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Specifications for conductors and proposed conductor configurations: Milestone M5.3

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MILESTONE REPORT

SPECIFICATIONS FOR CONDUCTORS AND PROPOSED CONDUCTOR CONFIGURATIONS

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Abstract:

This document summarises the specifications of a superconductor suitable to be used in a particle accelerator dipole magnet that can reach a field of 16 Tesla during regular operation. The document reports also on the conductor configuration. These specifications set the performance targets for industrial production requirements at large scale. The document motivates the specifications on one hand by taking a particular magnet baseline design as starting point and by considering the results of various conductor test campaigns carried out at partner institutes.

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Delivery Slip

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TABLE OF CONTENTS

1. INTRODUCTION

WP5 deals with the design and cost estimate of a superconducting dipole bending magnet for the FCC hadron collider (FCC-hh). Within WP5, task 5.5 provided scientific support to magnet designer for the characterization of the Nb_3Sn superconductor to be used in the EuroCirCol design study. Two main objectives were identified: 1) the definition of the reference superconductor for the design study and 2) the study of the effects of transverse loads on the superconducting properties of Nb_3Sn Rutherford cables.

The specifications of the Nb_3Sn superconductor to be used for developing 16 T magnets operating at 1.9 K are reported in Chapter 2. The conductor parameters defined there were used by the EuroCirCol collaboration to optimize the various magnet designs proposed.

The result of the study of the effects of transversal loads is reported in Chapter 3. These results, coming from an extensive campaign of measurements, allowed establishing how much Nb_3Sn Rutherford cables are affected by mechanical transverse loads and provide magnet designers a proper estimate of the margin of the magnet and the maximum transverse load that the conductor can stand before degrading irreversibly.

2. REFERENCE SUPERCONDUCTOR

Because of their high engineering critical current density and full transposition, only Rutherford cables were considered for the EuroCirCol design study. In particular, two different types of Nb_3Sn Rutherford cable were identified: an “high-field” cable and a “low field” one, both based on high J_c wires. The wire composing the high field cable is expected to have a Cu-to-non-Cu ratio around 1 (even if lower Cu-to-non-Cu ratios, down to 0.8, were considered explorable) and a wire diameter not larger than 1.1 mm in order to prevent self-field instabilities (although values up to 1.2 mm were considered explorable). For the “low field” cable, a wire with a Cu-to-non-Cu larger than 1.5 and a diameter equal to about 0.7 mm was advised.

Regarding the cable geometry, cables with no more than 40 strands were considered the most suitable although; up to 60 strands per cable could be considered by magnet designer to optimize the magnet cross-section. The cable can be produced either in rectangular shape or with a keystone angle. The keystone angle has to be sufficiently small to prevent a compaction c of the cable thin-edge, larger than 0.14 ($c = 1 - h/2d$; where h is the cable thin edge thickness and d the wire diameter). As a reference, a keystone angle not larger than 0.5° was suggested.

2.1. CRITICAL SURFACE

In order to properly calculate the limits and the margins of their magnets, magnet designers need an accurate critical surface of the superconductor to be used. In the literature [1]-[6], several scaling laws are available for describing the superconducting performance of Nb_3Sn wires. However, all of them show some limitation with respect to the temperature dependence of the superconducting properties. For the EuroCirCol design study, an accurate temperature dependence is mandatory because the magnets are expected to operate at 1.9 K and the wire manufacturer and most of the international laboratories can characterize the superconductor only at 4.2 K. Because of that, profiting of the critical current and magnetization measurements carried out at CERN for the HL-LHC conductor, a reference scaling law for state of the art high J_c Nb_3Sn wires was defined.

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1 - b)^2$$

$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$

Where: $t = \frac{T}{T_{c0}}$; $b = \frac{B_p}{B_{c2}(t)}$ with B_p peak field on the conductor

T_{c0}, B_{c20}, α, C_0 are fitting parameters computed from the analysis of measurements on the conductor. For a reasonable estimate of the critical current density of a round wire, magnet designers can assume the following parameters: $T_{c0} = 16\ K$, $B_{c20} = 29.38\ T$, $\alpha = 0.96$, $C_0 = 1.03*267845\ A/mm^2\ T$. The values for T_{c0}, B_{c20} and α were derived from measurements of the HL-LHC RRP conductor while the C_0 was set so to have a J_c *(16 T, 4.22 K)* equal to 1.03*1500 A/mm^2. A maximum critical current degradation of 3 % was assumed due to cabling. This scaling law and parameters were used to design all the different magnets.

2.2. SUMMARY OF CONDUCTOR SPECIFICATIONS

As anticipated, two different Nb_3Sn conductors are considered, one for the “high field” part of the coils, and another for the “low field” part of the coils. A summary of the conductor baseline specifications for the FCC 16 T dipole magnets is given in Table 1.

Because of the higher current density permitted by the operation of a lower field, the “lower field” conductor, once integrated in a magnet, needs more copper to be protected in case of a quench.

Table 1 - summary of “High Field Conductor” specifications

Parameter	*Value*	*Unit*
Minimum critical current density at 16 T, 4.22 K	1500	A/mm^2
Wire diameter (High-Field Conductor)	1.1	mm
Wire diameter (Low-Field Conductor)	0.7	mm
Maximum sub-element diameter	20	µm
Nominal copper to non copper ratio High-Field Conductor	0.8:1	
Nominal copper to non copper ratio Low-Field Conductor	2.0:1	
Wire twist pitch	19±3	mm
Wire twist direction	Right-handed screw	
Minimum RRR (after full treatment)	150	
Minimum *n-value** at 4.22 K and 16 T	30	
Maximum cable compaction *c***	0.14	

*The *n-value* is the slope of the Nb_3Sn wire voltage-current curve, at a given temperature and field, when plotted on a logarithmic scale.

** $c = 1 - h/2d$; where h is the cable thin edge thickness and d the wire diameter.

3. EFFECTS OF TRANSVERSE LOADS

The superconducting performance of Nb_3Sn wires are strongly dependent on the strain state of the material. In the case of applied axial strain, a compression equal to 0.3% can produce a reduction of the upper critical field B_{c2} of more than 10%. Such a B_{c2} reduction generates a decrease of the critical current at 12 T, 16 T and 19 T equal to about 20 %, 31 % and 44 % respectively. This means that the larger is the field, the larger is the effect of the strain on the critical current performance. In 2013 a Rutherford cable based on a 1 mm PIT Nb_3Sn wire was tested [7] under transverse load in the FRESCA test station at CERN; the results showed that the critical current reduces significantly when increasing the transverse pressure from 80 MPa to about 150 MPa, furthermore the data suggested that the I_c decrease was associated to a reversible reduction of the B_{c2} (about 10%). Measurements of the PIT wire under transverse load carried out at the University of Geneva in 2013-2014 [8], also showed a significant reversible reduction of the critical current and of the B_{c2} with the transverse load.

Because the goal of the EuroCirCol design study is to develop 16 T magnets that can operate with a sufficient margin and because the transverse load to be applied on the windings of these magnets is expected to be in the range of 200 MPa, the study of the transverse load effects immediately appeared as one of the main issue to deal with. For this reason, a campaign of cable and wire measurements under transverse load was set-up at CERN, University of Twente (UT) and Geneva Universities. The same cables were tested at UT and CERN to confirm the results and the wire used for manufacturing those cables were measured at the University of Geneva (UNIGE).

3.1. CABLE MEASUREMENTS

For this study it was used the same type of cable as the one tested at CERN in 2013: an 18-strands rectangular Rutherford cable based on a high-J_c 1 mm Nb_3Sn wire. This type of cable was manufactured by CERN in two variants: one using the 192 PIT wire and the other the 132/169 wire. These wires were procured for the FRESCA2 dipole project and the 18-strands cable was originally developed by CERN as a sub-cable of the FRESCA2 project to study its performance in Short Model Coils (SMC). This cable immediately appeared as the most suitable to our goals because it was: based on the wires that are presently the closest, for characteristics and performance, to the needs of the FCC project; already available at CERN and; already successfully tested (the PIT variant) under transverse loads in the FRESCA test station. The main questions we wanted to address with these tests were the following:

1) Reproducibility of the results obtained at CERN in 2013; both at CERN and in another set-up (UT).
2) Study the onset of the irreversible degradation.
3) Investigate whether or not the RRP conductor shows a similar behaviour to the PIT conductor and if it is more tolerant to transverse loads.

Four cable samples were prepared at CERN (and four at UT): two based on the PIT wire and two on the RRP wire. The four samples prepared by CERN were about 2-m long while those prepared by UT were less than 10 cm long. The CERN and UT samples were reacted by using the same heat treatment schedule (one optimized for the PIT conductor and another for the RRP), insulated with the same fiberglass sleeve and impregnated with CTD101.

3.1.1. Measurements at University of Twente

The first two measurements, one of a RRP and the other of a PIT sample, were not successful; both presented a too low load for the onset of the irreversible degradation: 120 MPa and 60 MPa respectively for the RRP and PIT samples. After an accurate analysis, UT's researchers found that the excessive degradation was due to a concentration of the forces on the sample caused by a misalignment between the anvil and the sample. Instead of being parallel, the anvil and the sample were forming an angle equal to approximately 0.14° and to 0.27° respectively during the test of the RRP and PIT cable. This misalignment produced a strain difference on the two sides of the anvil, which was measured via strain gages, equal to about 60 % and 80 % respectively. In order to solve this issue, a second impregnation including the sample and the anvil, was performed during the preparation of the remaining two cable samples. The second impregnation limited the unbalance of the strain in the anvil to less than 2 % and the measurements of the two samples (RRP and PIT) were carried out successfully.

3.1.2. Results of the PIT CABLE Samples

Before measuring the new PIT samples, in 2016 a PIT cable sample that was reacted together with the one measured in 2013, was tested under transversal load in FRESCA. This sample was almost identical to the one tested in 2013, the only substantial difference was that the 2 dummy cables [7] were substituted with Ti sheets, which make the cable sample more robust for handling (this solution was also adopted for the cable samples specifically reacted and prepared for the EuroCirCol study). In this second test campaign, the reversible transition between the superconducting and normal state could be observed and the critical current determined. Furthermore, it was experimentally verified that up to 135 MPa of transverse load, the decrease of the critical current was reversible and associated to the reduction of the upper critical field. When loading the sample to 155 MPa, the cable was damaged at room temperature because a too large bladder pressure was used.

In 2018, University of Twente successfully measured [9] its second PIT sample, see Figure 1. The measurement confirmed that up to 150 MPa, the reduction of the critical current is mainly reversible and it is dominated by the reduction of the upper critical field. At 150 MPa the reduction of B_{c2} is larger than 10% and at 11.6 T peak field, the critical current decreased by 24 %, in line with what observed by CERN.

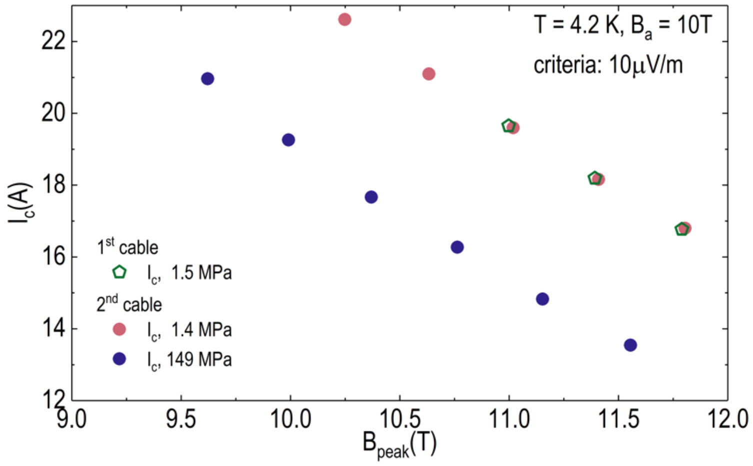

Figure 1 - PIT cable sample measured at UT: critical current vs magnetic field

It was also found that the irreversible I_c degradation starts around 120 MPa, see Figure 2, however up to 150 MPa is still limited.

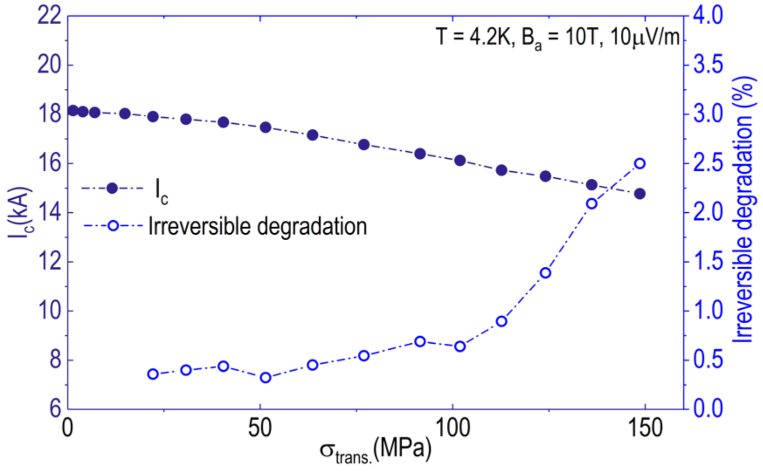

Figure 2 - PIT cable sample measured at UT: critical current and irreversible degradation measured at 10 T background field

Finally, the University of Twente test showed that cycling four times (at 4.2 K) the load between 150 MPa and 1.5 MPa did not further degrade irreversibly the critical current.

Measurements on the first new CERN PIT sample are presently on-going with the main goal of investigating the onset of the irreversible degradation with the CERN set-up.

3.1.3. Results of the RRP CABLE Samples

In 2017 two RRP cable samples were successfully measured, the first at CERN [10] and the second one at University of Twente [9]. CERN test showed that the RRP cable has a behaviour similar to the PIT cable: a significant reduction of the critical current with the transverse load, see Figure 3, associated to a reduction of the upper critical field, see Figure 4.

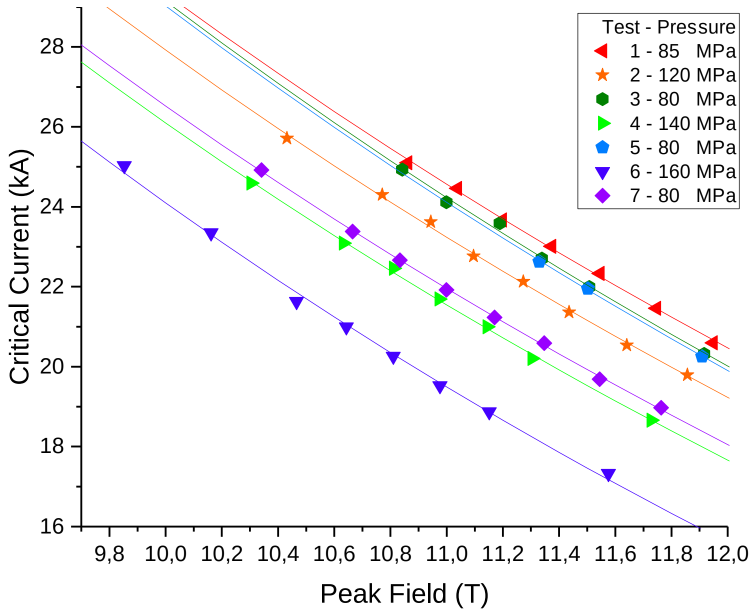

Figure 3 - RRP cable sample measured at CERN: critical current as a function of the field for different transverse loads

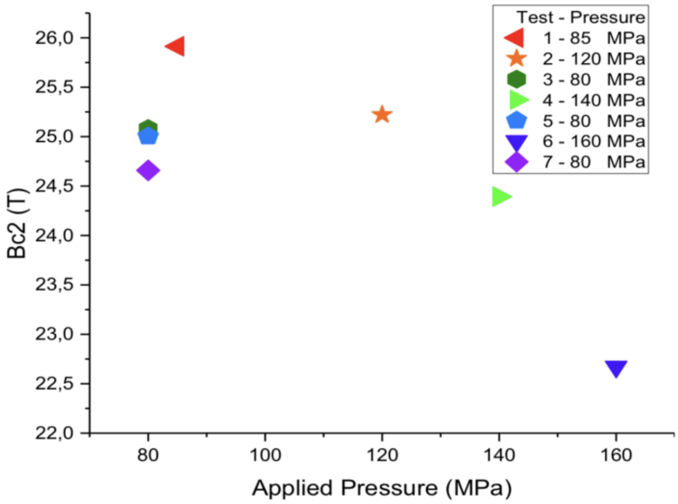

Figure 4 - RRP cable sample measured at CERN: upper critical field for different transverse loads

CERN test also showed that, in the reversible load region, the RRP cable is less sensitive to transverse loads with respect to the PIT cable: 5% reversible I_c reduction occurred at 120 MPa instead of 100 MPa.

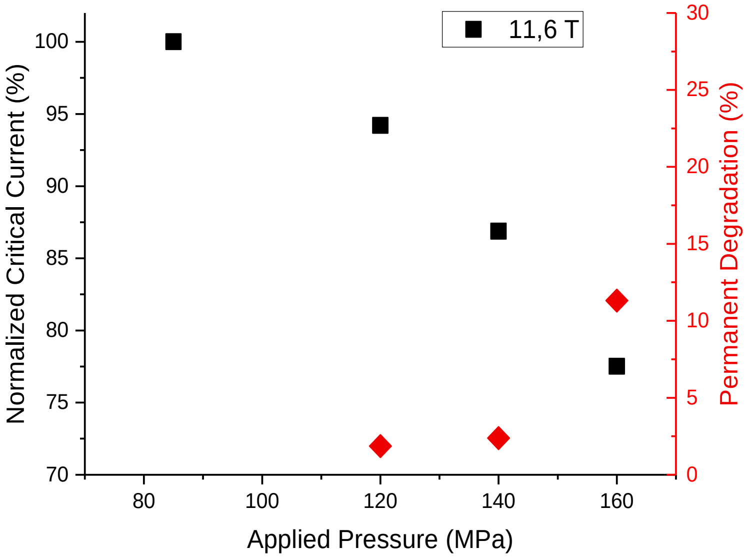

Figure 5 - RRP cable sample measured at CERN: normalized critical current at 11.6 T and permanent degradation

The same RRP cable measured by University of Twente showed results that were in line with what observed at CERN, see Figure 6. The RRP cable proved to be less sensitive to transverse loads than the PIT cable: at 150 MPa and 11.6 T peak field, the reversible reduction of the critical current was around 15% in the RRP cable, which is about 6-7% lower than in the PIT cable. More important was the difference in terms of irreversible degradation: the onset of the irreversibility was around 170 MPa for the RRP cable, which is a value about 50 MPa larger than what observed in the PIT sample test at UT.

The only substantial difference between CERN and UT results, was the larger irreversible degradation measured at CERN with 160 MPa. This difference might be due to the different load conditions: at UT the load is applied at 4.2 K while at CERN, the cable experiences a significant load already at room temperature.

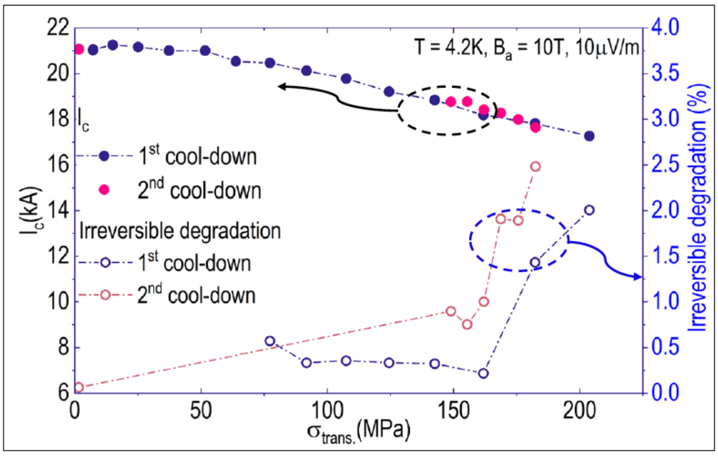

Figure 6 - RRP cable sample measured at UT: critical current and irreversible degradation measured at 10 T background field

3.2. WIRE MEASUREMENTS

The same wires used in the cable samples, were tested at the University of Geneva. An impregnated 1 mm 192 PIT was already tested by University of Geneva in 2012 [8] and showed a similar behaviour to what observed in cable measurements: a reduction of the critical current in the reversible region mainly due to the reduction of the upper critical field. Despite this similarity, wire measurements showed an irreversible degradation at transverse loads significantly lower than what observed in cable and magnet measurements. The main questions we wanted to address with the tests carried out in the framework of EuroCirCol were the following:

1) What is the origin of the discrepancy between wire and cable measurements?
2) What are the effects of different impregnations?
3) Has the RRP conductor a behavior that is similar to the PIT conductor and is it more tolerant to transverse loads?

3.2.1. Results of the PIT WIRE Samples

A possible explanation of the larger conductor degradation in wire tests with respect to cable measurements was the different geometry of the wires: round and flattened respectively in wire and cable tests. In order to investigate it, University of Geneva measured two adjacent pieces of a 1 mm 192 PIT wire: one piece was kept round and the other was rolled reducing the wire height by 15 %. As expected, the 15 % rolled wire, whose geometry resembles the one of the wires in the cable samples, had an irreversible degradation at larger transverse loads. The onset of the irreversibility was around 110 - 120 MPa and, 5% irreversible degradation occurred around 150 MPa, a value about 40 MPa larger than in round wires, see Figure 7. The results of the 15% rolled PIT wire were finally in line with the measurements performed by University of Twente on the PIT cable sample.

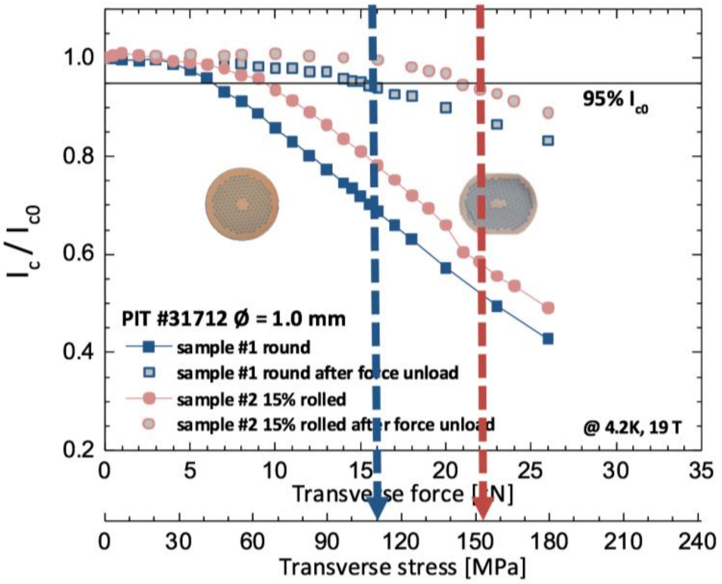

Figure 7 - 192 PIT wire measured at UNIGE: critical current reduction of a round and a 15% rolled sample measured at 19 T background field

In order to verify the impact of the impregnation, the University of Geneva prepared one sample with sty-cast, which has a Young modulus significantly larger than the one of the epoxy generally used for this type of experiment. As expected the sample impregnated with sty-cast was significantly more tolerant to transverse load, see Figure 8. Finally, they also verified that the introduction of a glass fibre sleeve in combination with the epoxy impregnation also improved the tolerance to transverse loads, see Figure 9.

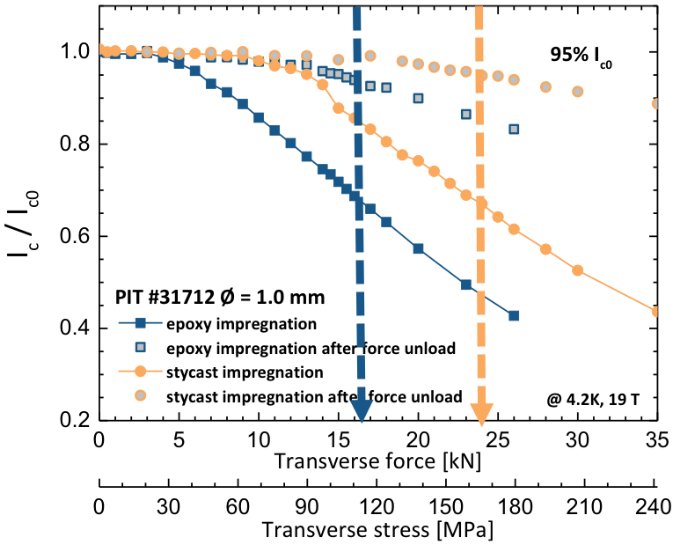

Figure 8 - 192 PIT wire measured at UNIGE: critical current reduction of two round wires impregnated one with epoxy and the other with sty-cast

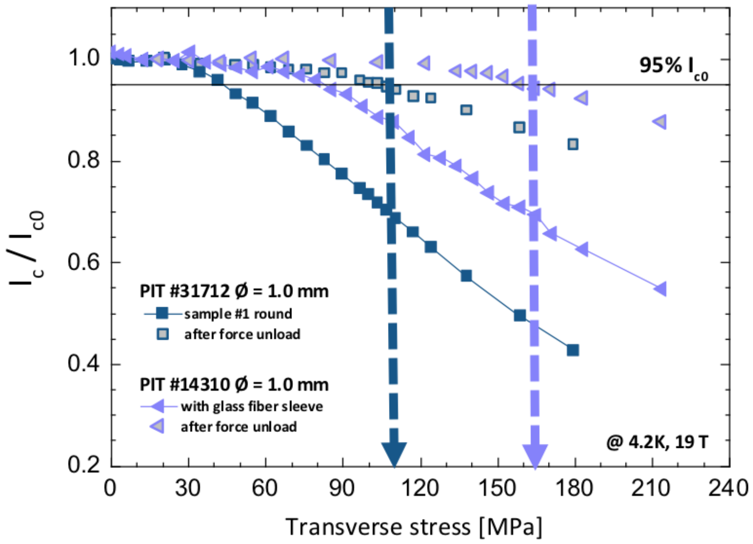

Figure 9 - 192 PIT wire measured at UNIGE: critical current reduction of a round wires impregnated one with epoxy and the other with epoxy and fiberglass

3.2.2. Results of the RRP WIRE Samples

The University of Geneva also measured round and 15% rolled 1 mm 132/169 RRP wire samples. It was found that the RRP wire is more robust than the PIT conductor and confirmed that the rolled wire is more tolerant to transverse loads, see Figure 10. The % 5 irreversible degradation occurred at 210-220 MPa, a results in line with what observed in the RRP cable test at Twente. Measurements of RRP wire samples using different types of impregnation are presently on-going.

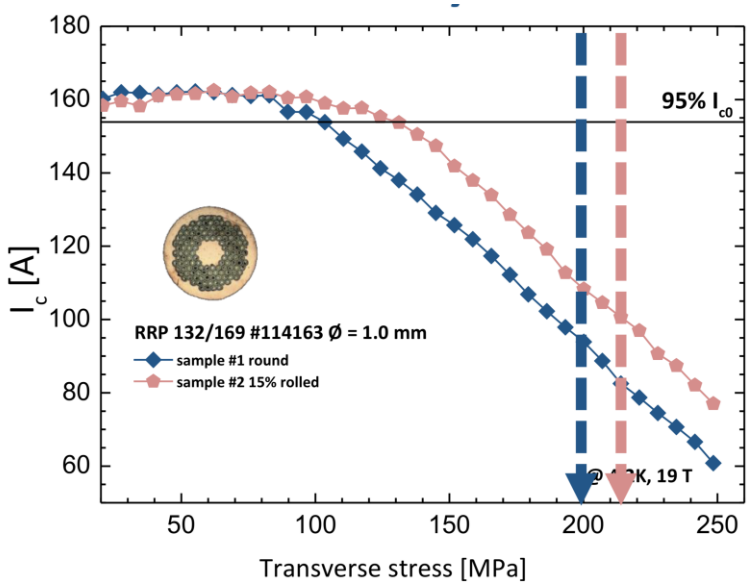

Figure 10 - 132/169 RRP wire measured at UNIGE: critical current reduction of a round and a 15% rolled sample measured at 19 T background field

4. CONCLUSION

In the framework of the task 5.5 of work package 5, the parameters of the superconductor for the design of the FCC magnets were defined and constituted a common base to compare all the magnet designs developed in the framework of EuroCirCol. Two different types of Nb_3Sn Rutherford cable were identified: an “high-field” cable and a “low field” one, both based on high J_c wires. The wire composing the high field cable is expected to have a Cu-to-non-Cu ratio around 1 and a wire diameter not larger than 1.1 mm. For the “low field” cable, a wire with a Cu-to-non-Cu larger than 1.5 and a diameter equal to about 0.7 mm was advised. Regarding the cable geometry, cables with no more than 40 strands were considered the most suitable. The cable can be produced either in rectangular shape or with a keystone angle. The keystone angle has to be sufficiently small to prevent a compaction c of the cable thin-edge, larger than 0.14. The superconducting properties of the conductor are defined by the equations and parameters of section 2.1

A comprehensive experimental study was carried out at CERN, at the University of Twente and at the University of Geneva to investigate the effect of transverse loads on the performance of the Nb_3Sn superconductor, which appears as one of the major challenges in the development of the FCC magnets. It was found that already at 150 MPa the critical current decreases substantially because of the reversible reduction of the upper critical field. The tests showed that the RRP conductor is less sensitive to transverse loads than the PIT conductor and the use of more rigid impregnations can help in sustaining a more important transverse load. From this experimental study, magnet designers can properly estimate the margin of the magnet and the maximum transverse load that the conductor can stand before degrading irreversibly.

5. REFERENCES

[1] Ekin J W 2010 Supercond. Sci. Technol. 23 083001 ‘Unified scaling law for flux pinning in practical superconductors: I. Separability postulate, raw scaling data and parameterization at moderate strains’
http://iopscience.iop.org/article/10.1088/0953-2048/23/8/083001/pdf

[2] Godeke A, ten Haken B, ten Kate H H J and Larbalestier D C 2006 ‘A general scaling relation for the critical current density in Nb_3Sn’ Supercond. Sci. Technol. 19 R100
http://iopscience.iop.org/article/10.1088/0953-2048/19/10/R02/meta

[3] Arbelaez D, Godeke A and Prestemon S O 2009 ‘An improved model for the strain dependence of the superconducting properties of Nb_3Sn’ Supercond. Sci. Technol. 22 025005
http://iopscience.iop.org/0953-2048/22/2/025005

[4] Taylor D M J and Hampshire D P 2005 Supercond. Sci. Technol. 18 S241 ‘Relationship between the n-value and critical current in Nb_3Sn superconducting wires exhibiting intrinsic and extrinsic behaviour’
http://iopscience.iop.org/article/10.1088/0953-2048/18/12/012/meta

[5] Oh S and Kim K 2006 J. Appl. Phys. 99 033909 ‘A scaling law for the critical current of Nb_3Sn Nb_3Sn stands based on strong-coupling theory of superconductivity‘
https://doi.org/10.1063/1.2170415

[6] Bottura L and Bordini B IEEE Transactions on Applied Superconductivity, Vol. 19, No. 3, June 2009 ‘J_c (B,T,ε) Parameterization for the ITER Nb_3Sn Production’
https://doi.org/10.1109/TASC.2009.2018278

[7] B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli IEEE Transactions on Applied Superconductivity, Vol. 24, No. 3, June 2014,‘Critical Current Measurements of High-J_c $hboxNb_3hboxSn$ Rutherford Cables Under Transverse Compression‘
https://doi.org/10.1109/TASC.2013.2287309

[8] C. Calzolaio, G. Mondonico, A. Ballarino, B. Bordini, L. Bottura, L. Oberli and C. Senatore 2015 Supercond. Sci. Technol. 28 055014 ‘Electro-mechanical properties of PIT Nb_3Sn wires under transverse stress: experimental results and FEM analysis’
http://iopscience.iop.org/article/10.1088/0953-2048/28/5/055014/meta

[9] P. Gao, M. Dhallé et *al.* abstract submitted to ASC 2018

[10] J. E. Duvauchelle, B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and accepted for publication in IEEE Transactions on Applied Superconductivity.

6. ANNEX GLOSSARY

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

ATS	Achromatic Telescopic Squeezing
BPM	Beam Position Monitor
c.m.	Centre of Mass
DA	Dynamic Aperture
DIS	Dispersion suppressor
ESS	Extended Straight Section
FCC	Future Circular Collider
FCC-ee	Electron-positron Collider within the Future Circular Collider study
FCC-hh	Hadron Collider within the Future Circular Collider study
FODO	Focusing and defocusing quadrupole lenses in alternating order
H1	Beam running in the clockwise direction in the collider ring
H2	Beam running in the anti-clockwise direction in the collider ring
HL-LHC	High Luminosity – Large Hadron Collider
IP	Interaction Point
LHC	Large Hadron Collider
LAR	Long arc
LSS	Long Straight Section
MBA	Multi-Bend Achromat
Nb_3Sn	Niobium-tin, a metallic chemical compound, superconductor
Nb-Ti	Niobium-titanium, a superconducting alloy
RF	Radio Frequency
RMS	Root Mean Square
σ	RMS size
SAR	Short arc
SR	Synchrotron Radiation
SSC	Superconducting Super Collider
TSS	Technical Straight Section
UNIGE	University of Geneva
UT	University of Twente