# Measurement of splice resistance and normal zone propagation velocity in REBCO tapes for the Superconducting Link of HL-LHC

**M. Matras, J. Fleiter, A. Ballarino**

European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland

m.matras@cern.ch

**Abstract**. The Superconducting Link (SC-Link) being developed at CERN in the context of the LHC High-Luminosity upgrade (HL-LHC) will supply the current to superconducting magnets of the HL-LHC Inner Triplets and Matching Sections. The SC-Link consists of $MgB_2$ high-current cables, and it includes high temperature superconducting REBCO cables making the electrical transition between the $MgB_2$ and the current leads. Electrical protection of superconducting devices made of REBCO against unexpected quenches is challenging especially when operation is at high current density. Adequate electrical protection of REBCO cables is crucial to insure good performance of the circuit over the lifetime of the machine; protection relies on the detailed knowledge of the quench propagation velocity. In this paper we reviewed the electromagnetic properties of REBCO tapes procured for prototype work. We measured the splice resistance ($R_S$) of the REBCO conductors and found a significant variation among the different batches of conductor. The normal zone propagation velocity (NZPV) was reported to be affected by the interfacial resistance which is governing the splice resistance: increasing the interfacial resistance enhances the NZPV. In order to determinate the influence of the internal resistance on the quench behaviour of the tapes, we investigated the normal zone propagation velocity of the epoxy-impregnated tapes at 77 K in self-field and 4.2 K in field up to 7 T in the FRESCA test station. We found that despite the $R_S$ variation observed (up to factor 4), the tapes show similar NZPV at both temperatures. In addition we observed a significant field dependence of the NZPV of the tapes at 4.2 K. The results are compared to numerical simulation and discussed.

## 1. Introduction

The Superconducting Link (SC Link) being developed at CERN [1] in the context of the High-Luminosity LHC upgrade (HL-LHC) [2] will transfer the current from the power converters to the superconducting magnets of the Inner triplets and Matching sections of HL-LHC. The SC Link is made of several $MgB_2$ cables (up ~140 m long) connected on one side to the Nb-Ti bus-bars cables coming from the magnet coils and on the opposite side to HTS flexible cables, providing the electrical connection to the HL-LHC current leads [3]. The HTS cables will be operated in He gas in the range 17-50 K. Due to the high engineering current density [4], [5] and the small propagation velocity (of about 200 cm/s at 4.2K in perpendicular field and at operating current corresponding to $I_C$, with respect to 2000 cm/s for $Nb_3Sn$ cables operated in the temperature range 1.9-4.3 K at about 50 % of $I_C$ in similar field [6]), the electrical protection of REBCO conductors is challenging. A detailed knowledge and understanding of the normal zone propagation velocity (NZPV) of REBCO conductors is mandatory in

order to elaborate the adequate strategy for their protection. In multi-strand superconducting cables, the current distribution is governed by the self/mutual inductance of the strands, their critical current and the inter-strand/splice resistance. In order to insure homogeneous distribution of current within the REBCO cable it is mandatory that all tapes show similar splice resistance. It was reported that the electrical resistance of REBCO splice is mainly driven by the internal interface layers of the conductor (REBCO/Ag and Cu/Ag) that is difficult to predict [7], [8] and could be fluctuating from one production batch to another. In this study we characterized the $I_C$, and splice resistance at 77 K in self-field of different batches of 4 mm wide REBCO conductors from SuperPower, as well as the residual-resistivity ratio (RRR) of their electroplated Cu layer. As we observed a significant variation in splice resistance between the tapes, and therefore a variation in interface resistance, we investigated the effect of such a splice resistance variation on the NZPV of the tapes at 77 K in self-field and at 4.2 K in applied magnetic field up to 7 T.

## 2. Experimental details

### 2.1. Samples investigated
A total length of 300 m of 4 mm wide Superpower REBCO tape (with 2×20 μm thick electroplated Cu layers) was characterized. The tape was produced in different production runs. Critical current ($I_C$) measured by the supplier at 77 K and in self-field was ranging from 165 A to 190 A. For all seven spools of conductor used, we measured the critical current at 4.2 K and 77 K and we computed the critical current from magnetization measurements in the temperature range 4.2-92 K, the RRR and the splice resistance. On three selected spools we performed, in addition to the previously listed measurements, NZPV characterization at 77 K and 4.2 K.

Transverse cross-sections of the tapes were made using ion beam milling (ILION II GATAN model 697) and images were taken to extract the thickness of the different layers, using a SEM Zeiss XB540 scanning electron microscope.

### 2.2. Critical current measurement
The $I_C$ at 77 K in self-field of the REBCO tapes was measured on 15 cm long samples. Voltage taps were soldered 5 cm apart and centered on the samples. Copper terminations were clamped on the sample over a length of 3 cm (2 cm away from the voltage taps). Tape $I_C$ and $n$-value were computed using an electric field criterion of respectively 1 μV/cm and 0.1-10 μV/cm range. The critical current of REBCO conductor as a function of temperature and field $(I_C(B,T))$ was computed from magnetization performed in a vibrating sample magnetometer. Squared samples of 4 mm were cut from the REBCO tapes and measured at temperatures from 4.2 K up to 92 K in magnetic fields perpendicular to the tape surface from 2 to 8 T. The $I_C(B,T)$ of sample was extracted from the magnetization measurements using the following equation [9], [10]:

$$I_C(B,T) = wt\frac{2\Delta M}{w\left(1-\frac{w}{3l}\right)} \qquad (1)$$

where $w$ is the width of the REBCO layer, $l$ the length of the measured sample, $t$ the thickness of the REBCO layer and $\Delta M$ the hysteresis moment of the sample. $w$ and $l$ were corrected to fit the experimental transport $I_C$ values measured at 4.2 K. The corrected $w$ and $l$ were less than 5% lower than the theoretical sample dimension, which is consistent with the fact that the sample edges may have been damaged during cutting.

## 2.3. RRR measurement

The RRR of the electroplated copper of the REBCO conductors was measured between 4.2 K and 300 K on 8 cm long modified samples. The characterization was done one of the two Cu layers electro-deposited on the tape and the non-magnetic Hastelloy C-276 substrate. The other Cu layer, Ag, REBCO and buffer layers were peeled off the substrate using a razor blade. Any leftover was mechanically polished away. Electrical resistivity of the Cu was then measured at 4.2 K and at room temperature. With the sample geometry, the electrical resistance of the Hastelloy during RRR measurements is about 100 times higher than the one of Cu, so Hastelloy can be ignored.
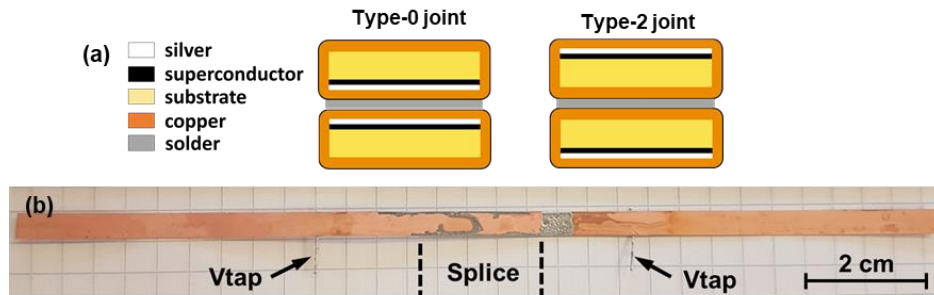


*Figure 1: a) Schematic of joint architecture. Type-0 joints have the tapes facing their superconductor side whereas type-2 joints have the tapes facing their substrate side. b) Picture of a type-0 joint.*

## 2.4. Splice resistance measurement

The electrical resistance of 2 cm long lap joint was measured at 77 K and in self field by four-point measurements. A 17 cm long piece length of REBCO tape was cut from the spool and then cut in half. The two 8.5 cm section were then soldered together over a 2 cm long overlap with $Sn_{60}Pb_{40}$ (wt%) (see Figure 1b). The soldering was done within an Al mold clamping the tapes together. The temperature was held to 200 °C for less than a minute, and a constant load of about 25 N was maintained during the soldering using 4 N/mm springs on each of the 4 screws of the soldering mold. Two types of splice were made. In Type-0 configuration, the two REBCO tapes were facing their superconductor side, whereas in Type-2 configuration the REBCO tapes were facing their substrate side [11], as shown in Figure 1a. The voltage taps were attached at 1 cm from the splice. The samples were ramped at a constant current ramp rate of 2 A/s up to the critical current. The splice resistance was determined as the best fitting slope of voltage versus current in the 0-90% range of $I_C$.

## 2.5. Quench propagation velocity measurement

The NZPV in REBCO conductors was measured by triggering a quench with a dedicated quench heater at constant external field, temperature and transport current. A set of voltage taps attached to the REBCO tape in the region of the heater location was used to compute the longitudinal NZPV by the time of flight technique. Voltage taps were photolithographed on polyimide foil with a controlled width and spacing of 0.5 mm and 2 mm respectively, as shown in Figure 2b. The voltage taps were made from a 17 μm Cu thin film with 5 μm Ni and 0.07 μm Au deposited on a 50 μm Kapton foil. Two blocks of 11 taps were cut from the Kapton® foil and soldered 5 mm away from the center of the sample, as shown in Figure 2a (#1), c and d. A 20 Ω resistive heater (RC series chip resistors from Yageo Reference: RC1206-20R0) was glued with a Stycast 2850 FT resin in the middle of the tape to initiate the quench, as shown in Figure 2a (#2), and d. The tape was then soldered at its two extremities over 4 cm onto a mechanical support made of 2 Cu leads (5 mm thick) held together with a G10 plate (2 mm thick), as shown in Figure 2a. Furthermore, another 2 mm G10 plate was fixed on top of the tape and two 2 mm thick stainless steel bars were added on top and bottom of the assembly to increase its rigidity (Figure 2a). Finally, the sample was wrapped into glass fibre clothing and vacuum impregnated with CTD101K epoxy resin, and cured at about 125 °C for 24 h. $I_C$ was measured before and after impregnation to make sure $I_C$ was not degraded during the impregnation process.
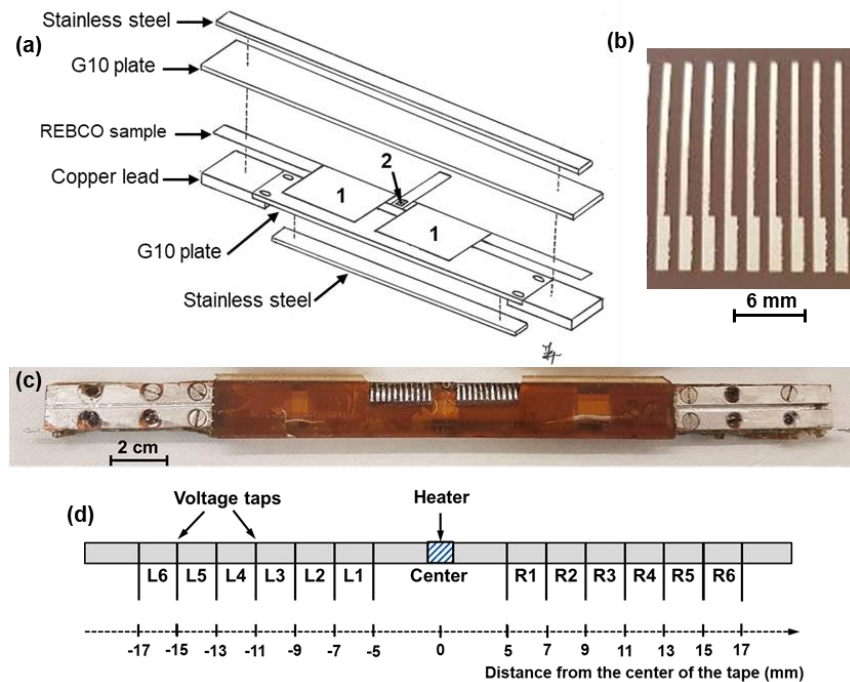
*Figure 2: a) Sample structure schematic before epoxy impregnation, with (1) bloc of photolithographed voltage taps and (2) heater. b) Bloc of 0.5 mm wide photolithographed Vtaps with 2 mm spacing on Kapton foil. c) Picture of a sample after epoxy impregnation. d) Heater and Vtaps position schematic. The signal from the first two Vtaps on the right and left sides of the heater are labeled R1 and L1 respectively.*

At 77 K, the quench was triggered with a short heat pulse generated with a Keithley model 2400 series SourceMeter controlled with Labview. At 4.2 K, the NZPV measurements were done in liquid helium in the FRESCA test station in perpendicular external fields of up to 7 T. The sample was connected to the current leads via 15 mm wide Nb-Ti Rutherford cables. The quench was triggered with a short heat pulse generated with a MCE SDAC 88 pulse generator. The rise in voltage was measured on each side of the heater. Arbitrarily one side of the heater was labeled right (R) and the other left (L). The segments of conductor equipped with pair of Vtaps were numbered R1 to R6 and L1 to L6 (R1 and L1 being the closest to the heater), as shown in Figure 2d. The voltage signals were recorded with high-speed data acquisition recorders Nicolet Vision and Gen3i at a frequency up to 50 kHz. Hyperbolic tangent function was used to fit the electric field-time (E-t) curves and the longitudinal NZPV was extracted using a criterion of 2 mV/cm.

*2.6. Simulations*

Numerical simulation of the splice resistance of type-0 and type-2 joints was done at 77 K using the COMSOL Multiphysics® electric current package. A 2D model of a joint cross-section with a 20 μm thick Sn-Pb solder was elaborated. The buffer layers of the REBCO conductor were represented as a 1D electrical insulation layer between the REBCO thin film and the Hastelloy substrate. The *RRR* values used for the simulation were the ones measured (see Figure 3b).

Simulation of NZPV at 4.3 K in perpendicular magnetic field was performed using the 1D model written by Van Nugteren [12]. Temperature, field and strain in the material are considered uniform and all material properties are homogenized in the cross section. We used the measured geometry and *RRR* of the tape as input parameters. The $I_C(B,T)$ surface used for the simulation of the quench propagation velocity is derived from the magnetization measurements. The thickness of epoxy considered in the simulation is 350 μm.

## 3. Results

### 3.1. Ic, RRR and Rs measurements

All seven tapes show similar $I_C$ (77 K, self-field) and n-values ranging from 177 A to 203 A, and 26 to 29 respectively, as shown in Figure 3a, whereas the *RRR* values of their Cu layer vary between 42 and 77 (see Figure 3b). For each of the seven batches of REBCO tape we measured the splice resistance of three different samples. Figure 3c shows the average splice resistance of the three samples for each tape for type-0 and type-2 splice architectures. For each tape, the three samples measured show similar $R_S$ with a standard deviation between 2 % and 8 % for type-0 joints (except tape #4 that shows a standard deviation of 26 %), and between 1 % and 9 % for type-2 joints. The average $R_S$ value of type-0 joints varies significantly by up to a factor 4 between the batches (41.5±3.3 nΩ·cm² and 201.9±4.3 nΩ·cm² for tapes 5 and 6 respectively). For type-2 joints, $R_S$ is significantly higher than for type-0 joints and similar variations are observed between 1345.5±84.8 nΩ·cm² and 2108.7±159.8 nΩ·cm² (tape 5 and 6 respectively). Magnetization measurements of the tapes were performed at temperature ranging from 4.2 K to 92 K, as shown in Figure 5a. Using equation (1), the magnetization critical current density was computed as explained above, and scaled to the transport critical current density ($J_C$) measured in the FRESCA test station in perpendicular magnetic field, as shown in Figure 5b.
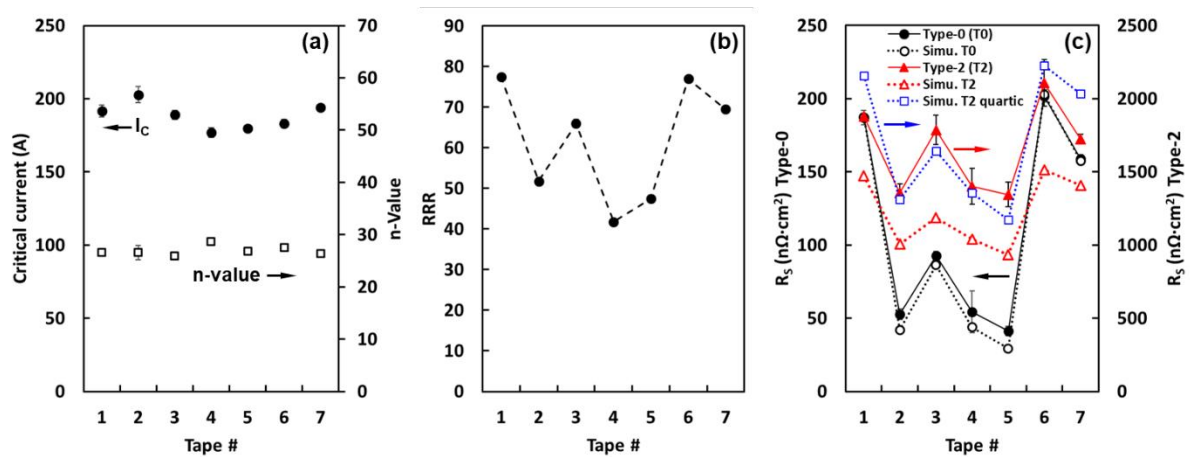


*Figure 3: a) $I_C$ and n-value (77 K, SF), (b) RRR, and (c) $R_S$ values (77 K, SF) of type-0 and type-2 joint of the seven tapes from SuperPower.*
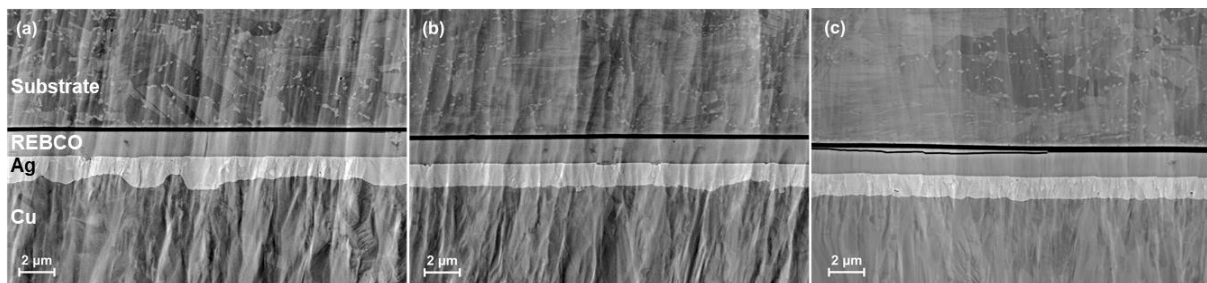


*Figure 4: Transverse cross-section micrographs of tape (a) #2, (b) #3, and (c) #6. The micro-crack visible in (c) through the REBCO layer is strongly believed to be from sample handling. Surface aspect difference between (c) and the other two samples (a) and (b) is from ion milling process and not from the sample itself.*
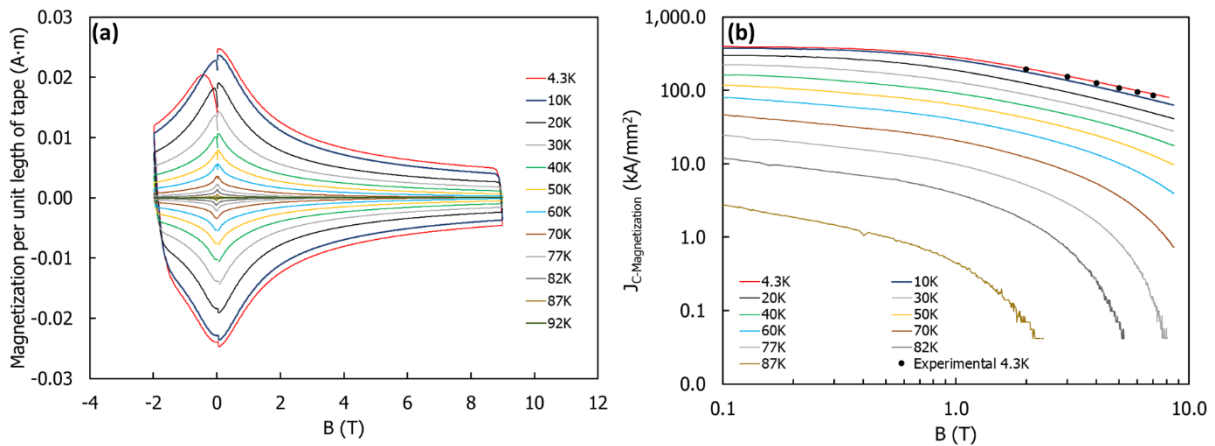
*Figure 5: (a) Measured magnetization of tape #2 as a function of magnetic field at temperature ranging from 4.2 K to 92 K. (b) computed magnetization $J_C$ using equation (1) scaled on transport $J_C$ at 4.2 K.*

### 3.2. NZPV measurements

The quench propagation velocity was measured on 3 samples tape #2, #3 and #6 with respectively low, medium and high $R_S$ value. Transverse cross-section SEM images of the three tapes are shown in Figure 4. All three samples show similar thickness of REBCO and Ag (1 um each). The REBCO layer thickness appears very uniform for the three tapes. In contrast, the thickness of Ag layer is quite uniform in tape #6 but shows medium and significant thickness variation in tape #3 and #2 respectively.
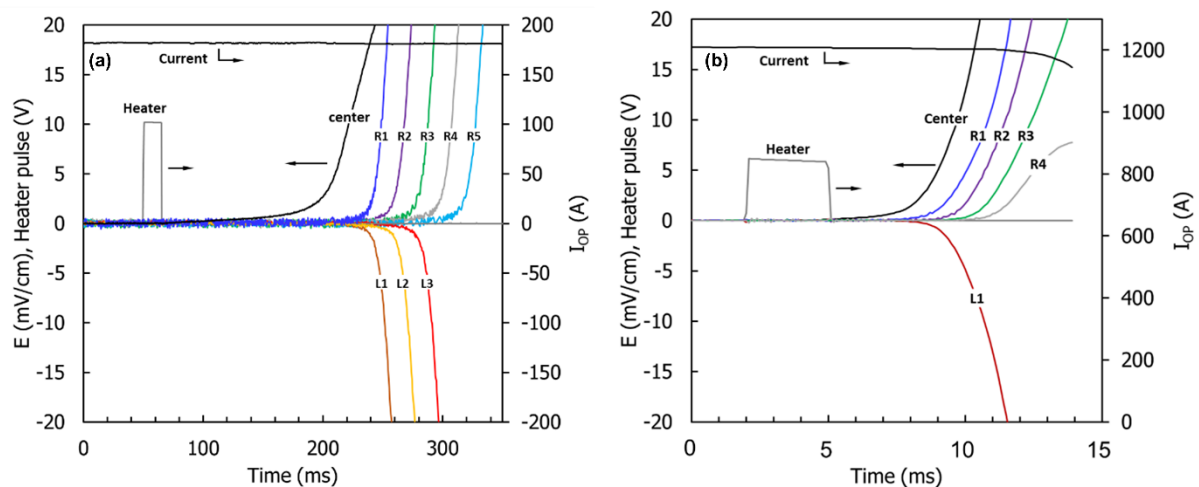


*Figure 6: Typical NZPV measurement at (a) 77 K in self-field and (b) 4.3 K at 2 T (perpendicular magnetic field) of tape #2 sample A. Current, heater voltage, and left and right side Vtaps electric field are shown. The number of channel of the data recorder were limited to the one shown in (a). Vtaps corresponding to L2 and L3 were lost between the 77 K and 4.3 K measurements.*

The quench propagation velocity of tapes #2, #3, and #6 was measured at 77 K and in self-field on two different samples (A and B) (Figure 7) and the NZPV of samples #2A and #6B was also measured at 4.3 K in perpendicular magnetic fields (Figure 8). After heat pulse, the center part of the tape shows an increase in voltage followed symmetrically by the first right and left segments (R1 and L1). At 77 K (Figure 7), segments R1 to R5 and L1 to L3 show similar  time rise in electric field, being distributed in time as function of their longitudinal position. At 4.3 K (Figure 8) we observe similar behavior as at 77 K: signals from segments L1 and R1 rise simultaneously showing a symmetrical quench. However, due to the rapid rise in voltage, the power supply was not able to maintain steady current, which rapidly

decreases after about 12 ms. Consequently, it was not possible to use signals further than R3 to compute the NZPV.

Figure 7 shows the NZPV computed from the measurements at 77 K in self-field as a function of the operating current ($I_{OP}$) (sample 6A which showed degraded properties is not reported). We observed that all 5 samples show a similar power law behaviour as a function of $I_{OP}$. The measured NZPV values of different samples are similar, ranging between about 15 cm/s at 100 % of $I_C$ and about 1.5 cm/s at 40% of $I_C$. Figure 8 reports the NZPV measured at 4.2 K in fields between 2 T and 7 T of sample #2A and #3C: ranging between 40 cm/s at high field and low current up to 250 cm/s at low field and high current. At each magnetic field, the NZPV increases with increasing $I_{OP}$. However, we observed that at fixed $I_{OP}$, increasing the magnetic field significantly increase the NZPV, which correlates with the decrease in $I_c$. Both samples show similar NZPV at similar $I_C$ fraction.
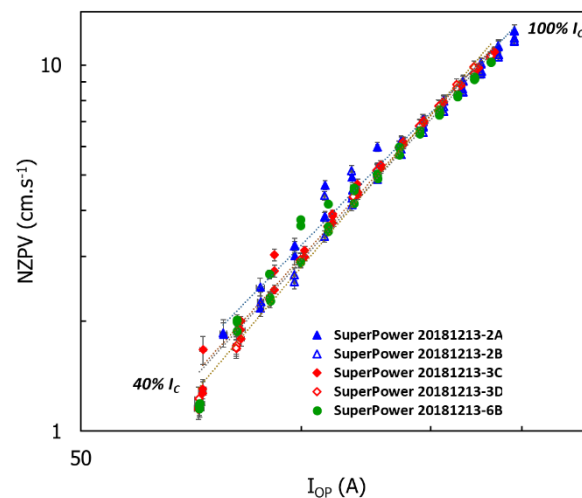


*Figure 7: Measured NZPV as a function of the operating current of samples A and B of tapes #2, #3, and #6 (sample B only) at 77 K in self-field.*

## 4. Discussion

### 4.1. Splice resistance

The splice resistance is an important parameter as it contributes to define the current distribution between the different tapes of a multi-strand cable, and may be the source of undesired heating. As reported in Figure 3c, the measured $R_S$ values of REBCO conductors from different batches vary significantly from the expected value: from about 40 n$\Omega \cdot$cm$^2$ [11], [13], to more than 4 times this value. This behaviour was previously reported in [13]. Despite a similar $I_C$, the measured variation in $RRR$ of the Cu layer between the seven tapes, as reported in Figure 3b, has a direct impact on the splice resistance as the current flows through the Cu, especially for type-2 architecture in which current has to mainly flow around the substrate due to the high electrical resistivity of the buffer layers. However, Cu and solder resistivity are not enough to provide a type-0 splice resistance of more than about 8 n$\Omega \cdot$cm$^2$, as shown by [11], which suggest an additional interface resistance most likely at the REBCO and Ag interface, as suggested in [14], which is strongly linked to the Cu RRR value. Therefore, the interface resistance of the tapes can be approximated as half of the measured splice resistance in type-0 configuration. In the cross section of the different tapes (Figure 4a) significant variation in the Ag thickness and tiny cavities in the Ag layers are observed in Figure 4c. However, we found no correlation (comparing the seven tapes) between the cross-section aspect of the Ag-REBCO interface and the $R_S$ variation. In the literature it was suggested [ref] that production line may affect the internal resistance of the tape.
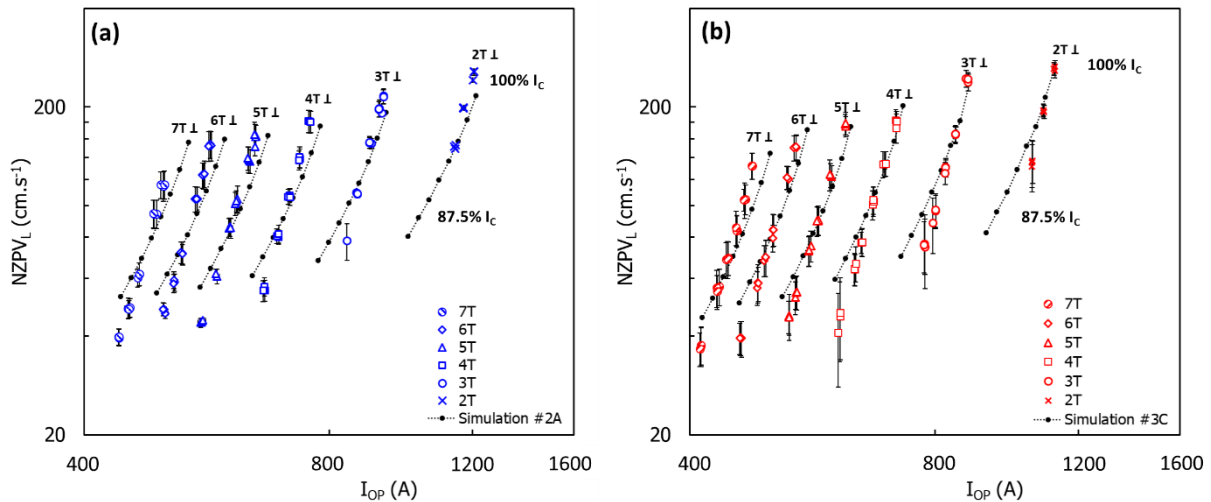
*Figure 8: Measured NZPV and simulation results as a function of the operating temperature of (a) sample #2A and (b) #3C at 4.3 K in perpendicular fields between 2 T and 7 T, at operating current ranging from 100 % of $I_C$ to about 87.5 % of $I_C$.*

In the numerical simulation, an artificial contact impedance was set between the REBCO and Ag to match the experimental $R_S$ values of type-0 as shown in Figure 3c (without this contact impedance the splice resistance of Type 0 lap joint is 7 nΩ·cm$^2$). For these specific value of contact impedance, the calculated $R_S$ values of type-2 joint is 26.2±4.8% lower than the measured data, as shown in Figure 3c. Non homogeneous $R_S$ across the width of the tape could explain the difference. A centered quadratic distribution of $R_S$ across the width of REBCO-Ag interface gave $R_S$ values in better agreement with the experimental values for both type-0 and type-2 joints (Figure 3c), which may suggest that most of the current flows from REBCO to Cu layers mainly at the center of the tapes, which increases the current path length through Cu in type-2 joints, but has limited effect on $R_S$ in type-0 joints. This hypothesis will be investigated on lap joint samples of different widths.

### 4.2. Normal zone propagation velocity

Simulation shown in Figure 8b is in rather good agreement with the experimental data. The slight difference in slope is most likely due to the slow diffusion of heat in epoxy, affecting the entropy of the system as a function of NZPV i.e. the higher the NZPV the smaller the expected amount of epoxy heated up. Therefore, for high $I_{OP}$, the simulation underestimated the NZPV and overestimate it for low $I_{OP}$. The strong influence of magnetic field on the NZPV in perpendicular field differs from measurements done in parallel field reported in literature [15], [16], which shows no effect of the magnetic field at temperature between 20 K and 50 K. To the best of our knowledge, no results were previously reported in perpendicular field. Our results show that the NZPV magnetic field dependence is significant at temperature around 4.2 K. The magnetoresistance of the Cu layer has limited effect on the NZPV. The magnetic field dependence of the NZPV at 4.2 K may be due to the large effect of the magnetic field on $I_C$ and consequently on the current sharing temperature, which is an important factor affecting the NZPV.

In addition, our measurements show that the NZPV in the investigated REBCO conductors at 77 K and in self-field as well as at 4.2 K and in fields of up to 7 T is not affected by the conductor interfacial resistance. This result differs from the measurement reported in [17], [18] performed on REBCO tapes with modified stabilizer, which shows that NZPV increases with increasing interfacial resistance (in the range $2 \cdot 10^{-7}$-$3.2 \cdot 10^{-4}$ Ω·cm$^2$). The quantity of Cu stabilization present in the investigated REBCO tapes from SuperPower, together with the relative small variation of the interfacial resistance (factor 4) didn't allow us to identify a visible improvement of NZPV for REBCO conductors presenting larger interfacial resistance.

## 5. Conclusion

We studied the splice resistance ($R_S$) and normal zone propagation velocity (NZPV) of multiple SuperPower tapes procured for the prototype leads of HL LHC. We found that using controlled soldering technique, $R_S$ varies significantly among the different production runs of REBCO conductors. The effect of the non-homogeneous splice resistance is attributed to a resistance internal to the tape, which appears to be not well controlled during the tape manufacturing process. For electrical applications, it is very important to have low and homogeneous $Rs$, independently from the batches. No obvious reason was observed in tape cross-sections for the measured $R_S$ variation between tapes, suggesting that microscopic defects (holes, Ag thickness variation…) are not the major interface resistance factor. We also found that tapes showing different $R_S$ values have similar NZVP at 77 K in self-field: being about 15 cm/s at 100 % of $I_C$ and 1.5 cm/s at 40% of $I_C$. At 4.2 K the quench propagation is much faster, being about 2 m/s at 100% of $I_C$ under 3 T. In addition, we observed a strong magnetic field dependence of NZPV at 4.3 K. The higher the field, the faster is the quench (for same operating current). REBCO tapes with different Rs values were found to have similar NZPV at 4.2 K in the range of field studied (2-7 T).

## References

[1] A. Ballarino, "Development of superconducting links for the Large Hadron Collider machine," *Supercond. Sci. Technol.*, vol. 27, no. 4, p. 044024, 2014, doi: 10.1088/0953-2048/27/4/044024.

[2] G. Apollinari, O. Bruening, T. Nakamoto, and L. Rossi, "High Luminosity Large Hadron Collider HL-LHC," *ArXiv170508830 Phys.*, 2015, doi: 10.5170/CERN-2015-005.1.

[3] L. Rossi and O. Brüning, "Progress with the High Luminosity LHC Project at CERN," *Proc. 10th Int Partile Accel. Conf*, vol. IPAC2019, p. Australia-, 2019, doi: 10.18429/jacow-ipac2019-moyplm3.

[4] J. Jiang *et al.*, "High-Performance Bi-2212 Round Wires Made With Recent Powders," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019, doi: 10.1109/TASC.2019.2895197.

[5] G. Majkic *et al.*, "Engineering current density over 5 kA mm-2 at 4.2 K, 14 T in thick film REBCO tapes," *Supercond. Sci. Technol.*, vol. 31, no. 10, p. 10LT01, Aug. 2018, doi: 10.1088/1361-6668/aad844.

[6] J. Fleiter, B. Bordini, A. Ballarino, L. Oberli, S. Izquierdo, and L. Bottura, "Quench Propagation in Nb$_3$Sn Rutherford Cables for the Hi-Lumi Quadrupole Magnets," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1–4, Jun. 2015, doi: 10.1109/TASC.2014.2367244.

[7] J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices," *IEEE Trans. Appl. Supercond.*, vol. 27, pp. 1–5, 2017.

[8] Youngjae Kim *et al.*, "YBCO and Bi2223 Coils for High Field LTS/HTS NMR Magnets: HTS-HTS Joint Resistivity," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 6800704–6800704, Jun. 2013, doi: 10.1109/TASC.2013.2243195.

[9] D. -X. Chen and R. B. Goldfarb, "Kim model for magnetization of type-II superconductors," *J. Appl. Phys.*, vol. 66, no. 6, pp. 2489–2500, Sep. 1989, doi: 10.1063/1.344261.

[10] M. Zehetmayer, "Simulation of the current dynamics in superconductors: Application to magnetometry measurements," *Phys. Rev. B*, vol. 80, no. 10, p. 104512, Sep. 2009, doi: 10.1103/PhysRevB.80.104512.

[11] J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices," *IEEE Trans. Appl. Supercond.*, vol. 27, pp. 1–5, 2017.

[12] J. van Nugteren, "Normal zone propagation in a YBCO superconducting tape: measurement and analysis of quasi-adiabatic normal zone propagation in a YBCO coated conductor," 20-Sep-2012. [Online]. Available: http://essay.utwente.nl/62096/. [Accessed: 10-Jul-2017].

[13] J. Lu, K. Han, W. R. Sheppard, Y. L. Viouchkov, K. W. Pickard, and W. D. Markiewicz, "Lap Joint Resistance of YBCO Coated Conductors," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 3009–3012, Jun. 2011, doi: 10.1109/TASC.2010.2091934.

[14] N. Bagrets, K. Weiss, R. Nast, and R. Heller, "Correlation Between Resistances of Face-to-Face Soldered Joints and Interface Resistance Between Layers in Superconducting Tapes," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, pp. 1–4, Jun. 2018, doi: 10.1109/TASC.2017.2784961.

[15] M. Bonura and C. Senatore, "An equation for the quench propagation velocity valid for high field magnet use of REBCO coated conductors," *Appl. Phys. Lett.*, vol. 108, no. 24, p. 242602, Jun. 2016, doi: 10.1063/1.4954165.

[16] J. van Nugteren, M. Dhallé, S. Wessel, E. Krooshoop, A. Nijhuis, and H. ten Kate, "Measurement and Analysis of Normal Zone Propagation in a ReBCO Coated Conductor at Temperatures Below 50K," *Phys. Procedia*, vol. 67, pp. 945–951, Jan. 2015, doi: 10.1016/j.phpro.2015.06.159.

[17] C. Lacroix, Y. Lapierre, J. Coulombe, and F. Sirois, "High normal zone propagation velocity in second generation high-temperature superconductor coated conductors with a current flow diverter architecture," *Supercond. Sci. Technol.*, vol. 27, no. 5, p. 055013, Mar. 2014, doi: 10.1088/0953-2048/27/5/055013.

[18] C. Lacroix, J. Fournier-Lupien, K. McMeekin, and F. Sirois, "Normal Zone Propagation Velocity in 2G HTS Coated Conductor With High Interfacial Resistance," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 4701605–4701605, Jun. 2013, doi: 10.1109/TASC.2013.2239696.