Progress in HTS CrossConductor (HTS CroCo) fabrication and characterization

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Motivation

Generation of high magnetic fields

Image Source:
Motivation – High DC current applications

Data centers
Chlorine electrolysis
Copper electrolysis
Aluminum electrolysis
DC power on ships
offshore wind park
particle accelerators & detectors
Fusion DEMO TF magnets

DC current (kA)
5 10 50 100 500

Data sources:
W. Reiser, Presentation at ZIEL V workshop (2014)
**Outline**

- Introduction of the HTS CrossConductor:
  - Design
  - Fabrication concept

- First results on partially REBCO equipped HTS CroCos
  - V(I) – measurements @ T = 77 K
  - Electromechanical tests in the FBI facility

- Terminations
  - Concept and fabrication
  - Achieved termination resistances

- Realization of smaller HTS CroCos

Unfortunately, a leak in the water cooling of the 10 kA power supply of the FBI facility did not allow to test the fully REBCO-equipped HTS CroCo sample yet. Maintenance is ongoing and to be finished soon.
HTS High Current Cable Concepts

**CORC:**
Conductor on Round Core
D. van der Laan,
SUST 22 (2009) 065013

**TSTC:**
Twisted Stacked Tape Cable
M. Takayasu et al.,
*IEEE TAS 21* (3) (2011), 2340

**Roebel - Cable:**
W. Goldacker et al.,
Stacked HTS High Current Cable Concepts

TSTC:
Twisted Stacked Tape Cable

M. Takayasu et al.,
*IEEE TAS* **21** (3) (2011), 2340

Round - TSTC:
D. Uglietti, *et al.*,  
*IEEE TAS* **24** (3) (2014), 4800704

TSTC - CICC
G. Celentano, *et al.*,  
*IEEE TAS* **24** (3) (2014), 4601805

STARS Fusion cable
N. Yanagi,
*FUS. SC. & TECH.* **60** (2) (2011), 648
How to fabricate easily long length –
high current HTS cables with TSTC-concepts?

Main Requirements

- Simple long-length production method

- Easy Joint Manufacturing & Current Transfer
  (jointing single tapes is not feasible for a large scale application)

- Twisting and bending without degradation
The KIT cable approach targeting a round strand

<table>
<thead>
<tr>
<th>Existing concepts use tapes of <strong>one</strong> width</th>
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<tbody>
<tr>
<td><strong>Rectangle or Square</strong></td>
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Diagram: A round cable with a rectangular or square tape wrapped around it.
The KIT cable approach targeting a round strand

Existing concepts use tapes of one width

Rectangle or Square

Max. geometrical filling factor 63,6 %
The KIT cable approach targeting a round strand

<table>
<thead>
<tr>
<th>Existing concepts use</th>
<th>KIT approach</th>
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<tr>
<td>tapes of <strong>one</strong> width</td>
<td>Use tapes of <strong>two different</strong> widths</td>
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<td><strong>Rectangle or Square</strong></td>
<td><strong>HTS CrossConductor &quot;HTS CroCo&quot;</strong></td>
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<tr>
<th>Max. geometrical filling factor</th>
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<td>63.6 %</td>
<td>+ 23 %&lt;sub&gt;rel.&lt;/sub&gt;</td>
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The KIT cable approach targeting a round strand

Benefits:

HTS CroCo offers more space for HTS tapes

To avoid jointing of single tapes:

*Use REBCO tapes with thick electro-plated Cu stabilization to optimize current transfer and electrical stabilization*

Twisting can be done in a form-fit way

**KIT approach**

Use tapes of **two different** widths

HTS CrossConductor "HTS CroCo"

Max. geometrical filling factor

78.7 %
Fabrication steps of a Stacked Conductor

- Arrange the tapes
- Pre-tin the tapes
- Solder all individual tapes
- Form the stack
- Twist the stack

For economical fabrication of long lengths:

all these steps in one continuous process

Apply a jacket or former
The fabrication routine
Jacketing by Rotary swaging

- Cu tube
- CroCo-Core
- Soft filler material, e.g. solder

Outer diameter: 9.3mm
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First trials with in total 30 tapes, 150 μm Cu tapes + some HTS-tapes with ≥ 100 μm electroplated Cu

- 20 tapes of 6mm width, 16 Cu + 4 HTS tapes
- 2 x 5 tapes of 4mm width, 2 x (4 Cu + 1 HTS)

Stack dimensions:
5.1 mm x 6.3 mm

Total solder thickness
~ 20 μm per tape
$I_c$-calculation of the 20%-equipped twisted CroCo

Cross-sectional layout:

- Sum of tape $I_c$s from the manufacturer: $\sim 950$ A

Input parameter for individual tapes

\[ j_c (77 \, \text{K, sf}) = 30 \, \text{A/mm}_{\text{HTS}} \]

Field dependence of $I_c$ from Bykovsky et al.,

\[ J. \, \text{Phys.} : \, \text{Conf. Ser.} \, (2014) \, 507 (2), \, 022001 \]

Calculation of overall $I_c$

\[ I_c \approx 810 \, \text{A} \]
LN$_2$ – testing of the 20%-equipped twisted CroCo

Twist Pitch ~ 80 cm

$\Rightarrow$ No degradation

- $I_c = 844 \text{ A}$,
- $n = 22.6$
- $T = 77\text{K}, \text{sf}$
Preparation of a sample for FBI testing

Sample Parameters:

- **Untwisted stack**, Total of 32 tapes
  - 4mm wide: 4 HTS, 8 Cu
  - 6mm wide: 4 HTS, 16 Cu
  - HTS tapes equally distributed between Cu tapes
- Calculated $I_c$: 920 A
- Sheath: first trial with slotted, solder filled copper tube

$\Rightarrow$ No degradation
The FBI test facility

- Heater
- Tensile force (100 kN)
- Magnetic field (12 T)
- Current (10 kA)
- \( T = 4.2-77 \) K
Performance in magnetic fields at $T = 4.2$ K

No degradation!

$I_c = 2.1$ kA @ $B = 12$ T

$I_c = 52.5$ A / mm$_{HTS \text{ width}}$

SuperPower AP – Tapes show $I_c \sim 45 - 65$ A / mm$_{HTS \text{ width}}$ for $B \parallel c$

Hazelton, LTHFSW (2013)
Hazelton, WAMHTS (2014)
Abraimov et al., WAMHTS (2014)
Celentano et al., WAMHTS (2014)

$\theta(B,c) = 45^\circ \approx I_c (B \parallel c)$

Xu et al, SUST 23 (1) 014003 (2010)
Senatore et al, WAMHTS (2014)
Tensile testing

HTS CroCo shows the same $I_c$-strain curve as individual tapes!
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Types of Terminations

Stack in Groove

The HTS stack is soldered (PbSn, InAg) to a groove in the terminal (10 x 30 x 120 mm)

„parallel“

„perpendicular“

Stair

The tapes are shortened individually by 4mm and soldered to a termination (InAg)

Ramp

Sloped cutting (< 3°) and polishing of a HTS stack followed by soldering to a matching part (InAg)

Tube termination

Solder the HTS CroCo as a whole to a terminal (R = 40 nΩ obtained in a different terminal and measurement geometry)

M. J. Wolf et al., IEEE TAS 26 (2) (2016), 2521323
Measuring the termination resistance

- „Current Leads“ are of the same length as the terminations (12 cm)
- Two voltage taps on the bottom side of the termination for statistics
- Corresponding tap on the HTS CroCo far from the termination

- Calculation of the solid-state contributions of solder and copper parts

\[ R = 13 \text{ n}\Omega \quad T = 77 \text{ K} \]
Resistance measurements

- Critical current was not reached (limited by the power supply)
- Linear V(I) curves observed
Results

„Stack in Groove“ and „Stair“ show both $R \sim 50 \text{ n}\Omega$
Comparison

D. Uglietti et al. (2014):
Development of high current HTS conductors for Fusion at CRPP.
Presented at WAMHTS workshop, DESY Hamburg, 21.05.2014.
Online, last accessed: Mar. 18, 2016:

Soldered termination:
$R \sim 125 \text{ n}\Omega$ for $L = 150 \text{ mm}$
Comparison

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**M. Takayasu et al. (2016):**

Soldered termination:
\[ R \sim 125 \, \text{n}\Omega \text{ for } L = 150 \, \text{mm} \]

soldered „folding fan“ termination:
\[ R = 6 \, \text{n}\Omega \text{ for } 24 \, \text{mm} \times 70 \, \text{mm} \]
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HTS CroCo: Now available in different sizes

- Motivation: smaller twisting pitch and bending radii and smaller basis units

- 6/4 CroCo
- 4/2 CroCo
- 3/2 CroCo

- 9.1 mm
- 6.8 mm
- 5.7 mm
# Parameters of the different HTS CroCos

<table>
<thead>
<tr>
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<th>4/2 CroCo</th>
<th>3/2 CroCo</th>
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<tbody>
<tr>
<td>Number of REBCO tapes</td>
<td>20 x 6 mm</td>
<td>16 x 4 mm</td>
<td>16 x 3 mm</td>
</tr>
<tr>
<td>tape thickness</td>
<td>~ 165 µm</td>
<td>~ 95 µm</td>
<td>~ 95 µm</td>
</tr>
<tr>
<td>Ø incl. tube</td>
<td>9.1 mm</td>
<td>6.8 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>$I_c(4.2 \text{ K, 12 T})$</td>
<td>8000 A</td>
<td>4800 A</td>
<td>3200 A</td>
</tr>
<tr>
<td>$I_c(77 \text{ K, s.f.})$</td>
<td>3000 A</td>
<td>1800 A</td>
<td>1300 A</td>
</tr>
<tr>
<td>Bending radius</td>
<td>&gt; 60 cm</td>
<td>&gt; 40 cm</td>
<td>&gt; 30 cm</td>
</tr>
</tbody>
</table>
Conclusions

- The concept of the HTS Cross conductor (HTS CroCo):
  Improving the filling factor by using tapes of two different widths

- The „all-in-one“ fabrication routine of the HTS stacks works!
  → easy long-length production of twisted HTS stacks is possible

- FBI testing of a partially equipped sample shows excellent results
  → The CroCo strand is electrically & mechanically as good as its tapes!

- Soldering the stacks as a whole to a copper termination of 12 cm length
  can provide termination resistances of ~ 50nΩ

- The fabrication routine can be extended to narrower tapes as well for
  better twisting and bending properties and smaller basis units.