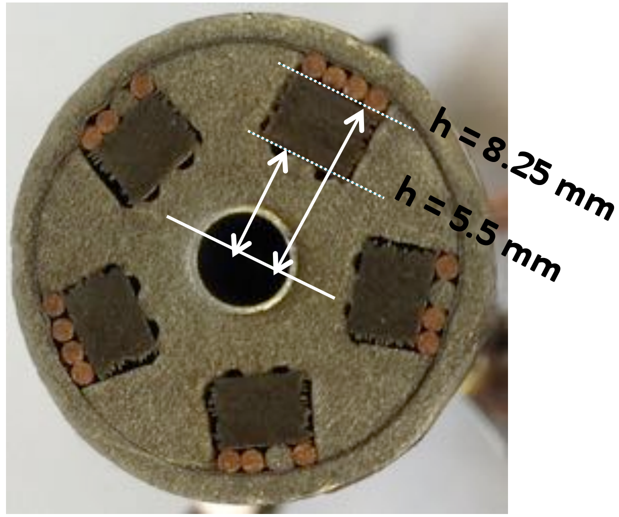
Bending Cable Capability

Bendability is one of the key features for real applications



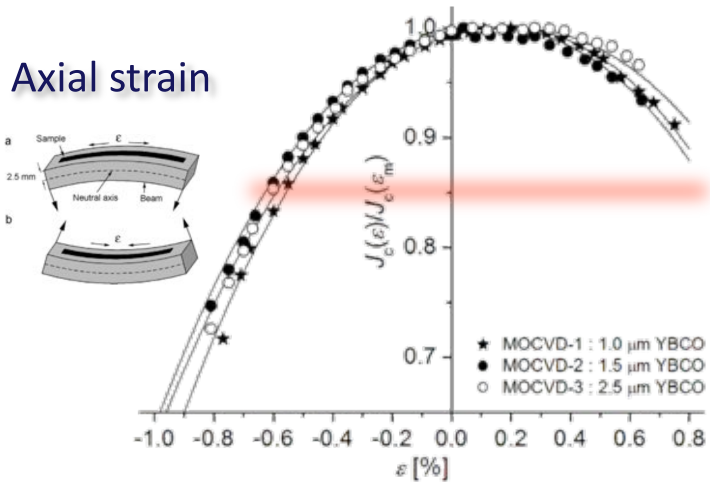
$$\varepsilon = y/R$$

R = bending radius,
y = distance from neutral surface

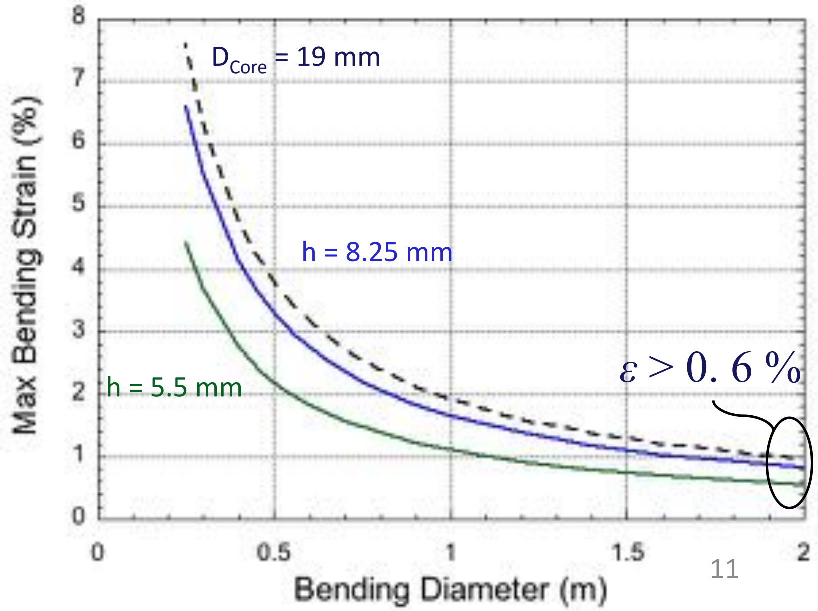


Significant I_c degradation (-15% @ $\varepsilon \approx 0.6$ %) expected already @ $D_{bend} \sim 2$ m

Axial strain



van der Laan and Ekin, SuST 21, (2008)



Bending Tests at MIT and Tufts

Investigation of the **bending behaviour** of HTS Al-slotted core CIC samples

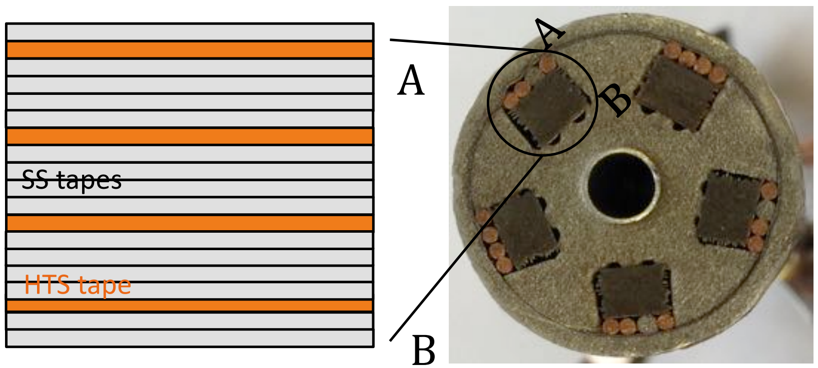
(M. Takayasu, and L. Chiesa)

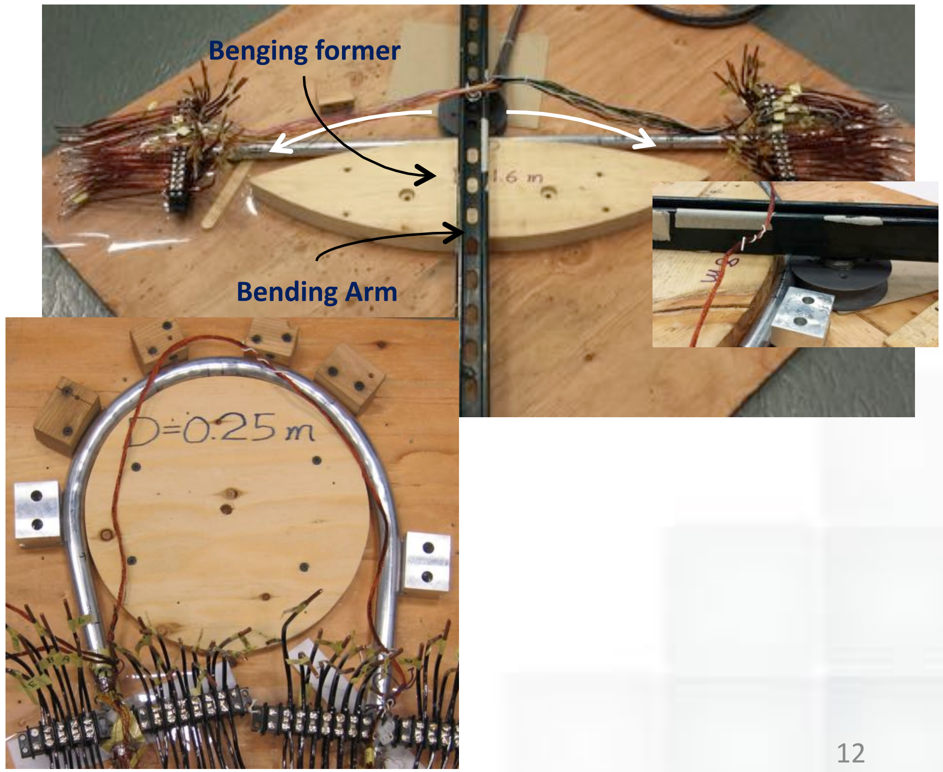
MIT PSFC Plasma Science and Fusion Center
Tufts University School of Engineering

Cable parameters	#7, #8
Length (m)	0.85
Twist Pitch (mm)	#8: 500 #7: 1400
Al-Jacket	yes
HTS tapes SuNAM	SCN04150 (150 um thick)
layout	4 HTS tapes + 15 SS

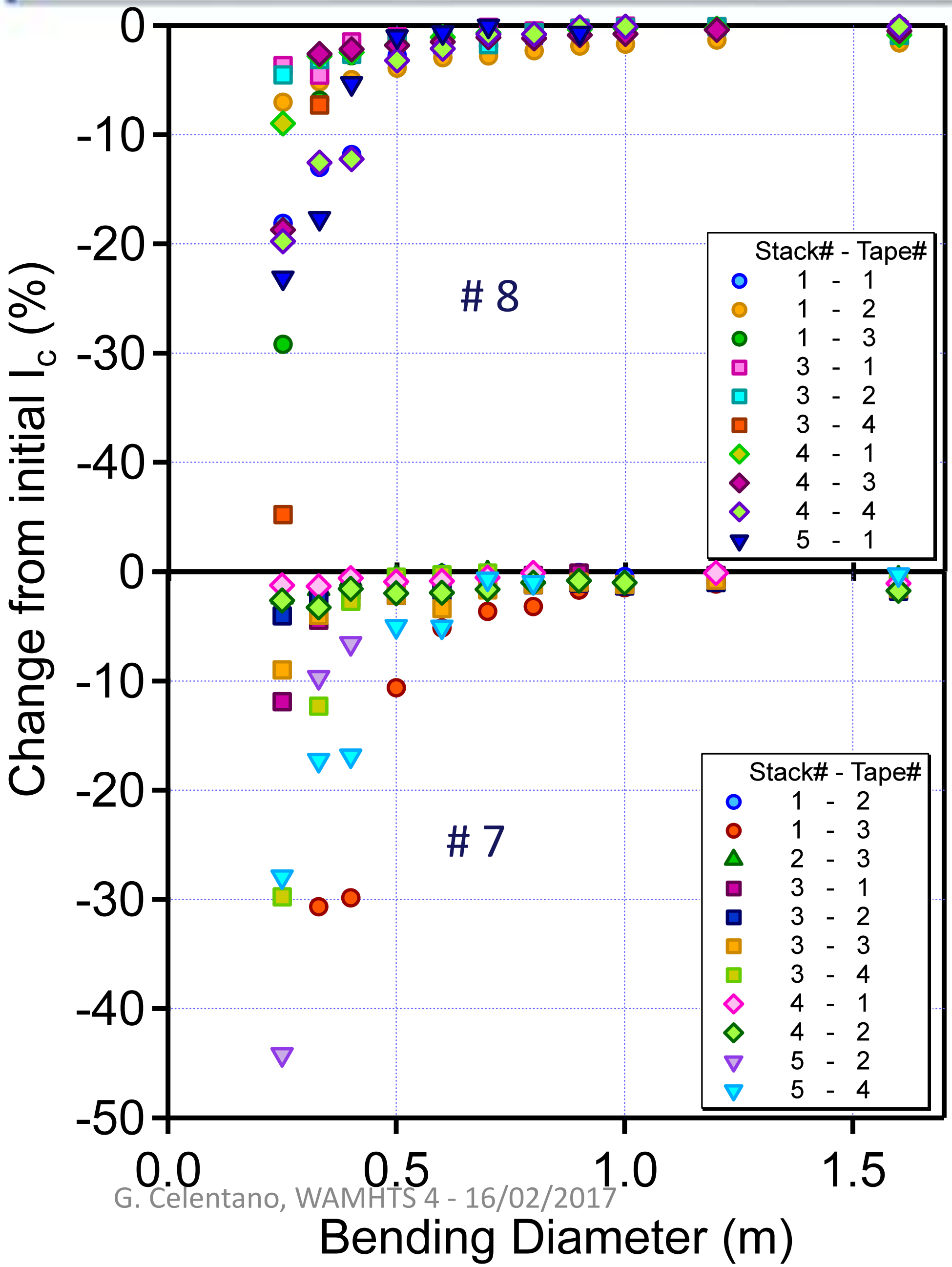
- Bending diameter was reduced in steps down to 0.25 m;
- Bent section is ≈ 0.55 m long;
- Effect of bending strain recorded *I-V* on each single tape @ LN2

D (m)
1.6
1.2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.33
0.25





% Change from initial I_c



G. De Marzi, *et al.*, IEEE TAS, 4801607 (2016)

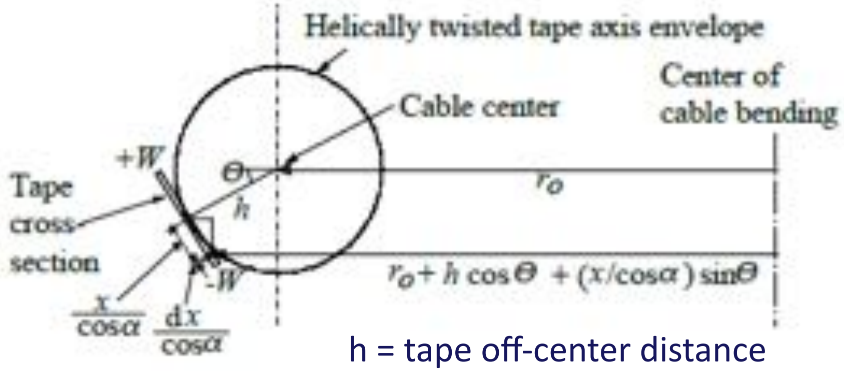
- No correlation between I_c degradation and position of tapes inside the stack
- Degradation of I_c found at low bend diameter values (D_{bend} < 0.5 m)
- %Change from initial I_c:

< -4% (# 8 - STP) & -10% (# 7 - LTP) @ 0.5 m Dia.

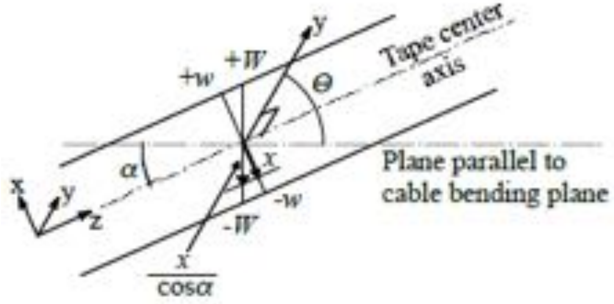
<-18% (# 8 - STP) & -31% (# 7 - LTP) @ 0.33 m Dia.

Cable Bending Model

Bending characteristic of TSTC conductors can be investigated by analytical models (*Takayasu, ICMC 2015, Tucson*)



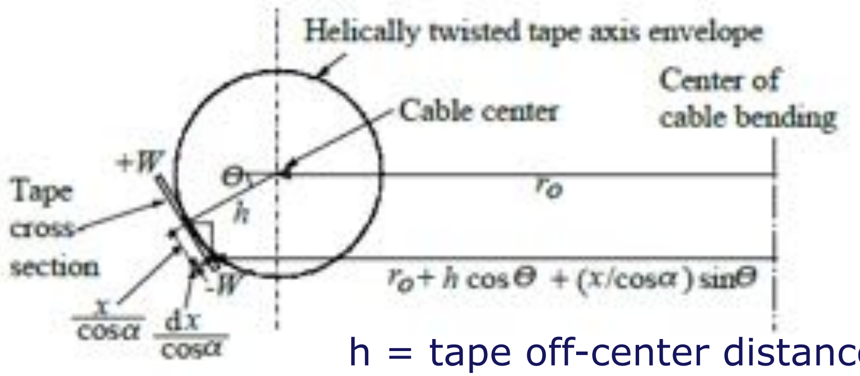
h = tape off-center distance



$$\varepsilon_b = \frac{\left(\frac{x}{cos\alpha}\right)sin\theta + hcos\theta}{r_0 + hcos\theta + \left(\frac{x}{cos\alpha}\right)sin\theta} \cos\alpha$$

No-Slip Model

Bending characteristic of TSTC conductors can be investigated by analytical models (*Takayasu, ICMC 2015, Tucson*)

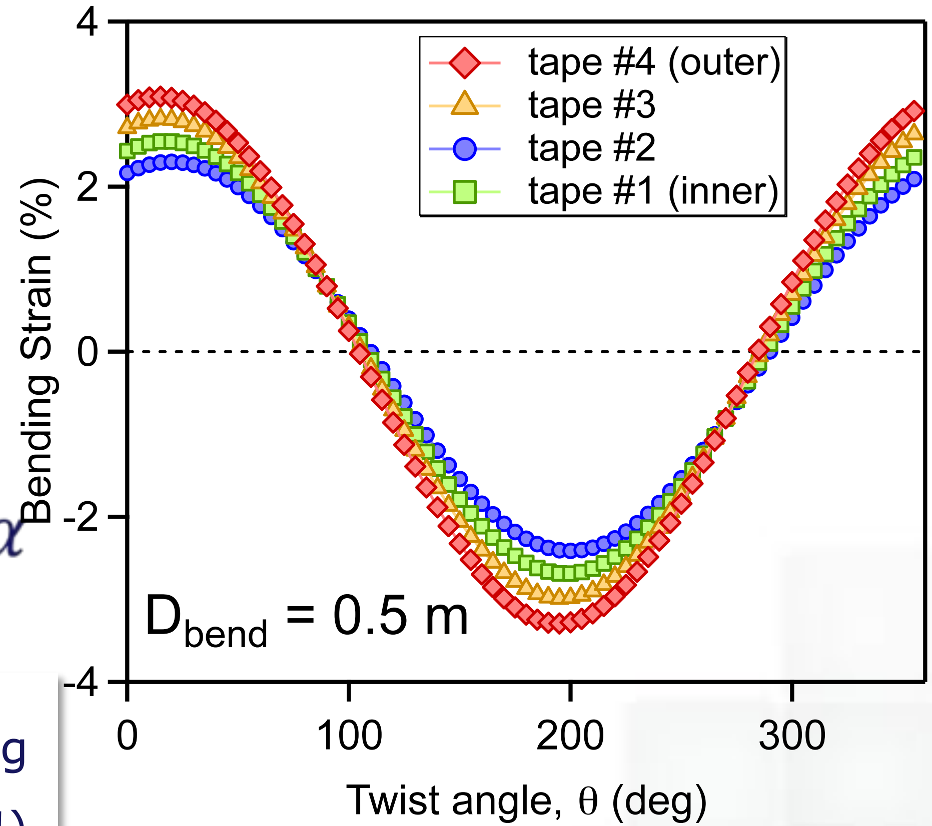


h = tape off-center distance

$$\varepsilon_b = \frac{\left(\frac{x}{\cos\alpha}\right)\sin\theta + h\cos\theta}{r_0 + h\cos\theta + \left(\frac{x}{\cos\alpha}\right)\sin\theta}\cos\alpha$$

strain due to the tape width

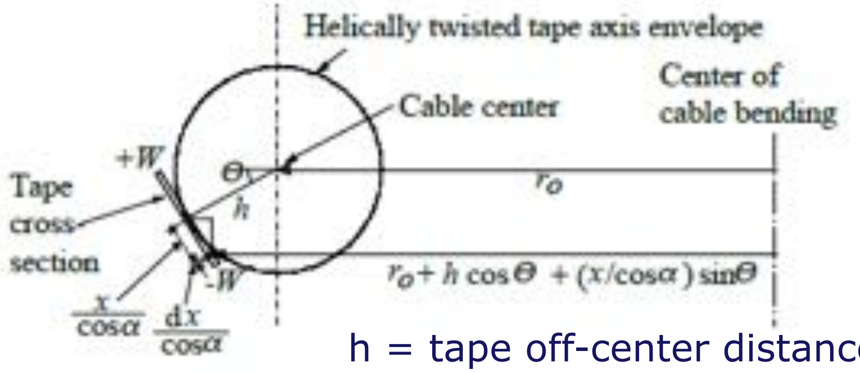
longitudinal strain along the tape (depend on *h*!)



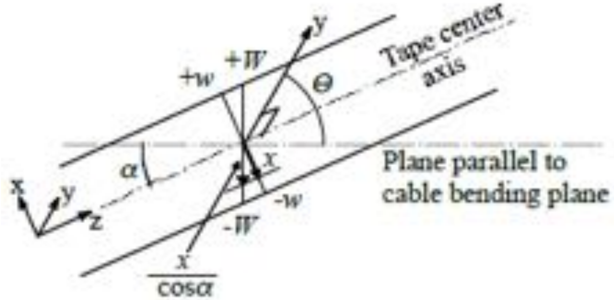
No-Slip Model (NSM)

Perfect-Slip Model

Bending characteristic of TSTC conductors can be investigated by analytical models (*Takayasu, ICMC 2015, Tucson*)



h = tape off-center distance



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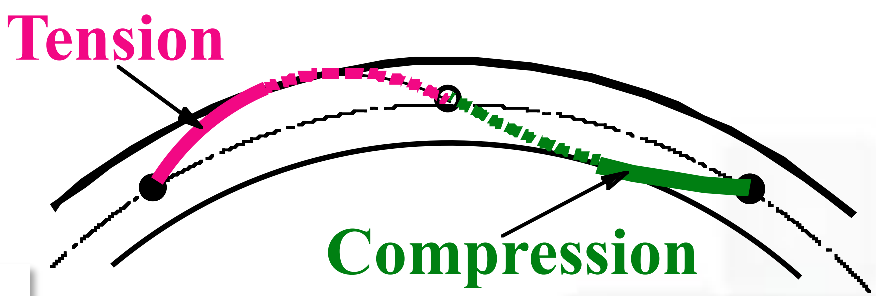
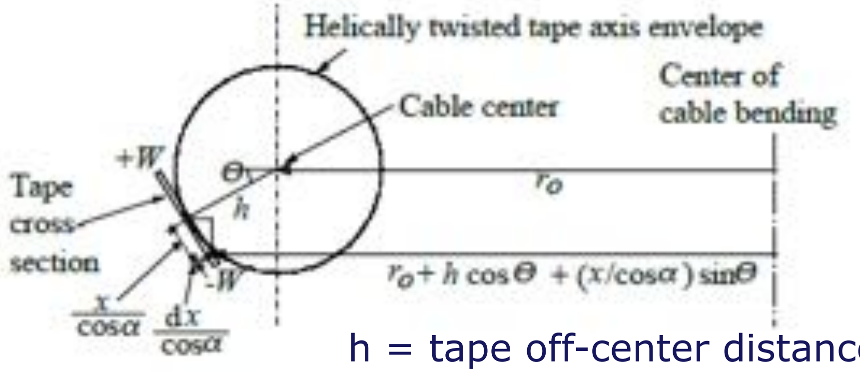


If the tapes can freely slip in a stack during bending, the longitudinal strain can be released by slipping

Compressive and tensional strains cancel out

Perfect-Slip Model

Bending characteristic of TSTC conductors can be investigated by analytical models (*Takayasu, ICMC 2015, Tucson*)



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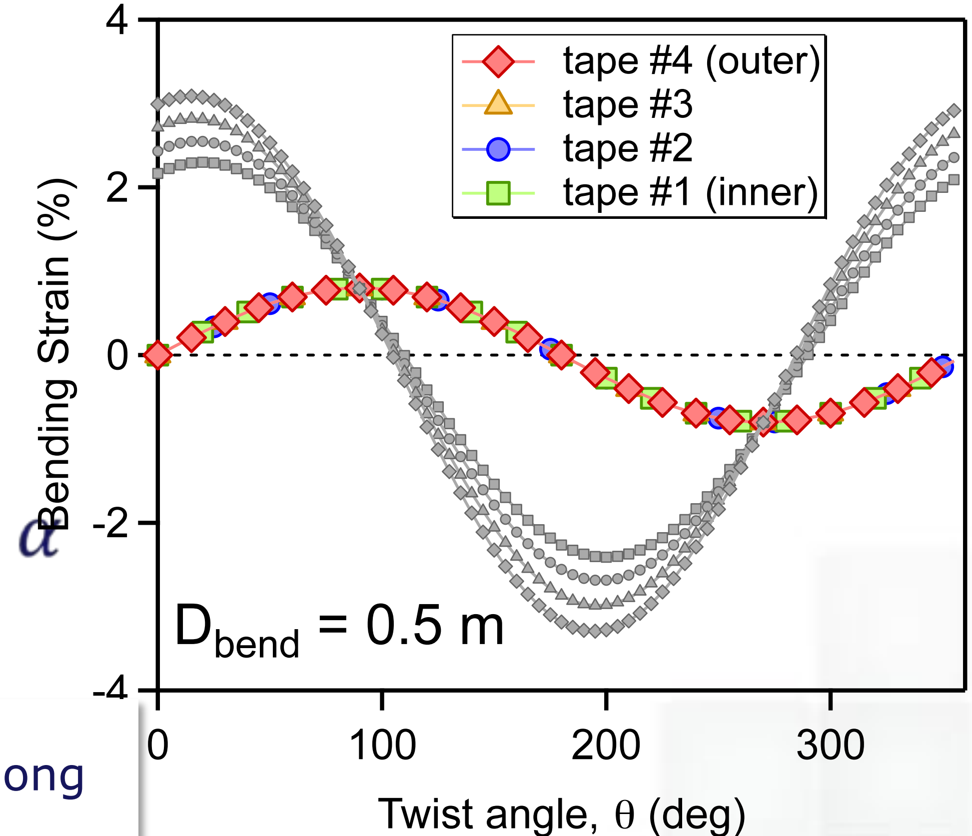
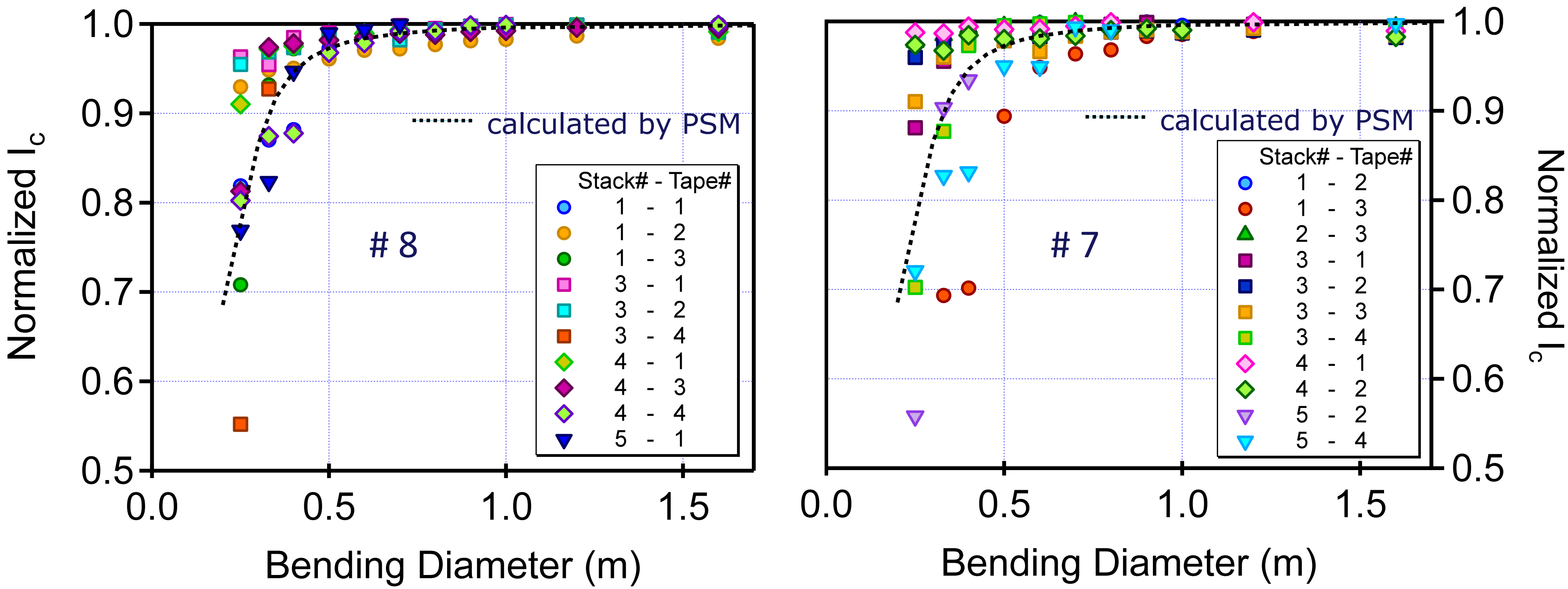


Perfect-Slip Model (PSM)

Normalized I_c vs. D_{bend}

G. De Marzi, *et al.*, IEEE TAS, 4801607 (2016)



The **Perfect Slip Model** is appropriate in describing the bending behavior

✓ Tapes inside the stacks are not rigidly held (**slip**)

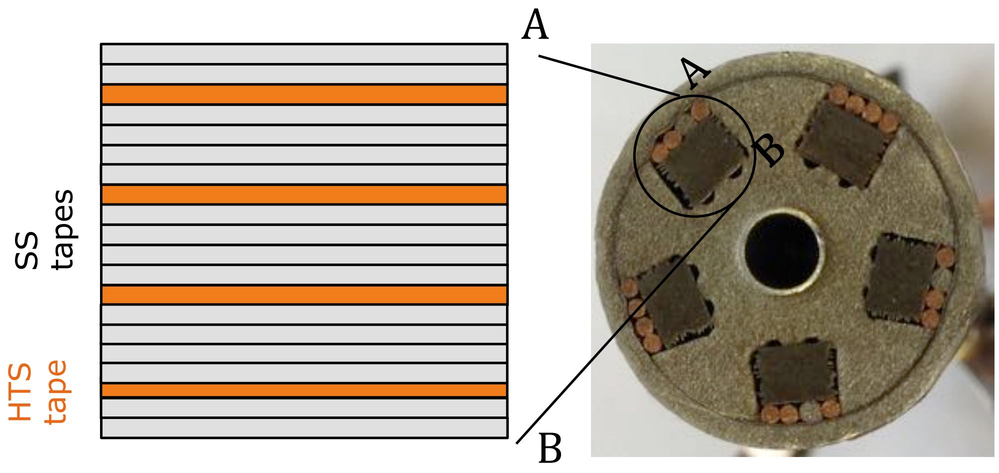
Is this a general behavior?

Bending behavior for longer sample

Test of a longer sample including more than a twist pitch

(M. Takayasu, and L. Chiesa)

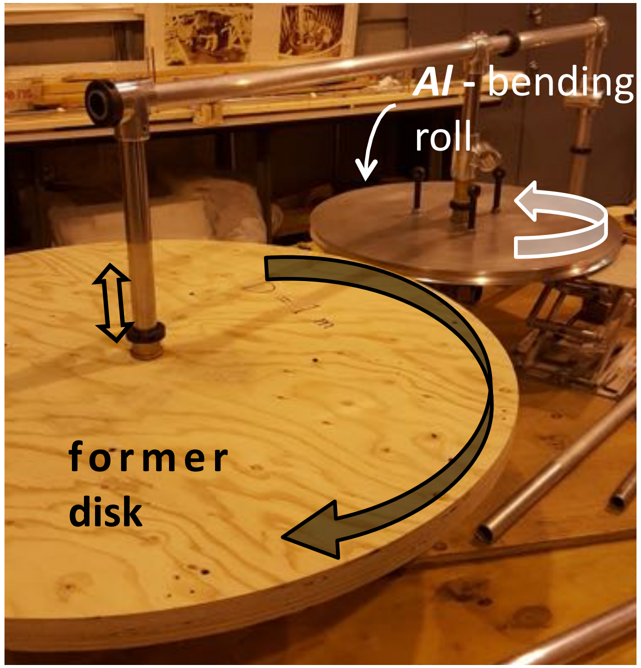
Cable parameters	HTS CIC#10
Length (m)	3.0
Twist Pitch (mm)	1000
Al-Jacket	yes
HTS tapes SuNAM	HCN04150 (100 um thick)
layout	4 HTS tapes + 16 SS



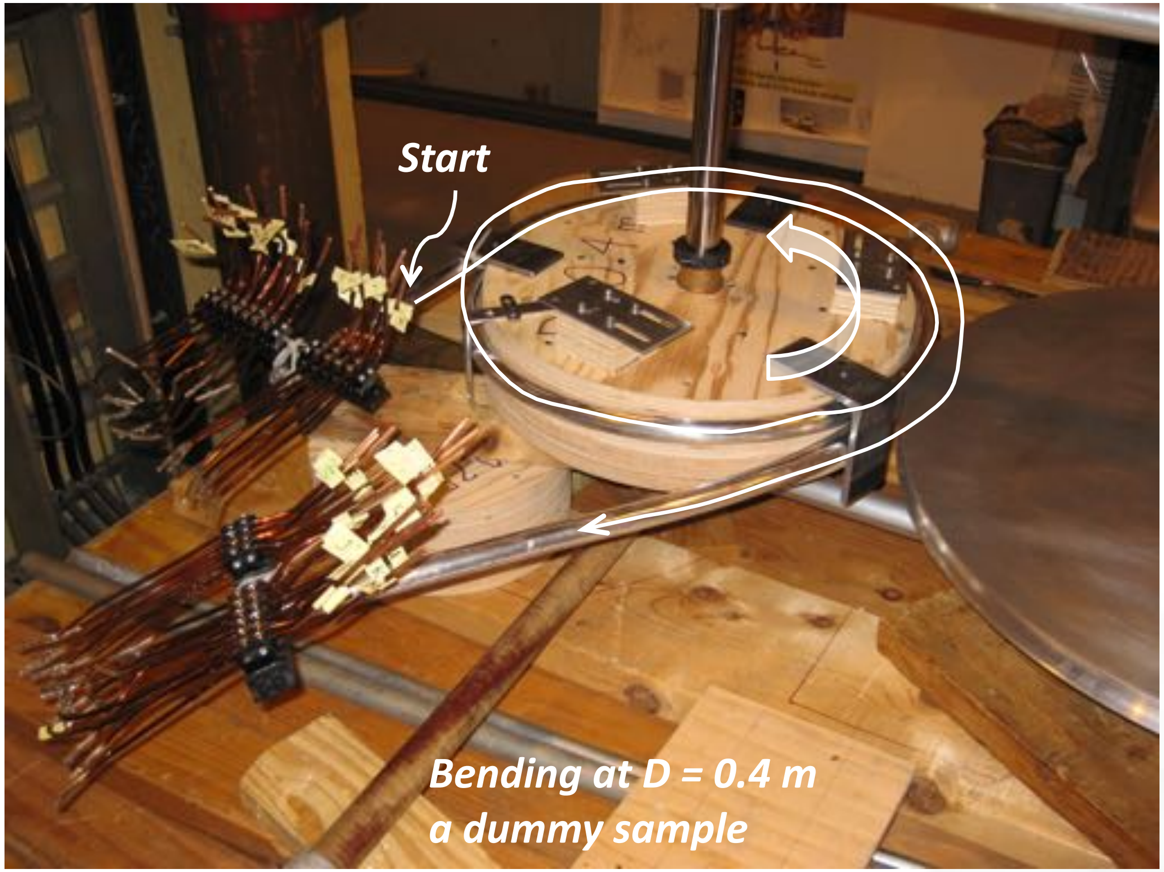
Bending Test Procedures

Bending tool for spiral winding of the sample (designed by M. Takayasu) composed of two disks: a wooden **former** with a given curvature D and an **Aluminum disk** as bending roll.

The distance between the axes is fixed to the given value and both disks can turn around their axes

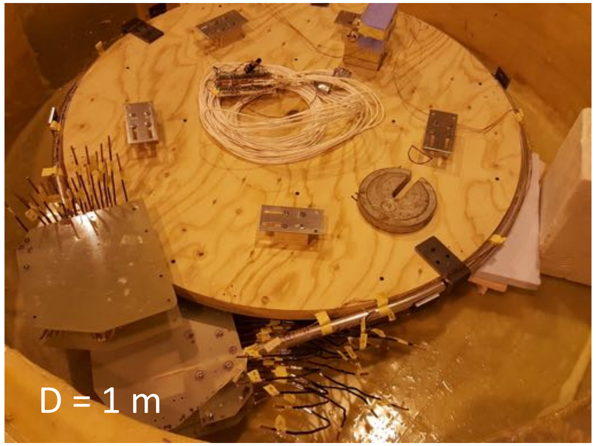


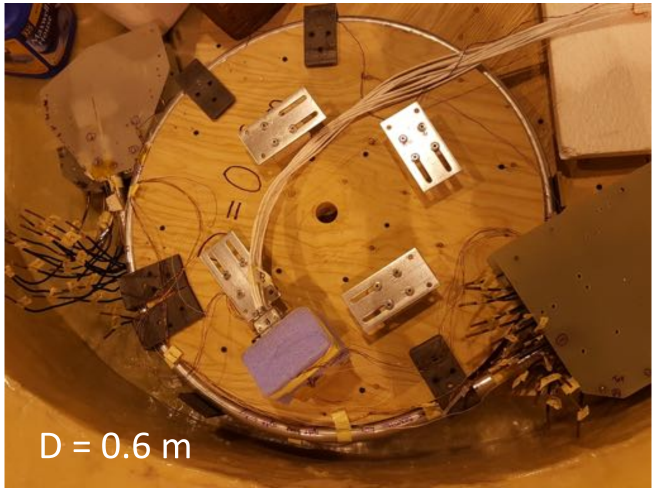
The former disk can be shifted up/down while turning

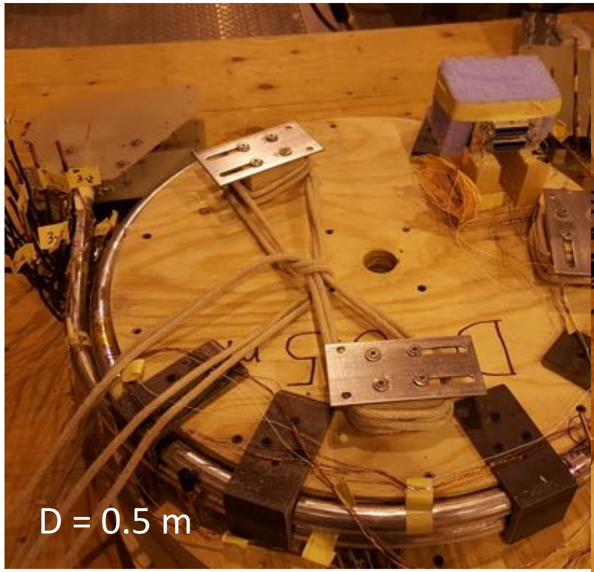


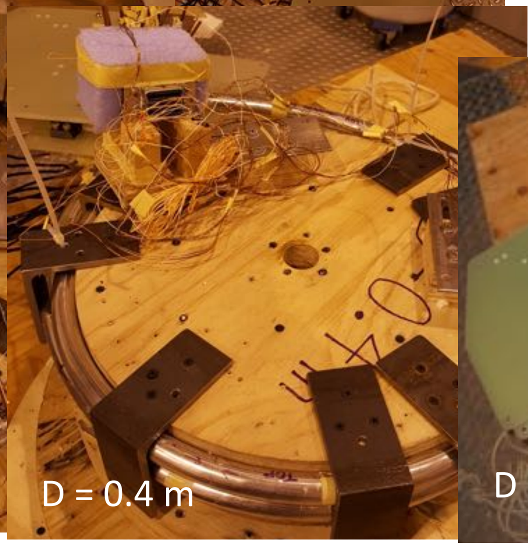
Bending Test Procedures

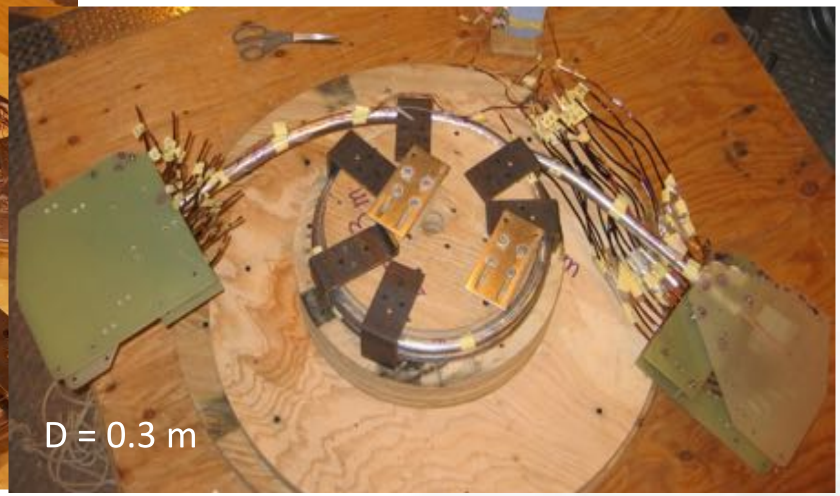
Bending diameter was reduced in steps from 1.0 m down to 0.3 m;



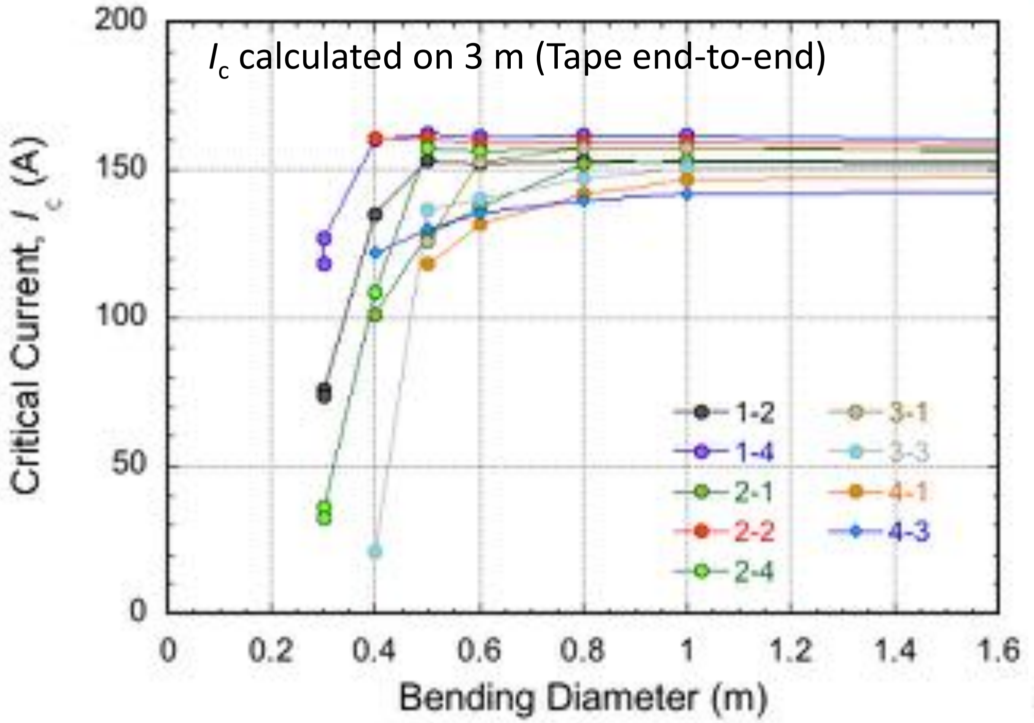




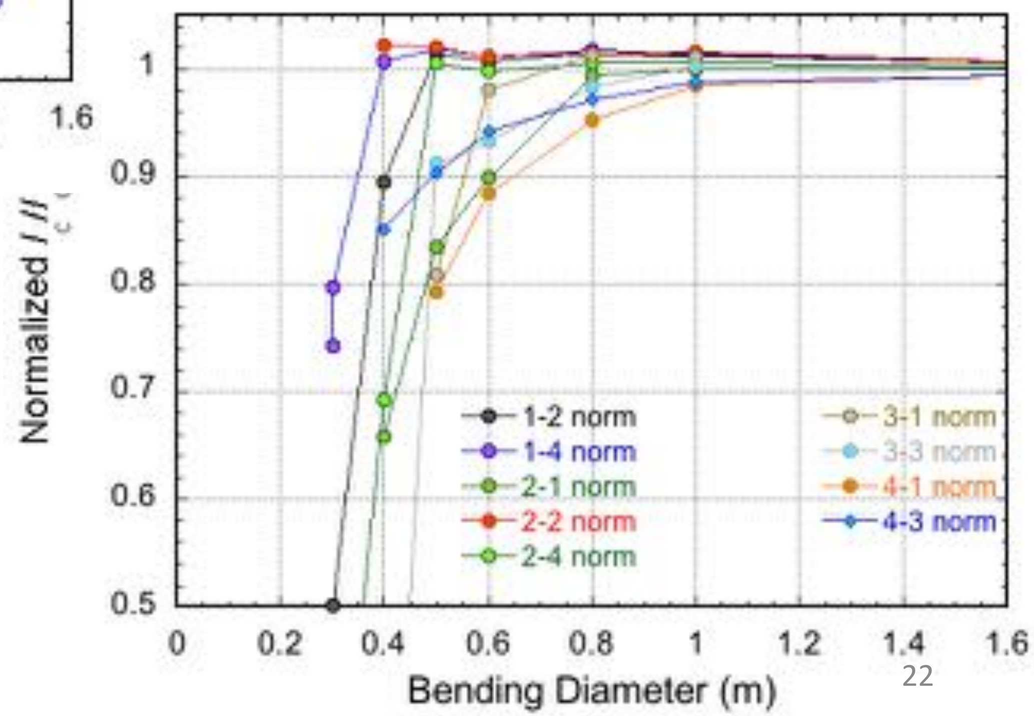




Bending test: I_c results



- End-to-end I_c decrease observed for D < 0.6 – 0.5 m.



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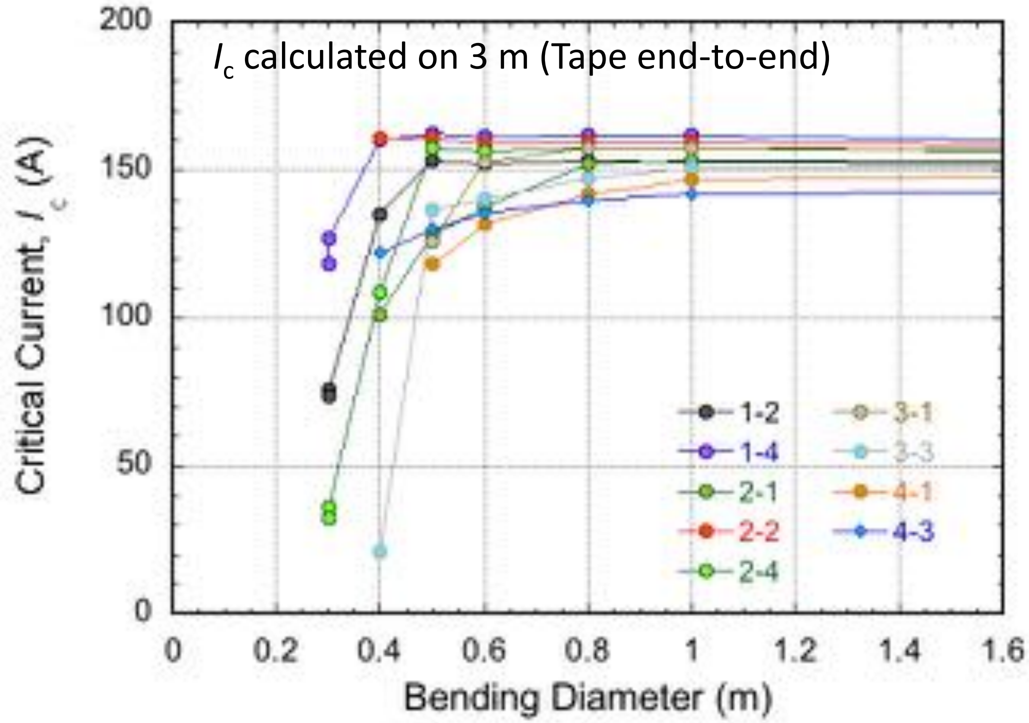

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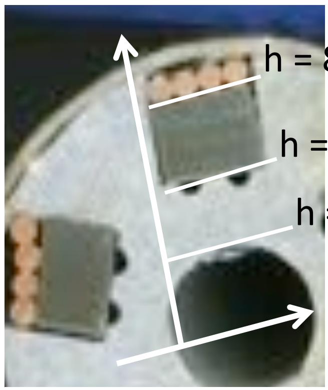
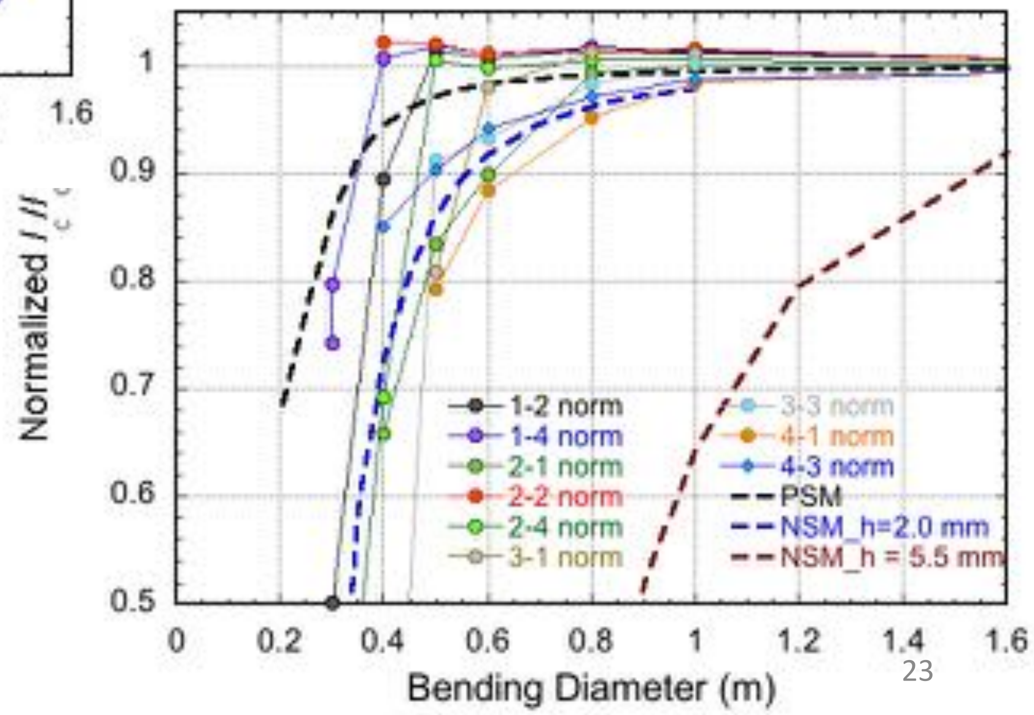
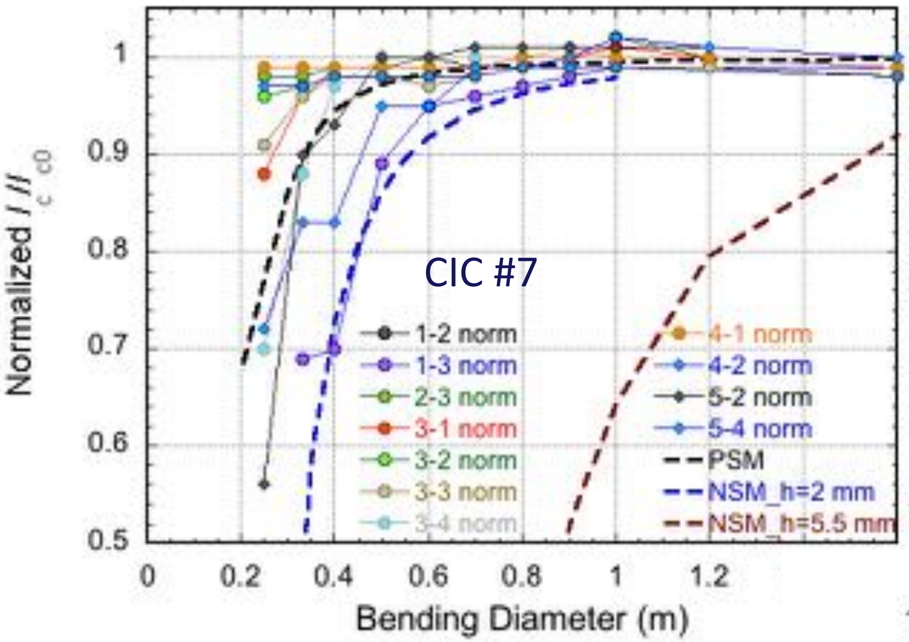
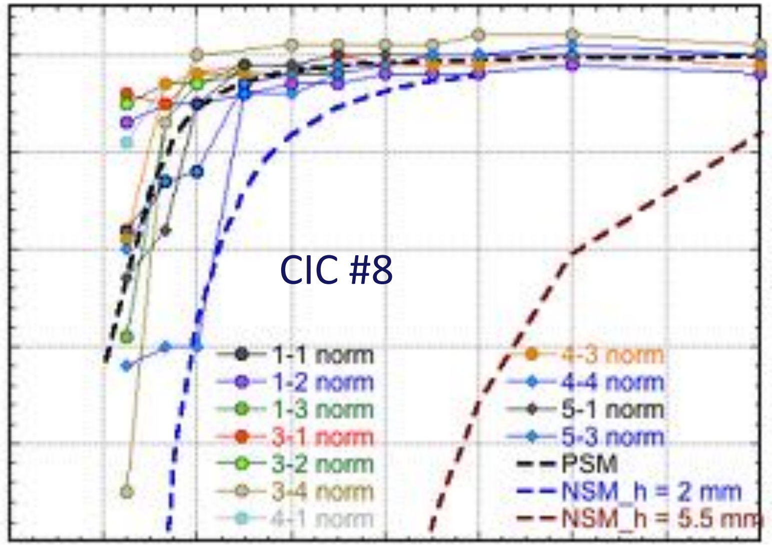


PSM better describes I_c degradation



Comparison with previous samples

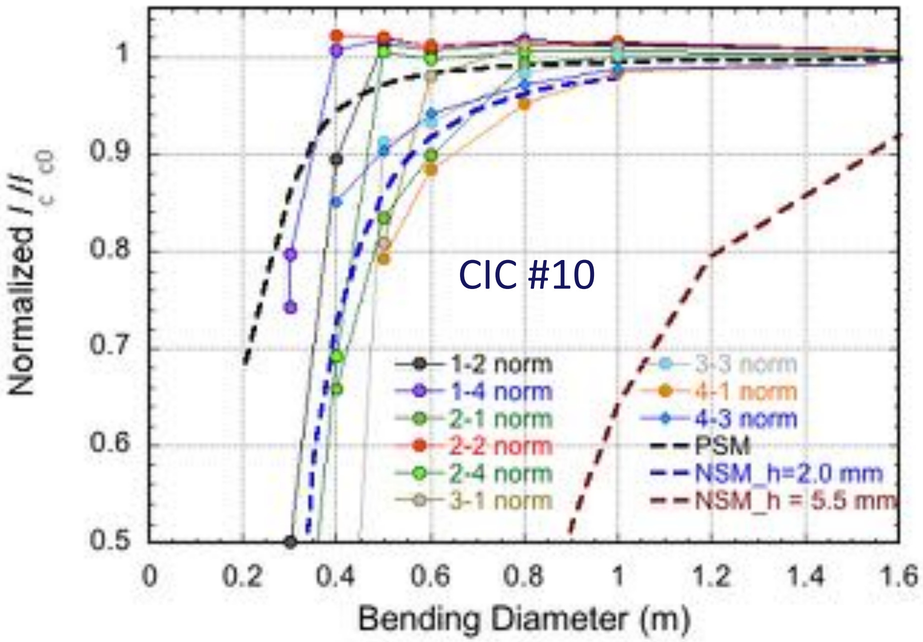




Sample CIC #7, 8 and 10 have similar bending behaviour well described by PSM

Tape slipping seems an intrinsic strain release mechanisms

Good tolerance to bending (good news for winding)



Further developments and perspectives

In perspective of *in-field* full current test of a fully superconducting length:

- In short **straight sample** configuration (*e.g.* at SULTAN / EDIPO test facility, Villigen, CH or at NAFASSY 8 T test facility, Salerno, IT)

- In **coil** configuration (*e.g.* at NIFS 15 T test facility, Toki, JP or at NAFASSY 8 T test facility, Salerno, IT)

Cu coated *Al*-core by electro deposition

Improvements in cable manufacturing:

- high current terminations for fully equipped sample;

- solder-filled stacks;

20 tape stack filled with Pb-Sn solder

Conclusions

- Performances of the ***Al*-stabilized, slotted core, twisted stack CIC** round conductor fabricated within **industrial environment** have been tested:

  - **Electrical**: **2.2 kA @ 10 T, 4.2 K** on sub-size (single stack, 18 tapes); **> 20 kA** extrapolated by FEM model for fully equipped, **5-slot, 150 tapes**;

  - **Thermo-hydraulic characteristics and cooling capability**;
    - first measured carried out and analyzed by 4C code;

  - **Bending behaviour**: Successfully tested on three samples with different length and TPs.
    - Good strain tolerance down to **0.6 - 0.5 m** bending diameter;
    - Tapes **can slip** inside the stack;
    - I_c degradation does not depends on TP and off-center distance;
    - **PSM model** is appropriate in describing the bending behaviour;

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    - I_c degradation does not depends on TP and off-center distance;
    - **PSM model** is appropriate in describing the bending behaviour;
    - new investigations are planned;
- **NEXT STEP**: full-size *in-field* e.m. test.

Acknowledgments

ENEA

Thanks for your kind attention

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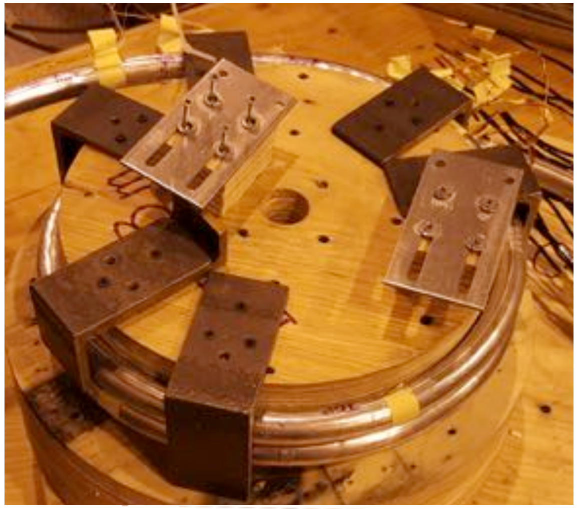

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