IOP Conference Series: Materials Science and Engineering

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To cite this article: P Raj *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **171** 012109

Design and fabrication of indigenous 30 kA Nb_3Sn CICC for fusion relevant superconducting magnet

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Abstract. “Magnet Technology Development Group” is engaged in focused research and development of indigenous fusion relevant superconducting magnet at Institute for Plasma Research in association with various R&D organizations. The fusion relevant superconducting magnet is under development using a cable in conduit conductor (CICC) with operating current of 30 kA at 12 T and 4.22 K. The 30 kA CICC has been designed in square cross-section (30 mm × 30 mm) consisting twisted Nb_3Sn strands and copper strands as superconducting cable, SS316LN tubes as jacket material and SS304L foil as wrapping around the cabled strands. It has been designed on the basis of required critical design parameters, operation requirements and mechanical consideration during its fabrication. Cabling technology required for twisting of Nb_3Sn and Copper strand in required configuration of cable is discussed in this paper. The effect of heat treatment on SS316LN jacket material as well as on Nb_3Sn strands is mentioned in paper. 100 m long Nb_3Sn based CICC is manufactured by pulled through technology on dedicated jacketing line. The manufacturing parameters and quality procedures for development of CICCs is successfully established and have been demonstrated with fabrication of 100 m Nb_3Sn based CICC without any technical difficulties.

1. Introduction

“Magnet Technology Development Division” at Institute for Plasma Research (IPR) is responsible for the indigenous development and fabrication of fusion relevant superconducting magnet (FRSM) and its associated technology. FRSM is designed for magnetic field of 12 T with maximum current carrying capacity of 30 kA. FRSM is conceptualized considering use of Niobium –Titanium (NbTi) or Niobium-Tin (Nb_3Sn) based CICCs with required operating parameters. CICC based approach is widely used for fusion magnets due its capability to increase current carrying capacity with high stability; low AC losses and it can withstand higher electromagnetic stresses during in actual operation of fusion relevant magnets. The design of Nb_3Sn based CICCs is carried out and optimized as per technical and operating requirements. A joint initiative between IPR and Atomic Fuels Division, Bhabha Atomic Research Center (AFD, BARC) has been taken for fabrication of such long length CICCs. Under this collaborative effort, number of trials for cabling and CICC fabrication has been performed with copper strands to establish cabling parameters and process parameters for fabrication of CICC. Pulled through technology has been selected for fabrication of long length CICCs. Dedicated jacketing line has been already developed, established and demonstrated for fabrication of such CICCs. The effect of fabrication processes and heat treatment on jacketing material is presented.

The design parameters, cabling technology and fabrication of 100 m Nb_3Sn based CICC have been discussed in this paper.

2. Design aspects of 30 kA Nb_3Sn CICC

The design of 30 kA Nb_3Sn based CICC is typically governed by stability criteria, critical current, critical temperature, critical field, copper to superconducting ratio, energy margin, void fraction and fabrication considerations. Following assumptions and analytical equations has been used for design of 30 kA Nb_3Sn based CICC [1]-[4].

- Energy deposition and the recovery times are negligible i.e. the process is instantaneous, so that the contribution of the joule heat to the energy balances is also negligible.
- All material has constant thermal properties and there is a linear relation between the critical current density (J_c) and temperature.
- Heat transfer coefficient (h) is constant in time and strands have negligible heat capacity.

Various design configurations for 30 kA CICC has been derived on the basis of analytical approach as discussed above. A feasible scheme along with its basic design parameter was mentioned in Table 1. [{(5+1) ×2+ 2× 6} ×4×6+ (1×6) ×4×4] configuration has been selected for development of 100 m Nb_3Sn CICC on the basis of its design and fabrication requirements. Basic design parameters and configuration of cabling for 30 kA Nb_3Sn based CICC is shown in Table 1 and figure 1. The stability in this CICC configuration is ensured by considering copper fraction, superconductor fraction, upper limiting current, stekly parameter, void fraction and energy margin etc. in its design. Upper limiting current for selected CICC configuration is 45.15 kA having energy margin of 934 mJ/cm^3 ensuring its thermal stabilization. Final superconducting cable was prepared by twisting of Nb_3Sn multi-filamentary strands with copper strands in sequential pattern as shown in figure 1. All the hybrid sub-cables from various stages was wound around the center cable made of only copper strands in final stage. Detail technical specification for 30 kA Nb_3Sn CICC @ 12 T is given in Table 2.There are 240 number of Nb_3Sn strands twisted with 432 copper strands as per required twist pitch. The microstructure and internal details of internal tin Nb_3Sn strand (make-LUVATA) is shown in figure 3 along with its technical specification. The critical temperature and operating temperature for given CICC is 7.4 K and 4.2 K respectively @ 12 T. The maximum critical current of Nb_3Sn strand is >250 A at 12 T magnetic field and 4.2 K temperature. SS316LN is used as jacket material while SS304L foil is used as wrapping foil over cable after its final stage. Wrapping foil increases the contact resistance, improves performance of CICC and avoids any damages to cable during insertion and orbital welding of jacket tubes.

Table 1.Design parameters for 30 kA Nb_3Sn based CICC

Configuration [{ (Sc + Cu)× 2+ k× Cu }× n×m + (1× Cu)×4×4]	Total no. of strands	No. of Cu strands	No. of SC strands
[{(5+1) ×2+ 2× 6}×4×6+(1×6)×4×4]	672	432	240

$(I_{lim})^{upp}$ (kA)	α	$(I_{lim})_{low}$ (kA)	Void fraction (f_v)	ΔE (mJ/cm^3)
45.15	0.4416	33.97	0.45	934.06

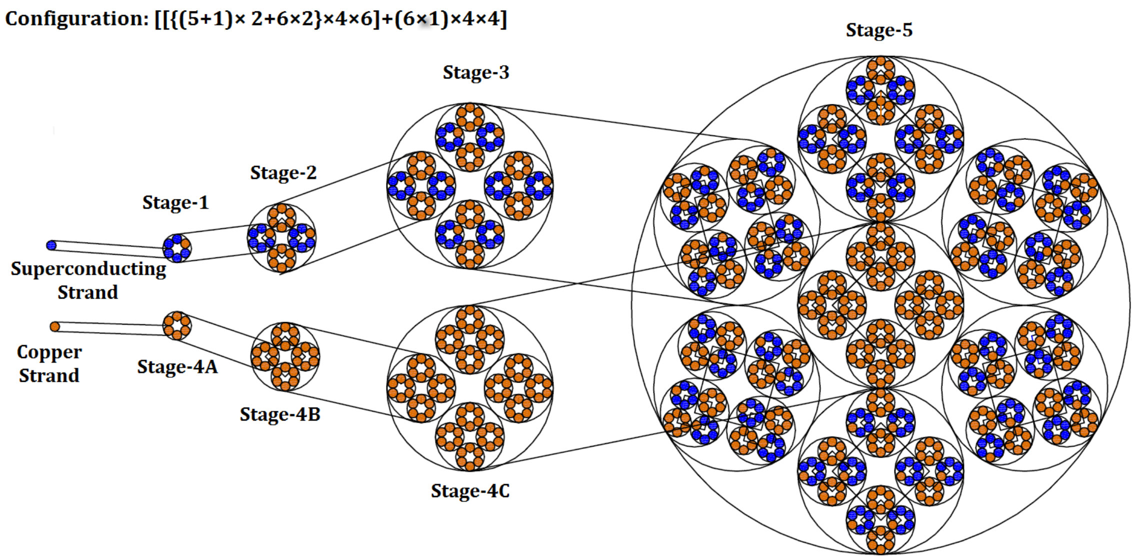
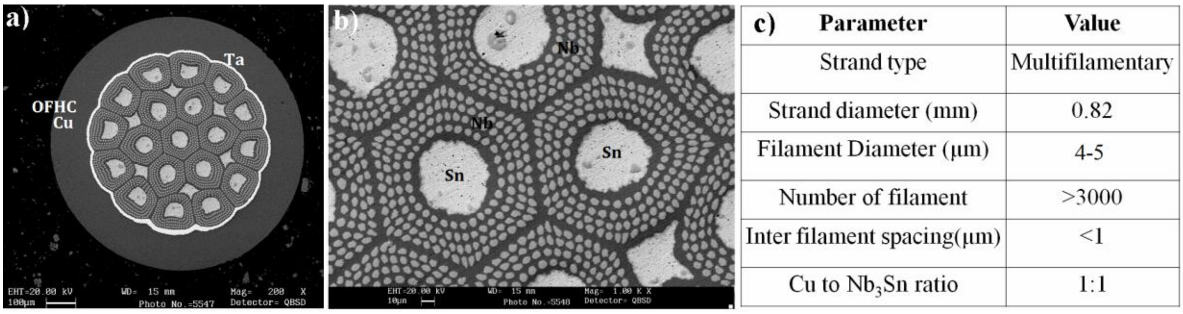


Figure 1.Design configuration and cabling scheme for 30 kA Nb_3Sn CICC

Table 2.Technical specification for 30 kA Nb_3Sn based CICC

Strand	Strand type	Internal Tin
	Strand diameter	0.82
	Cu to non-Cu ratio	1:1
	Critical current	>250 A @ 12 T
	Copper resistivity	4.5×10^{-10} Ω.m
	Critical temperature	18.3 K
	Critical Field	27.9 T
Cable	Number of Cu strands	432
	Number of Nb_3Sn Strands	240
	Void Fraction	45%
	Wrapping material	SS304L
	Final stage cable diameter	33.1 mm
	Cabling configuration	[{(5+1) ×2+ 2× 6} ×4×6+ (1×6) ×4×4]
Jacket	Jacket Material	SS316LN
	Outer diameter	38.1 mm
	Thickness	1.5 mm



Parameter	Value
Strand type	Multifilamentary
Strand diameter (mm)	0.82
Filament Diameter (µm)	4-5
Number of filament	>3000
Inter filament spacing(µm)	<1
Cu to Nb_3Sn ratio	1:1

Figure 2.a) Microstructure of green Nb_3Sn strand b) Internal details c) Specification of strand

3. Fabrication Aspect of 30 kA Cabling

The fabrication of Nb_3Sn CICC has been carried out adopting pulled through technology using dedicated jacketing line. The fabrication of CICC is done in following stages,

- Characterization of Nb_3Sn multifilamentary superconducting strand
- Cabling of strands in required design configuration
- Conduiting, shaping and sizing operation
- Qualification of CICC

The cabling process involves twisting of strands as well as sub-cables with each other in specific twist pitch as per design configuration. Conduiting of final superconducting cable has been done with the help of dedicated jacketing line developed for fabrication of long length CICC. Final stage of CICC fabrication involves insertion of cable in jacket tubes, welding of jacket tubes, forming and shaping operations. The fabrication of CICC in detail has been discussed in following sections.

3.1. Cabling Technology

CICC is manufactured by cabling the multifilamentary Nb_3Sn strands with copper strands in required scheme as per design configuration shown in figure 1. The contact resistance between strands is directly affected by void fraction. Increase in void fraction results in rise in contact resistance which ultimately decreases coupling losses in CICC. The accuracy in cabling process is very crucial as its affect the insertion process of final cable in jacket tube as well as its void fraction. Dedicated cabling setup and critical parameters of cabling process for superconducting strands has been already optimized and discussed for NbTi strands [5]-[6]. Outer diameter of cable to be achieved is dependent on the diameter of all sub-cables from each stage, twisting direction and force, settings and diameter of dies. The number trials have been performed with the help of dummy copper strands with same diameter as that of Nb_3Sn strands. The cabling parameters such as tension, cabling direction and die setting has been optimized by those trials. The cabling scheme of 30 kA Nb_3Sn CICC is shown in figure 1. The diameter of Nb_3Sn and Copper strand is 0.82 mm. Sub-cable from stage-1 consists of five strands of Nb_3Sn and one strand of copper twisted together with twist pitch of 40 mm. The observed diameter for this sub cables is found to be 2.4 mm. Cables from stage-2 consist of 2 sub cables from stage-1 and stage-4A respectively. The cable for stage-4A was prepared in parallel operation consisting 6 strands of copper only. Sub-cables from stage-3 consist of 4 sub-cables from stage-2 twisted together with twist pitch of 118 mm. Final stage cable consists of 6 sub-cables from stage-3 twisted around the pure copper cable from stage-4C with observed twist pitch of 260 mm. The observed diameter at the final stage is found to be 33.1 mm. Detail parameters of cabling process for fabrication of 30 kA Nb_3Sn based CICC are given in Table 4. Theoretical twist pitch and theoretical diameter has been observed to be nearly same in all sub-cables except final stage. The observed diameter in final stage is reduced up to 33.1 mm with increase in tension force and sizing die without damaging strands. It is required to insert superconducting cable inside SS316LN jacket tube (Inner diameter - 35.1 mm). Sub-cables from each stage of cabling are shown in figure 3a. No damage to strand surface has been observed during this exercise however untwisting of strands in some stages has been observed.

Table 3.Cabling parameters for 30 kA Nb_3Sn superconducting Cable

Stage	**Number of strands**		**Pitch (mm)**		**Die (mm)**	**Final Diameter (mm)**	
	Nb_3Sn	Copper	Theoretical	Observed		Theoretical	Observed
Stage-1	5	1	40	33.0	2.3	2.43	2.2
Stage-2	10	14	68	63	5.75	5.86	5.5
Stage-3	40	56	124	118	12	14.16	12.3
Stage-4A	0	6	40	36.0	2.47	2.43	2.35
Stage-4B	0	24	68	66.0	5.75	5.86	5.4
Stage-4C	0	96	124	122	12	14.16	11.5
Stage-5	240	432	280	260	32.5	42.48	33.1

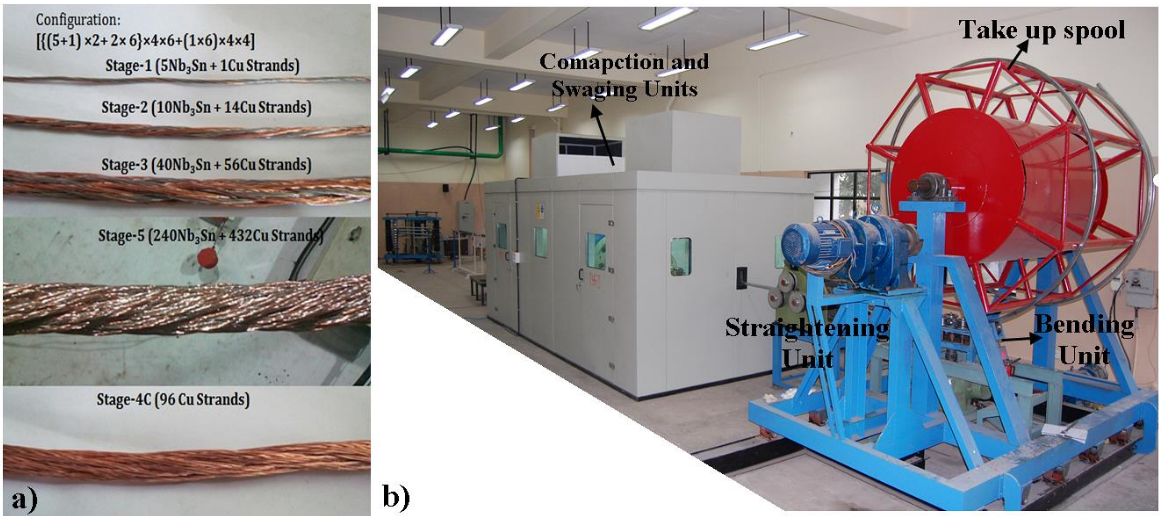


Figure 3. a) Sub cables from various stages for CICC b) Compact jacketing line

3.2. Fabrication of CICC

The fabrication of CICC involves preparation of long length conduits, insertion of superconducting cable, welding of tubes with precise penetration, qualification of weld joints, shaping operation and its spooling. The manufacturing of long length NbTi CICC adopting pulled through technology using dedicated jacketing line as shown figure 3b has been discussed and presented [6]. Seamless tubes [38.1 mm (OD) × 1.5 mm (thickness) × 5000 mm (length)] of SS316LN are used as jacket section. Each tube has been verified for their dimensional accuracies and finished by facing operation. Jacket tubes were grouped with respect to their dimensional accuracies to improve alignment during orbital welding. Final superconducting cable has been inserted through the jacket tubes supported on rotating tripod. One end of cable is connected to pulling rope. A pulling rope has been inserted through all the jacket tubes mounted on tripod support structure. Other end of steel rope was connected with spooling drum. Jacket tubes after insertion of cable were joined together by butt joint using orbital welding process and weld parameters as reported [6]. All the weld joints before shaping and sizing operation were qualified using online eddy current test setup in jacketing line. The compaction and swaging has been done on dedicated units by passing jacket tubes having cable inside it. SS316LN tube of 38.1 mm outer diameter jacket tube has been compacted to 35 mm which further shaped to square cross section of 30 mm × 30 mm.

3.3. Qualifications for CICC

Qualification of CICC fabrication has done by validation of welding procedures, NDE checks and investigating effect of cold work and heat treatment on jacket material. The welding procedure and weld parameter has been qualified and validated by extensive investigation on jacket samples. Weld samples has been validated for weld penetration, weld beads characteristics, protrusion of weld inside tube. Various qualification tests for sample involves eddy current testing, penetrant test, tensile testing, microstructural studies and leak tests. All weld samples were prepared on jacketing line with actual weld parameters used in fabrication of Nb_3Sn CICC. Along with weld qualification, it is necessary to evaluate effect of cold working and heat treatment on properties of jacket material during shaping and sizing operations for qualification of CICC [7]-[8]. The effect of weld joints and cold working on SS316LN jacket tube has been observed by extensive mechanical and metallurgical characterization at room temperature and reported [9].

Heat treatment of Nb_3Sn strands along with samples of SS316LN tube has been carried out with respect to schedule suggested by LUVATA. Straight samples of Nb_3Sn strands, its sub cables as well as strands wound on Ti-6Al-4V alloy bobbin have been carefully prepared. The multi-step heat treatment was carried out in indigenously developed furnace with temperature uniformity of ±2°C at 650°C with required ramp rate suggested in schedule,

a) Ramp up at 10°C /hr to 210°C, hold for 50 hr b) Ramp up at 5°C /hr to 340°C, hold for 25 hr
c) Ramp up at 15°C /hr to 450°C, hold for 25 hr d) Ramp up at 15°C /hr to 575°C, hold for 100 hr
e) Ramp up at 15°C /hr to 650°C, hold for 200 hr f) Ramp down at 25°C /hr to RT

Heat treated strands has been investigated in detail with SEM and EDAX analysis for its metallurgical characteristics. Figure 4 shows heat treated strands on bobbin along with formation of different phases such as Cu-Sn and Nb-Sn. Further metallographic studies have confirmed the formation of Nb_3Sn phases with respect to stoichiometric requirements. It is observed that entire Nb filaments have been consumed. Uniform tin diffusion at each Nb-filament (as per the stoichiometry 74% to 78% at Nb and 22% to 26% at Sn) is observed as shown in figure 4c. In bordering areas of Nb-filaments, α-phase has been observed. Heat treated strands sample has been evaluated for its superconducting performance in self field. It has successfully carried more than 400 A current. Due to limitation of test set up and power supply, further evaluation of Nb_3Sn strand at higher current is not carried out.

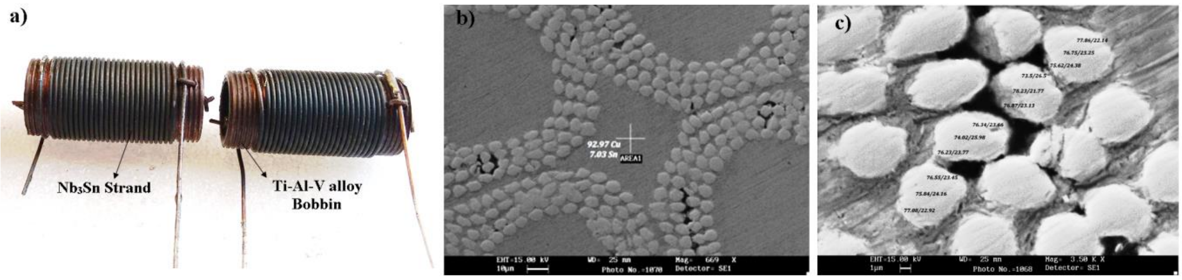


Figure 4. a) Heat treated Nb_3Sn strands on bobbin b) Cu-Sn phases c) Nb-Sn phase formation

The mechanical properties of SS316LN tube has been investigated after its heat treatment with respect to applicable ASTM standards. Figure 5a shows the tube samples from various stages of manufacturing i.e. tubes without any cold work (Stage-1), after circular compaction (Stage-2) and square swaging (Stage-3). Samples for tensile testing, impact testing, hardness testing has been prepared following applicable ASTM standards. The results of tensile testing for jacket tube samples at room temperature is shown in figure 5c. It is observed that ultimate tensile stress (UTS) and yield stress (YS) is increasing with increasing cold work even after heat treatment. Qualification test results shows that, it satisfy requirements of FRSM at room temperature. However, further qualification for fatigue life and impact at low temperature (4 K) on jacket material needs to be carried out.

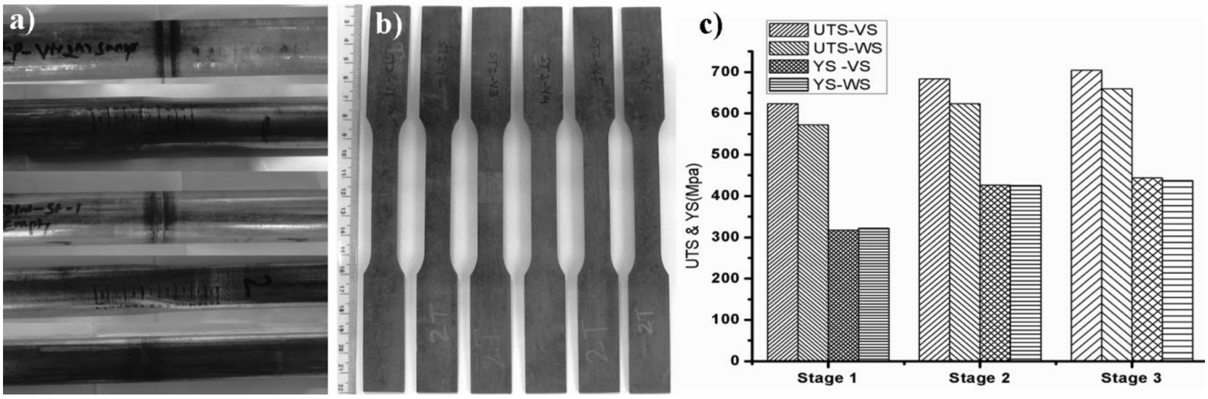


Figure 5. a) SS316LN jacket tubes after compaction and swaging b) Tensile samples from tubes c) UTS &YS of samples at room temperature (VS- sample without weld, WS–sample with weld)

3.4. Dimensional Inspection and Spooling of CICC

The spool of 30 kA Nb_3Sn CICC, its cross-section and wrapped cable of final stage are as shown in figure 6. Outer dimension of CICC after swaging has been measured at interval of 10 m. The dimension of CICC is found to be 30 mm ± 0.2 mm which is acceptable. Jacketing line is equipped with spooling drum for winding of square CICC as required. The specifically designed bender unit is located beneath the spooling drum which guides CICC and ensures tight spooling. CICC has been checked for any cracks, surface damages during spooling.

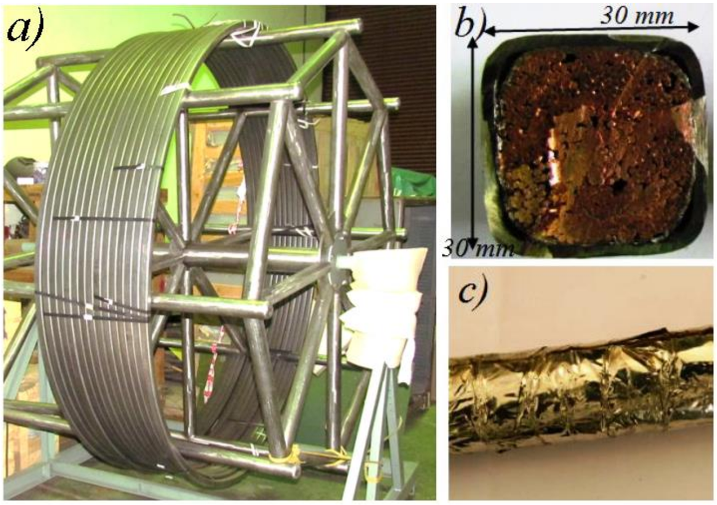


Figure 6. a) 30 kA Nb_3Sn CICC spool b) Cross-section of Nb_3Sn CICC c) Wrapped Cable of CICC

3.5. Leak Testing of CICC

Each weld joint in CICC has been qualified by in-situ eddy current test setup in jacketing line. However, leak testing of final 100 m Nb_3Sn based CICC has been done to ensure its leak tightness. CICC was pressurized with helium at 5 Kg/cm^2 and pressure has been monitored for long duration. No leaks were observed.

4. Conclusion

- The manufacturing of 100 m Nb_3Sn CIC capable of carrying 30 kA @ 12 T at 4.22 K is successfully completed.

- Developed cabling setup and dedicated jacketing line has been successfully demonstrated in manufacturing of Nb_3Sn CICC.

- The optimized process parameters for compaction, swaging and welding of jacket tubes have been applied and demonstrated in manufacturing of Nb_3Sn CICC.

- Mechanical and metallurgical characterization after heat treatment of Nb_3Sn strands and SS316LN jacket tube has been carried out.

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Acknowledgments: This work has been done under “Magnet Technology Development Programme”. We are thankful to colleagues at LTSC, BARC and MTDD, IPR for their assistance in fabrication of CICC.