In-Field Resistance of REBCO Electrical Joints at 4.2 K

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EuCARD WP10.2

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Introduction

HTS splices for magnet application. Required:

- reproducible low electrical resistance
- high mechanical strength

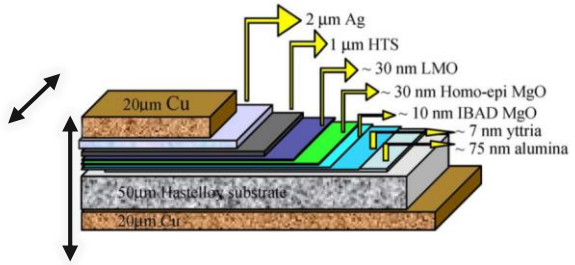
⇒ **Use of soft solder for splicing (Sn-Pb and Sn-In)**

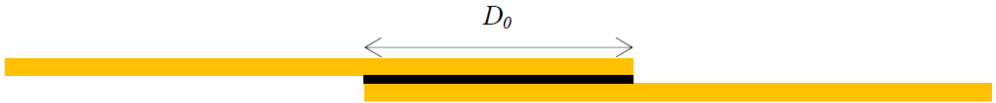
⇒ Three types of joints can be made between REBCO tapes

- ⇒ 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)

4-12 mm

0.1 mm





Conductors investigated

Splices of Type 0,1 and 2 made from **4 mm wide** conductors investigated at both **4.2 K** (0.3-12.4 T) and **77 K** (self field).

Soft solder used: **Sn-Pb** for **all except AMSC (Sn-In)**

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

Measurements reported as: splice resistance x surface (S_c (nΩ· cm^2))

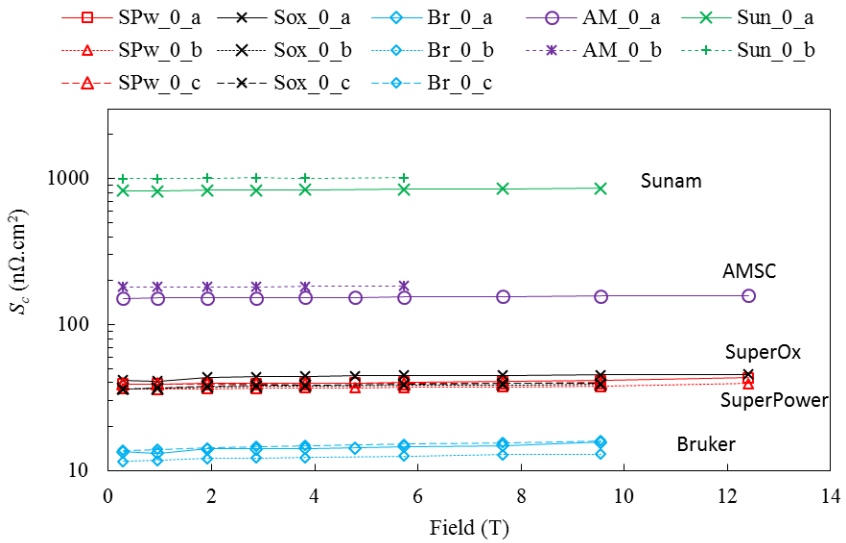
J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", *CERN internal note 2015-10* , EDMS Nr: 1562549.

Splice resistance at 4.2 K (1/3)

Type 0: lowest resistance

- 11.6 nΩ·cm^2 for Bruker
- 36.1 nΩ· cm^2 for SuperOx
- 36.2 nΩ· cm^2 for SuperPower
- 152 nΩ· cm^2 for AMSC
- 825 nΩ· cm^2 for SUNAM*

*measured excessive internal resistance on this batch



Type 0 resistance almost unchanged (< 20%) vs. field and temperature (see next slides)

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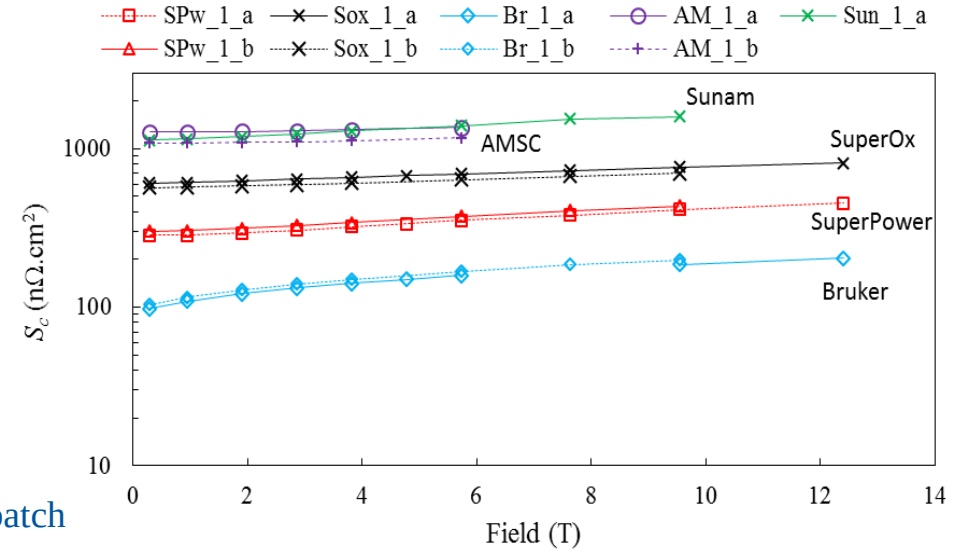
Splice resistance at 4.2 K (2/3)

Type 1: ~7-16 times more resistive than Type 0 (except SuNAM)

- 98 nΩ·cm² for Bruker (x8.6)
- 284 nΩ· cm² for SuperPower (x7.8)
- 567 nΩ·cm² for SuperOx (x16)
- 1138 nΩ·cm² for SuNAM (x1.38)*
- 1092 nΩ·cm² for AMSC (x7.2)



*measured excessive internal resistance on this batch

Type 1 resistance depends on field and temperature (see next slides)

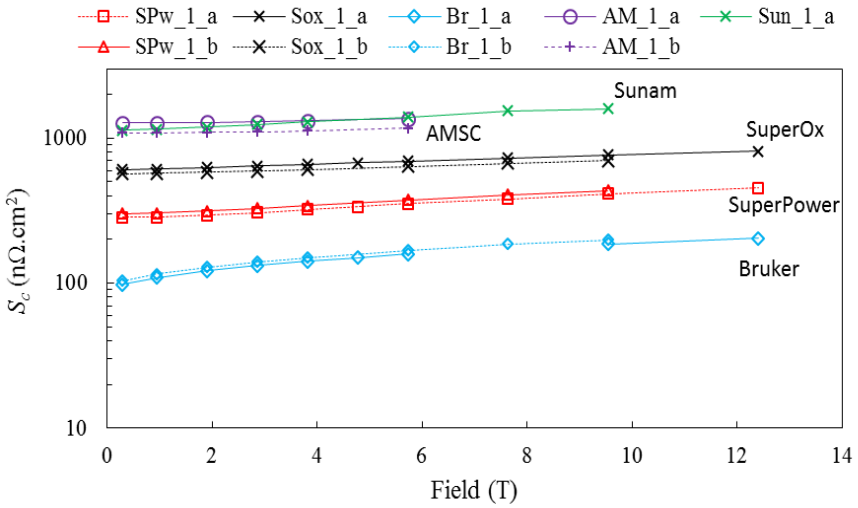
J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", *CERN internal note 2015-10* , EDMS Nr: 1562549.

Splice resistance at 4.2 K (3/3)

Type 2: ~10-25 times more resistive than Type 0 (except SuNAM)

- 148 nΩ·cm² for Bruker (x13.04)
- 371 nΩ·cm² for SuperPower (x10.2)
- 884 nΩ· cm² for SuperOx (x 24.5)
- 1396 nΩ· cm² for SuNAM (x1.70)*
- 2127 nΩ· cm² for AMSC (14.027)

*measured excessive internal resistance on this batch



Type 2 resistance strongly dependent on field and temperature (see next slides)

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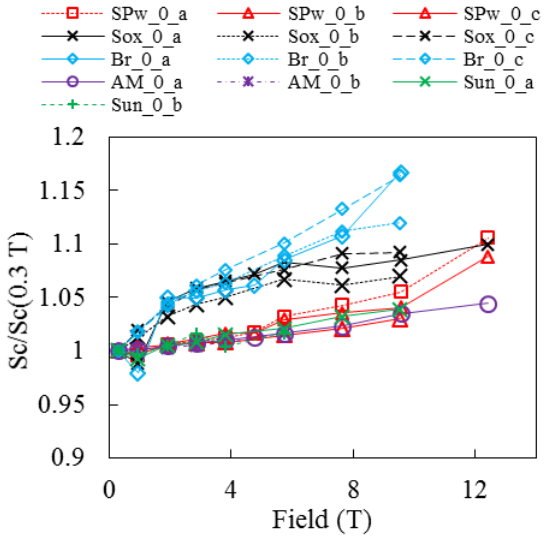
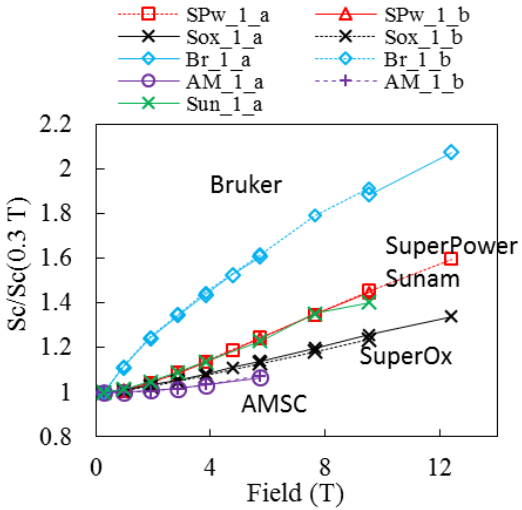
Normalized change of S_c vs. B at 4.2 K

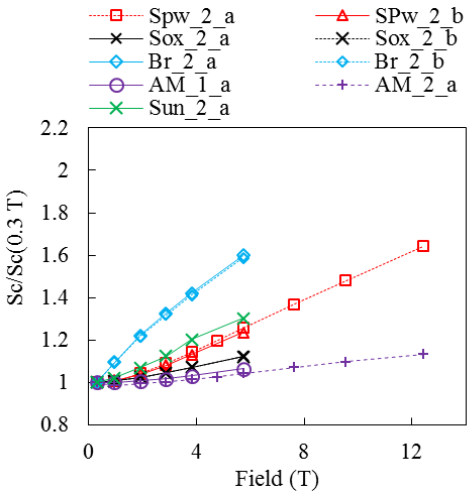
Type 0



Type 1



Type 2



Type 1 and 2 joints strongly affected by field, not the case for Type 0 joints

J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", *CERN internal note 2015-10* , EDMS Nr: 1562549.

Splice resistance at 77 K and Lift Factor Ratio

Type **0** : lift factor~**1**

=> main contribution to S_c from conductor internal resistances

Sc (nOhm.cm2)	Type 0	Type 1	Type 2
SuperPower	**39.1**	952	1287
SuperOx	**36.5**	1151	1878
Bruker	**8.2**	405	632
SuNAM	**922.0**	2976	4013
AMSC	**179.3**	2031	3598

Type **1** and **2** : lift factor **0.23-0.59**

=>Part of the current circulates around substrate: Sc depends on copper properties

Lift factor Sc(4 K)/Sc(77 K)	Type 0	Type 1	Type 2
SuperPower	0.93	0.30	0.29
SuperOx	0.97	0.49	0.46
Bruker	1.29	0.24	0.23
SuNAM	0.92	0.37	0.35
AMSC	0.84	0.55	0.59

RRR must be measured: **on-going** work

J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", *CERN internal note 2015-10* , EDMS Nr: 1562549.

Conclusions

- Electrical resistance of REBCO lap joints characterized at 4.2 K versus field and at 77 K
- Three topologies of lap joint investigated: no substrates (Type 1), one substrate (Type 2) or two substrates (Type 3) interleaved in between the HTS layers.

- **Lowest resistances measured for Type 0 at 4.2 K**:
  - 11.6 nΩ·cm^2 for Bruker,
  - 36 nΩ·cm^2 for SuperPower and SuperOx tapes
  - 151 nΩ·cm^2 for AMSC tapes.
  - 825 nΩ· cm^2 for SUNAM (excessive value, could be smaller)
  - **Type 0 resistance almost unchanged (<20%) vs. field and temperature**

- **Type 1** joints: **7-16** times more resistive compare to **Type 0** (except SuNAM*)
- **Type 2** joints **10-25** times more resistive compare to **Type 0** (except SuNAM*)

- **On-going work:**
  - RRR measurement of Cu stabilizer
  - Characterization of 12 mm wide splices

* measured excessive internal resistance on this batch

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Sample ID	Supplier	Spool ID	Overlap length	Solder	S_c (nOhm.cm^2) 4.3 K B//0.29 T	4.3 K B//9.54 T	77 K 0 T	*Lift factor* Sc(4K)/Sc (77K)
SPw_0_a	**SuperPower**	20110701	21 mm	Sn-Pb	39.2	41.4	42.7	0.92
SPw_0_b		20110701	20 mm	Sn-Pb	36.2	37.7	39.1	0.93
SPw_0_c		20150824	19.5 mm	Sn-Pb	39.1	40.2	40.2	0.97
Sox_0_a	**SuperOx**	2014-23-3	40 mm	Sn-Pb	41.6	45.1	41.5	1.00
Sox_0_b		2014-23-3	18 mm	Sn-Pb	36.3	38.8	36.5	0.99
Sox_0_c		2014-23-3	20.5 m	Sn-Pb	36.1	39.5	40.0	0.90
Br_0_a	**Bruker**	278C-Cu	30 mm	Sn-Pb	13.4	15.7	11.1	1.21
Br_0_b		278C-Cu	22 mm	Sn-Pb	11.6	13.0	8.2	1.42
Br_0_c		278C-Cu	21 mm	Sn-Pb	13.8	16.0	10.1	1.36
Sun_0_a	**SuNAM**	HCN04160	18 mm	Sn-Pb	825.4	857.7	922.0	0.90
Sun_0_b		HCN04160	18 mm	Sn-Pb	996.9		1051.6	0.95
AM_0_a	**AMSC**	#578B-5-1-101	40.5 mm	Sn-In	151.6	157.0	179.3	0.85
AM_0_b			40.5 mm	Sn-In	180.8		216.2	0.84

Sample ID	Supplier	Spool ID	Overlap length	Solder	S_c (nOhm.cm^2) 4.3 K B//0.29 T	4.3 K B//9.54 T	77 K 0 T	*Lift factor* Sc(4K)/Sc (77K)
SPw_1_a	**SuperPower**	20110701	40 mm	Sn-Pb	284	413	952	0.30
SPw_1_b		20150824	39.5 m	Sn-Pb	302	437	908	0.33
Sox_1_a	**SuperOx**	2014-23-3	37 mm	Sn-Pb	609	766	1299	0.47
Sox_1_b		2014-23-3	30 mm	Sn-Pb	567	700	1151	0.49
Br_1_a	**Bruker**	278C-Cu	38.5 mm	Sn-Pb	98	186	405	0.24
Br_1_b		278C-Cu	40 mm	Sn-Pb	104	199	408	0.25
Sun_1_a	**SuNAM**	HCN04160	39.5 mm	Sn-Pb	1138	1595	2976	0.38
AM_1_a	**AMSC**	#578B-5-1-101	43 mm	Sn-In	1277		2329	0.55
AM_1_b			40 mm	Sn-In	1092		2030	0.54

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Sample ID	Supplier	Spool ID	Overlap length	Solder	S_c (nOhm.cm^2)			*Lift factor* Sc(4K)/S (77K)
					4.3 K B//0.29 T	4.3 K B//9.54 T	77 K 0 T	
SPw_2_a	SuperPower	20110701	40 mm	Sn-Pb	371	466	1287.46	0.29
SPw_2_b		2014-23-3	40 mm	Sn-Pb	433	535	1392.87	0.31
Sox_2_a	SuperOx	2014-23-3	40 mm	Sn-Pb	981	1102	2139.28	0.46
Sox_2_b		2014-23-3	41 mm	Sn-Pb	884	992	1868.48	0.47
Br_2_a	Bruker	278C-Cu	20 mm	Sn-Pb	148	237	631.61	0.23
Br_2_b		278C-Cu	35 mm	Sn-Pb	163	259	677.84	0.24
Sun_2_a	SuNAM	HCN04160	39 mm	Sn-Pb	1396	1816	3992.85	0.35
AM_2_a	AMSC	#578B-5-1-101	40.5 mm	Sn-In	2127	2218	3598.20	0.59

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