Development of high current HTS conductors for Fusion at CRPP

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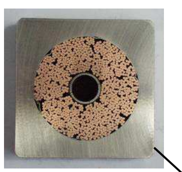
- Motivation
- Cable design
- Strand fabrication
- Electromechanical characterisation
- Summary and outlook

Motivation

Requirements for Fusion Magnets

- *Peak field in the 12 T ~ 18 T range.*
- *Large bending radius (> 3 m) during winding.*
- *Very large current (>50 kA) and large Cu cross section (500 to 900 mm^2), thus low J_e.*
- *Loose requirements on field quality; moderate AC losses.*
- *Cheap and easy industrial production (Km length).*
- *Steel structures takes up most of the longitudinal load (Hoop stress), but large transverse loads are still present.*



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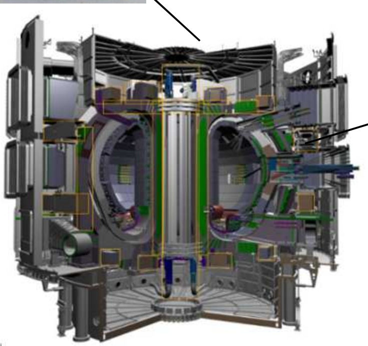
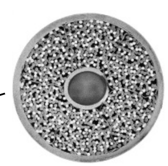
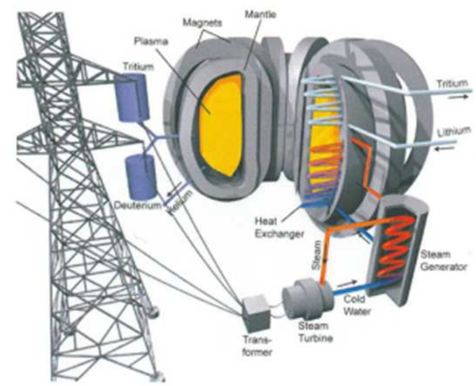




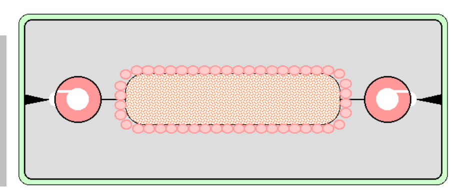
68 kA Cu: 530 mm^2
Void fraction 30%
J_e(5 K, 12 T) = 55 A/mm^2

DEMO



82 kA Cu: 800 mm^2
Void fraction 23%
J_e(5 K, 13 T) = 65 A/mm^2

Insulated conductor 112 x 45 mm



Motivation

Why HTS (tapes or wires) for Fusion Magnets?

In high field laboratory magnets the advantages of coated conductors with respect Nb_3Sn are:

- ***high J_{nonCu} at fields > 18 T***
- ***large longitudinal tensile stress***

An 18 T lab magnet made with coated conductors is not more expensive than NbTi/Nb_3Sn

A 30 T c.c. magnet is much cheaper (construction and operation) than an hybrid magnet

		Wire/tape cost for 1 m of cable (operating current of 80 kA at 5 K, 15 T)
Nb_3Sn		3'500~5'000-CHF
Bi2212		5'000~9'000-CHF 1x~2x
Bi2223		9'000~12'000-CHF 2x~3x
REBCO		15'000~40'000-CHF 3x~10x

State of the art of commercial HTS tapes

All solution processes (Oxolutia, BASF) may get much cheaper

Cost is not yet an advantage for HTS materials and for REBCO in particular

GOAL: c.c. should not be more expensive than Nb_3Sn

Motivation

Why HTS (tapes or wires) for Fusion Magnets?

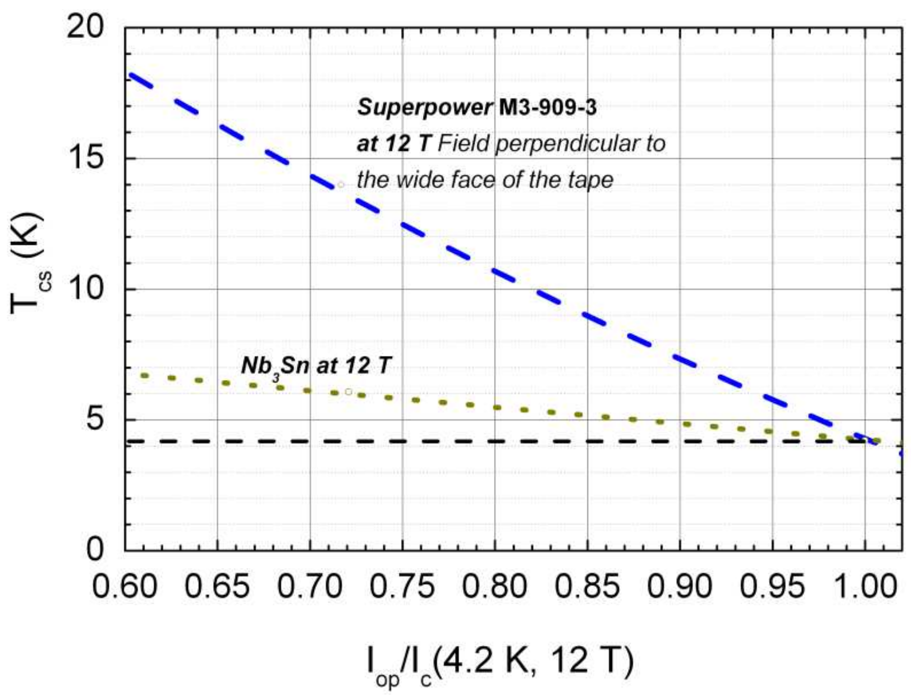
- ***high J_{nonCu} at fields > 18 T***
- ***large longitudinal tensile stress***

Have modest advantages in Fusion magnets

In fusion magnets

Advantage of HTS: for the same operating condition the temperature margin can be much higher (i.e. 15 K instead of 2-3 K)

- **Operation at temperatures > 5 K** (cost balance: cryogenic, AC losses, conductor cost)
- **HTS cable could easily sustain the large nuclear heat load in the innermost layer**



Cable design with tapes

<u>FOCUS: developing cables made with tapes (not necessary REBCO c.c.)</u>

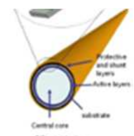
Bi2212 comes in wires: modify R&W techniques used for Nb_3Sn

Two types of tapes: thin films (coated conductors) or P.I.T. (mono or multifilamentary)

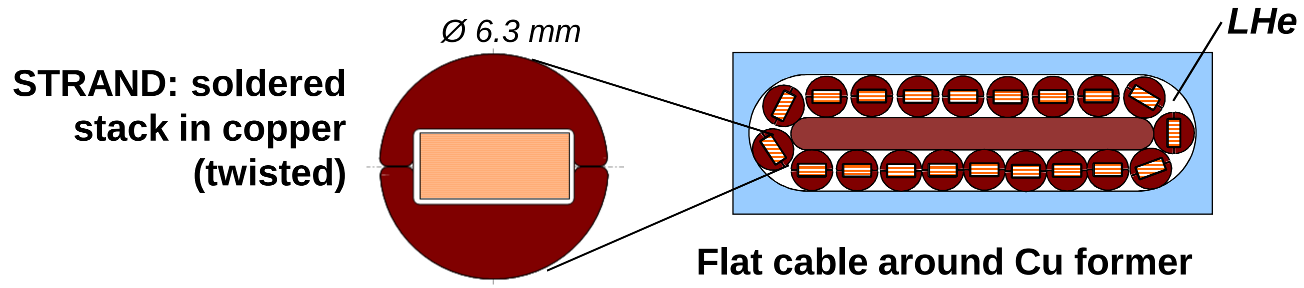
Coated Conductors: REBCO, *maybe in future FeSeTe, …*

Powder In Tube : Bi2223, *maybe in future Sr-122, BaK-122, …*

CABLING TECHNIQUES FOR TAPES

	 ***Stack strand*** *(MIT)*	*Paralle tapes: effective use of Ic(theta)*  ***Roebel*** *(KIT, IRL)*	 ***Round hollow wire*** *(Nexans)*	 ***C.O.R.C.*** *(Advanced Conductor Technologies)*
Thin film	applicable	applicable	applicable	applicable
P.I.T.	applicable	**difficult**	**very difficult**	**difficult**

CRPP Cable design



Why soldered stack strand?

- Mechanically solid (no voids)
- Low inter-tape resistance which is beneficial for current redistribution (inductive or during quenches)

Why flat cable?

- Limit transverse stress accumulation (see ITER cables…)
- Optimal cross section
- Less strain during winding than with a round cable

Twisted strands for large amount of transposition:

- Equal redistribution of current during ramping
- Reduction of coupling losses

Even if not fully transposed (the tapes have not exactly the same inductance), the low inter-tape resistance ensures that a small mismatch of inductance is tolerable.

CRPP Cable design

<u>Main challenge for ceramic wires/tapes: strain management from tape to coil</u>

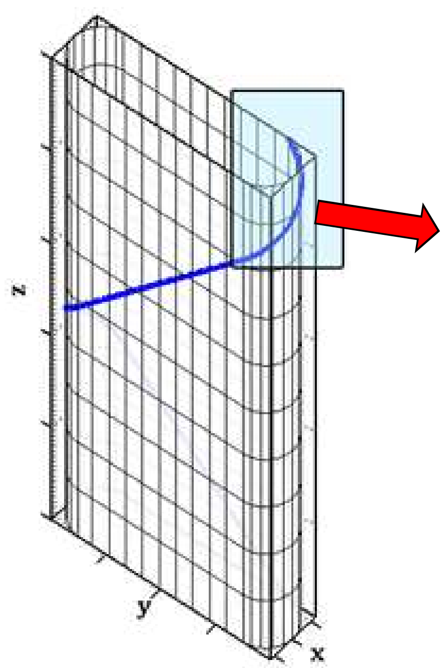
Nb_3Sn: 1.cabling 2.winding 3.reacting   or   1.cabling 2.reacting 3.winding

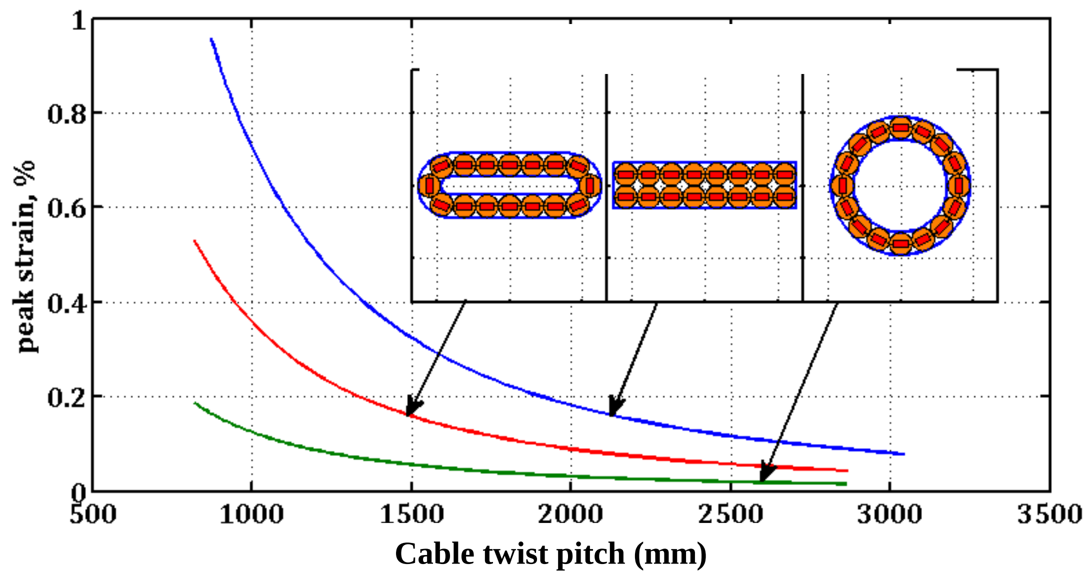
CC: 1.<u>reacting</u> 2.cabling 3.winding

<u>Strain accumulation</u> (for REBCO tot. strain <0.6%):

- Strand twisting; <1% torsion shear strain
- Cabling; <0.20%
- Winding (r=3.5 m); <0.05%

<u>Strands are twisted before soldering</u>





Cable twist pitches > 1000 mm are required

CRPP Cable design

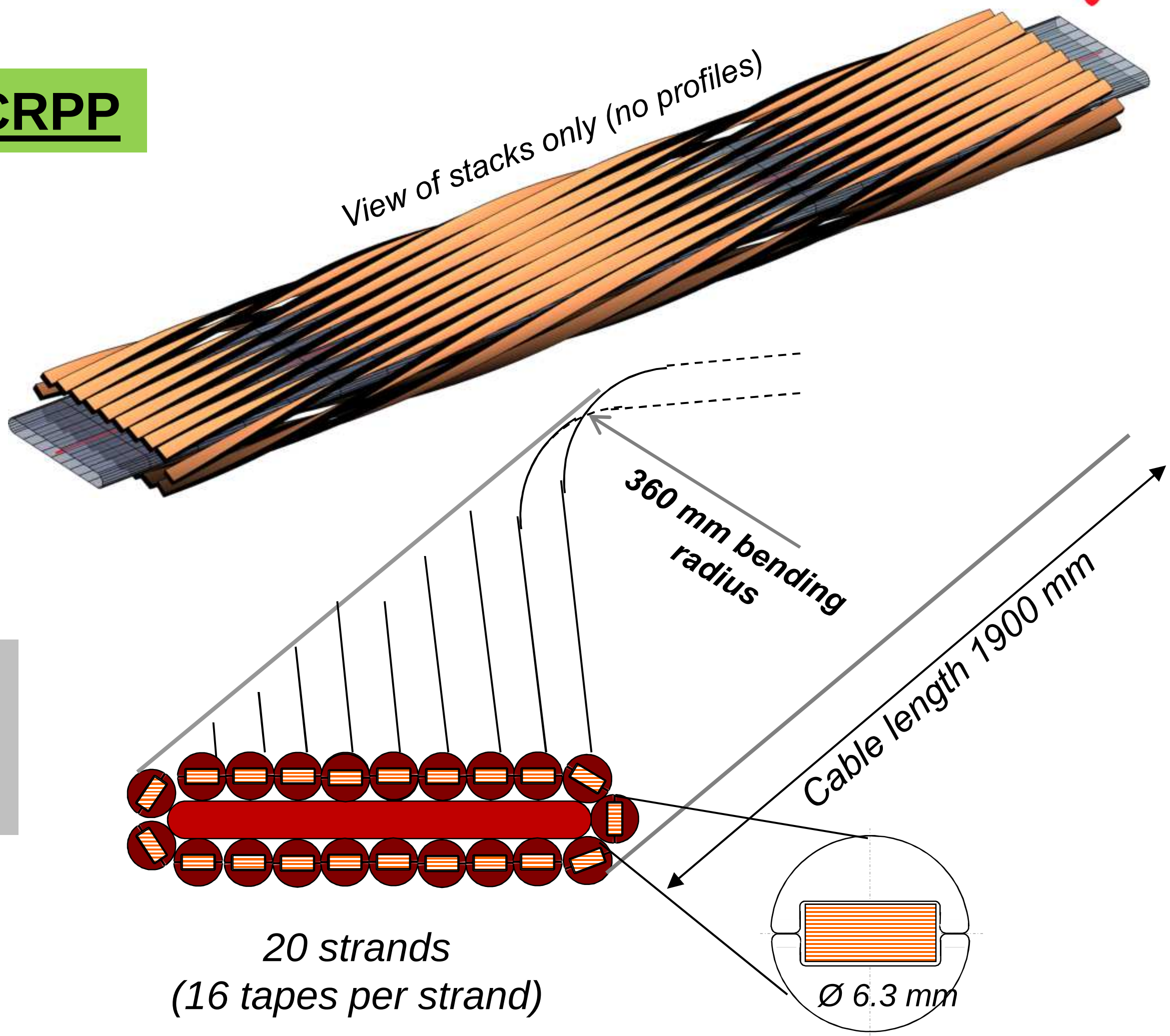
Cable in construction at CRPP

Strand twist pitch = 320 mm
(Strand twisted before soldering to limit the strain accumulation)

Cable twist pitch = 1000 mm

Cu: 790 mm² (Cu/nonCu = 2)
Void fraction 23%
J_e(5 K, 12 T) = 45 to 55 A/mm²

Critical current at 12.5 T
55~65 kA ***at 4.2 K***
35~40 kA ***at 15 K***
20~25 kA ***at 30 K***



About 800 m of tape for 1.9 m of cable

HTS Sample Test in SULTAN/ EDIPO

EDIPO

<u>12.3 T</u>

(homogeneous over 100 cm)

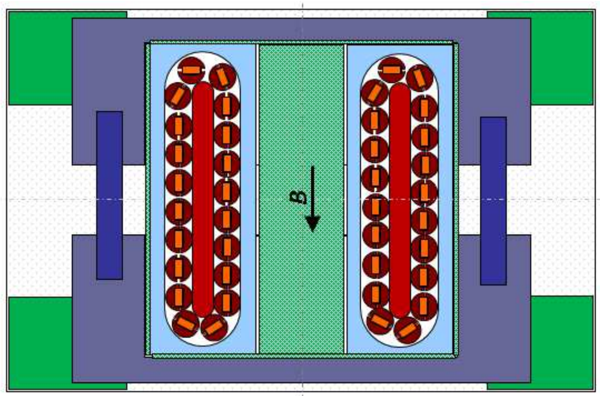
SULTAN

<u>10.8 T</u>

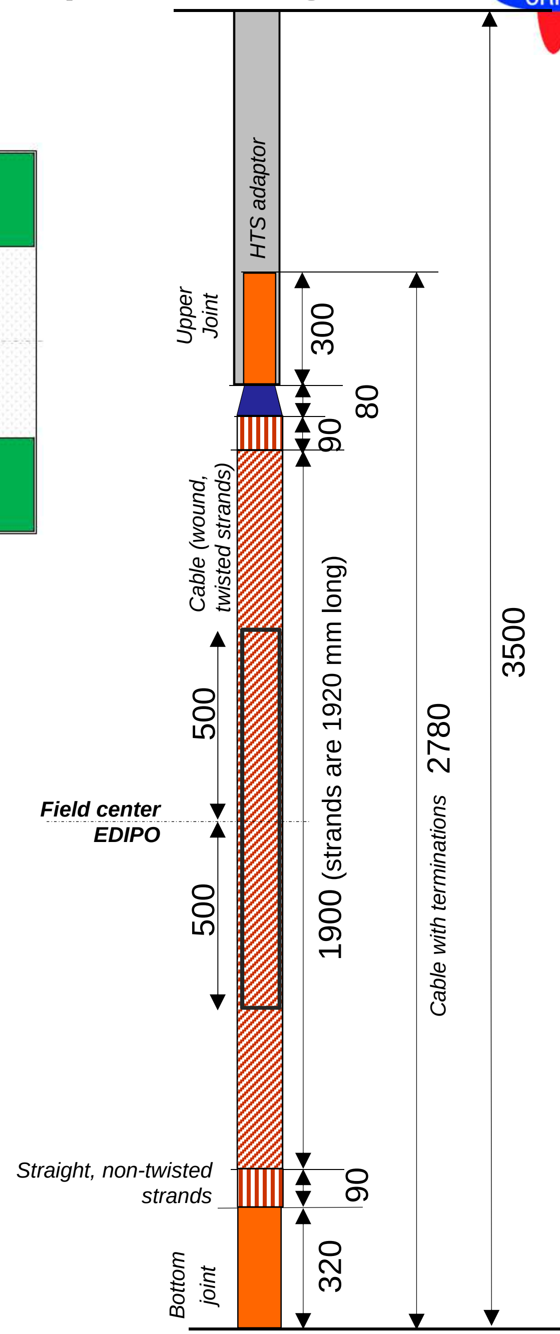
(homogeneous over 40 cm)

- **<u>DC current up to 100 kA</u>**
- **<u>Supercritical helium between 4.5 K and 50 K</u>**

Test well: 142 mm $\times$ 92 mm

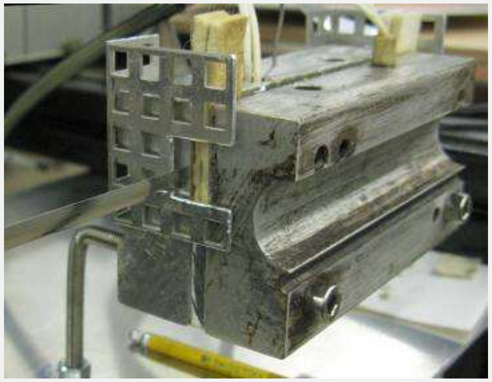


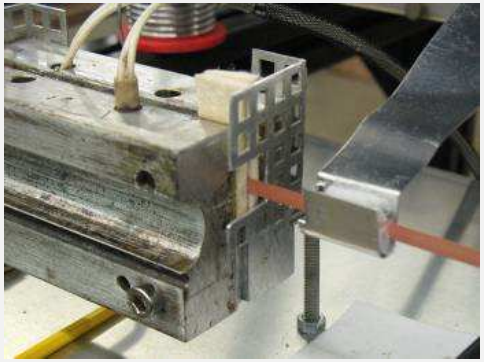
Sample cross section



Fabrication - tape and profile tinning

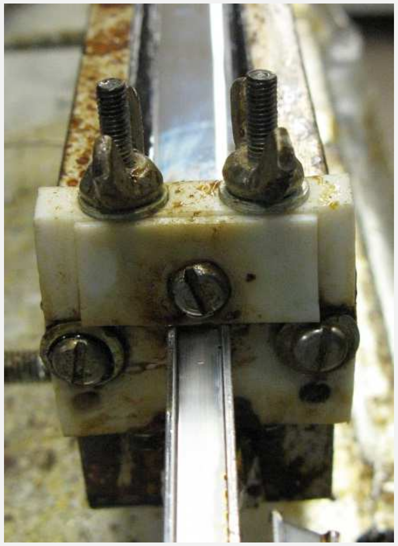
Tape tinning



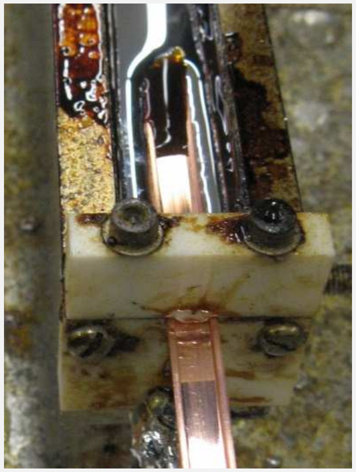


- Coating: eutectic PbSn at 200°C.
- Tape speed about 6 cm/s (3.5 km/h)
- Colofonium flux

Profile tinning

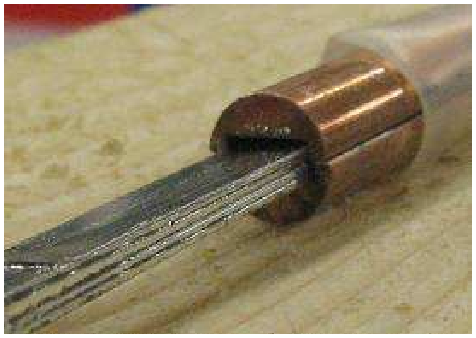


- Coating: eutectic PbSn at 200°C.
- Speed about 1 cm/s
- Colofonium flux



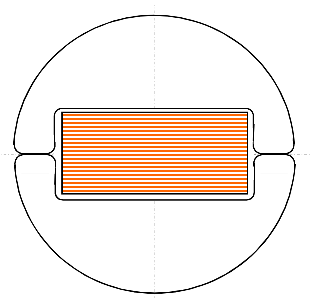
Fabrication – strand

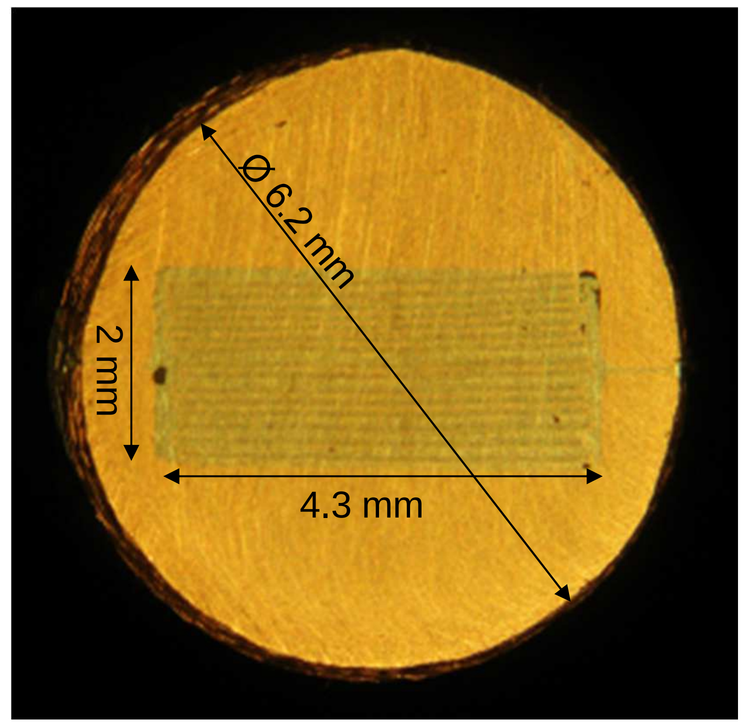
1. Stacking 16 tapes between two Cu profiles



2. Twist the strand (320 mm twist pitch)

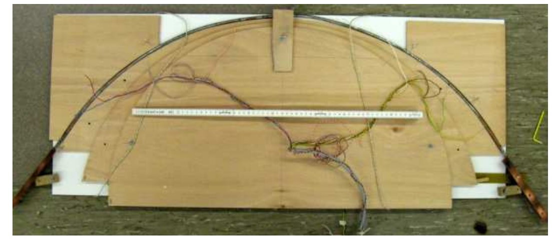
3. Solder the twisted strand





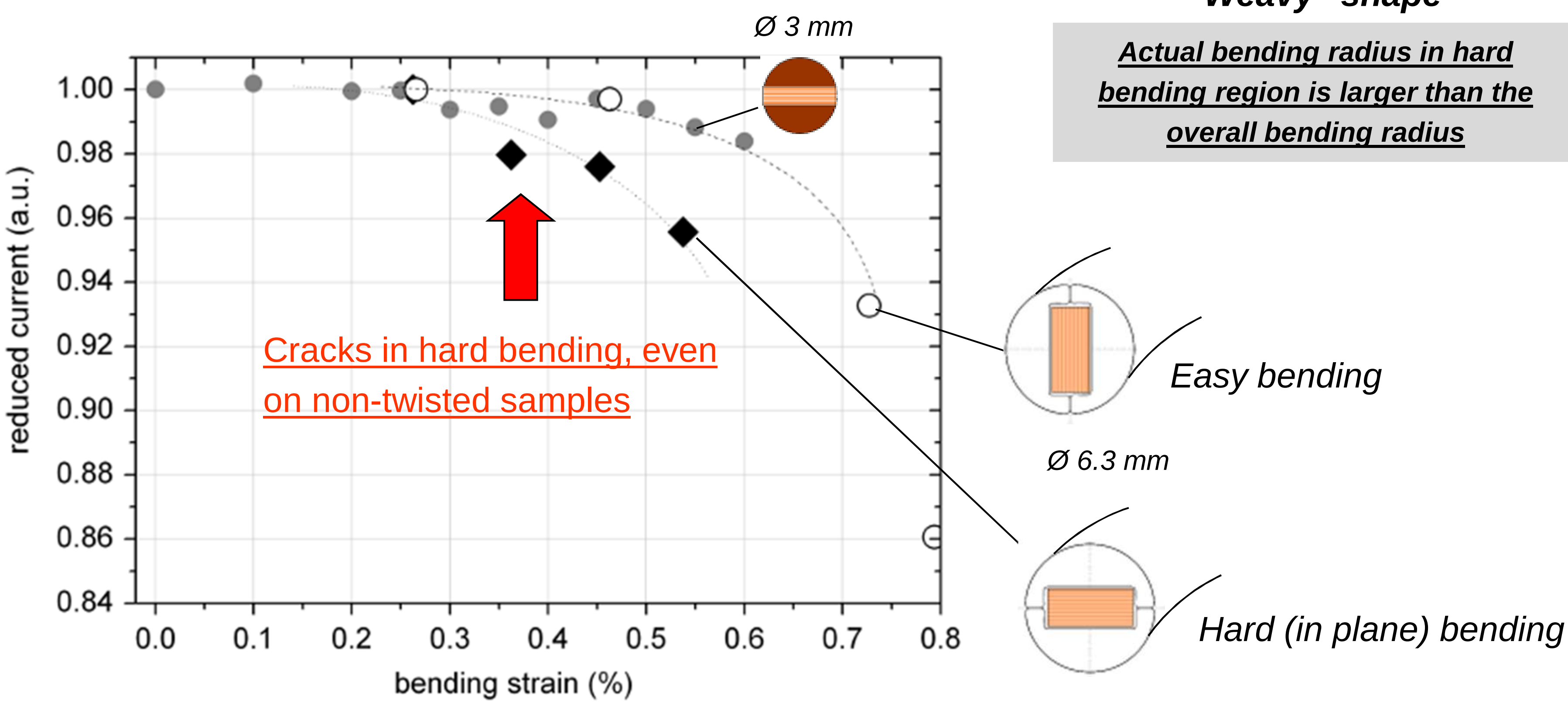
Electromechanical characterisation

I_c vs. bending

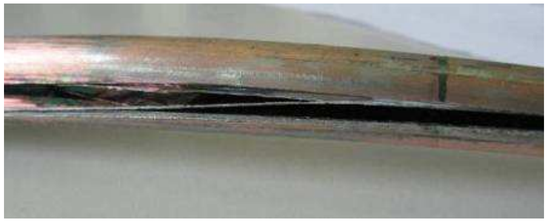
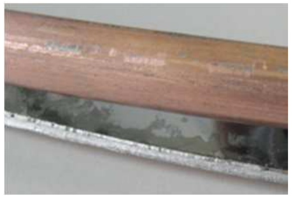


"Weavy" shape

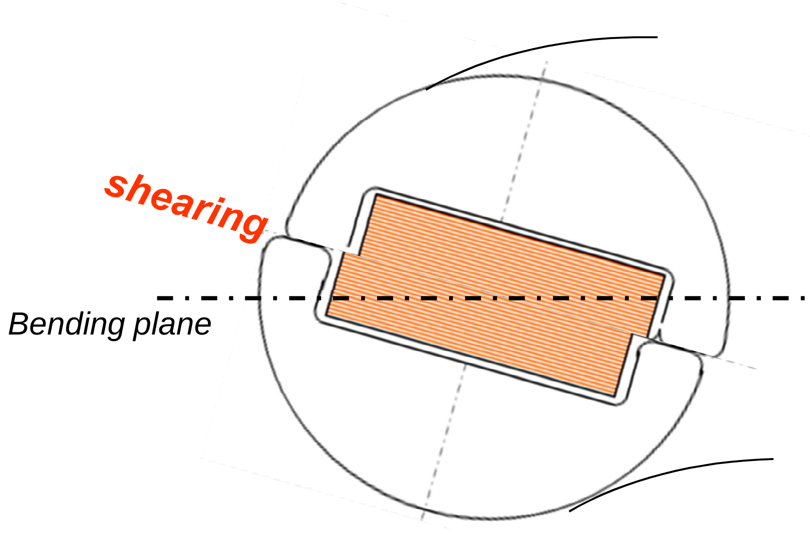
Actual bending radius in hard bending region is larger than the overall bending radius



Electromechanical characterisation
I_c vs. bending

After pulling the cracked parts apart

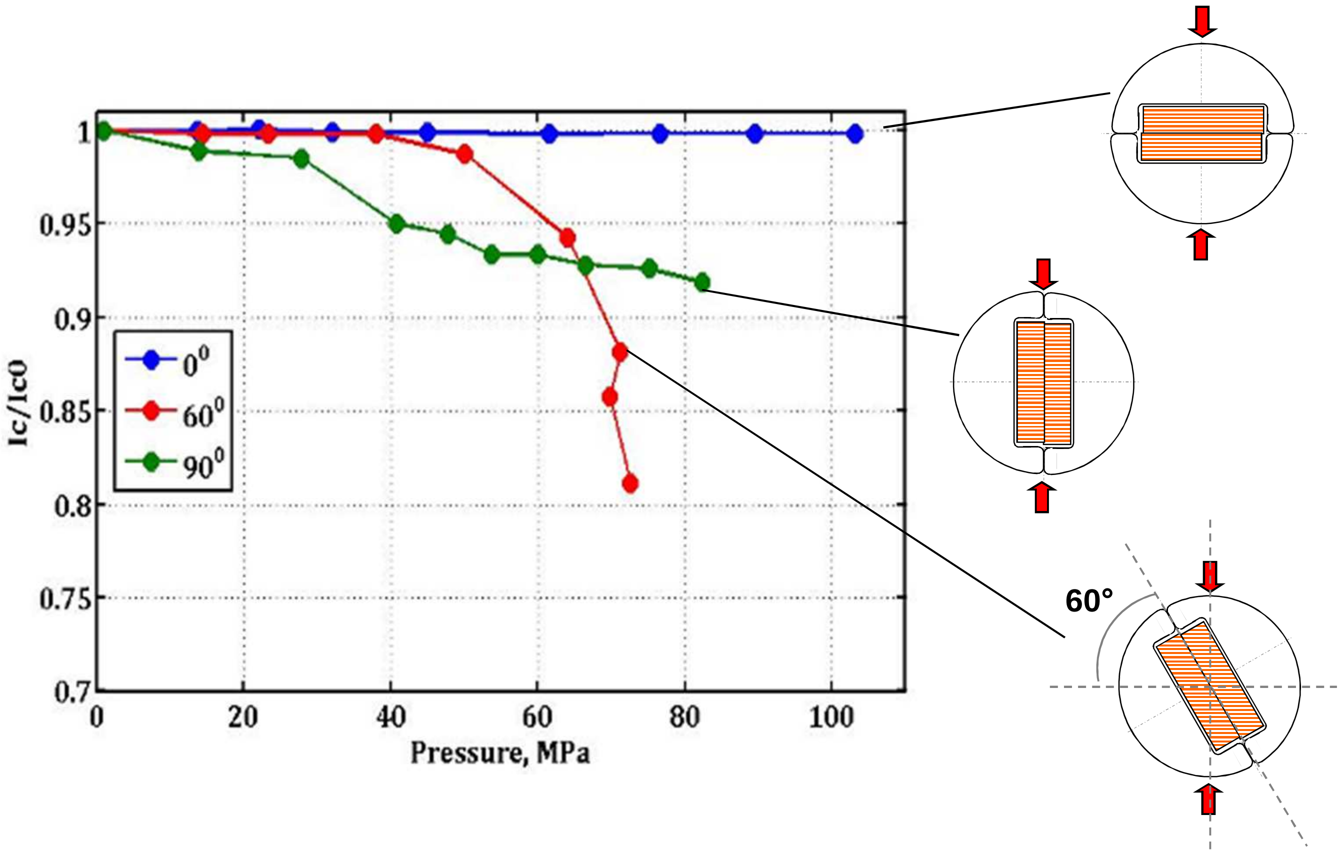


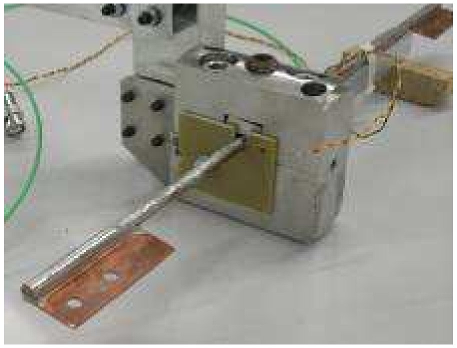
Coated conductors can be easily delaminated (few MPa)

Solder strength is low

Limit is the mechanical failure of the solder and not the strain on the ceramic

Electromechanical characterisation
I_c vs. transverse pressure

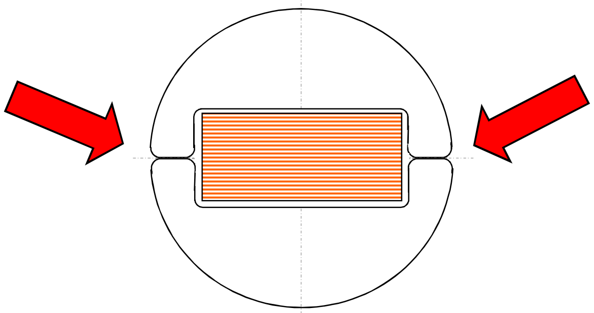




Limit < 30 MPa

Maximum pressure in the flat cable (15 T, 3 kA per strand): 15 MPa

Electromechanical characterisation



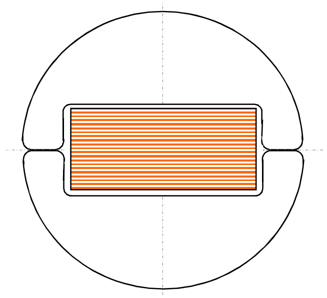
Weak point (under shearing) of this first type of Cu profiles

1 - Re-crystalisation heat treatment (300°C) on as drawn Cu profiles

Main reason was for making twisting and cabling easier (copper is softer and easier to plastically deform)

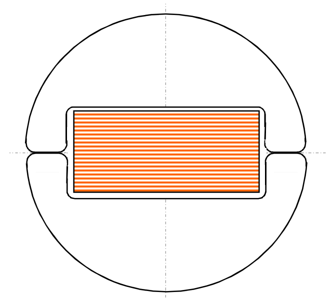
2 - Two new Cu profiles are introduced

Electromechanical characterisation
I_c vs. bending



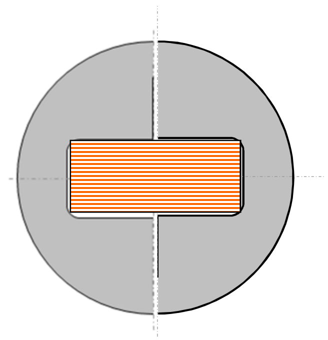
Standard profile,
as drawn

Solder failing at bending radius ***500 mm<R<700 mm***



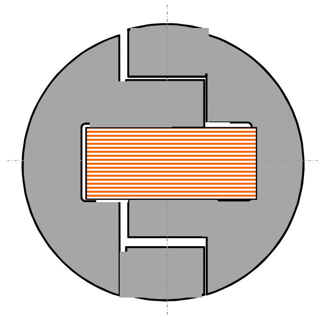
Standard profile,
softened copper

Solder failing at ***R<240 mm***



Alternative profile,
softened Cu

Solder did not fail down to ***R=180 mm***



Alternative profile,
softened Cu

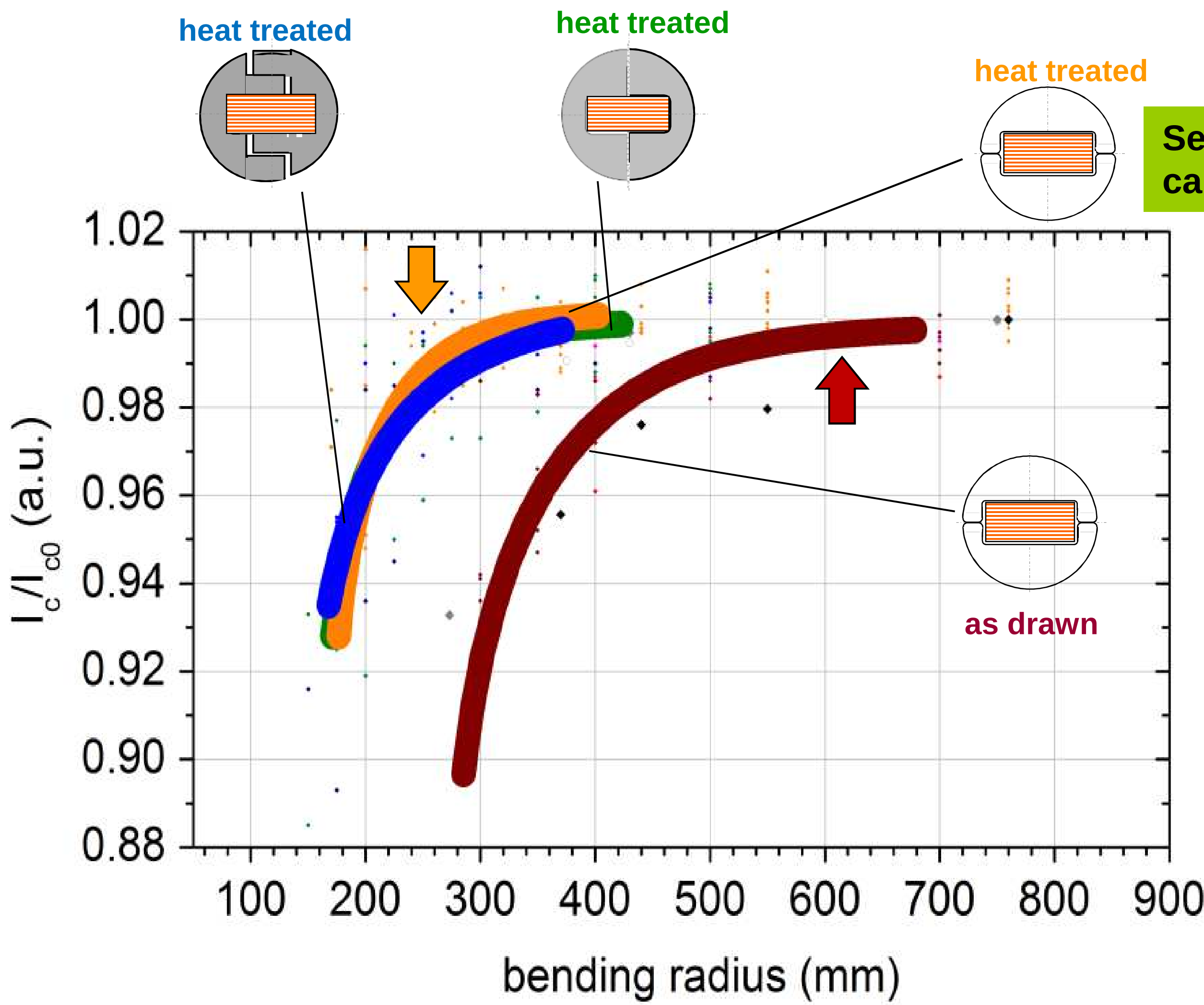
Solder did not fail down to ***R=180 mm***

In strands made with softened copper the solder breaks at smaller bending radius than in strands with as drawn profiles.

New Cu profiles can sustain very short bending radius.

Electromechanical characterisation

I_c vs. bending

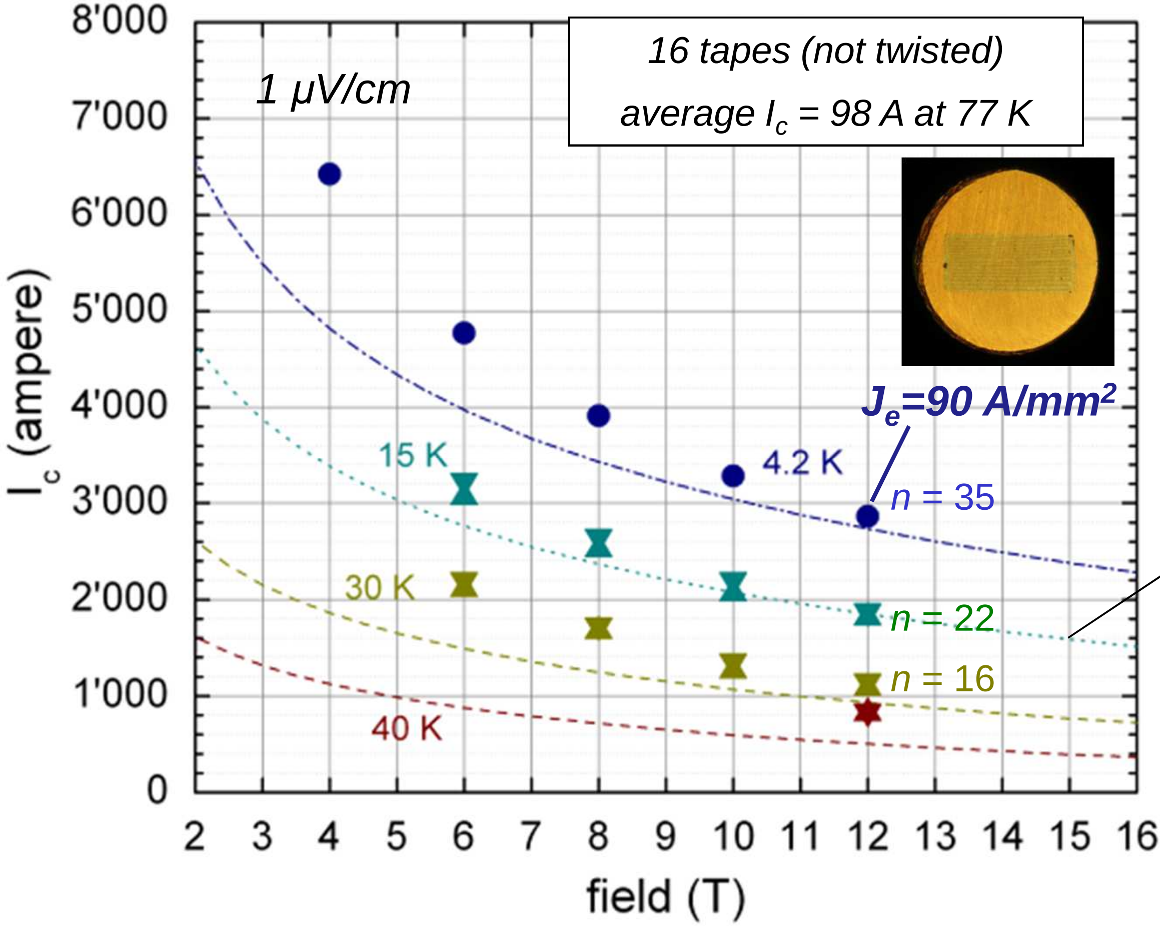


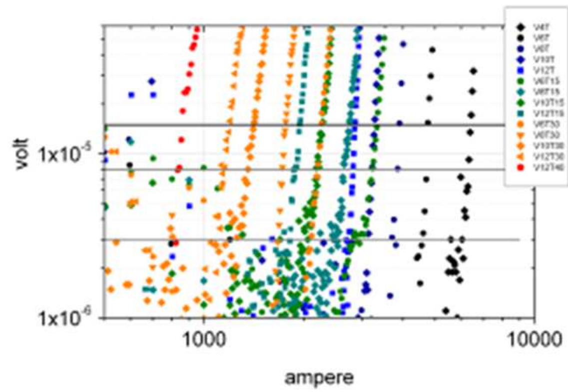
Selected for the 1.9 m cable (R=360 mm).

Actual bending radius in easy bending region is smaller than the overall bending radius

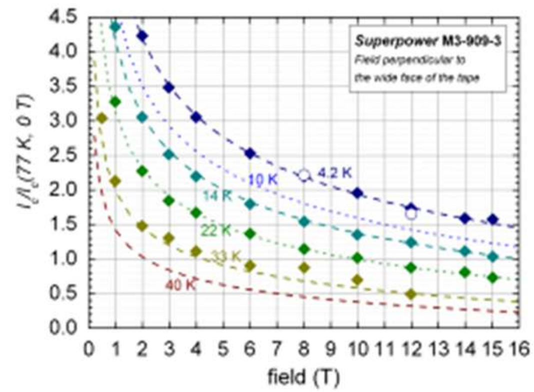
Electric characterisation - $I_c(B,T)$

Measured by C. Bayer (KIT)





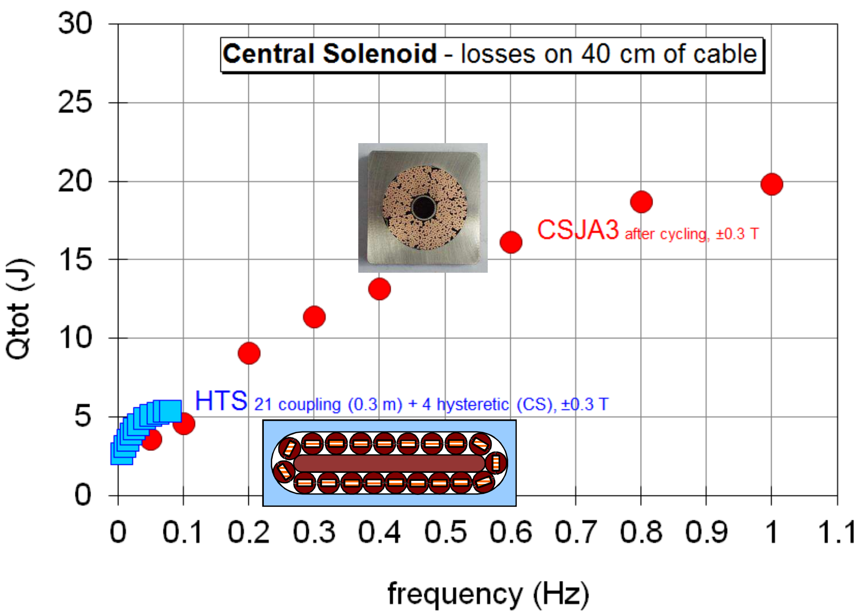
Average tape I_c x N. of tapes x lift factor

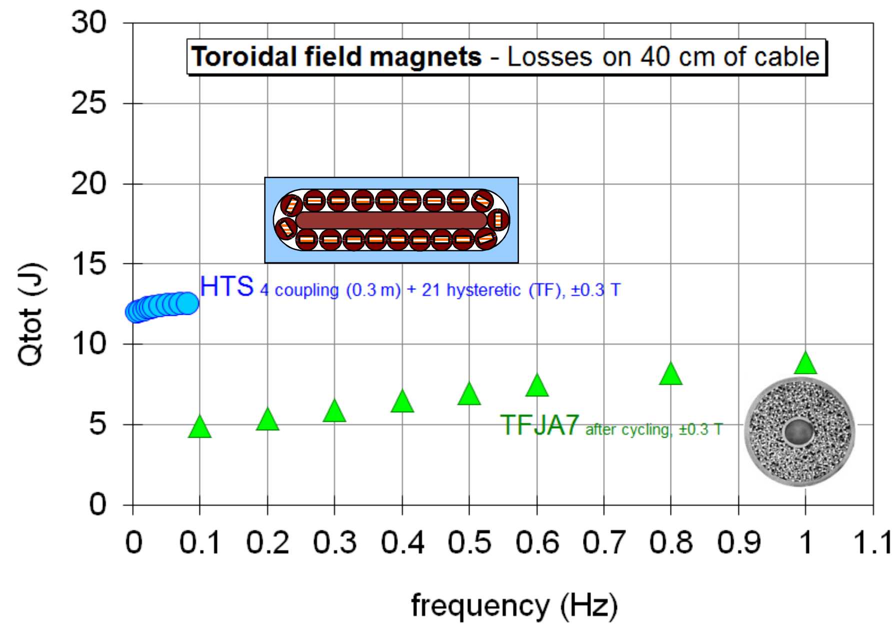


Critical current at low temperature and high magnetic field (⊥ to the *ab* plane) was in line with expectations

Electric characterisation - AC losses

Calculations based on measurements from A. Nijhuis (Twente University)





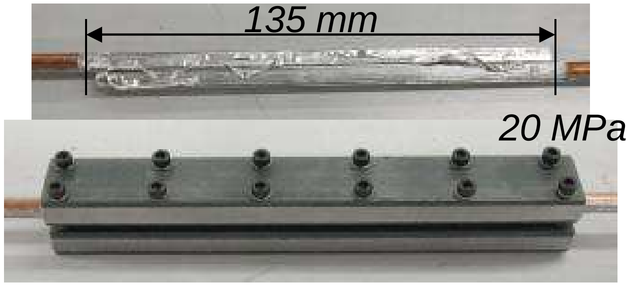
CS cable: about four times smaller than Nb_3Sn for ITER

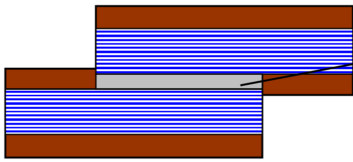
TF cable: less than twice higher than Nb_3Sn for ITER

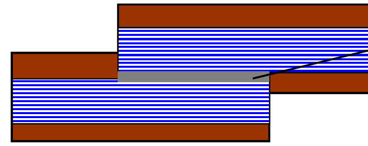
Small coupling losses expected despite the low inter-tape resistance because the strand twist pitch was kept short (300 mm)

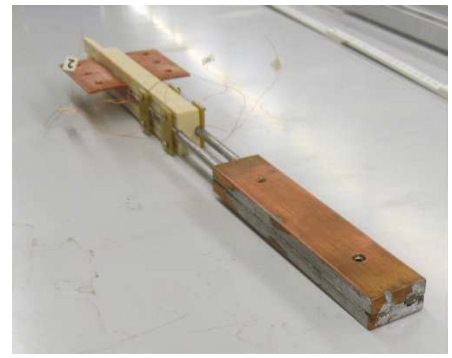
Anyway AC losses could be tolerable because of the large temperature margin

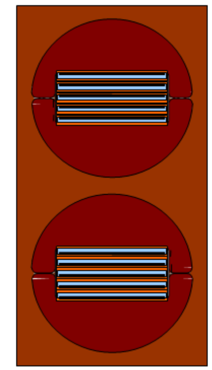
Joint fabrication

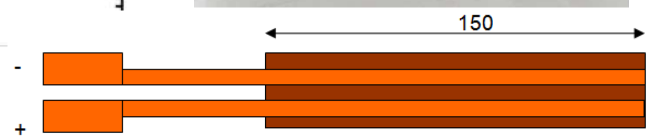


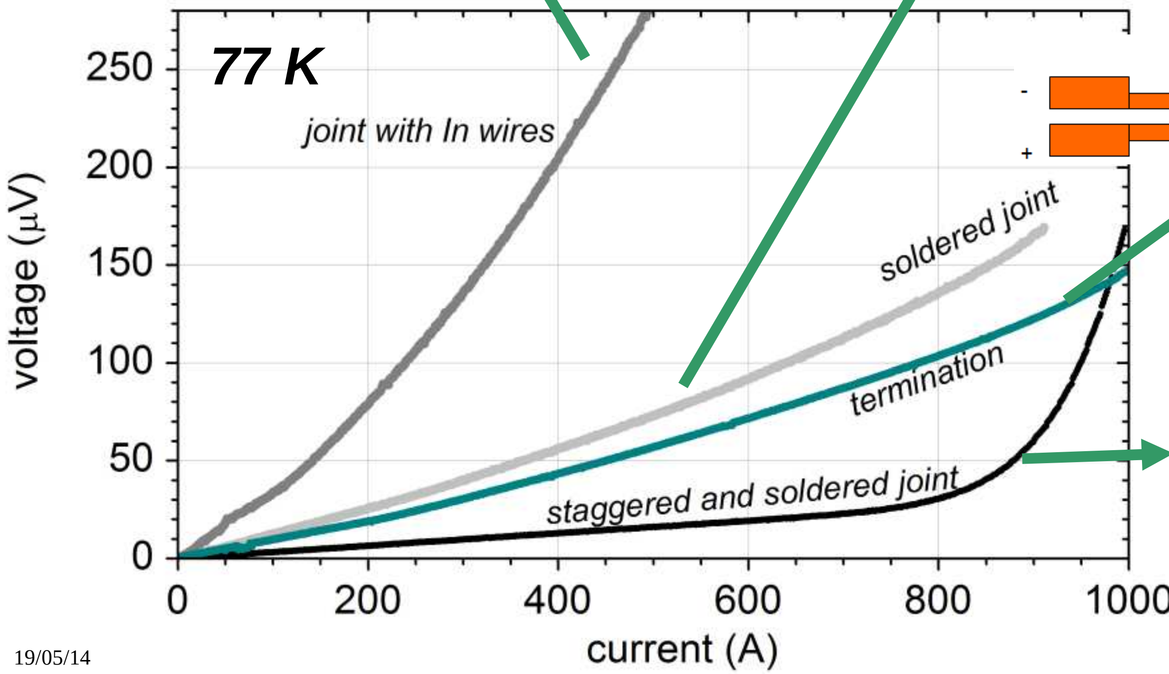


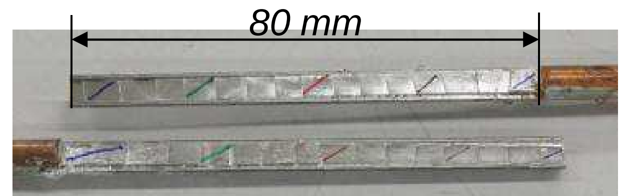


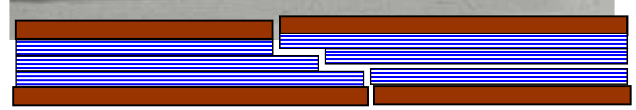






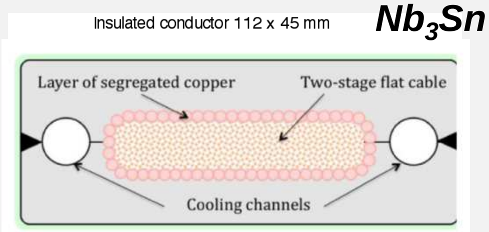






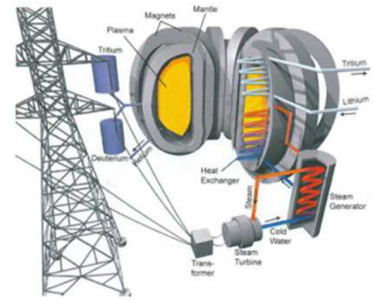
30 nΩ, corresponding to $9 \times 10^{-12} \Omega m^2$

Outlook - 80 kA class conductor

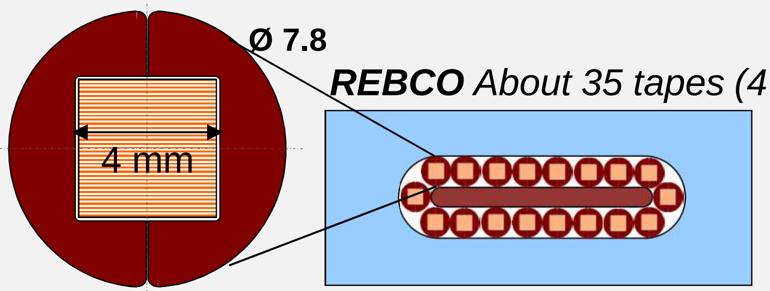


Nb_3Sn for DEMO

Cu: 800 mm^2
Void fraction 23%
J_e(op. cond.) = 65 A/mm^2

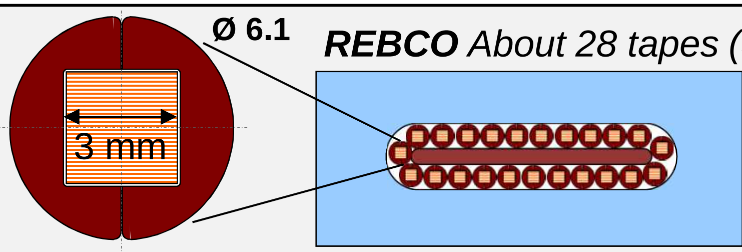


5 K, 12 T



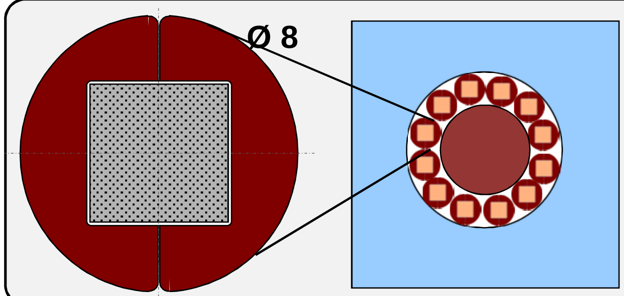
REBCO *About 35 tapes (4 mm wide) per strand, 18 strands in the cable*

Cu: 900 mm^2
Void fraction 26%
J_e(op. cond.) = 58 A/mm^2



REBCO *About 28 tapes (3 mm wide) per strand, 23 strands in the cable*

Cu: 770 mm^2
Void fraction 26%
J_e(op. cond.) = 70 A/mm^2



DI-BSCCO *About 18 tapes (4 mm wide) per strand, 12 strands in the cable*

Cu: 800 mm^2
Void fraction 20%
J_e(op. cond.) = 70 A/mm^2

Critical current at 5 K, 12 T:
100~110 kA ***at 4.2 K***
65~75 kA ***at 15 K***
40~50 kA ***at 30 K***

Summary

- Design of cables with tapes: long twist pitches are needed at cable level.
- Trial fabrication of several round strand (stacked tapes): Ø 6.2 mm, 14 to 16 stacked tapes
- Electro-mechanical limits have been determined.
- I_c(B,T) measured in 4 K – 40 K and 6 T – 12 T range (strand made with 15 tapes).
- Improved design of Cu profiles and softened copper: min. bending radius is now 250 mm.
- Various types of joints have been fabricated: staggered soldered joints have specific resistance similar to single tape joints.

Outlook (within the end 2014)

- Construction of an EDIPO/SULTAN sample (two cables, each 1.9 m long) under way.
- Fabrication and test of a strand (35 REBCO tapes, 0.5 m long) for a 100 kA class cable.
- Fabrication and test of a strand (16 Bi2223 tapes, 0.5 m long) for a 100 kA class cable.
- Cable design using Bi2212 wires. Issues: strain management during cabling (R&W), transverse stress.