Experimental Study on Effect of Twisting on Critical Currents of Nb_3Sn Cable-in-conduit Conductors

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Abstract

Cable-in-conduit (CIC) conductors made of Nb3Sn wires have been developed for use in large high-field magnets. A "wind, react, and transfer" method has been established through the manufacture of ITER magnets. The "react and wind" method is, however, preferred for a helical coil for a helical fusion reactor, because the "transfer" process will be difficult for tree-dimensional coils. In this concept, a CIC conductor is heated for reaction of Nb3Sn on a bobbin with the same equivalent radius of the helical coil, and transferred to a reel that revolves through the helical coil. Next, the conductor is pulled aside, that is, twisted, and wound in a coil case.

According to the experimental study with a model CIC conductor, the tensile strain is induced in the wires by twisting the conduit in the wire twisting direction, as expected. In this experiment, the amounts of strain change in the wires are in the order of 1/20 of the normal strain in the conduit. Since the high compressive strain in the wires can be slightly lessened by twisting the conductor, the react-and-wind method is expected to be applicable for the helical coil without degradation or with slight improvement of the conductor performance. In order to confirm this effect, small CIC conductor samples in spring-shape are being manufactured. The change of the critical current by being twisted will be measured in liquid helium with a background field.

Research Objectives

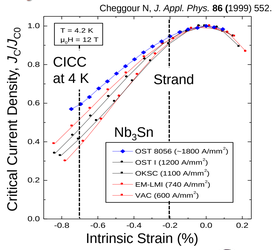
The superconducting wires in CIC conductors are under compressive strain of 0.7% after heat treatment due to the difference of thermal contraction against the conduit.

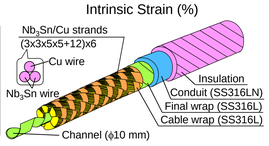
The compressive strain in the wires should be lessened by twisting the conductor in the wire twisting direction.

Pure torsional strain is induced by elongating the pitch length of a spring.

The objective is to show the feasibility of helical winding with a react-and-wind method, by which CIC conductors are wound into a helical coil case with only being twisted.

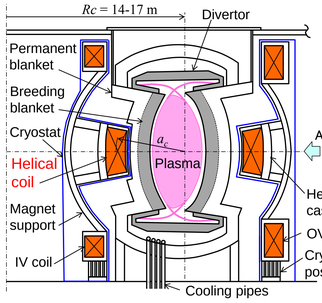
Cheggour N, *J. Appl. Phys.* **86** (1999) 552.





Layout of Magnets of Heliotron

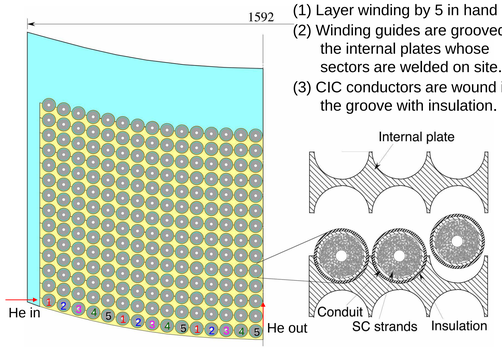
- Two sets of PCs are preferred for the axis control and for the lower stored energy.
- The relative plasma minor radius is the shorter with the smaller pitch parameter γ. The space for blanket is enlarged with the smaller γ for the same major radius.



Heliotron power plants	
Coil pitch parameter, γ	1.20
Coil major radius, R_c (m)	16.74
Coil minor radius, a_c (m)	4.02
Coil center line length (m)	164
Central magnetic field, B_0 (T)	4.90
Max. field on coils, B_{max} (T)	**11.6**
Conductor current, I (kA)	**90.2**
Coil current density, j (A/mm²)	25.0

$$g = \frac{m\, a_c}{l\, R_c}$$

Concept of Helical Coil with CICC

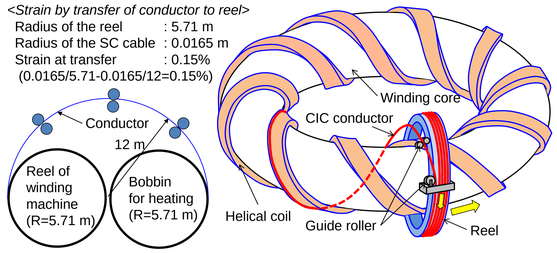


(1) Layer winding by 5 in hand
(2) Winding guides are grooved in the internal plates whose sectors are welded on site.
(3) CIC conductors are wound into the groove with insulation.

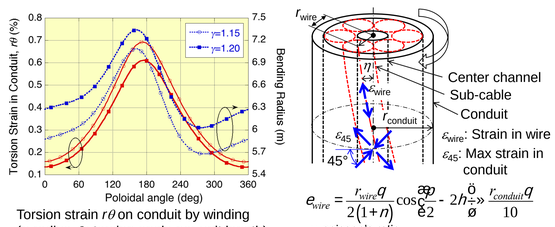
Concept of Helical Winding by React&Wind

(1) Conductors are heated for reaction of Nb_3Sn on a bobbin the circumference of which is same as the length of one pitch of the helical coil.
(2) The conductors are transferred to the reel of the winding machine.
(3) The conductors are pulled aside by the winding guide and wound in grooves of the inner plate with being wrapped with glass tapes.
(4) After winding the whole turns in a layer, the next inner plate are assembled.

<*Strain by transfer of conductor to reel*>
Radius of the reel : 5.71 m
Radius of the SC cable : 0.0165 m
Strain at transfer : 0.15%
(0.0165/5.71-0.0165/12=0.15%)



Strain during Winding Helical Coil



Torsion strain $r\theta$ on conduit by winding
(r: radius, θ: torsion angle per unit length)

$$\varepsilon_{wire} = \frac{r_{wire} q}{2(1+\nu)} \cos\frac{\pi\theta}{2} - 2h\theta \approx \frac{r_{conduit} q}{10}$$

ν: poisson's ratio

(1) The bending strain after the reaction on the bobbin is less than 0.05%.
(2) The torsional strain τ in the conduit is the largest at the inside of the torus. It is almost 0.7%.

Max tensile strain in conduit is induced in the XY direction, and it is given by $1/2(1+\nu)\ \tau = 0.27\%$
Tensile strain in the wire is 0.07% even if the wires were deformed with the conduit without any slippage.

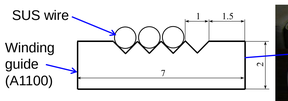
Research Plan

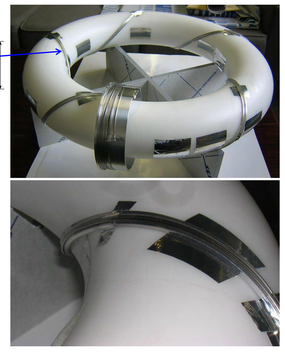
1. Feasibility study on helical winding with twisting conductors
(Experiment 1) Trial of helical winding with twisting conductors by using a mockup winding core and copper wires.
→ The possibility has been confirmed (in 2011)

2. Research on effects of twisting a CIC conductor
(Experiment 2) The measurement of the strain change of strands by twisting a model CIC conductor
→ Weak tensile strain is induced in the wires by twisting the model conductor in the same direction of the wire twisting. The strain is 1/5 of the estimated value without any slippage. (2011-14)
(Experiment 3) The measurement of the change of the critical current by twisting a small CIC conductor samples in spring-shape.
→ The testing samples are being manufactured. The first experiment is scheduled in the end of 2017.

3. Demonstration of helical winding with R&W method
(Experiment 4) The measurement of the change of current sharing temperatures by twisting a CIC conductor in 20 kA class
→ Future plan

Exp.1: Helical Winding with 1/84 Mockup

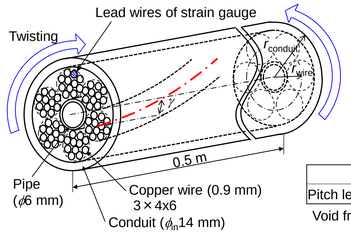




- The coil case is wound on the core with being bent and twisted by hand. Its trajectory tends to be shifted to the geodesic line.
- A stainless wire of the diameter of 0.9 mm is once wound on a bobbin of the radius of 62 mm. The bobbin is moved along the core as the wire is settled in the groove of the coil case.
- By being pulled by hand, the wire is settled correctly in the grooves. This method is feasible in principle.

Exp. 2-1: Model CIC Conductor

- A sub-size sample of CIC conductor is prepared. Six sub-cables made of 3x4 copper wires are twisted around a SUS304 pipe of the diameter of 6 mm, and they are inserted into a SUS304 conduit of the diameter of 17.3 mm. Two 1-axis strain gages are attached on a copper wire around the center in length.
- The cable is fixed to the conduit with epoxy resin at both sides. The conduit is twisted with a special tool.




Strain gage on a Cu wire

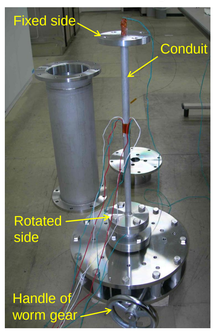

3rd stage (3x4x6 + pipe)

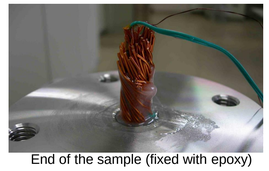
	1st	2nd	3rd
Pitch length (mm)	33.4	50.4	130

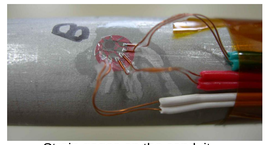
Void fraction of wires ~50%

Exp. 2-2: Experimental Setup

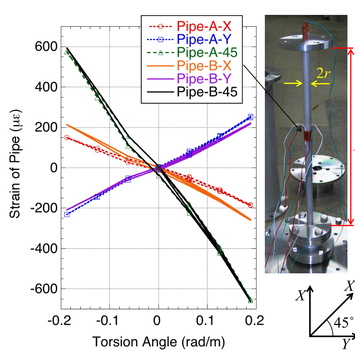
The upper side of the sample is fixed, and the lower side is rotated with the worm wheel and worm gear. The upper side is free in the vertical direction.




End of the sample (fixed with epoxy)


Strain gages on the conduit

Exp. 2-3: Strain of Conduit by Twisting



$$\tau = \sigma_{XY} \qquad \tau = \gamma G \qquad \sigma = \varepsilon E \qquad G = \frac{E}{2(1+n)}$$

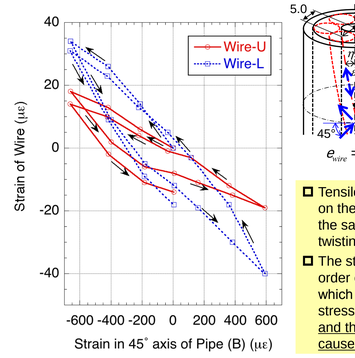
ν: poisson's ratio

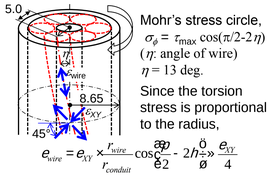
$$\varepsilon_{XY} = \sigma_{XY}/E = \gamma G/E \qquad \gamma = r\theta$$

$$4\quad e_{XY} = \frac{r \times q}{2(1+n)} = 0.00665q \qquad e_X = e_Y = 0$$

The measured strain of the conduit in 45° direction is in good agreement with the design.

Exp. 2-4: Strain of Wires by Twisting





Mohr's stress circle,
$\sigma_\phi = \tau_{max} \cos(\pi/2\text{-}2\eta)$
(η: angle of wire)
η = 13 deg.
Since the torsion stress is proportional to the radius,

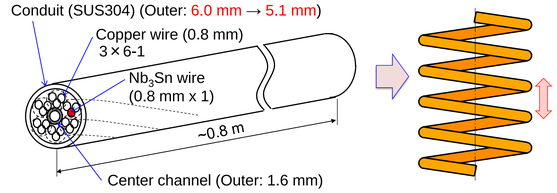
$$e_{wire} = e_{XY} \times \frac{r_{wire}}{r_{conduit}} \cos\frac{\pi\theta}{2} - 2h\theta \approx \frac{e_{XY}}{4}$$

- Tensile/compressive strain is added on the wire by twisting the conduit in the same/counter direction to the wire twisting direction, respectively.
- The strain change of wires is in the order of 1/20 of ε_{XY} of the conduit, which is smaller than the Mohr's stress circle. The reduction of strain and the hysteresis loop should be caused by slippage of wires.

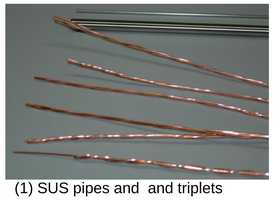
Exp. 3-1: I_c Test Samples of CICC

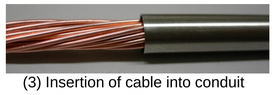
Sub-size samples of CIC conductors are being prepared for demonstration of I_c improvement by being twisted.

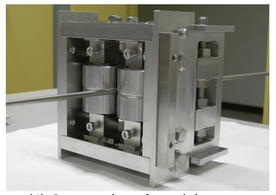
- Six sub-cables made of one Nb_3Sn wire and 17 copper wires are twisted around a SUS304 tube of the diameter of 1.6 mm, and they are inserted into a SUS304 conduit of the diameter of 6 mm. The diameter of conduit is reduced to decrease the void faction in the conduit less than 40%.
- The CIC conductor is wound by 5 turns into a spring-shape with the bending radius of 20 mm with a pitch length of 15 mm. After that, they are heat up to 650℃.

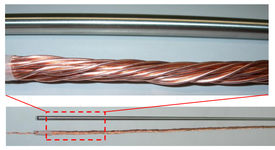


Exp. 3-2: Manufacture of Samples


(1) SUS pipes and and triplets


(3) Insertion of cable into conduit


(4) Compaction of conduit


(2) Conduit and cable (center channel + 6 triplets)

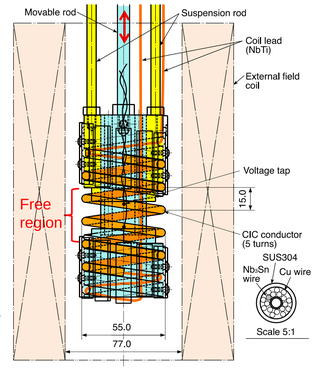
Exp. 3-3: Experimental Setup

CIC model conductors are wound into a spring-shape
in progress
Nb_3Sn heat treatment
I_c of the CIC conductor is measured in liquid helium with being twisted by changing the length of the samples.

<Torsion strain in the conduit>

Stroke of rod	Torsion strain
±20 mm	±0.65%

Ic measurement will be carried out in the end of 2017.



Summary

(1) According to a design study on helical coils made from CIC conductors with React-and-Wind method, the highest torsional strain in the conduit during winding is estimated at 0.7%. The tensile strain in the SC wires is, however, estimated at less than 0.07%. Therefore, R&W method is expected to be applicable to the helical coils.

(2) According to the experiments in twisting a model CIC conductor, the strain induced in the wires is approximately 1/5 of the design value estimated without any slippage.

(3) Small spring-shaped coils made from CIC conductors are being manufactured to examine the effect of being twisted on the critical current. The first experiment will be carried out in the end of 2017.

Acknowledgement
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