Characterization of REBCO Tape and Roebel Cable at CERN

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Outline

- CERN strand and cable test facilities
- Tape I_c measurements (transport and magnetization)
- Tape splice resistance
- RRR measurements
- Cable I_c characterization
- Cable splice resistance
- Transverse Effective section of Roebel cable

CERN strand and cable test facilities

Strand test stations

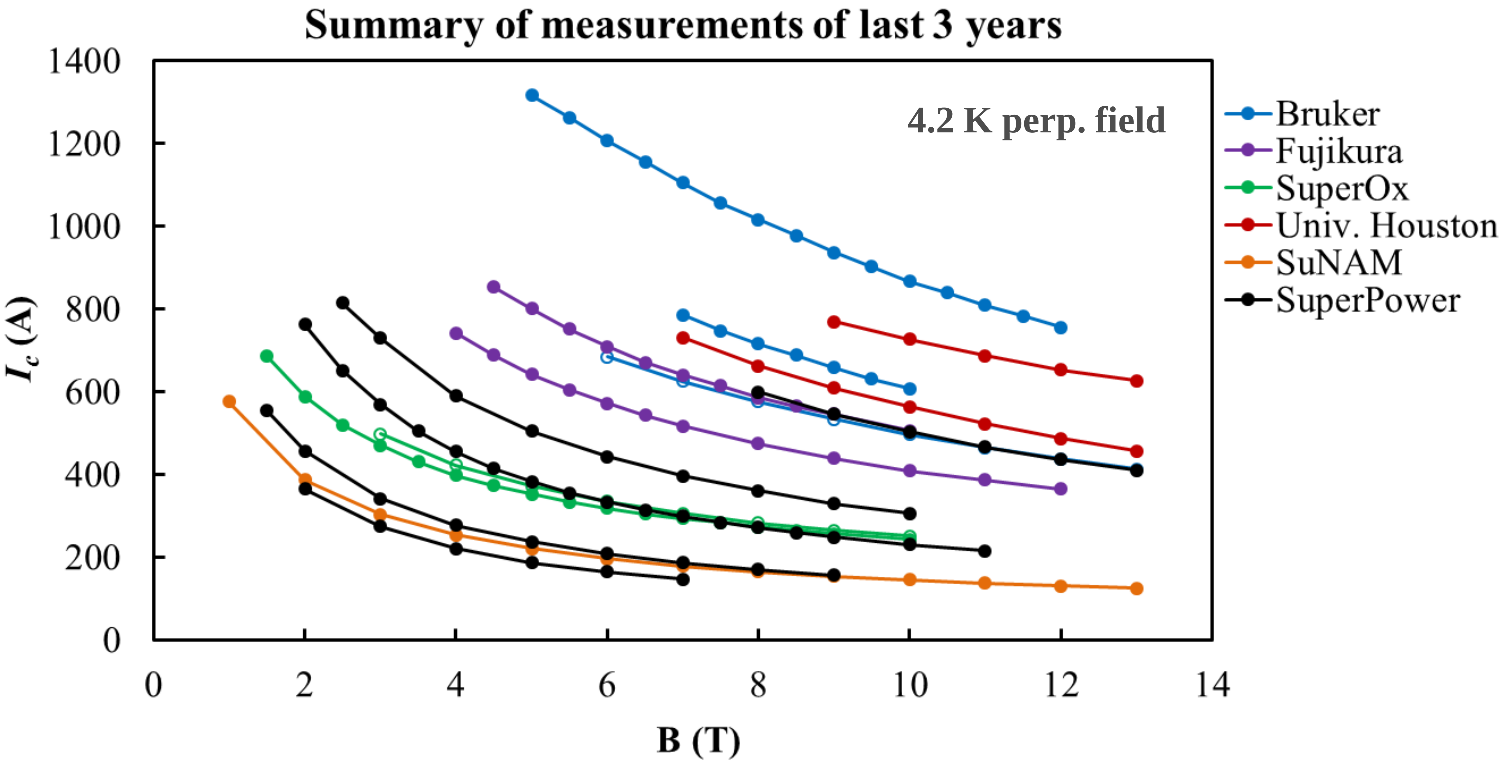
- I_c measurements 1.9-4 K, 15 T and 2 kA
- Magnetization measurements: VSM +/-10.5 T, 1.9-100 K
- RRR measurements
- Quench propagation, inter-strand and splice resistance…

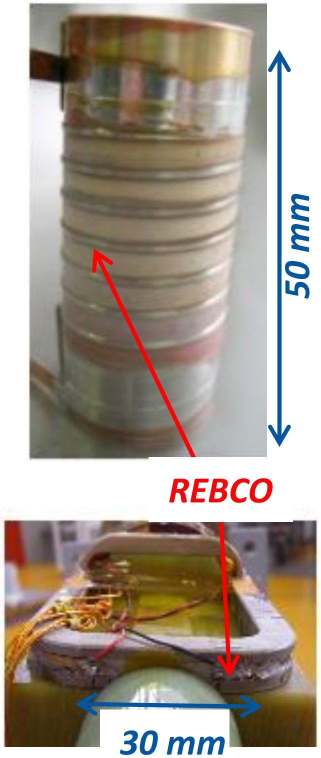
Cable test stations

- I_c measurements LHe 1.9-4 K, 9.6 T and up to 70 kA
- I_c measurements GHe 10-40 K, 20 m long and up to 20 kA
- Quench propagation and splice resistance…

Tape I_c measurements (transport)

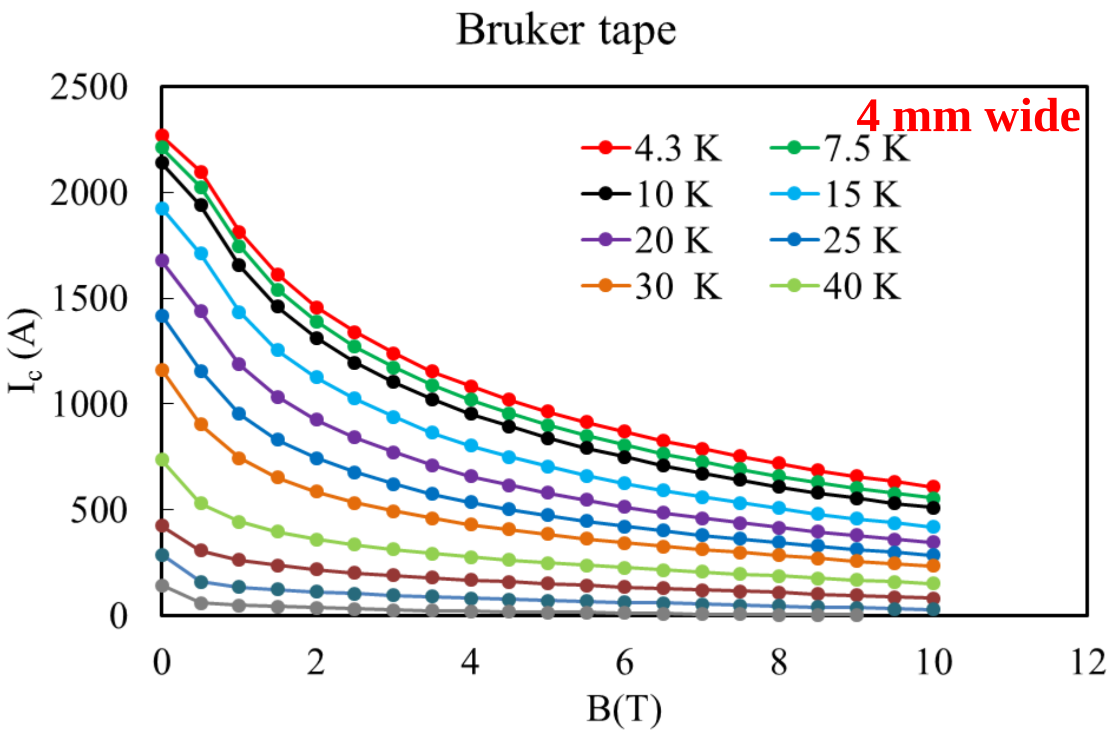
- Perp and // field up to 15 T and 2 kA
- 4 mm wide or 12 mm wide conductors (including meander tapes)
- Samples mechanically stabilized on thin stainless steel support
- Measurement of 2 samples/cool down

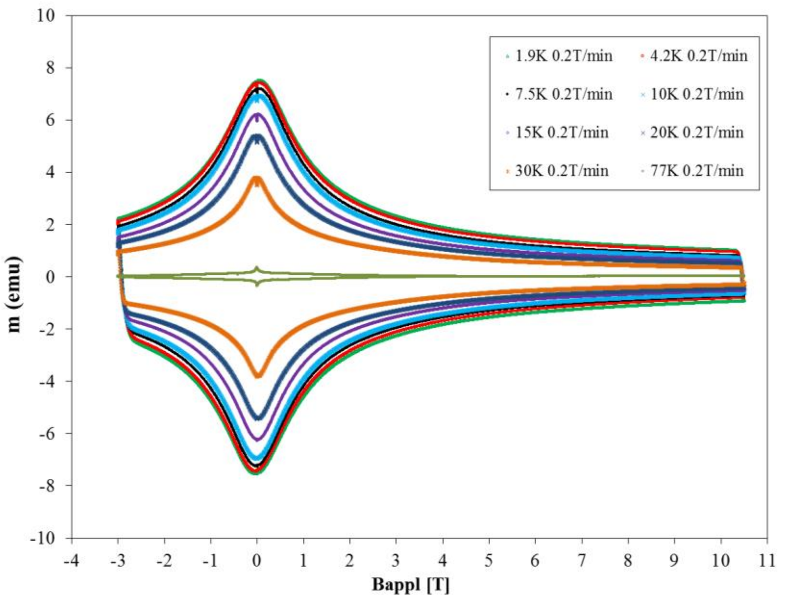




Tape I_c measurements (Magnetization)

- Magnetization measurements with VSM +/-10.5 T, 1.9-100K (measurement performed by D. Richter)
- Tapes from different suppliers were investigated





All Ic measurements are fitted using the generic scaling law presented in next slide

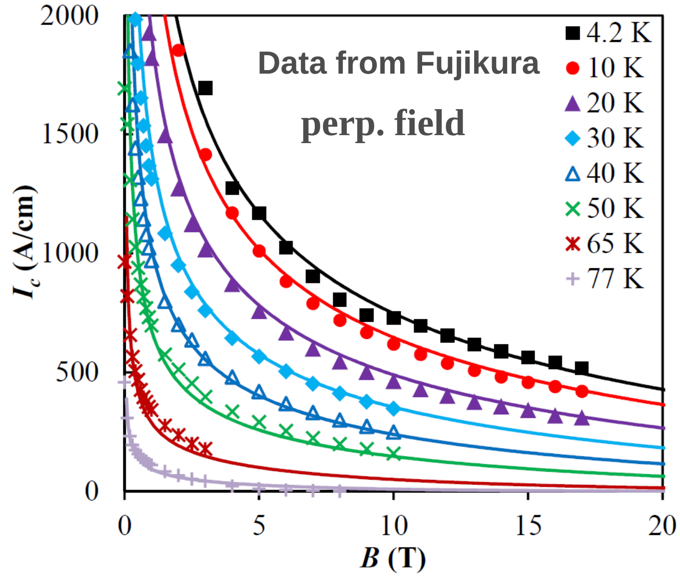
Generic $J_c(B,T,\theta)$ scaling for REBCO materials

$J_c(B,T)$ in perp. and parallel field

$$b_{ab} = B/B_{i,ab} \qquad b_c = B/B_{i,c} \qquad t = T/T_{c0}$$

$$J_{c,c} = \frac{\alpha_c}{B}\, b_c^{\,p_c}(1-b_c)^{q_c}(1-t^n)^{\gamma_c}$$

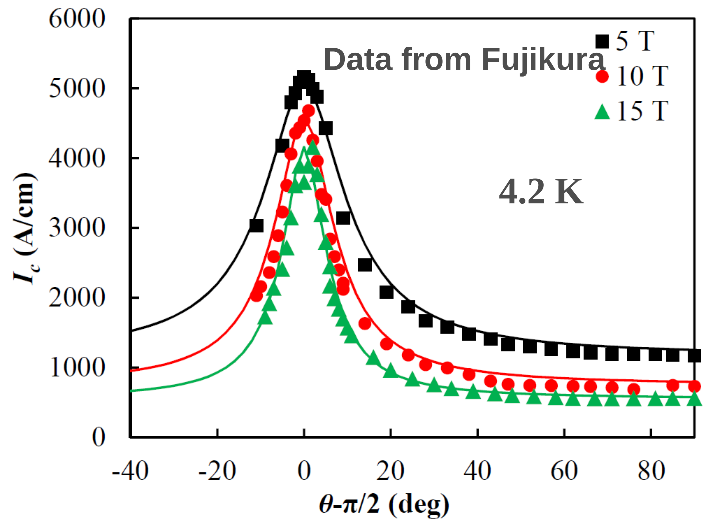
$$J_{c,ab} = \frac{\alpha_{ab}}{B}\, b_{ab}^{\,p_{ab}}(1-b_{ab})^{q_{ab}}\left[\left(1-t^{n1}\right)^{n2} + a\,(1-t^n)\right]^{\gamma_{ab}}$$



Adding fit of angular dependence (θ)

$$J_c(B,T,\theta) = J_{c,c}(B,T) + \frac{J_{c,ab}(B,T) - J_{c,c}(B,T)}{1 + \left(\frac{\theta - \pi/2}{g(B,T)}\right)^{v}}$$

$$g(B,T) = g_0 + g_1 \exp(-[g_2 \exp(g_3\, T)]B)$$



Unified, accurate and generic scaling law for all manufacturers

J. Fleiter and A. Ballarino, "Parameterization of the critical surface of REBCO conductors from Fujikura", CERN Internal Note, EDMS Nr: 1426239, 2014.

Splices: a key technology for HTS magnets

HTS splices for magnet application must satisfy two main requirements:

- reproducible low electrical resistance
- high mechanical strength

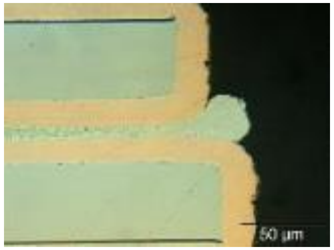
=>The use of soft solder for splicing can meet both requirements (Sn-Pb and Sn-In)

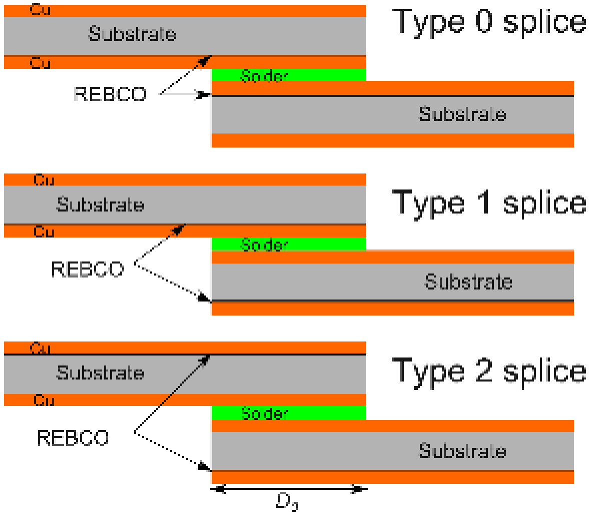
Three types of joints can be made between REBCO tapes

⇒ Type 0 : direct facing of the HTS films (no substrates interleaved)

⇒ Type 1: no direct facing of the HTS films (one substrate interleaved)

⇒ Type 2 : no facing of the HTS films (two substrates interleaved)





Investigations performed on

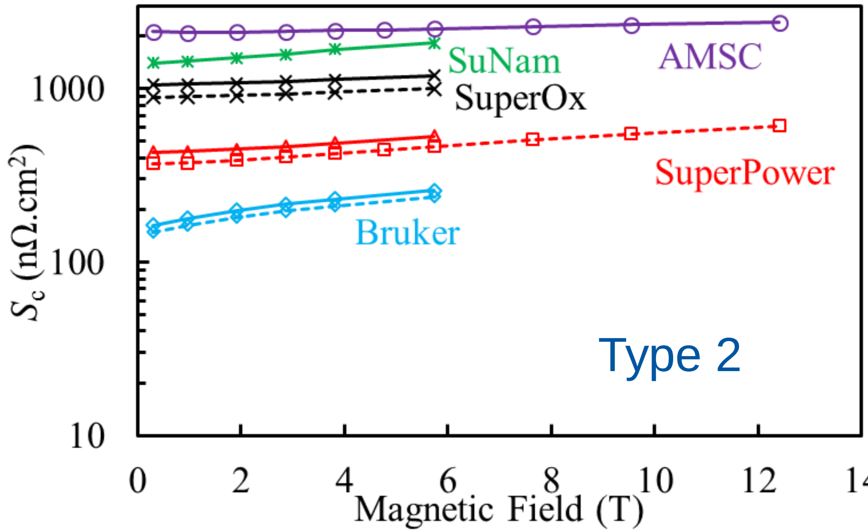
Supplier	Tape width	Tape thickness	Substrate material/thickness	Stabilizer
SuperPower	4.00 mm	100 µm	Hastelloy, 50 µm	2x20 µm, Cu electroplated
SuperOx	4.04 mm	110 µm	Hastelloy, 60 µm	2x20 µm,Cu electroplated
AMSC	4.4 mm	440 µm	Ni-W, 75 µm	2x160 µm,Cu alloy laminate
SunaM	4.00 mm	110 µm	Hastelloy, 60 µm	2x20 µm,Cu electroplated
Bruker	4.1 mm	150 µm	Stainless steel, 100 µm	2x20 µm,Cu electroplated

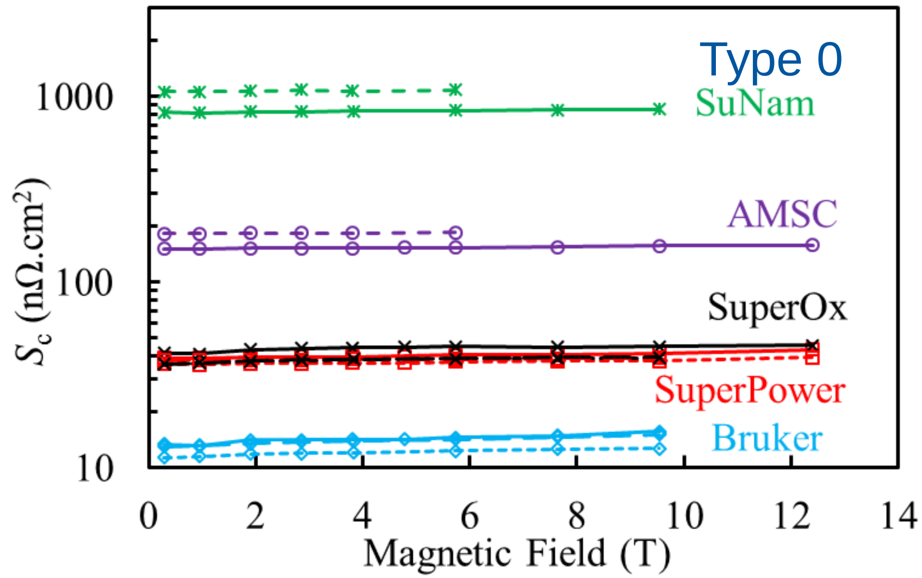
Splice resistance at 4.2 K

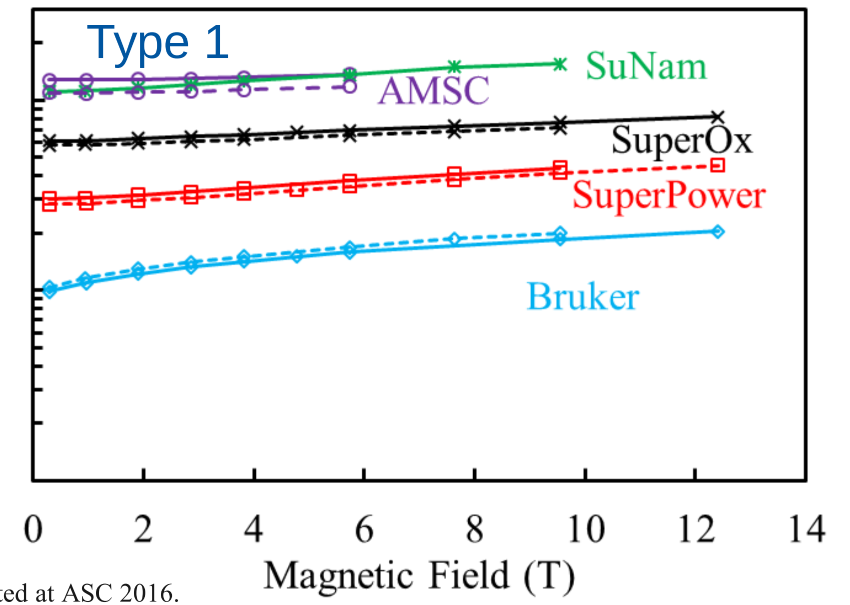
Measured between 0.3-12 T and up to 800 A

- **Type 0:** Lowest resistance (**13-40 nΩ· cm²**)*
- **Type 1**: High resistance (**98-570 nΩ· cm²**) *
- **Type 2**: Very High resistance (**150-884 nΩ·cm²**) *

* Values for Bruker, SPower and SuperOx



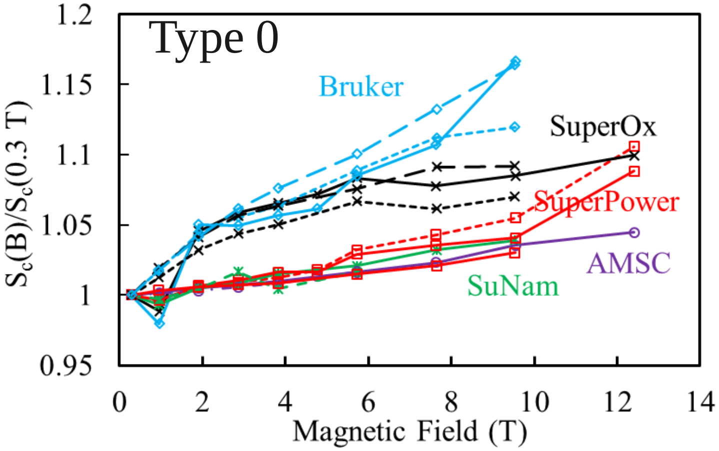


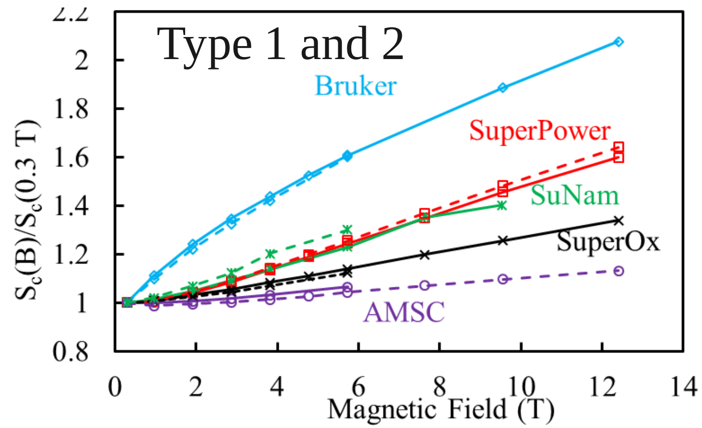


J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices", presented at ASC 2016.

Change of Splice resistance vs. B and T

- Normalized change of S_c vs. B at 4 K





- Ratio of resistance at 4 K and 77 K

Lift factor Sc(4 K)/Sc(77 K)	Type 0	Type 1	Type 2
SuperPower	**0.92**	**0.30**	**0.29**
SuperOx	**0.90**	**0.47**	**0.46**
Bruker	**1.21**	**0.24**	**0.23**
SuNAM	**0.90**	**0.38**	**0.35**
AMSC	**0.84**	**0.54**	**0.59**

Weak dependence of splice resistance on field and temperature for Type 0
Strong dependence of splice resistance on field and temperature for Type 1-2

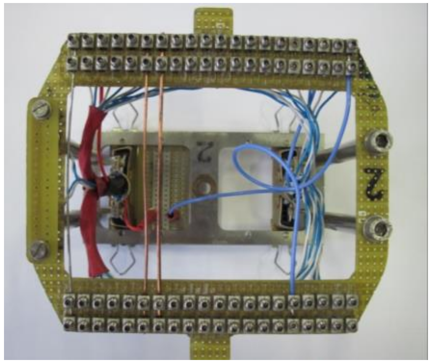
J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices", presented at ASC 2016.

RRR measurements

- RRR measurements required for modelling the electrical resistance of splice and designing the magnet protection.
- Residual Resistivity Ratio (RRR) of the electroplated copper or copper alloy laminations were measured on 80 mm long samples

TABLE 2.
MEASURED ELECTRICAL RESISTIVITY OF CU STABILIZER

	Electrical resistivity[a] (nΩ-m) at 0 T		
	290 K	4 K	RRR
SuperPower	16.5	0.4	41
SuperOx	18.1	1.0	18
Bruker	15.4	0.3	61
SuNAM	19.6	0.4	46
AMSC (Cu alloy)	80.3	28.6	3

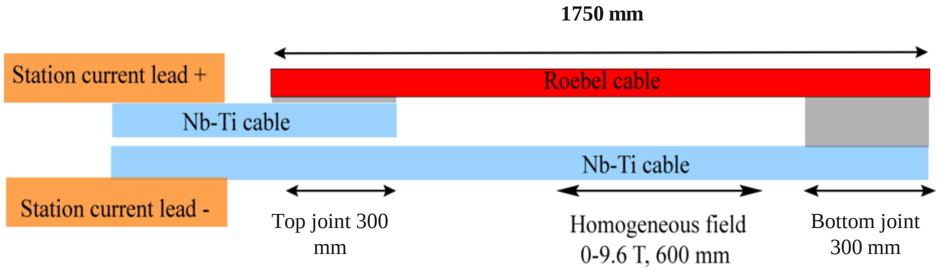


Low value of RRR among the different conductors investigated (3-61) with a large spread.

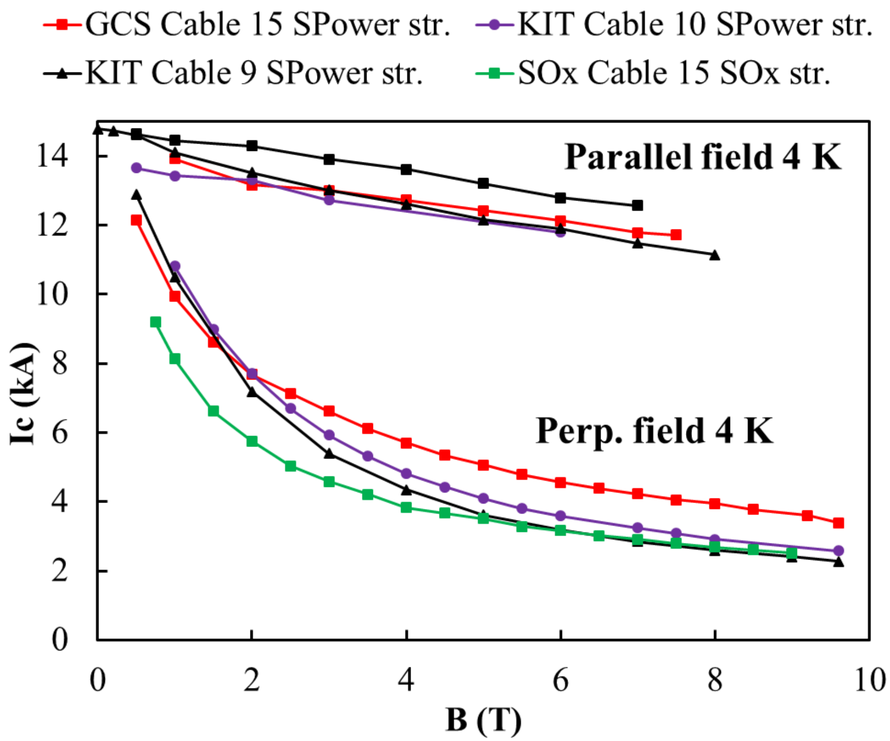
Roebel cable electrical performances at 4.2 K

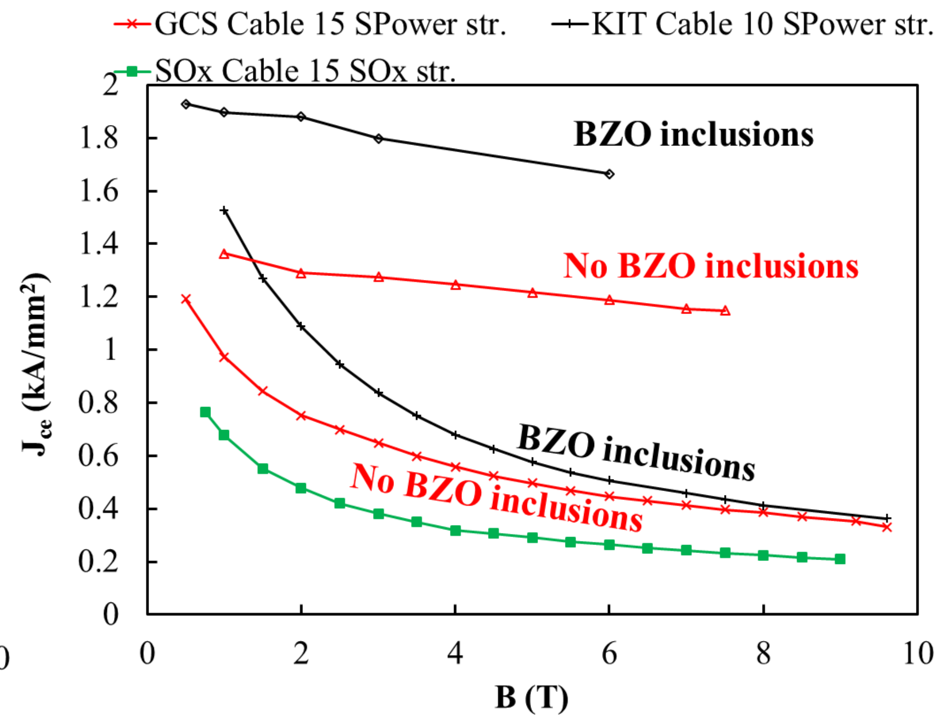
Measurements at CERN in FRESCA test station in ⊥ and // fields

- Cables from **KIT:** 126 mm pitch, **9**, **10** and **16** strands
- Cables from **GCS:** 300 mm pitch **15** strands
- Cable from **SuperOx** 300 mm pitch **15** strands
- Additional 5-12 mm^2 cooper shunt, segregated or distributed
- No impregnation at the moment
- Vtaps on each strand
- **Low joint resistance ~1 nΩ (256-300 mm long)**



Electrical performances at 4.2 K of Roebel cables



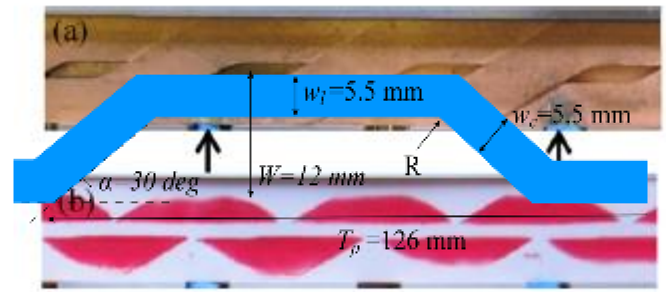


- **All cables reach their expected Ic**
- **Cable I_c depends on the raw characteristics of REBCO tapes**

J. Fleiter et al., Electrical characterization of REBCO Roebel cables Supercond. Sci. Technol. 26 (2013)
J. Fleiter et al., Characterization of Roebel Cables for Potential Use in High-Field Magnets IEEE Trans. Appl. Super. vol. 25, no. 3, June 2015
J. Fleiter et al. "Electrical characterization at 4 K of SuperOx Roebel cable" CERN Internal Note 2017_15, EDMS: 1757653.

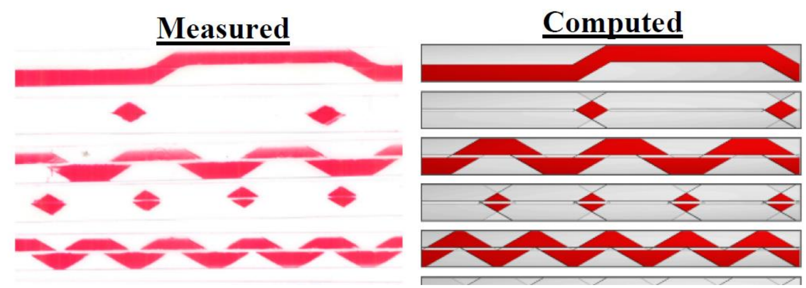
The transverse effective section (E_s) of Roebel cable

- Driving the transverse stress in bare cable and Interstrand resistance in potted cables.
- Analytical and numerical models developed and validated vs. measurements.



Red=thicker spots =>stress *White =thinner spots =>no stress*

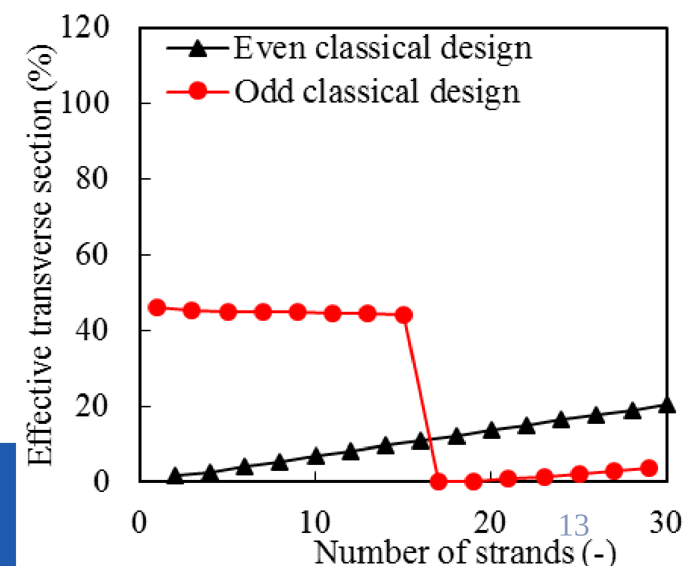
$$E_{s,even} = \frac{2N}{T_p W \tan\alpha}\left[\frac{w_c \sin\alpha}{\sin 2\alpha} - \frac{W}{2} + w_l\right]^2$$



$$E_{s,odd(N \le N_c)} = \frac{2Nw_l}{T_p W}\left[\frac{T_p}{2N} + \frac{w_c}{\sin\alpha} + \frac{w_l - W}{\tan\alpha}\right]$$

=>E_s is up to about 50% for odd number of strands(↦=30°).

=>We should not exceed the critical number of strands to avoid too high Interstrand resistance Ra



J. Fleiter et al., “Characterization of Roebel Cables for Potential Use in High-Field Magnets”, IEEE Trans. Appl. Supercond. , vol. 25, no. 3, June. 2015

Summary (1/2)

- Large variety of tape I_c samples investigated with different doping.
- Elaboration of generic formulation for the $J_c(B,T,\theta)$ of REBCO tapes from different suppliers
- Systematic investigations on splice resistance vs. field and temperature performed.
- Electrical characterization of full scale Roebel cable at 4.2 K and in field of up to 9.6 T.

Summary (2/2)

- All Roebel cable reached their expected performances in perp field.
- Cable splice resistance are about 1 nΩ (256-300 mm long)
- Analytic formulation for the effective section of Roebel cable were derived for stress distribution and inter-strand resistance computation.

Thank you

CERN