IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) October 2014
Invited Presentation 2LOr2B-01 given at ASC 2014, Charlotte, August 10 – 15, 2014.

Development of Prototype HTS Conductors for Fusion Magnets

D. Uglietti, N. Bykovsky, R. Wesche, and P. Bruzzone

EPFL-CRPP Fusion Technology, 5232 Villigen PSI, Switzerland

- Motivation
- Bi2212 - Cable design
- REBCO - Cable design
- REBCO - Strand fabrication and electromechanical characterisation
- REBCO – Cabling
- Bi2223 – test of trial strand and preliminary cable design
- Summary and outlook

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Motivation

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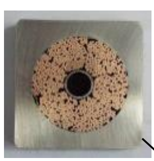
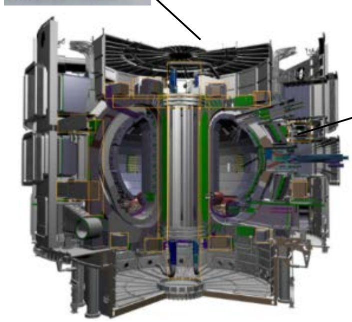
Requirements for Fusion Magnets

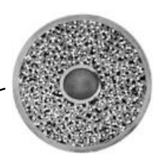
- *Peak field in the 12 T ~ 18 T range.*
- *Large bending radius (> 3 m) during winding.*
- *Very large current (>50 kA) and large Cu cross section (500 to 900 mm²), thus low J_e.*
- *Moderate AC losses. High quality of magnetic field is not required.*
- *Cheap and easy industrial production (at Km length).*
- *Steel structures takes up most of the longitudinal load (Hoop stress), but large transverse loads are still present.*



46 kA

ITER
(2013-2030)

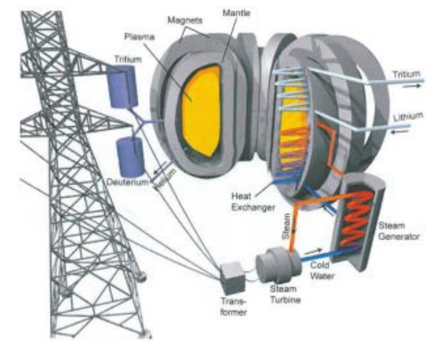




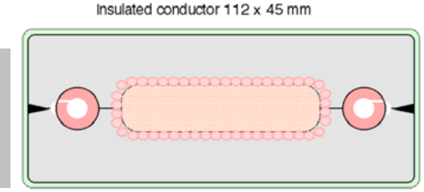
68 kA Cu: 530 mm²
Void fraction 30%
J_e(5 K, 12 T) = 55 A/mm²

DEMO EuroFusion
(2030-…)

P. Bruzzone, Fusion Engineering and Design, **88** (2013), p. 1564-1568



Insulated conductor 112 x 45 mm



82 kA Cu: 690 mm²
Void fraction 23%
J_e(5 K, 13 T) = 65 A/mm²

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Motivation

Three HTS materials available from industry:

Bi2212 wires **cheap, easy to cable, high temp. and pressure HT, mech. Weak …**

Bi2223 tapes **difficult to cable, … long length …**

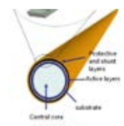
REBCO tapes **difficult to cable, expensive ... , a lot of potential improvement …**

For all of them cost should decrease by at least 10 times

But REBCO: may work at > 12 T, > 30 K; potential for low cost fabrication, larger margin of improvements (newest)

Stack strand *(MIT)*

Roebel *(KIT, IRL)*



Round hollow wire *(Nexans)*

C.O.R.C.

Advantage of HTS in Fusion Magnets

- **At 5 K temperature margin can be higher.** For example HTS cable could easily sustain the large nuclear heat load in the innermost layer (less demanding for cryogenic and cooling)
- **More compact coils.** Therefore more space for blanket and other components
- **Operation at temperatures > 5 K** (cost balance: cryogenic, AC losses, conductor price)

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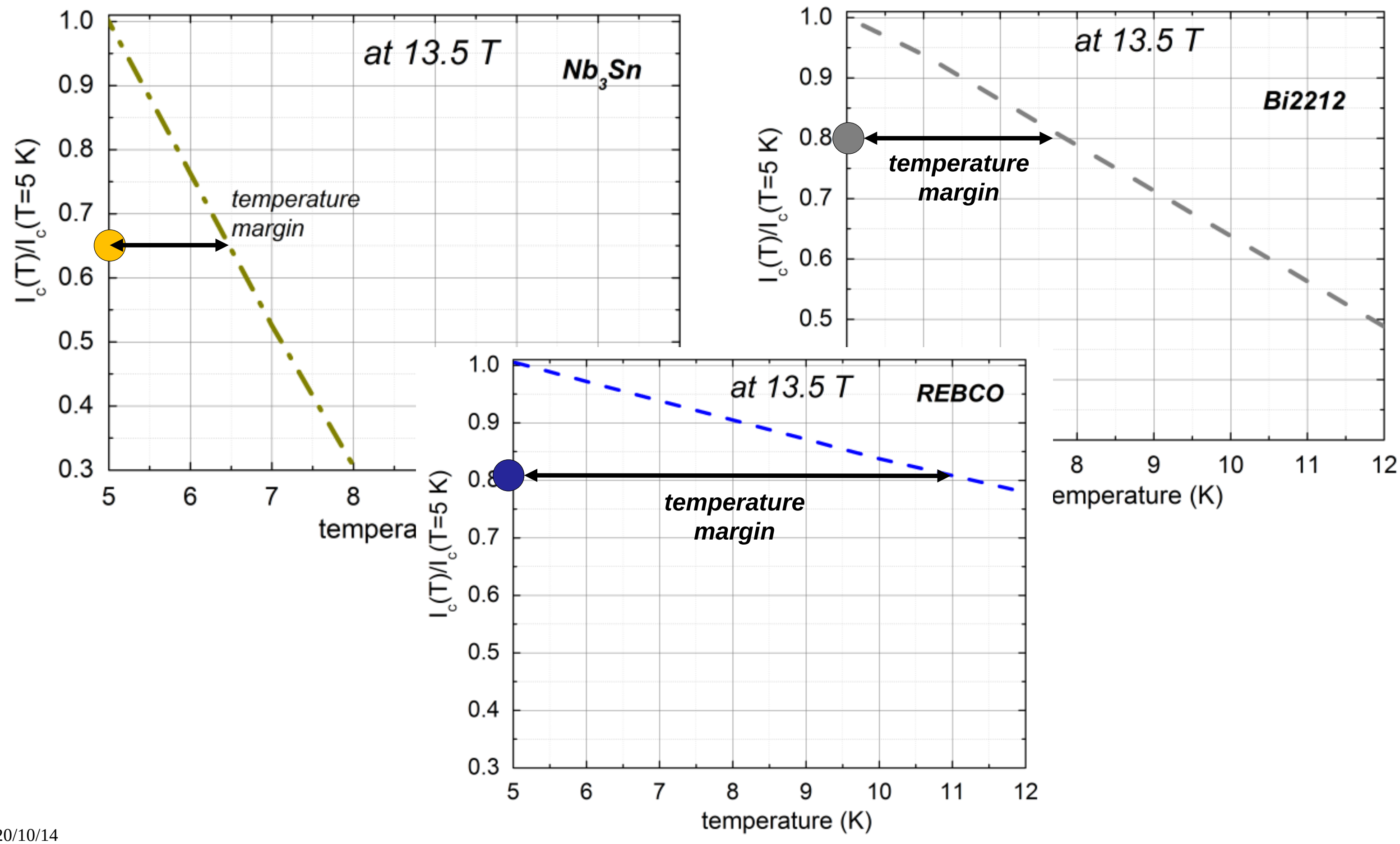
Motivation

Because of the weaker dependence of the temperature, HTS materials can be operated closer to the critical current, thus saving superconducting material.

Nevertheless the temperature margin is larger than in LTS.



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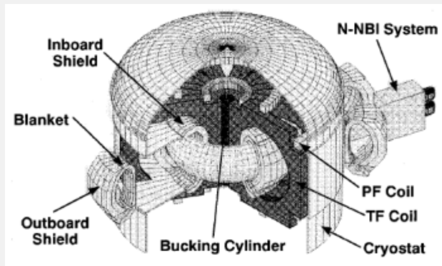
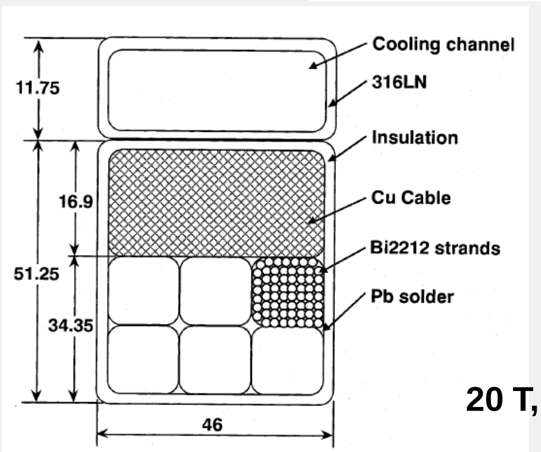
Bi2212 wires for Fusion Magnets

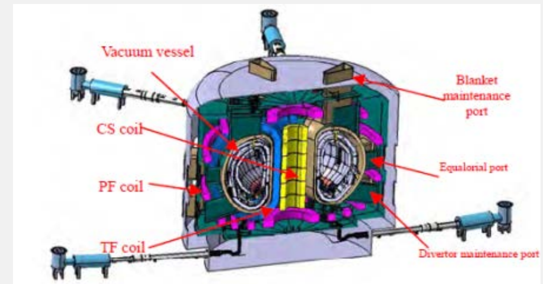
T. Ando et al., "Design of the toroid field coil for A-SSTR2 using high Tc superconductor", *Fusion Engineering and Design* **58–59** (2001) 13–16

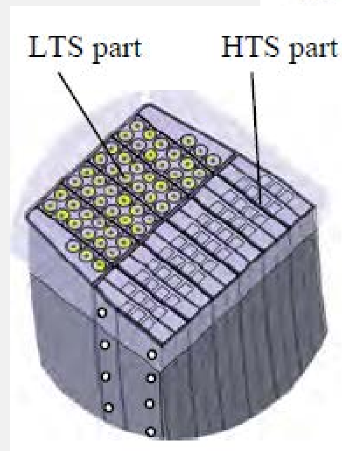




20 T, 20 K

J. Zheng et al., "Concept design of hybrid superconducting magnet for CFETR Tokamak reactor", (2013) *IEEE 25th Symposium on Fusion Engineering (SOFE)*





12 T, 20 K

Different cooling system for LTS and HTS sections.

HTS section is compact, more space for the blanket.

Not many details on the cables…

Bi2212 cable design. Issues: strain management during cabling (R&W), transverse stress.

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Bi2212 wires for Fusion Magnets

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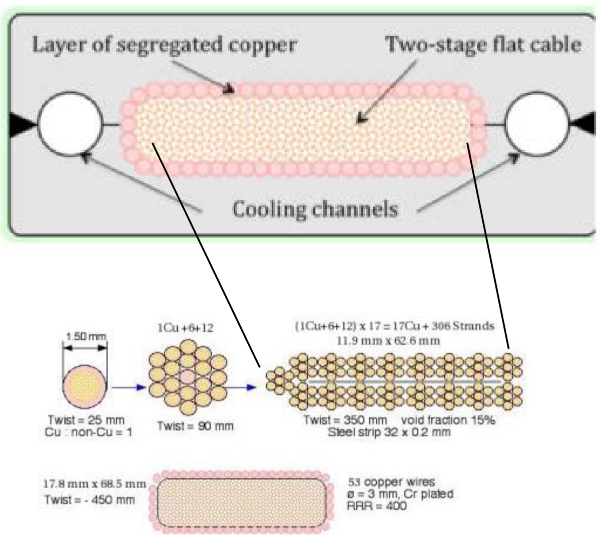
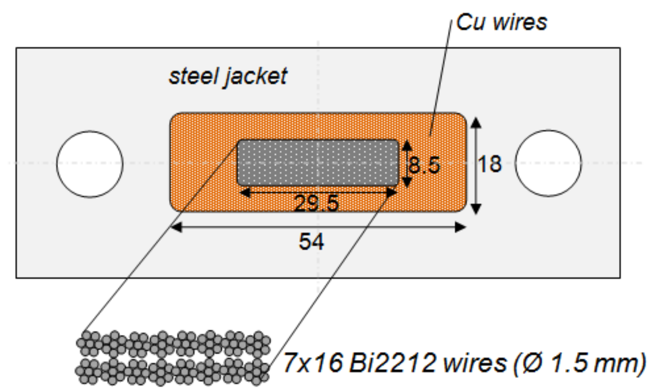
For large Nb_3Sn coils React & Wind is technologically and economically more interesting than W&R

Bi2212 has wire dimension and critical tensile strain limit comparable to Nb_3Sn wires

From R&W Nb_3Sn cable for DEMO ***to*** ***R&W Bi2212***

Fusion Engineering and Design, **88** (2013), p. 1564-1568



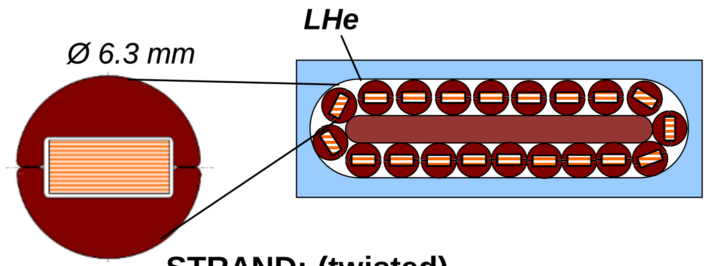


Transverse load at operation < 35 MPa

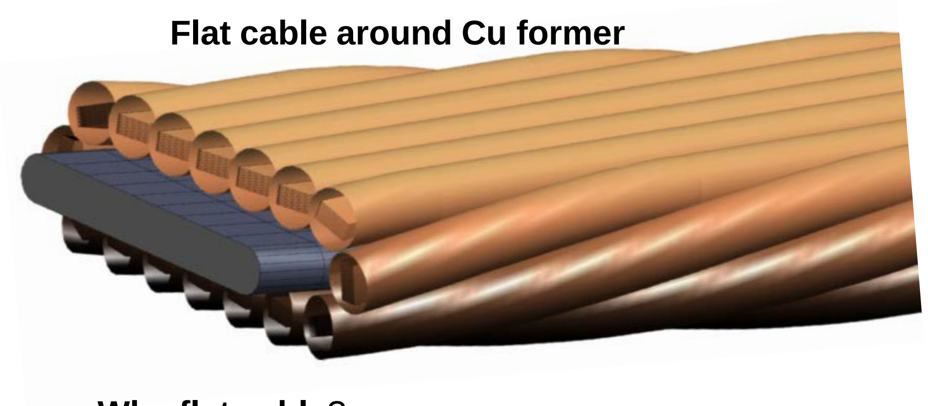
-0.08% ~ +0.08% ***strain state after winding*** ***-0.07% ~ +0.07%***

I_c reduction would be -1% (irr.) at -0.07% strain and -0.5% (rev.) at +0.07% strain

REBCO tapes for Fusion Magnets CRPP Cable design



STRAND: (twisted) soldered stack in copper



Flat cable around Cu former

Why soldered stack strand?

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

Twisted strands for large amount of transposition:

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

Why flat cable?

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

Poster on Wednesday, 9:30 AM - 11:30 AM
3LPo1C-04 Strain management in HTS high current cables, by N. Bykovsky

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

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CRPP Cable design

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

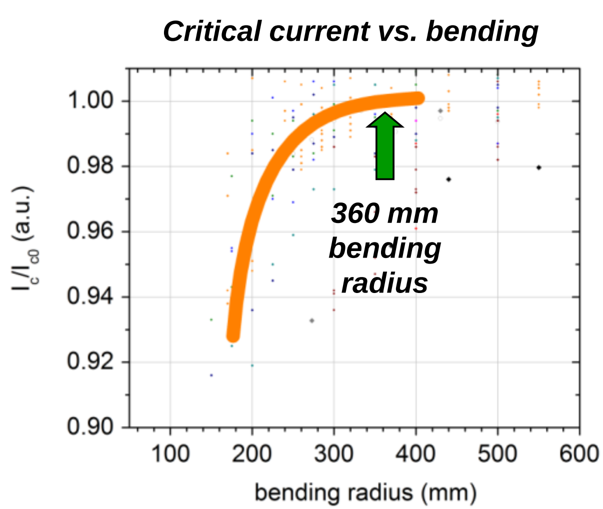
Nb_3Sn: 1.cabling 2.winding 3.reacting or 1.cabling 2.reacting 3.winding

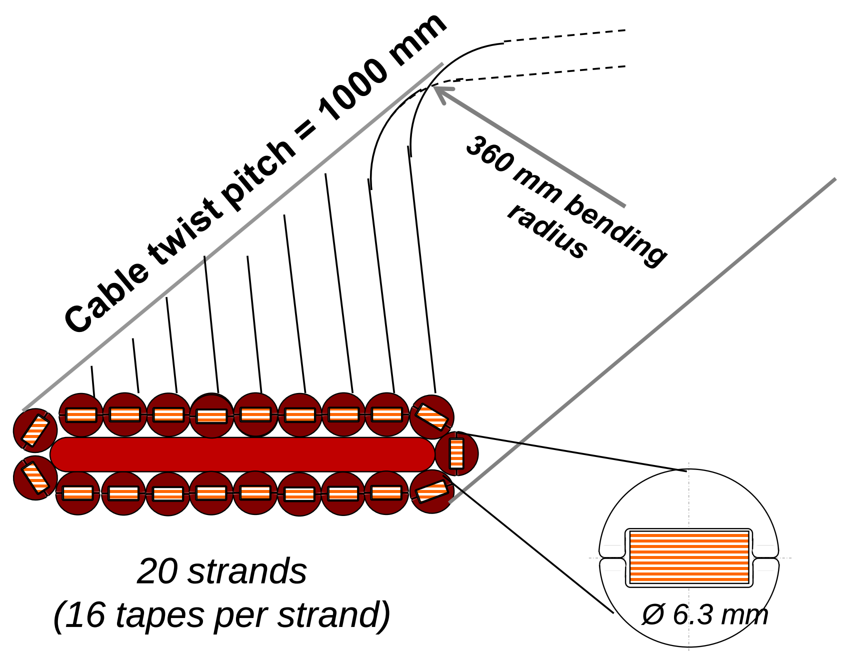
CC: 1.reacting 2.cabling 3.winding

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

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

Strands are twisted before soldering





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Strand Fabrication

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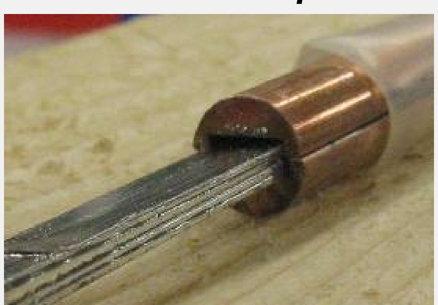
1. Tape tinning

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

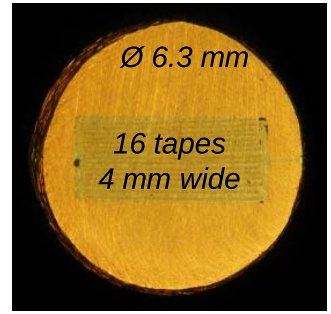
2. Profile tinning

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

3. Stacking tapes between two Cu profiles



4. Twist the strand *(320 mm twist pitch)*



5. Solder the twisted strand

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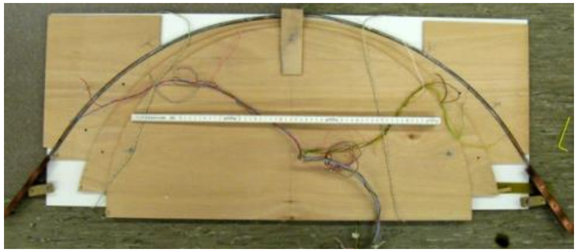
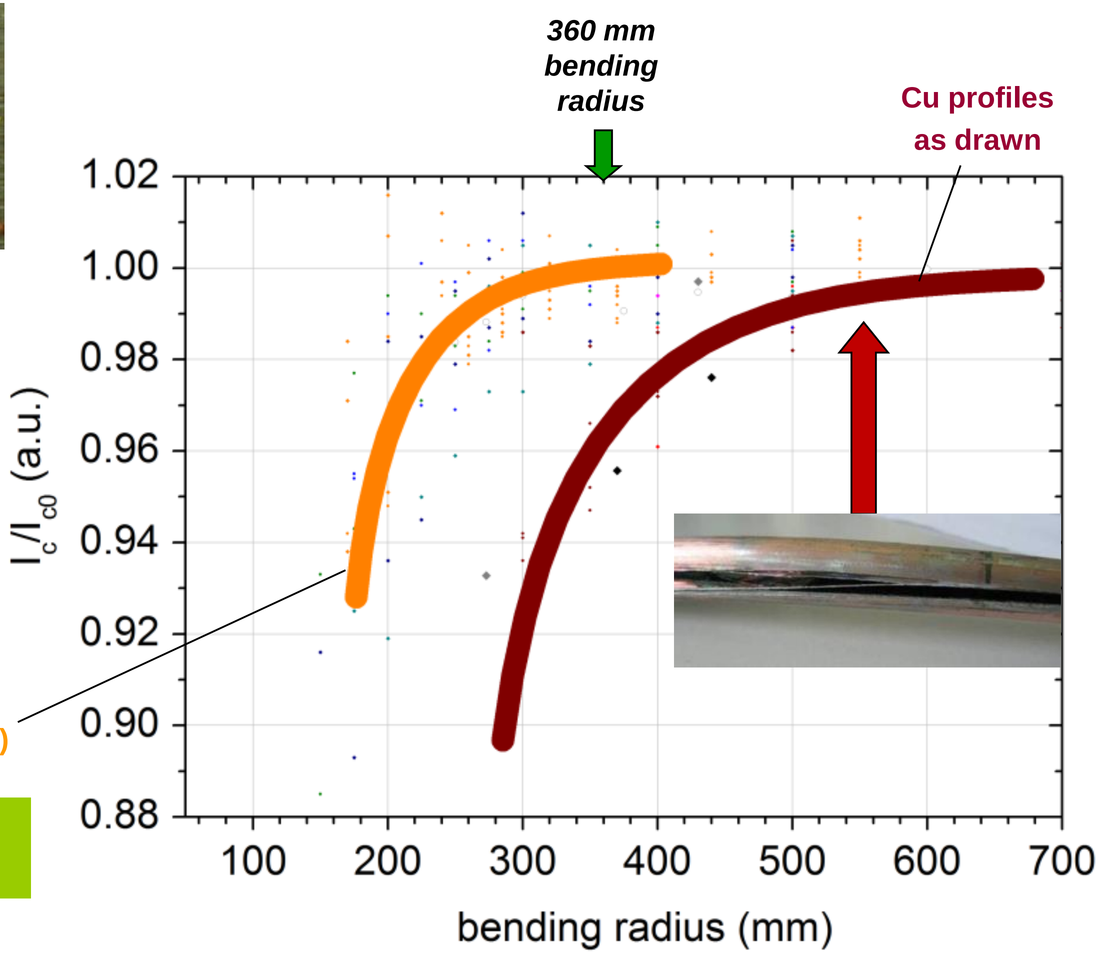
Electromechanical characterisation
I_c vs. bending



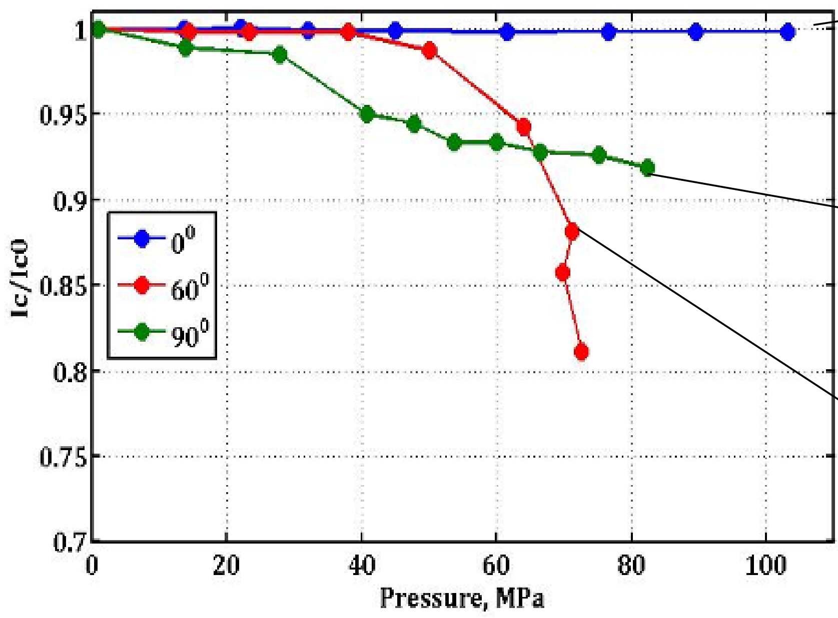
Bending radius is not constant along te length: shorter in easy bending regions and longer in hard bending regionsa

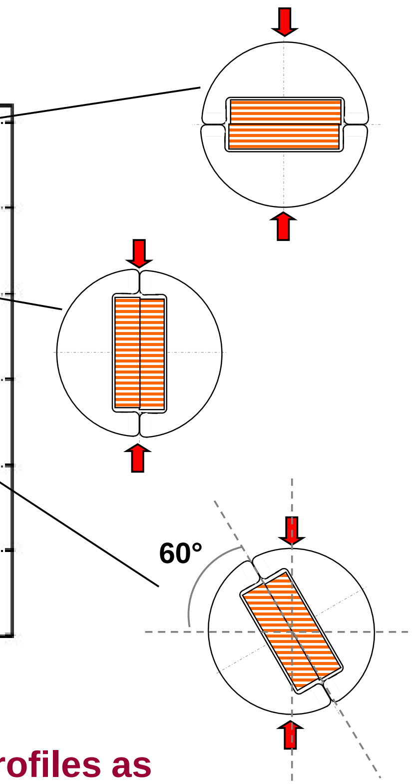


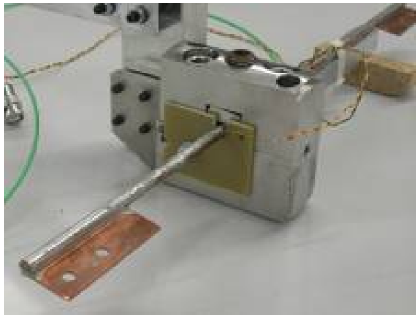
Selected for the 1.9 m cable (R=360 mm).

Electromechanical characterisation

I_c vs. transverse pressure







Cu profiles as drawn

Limit < 30 MPa

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

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Electric characterisation - $I_c(B,T)$

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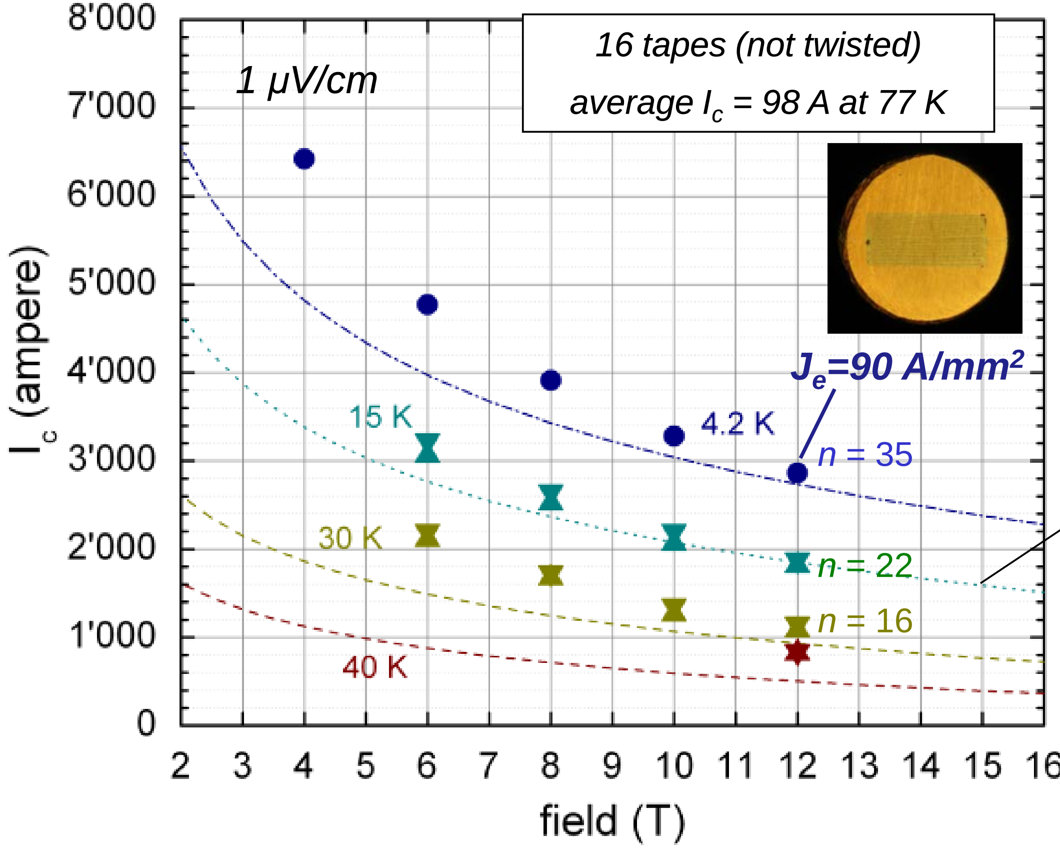
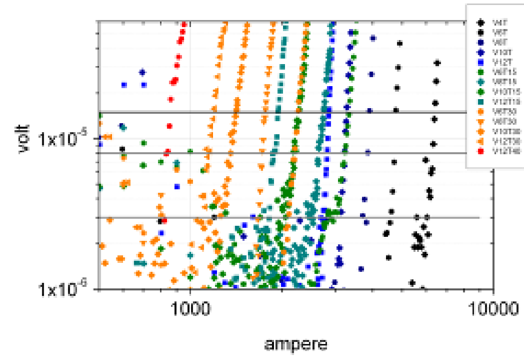
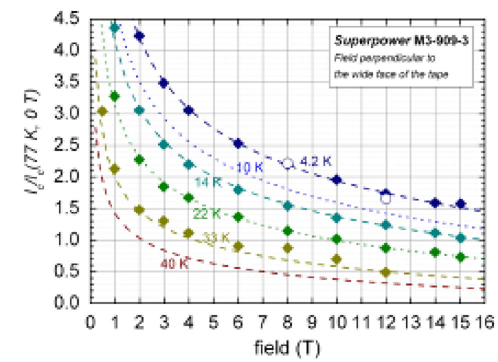
Measured by C. Bayer (KIT)





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

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Cable assembling

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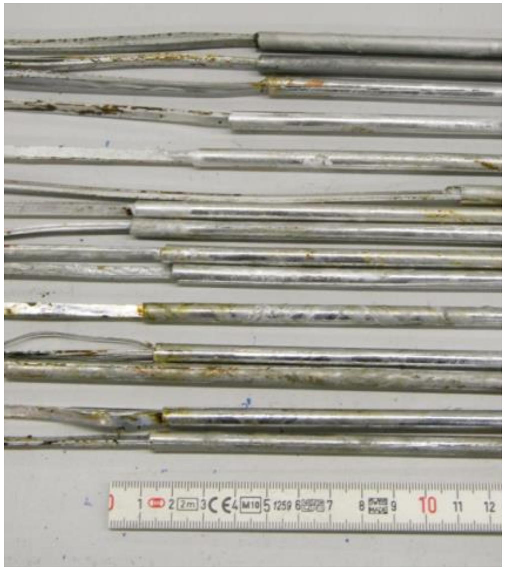
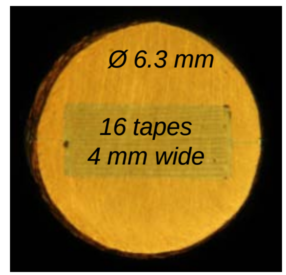


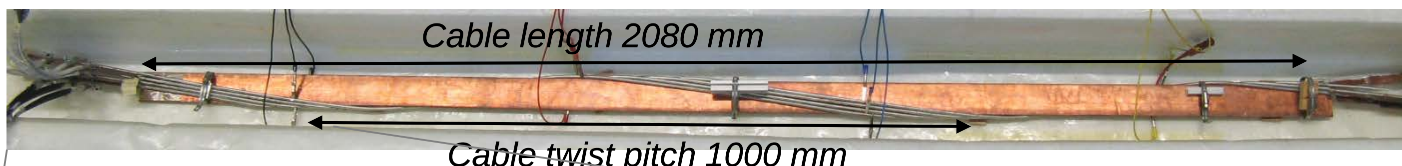
- First cable in construction is made with SuperPower tapes (SCS4050)
- Lift factor (77 K self field to 12 T, 4.2 K) is between 1.2 and 2.5

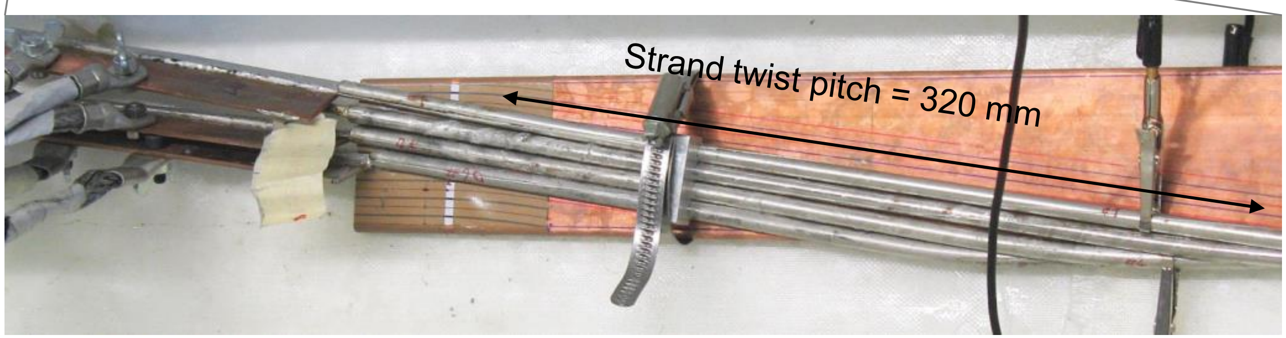


Expected critical current at 12 T, 5 K

59±2 kA

About 320 m of tape for 1 m of cable





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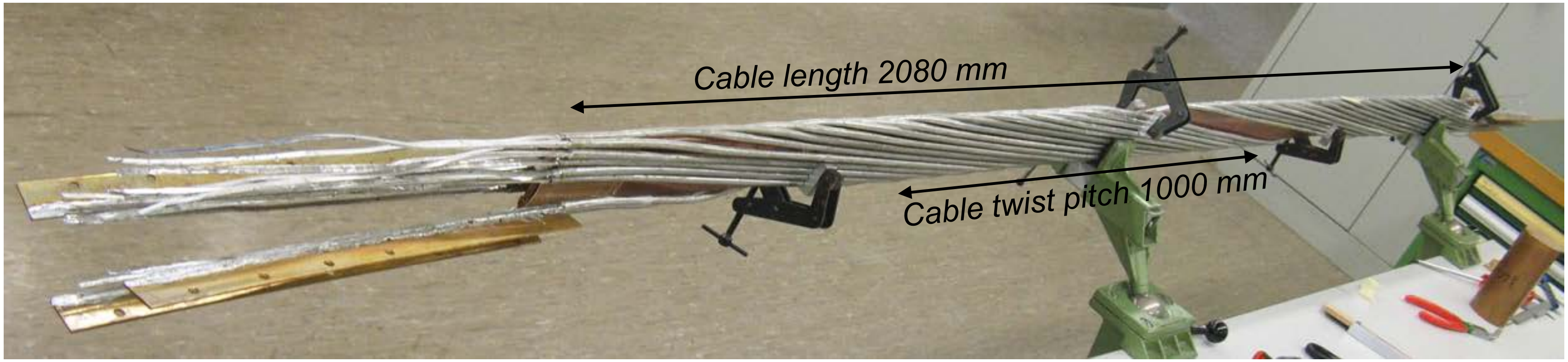
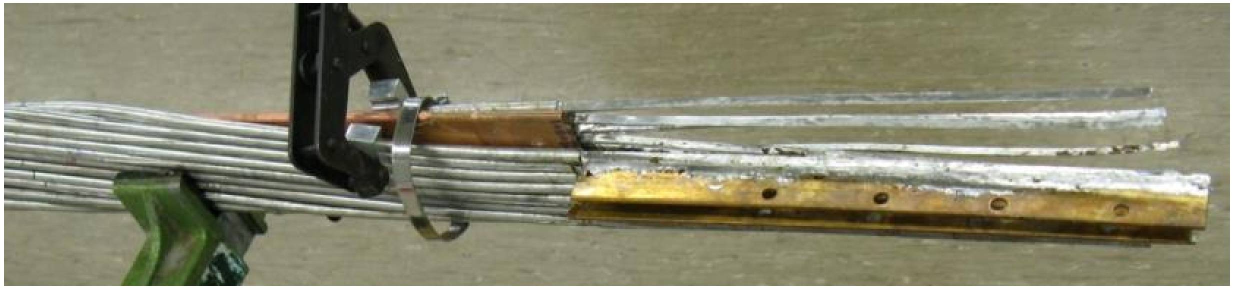
Cable assembling

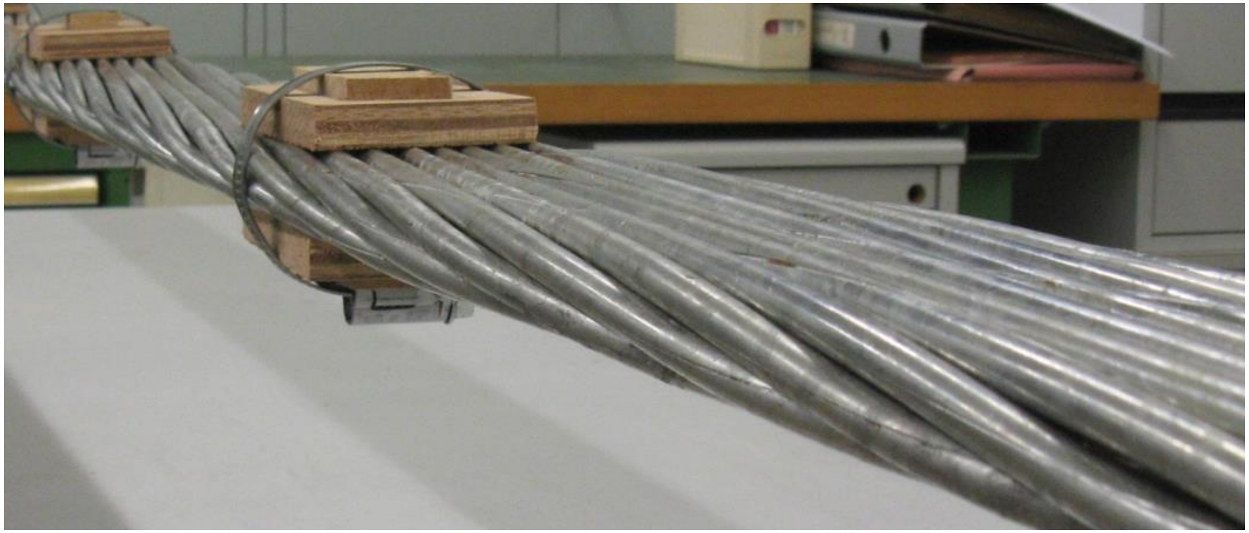
CRPP

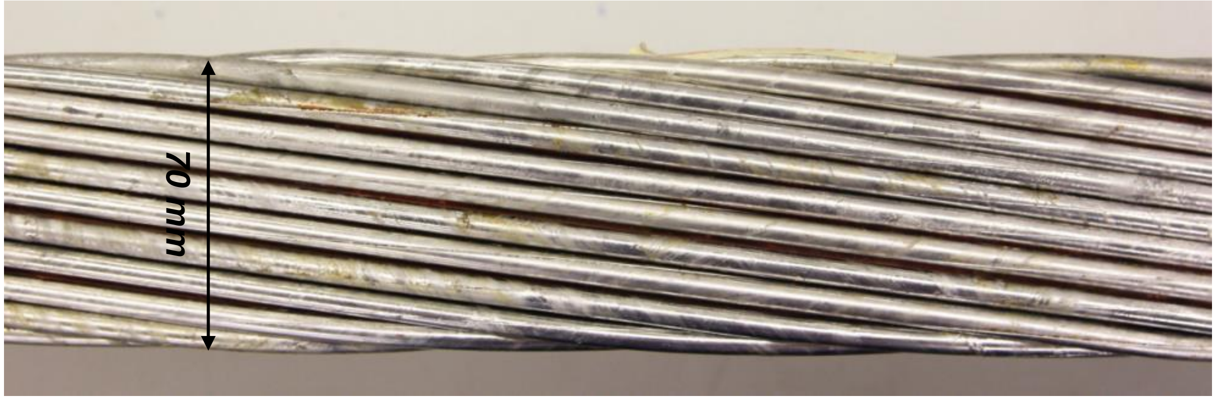




- **I_c was measured before and after cabling on seven strands**
- **After cabling critical current and *n* value did not decrease**

Cable assembling





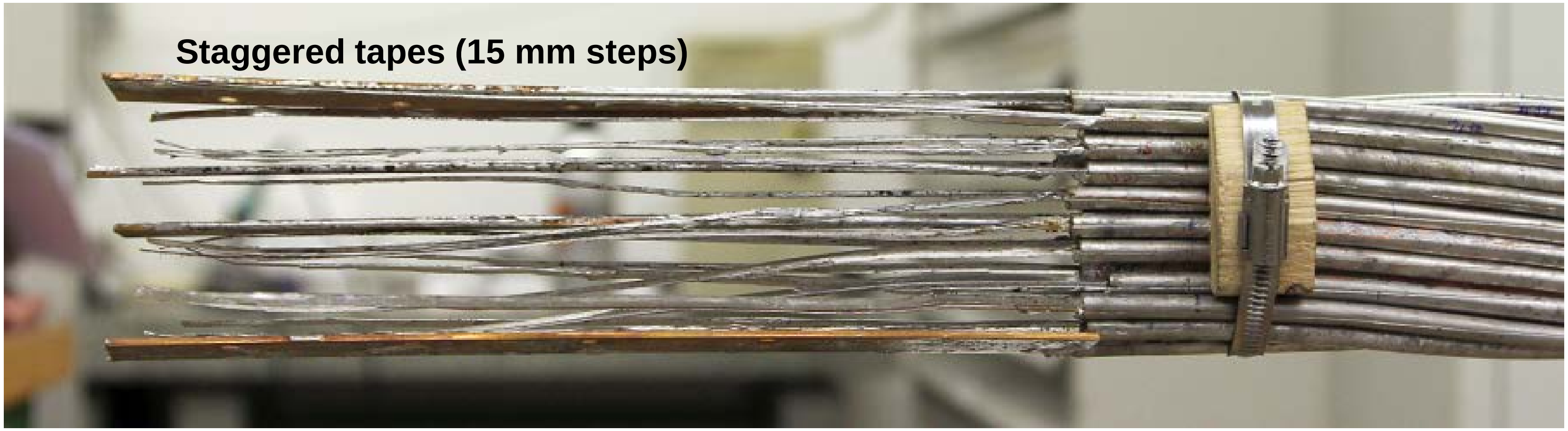
Expected critical current at 12 T, 5 K

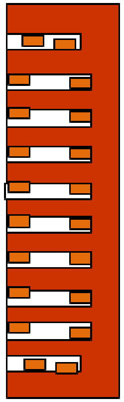
59±2 kA

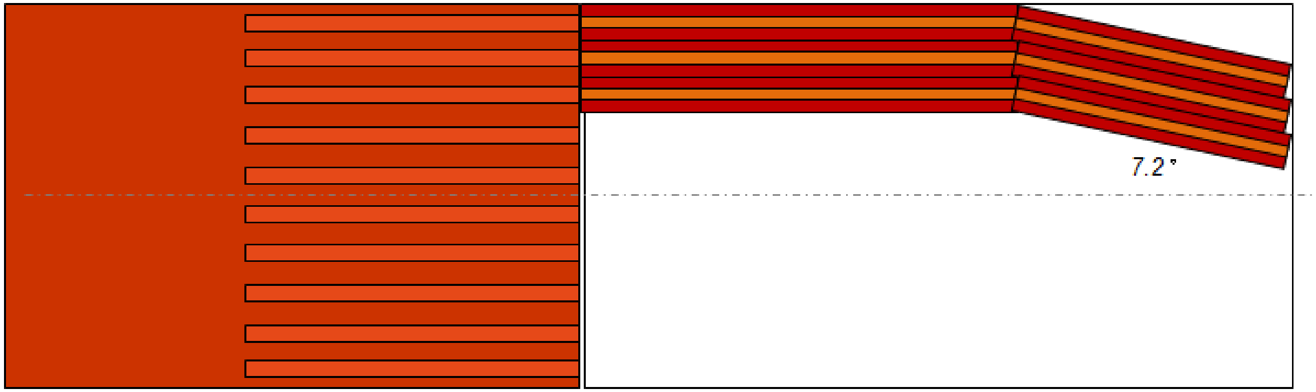
A second cable is being assembled with SuperOx tapes.

Cable Termination

Operation at 100 kA with a superconducting transformer requires low total resistance (<5 nΩ)







Every tapes has the ceramic side in contact with the Cu terminal (over 15 mm)

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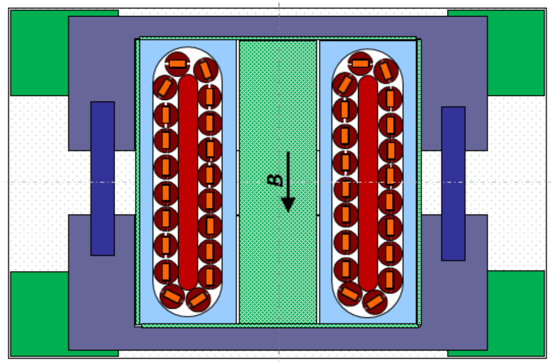
HTS Sample Test in SULTAN/ EDIPO

Test well: 142 mm × 92 mm



Sample cross section

Expected Critical current at 12.5 T

55~65 kA at 4.2 K

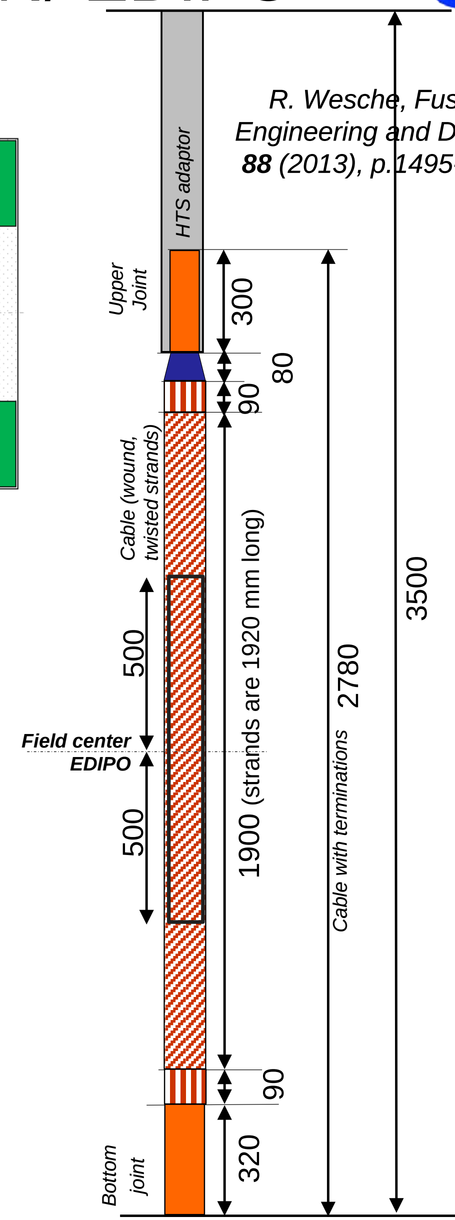
35~40 kA at 15 K

20~25 kA at 30 K

EDIPO	**SULTAN**
12.3 T	**10.8 T**
(homogeneous over 100 cm)	(homogeneous over 40 cm)

- **DC current up to 100 kA**
- **Supercritical helium between 4.5 K and 50 K**

*R. Wesche, Fusion Engineering and Design, **88** (2013), p.1495-1498*



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Outlook - 80 kA class conductor

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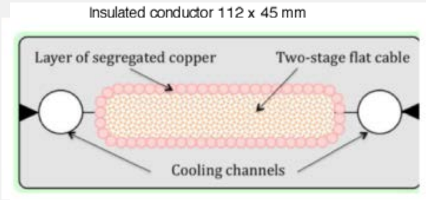
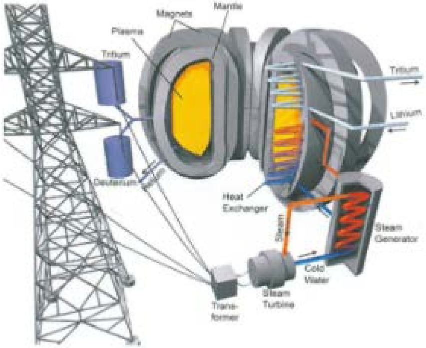


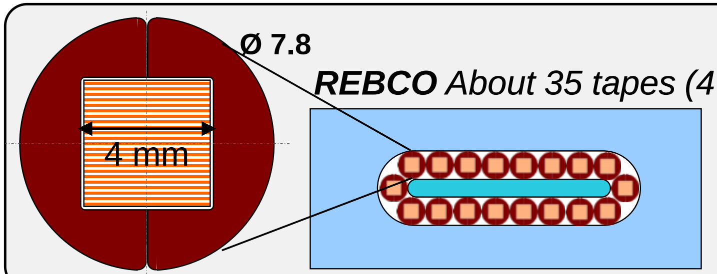
Nb_3Sn for DEMO

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

P. Bruzzone, *Fusion Engineering and Design* **88** (2013) 1564-1568

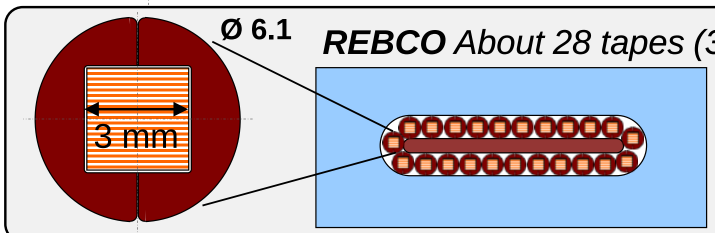


5 K, 13.5 T



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

Cu: 680 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

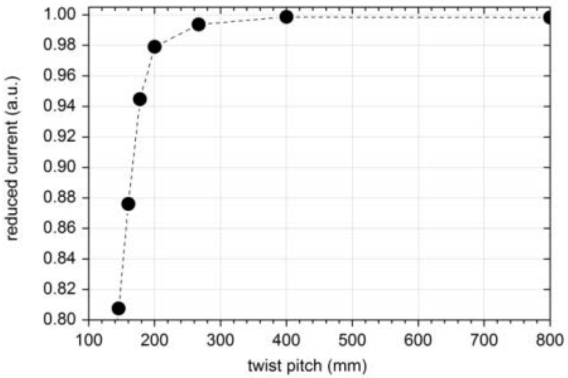
Critical current at 5 K, 12 T:
100~110 kA ***at 4.2 K***
65~75 kA ***at 15 K***
40~50 kA ***at 30 K***

Test strands (50 cm long) in preparation

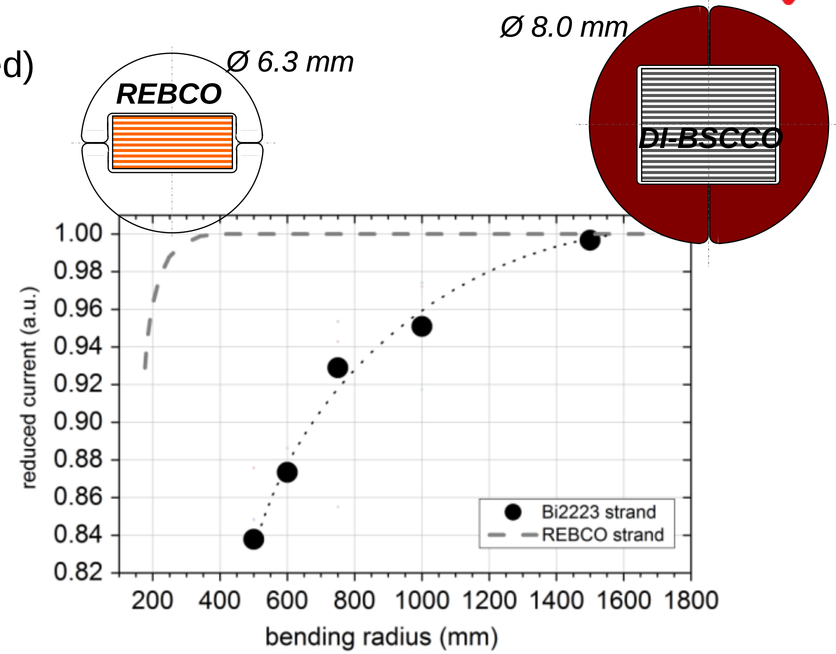
Bi2223 tapes for Fusion Magnets

DI-BSCCO type H from Sumitomo (non reinforced)

Single tape twisting

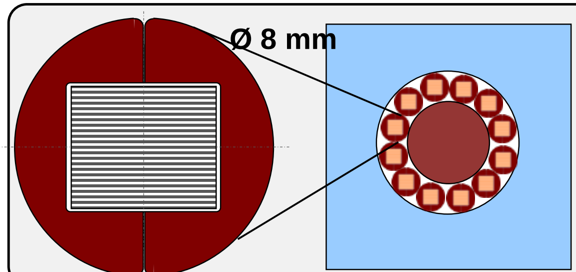


400 mm strand twist pitch



Large bending radius ⇒ long cable twist pitch

Tentative design



DI-BSCCO *About 16 tapes (4.3 mm wide) per strand, 12 strands in the cable*

Cu: 800 mm²

Void fraction 20%

J_e(op. cond.) = 70 A/mm²

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CRPP

Summary

- Preliminary design of a **Bi2212** cable (R&W) for DEMO magnets.

- **Bi2223** trial strand was fabricated and tested. Cable design should take into account the fragility of Bi2223, which appears to be not so suitable for this cabling method.

- Prototype cable with stacked strand (**REBCO**) was prepared.
- Length is 2 m, 20 strands each with 16 tapes (4 mm wide). Expected I_c(5 K, 12 T) = 60 kA
- The construction of an EDIPO/SULTAN sample (two cables, each 2 m long) is under way.

Outlook (within the end 2014)

- Testing of the 60 kA (REBCO) prototype cables in EDIPO/SULTAN.
- Fabrication and test of strands (REBCO tapes, 0.5 m long) for 100 kA class cables.

Outlook (2015)

- Test of subscale Bi2212 cables.
- Quench tests on REBCO cable.