Critical Current Measurements of High- J_c Nb₃Sn Rutherford Cables under Transverse Compression

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Abstract— For the LHC upgrade, CERN has launched a large program to develop next generation accelerator magnets based on high- J_c Nb₃Sn Rutherford cables. These magnets are characterized by a magnetic field and/or an aperture significantly larger than that of current Nb-Ti LHC magnets. The increased field/aperture will require coil pre-stresses much larger than 100 MPa. Since Nb₃Sn cables are extremely sensitive to strain, critical current measurements under traverse compression are essential to estimate the transport current properties of the conductor within the magnet. To this purpose CERN has developed a sample holder (to be used in the FRESKA test station) that allows testing Rutherford cables under a transverse force of up to 2 MN/m. The new holder can house cable samples up to 1.8 m long and 20 mm wide. The large transverse force is only applied over the sample high field region, which is 70 cm long and over which the FRESKA dipole magnet generates a homogeneous fields of up to 10 T. Recently the critical current of the first cable sample has been measured at different transversal loads ranging from 90 MPa to 155 MPa. The measurement was carried out at 4.3 K on a 10 mm wide Rutherford cable based on eighteen Powder In Tube (PIT) wires with a diameter of 1.0 mm. In this paper the results of the test are reported, discussed and compared with recently measured data of the same single wire (1.0 mm PIT) tested under transverse loads.

Index Terms—Critical current, Rutherford cables, Nb₃Sn, transversal pressure.

I. INTRODUCTION

IN THE FRAMEWORK of the High Luminosity upgrade (HiLumi) [1], CERN is developing next generation accelerator magnets [2] based on Nb₃Sn Rutherford cables [3]. These magnets will have a peak magnetic field and/or an aperture significantly larger than that of the Nb-Ti LHC magnets. That implies coil pre-stresses and transverse loads, which act on the wide face of the magnets' cables, larger than 100 MPa. Considering the brittleness of Nb₃Sn and the strong dependence of its critical current on the strain, these large mechanical loads are a concern for magnet designers. Some studies have shown that the critical current of Nb₃Sn cable under transversal load significantly degrades with a pressure in excess of 100 MPa. On the other hand, there are not much data in the literature on this subject [4]–[10] and some of the published results appear to be contradictory. Furthermore several Nb₃Sn magnets manufactured and tested during the

last years show that they can stand pre-stresses of up to 150 MPa. The lack of accurate cable measurements under transverse pressure is most likely due to the fact that: 1) there are only two test stations worldwide (at Twente University, The Netherlands – at the National High Magnetic Field Laboratory, Florida, USA) capable of measuring superconducting Rutherford cables under high transverse compression (> 100 MPa) and; 2) in these stations the load can be applied on a limited sample length (approximately 5 cm at Twente [4] and 12 cm at NHMFL [5], [6]). Beside these two test stations, at Fermilab it has been developed a device that allow measuring the critical current of one superconducting wire housed in a dummy copper cable under transverse compression [9]. Also in this case the sample has a length of few centimeters (less than 6 cm).

In order to assess the performance of the cables in conditions as close as possible to the ones experienced by the conductor in the magnet, CERN has developed and manufactured a sample holder to test cables in FRESKA [11] under transverse forces of up to 2 MN/m. The new holder can house cable samples up to 1.8 m long and 20 mm wide. The large transverse force is applied over 70 cm in the region where the FRESKA dipole magnet applies a homogeneous fields of up to 10 T. Recently the critical current of the first cable sample has been measured at different transversal pressure ranging from 90 MPa to 155 MPa. The measurement was carried out at 4.3 K on a 10-mm-wide Rutherford cable based on eighteen Powder In Tube (PIT) wires with a diameter of 1.0 mm. In this paper the main characteristics of the new sample holder and the results of the first cable test are presented and discussed.

II. A NEW SAMPLE HOLDER FOR FRESKA

The new sample holder is based on the conceptual design described in an earlier paper [12]. This design consisted in an external Al 7075 tube that houses two Ti6Al4V pads, a Ti6Al4V 'U-cage', 2 stainless steel keys and a cable sample, see Fig. 1a. At room temperature a bladder [13] is inserted between the lower pad and the U-cage and it is inflated with pressurized water in order to push the two pads towards the Al tube and to exercise a transversal pressure on the cable stack. Once the required pressure is reached the keys are inserted; they will maintain a certain pressure when the bladder is depressurized and removed. Additional pressure on the cable stack is applied during the cool down of the sample holder thanks to the differential thermal contraction between the Al 7075 and the Ti6Al4V [12]. For example, a 10-mm-wide Al

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Fig. 1. Drawings of the new FRESKA Sample Holder for cable's critical current measurements under transversal pressure: a) cross section of the high-pressure region; (b) axonometric projection of the whole assembly

bar that substitutes the cable stack and is compressed with 55 MPa at room temperature would experience 200 MPa at 4.2 K [12]. The conceptual design was implemented in the final sample holder by building: a 2-m-long U-cage, two Al 7075 tubes (30 and 40 cm long respectively), two 36-cm-long Ti6Al4V upper pads, two Ti6Al4V lower pads (30 and 40 cm long respectively), a 70-cm-long, 2.5-cm-wide bladder and twelve 316LN 11.65-cm-long keys. Ideally the pads and the high pressure tube should have been 70 cm long, which is the length of the cable that we want to compress; nevertheless, due to the required tight tolerances (about 20 μm), it was decided to manufacture pieces 40 cm long. In the high-pressure region the different pieces were assembled in such a way that the discontinuity between two pieces of a certain type (for example two lower pads) was not in the same plane as the discontinuity of two pieces of another type (for example the two upper pads), see Fig. 1b. In the low pressure/field region the holder is constituted by three Al 7075 tubes: two made of a single piece (see Fig. 1b) and one built in two halves connected by not magnetic screws (see Fig. 1b). These three tubes provide a minimal compression (30-50 MPa) on the cable stack through to a series of not magnetic screws that push to the bottom of the U-cage. This compression is applied to prevent premature quenches induced by cable motion.

To assess the compression on the cable stack at room and cryogenic temperatures, twelve strain gauges were installed in pair on the inner walls of the high-pressure tubes (see Fig. 1a). Each pair measures the strain along the length of the sample holder and along the direction of the applied pressure. The gages were placed in such a way as to monitor the center of the high-pressure region and its extremities. All gages are 3 cm far from the ends of the tubes: eight on the 40 cm tube and four on the 30 cm tube.

III. MEASUREMENTS

The first cable sample tested in the new holder was a rectangular eighteen-strand Rutherford cable based on the 1 mm Nb₃Sn PIT [14]. The main characteristics of the cable

TABLE I
CABLE PROPERTIES

Copper to non-copper (adim.)	1.22
Twist Pitch, (mm)	63
Width, (mm)	10
Mid Thickness, (mm)	1.81
Keystone Angle (degrees)	0

are summarized in Table I. The sample is constituted by: two 1.8 m long active cables that carry the current, two dummy cables that sandwich the active cables, and a Ti6Al4V bar, 3 mm thick, which lays on one of the dummy cable, see Fig. 1a. The dummy cables are also rectangular Nb₃Sn Rutherford cables 10 mm wide, but they are based on the 1.25 mm PIT wire and are constituted of fourteen strands. The role of the dummy cables is to recreate boundary conditions for the active cables that are similar to those experienced in the magnet. The Ti6Al4V bar on the top of the sample stack softens potential stress concentrations on the cables possibly caused by the discontinuities in the upper Ti6Al4V pads.

The different components of the sample stack are separated by fiberglass braid and the sample is vacuum impregnated with epoxy resin. The two active cables are spliced together in the bottom (along 15 cm) while on the top they are each connected to a Nb-Ti cable (along 20 cm). The Nb-Ti cable is connected to the current leads of the FRESKA insert.

The test consisted in measuring the critical current of the cable at 4.3 K and four different transversal pressures. At first the measurement was carried out at the lowest transversal load and then the sample was warmed up, loaded with a larger pressure, cooled down and measured again. The first test was carried out with a minimal transversal pressure in order to have a limited effect of the induced strain on the quench performance. Then three additional tests were performed with increasing keys height: + 60 μm , + 150 μm and + 240 μm . The keys dimensions were changed employing stainless steel foils as shims. In these four tests the reading of the signals from the strain gauges presented problems at 4.3 K, for this reason a fifth test was performed, using the same keys dimension as the fourth test (+ 240 μm), once the gage DAQ system was substituted.

Fig. 2. Transversal pressure acting on the cable stack at room temperature during the five different tests. The pressure is estimated in 6 different location by using the gages that monitor the strain on the Al tubes.

A. Assessing the pressure on the cable sample

At Room Temperature (RT) the compression on the cable stack P_c can be applied either by the bladder or by the keys. When the compression is given by the bladder, P_c is calculated as the pressure of the bladder P_b times the ratio R between the active width of the bladder (2.3 cm) and the width of the cable stack (1.0 cm). The active bladder width was estimated by means of the imprint left by the pressurized bladder on a Fuji film inserted between the bladder and the U-cage.

The compression applied by the keys on the cable at room temperature was estimated through the strain gauges mounted on the Al shell. Before inserting and after removing the keys, the strain on the transversal direction ϵ_t was measured for different values of the bladder pressure; in all cases, for a pressure larger than 50 bars, we found a linear relationship between P_b (or $P_c = R P_b$) and ϵ_t . By using this relationship and the value of the transversal strain applied by the keys ϵ_{t_Keys} , we derived the pressure on the cable due to the keys P_{c_Keys} . It was found that at room temperature P_{c_Keys} was lower after a thermo-cycle (RT - 4.3 K - RT), see Fig. 2. That was attributed to the yielding of the cable stack when pressurized during the cool down at 4.3 K. By using a 2 D FEM mechanical model, which is in good agreement with experimental data, we could estimate: 1) the value of the interference between the keys and the U-cage that corresponds to the pressure on the cable at RT and; 2) the reduction of the cable stack height due to the yielding. During the first cool down, the reduction of the cable stack was estimated at about 5 μ m. In Fig. 2 one can also notice that: 1) for the first test there are no data in points 5 and 6 after the thermo-cycle (because we realized later the relevance of taking strain data after the thermo-cycle); 2) starting from the third test we lost some of the strain gages.

The compression at 4.3 K was estimated with the FEM model and the interference calculated taking into account the strain gages data collected at RT after the thermo-cycle (in order to take in to account the yielding of the cable). Because the strain gages were not properly working at 4.3 K during the first four tests, we could not directly cross check our calculation with experimental data. Nevertheless, the reliability of the FEM mechanical model in simulating the cryogenic conditions was demonstrated by the fifth test that

Fig. 3. Transversal pressure acting on the cable stack at 4.3 K during the five different tests. The pressure is estimated in 6 different location by using the strain measured on the Al tube at room temperature after a thermo-cycle. In the fifth test the gages 3 and 4 were properly working at 4.3 K, hence there the pressure is also derived from the strain data at cold.

showed a good agreement between the model and the experimental data. Fig. 3 summarizes the pressure values at 4.3 K on the cable stack estimated by using the different strain gages. During the fifth test we had the gages 3 and 4 that were properly measuring the strain at 4.3 K; from Fig. 3 one can see that deriving the pressure on the cable by using the RT or the 4.3 K strain data practically produces the same result.

B. Critical Current Measurements Results

The first four assemblies were followed by critical current measurements in FRESKA. Because the voltage signal was too noisy, the critical current could not be properly determined. For this reason, in the rest of the paper we will report about the quench current values. Nevertheless, considering the results obtained, the quench current did not differ more than 2 % from the critical current. The four tests used the same measurement plan. Initially the applied field was set at 9 T and the current was ramped to quench several times in order to train the sample. During the first test, it took seven quenches to train the sample, while for all the other tests there was no training. Afterwards the quench current was measured with an applied field of 9.6 T and 10 T. Finally the measurements were carried out with lower applied fields: 8.5, 8, 7, 6 and 4.5 T. At each field the quench current was measured by applying different ramp rates ranging from 300 A/s to 20 A/s; the different ramp rates did not have any influence on the quench current values. In all the cases the quench started in the high field region of the sample, at the same time in both cables. Fig. 4 summarizes the results of the measurements performed in FRESKA as a function of the peak field on the conductor. This field was calculated as the sum of the applied field and the self-field contribution, which was estimated at 1.17 T per 10 kA on the cable sample. The self-field contribution was calculated with a FEM magnetic model. In Fig. 4, the line represents the cable expected critical current estimated from the strand short samples that were reacted with the cable sample. The short samples consisted of two round wires about 1.5 m long that were wound, reacted and tested on two Ti6Al4V ITER barrels. These wires were coming from the same billet used for manufacturing the cable samples. Comparing the expected critical current and the quench current during the first test, one can conclude that: 1)

Fig. 4. Quench current of the cable for different transversal pressures.

the critical current degradation due to cabling is negligible for this cable (less than 2 %); 2) a transversal compression of 90 MPa has a limited impact on the quench performances. When increasing the pressure above 100 MPa the reduction of the quench current starts to get significant. It is interesting to notice that at larger fields, the reduction of the quench current is more important, see Fig. 5. In the strain region where the superconducting properties are reversible, the strain has a strong impact on the upper critical field and that is the reason of the stronger reduction of the critical current at larger fields. By fitting the quench current data with the classical scaling law of the critical current as a function of the field: $I_c = C b^{-0.5} (1-b)^2$ where $b = B/B_{c2}$ and C , B_{c2} are the fitting parameters, we obtain that B_{c2} significantly reduces when increasing the transversal pressure while C is practically constant. This behavior suggests that the critical current reduction is dominated by the reversible strain on the superconductor (and not by cracks). Similar results can be found analyzing the critical current measurements under transversal pressure of an impregnated single 1.25 mm PIT strand [17]. These measurements were carried out at the University of Geneva, where recently the same type of measurement was repeated on the wire used in our cable sample [18]. Also in this case the transverse pressure mainly affects the B_{c2} while the C parameter practically does not change. Fig. 6 summarizes the dependence of the B_{c2} from the transversal pressure for the tested cable and for a 1 mm PIT (the same wire used for the cable).

IV. CONCLUSION

A new sample holder for testing cables in FRESKA under large transverse pressure was designed and manufactured at CERN. The new device can house cable stack up to 20 mm wide, 13 mm height and can apply a transversal load on the sample of up to 2 MN/m. The load is uniformly applied over the 70 cm long region where the FRESKA dipole magnet generates homogeneous fields of up to 10 T.

Recently the critical current of the first cable sample has been successfully measured at different transversal pressures ranging from 90 MPa to 155 MPa. The measurement was carried out at 4.3 K on a 10 mm wide Rutherford cable based

Fig. 5. Ratio between the cable quench current and the cable critical current as estimated from the strand short sample.

Fig. 6. Upper critical field at 4.2 K estimated from the critical current measurements under transversal pressure.

on eighteen 1 mm Nb₃Sn Powder In Tube (PIT) wires. The tests showed that a transverse pressure of 90 MPa has a limited effect on the cable performance while for larger pressures the strain effect becomes significant especially at high fields. With a peak field of about 11.6 T and a transversal load of approximately 155 MPa, the quench current has a reduction of 24 %. In the analyzed pressure range, the effect of the transversal load is strongly dependent on the peak field suggesting that the critical current reduction is dominated by the reversible strain on the superconductor.

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