Characterisation of Nb_3Sn Rutherford cables for the LHC 11 T Dipole Magnet

A. J. Wuis, B. Bordini, A. Ballarino, L. Oberli and H. H. J. ten Kate

***Abstract*—The so-called CERN-LHC DS upgrade relies on the use of 11 T dipole magnets. For these magnets 40 strands Nb_3Sn type Rutherford cables based on 0.7 mm wires are being developed. Recently four samples of the cables were characterized in the CERN FRESCA cable test station. The critical current and the premature quench current due to magneto-thermal instability were measured at 1.9 K and 4.3 K in a background magnetic field between 0 and 9.6 T (the peak magnetic field on the conductor, including the self-field of the cable, ranges from ~ 2 T to ~ 12 T). Two cable samples were based on Powder-In-Tube (PIT) wire and two on Restacked-Rod-Process (RRP) wire. The PIT samples were identical and without a core in the cable while one of the RRP samples features a 25 µm thick stainless steel core. All cables samples tested have a width and a thickness of about 14.7 mm and 1.25 mm, respectively. Cables and sample holders were manufactured at CERN. In this paper we report and discuss the cable test results and compare them to the performance of witness strands, heat treated and measured on ITER-VAMAS type sample holders.**

***Index Terms*—Nb_3Sn, Rutherford cable, Stability, Superconductor**

I. INTRODUCTION

THE NEXT generation accelerator magnets may be based on high critical current density (J_c) Nb_3Sn superconductors [1], [2]. One of the scenarios of the LHC operation foresees Nb_3Sn magnets replacing some of the Nb-Ti main dipole magnets in the Dispersion Suppression (DS) region. By placing 11-m-long Nb_3Sn magnets with an 11 T field at the locations of 15-m-long 8.35 T Nb-Ti main dipole magnets, there will be 4 m available per magnet for the installation of additional collimators considered necessary. These so-called 11 T Nb_3Sn DS magnets will operate at 1.9 K and produce a magnetic field of 11 T at a current of 11.85 kA, being in series with the main dipoles [3].

At CERN, an extensive R&D campaign has been launched for the development and manufacturing of the Rutherford cables for the 11 T dipole magnets. The cables developed are based on the 0.7 mm diameter Nb_3Sn wires produced by Bruker-EAS and Oxford Superconducting Technology (OST). Their main properties are listed in Table 1. The Bruker-EAS wire is made using the Powder-In-Tube (PIT) technology while the OST wire is based on the Restack Rod Process (RRP). Recently the first three 11 T cables manufactured at CERN were tested in the FRESCA facility.

TABLE I
STRAND PROPERTIES

	PIT-114	RRP 54/61
$D_{strand,}$ [mm]	0.70	0.70
Cu/non-Cu	1.21	0.89
$D_{filament,}$ [µm]	44	70
Billet identification number	0802	9271, 9152, 9318, 9385
Heat treatment schedule	90h/650 °C [1]	48h/640 °C [2]
RRR in virgin state	91, 131, 106	178, 171, 152
RRR of extracted strands	(not measured)	129,133,127
Virgin I_c (12 T, 4.3 K), [A]	435, 430, 422	523, 520
Extracted I_c (12 T, 4.3 K), [A]	386, 366, 362	522, 513

[1] Intermediate temperature plateau: 120h/620 °C.
[2] Intermediate temperature plateaus: 48h/210 °C and 48h/400 °C.

II. SAMPLE PREPARATION

The PIT cables were made from wires of the same billet while the RRP cables comprise wires of four different billets. In Table I relevant information is provided regarding the wires, including their heat treatments and the main test results of the witness samples. For the critical current measurements, virgin and extracted strands were heat treated and tested on ITER type sample holders, while for the residual resistance ratio (RRR) measurements 10 cm long straight samples were heat treated.

The measured degradation of the RRP and PIT type extracted strands is 1% and 13%, respectively. Metallographic cuts of the PIT strands confirmed the presence of broken filaments after cabling and no damage after rolling down the diameter before cabling. It should be noted that this PIT billet was not designed specifically for a 0.7 mm diameter wire, but was derived from a previous development optimized for a larger wire diameter in order to start the cabling study for the 11 T magnet. The sample is schematically shown in Fig. 1 and the cross section in Fig. 2. Details of the samples preparation are described in [4], [5]. A few changes are introduced though in order to strengthen the sample mechanically and minimize the number of manipulations. In particular, fiberglass insulation is incorporated before the reaction heat treatment. The cables sections are placed inside a fiberglass sock that covers the entire sample except the location where the

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TABEL II
CABLE SAMPLE PROPERTIES

Sample Name	Cable ID	Cross section [mm × mm]	Keystone angle[°]	RRR
PIT Sample 1 [1]	H10EC0111A	14.7 × 1.255	0.75	50
PIT Sample 2 [1]				
RRP w/o core [1]	H15OC0113B	14.7 × 1.253	0.80	>140
RRP with core [1,2]	H15OC0113A	14.7 × 1.252	0.77	

[1] All cables have a twist pitch of 100 mm.

[2] The stainless steel (316L) core is 25 μm thick and 12 mm wide.

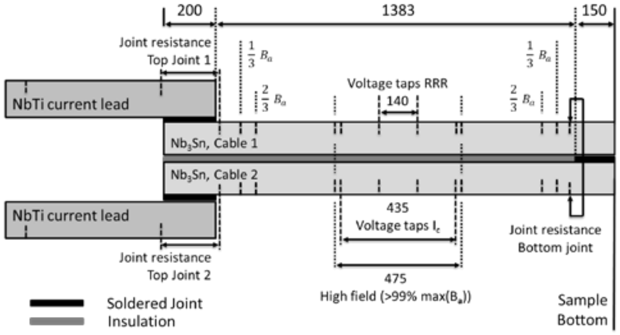

Fig. 1. Schematic view of a hair-pin shaped cable sample consisting of two Nb$_3$Sn cables soldered together at the right and connected to two Nb-Ti current leads at the left. The numbers indicate lengths in millimeters. Small dashed lines indicate locations of available voltage taps. The use of the voltage taps is indicated by text.

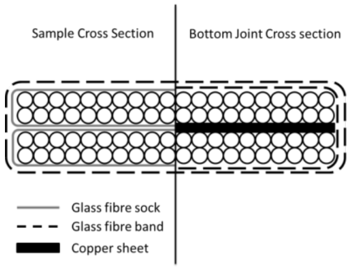

Fig. 2. Cross section of the cable sample indicating the location and type of fiberglass used. The band is made of E-glass and the sock of S2-glass.

electrical joint is made. Here a copper sheet is placed between the cables that are then wrapped together with a fiberglass band, see Fig. 2.

Voltage taps are also put in place before the heat treatment. They consist of commercially available 5 mm wide CuSn6 strips that cover the entire cable width and have a thickness of 0.02 mm. Finally the two cables sections are wrapped with fiberglass along the entire length to keep the cables well aligned. The samples are placed in a heat treatment mold which keeps the sample streight. During the reaction heat treatment bolts on the mold are tightened to keep the samples from moving without applying pre stress.

III. MEASUREMENTS

A. Strand Samples

The strand witness samples, both virgin and extracted, are tested on ITER-VAMAS type barrels at CERN measuring critical and stability current at 1.9 K and 4.3 K, the setup is described in [6]. The strands are not bonded to the barrel. The extracted strands are not straightened before mounting. Voltage taps used are placed 60 cm apart. The critical current is determined by increasing the transport current in the sample with constant applied magnetic field. The self-field of the strand is determined by a formula derived from FEM modeling [7]. At relatively high magnetic field (> 8 T at 4.3 K and > 11 T at 1.9 K), shown in Fig. 3, the wire reaches its critical current while for lower magnetic field it is limited by magneto-thermal instability.

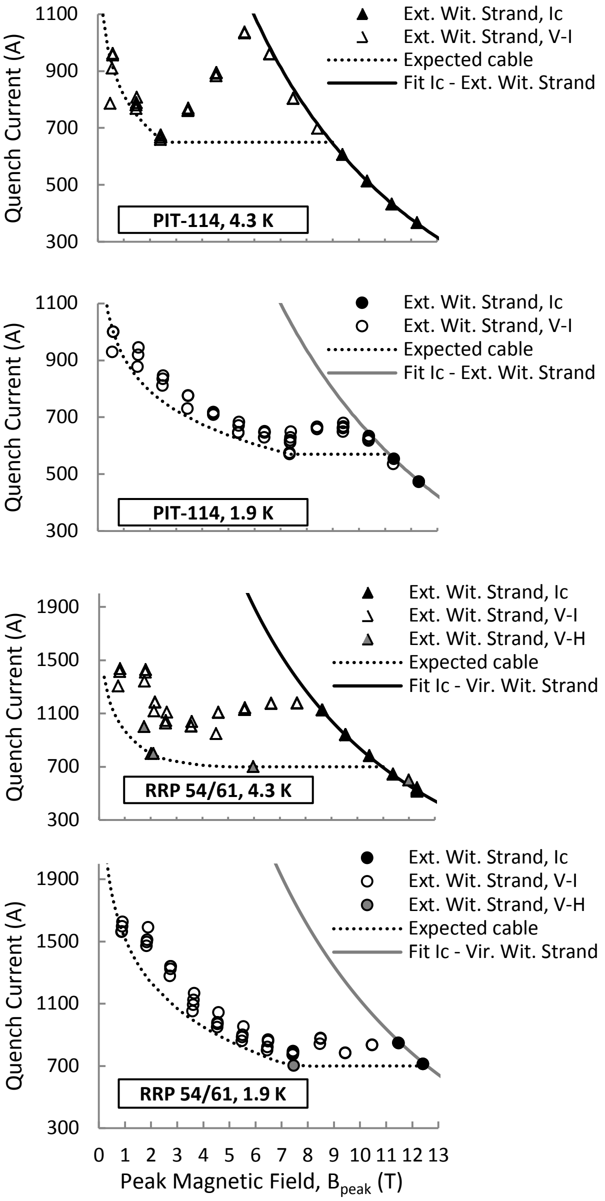

Fig. 3. Critical and quench currents versus peak magnetic field at 1.9 K and 4.3 K for the PIT-114 and the RRP-54/61 extracted witness strands. The critical current (I_c) values are determined using the criterion of 10 μV/m.

Instability during V-I measurements are mainly caused by the re-distribution of the transport current, i.e. self-field instability [8]. Instability can also be caused by the magnetization generated by persistent currents [9], [10]. This type of instability is measured more distinctively by a so-called V-H measurement, first applying a transport current in the sample without a background field and then increasing the

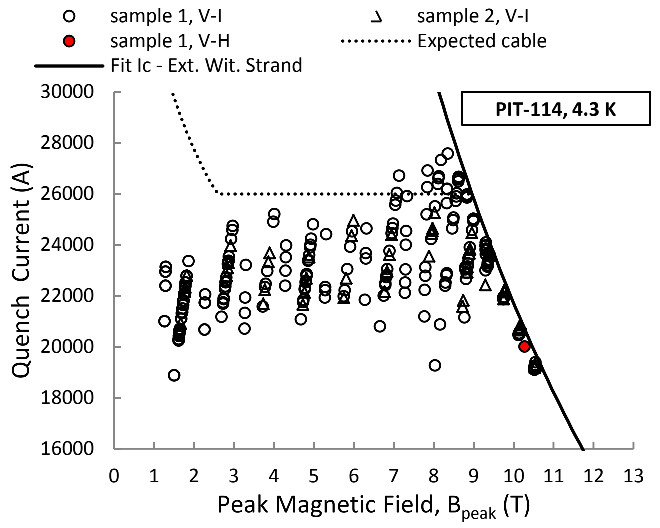

Fig. 4. Quench current versus peak magnetic field for the PIT-114 cable sample at 4.3 K. The critical current fit and the expected cable quench current are based on strand test data multiplied by the number of strands.

magnetic field until a quench occurs [11], [12], [13].

The RRR of witness samples were measured at CERN in a dedicated setup.

B. *Cable Samples*

The FRESCA test station [14] allows measuring cables at 1.9 and 4.3 K with a background magnetic field of up to 10 T. The magnetic field is within 1% of its maximum value across a length of 475 mm. The voltage taps for I_c-measurements are centered within this high field region and span a length of 435 mm. The samples critical current is determined by V-I measurements while the stability is determined through V-I and V-H measurements. The voltages between different sections of the sample are measured with a 16-channel digital oscilloscope to determine if the quench starts in the high field region.

To obtain the RRR value of the cable a small current of 10 A is in the cable while the sample is passively warming up. The voltage measured as soon as the entire section between the voltage taps, shown in Fig. 1, is above the critical temperature is used to calculate the RRR value. Temperature probes on the sample holder indicate only a 1.5 K thermal gradient between the voltage taps used to determine the RRR(Fig. 1). The joint resistance is measured by applying a plateau current and measuring the voltage across the joint, the three sets of voltage taps used to measure the resistance of the three joints are indicated in Fig. 1.

IV. RESULTS AND DISCUSSION

A. *Strands*

The results of the measurement on strands are summarized in Fig. 3. Due to the cabling degradation, influenced by the rolling down of the PIT wire from a larger diameter, the theoretical critical current is fitted to the extracted strand data for the PIT strand. As expected, at high magnetic field the conductor is stable and reaches its critical current while at lower magnetic field it quenches prematurely because of magneto-thermal instability. During V-I measurements the premature quenches are due to the self-field instability while during a V-H measurement they are caused by the combined effect of self-field instability and magnetization instability [9].

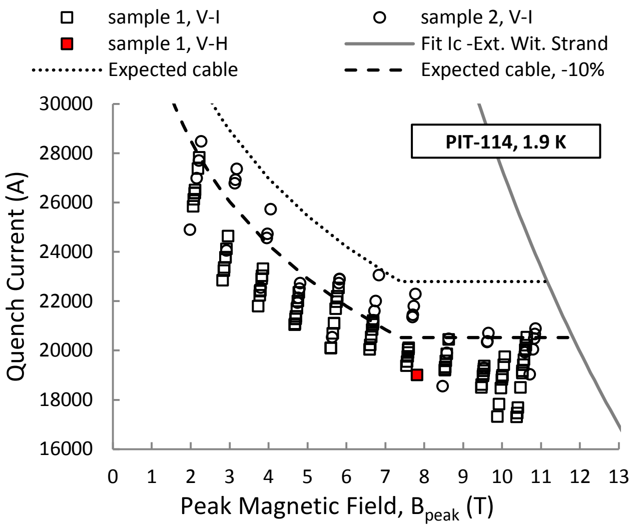

Fig. 5. Quench current versus peak magnetic field for the PIT-114 cable sample results at 1.9 K. The critical current fit and expected cable quench current are based on strand test data multiplied by the number of strands. The ~10% reduction of the expected quench current is likely caused by reduced thermal conditions caused by the impregnation [8].

At 1.9 K the effect of the instabilities is more pronounced because the specific heat is lower and the critical current is higher, which increases the amount of energy in the re-distribution of transport current which causes self-field instability. In the figure the expected quench current of a strand in a cable is also indicated. This value is based on the strand measurements and it takes into account that a cable, which carries a certain current in a specific applied magnetic field, always experiences the entire magnetic field range from 0 T to the peak magnetic field B_{peak}.

B. *Cables*

The result of the critical and stability current measurements is summarized in Figs. 4 to 7. At 4.3 K and high magnetic field, when the cable is stable, the critical current of the PIT-114 (Fig. 4) and RRP-54/61 cables (Fig. 6) is in good agreement with the critical current of the single strand multiplied by the number of strands in the cable. In order to confirm that the peak magnetic field is the proper value that allows comparing strands and cable data, we successfully performed critical current measurements with different orientations of the cable sample with respect to the applied magnetic field [15]. With the applied magnetic field in the opposite direction there is a change in the peak field, both in amplitude and location within the cross section, the critical current value stays the same for the peak field value in both orientations.

At 1.9 K the test station cannot deliver a magnetic field high enough to reach the stable condition of the cable needed to determine the critical current, see Fig. 5 and Fig. 7 for the

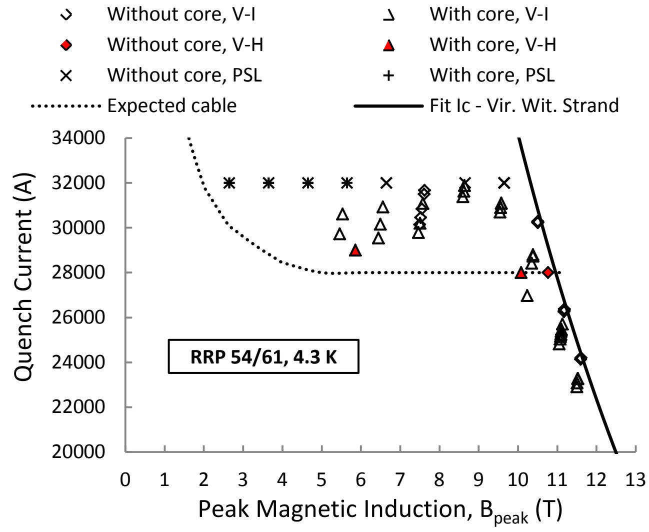

Fig. 6. Quench current versus peak magnetic field for the RRP-54/61 cable sample at 4.3 K. The critical current fit and the expected cable quench current are taken from the strand results multiplied by the number of strands.

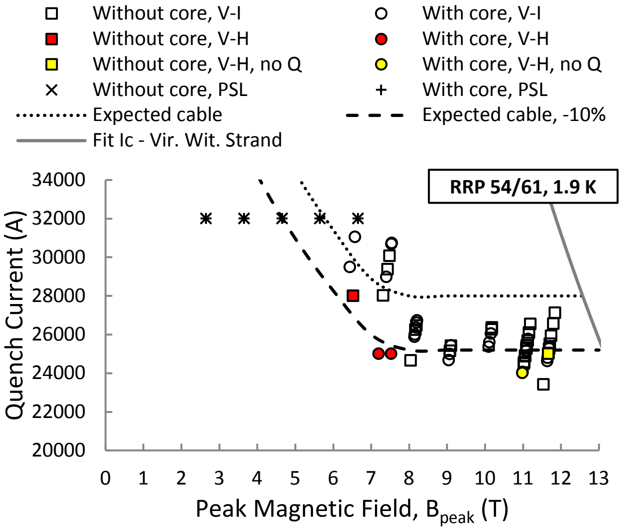

Fig. 7. Quench current versus peak magnetic field for the RRP 54/61 cable sample at 1.9 K. The critical current fit and the expected cable quench current are taken from the strand results multiplied by the number of strands. The ~10% reduction of the expected quench current may be caused by the impregnation as discussed in [8].

PIT-114 and RRP-54/61 cable samples, respectively.

At 4.3 K, the premature quench currents are in good qualitative agreement with the values measured in the strands (see Figs. 4 and 6). Furthermore, the premature quenches are not occurring in the high field region of the sample, indicating the local magnetic field at the quench is lower and could correspond to the most unstable field of the strand, ~2.5 T shown in Fig. 3.The length of cable in this unstable field is much longer when the high field region is at this field than when this field is made within the gradient of the applied field. The stochastic nature of instability and the length of the sample at the most unstable field cause the quenches to be at lower current when at lower field, Fig. 4.

At 1.9 K, all samples are much more unstable and the premature quenches occur in the highest magnetic field region as well because of self-field instability. On cooling down from 4.3 to 1.9 K, the minimum value of the premature quench current reduces from 19 to 17 kA for the PIT cable and from 27 to 24 kA for the RRP cable.

The observed trend in the premature quench currents can be expected considering the strand measurements. Nevertheless, the cable quench currents are about 10% lower. This might be due to the worse cooling condition of the cable samples as they are epoxy impregnated while the strand samples are in direct contact with liquid helium. Indeed previous results on similar strands suggest that the worse heat transfer coefficient at 1.9 K affects the magneto-thermal instability [8]. They show that covering a wire with a thick layer of epoxy reduces the quench current by about 10% at 1.9 K, while at 4.3 K no difference was observed.

The lower premature quench currents of the PIT samples with respect to the RRP samples can be explained by the lower RRR and lower critical current of the PIT wire, a consequence of the not optimal billet. This effect is expected to disappear in the next PIT type 11 T cable. In any case, although the cables were quite unstable, the measurements show that instability would not limit the quench performance of the 11 T dipole magnet designed for a nominal current of 11.85 kA.

Concerning the Nb_3Sn cored cable, the first one tested in FRESCA, it can be concluded that its performance in terms of critical current and stability limited quench currents are qualitatively not significantly different from those of the un-cored RRP cable. Also, the core does not significantly affect the joint resistance. Both joints to the Nb-Ti current leads and the return joint show a resistance of less than 0.2 nΩ. Of course the cored cable shows much lower inter-strand coupling currents, results that will be presented in more detail elsewhere [16].

V. CONCLUSION

Four samples of PIT and RRP type of Nb_3Sn cables developed for a new 11 T magnet were measured in FRESCA at 1.9 and 4.3 K in applied magnetic field of up to 9.6 T (peak field in strand ~12 T). Tests of two identical PIT samples gave reproducible results.

The cable results were consistent in terms of critical and stability limited quench currents, with the strand data of extracted witness samples. In particular it was shown that: (1) the peak magnetic field is the proper value allowing comparing strand and cable data; (2) strand measurements can give a good estimate of the stability of cables.

Two similar samples based on the RRP-54/61 wire, one with a stainless steel strip core and one without core, showed that the core does not degrade the transport current property of the cable. The core also does not significantly affect the joint resistance.

At 1.9 K the cable samples were quite unstable and the samples never reached their critical current at the highest applied field the test setup can supply.

The measurements show that observed instability will not limit the quench performance of the 11 T dipole magnet.

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