Development of the Nb₃Sn Rutherford Cable for the EuCARD High Field Dipole Magnet FRESCA2

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Abstract

This paper reports on the development of the Nb₃Sn Rutherford cable for the EuCARD high field dipole magnet FRESCA2 designed to achieve a central field of 13 T at 4.2 K in a 100 mm bore. The FRESCA2 cable is rectangular and made of 40 strands of 1.0 mm diameter. The cable shall be able to carry a current of 15.7 kA at 4.2 K in a field of 15 T. In the first stage of cable development, focus was put on the cable parameters (cable width, cable mid-thickness and pitch length) to provide a cable made with Nb₃Sn PIT strands achieving both a minimal critical current reduction of the strand during cabling and a good mechanical stability of the cable for coil winding. In the second stage of cable development, the cable was produced with Nb₃Sn RRP strands. The cables, which were produced following an iterative process, were characterized and the results of the critical current measurements of extracted strands are discussed together with the cabling parameters and the type of strand.

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Index Terms—Nb₃Sn, Rutherford cable, Accelerator magnet, Critical current degradation.

I. INTRODUCTION

During the last two years, CERN has been developing the Nb₃Sn Rutherford cable for the dipole magnet FRESCA2 [1]. This paper reports on the development process and on the experience gained during the cabling of both PIT and RRP strands for the FRESCA2 cable.

II. FRESCA2 CABLE DESIGN

The Nb₃Sn cable for the FRESCA2 high field dipole magnet is a rectangular Rutherford cable made of 40 strands of 1.0 mm diameter. A typical cross-section is shown in Fig. 1. Cabling strands into a Rutherford cable inevitably results in large deformation of the strands near the edge of the cable, causing severe distortions of the sub-elements inside the Nb₃Sn strands. To minimize the deformations of all the strands in the cable, the width of the cable was initially fixed at 21.4 mm independently of its thickness set at 1.82 mm and the pitch length was set at 160 mm. The width of the cable was defined with the formula $Nd/(2\cos(PA)) + 0.72d$, in which N is the number of strands in the cable, d is the strand diameter and PA is the pitch

angle in the cable. This formula [2] gives a good target value to estimate the width of the cable in order to limit the compaction of the strands at both edges of the cable.

Fig. 1. Typical cross-section of the FRESCA2 cable made of 40 strands of 1.0 mm diameter.

The thickness of the cable was fixed at 1.82 mm corresponding to a thickness deformation of 0.09, given by $1 - t/2d$ in which t is the thickness of the cable. Table I gives the parameters of the FRESCA2 cable tried during cable development. For the width originally fixed to 21.4 mm and for the width of 20.9 mm chosen at the end of the cable development process, the parameters of the cable are given for two values of the pitch angle.

TABLE I
Parameters of the FRESCA2 Cable tried during cable development

Cable width	Thickness	Pitch length	Pitch Angle	Overall compaction
22.0 mm	1.82 mm	120 mm	20.1°	83.6%
21.4 mm	1.82 mm	160 mm	15.0°	84.3%
21.4 mm	1.82 mm	120 mm	19.6°	85.6%
20.9 mm	1.82 mm	120 mm	19.2°	87.5%
20.9 mm	1.82 mm	140 mm	16.6°	86.2%
20.4 mm	1.81 mm	120 mm	18.8°	89.9%
20.4 mm	1.86 mm	120 mm	18.8°	87.5%

III. FIRST STAGE OF THE CABLE DEVELOPMENT WITH PIT STRANDS

In the first stage of the cable development, focus was put mainly on the parameters to provide a cable mechanically stable for coil winding and to assure a minimum critical current degradation due to cabling. During the first stage CERN made cables with four different widths using only ethanol as lubricant. These cables were made with Powder In Tube (PIT) strands fabricated by Bruker-EAS. The PIT strand used to fabricate all the cables of the first stage of the cable development has 192 sub-elements of approximately 48 μm in diameter. The first cable was fabricated with a width of 21.4 mm. The pitch length was reduced from 160 mm to 120 mm to

close small gaps appearing between the strands in the middle of the cable and to obtain a cable that was mechanically stable. Metallographic observations showed that some strands had shear areas. Critical current measurements were performed on one virgin strand and on five extracted strands for the heat treatment schedule given in Table II. The extracted strands showed on average a reduction of 19% of their critical current in comparison to the virgin strands.

TABLE II
Heat Treatment Schedule

Cable	Heat treatment	Step 1	Step 2	Step 3
RRP	Temperature, °C	210	400	665
	Duration, h	48	48	50
PIT	Temperature, °C	620	650	
	Duration, h	120	90	

Following this result, a second cable was fabricated with a width of 22 mm in order to decrease the compaction of the strands at the edge of the cable. This cable which had a pitch length of 120 mm showed again gaps appearing between the strands, which were suppressed by a further reduction of the pitch length to 100 mm. Critical current measurements of virgin and extracted strands from this second cable fabricated with a pitch length of 120 mm show a significant increase of the degradation to 26%, at the opposite of what was expected as the width of the cable was increased with the aim to minimize the deformation of the strands at both edges of the cable. Metallographic observations at the edge of the cable showed that the shear regions of some strands are more extended as it can be seen in Fig.2.

Fig. 2. Cross-section at the edge of the 22.0 mm wide cable fabricated with PIT strands, with a thickness of 1.82 mm and with a pitch length of 120 mm.

Following this observation and considering the large increase of the critical current degradation, the next cables were fabricated with a width smaller than 21.4 mm. It could be expected that a small reduction of the width would release some of the shear stress by providing a better mutual support between neighbor's strands during their flattening in the Turks-head of the cabling machine.

A third cable was fabricated with a width of 20.9 mm and with a transposition length which was set either to 120 mm or to 140 mm. Both cables met all the quality surface requirements with no gaps between the strands. The critical current measurements of the strands extracted from the cable showed an average degradation of 15% for the pitch length of 120 mm and of 18.5% for the pitch length of 140 mm. These results suggested that the degradation could be further decreased by fabricating a cable narrower. Two cables were fabricated with a width of 20.4 mm, with the same pitch length of 120 mm but with a different thickness. Indeed, the average critical current degradation of the cable fabricated with a width of 20.4 mm stayed at 15% with a thickness of 1.81 mm but was reduced to 10% with a thickness of 1.86 mm. Metallographic observations of both edges of the cable show highly deformed strands but with limited distorted sub-elements in the three strands near the edge as it can be seen in Fig. 3. The high level of deformation of the three strands at the edges of the cable indicates that the strands are already too much compacted and therefore a further reduction of the cable width has not to be envisaged, even though the average degradation was reduced to 10% with the width of 20.4 mm.

Fig. 3. Cross-section at the edge of the 20.4 mm wide cable fabricated with PIT strands, with a thickness of 1.86 mm and with a pitch length of 120 mm.

Following these last results, the next cable was fabricated with a width of 20.9 mm, a pitch length of 120 mm and a slightly smaller width of the mandrel. This time, to improve strand wrap around the mandrel, vanishing oil (V4B NAPHTHA) was used as a lubricant on the part of the mandrel in contact with the strands. Critical current measurements of

virgin and extracted strands from the cable with a mid-thickness of 1.82 mm showed in average 9% reduction of the critical current value when the usual lubrication with ethanol was used and 5.5% reduction of critical current when oil was used. It is also interesting to point out that when the lubrication is done by oil the width of the distribution of the critical current values among the eight extracted strands measured to determine the critical current degradation due to cabling is characterized by a sigma of 1%, compared to a sigma of 2.8% when the lubrication is done by ethanol.

IV. SECOND STAGE OF CABLE DEVELOPMENT WITH RRP STRANDS

In the second stage of the cable development, two cables were fabricated with RRP strands fabricated by Oxford Superconducting Technology (OST). The RRP strand used for the fabrication of the two cables was a 132/169 restack which has sub-elements of approximately 58 μm in diameter. The cables were fabricated using either oil or buthanol as lubricant during cabling with a width of 20.9 mm, a transposition pitch length of 120 mm and a mid-thickness of 1.82 mm. Metallographic observations of the edge of both cables showed severe distortions of the sub-elements inside the three strands near the edge as it can be seen in the Fig. 4. The region noted with a circle show sub-elements that are highly strained by shear stress during cabling.

Fig. 4. Cross-section at the edge of the 20.9 mm wide cable fabricated with RRP strands using oil as lubricant, with a thickness of 1.82 mm and with a pitch length of 120 mm.

Despite these highly strained areas, the critical current measurements of the strands extracted from the cables fabricated either with oil or buthanol have shown an average degradation of only 4% for the standard heat treatment

schedule given in Table II. The width of the distribution of the critical current values among the extracted strands is characterized by a sigma of 1.4%. Following the successful fabrication of the cable with RRP strands by using buthanol as lubricant, a new 20.9 mm wide cable was fabricated with PIT strand by using the same lubricant. The critical current measurements of six PIT strands extracted from the cable have shown an average degradation of 7.8% to be compared to the value of 9% obtained when ethanol is used as lubricant and to the value of 5.5% when oil is used as lubricant. Cross-sectional photographs of the edge of the cable fabricated by using either ethanol, oil or buthanol are shown in Fig. 5. From these results, it can be concluded that buthanol gives better results than ethanol.

Fig. 5. Cross-sectional photographs of the 20.9 mm wide cable fabricated with PIT strands using either ethanol (left), oil (middle) or buthanol (right) as lubricant.

The PIT strands also seem to be less deformed for the cable fabricated using oil as lubricant compared to the cable fabricated with buthanol, which is not the case when a cable is fabricated with RRP strands as it can be seen in Fig. 6.

Fig. 6. Cross-sectional photographs of the cable fabricated with RRP strands using either oil (left) or buthanol (right) as lubricant.

V. CHARACTERIZATION OF THE CABLES BY V-H MEASUREMENTS

To guarantee that the FRESA2 cable is not limited in performance at low magnetic field because of magnetic instabilities, the stability current of the extracted strands was determined at 4.3 K from V-H measurements. V-H measurements are done by ramping to a fixed transport current

and sweeping the field up. If a quench was observed at low field, the current was decreased and the measurement repeated until no quench occurred during the magnetic field sweep.

V-H tests were performed on extracted strands from two cables fabricated with PIT strands. For each of the two cables, the PIT strands came from a different batch of strand. One cable was fabricated with a width of 21.4 mm using ethanol as lubricant and another cable was fabricated with a width of 20.9 mm using oil as lubricant. For the cable having a width of 21.4 mm, the RRR values of the extracted strands ranged from 31 to 39, caused by Sn leakages near the edge of the cable. Despite low RRR values, the stability current of the extracted strands was 1100 A. A much higher stability current, 1400 A, was measured on an extracted strand from the cable having a width of 20.9 mm for which the RRR value was around 120.

V-H tests were also performed at 4.3 K on extracted strands from the cable fabricated with RRP strands using oil as lubricant. The results obtained from the measurements of five extracted strands are shown in Fig. 7. The current in a strand of the FRESCA2 dipole magnet is also reported in this figure by the magnet load line.

Fig. 7. Critical current measurements (filled black markers for I_c data) and sweeping field measurements (open markers for B_q data) for RRP strands.

The stability current of the RRP extracted strands was 1050 A, a value more than two times higher than the value of current defined by the intersection of the magnet load line with the critical current line fitting the critical current values measured between 10 T and 12 T. The RRR values of the RRP extracted strands were ranging from 84 to 125. We have also observed during V-I measurements, that premature quenches started at or below 10 T for all the RRP extracted strands while for all the PIT extracted strands premature quenches started at 7 T. Better results could probably be obtained for the RRP strands by reducing the temperature of the step 3 of the heat treatment schedule to increase the RRR value of the RRP strands.

VI. CONCLUSION

Due to its large aspect ratio, it was challenging to make the FRESCA2 cable mechanically stable for winding and to have a reduction of the strand critical current due to cabling within acceptable range. The cable transposition pitch initially fixed to 160 mm was reduced to 120 mm to improve the mechanical stability of the cable. The width of the cable was optimized to minimize the strand critical current degradation during cabling. A strand critical current degradation due to cabling of 4-5% was achieved for a 20.9 mm wide cable fabricated, either with PIT or RRP strands, using oil as lubricant. V-H measurements have shown that the stability current measured on PIT or RRP extracted strands is quite high, which should not affect the FRESCA2 dipole performance according to our present knowledge and capability of modeling low magnetic field instabilities.

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REFERENCES

- [1] A. Milanese, M. Devaux, M. Durante, P. Manil, J-C. Perez, J-M. Riflet, G. de Rijk and F. Rondeaux, "Design of the EuCARD high field model dipole magnet FRESCA2", *Proceedings of the 22nd International Conference on Magnet Technology*, Vol. 22, no. 3, June 2012.
- [2] D.R. Dietderich and A. Godeke, "Nb₃Sn Performance and Potential in the U.S.A.-Wires and Cables", *Cryogenics*, Vol. 48, Issues 7-8, pp. 331-340, 2008.