Critical Current and Stability of High- J_c Nb_3Sn Rutherford Cables for Accelerator Magnets

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Abstract—In the framework of future LHC upgrades using Nb_3Sn magnets, supported in part by the US LHC Accelerator Research Program (LARP) and the European EuCARD program, CERN is intensifying its research on Nb_3Sn Rutherford cables. In the FRESKA cable test facility at CERN, two new Nb_3Sn cable samples were investigated concerning their quench and critical current as well as stability performance. The two samples are based on RRP type strands with comparable layout. They have 27 strands with 0.7 mm diameter while the strands have 54 or 108 superconducting sub-elements. The cables are 10 mm wide and have a transposition pitch of about 75 mm. The cables are used in magnets built for LARP. Their performance is measured as a function of magnetic field up to 10 T with ramp rates of 10 to 1000 A/s and temperature of 1.9 and 4.3 K. A hall probe array is present to study the current distribution. Point heaters are used to study cable stability and current redistribution.

Index Terms— Nb_3Sn , Rutherford cable, stability.

I. INTRODUCTION AND SAMPLES

TWO major challenges in Nb_3Sn magnet design are critical current (I_c) degradation and stability of the conductor. At CERN there is a continuous effort to measure and study both phenomena and for this the existing infrastructure [1] is upgraded to accommodate Nb_3Sn type Rutherford cables. In this paper the latest developments and two cable tests are presented.

Two samples are tested: the LARP 982 and LARP 983 cables [2]. The cables are identical aside from the strand, average sized 10 mm $\times$ 1.27 mm and have a keystone angle of about 1 degree. Each cable has 27 strands with diameter of 0.7 mm and a transposition pitch of 75 mm. The 983 cable has a 54/61 restacked rod process wire with a Cu/non-Cu ratio of 0.87. The 982 cable is made from a 108/127 RRP strand with a Cu/non-Cu ratio of 1.17. Results of witness samples tested before are reported in [3]. The heat treatment is done in three steps: 200°C for 72 hrs; 400°C for 48 hrs and 640°C for 48 hrs, with ramps of 50°C per hour, which results in a high RRR (>200) for both samples. Both cable types are assembled in two separate samples, which were tested one after the other.

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Fig. 1. Schematic of the sample hairpin, sizes are in mm. The vertical black lines indicate the location of the voltage taps.

Fig. 2. Cross section of the sample holder. From coarsest to finest hatching: stainless steel, G10 and Nb_3Sn cable. The ss plates are clamped to fix the sample. The applied magnetic field directions are indicated assuming current flow towards paper in the top cable and vice versa for the bottom cable.

II. EXPERIMENTAL METHODS

The tests are performed in FRESKA [1], a test station that can provide a magnetic field up to 10 tesla, with 1% field homogeneity along 500 mm in 4 directions perpendicular to the sample length. The test temperature can be 4.3 or 1.9 K.

The sample is in a hairpin configuration, see Fig. 1. The sample preparation is explained in [4]. The Nb_3Sn cables are soldered before the impregnation. To accommodate the instrumentation, the samples are prepared without any type of glass fiber wrap around the cables and unloaded epoxy. After the impregnation the resin is carefully removed locally to make the solder connection to the Nb-Ti cables.

The sample holder consists of a stainless steel collar compressing two stainless steel plates with bolts. Between the plates is the cable sample surrounded by G10 spacers. The transversal pressure on the cable is ~ 40 MPa. Two channels facilitate helium flow and provide space for instrumentation wiring (see Fig. 2). A thin and flexible printed circuit on polyimide foil is in contact with both wide sides of the cables to read the voltage at key positions (see Fig. 11) without soldered connections.

To test the minimum quench energy of the cable, graphite paste point heaters are applied. The design evolved from a previous one [5]. The heaters are based on a 50 μ m thick adhesive polyimide foil perforated with 0.5 mm diameter holes at

Fig. 3. Cross section of a graphite paste heater. Black is the cable, white is polyimide tape, light grey is copper and dark grey is graphite paste.

Fig. 4. Placement and naming of the heaters on the cable. There are 3 heaters on five different strands. The heaters are always labeled by strand name and then the position i.e. HC2 is the center heater on the center strand.

the desired heater locations. 25 μm thick copper paths on the foil are connected to the power supply. The foil is glued to the broad side of the cable and then the holes are filled with graphite loaded epoxy. This closes the circuit between the copper paths and the cable (see Fig. 3). Additional layers of polyimide foil are glued on top for protection of the heaters and to ensure a uniform pressure distribution on the cable.

The heaters are placed in the center and edges of the cable. Five neighboring strands get 3 point heaters each, see Fig. 4. This distribution makes it possible to compare several strands and the effect of the keystone in the edges.

To be able to draw any valid conclusions from the quench energy measurements, the current distribution in the cable must be known. Since there are two more cable splices in the sample there is a higher chance of inhomogeneous current distributions. For this purpose the self field distribution of the sample is measured with a Hall probe array (HPA), consisting of 26 Hall elements placed over 93 mm, which was validated before on Nb-Ti cables [5]. The HPA is placed along the cable length next to the short edge of the cable, where the letters A-E are located in Fig. 4. It measures the local self field and is calibrated to the current density in the cable using very fast ramps forcing a homogeneous current flow.

III. RESULTS

A. Training and Transport Current Performance

Both samples required at least 30 training quenches to reach the critical current. The training was done at 4.3 K in a background field in the c-direction, which results in the highest peak field and forces in the conductor. The current is ramped up until the cable quenches. This is repeated until there is sufficient voltage build up to extrapolate the critical current and the cable quenches at the same current each run. The 982 cable needed 38 quenches from 8.9 to 15.3 kA in a background field of 9 T, and cable 983 needed 33 quenches from 5.3 to 15.3 kA with a background field of 9.6 T. After the first training, the cable remains stable and continues to reach the critical current (I_c). This ensures that the following discussion is not effected by quenches originating from conductor motion. Earlier a sample of the 983

Fig. 5. Quench/critical current versus peak magnetic field of the LARP 983 cable. Round markers are I_c values. The triangles are premature quenches. All closed symbols are at 4.3 K and the open symbols are at 1.9 K. Black lines are for the virgin strands at 4.3 K (solid) and 1.9 K (dashed).

Fig. 6. Quench/critical current versus peak magnetic field of the LARP 982 cable. Round symbols are I_c values. The triangles are premature quenches. All closed symbols are at 4.3 K and the open symbols are at 1.9 K. Black lines are for the extracted strands at 4.3 K (solid) and 1.8 K (dashed).

cable with glass fiber wrap was impregnated inside the sample holder [6] by FERMI lab and also tested in FRESKA [7]. This sample required only 9 quenches from 12.0 to 15.9 kA to reach I_c in a background field of 9.6 T. This is a good example of how cable insulation and fixation can affect the training curve of a cable sample.

After having completed the training of the sample, the I_c is measured across the full range of the applied magnetic field, unless there is a premature quench in which case the quench current is recorded, see Fig. 5 and Fig. 6. In case of a premature quench, the measurement is repeated at least 3 times and the maximum value is plotted. In the figures the cables are compared to their respective strands. The round symbols give the I_c values, the triangles represent the quench currents, open symbols are points at 1.9 K, closed symbols are measured at 4.3 K and the lines denote the strand results. The strand results are multiplied by the number of strands in the cable. All current values are plotted versus the calculated peak field in the strand and cable cross section at that current to facilitate the comparison between strand and cable. The peak field was chosen because it is the most relevant factor in the I_c measurement.

In Fig. 5 the 983 cable performance is compared to the round, uncabled so-called virgin strand. The cable has 6% less I_c compared to the virgin strand, which is the same as found in the magnet tests [3]; this is due to the expected degradation from

the cabling of the strands. The cable is also much less stable than the strand. At 4.3 K the cable is only able to reach its critical current above peak fields of 10 T, at 1.9 K the cable has premature quenches over the entire measurable range.

The 982 cable (Fig. 6) can be directly compared to an extracted strand and shows no additional degradation in critical current. This cable was stable over the entire measurable range at 4.3 K, at 7 T peak field the power supply limit is reached and no further data could be taken. When the temperature was decreased to 1.9 K, there is the expected increase in critical current, but the cable also becomes unstable below approximately 10 T. The performance of the cable drops below the 4.3 K performance at peak fields lower than 8.5 T.

When the two cables are compared, it is noted that Cable 983 has a higher I_c than 982. This is due to the lower Cu/non-Cu ratio in the first one. This advantage is negated when the cables are cooled down to 1.9 K where the instabilities in the 983 cable make the performance drop well under the level reached by the 982. The increased stability in the 108/127 strand and 982 cable is mostly due to increased copper content as well as the reduced filament size.

The quench currents of cable and strand of the 983 cable at 1.9 K seem to follow the trend predicted in the self-field stability model discussed in [8]. This model predicts a stability curve, the minimum quench current due to self field instabilities, as a function of magnetic field in the conductor and three magnetic field regions where the conductor stability is different. At low magnetic field, the quench current follows the stability curve while at high magnetic field the conductor is stable and can reach its I_c . At intermediate magnetic field the quench current falls between the I_c and the minimum stable current. The two magnetic field values at which the transition between the regimes takes place strongly depend on the level of perturbations that initiates the instability (e.g. strand micro-motion). A good example of the stability regimes is the performance at 1.9 K of the virgin witness sample of the 983 cable (the dashed line seen in Fig. 5). At low magnetic field the quench current follows the minimum quench current curve up to about 8 T. Then there is an intermediate magnetic field regime where the quench current starts to approach the I_c up to 10.5 T where it finally reaches the critical current.

When this model is used to evaluate the cables there are some interesting results; at 1.9 K, the 983 cable, see open triangles in Fig. 5, and its strand follow the same curve at low field. However, the cable fails to recover at high field, presumably due to larger perturbations acting on the cable than on the strand. This means that it is possible to estimate the worst case performance of the cable by extrapolating the unstable behavior of the strand. At 4.3 K the 983 cable is stable at high magnetic field, followed by the intermediate stability region below 10 T. The strand is stable up to the point where it is limited by low-field instabilities, so it is not possible to compare the strand and the cable.

The 982 cable sample itself is much more stable and so there is nothing to compare. However, when both cables are compared, it is found that between 5 and 7 T peak magnetic field, both cables follow the same curve even though they have a different critical current, as predicted by [8].

Fig. 7. Maximum and minimum local current density at 9 T versus time, for varying transport current. At 9 T the quench current is 15.3 kA and the critical current is 15.0 kA.

B. Current Redistribution

Because there are two extra joints in the hairpin sample, the current redistribution is checked as a function of time. The sample is ramped at 300 A/s to a current plateau and the current distribution is measured for 100 s and then the current is ramped up to a quench. This is repeated at several current plateaus in the same background magnetic field.

For a comprehensible plot all values are normalized to the transport current and the maximum and minimum values are shown in Fig. 7. It is interesting to see that the spread in the self field is 4% maximum. The spread is lowest at the lowest current plateau and then starts to increase when current increases. When the quench current is almost reached, the spread starts to decrease again. Overall it seems that there is only a small distribution in self field, indicating a small spread in transport current over the strands.

C. Quench Energy Measurements

The Quench energy of the 982 cable is measured using the point heaters. The current is ramped up at 300 A/s to a plateau at which a heat pulse is triggered in one of the heaters. This results in either a quench of the cable or not. If not the current is ramped up to the quench current to reset the experiment. This measurement is repeated at different pulse energies until the lowest quench energy and the highest no-quench energy are within 5% of their average. The pulse is a 100 μ s long square wave. Voltage and current of the pulse is measured and integrated to calculate the pulse energy. The ratio of heat deposited in the sample and the surroundings is not precisely known, but previous versions reached .5 to .6 [9]. This ratio is called the heater efficiency. A thermal model and new measurements are planned to find a good estimate of the heater efficiency. The efficiency of the heaters might change over the range of the experiment. It is important to note that all data presented here is still untreated energy data and thus reflect the amount of heat added to the heater and not the heat deposited in the cable.

The results of several measurements are pictured in Fig. 8. Most basic is the measurement in the center of the cable at 4.3 K (dark grey symbols). The curve follows the single strand behavior at high current and around 8 kA ($I/I_c = 0.4$) the transport current is low enough to let the cable redistribute the current

Fig. 8. Quench Energy versus current in the center and at the edge of the 982 cable. Icons are labeled by bath temperature in kelvin, applied magnetic field in tesla and field direction. The cable I_c is 15.0 kA in the c direction and 19.5 kA in the d direction. The inset illustrates the field distribution in the cable cross section at the experiment, the black square is the heater.

around the quenched strand. This sudden change in behavior results in the transition point shown in the graph called the “kink”. As is shown in [9] the efficiency can increase at lower currents, which would make the gradient at low current steeper. The 4 working heaters placed on in the center of the cable yielded within 15% the same results in the single strand regime. This indicates a homogeneous current distribution in the strands, similar heater properties and homogeneous conductor properties. The measurement is repeated in two opposing field directions. This yields almost identical results even though there is a 30% difference in critical current of the total cable. The difference in sample I_c is present due to the self-field adding up or subtracting from the applied magnetic field. Because the self field is highest in between the two cables of the sample and nearly zero at the outside of the sample stack (where the heaters are located), it is to be expected that there is very little effect on the local I_c where the heaters are located. This shows that the QE curve depends mostly on local effects and not on properties at the other side of the cable stack. Only when the current reaches $>80\%$ of the I_c the measurement in the c direction starts to deviate from the measurements in the d direction. Here the other side of the cable is so close to I_c that the cable quenches due to the small heat leak into the high field region of the cable cross section before the heater can quench the strand it is attached to.

Such stability measurements have been done extensively on Nb-Ti cables; see the survey in [10]. The kink in the curve is at much lower I/I_c in this cable (~ 0.4) than what is observed in Nb-Ti cables (> 0.7). Note that the I_c -training of this cable is done at the same field and that the training starting above kink current at the point where the stability suddenly drops.

The next measurement is the heater at the edge of the cable (light grey symbols). Here the QE is lower at currents above the kink. Interestingly, the kink is at the same position as for the center heater and for currents lower than the kink the QE is similar to the center heater. This is unlike previous work done on Nb-Ti [11], where it was shown that the single strand behavior was the same, but the kink in the QE curve shifts.

Finally, the Quench Energy is measured at 1.9 K. There is only a small gain in QE by reducing the temperature from 4.3 to 1.9 K. The temperature margin to the transition to the normal state might increase, but the increase in enthalpy is negligible due to the much reduced heat capacity of the strand.

IV. CONCLUSION

It is shown that self field instability in a cable can be correlated to the strand behavior. It will not predict the exact behavior but can provide a minimum stability curve. Sample preparation and mechanical fixation determine the regime where the cable can rise above this curve.

It is found that the scaled critical current at which the kink appears in the Quench Energy curve is much lower than for Nb-Ti cables. This is most likely due to the reduced level of cooling in impregnated cables.

The Quench Energy in the edge strands of the cable is lower than in the center of the cable for currents above the kink. This can be explained by critical current degradation in the edge strands of the cable. However, there is no change in the position of the kink.

Further investigation of the Minimum Quench Energy in relation to cable insulation and fixation to reduce training is crucial for Nb₃Sn accelerator magnet development, since the presently too long training sequences have to be reduced.

An improved method of cable impregnation and interfacing to neighbors can help to improve Nb₃Sn cable stability by shifting the intermediate regime further towards lower field, thus improving the cable performance at low field.

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