- *JAERI-NAKA* -

Development of Nb_3Sn and NbTi CIC Conductors for Superconducting Poloidal Field Coils for JT-60

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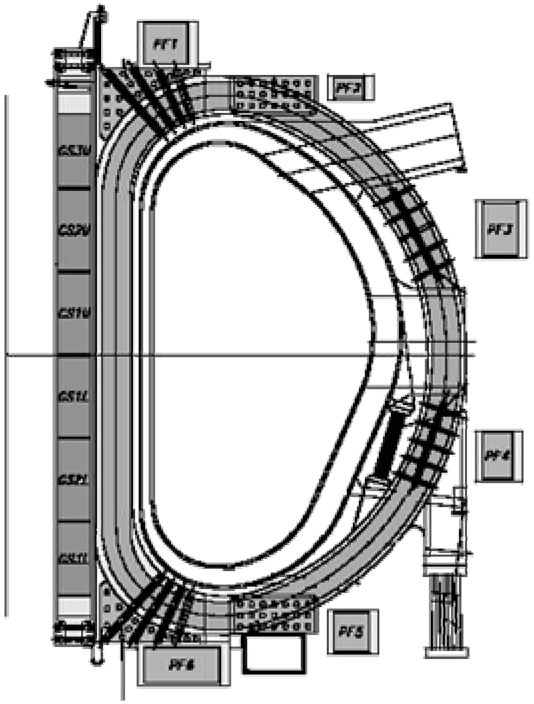
Abstract

The full-size samples of 20-kA Nb3Sn and NbTi cable-in-conduit conductors for the superconducting poloidal field coils of the fusion experimental tokamak JT-60 were manufactured. Since these coils operate in pulse mode, reduction of AC losses is one of the key issues. For the Nb3Sn conductor, in order to separate the strands sintered with Cr coat after heat treatment, bending strains were applied on it. As a result, AC loss was effectively reduced, and it was found that 0.2 % bending strain is enough to realize the design value level of 60 ms. Its critical current was also measured, and it was estimated that the compression strain due to difference between thermal contractions of the stranded wire and stainless steel conduit was -0.6 %. For the NbTi conductor, comparison between the AC losses of the SnAg- and Cr-coated conductors was carried out. The measured coupling time constant of the Cr-coated conductor satisfied the design requirement of 50 ms, however one of the SnAg-coated conductor was more than five times of the Cr-coated.

Outline

- Design of poloidal field (PF) coils conductors of JT-60SC.
- Manufacture of full-size samples of Nb_3Sn and NbTi conductors for PF coil.
- Reduction of AC loss by applying of bending strains to the Nb_3Sn conductor.
- Estimation of decrease in critical current of the Nb_3Sn conductor, which is caused by strain due to difference of thermal contraction between the strands and stainless steel conduit.
- Comparison of the coupling loss between Cr and SnAg coating for the NbTi conductor.

Superconducting Magnet System of JT-60SC



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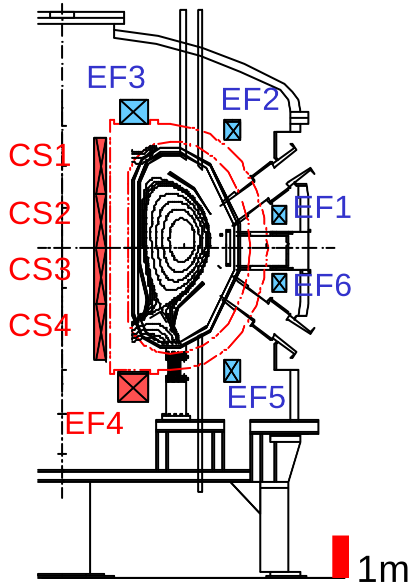
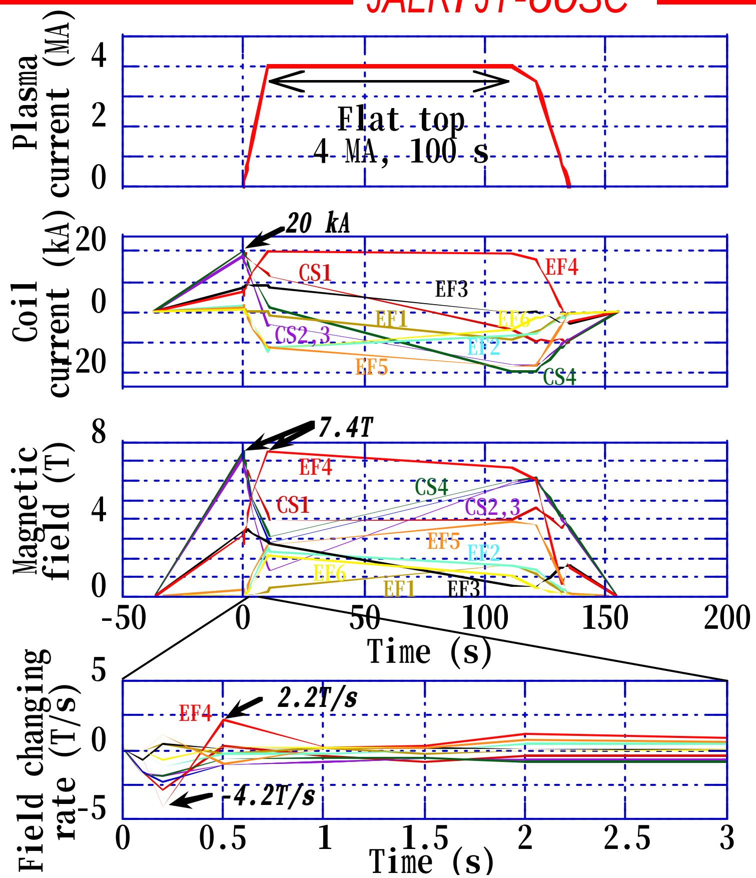


JT-60SC



The large fusion experimental tokamak JT-60 is planned to be modified to a full-superconducting coil machine (*JT-60SC*).

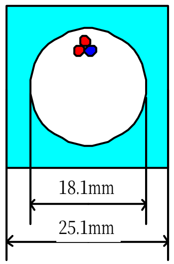
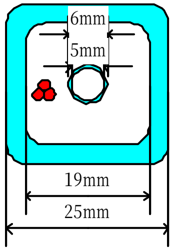
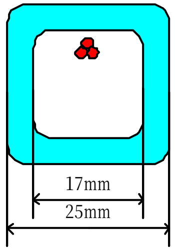
Maximum changing magnetic field rate:

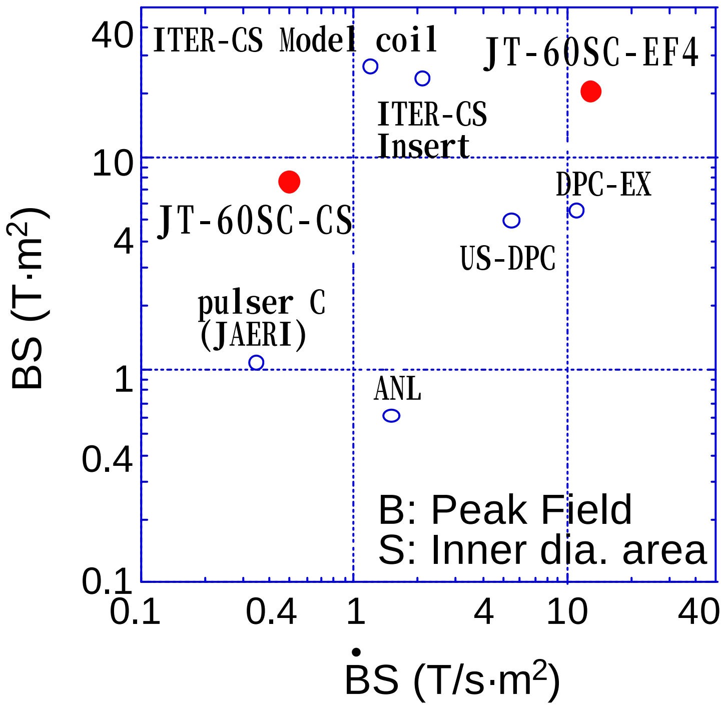
Nb_3Sn conductor (CS, EF4) -4.2~+2.2T/s

NbTi conductor (EF1,2,3,5,6) -1.0~+1.2T/s

Development of the low-AC-loss conductors is required.

Conductors Design of JT-60SC PF Coils

	CS and EF4 coil	EF coils (2001)	EF coils (2000)
Structure SS 316 LN SC strand Cu strand			
Max. Magnetic Field	7.4 T	5.0 T	5.0 T
Operating Current	20 kA	20 kA	20 kA
Operating Temp.	5.0 K	4.8 K	4.8 K
SC Material	Nb_3Sn	NbTi	NbTi
No. of Total Strands	324	486	432
No. of SC Strands	216	486	432
No. of Cu Wires	108	0	0
Cu / non-Cu Ratio	2.3	7	7
Strand Diameter	0.78 mm	0.70 mm	0.74 mm
Void Fraction	36 %	36 %	36 %
Coupling Time Constant *nt*	50 ms	50 ms	50 ms



The PF coil system of JT-60SC will be one of the largest flux swing coils among coils in the world.

Strands and Conductors Data of Full-size Samples

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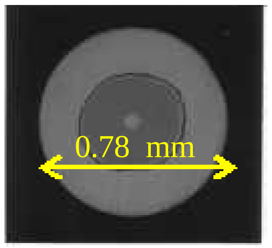
Strands Data

	Nb_3Sn Sample	NbTi Sample A	NbTi Sample B
Strand diameter	0.780 mm	0.740 mm	0.740 mm
Plating material	Cr	Cr	SnAg
Plating thickness	2 μm	2.75 μm	0.5 μm
Twist pitch	18.9 mm	12.4 mm	12.4 mm
Cu : non-Cu ratio	2.25	7.05	7.05
Resistivity of Cu stabilizer at 4.2 K	1.5×10^{-10} Ωm	1.2×10^{-10} Ωm	1.3×10^{-10} Ωm
Effective filament diameter	12 μm	65 μm	73 μm

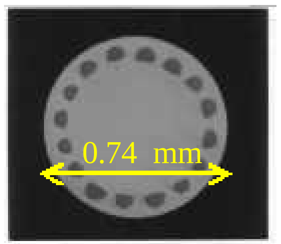
Conductors Data

	Nb_3Sn Sample	NbTi Sample A	NbTi Sample B
Cable configuration	(2-SC+1-Cu)x3x3x3x4	3x3x3x4x4	3x3x3x4x4
Number of SC strands	216	432	432
Number of Cu strands	108	0	0
Cable pitches	31/61/120/ 164/245 mm	31/62/118/ 165/250 mm	331/59/117/ 168/243 mm
Void fraction	36.2 %	35.3 %	35.9 %
Jacket material	SS304	SS304	SS304
Jacket thickness	1.95 mm	1.85 mm	1.85 mm

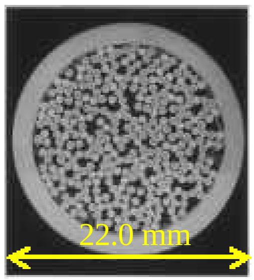
- The actual conductors have square ones, however these samples have circular jackets.
- Nb_3Sn strand was made by the bronze process.
- Effective filament diameter of the NbTi strand will be changed to 10 μm for the actual coils in order to reduce hysteresis loss.
- For sample B, oxidation treatment for SnAg coat was carried out after final cabling to increase the interstrands resistance under the condition of *200 °C x 5 hr , in the air*.



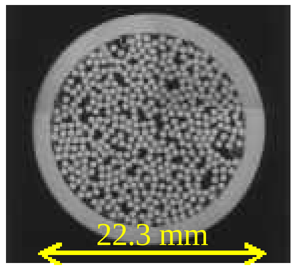
Nb_3Sn strand



NbTi strand



Nb_3Sn conductor



NbTi conductor

Development of Nb_3Sn Conductor (1)
~ Sintering with Cr increases interstrands coupling loss of the Cr-coated Nb_3Sn conductor. ~

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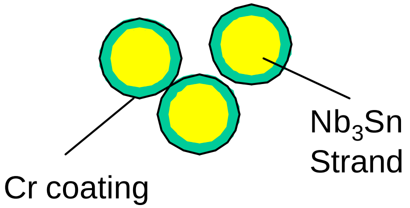
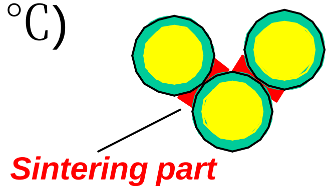
Before heat treatment



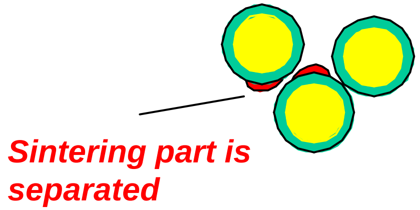
Cr coating realizes adequate interstrands resistance
- making coupling loss small,
- sharing current among strands.

After heat treatment (650 ℃)



Interstrands resistance is decreased by sintering with Cr coat.

Cyclic operation

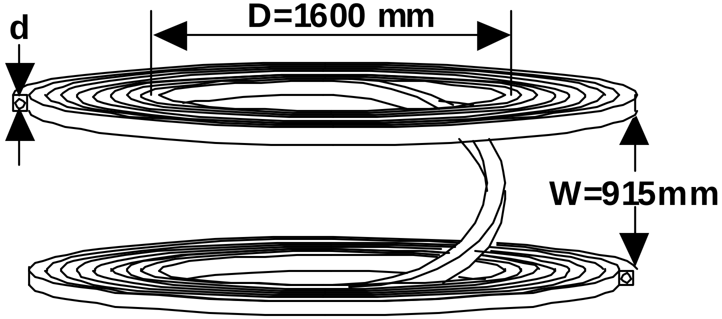


Interstrands resistance will be increased by mechanical cyclic load due to electro-magnetic force.

How should we make the coupling resistance large even at the beginning of the operation?

Bending Strain Technique

After heat treatment of the double pancakes, strain is applied to the conductors due to expanding the space between the pancakes. At that time, turn insulation work is carried out.



Strain $\varepsilon_t = \frac{Wd}{\pi D^2}$

How much strain is enough to reduce the coupling loss?

Development of Nb_3Sn Conductor (2)
~ Reduction of AC losses of the Cr-coated Nb_3Sn conductor by applying of bending strain ~

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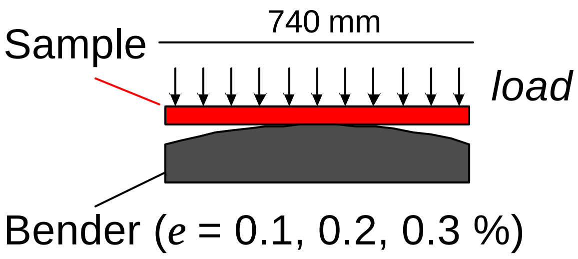
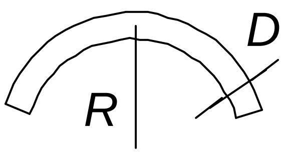
Applying of bending strain



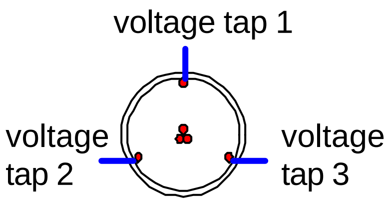
Definition of bending strain

$$e = \frac{D}{2R}$$

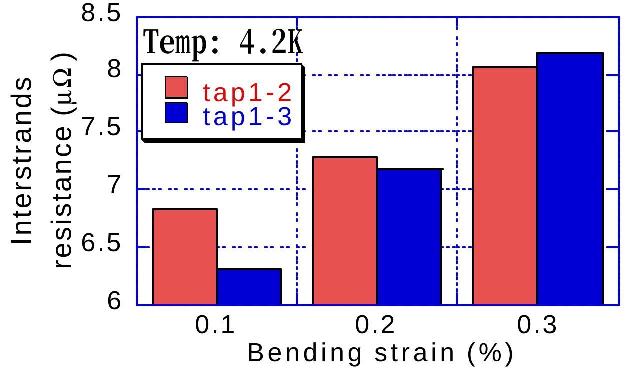


The sample was loaded to 0.1, 0.2, 0.3% bending strains in the same direction. Each strain load was not repeated.

Increase in interstrands resistance

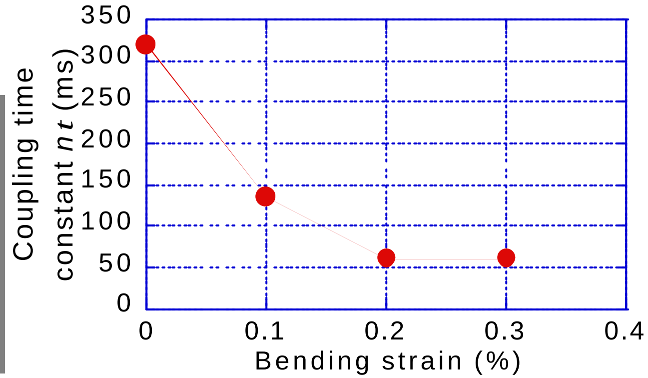


Interstrands resistance at 4.2 K shows a tendency to increase according to applied bending strain.



Reduction of AC loss

The coupling time constant $n\tau$ was reduced from 330 ms to 60 ms by applying bending strain.



- In order to satisfy the design value (50 ms) level of $n\tau$, 0.2% bending strain is enough.
- It is considered that 0.2 % bending strain can be applied on the conductor after heat treatment unless degradation of its superconductivity performance.

Development of Nb_3Sn Conductor (3)
~Decrease in critical current due to compression strain of strand from SS conduit ~

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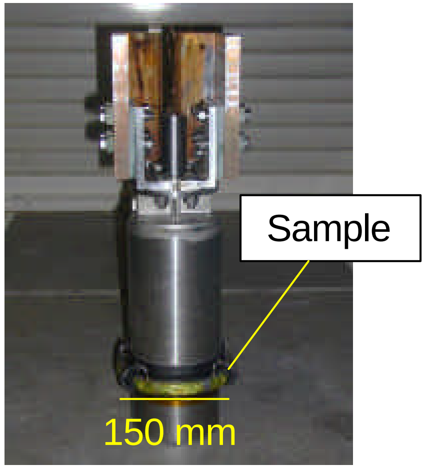
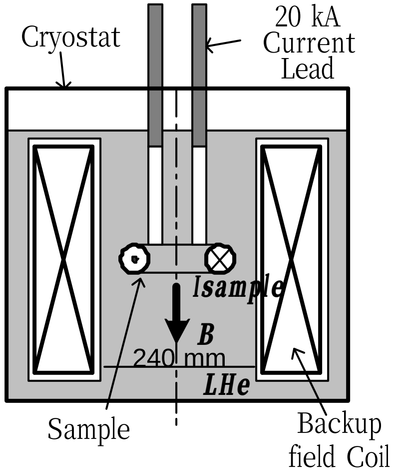


Sample for critical current measurement



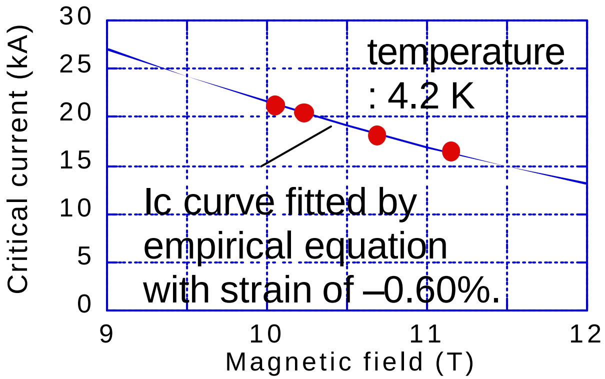
Experimental Apparatus

Critical current of the Nb_3Sn conductor is decreased due to strain caused by difference of thermal contraction between stranded wire and stainless steel conduit.

- Magnetic field was estimated taking account into self field of the conductor.
- Ic curve was fitted by the empirical equation[1].

The strain on the Nb_3Sn strands was estimated to be ***–0.60 %***.

The conductor of JT-60SC is designed under assumption that the strain is –0.7%. This measurement result suggests that the assumption is reasonable.



Results of critical current measurement

(Ic is defined as the current at which an electric field of 0.1 μV/cm appears.)

[1] ITER design description document 1.1-1.3 App. C-II Superconductor, II Superconducting magnet design criteria, December 1997. pp. 1.

Development of NbTi Conductor
~ Comparison of plating materials and critical current~

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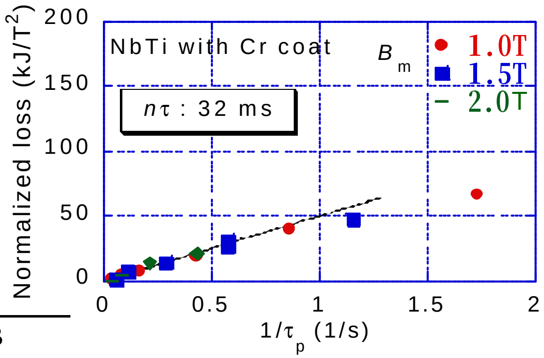
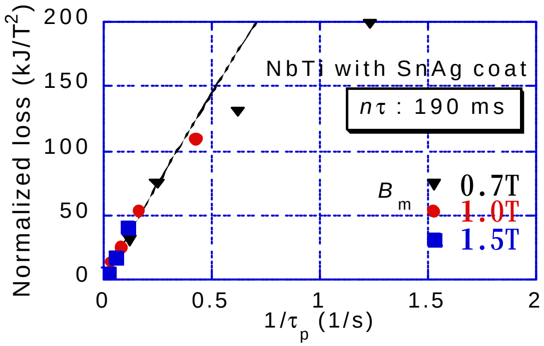
Comparison of coating materials

SnAg is very attractive for coating material of the NbTi conductor because its cost is much lower than that of Cr coating.



Cr coating



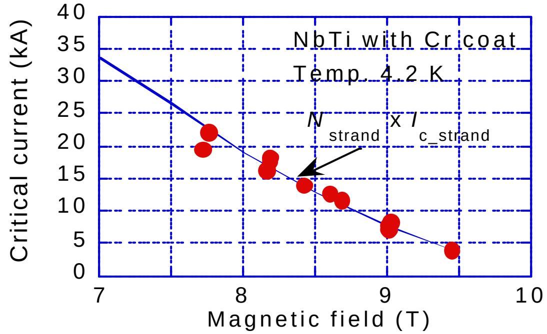
SnAg coating

	Sample A	Sample B
Coating material	Cr	SnAg with oxidation
Coupling time constant $n\tau$	32 ms	190 ms

- The coupling time constant of Cr coating is under the design value (50 ms).
- The reason why the coupling loss of the SnAg-coated conductor is more than five times of that of Cr-plated is considered that the strands inside the cable might not be oxidized sufficiently because the oxidation treatment was carried out after final cabling.

Development of more effective oxidation technique for CIC conductors is required.

Critical current



Measurement result of critical current of the full-size sample shows good agreement with value expected from the strands.

It was confirmed that no degradation has occurred during manufacturing process.

Conclusions

AC losses and critical currents measurements using the full-size conductor samples of the JT-60SC PF coils were carried out and the following results were obtained:

- Applying of 0.2% bending strain on the Cr-coated Nb_3Sn conductor is enough to reduce the interstrands coupling loss to the design value level.
- It is reasonable that designed value of the compression strain on the Nb_3Sn stranded wire due to SS conduit is -0.7%.
- For NbTi conductor, Cr coating realizes lower coupling time constant than design value of 50 ms.
- More effective oxidation technique is needed for the NbTi CIC conductor to employ the SnAg coating.

From above results, it is concluded that 20-kA and 7.4-T Nb_3Sn and 20-kA and 5-T NbTi conductors can be manufactured for PF coils of JT-60SC.