Effect of heating time and temperature on joint resistance of REBCO tapes

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Outline

- Context
- Background information
- Motivation
- Experimental setup and methodology
- Effect of thermal cycles
- Effect of different soldering temperature
- Summary

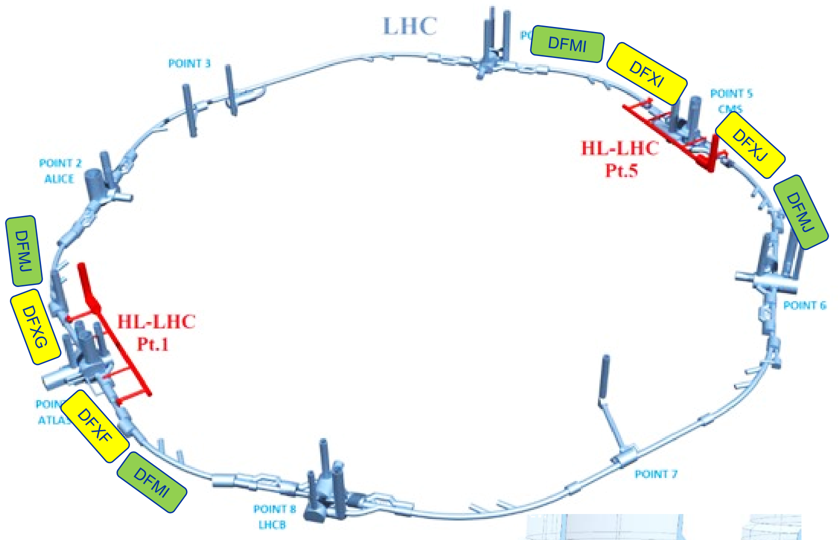
Context-Cold powering

- **Remote powering of the magnets in IP1 and IP5, with power converters located in a gallery 10 m above the tunnel;**

- **New superconducting cables (SC-Link) allow connection between the power converter in the survey gallery and the magnets in the tunnel;**

- **Each SC-Link consist of multiple sub-cables rated between 0.6kA and 18kA and hosted in a flexible cryostat approx. 100 m long;**

- **Electrical interconnections at the extremities of the SC-Link cables are foreseen to be performed in the laboratory.**



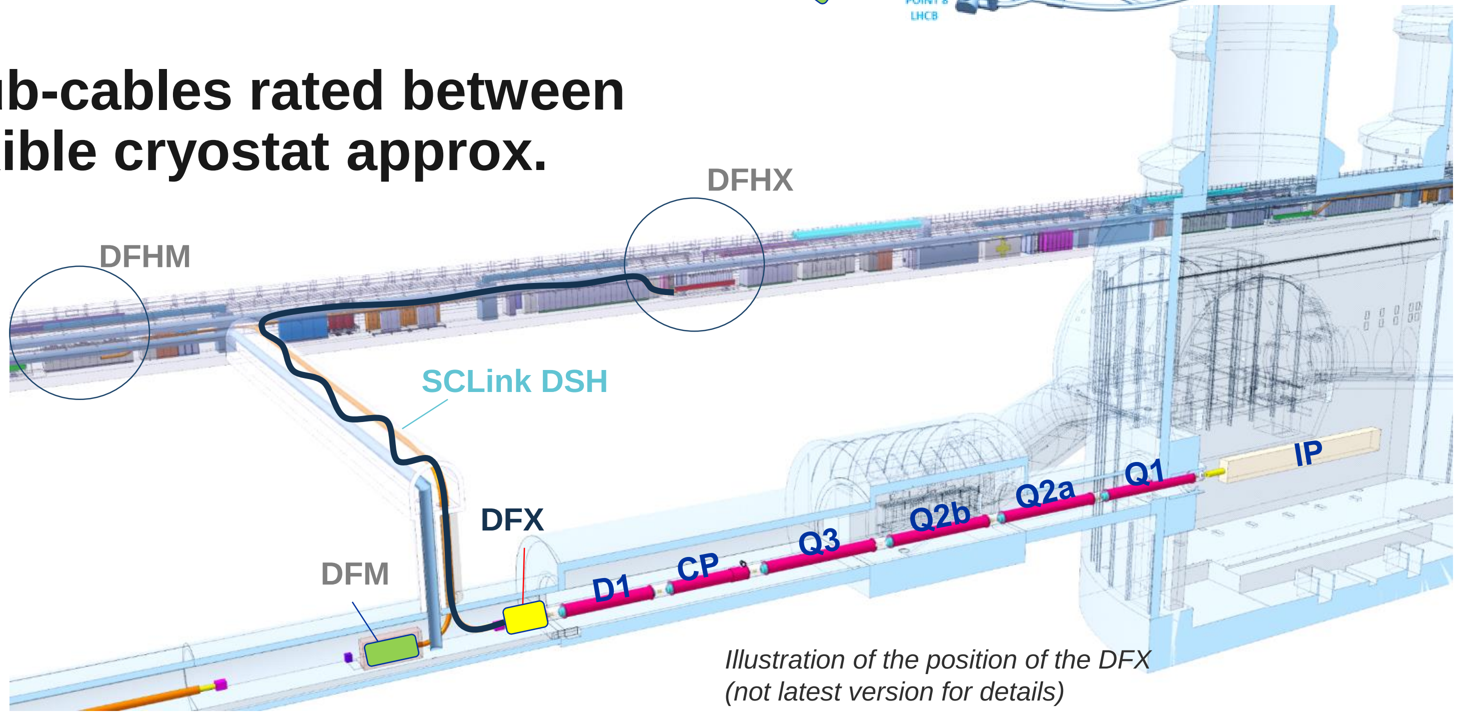


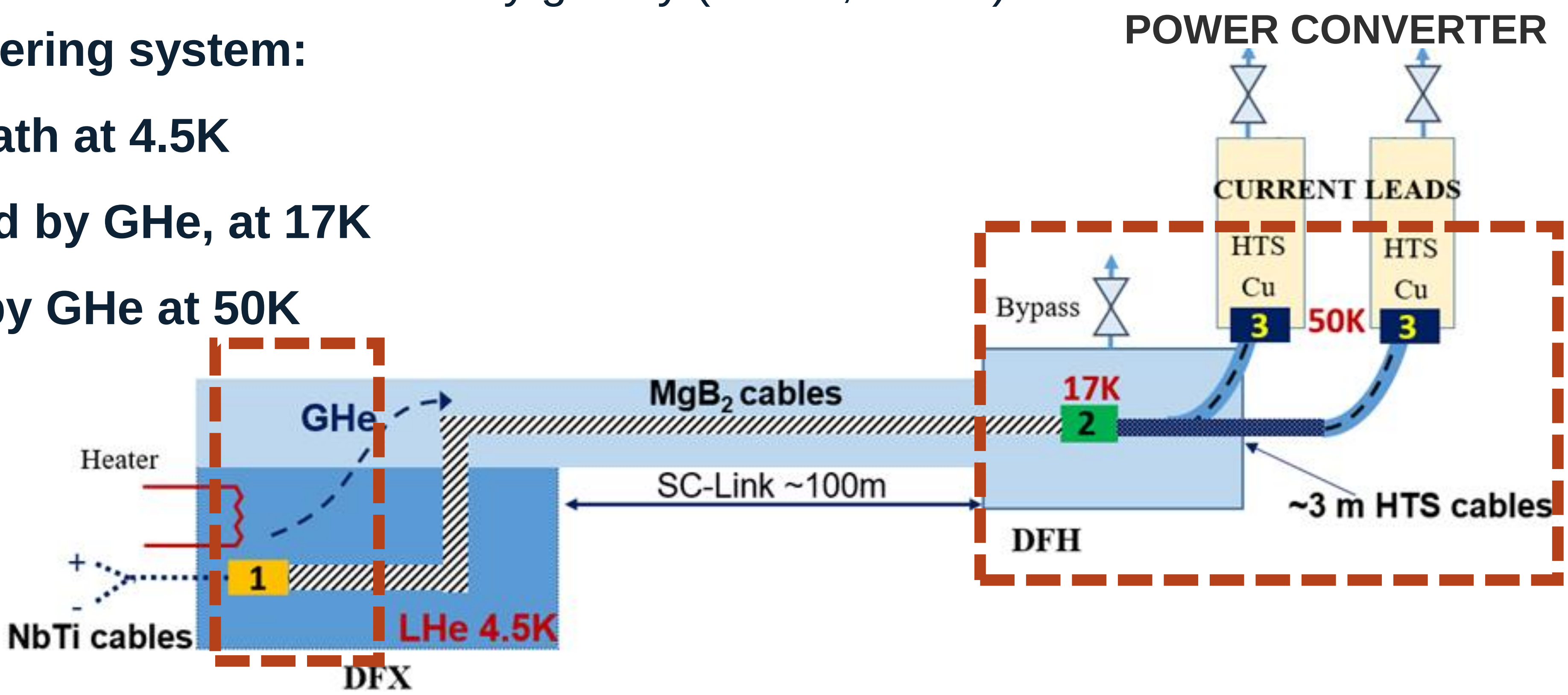
Illustration of the position of the DFX (not latest version for details)

Context-Cold Powering

The MgB_2 cables of the Sc-Link are connected to the NbTi busbars in the tunnel (DFX/DFM) and (via HTS cables) to the current leads in the survey gallery (DFHX,DFHM).

Splices in the cold powering system:

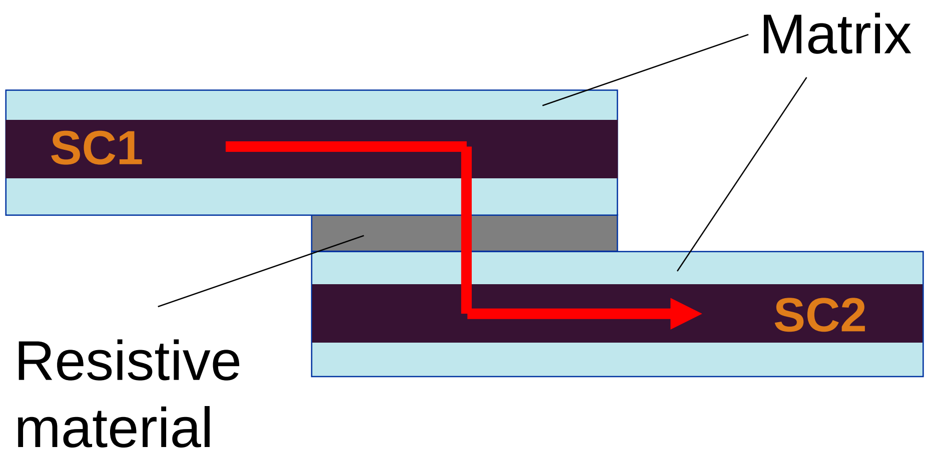
1. **NbTi-MgB_2, in LHe bath at 4.5K**
2. **MgB_2-REBCO, cooled by GHe, at 17K**
3. **REBCO-Cu, cooled by GHe at 50K**



The splices must be **reliable, predictable** and have a **reproducible low resistance**, in order to avoid excessive heat dissipation and redistribution of current among sub-cables

Background

Conductor contribution to the splice



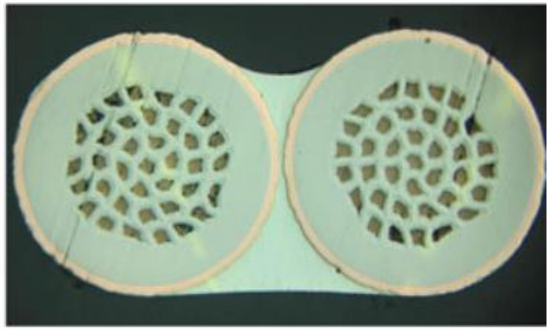
A superconducting wire/tape is generally embedded in a matrix.
When splicing two superconductors, the contribution to the splice resistance comes from

- the **matrix of the superconductor**
- the **resistive material**
- the **interface** between components

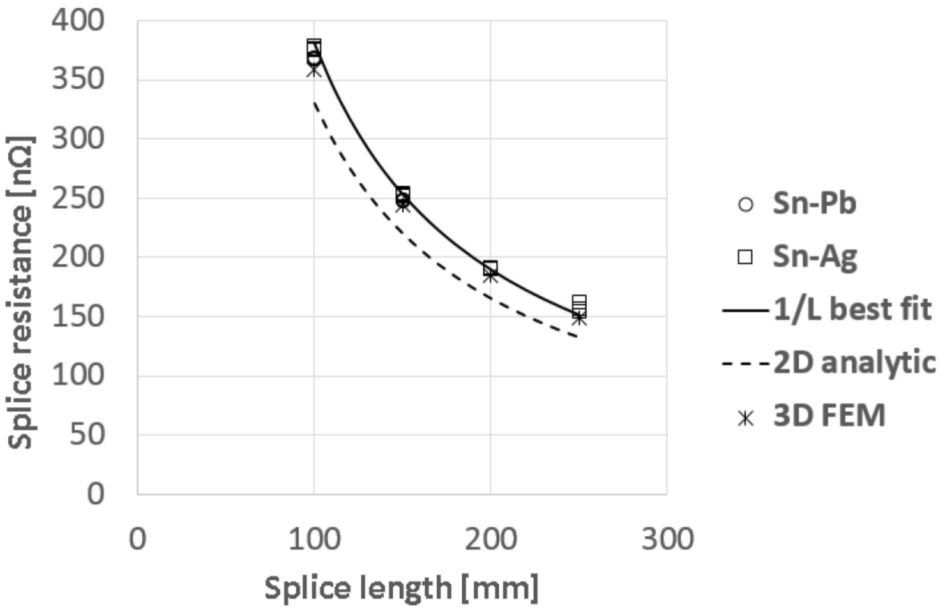
It is important to quantify the internal resistance of a wire/tape

- **MgB_2: wire soldered side to side**
- **REBCO: lap-joint with superconductor tapes overlapping over a length**

MgB_2 conductor-Contribution to splice



- Φwire =1 mm
- 37 MgB_2 filaments surrounded by niobium barriers and embedded in nickel matrix
- 200 μm thick Monel sheath
- ACu ~ 5 % Awire (th=20 μm)



- **Measurements carried for different splices length;**
- **Negligible contribution of solder;**
- **90% of contribution to the resistance comes from the Monel**

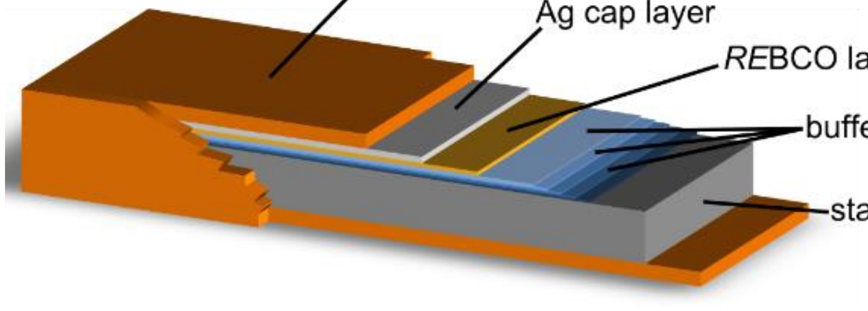
$$R_C = f\rho_{sheath}\frac{1}{2\,\pi\,n_w}\ln\left(\frac{d_w}{d_{sc}}\right)$$

- **Measurements on of MgB_2 sub-cables agree with the expected values due to the Monel contribution**

IEEE Paper ID:2484773
S.Giannelli, G. Montenero and A. Ballarino

REBCO conductor

4 mm wide



Layered structure od the REBCO conductor:

- **SUBSTRATE**: provides mechanical strength;
- **BUFFER LAYERS**: provided texture template for growing aligned superconductor;
- **Ag LAYER**: provides good current transfer;
- **Cu LAYER**: provides stabilization (parallel path) during operation and quench conditions.

Large anisotropy of the conductor leads to large anisotropy of the contact resistance depending on the conductor orientation:

- Current coming from the ‘top’ of the conductor has to pass through the copper stabilizer and the silver;

- Current passing from the bottom has to pass through the substrate or (if too resistive) it would through the narrow copper channels on the sides.

REBCO Lap-joints

Lap-joints are not in the baseline, but:

- **They allow to quantify and to understand the contribution of REBCO components to the resistance;**
- **Measurements can be performed at 77K;**

<u>Specific contact resistance,</u> $R_s = R \cdot A$
(*R* lap-joint resistance and *A* contact surface)
Note: if REBCO is spliced to MgB_2 the contribution of one REBCO tape is $R_s/2$

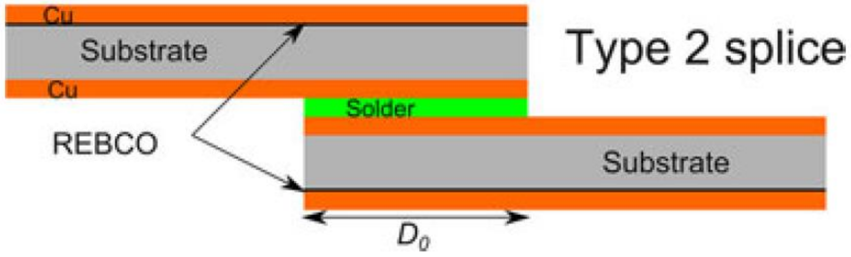
IEEE Paper ID:6603305
J.Fleiter and A. Ballarino, 2017

Three lap-joints configurations:

- **<u>Type 0</u>: direct facing of SC films**

- **<u>Type 1</u>: SC film facing substrate**

- **<u>Type 2</u>: Substrate facing substrate**



Background-Lap-joint

TABLE III
SPLICE RESISTANCE OF TYPE 0 LAP JOINTS AT 4.2 AND 77 K

Sample ID	Spool ID	D_0 (mm)	R_s ($n\Omega \cdot cm^2$)			*Lift factor*
			4.2 K 0.3 T	4.2 K 9.5 T	77 K 0 T	S_c(4 K,0.3 T)/ S_c(77 K, 0 T)
SPw_0_a	20110701	21	39.2	41.4	42.7	0.92
SPw_0_b	20110701	20	36.2	37.7	39.1	0.93
SPw_0_c	20150824	20	39.1	40.2	40.2	0.97
SOx_0_a	2014-23-3	40	41.6	45.1	41.5	1.00
SOx_0_b	2014-23-3	18	36.3	38.8	36.5	0.99
Sox_0_c	2014-23-3	21	36.1	39.5	40.0	0.90
Br_0_a	278C-Cu	30	13.4	15.7	11.1	1.21
Br_0_b	278C-Cu	22	11.6	13.0	8.2	1.42
Br_0_c	278C-Cu	21	13.8	16.0	10.1	1.36
Sun_0_a	HCN04160	18	825.4	857.7	922.0	0.90
Sun_0_b	HCN04160	18	996.9		1052	0.95
AM_0_a	#578B-5-1-101	41	151.6	157.0	179.3	0.85
AM_0_b	#578B-5-1-101	41	180.8		216.2	0.84

SOx stands for SuperOx, SPw stands for SuperPower, Br stands for Bruker, Sun stands for SuNAM and AM stands for AMSC.

IEEE Paper ID:6603305
J.Fleiter and A. Ballarino, 2017

TABLE IV
SPLICE RESISTANCE OF TYPE 1 AND TYPE 2 LAP JOINTS AT 4.2 AND 77 K

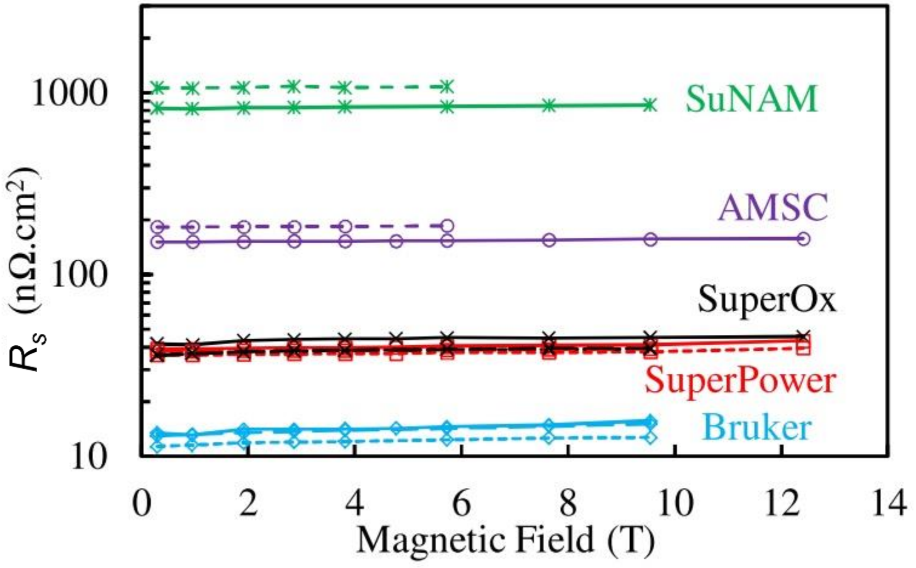
	Sample ID	Spool ID	D_0 (mm)	R_s ($n\Omega \cdot cm^2$)		*Lift factor*
				4.2 K 0.3 T (9.5 T)	77 K 0 T	S_c(4 K, 0.3 T)/ S_c(77 K, 0 T)
Type 1	SPw_1_a	20110701	40	284 (413)	952	0.30
	SPw_1_b	20150824	40	302 (437)	908	0.33
	SOx_1_a	2014-23-3	37	609 (766)	1299	0.47
	SOx_1_b	2014-23-3	30	567 (700)	1151	0.49
	Br_1_a	278C-Cu	39	98 (186)	405	0.24
	Br_1_b	278C-Cu	40	104 (199)	408	0.25
	Sun_1_a	HCN04160	40	1138 (1595)	2976	0.38
	AM_1_a	#578B-5-1-101	43	1277 (2329)	2329	0.55
	AM_1_b	#578B-5-1-101	40	1092 (2030)	2030	0.54
Type 2	SPw_2_a	20110701	40	371 (466)	1287	0.29
	SPw_2_b	20150824	40	433 (535)	1392	0.31
	Sox_2_a	2014-23-3	40	981(1102)	2139	0.46
	Sox_2_b	2014-23-3	41	884 (992)	1868	0.47
	Br_2_a	278C-Cu	20	148 (237)	631	0.23
	Br_2_b	278C-Cu	35	163 (259)	677	0.24
	Sun_2_a	HCN04160	40	1396 (1816)	3992	0.35
	AM_2_a	#578B-5-1-101	41	2127 (2218)	3598	0.59

SOx stands for SuperOx, SPw stands for SuperPower, Br stands for Bruker, Sun stands for SuNAM and AM stands for AMSC.

Type 0 lap-joint:

- **Lowest resistance (type 1: factor of ~7.5 and type 2 factor of ~11);**
- **Negligible dependence on the operative temperature.**

Background Lap-joint



- R_s of Type 0 lap-joint shows negligible dependence on field;
- **Wide spread of R_s between 10 and 1000 nΩcm^2;**
- **Values much higher than the ones calculated analytically!!**

IEEE Paper ID:6603305
J.Fleiter and A. Ballarino, 2017

Calculation of R_s for a SuperPower tape:

Components	ρ-77K (Ωm)	Thickness(μm)
Cu-RRR100	2.1e-9	20
Ag-RRR1800	2.7e-9	1
$Pb_{38}Sn_{62}$	4.1e-8	15

$$R_s = (2{\cdot}R_{Ag} + 2{\cdot}R_{Cu} + R_{SnPb}) \cdot A$$
$$= 2{\cdot}\rho_{Ag} \cdot t_{Ag} + 2{\cdot}\rho_{Cu} \cdot t_{Cu} + \rho_{SnPb} \cdot t_{SnPb} = 7.1\ \mathrm{n\Omega cm^2}$$

- **Major contribution to the resistance comes from internal interface among the constituent materials (i.e. REBCO/Ag, Cu/Ag..);**
- **The only way to predict the contact resistance of the splice is to measure the contact resistance of the conductor.**

Motivation

SC Link cables

High current cables are composed by multiple tapes, higher complexity:

SC Link cables to magnets:

- **2x18kA to D1**
- **2x18kA to triplets**
- **3x7kA for trim**
- **12x2kA to MCBXF**

SC Link cables to matching sections:

- **2x18kA to D2**
- **8x600A to MCBRD**

Example: 2x18kA cables tested during DEMO1 :

- **each 18kA made by 6x3kA sub cables;**
- **each 3kA sub-cables made by 12 REBCO tapes**

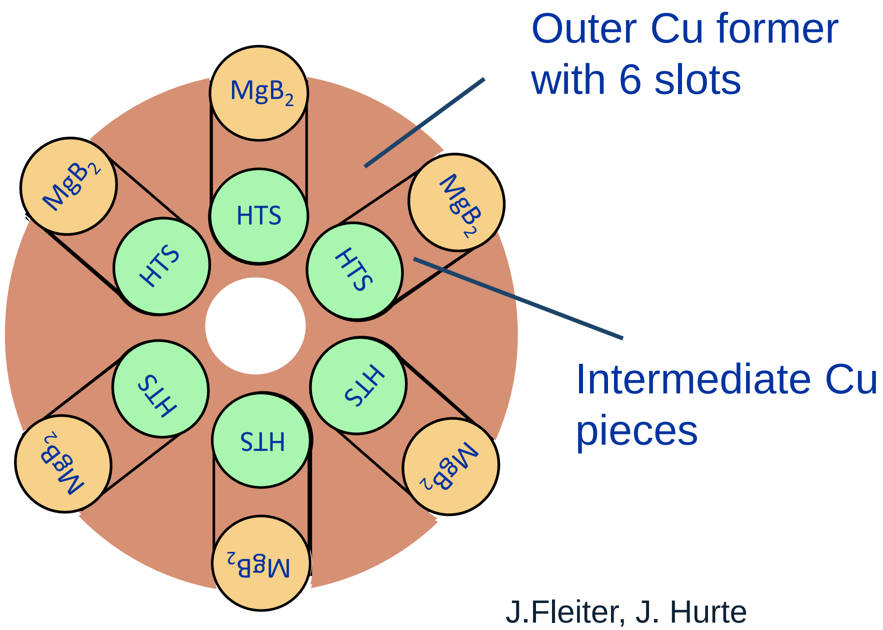
→ **12x6x2=144 REBCO tapes**
Impossible to splice them individually!!

18kA cables and terminations

The 18kA splices process is foreseen to be performed in two steps with pre-made terminations :

- Preparation of a pre-terminations in copper of individual 3kA MgB_2 and REBCO sub-cables, at 200°C;
- Assembly between different terminations in a Cu former;
- Soldering of terminations of different cables at 150°C;

The two steps process allows: the preparation and test of individual sub-cables terminations at the surface

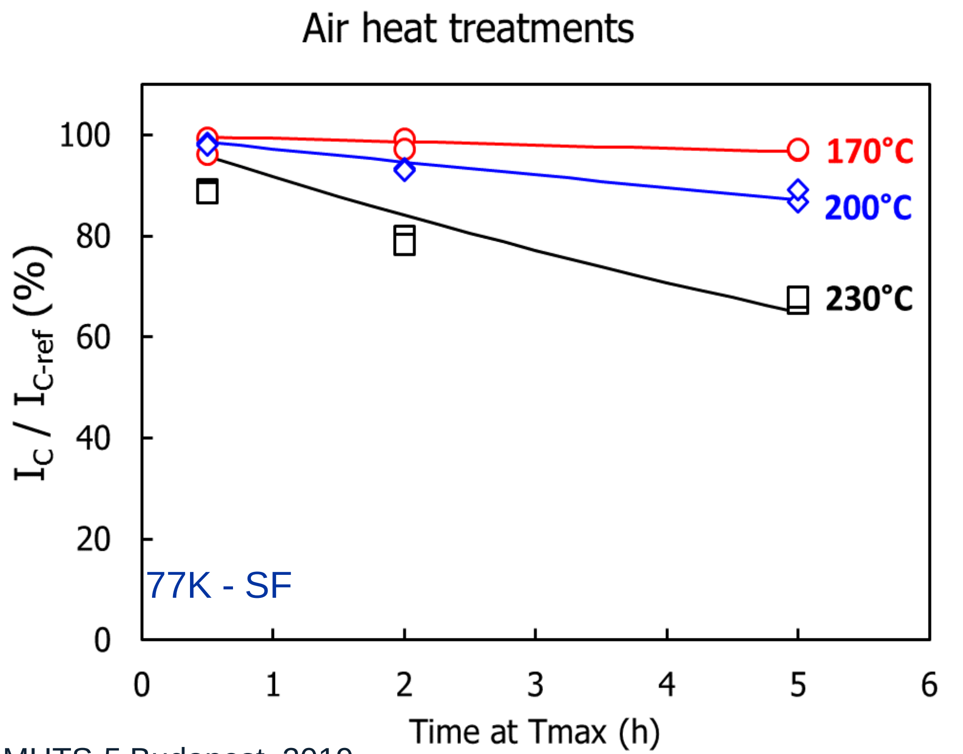


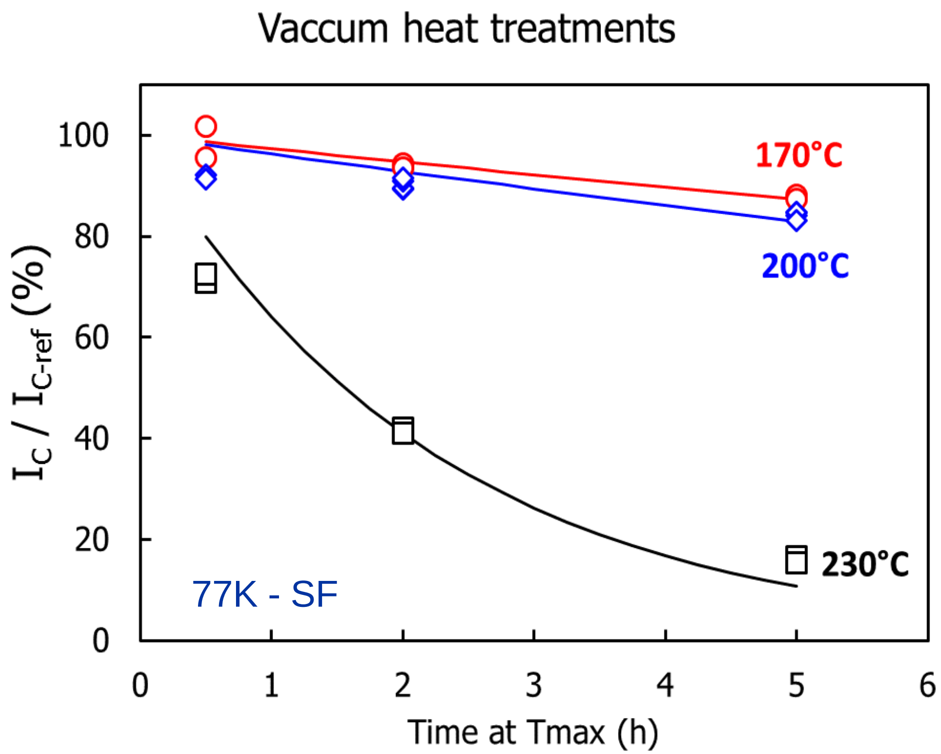
J.Fleiter, J. Hurte

The terminations present a consistent amount of copper: the time required to perform a splice is longer than the one required to perform a lap joint→ thermal cycle study

Thermal cycle effect on I_c

- Air soldering degrades I_C by 10% at 230°C after 30min heating time
- Vacuum soldering significantly degrades I_C at 230°C after 30min (30%)
- I_C degradation is from oxygen diffusion





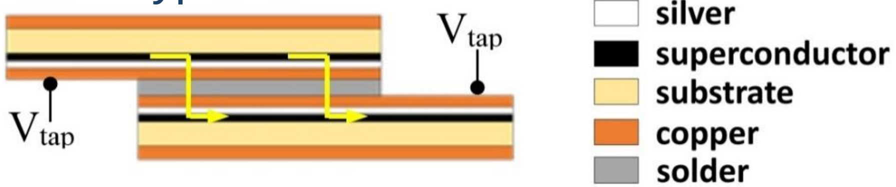
M. Matras,WAMHTS-5 Budapest, 2019

Experimental setup and methodology

Experimental setup and methodology

- **Type 0 Lap-joint preparation:**
  - 8 cm long tapes overlapped over 2 cm to form the splice;
  - SnPb with MOB39 flux for splices at 200°C;
  - SnIn with (Spirflux 330) for splices at 150°C;
  - Aluminum mold with groove matching the width of the superconductor;
  - **Holding the temperature 1 minute to make *0-time* lap-joint;**
  - Voltage tap at 6.2-6.6 mm distance;

Type 0



EDMS Nr 2366622
I. Falorio, M.Matras, J.Fleiter, A. Ballarino

Thermal cycles representative of high current cables soldered joints:

- Different length plateau:

  1 min (0-time), 10 min, 20 min, 60 min and 120min

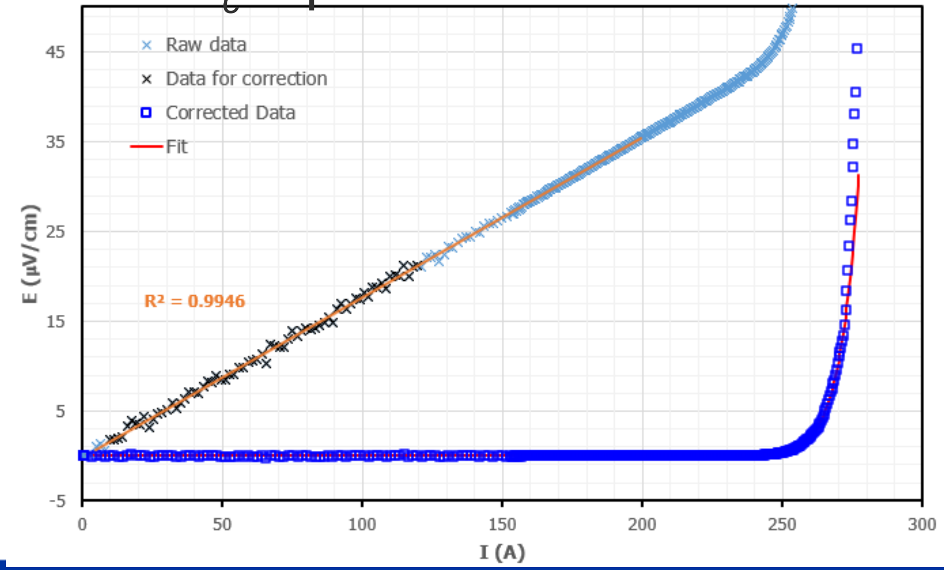
- Two approaches for the thermal cycles have been performed

Experimental setup and methodology

Measurements at 77 K and self field:

- Different tapes manufacturers;
- R_s calculated as the slope of the IV characteristic in the range of current 10A to 120A multiplied by the lap-joint surface
- Critical current with power law fitting $E/E_c=(I/I_c)^n$ with criteria E_c=1μV/cm

Supplier	Substrate	Texturing	REBCO deposition	REBCO film	APC
SuperPower	Hastelloy	IBAD-MgO	MOCVD	Gd,Y	BZO
Theva	Hastelloy	ISD-MgO	EBPVD	Gd	None
SuperOx	Hastelloy	IBAD-MgO	PLD	Not specified	None
Fujikura	Hastelloy	IBAD-MgO	PLD	Eu	BHO
Shanghai	Hastelloy	IBAD-MgO	PLD	Not specified	None
SuNAM	Hastelloy	IBAD-MgO	RCE-CDR	Gd	None



Number of measurements:

- Critical current of two lap-joints and of a reference tape for each manufacturer;
- Contact resistance of the lap-joints: performed multiple measurements for the same sample (average taken).

Experimental setup and methodology

Method A

1. *0-time* lap-joint prepared (1 min at the soldering temperature);
2. Cool down;
3. Measurements at 77K and self-field;
4. Warm up to room temperature;
5. Heat up to the experiment temperature held for 10 minutes;
6. Repeated points 2,3,4,5 changing the length of the plateau (total time of 20, 60 minutes and 120 minutes);

Same sample undergoes five warming up and five cooling down thermal cycles

Method B

1. Short length tapes pre-heated to the soldering temperature;
2. Cool down to room temperature by natural convection;
3. Polish both sides of the tapes with Scotch-BrightTM cleaning sponge to remove oxides;
4. Perform a *0-time* lap-joint (1 min at soldering temperature);
5. Measurements at 77K and self field

Use of one sample per test

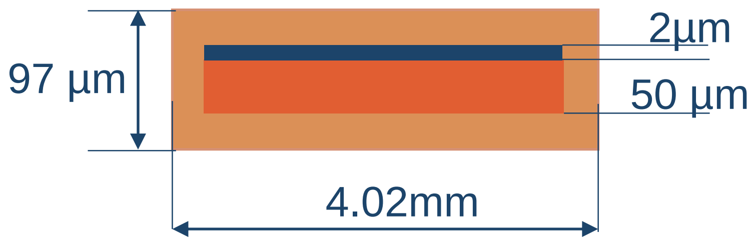
Effect of thermal cycles

Methodology-Preliminary measurements

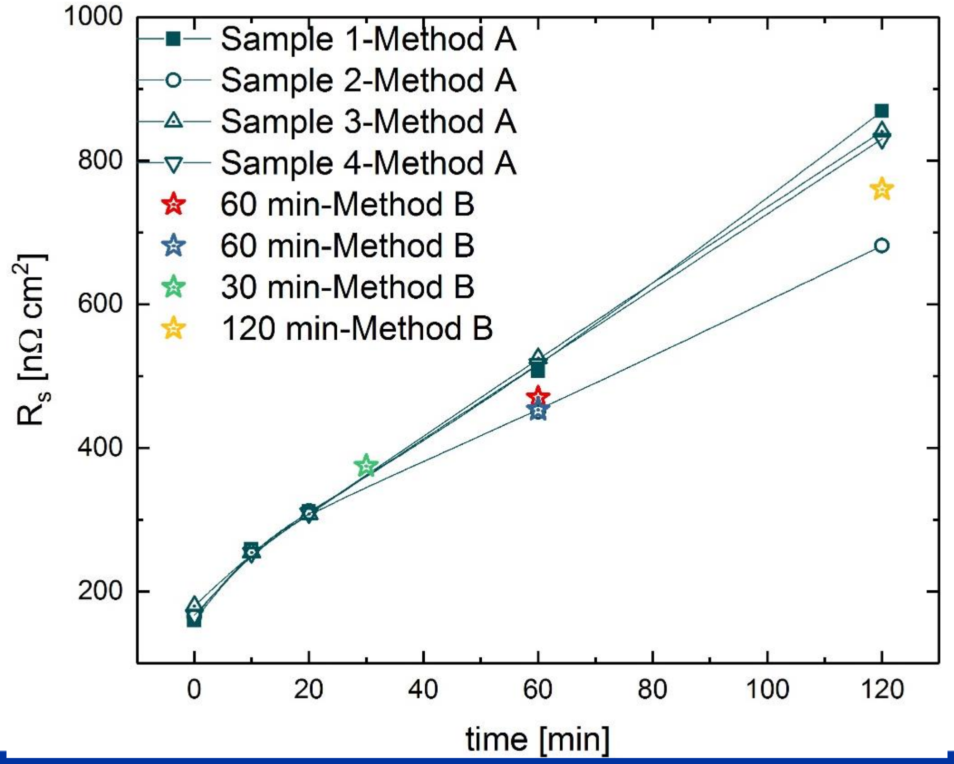
Is the thermal cycle affecting R_s?

Measured SuperPower tape 20181213-1:

- 4 samples prepared with method A
- 4 sample prepared with method B



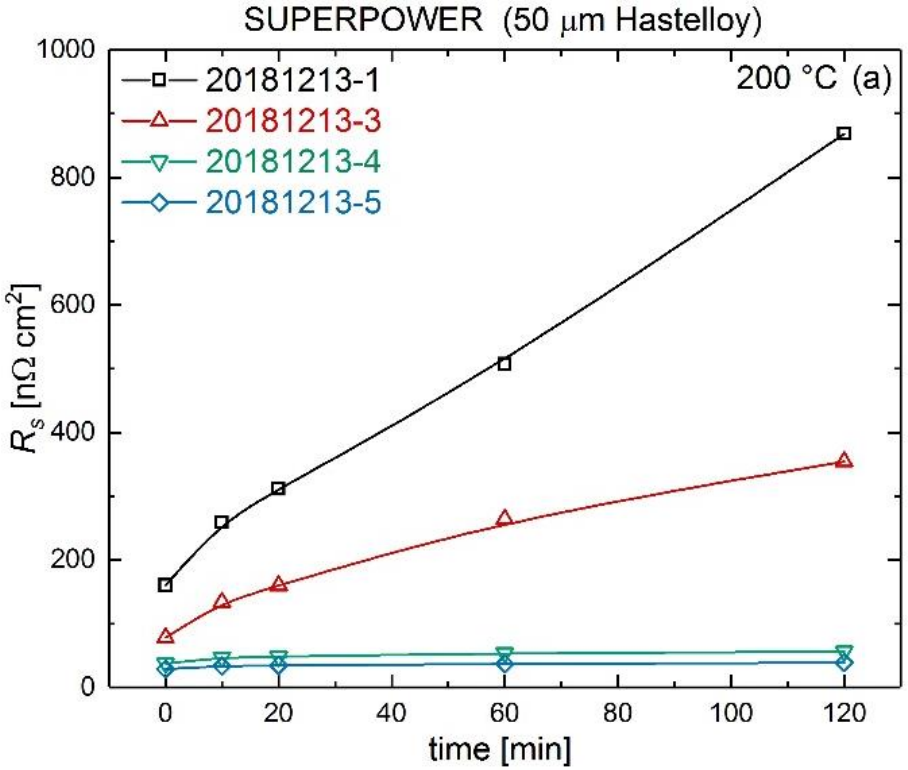
Method A: multiple thermal cycles per lap-joint
Method B:one thermal cycle per lap-joint

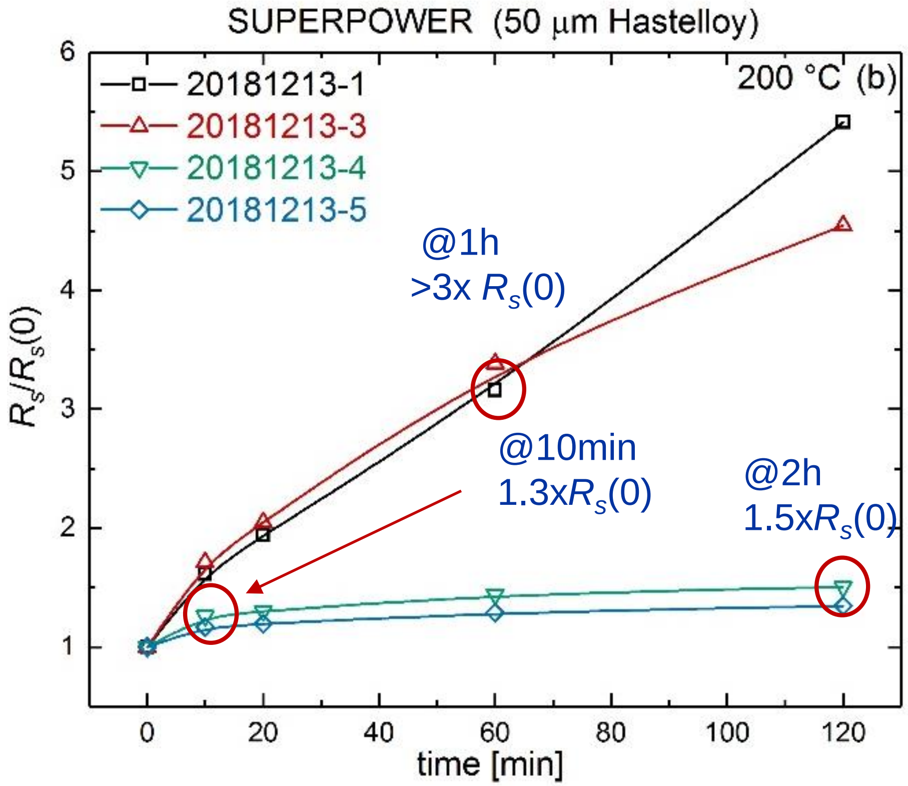


- R_s at *0-time* in the range 167-180 nΩcm^2
- **Strong increase of R_s with temperature (up to 4 times after 2 hours)**
- **The impact of the thermal cycle on the resistance is independent of the methodology applied and of number of thermal cycles**
- **The resistance increase can be fully ascribed to changes/degradation at the superconductor to silver and /or silver to copper interfaces internal to the tape**

SuperPower-50µm substrate

Looking at tapes from same supplier and same specification….



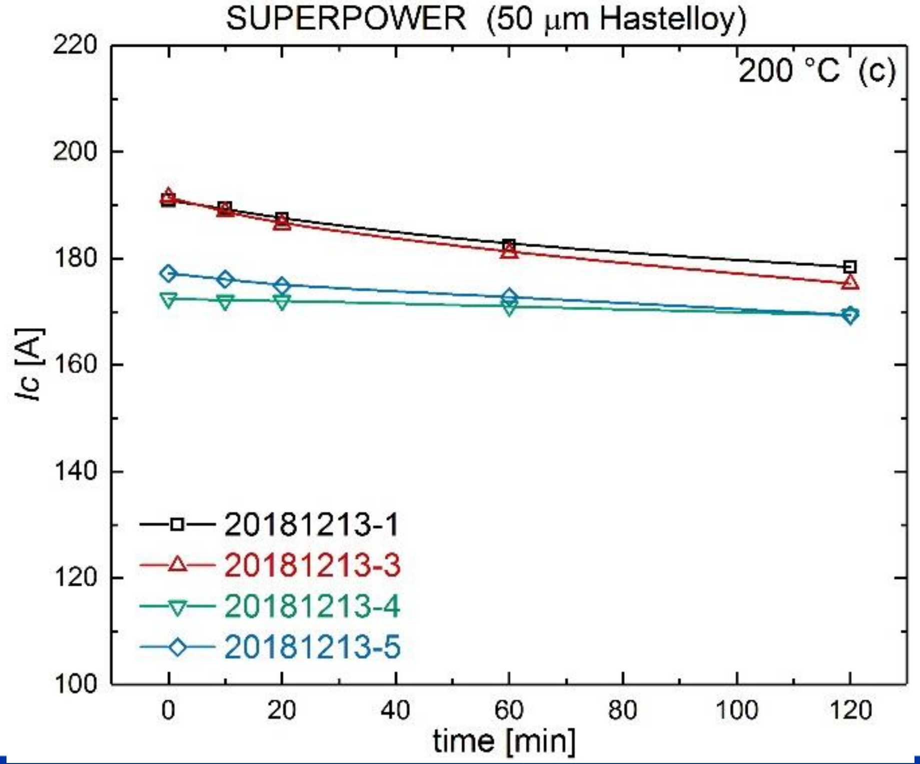


- Wide spread of $R_s(0)$: 30 to 190 nΩcm^2 (factor of 6);
- Less performant tapes present >3x$R_s(0)$ after 1 hour
- Performant tapes present saturation after 10 minutes, about 1.5x$R_s(0)$ after 2 hours

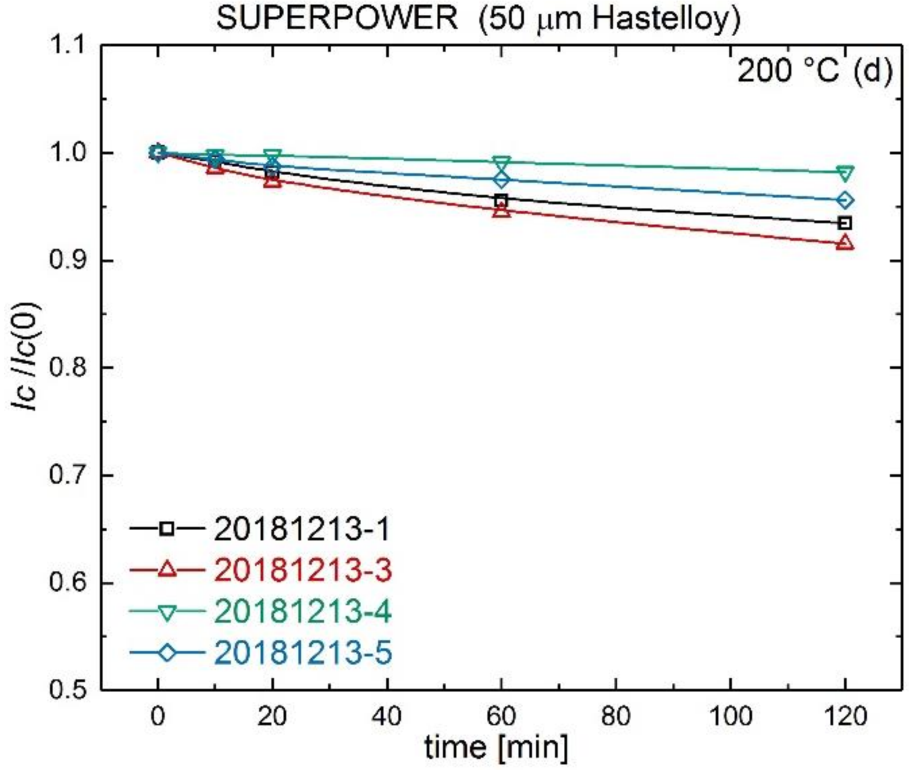
SuperPower-50µm substrate

Critical current provided by supplier at 77K, s.f.

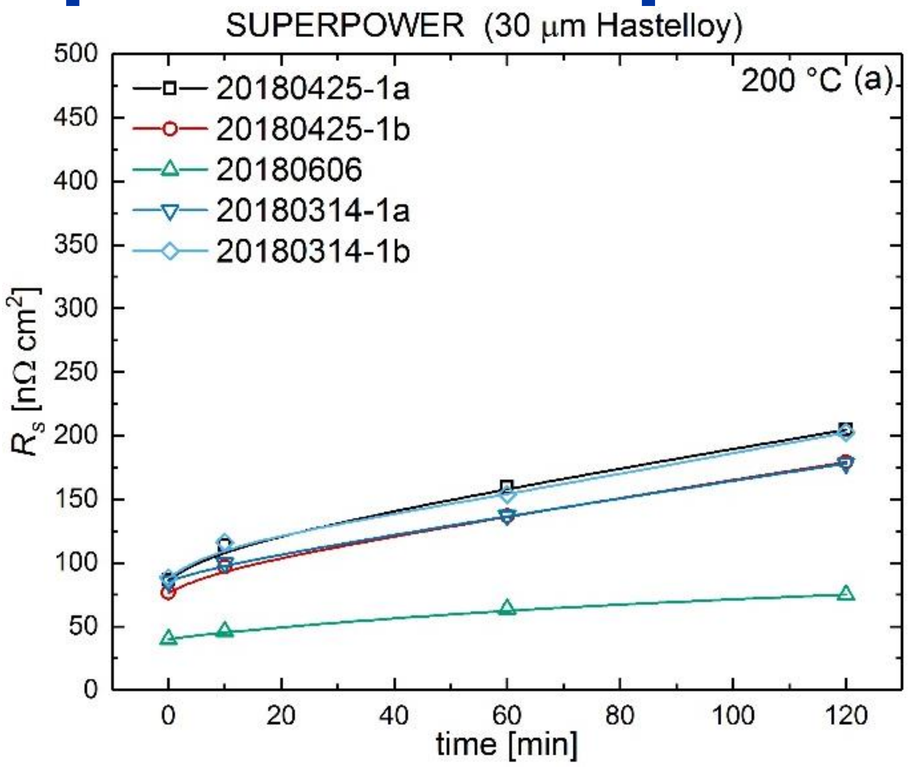
Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
20181213-1	185	184.1	185.9
20181213-3	182	180.2	183.8
20181213-4	165	164	166
20181213-5	168	167.7	168.5

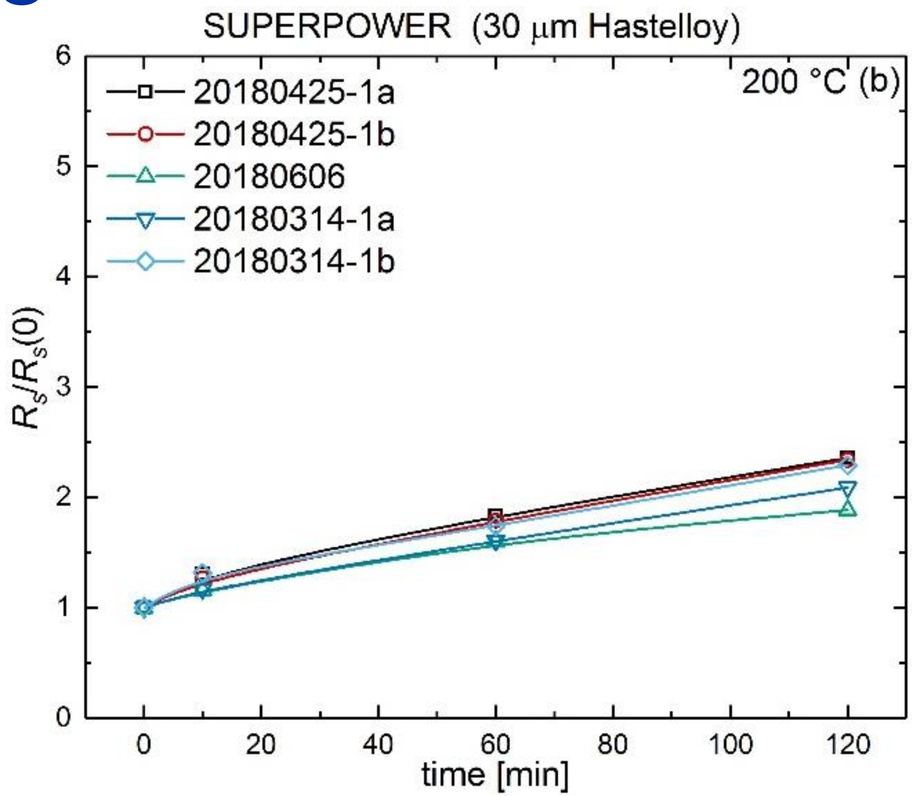


- I_c at *0-time* in line with values provided by the supplier
- I_c affected by thermal cycles
- I_c degradation up to 9% after two hours



SuperPower-30µm substrate



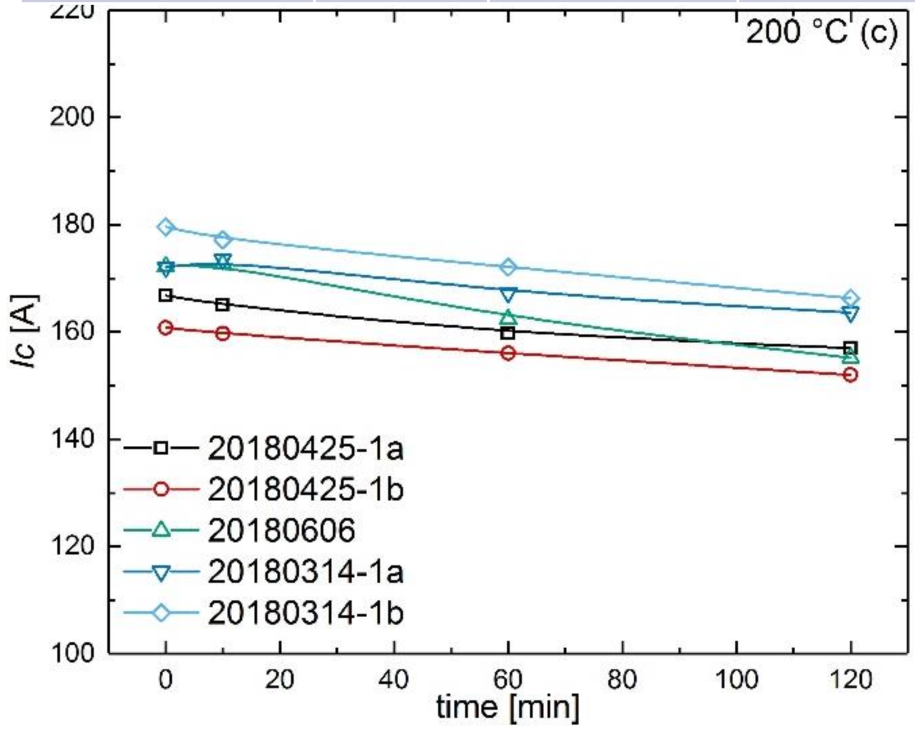


- Wide spread of contact resistance among 30 µm tapes at *0-time* (40 to 90 nΩcm^2);
- R_s after 2 hours lie between 1.5 and 2 times $R_s(0)$;
- With the data available, no correlation between the contact resistance behaviour and the substrate thickness

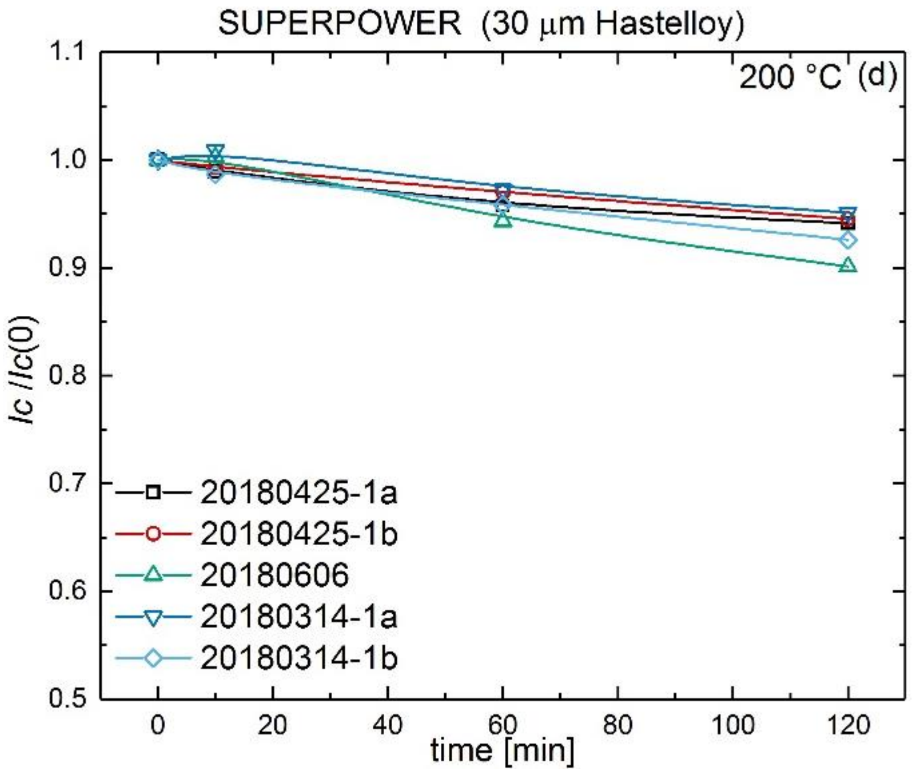
SuperPower-30µm substrate

Critical current provided by the supplier @ 77K, s.f.

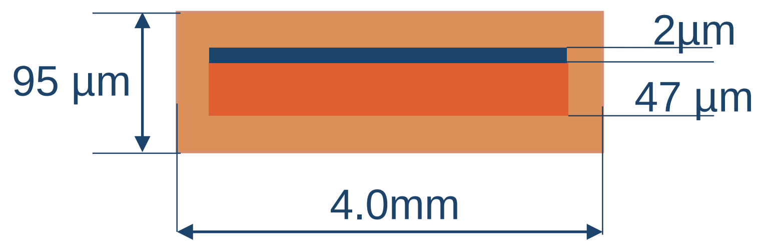
Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
20180314 1a	162	159.4	164.6
20180314 1b	167	165.8	168.2
20180425 1a	154	152.9	155.1
20180425 1b	154	152.5	155.5
20180606	169	168	170

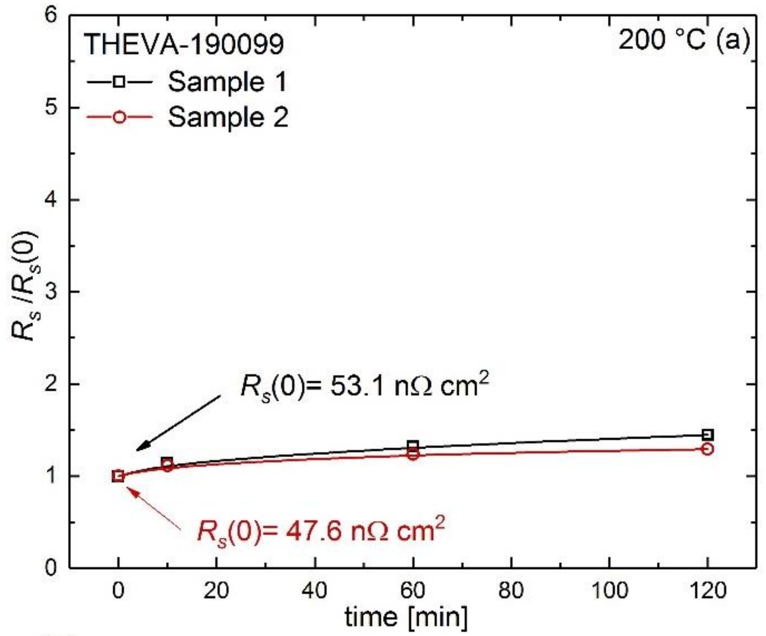


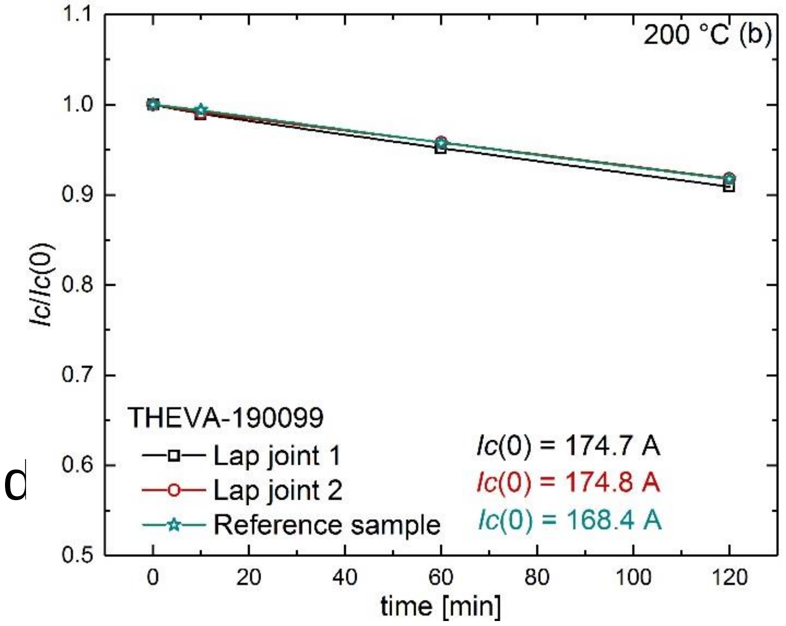
- I_c in line or higher than what given by the supplier;
- I_c degradation up to 9% after two hours



Theva tapes





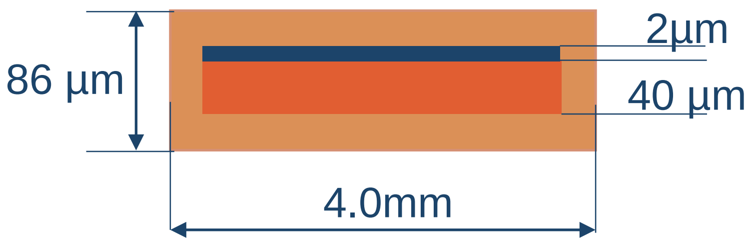


Critical current provided by supplier at 77K, s.f.

Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
190099	162	150	230

- $R_s(0)$ ~50 nΩ cm^2;
- Modest dependence of R_s on the heating time: **1.5xR_s(0) after 2 hours plateau**;
- 9% reduction of I_c after 2 hours plateau for both lap-joint and reference tape.

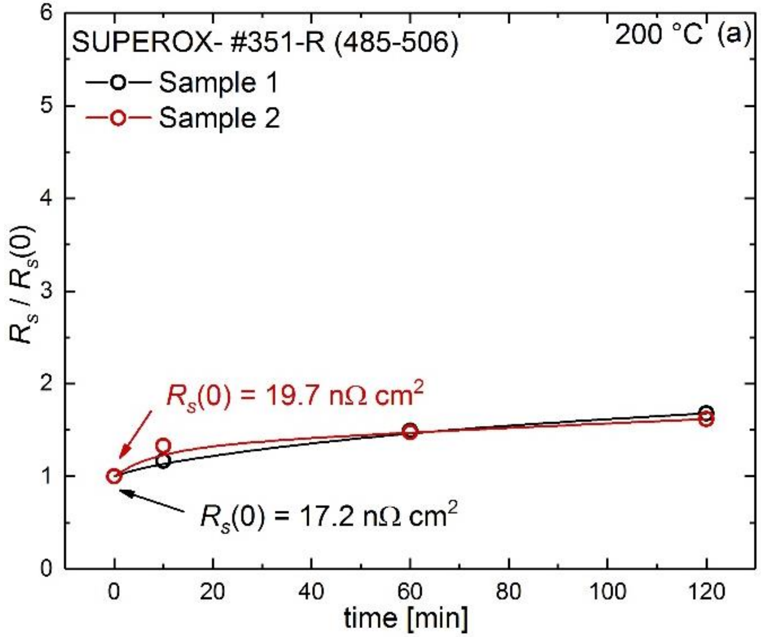
SuperOx tapes

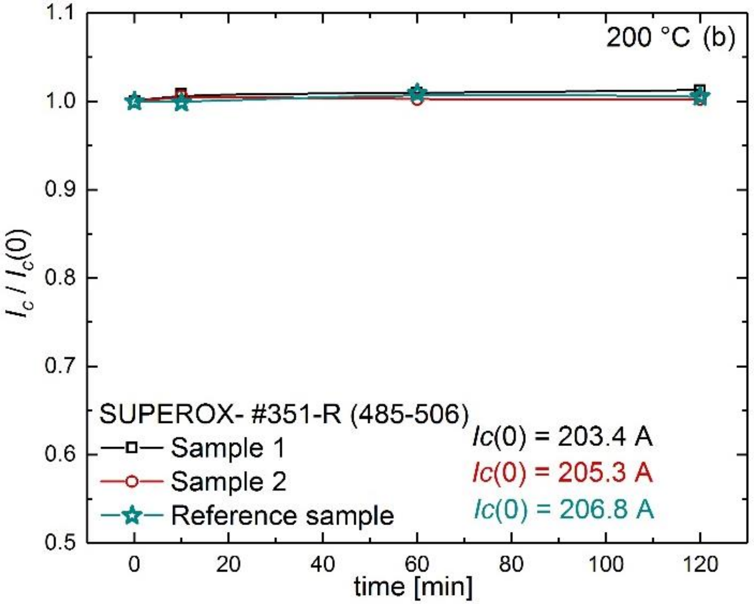


Critical current provided by supplier at 77K, s.f.

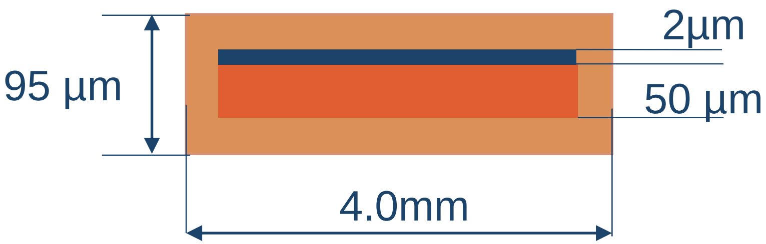
Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
#359-R (485-506)	217	200	N/A

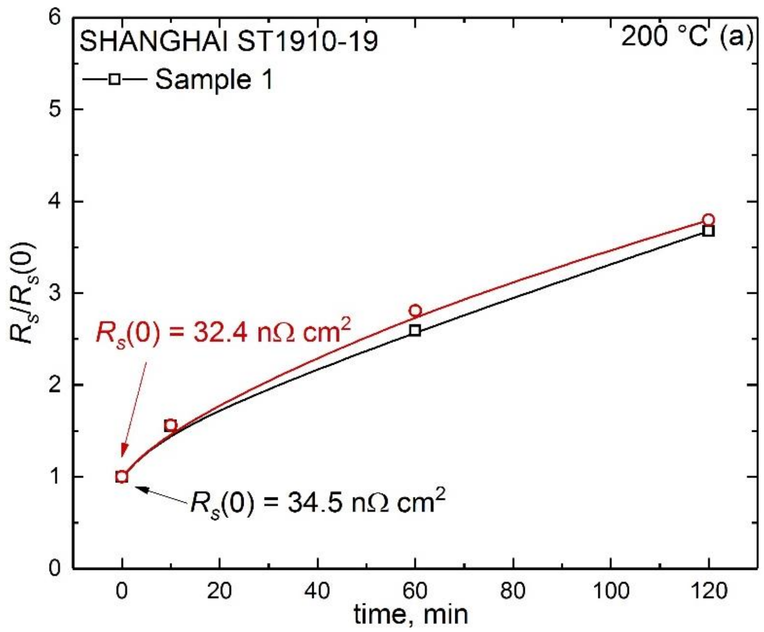
- $R_s(0)$ ~20 nΩ cm^2-smallest values measured
- Modest dependence of R_s on the heating time: 1.7x $R_s(0)$ after 2 hours plateau
- ***I_c* independent on the heating time**, for both the reference sample and lap-joints.





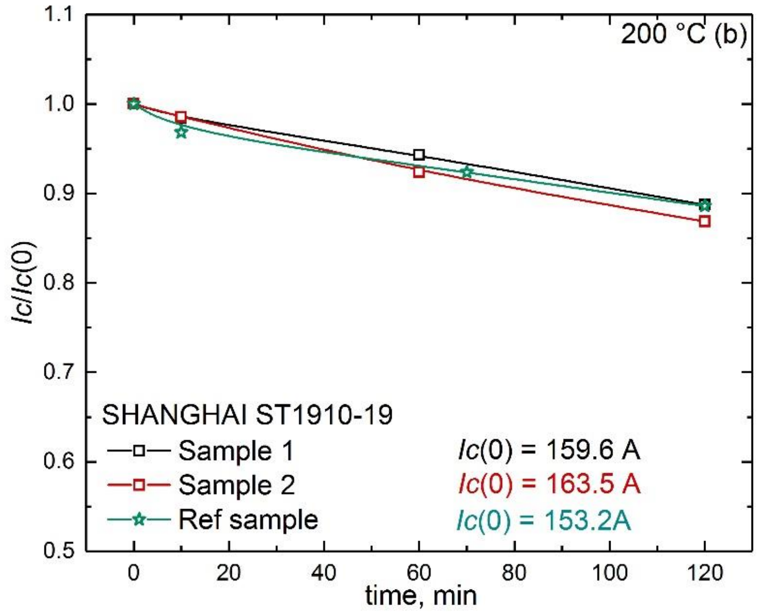
Shanghai Superconductors tapes





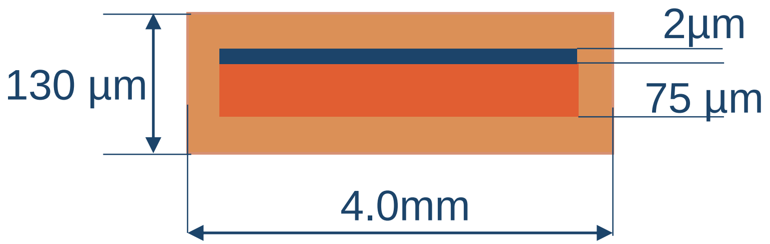
Critical current provided by supplier at 77K, s.f.

Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
ST1910-19	170	159.0	180.0



- $R_s(0)$ ~34 nΩ cm^2
- Significant dependence of R_s on the heating time: more than 2x$R_s(0)$ after 1hour plateau and more than 3x$R_s(0)$ after 2 hours plateau
- 9% reduction of *Ic* after 2 hours plateau for both lap-joint and reference tape

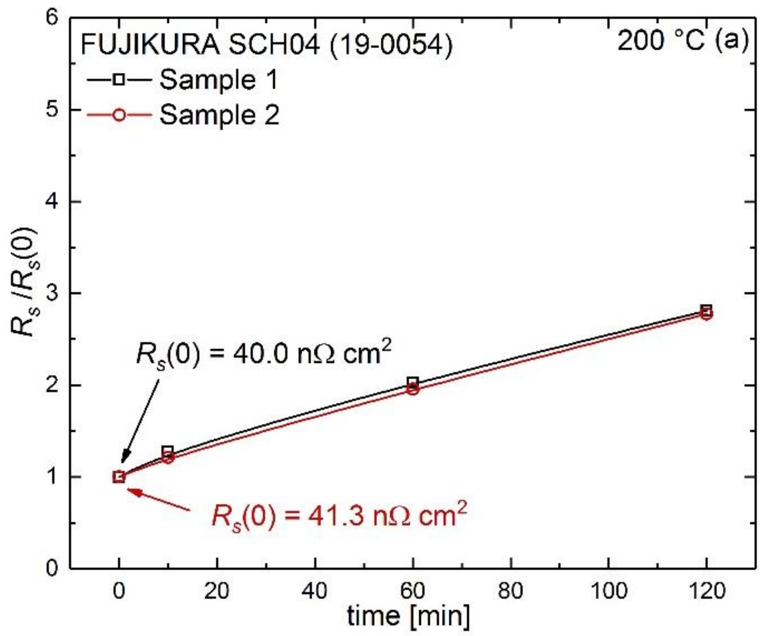
Fujikura tapes

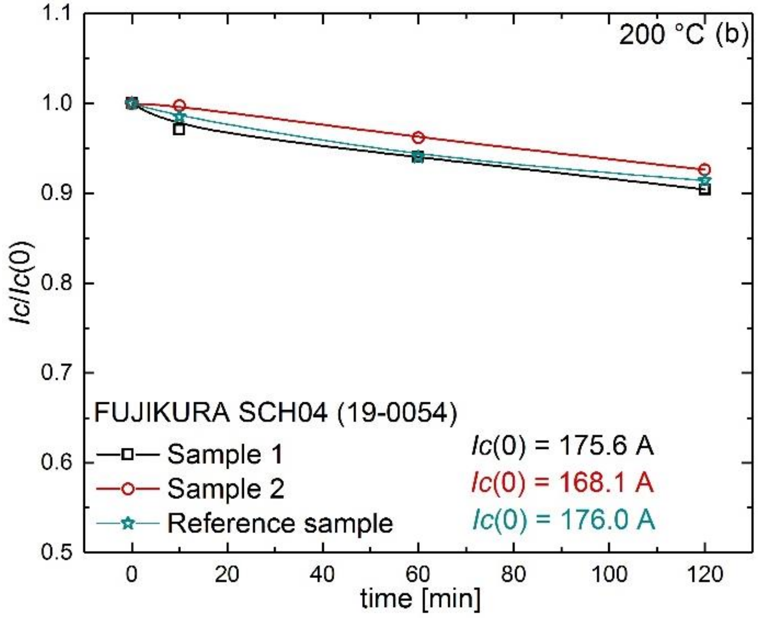


Critical current provided by supplier at 77K, s.f.

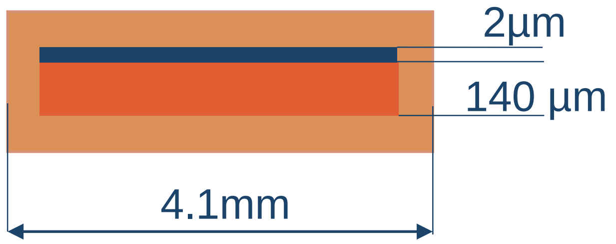
Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
#359-R (485-506)	164	163.0	165.0

- $R_s(0)$ ~40 nΩ cm^2
- Significant dependence of R_s on the heating time: 2x$R_s(0)$ after 1hour plateau and ~3x$R_s(0)$ after 2 hours plateau
- 9% reduction of I_c after 2 hours plateau for both lap-joint and reference tape





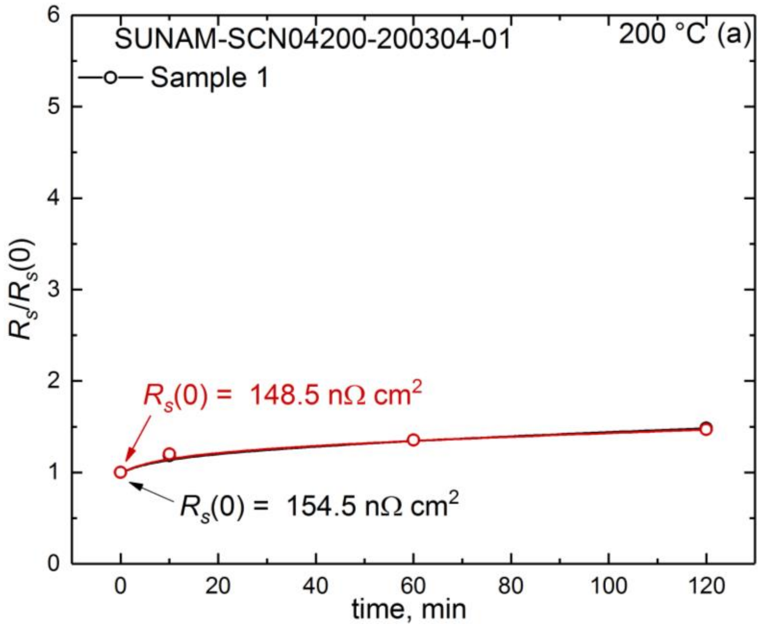
SuNAM tapes

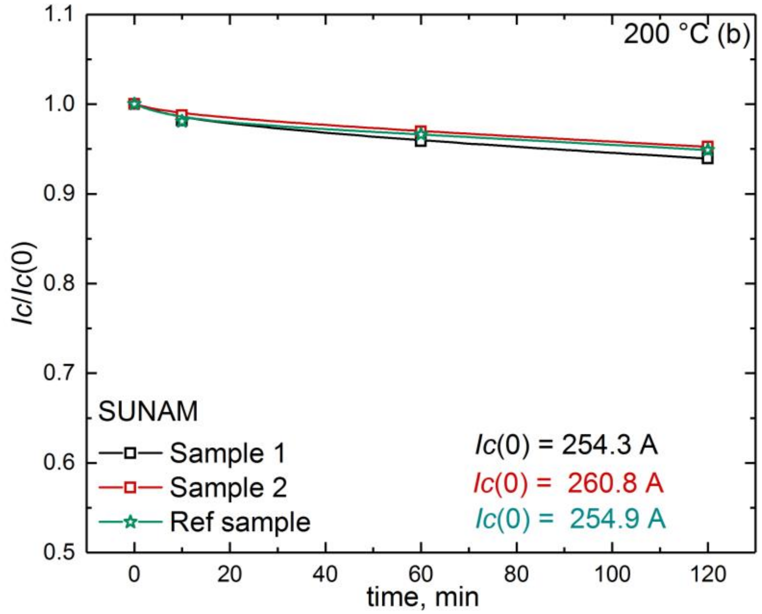


<u>Critical current provided by supplier at 77K, s.f.</u>

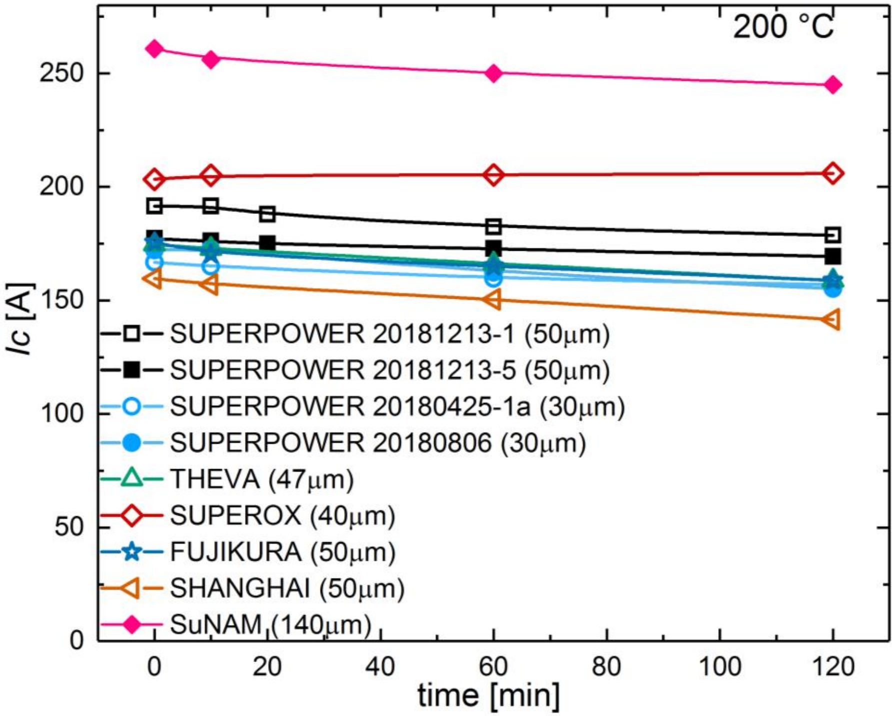
Tape ID	*Ic* (A)	*Ic,min* (A)	*Ic,max* (A)
SCN04200 200304-01	254	249	263

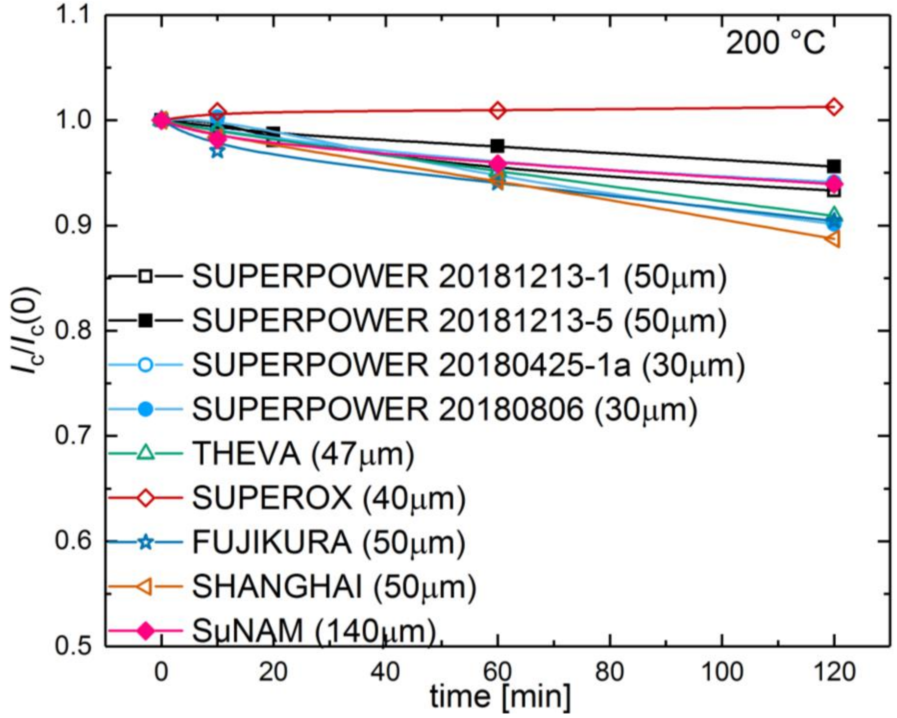
- $R_s(0)$ ~150 nΩ cm^2, highest measured
- Modest dependence of R_s on the heating time: less the 1.5x$R_s(0)$ after 2 hours plateau
- Critical current in line with what indicated by the producer.
- 8% reduction of *Ic* after 2 hours plateau for both lap-joint and reference tape





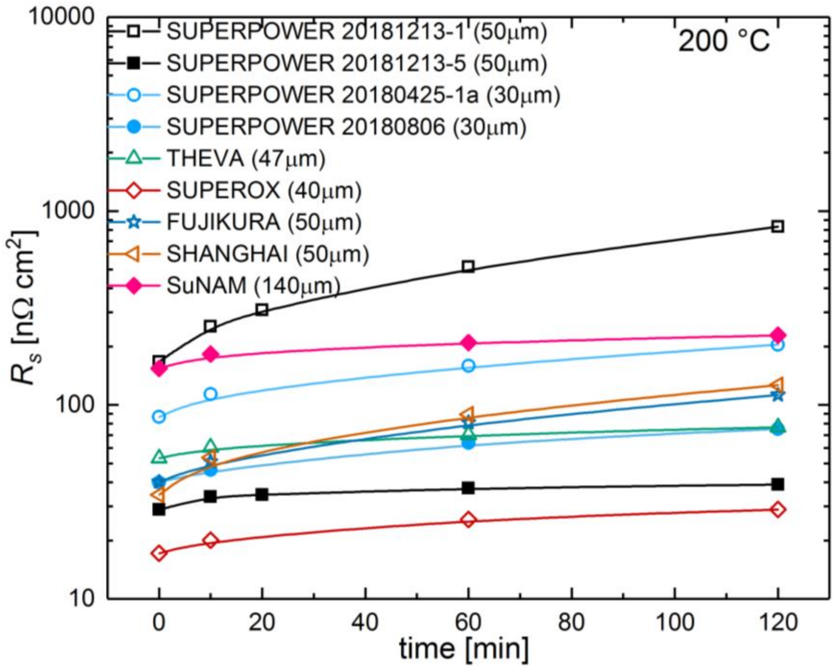
Comparison among suppliers-Ic

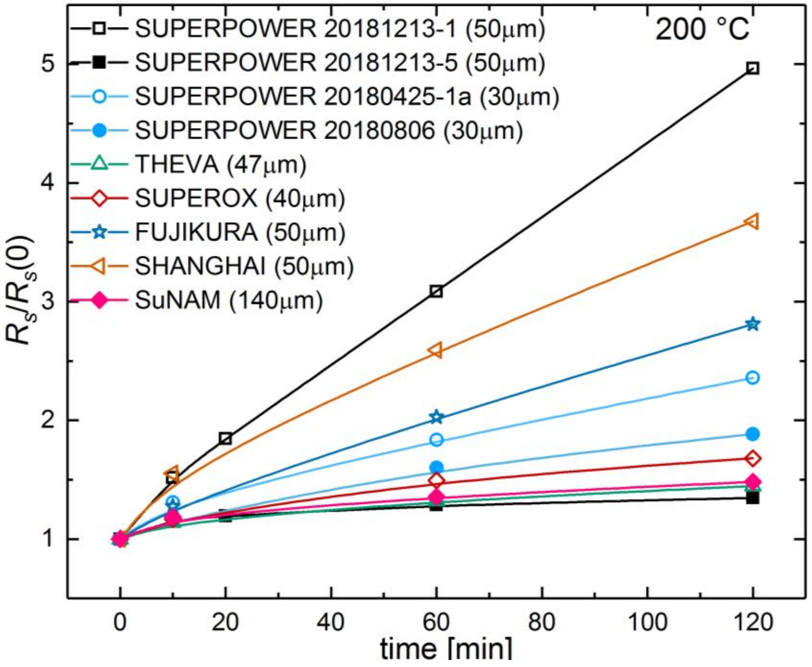




- SuNAM has the highest critical current at 77K;
- A maximum degradation of about 9% has been measured for the longest plateau;
- The most stable is SuperOx that shows less than 1% I_c reduction after been heated for 120 min;
- Measurements on more spools from the same supplier will be carried to investigate eventual deviation from the trend observed.

Comparison among suppliers

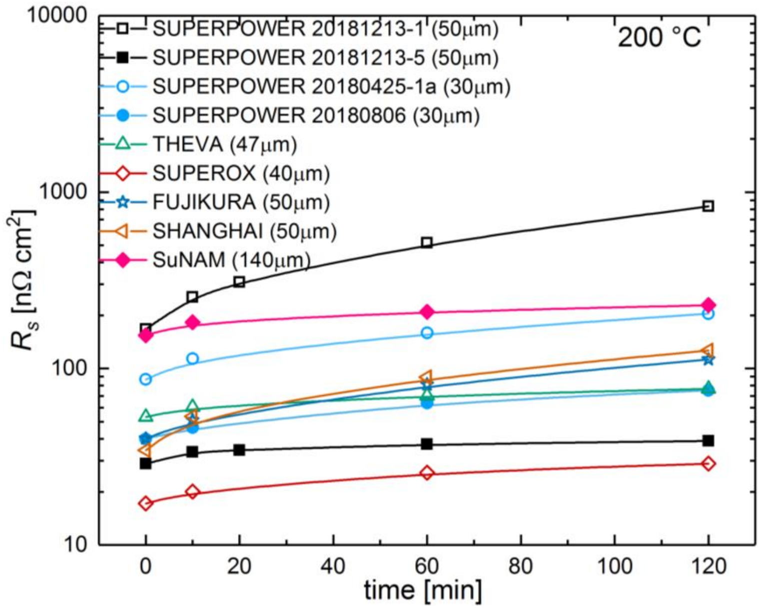


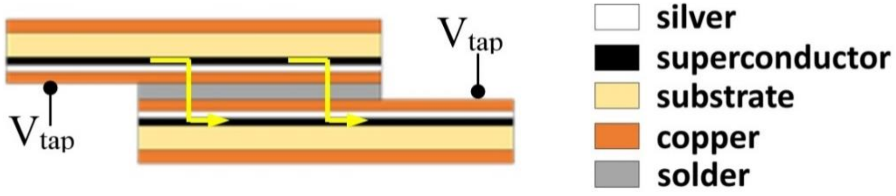


- Wide variation of R_s among superconductors from different suppliers;
- Wide variation of R_s among different spools of **the same supplier;**

- **A low contact resistance at *0-time* does not predict a better time-dependent behaviour** (i.e. Shanghai and Fujikura both with R_s (0)<40 nΩ cm^2)
- There is not clear pattern in the dependence of the contact resistance with heating time

Practical implications

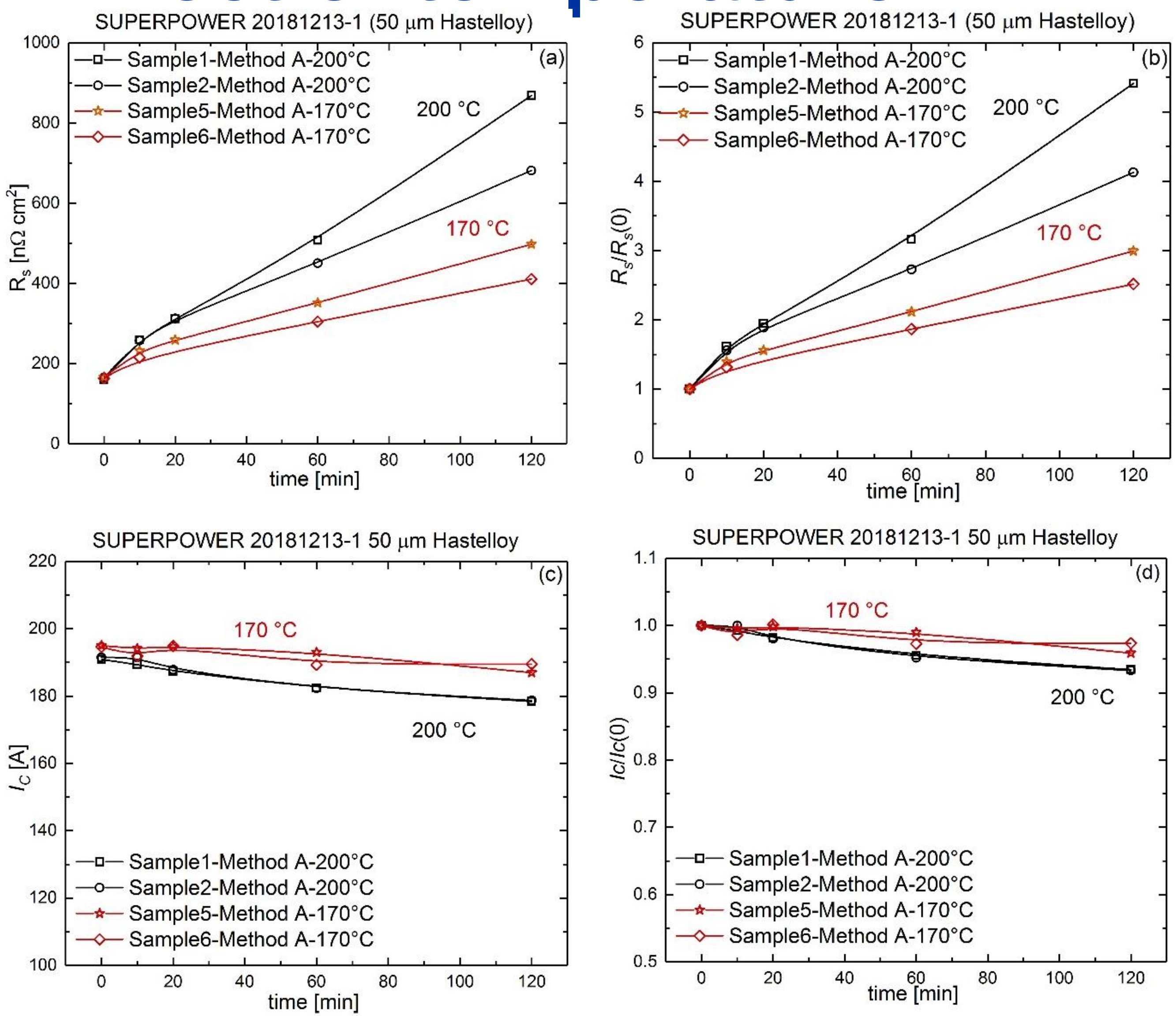




$$R_s = (2 \cdot R_{Ag} + 2\ R_{Cu} + R_{SnPb}) \cdot A =$$
$$2 \cdot \rho_{Ag} \cdot t_{Ag} + 2 \cdot \rho_{Cu} \cdot t_{Cu} + \rho_{SnPb} \cdot t_{SnPb} \sim 7.1 \mathrm{n\Omega cm^2}$$

- The variation observed in the results suggests the importance of including in the specification the desired contact resistance and its dependence on time when procuring the conductor (i.e. desired Rs at 0-time and after 30/60 minutes of heating);
- With the exception of SuperPower only one spool for supplier was measured. More measurements on other spools should be carried to see possible deviation.

Effect of temperature

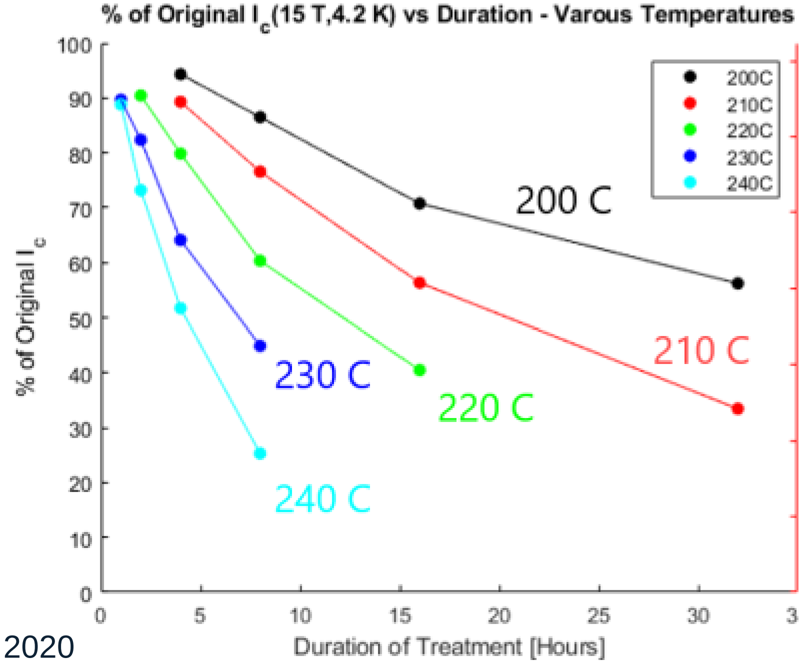


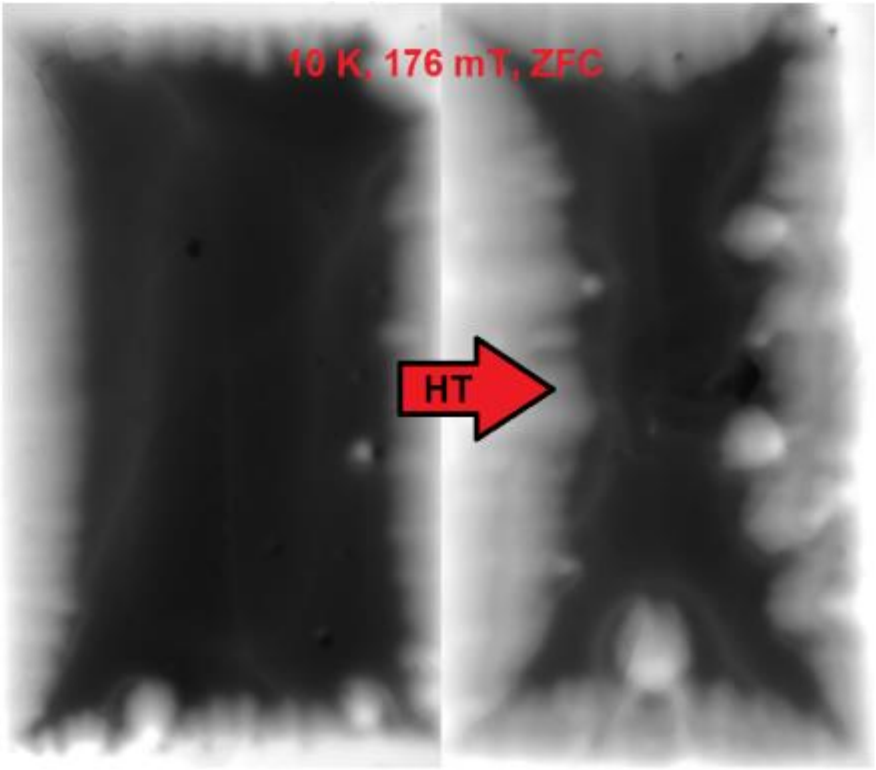
- SuperPower 20181213-1;
- SnIn solder, temperature plateau performed at 170◦C;
- Observed about 2xR_s(0) after 1 hour;
- For the same heating time **25-40% reduction in contact resistance if the heating temperature is lowered to 170◦C;**
- **Critical current degradation is less severe**: 2-3% after 1 hour plateau at 170◦C against 5% reduction at 200◦C.

Possible causes

Similar results have been found on tapes subjected to controlled removal of oxygen via heat treatment in Argon atmosphere;

According to this study, deoxygenation is the possible cause for the observed reduction in critical current and contact resistance.





Magneto-Optical Imaging (MOI). Dark regions correspond to areas which are superconducting, ighter areas represent greater magnetic flux.

Poster ASC 2020
Bradford, A.A. Polyanskii,D. Labalestier
Controllable Ic Reduction of ReBCO Coated Conductors by Controlled Removal of Oxygen

Conclusion

- A strong dependence of the specific contact resistance on the heating time has been observed in several lap-joints;
- This trend has been observed among different manufacturers and among spools from the same manufacturer (obtained with the same specification);
- If we want to predict the total resistance of a complex splice**, this study suggests that when ordering unit lengths of REBCO, the desired specific contact resistance should be specified at least for two thermal cycles** (i.e. at 0-time and after 30/60 minutes of heating);
- For QA, the same lap-joint can be used to measure the effect of the thermal cycle on one given spool but at least one sample should be measured for each different spool;
- The clearest correlation observed between the R_s and the thermal cycle degradation is: **the lowest the temperature the better;**
- Future work should be carried to understand the causes of the dependence of R_s on time and temperature.

Thanks!

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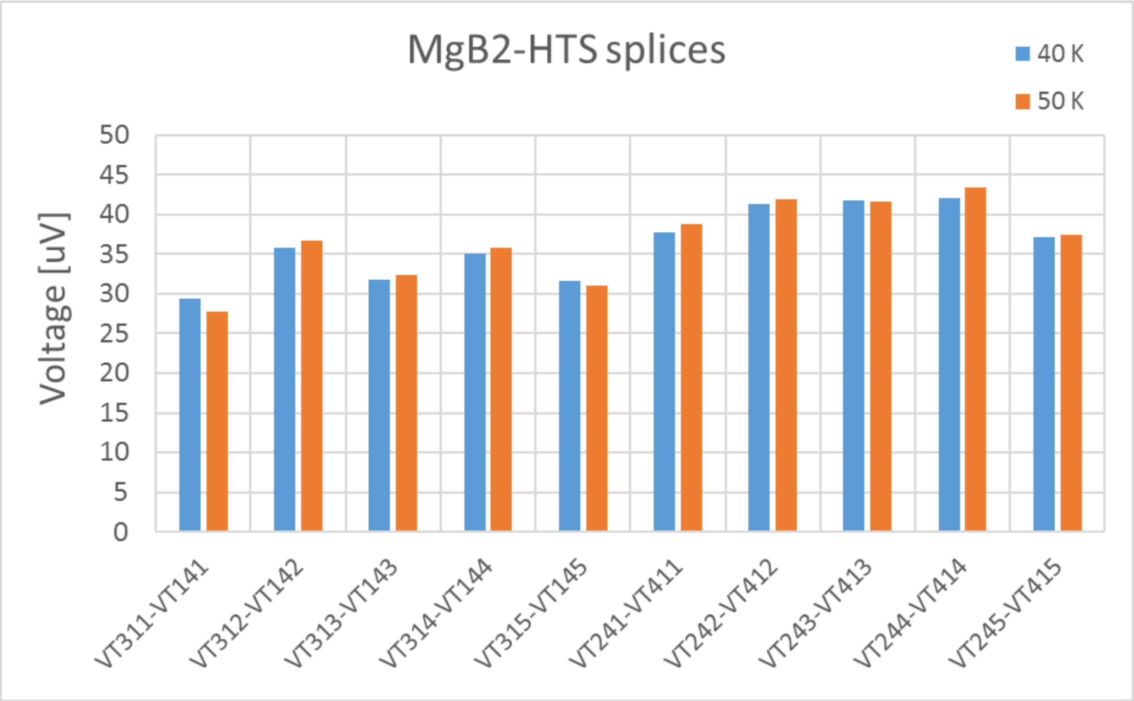
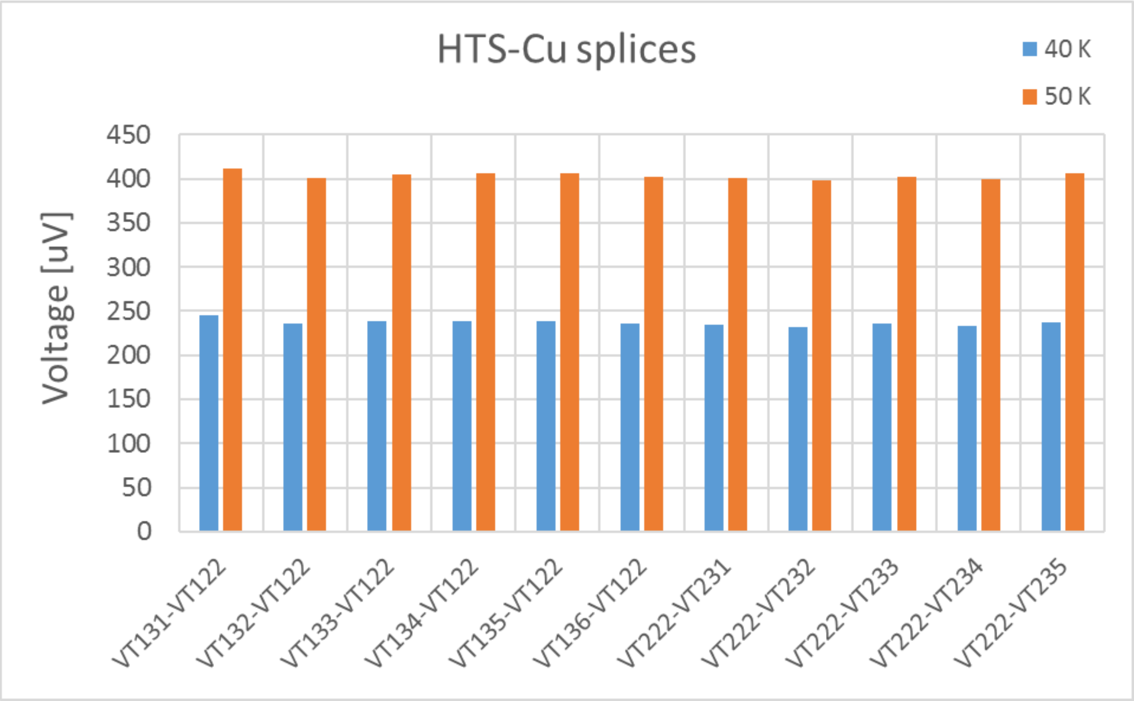
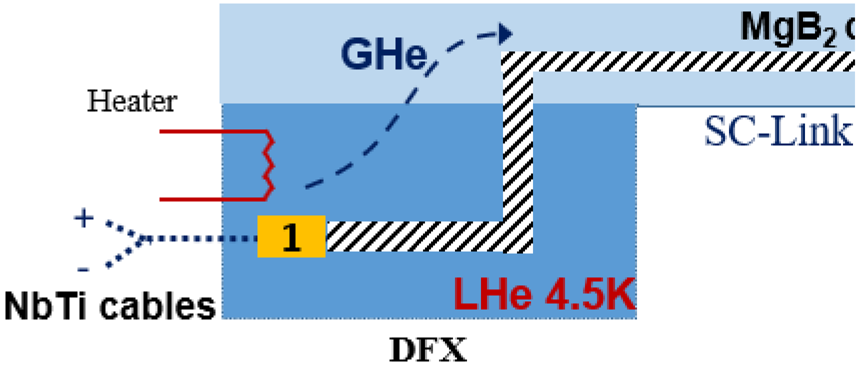
More info @ Internal note 2020-16, EDMS Nr 2366622I. Falorio, M.Matras, J.Fleiter, A. Ballarino

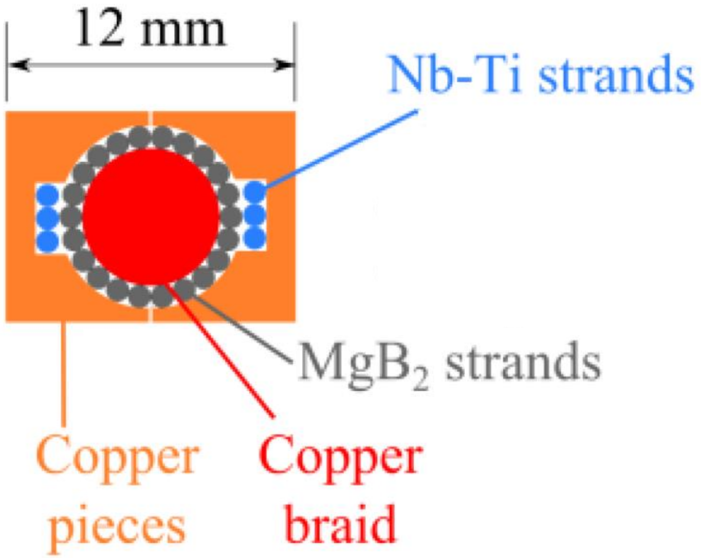
Splice resistance during Demo 1





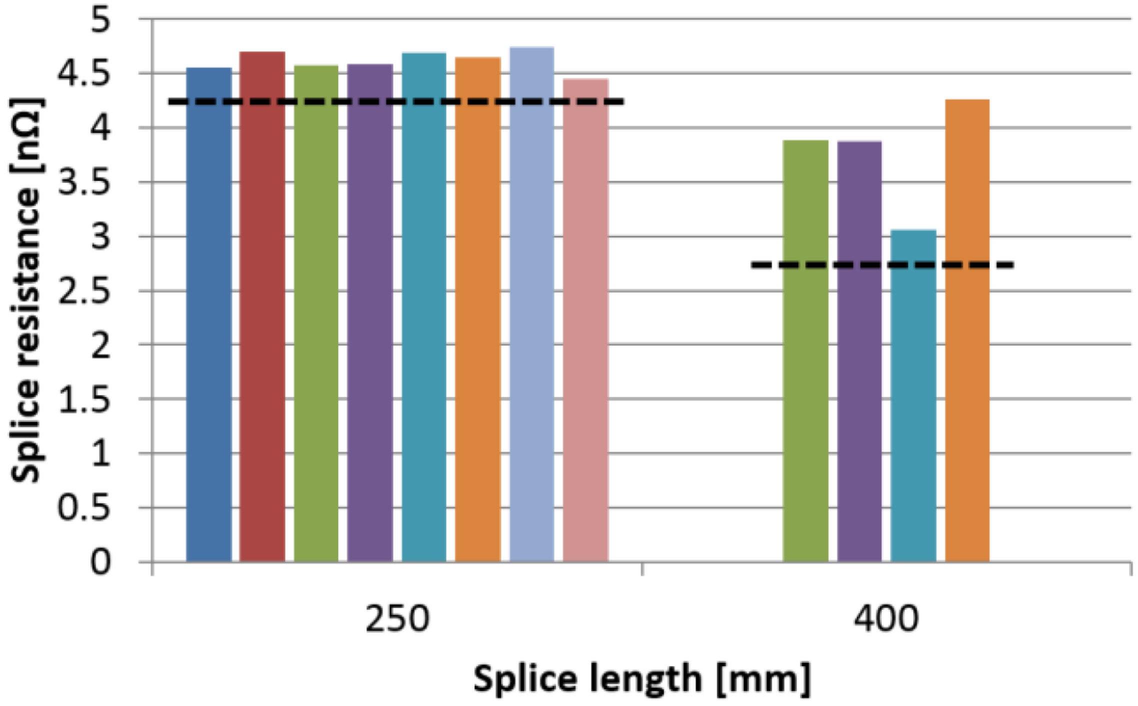
Splices between MgB_2 cable-NbTi bus bars





Expected splice resistance for a 250 mm long splice is around 4 nΩ

- **Example: 3kA sub cable spliced to 6 NbTi wires**
- **Measurements carried in FRESCA**



IEEE Paper ID:2484773
S.Giannelli, G. Montenero and A. Ballarino

Future work

- **Further research is required to fully understand the physical mechanism of the degradation observed (and try to mitigate it):**
  - ➢ **Impact of flux?**
  - ➢ **Phase of solder after long time heating?**
  - ➢ **Oxygen diffusion?**
  - ➢ **Interface oxidation? Maybe some measurements in vacuum could be performed**
  - ➢ **Diffusion of silver or solder into copper?**
  - ➢ **Interface impurity during manufacturing?**
- **Procurement strategy;**
- **Quality control plan once the conductor is received.**